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Probabilistic Risk Assessment Modelling of
Passenger Aircraft Fire Safety

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Paul Macey

**Probabilistic Risk Assessment Modelling of
Passenger Aircraft Fire Safety**

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Abstract

This thesis describes the development of a computer simulation model for the investigation of airliner fire accident safety.

The aim of the work has been to create a computer-based analysis tool that generates representative aircraft accident scenarios and then simulates their outcome in terms of passenger injuries and fatalities. The details of the accident scenarios are formulated to closely match the type of events that are known to have occurred in aircraft accidents over the last 40 years. This information has been obtained by compiling a database and undertaking detailed analysis of approximately 200 airliner fire accidents. In addition to utilising historical data, the modelling work has incorporated many of the key findings obtained from experimental research undertaken by the world's air safety community.

An unusual feature of the simulation process is that all critical aspects of the accident scenario have been analysed and catered for in the formative stages of the programme development. This has enabled complex effects, such as cabin crash disruption, impact trauma injuries, fire spread, smoke incapacitation and passenger evacuation to be simulated in a balanced and integrated manner.

The study is intended to further the general appreciation and understanding of the complex events that lead to fatalities in aircraft fire accidents. This is achieved by analysing all contributory factors that are likely to arise in real fire accident scenarios and undertaking quantitative risk assessment through the use of novel simulation methods. Future development of the research could potentially enable the undertaking of a systematic exploration and appraisal of the effectiveness of both current and future aircraft fire safety policies.

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Contents

CHAPTER 1: AN INTRODUCTION TO AIRCRAFT SAFETY

- 1.1 Safety in Commercial Air Transport..... 1
 - 1.1.1 Unavoidable Hazards - Aircraft Accident Survival..... 1
 - 1.1.2 Air Travel: an “Acceptable” Risk?..... 2
 - 1.1.3 True Risk Versus Perceived Risk 3
 - 1.1.4 Safety and the Future 4
- 1.2 Airline Safety: An Historical Perspective..... 4
 - 1.2.1 The Development of Aircraft Safety 4
 - 1.2.2 Leadership of the United States 5
 - 1.2.3 Europe and the Rest of the World..... 6
 - 1.2.4 Other Safety Organisations..... 7
- 1.3 The Formulation of Safety Policy & Legislation 8
 - 1.3.1 Safety Regulations Applying to Airline Operations..... 8
 - 1.3.2 Formulation of Safety Legislation..... 9
 - 1.3.3 The Application of Regime Theory to Airline Safety 10
 - 1.3.4 Knowledge Resources for Improving Safety..... 13
 - 1.3.5 Certification of Aircraft for Accident Safety..... 14
- 1.4 Outline of Thesis 16
 - 1.4.1 Summary..... 16
 - 1.4.2 Path of the Research 16
 - 1.4.3 Thesis Map..... 17

CHAPTER 2: A SURVEY OF AIRCRAFT SAFETY RESEARCH

- 2.1 Air Safety Research - An Introduction..... 19
 - 2.1.1 The Need for Research 19
 - 2.1.2 Topic Areas Covered 19
- 2.2 Historical Air Accident Data 20
 - 2.2.1 Accident Data Collection and Analysis..... 20
 - 2.2.2 The Aircraft Accident Report 20
 - 2.2.3 Compilation of World-wide Accident Data..... 20
 - 2.2.4 Data Classification and Analysis..... 21
- 2.3 Aircraft Crash Testing and Impact Modelling 22
 - 2.3.1 Introduction..... 22
 - 2.3.2 Airframe Crash Tests..... 22
 - 2.3.3 Occupant Impact Testing..... 23
- 2.4 Experimental Fire Tests and Fire Modelling..... 24
 - 2.4.1 The Danger of Fire..... 24
 - 2.4.2 External Fuel Fire Tests of Airframe Structures..... 24
 - 2.4.3 Cabin Mock-up Fire Tests 25
 - 2.4.4 Fire Characteristics of Materials..... 26
 - 2.4.5 Fire Containment and Extinguishment 27
 - 2.4.6 Modelling of Fires 28
- 2.5 The Effects of Fire on People..... 30

2.5.1 Fire Lethality	30
2.5.2 Physiological Effects of Fires.....	31
2.5.3 Origin and Nature of Fire Products.....	31
2.5.4 Fire Toxicology	32
2.6 The Evacuation of Aircraft.....	33
2.6.1 The Fire Evacuation Problem	33
2.6.2 Experimental Aircraft Evacuation Trials.....	34
2.6.3 Evacuation in Smoke	36
2.6.4 Computer Simulation of Occupant Evacuation	37
2.6.4.1 Background.....	37
2.6.4.2 EXODUS	38
2.6.4.3 STRATVAC	38
2.6.4.4 EVAC	38
2.6.4.5 TAKAHASHI	39
2.6.4.6 EXITT	39
2.6.4.7 KOSTREVA	39
2.6.4.8 EXIT89	40
2.6.4.9 Colt Vegas	40
2.6.5 Computer Evacuation Models: Conclusions	41
2.7 Evaluation of Research: Implications for the Study	43
2.7.1 Breadth and Balance of Air Safety Research.....	43
2.7.2 Implications for the Current Programme of Research.....	44

CHAPTER 3: DERIVATION OF RESEARCH METHODOLOGY AND OBJECTIVES

3.1 Background to the Research.....	45
3.1.1 The Formulation of a PhD	45
3.1.2 The Research Design Process	46
3.1.3 Personal, Departmental & Institutional Influences.....	48
3.2 Initial Findings Obtained from Accident Data and Statistics	49
3.2.1 The Relevance of Historical Information	49
3.2.2 The Construction of a Preliminary Accident Database	51
3.2.3 The Nature of Past Aircraft Fire Accidents	52
3.2.4 The Diversity of Aircraft Fires	53
3.2.5 Implications for the Modelling of Aircraft Fires	55
3.2.6 The Importance of the "Total Accident Scenario"	58
3.3 A Re-appraisal of Fire Safety Research.....	62
3.3.1 The Interpretation of Scientific Work.....	62
3.3.2 Evaluation of Research in a Scientific Context	63
3.3.3 Compatibility with Historical Events	66
3.3.4 Related Difficulties.....	67
3.3.5 Conclusions.....	69
3.4 Formulation of a Computer-based Modelling Methodology	69
3.4.1 Challenges Faced in Improving Aircraft Accident Safety.....	69
3.4.2 Identification of a Research Need.....	70
3.4.3 Establishment of a Methodology	70

3.5 Thesis Aim and Objectives.....	72
3.5.1 Research Aim.....	72
3.5.2 Research Objectives.....	72

CHAPTER 4: USE OF PAST ACCIDENT DATA AND STATISTICS

4.1 Introduction: Investigation and Reporting of Civil Aircraft Accidents.....	73
4.1.1 The Investigation of Aircraft Accidents	73
4.1.2 Aircraft Accident Reports.....	76
4.1.3 Other Sources of Accident Data	78
4.1.4 Inclusion Criteria for Aircraft Accidents	79
4.2 Initial Analysis & the Formulation of an Accident Database.....	81
4.2.1 Data Requirements.....	81
4.2.2 Definitions for Categorical Classifications.....	83
4.3 Treatment and the Use of Data in Modelling.....	87
4.3.1 Determining the most Relevant Accident Parameters	87
4.3.2 Use of Categorical Data.....	89
4.3.3 Obtaining Numerical Data.....	90
4.4 The Accident Data	90
4.4.1 Two Stages of Information Gathering	90
4.4.2 Preliminary Database.....	91
4.4.3 Main Database	91

CHAPTER 5: MODEL CONSTRUCTION AND DEVELOPMENT

5.1 Conceptualisation of the Risk Assessment Model.....	93
5.1.1 General Requirements for the Computer Programme	93
5.1.2 Matching the Level of the Analysis to Data Quality	93
5.1.3 Linking of Sub-Models.....	94
5.1.4 User-Interface Requirements	95
5.1.5 Perceived Customers for the Work.....	98
5.2 Utilisation of the Model.....	99
5.2.1 Developmental Usage and Performing Formal Runs	99
5.2.2 Probabilistic Methods and Monte Carlo Simulation	100
5.2.3 Intended Use of the Model.....	102
5.2.4 Current Issues in Air Safety.....	103
5.3 Choice of Modelling Environment	103
5.3.1 Requirements for the Programming Environment.....	105
5.3.2 Computer Platform Considerations	105
5.3.3 General Purpose Simulation Software.....	106
5.3.4 Programming Languages: Basic, Fortran and C.....	108
5.3.5 The Need for an Animated Graphics Display.....	108
5.4 Strategy for Model Development.....	109
5.4.1 Structuring of the Programme	109
5.4.2 Development in the Longer Term.....	111

CHAPTER 6: ACCIDENT SCENARIO GENERATION AND MODELLING OF IMPACT EFFECTS

6.1 Analysis of Accident Scenarios	113
6.1.1 Dealing with the Diversity of Aircraft Fire Accidents	113
6.1.2 Structuring of the Scenario Generation Module	115
6.1.3 Treatment of Historical Trends in Airliner Fire Safety	118
6.1.4 Modelling of Occupant Fatalities	124
6.2 Implementation of Scenario Generator: Primary Parameters.....	125
6.2.1 Primary Accident Parameters	125
6.2.2 Prerequisites for Establishing the Category of Fire Present	125
6.2.3 Phase of Flight in which the Accident Occurs.....	126
6.2.4 Construction of Scenario Event Tree.....	127
6.2.5 Type and Configuration of Aircraft Involved.....	128
6.3 Impact Classification & Disruption Modelling.....	130
6.3.1 The Nature of Aircraft Crashes.....	130
6.3.2 Research into Aircraft Crashworthiness	131
6.3.2 Fuselage Structural Damage	132
6.3.3 Cabin Disruption.....	135
6.3.4 Cabin Orientation and Exit Opening Delays	136
6.3.5 Trauma Injuries and Fire Survival	138
6.3.6 Psychological Considerations in Aircraft Crashes.....	140
6.4 Miscellaneous Accident Parameters.....	140
6.4.1. The Significance of other Scenario Features	140
6.4.2 Determination of Airport Distance	141
6.4.3 The Nature of the Accident Site	141
6.4.4 Effects of Wind and Weather.....	141
6.4.5 Time of Day at Which Accidents Occur.....	142

CHAPTER 7: FIRE AND CABIN THERMOTOXICITY MODELLING

7.1 The Nature of Aircraft Fires.....	145
7.1.1 Introduction.....	145
7.1.2 Categories of Fire	145
7.1.3 Open Liquid Fuel Pool Fires.....	147
7.1.4 Internal Fires	148
7.1.5 Miscellaneous Fire Types	151
7.2 Computer Modelling of Fires	152
7.2.1 Emergence of Computational Fire Analysis.....	152
7.2.2 Development of Fire Modelling Approach.....	154
7.3 Representation of Cabin Thermo-toxic Environment.....	161
7.3.1 Formulation of the Modelling Approach.....	161
7.3.2 A Note on the Measurement of Smoke Intensity.....	163
7.3.3 Choice of Cabin Fire Effects to be Modelled	163
7.3.4 Representation of Cabin Geometry.....	165
7.3.5 Calibrating Levels of Fire Effects.....	166
7.4 Modelling of External Pool Fires.....	167
7.4.1 Empirical Quantification of Open Pool Fires	167
7.4.2 Fire Geometry Analysis: Equivalent Pool Fire Areas	170

7.4.3 Modelling of Fire Geometry and Growth Rate.....	171
7.4.4 Heat and Smoke Production	173
7.5 Cabin Airflow Model.....	175
7.5.1 The Requirement to Model Cabin Air Flows	175
7.5.2 Potential Flow Modelling: The Panel Method.....	176
7.5.3 Initialisation of Panel Geometries	177
7.5.4 Impact Damage and Destruction of Cabin by Fire	180
7.6 Cabin Fire Development	181
7.6.1 Fire Ingress	181
7.6.2 Fire Spread inside the Passenger Cabin.....	182
7.6.3 Effects of Airflow on Cabin Fire Development.....	185

CHAPTER 8: PASSENGER EVACUATION MODELLING

8.1 Modelling Approach.....	189
8.1.1 Conceptualisation of the Evacuation Process	189
8.1.2 Integration of the Evacuation Model within the Analysis	189
8.2 Spatial Representation of Aircraft.....	190
8.2.1 Aircraft Cabin Grids	190
8.2.2 Grid Dimensions.....	191
8.2.3 Cell Contents	192
8.2.4 Treatment of Exits	192
8.2.5 Programming of Cabin Data.....	188
8.2.6 Structural Disruption & Fuselage Breakages.....	193
8.3 The Simulation Clock & Passenger Movement	196
8.3.1 Event Driven Simulation Methodology.....	196
8.3.2 Movement at Different Speeds	197
8.3.3 Passenger Crossing and Overtaking	199
8.4 Passenger Decision Making & Behaviour	200
8.4.1 Representation of Passenger Characteristics	200
8.4.2 Escape Strategy.....	201
8.4.3 Exit Choice	204
8.4.4 Effecting Changes in Escape Evacuee Plans	205
8.4.5 The Role of Passenger Behaviour.....	206
8.4.6 Conflict Resolution and Parallel Queuing	208
8.5 Exits & Stairways	209
8.5.1 Exit Types.....	209
8.5.2 Door Exits.....	211
8.5.3 Escape Hatches	211
8.5.4 Stairways and Double-Deck Aircraft.....	212
8.6 Evacuee Injuries & Incapacitation.....	212
8.6.1 Fractional Incapacitation Approach.....	212
8.6.2 Irritant Effects.....	213
8.6.3 Narcosis	214
8.6.4 Heat.....	215
8.6.5 Impact Trauma Injuries.....	216

CHAPTER 9: MODEL USAGE

9.1 Undertaking Simulation Analysis 217
 9.1.1 Use of the Simulation Model 217
 9.1.2 Analysis Approach..... 218
 9.1.3 Presentation of Simulation On-Screen..... 219
 9.1.4 Model Output and Presentation of Results 221
9.2 Certification Evacuation Trials 222
 9.2.1 Introduction..... 222
 9.2.2 Model Set-up 223
 9.2.3 Discussion of Evacuation Trials Results 223
9.3 Representation of a Manchester-Type Fire Scenario 226
 9.3.1 Introduction..... 226
 9.3.2 Model Set-up 226
 9.3.3 Discussion of Accident Features..... 227
 9.3.4 Simulation of Alternative Outcomes 231
9.4 Multiple Accident Analysis 233
 9.4.1 Introduction..... 233
 9.4.2 Model Set-up 233
 9.4.3 Findings and Discussion..... 234
9.5 Safety Implications of New Very Large Aircraft Designs 235
 9.5.1 Introduction..... 235
 9.5.2 Model Set-up 236
 9.5.3 A3XX Upper and Lower Deck Comparison..... 236
 9.5.4 Experimentation with Boeing VLA Design 237

CHAPTER 10: EVALUATION AND CONCLUSIONS

10.1 Evaluation of Research..... 239
 10.1.1 Attainment of Research Objectives 239
 10.1.2 Limitations in the Work..... 241
 10.1.2.1 Dealing with Difficulties 241
 10.1.2.2 Modelling of Evacuee Behaviour 242
 10.1.2.3 Analysis of Crash Effects 244
 10.1.2.4 Approach to Fire Modelling 245
 10.1.2.5 Implementation Issues 248
 10.1.2.6 Limitations Inherent in the Use of an Holistic Approach..... 248
 10.1.3 Implications for Design & Implementation of Research..... 249
 10.1.4 Implications at Policy Level 251
10.2 Suggestions for Further Research 254
 10.2.1 Improvement of the Model 254
 10.2.2 Safety Studies that could be Undertaken with Model..... 254
 10.2.3 Research within the Field of Aircraft Safety 255
10.3 Conclusions..... 255

APPENDIX A: PRELIMINARY ACCIDENT DATABASE 259

APPENDIX B: AIRLINER CABIN CONFIGURATIONS283

APPENDIX C: CRASH SCENARIO ANALYSIS291

APPENDIX D: THERMAL RADIATION FROM OPEN POOL FIRES301

APPENDIX E: FIRE SPREAD DIAGRAMS.....309

APPENDIX F: FIRE SCENARIO ANALYSIS319

REFERENCES329

List of Figures

Figure 1.1: Influences in Policy Selection & Implementation	13
Figure 1.2: Map of the Thesis.....	17
Figure 2.1: Zonal and Field Representations of Fires.....	29
Figure 2.2: Aircraft Safety Research: Current State of the Art.....	43
Figure 3.1: The Research Design Process	46
Figure 3.2: The Occurrence of Impacts in Fire Accidents.....	53
Figure 3.3: Fire Classification as a Function of Ingress Time.....	55
Figure 3.4: Casualties in Aircraft Fire Accidents	61
Figure 3.5: Accident Simulation Methodology	71
Figure 4.1: Example Entry from World Airline Accident Summary	78
Figure 4.2: Information Categories Used for Initial Data Survey	82
Figure 4.3: Stages of a Typical Airline Flight	84
Figure 4.4: Example Entry from Main Accident Database	92
Figure 5.1: Model Simplification Through Structuring of Data.....	95
Figure 5.2: Multiple Regression Analysis of Monte Carlo Output	101
Figure 5.3: Historical Aircraft Evacuation Times	102
Figure 5.4: Schematic of STELLA Fire Scenario Model	107
Figure 5.5: Structure of the Simulation Programme.....	110
Figure 6.1: The Complexity of Aircraft Accident Scenarios.....	114
Figure 6.2: Creation of Accident Scenarios.....	117
Figure 6.3: Annual Frequency of Airliner Fire Accidents.....	120
Figure 6.4: Annual Frequency Trends in Airliner Fire Accidents.....	121
Figure 6.5: Historical Fatality Rates in Airliner Fire Accidents.....	123
Figure 6.6: Probability Event Tree for Primary Scenario Parameters	127
Figure 6.7: Cabin Configurations used in Initial Development.....	129
Figure 6.8: Airbus A310 Widebody Cabin Configuration	130
Figure 6.9: Probability Distribution for Determining the Position of a Single Fuselage Break.....	133
Figure 6.10: Probability Distribution for Determining the Positions of Two Fuselage Breaks	134
Figure 6.11: Cabin Disruption as a Function of Fuselage Structural Damage Present in an Incident	136
Figure 6.12: Impact Fatality Rates.....	138
Figure 6.13: Radial Plot of Wind Velocities in Past Aircraft Fire Accidents.....	142
Figure 6.14: Variation in Accident Frequency with Time of Day.....	142
Figure 7.1: Proportion of Energy Radiated from Gasoline Pool Fires	148
Figure 7.2: Stages in the Development of a Closed Compartment Fire	149
Figure 7.3: Stratification of Fire Effects.....	151
Figure 7.4: Basic Features of Aircraft Fire Scenarios	155
Figure 7.5: Primary Mechanisms of Fire Spread.....	159
Figure 7.6: The Potential Flow Analogy	160
Figure 7.7: Use of Different Grid Resolutions to Represent Fuselage Geometry	166

Figure 7.8: Cylindrical Model of Flame Geometry	168
Figure 7.8: Plotting of Fire Location and Spread	171
Figure 7.9: Probability Contour Map for Fire Starting Position.....	172
Figure 7.10: Use of Generic Fire Growth Curve	173
Figure 7.11: Implementation of External Fuel Fire Model.....	174
Figure 7.12: The Panel Method	177
Figure 7.13: Panel Model of Aircraft Fuselage	178
Figure 7.14: Cabin Airflow Vectors Resulting from Exit Opening.....	179
Figure 7.15: Airflow Inside and Around a Broken Fuselage.....	180
Figure 7.16: Variation in Time Required for Fire Ingress.....	182
Figure 7.17: Use of Cell-Vertex, Cell-Boundary and Cell-Centred Cabin Fire Parameters.....	184
Figure 7.18: Fire Burnthrough and Internal Fire Development.....	185
Figure 7.19: Effects of Cabin Airflow on Fire Spread	186
Figure 8.1: Cabin Grid Approximation	191
Figure 8.2: Example Grid Construction Command.....	194
Figure 8.3: Definition of Cabin Grid for a Small Airliner.....	195
Figure 8.4: Insertion of Fuselage Breaks into Cabin Grid.....	196
Figure 8.5: Event Driven Simulation of Evacuee Movement.....	198
Figure 8.6 : Crossing and Overtaking in a Narrow Aisleway.....	199
Figure 8.7: Method of Measuring Exit Distances.....	202
Figure 8.8: Choosing Between Multiple Escape Routes	203
Figure 8.9: Determining Evacuee Escape Options	207
Figure 8.10: Refinement of Passenger Movement Capabilities	209
Figure 8.11: Categorisation of Aircraft Exits	210
Figure 8.12: Calibration of Exit Flow Rates.....	211
Figure 9.1: On-screen Presentation of Simulation Model	220
Figure 9.2: B-757 Certification Evacuation Trial.....	224
Figure 9.3: Distribution of Evacuation Times Achieved in 100 A320 Trials.....	225
Figure 9.4: Development of Cabin Thermo-Toxic Environment	228
Figure 9.5: Passenger Evacuation Sequence.....	230
Figure 9.6: Evacuation Progress Plot.....	230
Figure 9.7: Evacuation Times Achieved in 100 A310 Accidents.....	234
Figure 9.8: Progress of Airbus A3XX Evacuation	236
Figure 9.9: Modification of Boeing VLA Design	238
Figure C.1: Fuselage Structural Damage Levels (Fuselage in one Piece).....	293
Figure C.2: Fuselage Structural Damage Levels (Fuselage in two Pieces: Front Section)	293
Figure C.3: Fuselage Structural Damage Levels (Fuselage in two Pieces: Rear Section)	293
Figure C.4: Fuselage Structural Damage Levels (Fuselage in Three Pieces: Front Section)	294
Figure C.5: Fuselage Structural Damage Levels (Fuselage in Three Pieces: Centre Section)	294
Figure C.6: Fuselage Structural Damage Levels (Fuselage in Three Pieces: Rear Section)	294
Figure C.7: Variation in Cabin Orientation at Structural Disruption Level of 0.00..	295

Figure C.8: Variation in Cabin Orientation at Structural Disruption Level of 0.25 .. 295

Figure C.9: Variation in Cabin Orientation at Structural Disruption Level of 0.50 .. 295

Figure C.10: Variation in Cabin Orientation at Structural Disruption Level of 0.75 296

Figure C.11: Variation in Cabin Orientation at Structural Disruption Level of 1.00 296

Figure C.12: Variation in Exit Opening Times at Structural Disruption Level of 0.00
..... 297

Figure C.13: Variation in Exit Opening Times at Structural Disruption Level of 0.25
..... 297

Figure C.14: Variation in Exit Opening Times at Structural Disruption Level of 0.50
..... 297

Figure C.15: Variation in Exit Opening Times at Structural Disruption Level of 0.75
..... 298

Figure C.16: Variation in Exit Opening Times at Structural Disruption Level of 1.00
..... 298

Figure C.17: Variation in Airport Distance for Landing and Approach Accidents
Involving Impact Fires..... 299

Figure C.18: Variation in Airport Distance for Landing and Approach Accidents
Involving Burnthrough Fires 299

Figure C.19: Variation in Airport Distance for Landing and Approach Accidents
Involving External Fires 299

Figure C.20: Variation in Airport Distance for Takeoff and Climb Accidents
Involving Impact Fires..... 300

Figure C.21: Variation in Airport Distance for Takeoff and Climb Accidents
Involving Burnthrough Fires 300

Figure D.1: Cylindrical Model of Fire Geometry..... 302

Figure D.2: Atmospheric Transmissivity for a1400 K Thermal Radiation Source... 303

Figure D.3: Mean Surface Emissive Power for Gasoline, Kerosene and JP-4 Pool
Fires 305

Figure D.4: Notation used in Cylindrical Flame Model 306

Figure F.1: Place of Fire Initiation (Burnthrough Fires) 319

Figure F.2: Place of Fire Initiation (Impact Fires)..... 320

Figure F.3: Place of Fire Initiation (Internal & External Fires)..... 320

Figure F.4: Variation in Fire Area: Burnthrough and Impact Fires..... 321

Figure F.5: Variation in Fire Area: Internal Fires..... 321

Figure F.6: Variation in Fire Area: External Fires..... 322

Figure F.7 Variation in Shape of Equivalent Pool Fires..... 322

Figure F.8 Change in Fire Shape with Spanwise Position..... 323

Figure F.9: Change in Fire Shape with Lengthwise Position 323

Figure F.10: Fire Movement in Spanwise Direction 324

Figure F.11: Fire Movement in Lengthwise Direction..... 324

Figure 7.12: Parametric Fire Growth Function..... 325

Figure F.13: Fire Extinguishment Times for Different Fire Types 326

Figure F.14: Variation in Fire Extinguishment Times with Type of Terrain Present at
the Accident Site..... 327

Figure F.15: Dependency of Extinguishment Time on Fire Area 327

List of Tables

Table 1.1: Regulations Governing Air Carriers Operating in the USA.....	9
Table 2.1: Polymer Thermal Decomposition Products.....	32
Table 2.2: Classification of Evacuation Simulation Models	41
Table 3.1: Three Aircraft Fire Accidents.....	59
Table 4.1: Parameters Associated with High Fire Fatality Rates	88
Table 5.1: Computer Platforms Available for Use	105
Table 6.1: Exit Opening Delay Factors	137
Table 6.2: Impact Casualty Rates	139
Table 7.1: Categories of Fire Model Available for Use	155
Table 7.2: Scaling of Cabin Conditions Present During Fire Flashover	167
Table 7.3: Pool Fire Penetration into the Passenger Cabin	183
Table 8.1: Evacuee Actions	203
Table 8.2: Incapacitation and Death from Irritant Fire Products.....	214
Table 9.1: Results of Certification Trial Evacuations.....	225
Table 9.2: Exit Details in Manchester Fire Accident.....	227
Table 9.3: Results of Manchester Accident Analysis	229
Table 9.4: Modification of Exit Usage in Manchester Accident Scenario	232
Table 9.5: Summary Results of 100 A310 Accident Simulations.....	234
Table 9.6: Evacuation Details for A3XX Upper and Lower Decks	237
Table 9.7: Effect of Revision to Galley Configuration on Time Required for Passenger Evacuation	234

Chapter 1: An Introduction to Aircraft Safety

1.1 Safety in Commercial Air Transport

1.1.1 Unavoidable Hazards - Aircraft Accident Survival

Every form of human transportation exposes its participants to some type of risk. In most circumstances, hazards can be interpreted as originating from a combination of two factors that are inevitably associated with any transport system; the presence of significant quantities of energy and the influence of human actions. Thus, at the most general level, transportation accidents can be taken to comprise a loss of control over energy, caused by human fallibility. The unavoidability of both these factors suggests that we will forever be dealing with issues of travel safety.

This thesis is concerned with the examination of hazards associated with one of the most recent (and potentially safest) forms of travel; commercial air transport. Although the risks of air travel currently appear to be acceptable to most passengers flying with airlines around the world, this situation has not always existed and it may become steadily more difficult to maintain in the future. However, before these issues are discussed further, it is perhaps necessary to briefly examine what the existing standards of airline safety are and determine where opportunities for further improvement might lie.

Over recent decades, somewhere in the region of 1000 people have typically died per annum, world-wide, in aircraft accidents (Taylor, 1996). Notably, this figure has remained remarkably consistent over the last 30 years. Most of these deaths accrue in major accidents, which tend to occur at a frequency of 10 - 25 events each year. With current traffic levels, these statistics imply an average hull-loss rate of around 1.5 aircraft per million airline departures flown (Murray, 1996). As a result, the average risk of a passenger losing their life when making a single airline flight today is just under one in a million.

These figures clearly demonstrate that aircraft accident *rates* (measured per hour flown) are very low. Nevertheless, although accident rates have been decreasing steadily since the 1950's, further improvements are becoming progressively harder to achieve. As a result, for the first time, we may now be seeing a levelling off in accident rates (Taylor, 1996). Over the same period, growth in levels of air traffic has been sufficient to ensure that accidents have occurred at a reasonably consistent *frequency* world-wide and have resulted in the deaths of similar numbers of people from year to year. However, if traffic levels continue to rise as they have done in the past and accident rates do not improve any further, we should expect accidents to occur at greater frequencies in coming years.

Given that even the prevailing figure of around 1000 fatalities per year is generally acknowledged as being unacceptable, both in human and economic terms, what can be done to improve (or at least maintain) the situation in the future? Obviously, the most direct way of reducing fatality numbers is to prevent accidents from happening in the first instance. Overall, approximately 60 percent of aircraft accidents are deemed as being "unsurvivable" (Taylor, 1996). In these scenarios, precluding the event from occurring appears to be the only feasible way to reduce the losses of life involved. Consequently, the adoption of a preventative safety policy

approach constitutes the primary approach of aviation authorities, aircraft manufacturers and operators alike. Accident prevention measures address areas such as Crew Resource Management (CRM), safety training and awareness, technological developments, systems redundancy, aircraft maintenance and operating procedures.

However, accident prevention does not fall within the scope of the current thesis. Instead, attention is focused on a second way to improve safety in air travel - by reducing the lethality of accidents when, inevitably, they do occur, wherever opportunities might exist for doing so. Obviously, in order for such an approach to be worthwhile, there must be a reasonable prospect of occupants surviving in a significant number of aircraft accidents. The figure given above indicates that this survival potential is present in about 40 percent of cases. Although this proportion might appear to unfavourably small, it still constitutes a major area in which lives might be saved. In numerical terms, these "survivable" or "partially survivable" events have involved an average of about 600 passenger fatalities per annum in recent years (Taylor, 1996). This figure is too great to accept and consequently needs to be dealt with both through accident prevention and through accident lethality reduction measures.

1.1.2 Air Travel: an "Acceptable" Risk?

Air travel has developed over the last fifty years to become the pre-eminent form of transport over long distances. The scale of the industry has grown to the point where, world-wide, a commercial aircraft takes off on average almost every two seconds, twenty-four hours a day, 365 days a year. The passengers aboard these flights are able to travel large distances in less time, with less cost and more convenience than provided by most other modes of transport.

Most of these people will not pause to consider their implicit assumption that they will be arriving safely at their destination without drama or mishap. Passengers demand and pay for the right to expect travel cocooned in a comfortable, benign, environment, provided with in-flight facilities and professional cabin attendant services. Half-hearted safety demonstrations given before take-off may often be perceived as being irrelevant and cockpit announcements given in a relaxed, authoritative tone help to engender an air of absolute safety in the minds of passengers. Detachment from the technology and challenges associated with flight operations has grown to the point where frequent flyers may take air travel as for granted as riding in a taxi or train.

However, these considerations cannot change the inescapable fact that air travel is, inherently, perhaps the most dangerous form of public transport. Modern transport aircraft consist of delicate, lightweight structures, with wings full of potentially explosive fuel and a fuselage typically crammed with large numbers of oblivious passengers. Engines provide a continual source of fire and propel the vehicle through an unpredictable and continuously changing environment as fast as technological limits will allow. If a catastrophic event occurs, an airliner may have to limp onwards for many hundreds of miles before an attempt at a safe landing can be made. When examined in these terms, all commercial passenger flights constitute potential disasters waiting to happen. It has only been through the continual refinement of safety standards and procedures that air travel has grown to become an acceptably safe form of transport.

In recent decades, it has become apparent that there have been two keys to attaining this achievement. Firstly, travelling by air has continued to become safer in *real terms*, measured either as exposure to danger per mile or per trip flown. However, arguably, this factor alone has not been enough to ensure the continued acceptance of air travel. It has also been necessary to ensure the *perceived* risks of flying have remained acceptable in the minds of the general public. Although this second factor has been dealt with satisfactorily up until the present, problems may be encountered in maintaining this situation into the future. The reasons for this will be discussed in the next section.

1.1.3 True Risk Versus Perceived Risk

It was stated in the introduction that the average chance of a passenger losing their life when taking a commercial flight is slightly less than one in a million. By almost any measure, this is an extremely low level of risk exposure and it appears to be acceptable to most people, especially when presented logically in these terms. However, inevitably, accidents are impossible to eliminate entirely in aircraft operations. When these events occur, they are often extremely severe and involve loss of life both in a violent manner and on a very large scale. As a consequence of this, aircraft accidents have been to be subject to increasingly graphic and prominent coverage in the news media over recent years. Regardless of whether these developments are in the public interest or not, greater levels of awareness are liable to mean that people may become sensitised to the nature of hazards posed by air travel. For most passengers, any fears associated with the occurrence of a major incident appear to subside quickly or else they are overridden by the necessity for travel or other practical considerations. A small proportion of airline passengers, however, may find their fears harder to overcome and have to travel under considerable stress or, in extreme circumstances, may even be unable to fly at all. In these cases, the perceived safety of air travel has decreased significantly, even though actual safety standards have remained unaltered. Unfortunately for the airline industry, perhaps, it is these perceptions rather than true facts that are most likely to be foremost in the minds the travelling public in the aftermath a major incident.

For the lay person, the perceived risks of flying are directly related to the information that they receive about aircraft accidents. For most people, this knowledge is obtained predominantly from media headline reporting of catastrophic incidents. The frequency at which this type of coverage occurs is obviously proportional to the number of major air accidents that occur world-wide. Unfortunately, given long-term developments in air traffic and the levelling off of safety rates seen in recent decades, media coverage of major aircraft disasters looks set to increase significantly in the future. It is therefore not unreasonable to expect that greater exposure to these news events, in combination with ever more graphic depiction of their details, will result the perceived risk of air travel increasing in the future.

In revenue terms, the air transport industry is reliant on passenger perceptions of safety rather than the actual safety levels being achieved. Given the previous argument, this implies that the frequency, rather than the rate of occurrence of major accidents must be seen to be acceptable in the eyes of the general public if the air transport industry is to continue to prosper. It has already been seen that limiting the frequency of accident occurrence in times of burgeoning traffic growth may not be

possible to achieve. Also, with the prospect of larger aircraft types entering service, accidents are set to become more substantial (and even more newsworthy) in terms of size of the human tragedy involved. In business terms, the financial impact of these trends is likely to be compounded by spiralling rates of compensation settlements and ever tighter operating margins. These are clearly some very ominous problems for the air transport industry to deal with.

1.1.4 Safety and the Future

If it is not possible to prevent accidents from occurring at greater frequencies in coming years, what can be done to maintain public acceptance of air travel? It was seen earlier that the air transport industry has essentially adopted a two-way approach in dealing with air safety; firstly through accident prevention and then by increasing the survivability of accidents when they do occur. Because using the former approach alone is not proving to be sufficient, then mitigating the human losses incurred in aircraft accidents occur looks set to become increasingly important in the future. Currently, most of the flying public choose not to ponder on the issue of aircraft accident survival and are thus likely to regard their prospects in such an event as being hopeless. If perceptions of safety are to be maintained, however, public attitudes towards aircraft accidents and even the treatment of these events in the media will have to change.

This task will not be straightforward to achieve. The nature of aircraft accidents means that many lives are lost in unsurvivable crashes. The hopelessness of the situations that are encountered in these scenarios cannot be denied or concealed. However significantly more potential may exist when attempting to deal with events that involve less severe circumstances and in reducing the large number of passenger deaths suffered as a result of aircraft fires. It is the assessment of precisely these aspects of aircraft safety that form the subject of this thesis.

1.2 Airline Safety: An Historical Perspective

1.2.1 The Development of Aircraft Safety

Commercial aviation was born in the years immediately following the First World War. Surplus war aircraft and the availability of returning pilots lead to a rapid rise in the use of aircraft in a miscellany of tasks, in both Europe and North America. These activities included entertainment (such as "barnstorming"), aerial photography, limited passenger services, advertising and postal delivery. In the years immediately following the war, many of the aircraft operators possessed a pioneering spirit that could sometimes verge upon recklessness and there existed an amateurish outlook towards the matter of safety. Correspondingly, accidents occurred at what now seems an appallingly high rate in the post First World War period.

The regulation of fledgling commercial aviation industry was greatly facilitated by the formation of the US Airmail Service in the early 1920's. The operators of this service, the American Post Office Department, required its pilots to be tested and to have at least 500 hours of experience. An aircraft inspection and maintenance programme was also set up in concert with the training of pilots. The results of these activities were notable; in 1924 the US Air Mail Service experienced

one fatality every 463,000 miles flown, in comparison with the average of one fatality every 13,500 miles for the remainder of the US commercial aviation industry.

In 1925, the US Post Office Department transferred its air mail services to private operators, establishing the World's first scheduled air services. Some of these early operators evolved into some of today's major American airlines. These carriers also offered a limited passenger service for wealthy customers, but this proved much less profitable than the carriage of mail.

The first government legislation concerning the growing commercial aviation industry was the 1926 US Air Commerce Act. This gave the Department of Commerce regulatory authority over all commercial aviation activities and established responsibilities that were designed to promote the fledgling industry. A new Aeronautics Branch was formed within the Department of Commerce, to oversee the regulation of aircraft and airmen and to help establish a commercial aviation infrastructure. These early programmes created proper procedures for pilot training and regulated aircraft certification, operation and accident investigation for the very first time.

The expansion of the US aviation industry in the 1930's and the development of new higher performance aircraft left the Department of Commerce struggling to provide the necessary oversight and support. Consequently, in 1938 the Civil Aeronautics Authority (CAA¹) was formed to deal with safety programmes and, for the first time, economic regulation. In 1940, the new authority was transferred back into the Department of Commerce and the Civil Aeronautics Board (CAB) was formed, responsible for all regulatory and investigatory matters.

After the Second World War, surplus transport aircraft and a ready supply of trained pilots lead to the expansion of non-scheduled services, by air taxi operators. The US CAA, at the time sympathetic to private and small operators, exempted these companies from economic regulation. In addition their small aircraft were allowed to be operated to less stringent safety regulations than those imposed on the scheduled airlines. This differentiation is still maintained in airline operations today throughout the world.

1.2.2 Leadership of the United States

The introduction of commercial jet aircraft in the 1950's and the mid-air collision of two large passenger aircraft in 1956 led to the establishment of a new aviation organisation, the Federal Aviation Agency (FAA), in 1958. This agency combined most of the functions of the old CAA and CAB, although the latter was still maintained to deal with areas where a conflict of interest could potentially occur, such as economic regulation and accident investigation.

The major roles of the FAA can be summarised as (Wells, 1991):-

1. Setting minimum standards for the design, materials, workmanship, construction, and performance of aircraft, aircraft engines, propellers and appliances.
2. The provision of reasonable rules and regulations and minimum standards for inspection, servicing, and overhauls of aircraft, aircraft engines, propellers and appliances, including equipment and facilities used for such activities.

¹ As distinct from the current UK Civil Aviation Authority

3. The specification of the timing and manner of inspections, servicing and overhauls and the delegation of private persons to conduct examinations and make reports in lieu of Agency officers and employees.
4. The prescription of reasonable rules and regulations governing the reserve supply of aircraft, aircraft engines, propellers, appliances, and aircraft fuel and oil, including fuel and oil carried in flight.
5. The provision of other reasonable rules, regulations, or minimum standards governing other practices, methods and procedures necessary to provide adequately for national security and safety of air commerce.

Following its creation, the FAA strengthened many regulations concerning training and equipment, creating intense opposition within the air transport industry. In 1966, The Federal Aviation Agency became the Federal Aviation Administration, coming under the auspices of the newly formed Department of Transportation (DOT). It has held this name to date and the organisation remains the most prominent aviation safety authority in the World.

The National Transportation Safety Board (NTSB) was also established at the time that these changes were being made. The role of the NTSB was defined as providing an independent investigative body to determine and report the cause of transportation (rather than just aviation) accidents. Currently, all major US aircraft accidents are investigated by the NTSB, without obligation to either the FAA, airline operators or aircraft manufacturers. The body's responsibilities also include the undertaking of special studies related to safety and accident prevention. The remaining accident investigation duties of CAB also were moved to the NTSB.

Following industry-wide dissatisfaction with CAB policies the operations of US airlines were deregulated in 1978. In the following six years, the CAB control of carrier routes and fares was phased out and the remaining functions of CAB were transferred to the DOT. The latter included performing carrier fitness evaluations, issuing operating certificates, collecting and disseminating airline financial data and providing consumer protection services.

1.2.3 Europe and the Rest of the World

Regulation of safety in commercial aviation was also quickly established in Europe and other countries after the close of the First World War. However, due to the fragmentation of civil aviation activities between countries, progress was slower and on a somewhat smaller scale than in developments in the United States. More recently, this situation has been addressed with the establishment of the pan-European Joint Aviation Authorities (JAA). This organisation has been formed with the aim of harmonising civil aviation operations, regulations and safety standards across all 23 of its member-states, operating on a scale directly comparable to that of the FAA. Significant progress is now starting to be made towards merging some of the safety regulations issued by the FAA and JAA. For example, in the case of airworthiness requirements for large aeroplanes, the US FAR 25 and European JAR 25 regulations are produced in an identical format and differences in wording are few enough for them to be highlighted with underlining in each of the two documents.

Because the JAA is still at a relatively early stage in its establishment, it currently operates through its constituent national aviation authorities (Frantzen, 1991). The most prominent of these include the UK Civil Aviation Authority (CAA),

the French DGAC, the Italian RAI and the DFVLR in Germany. Each of these organisations possesses expertise in particular areas of regulation and safety within the civil aviation industry; consequently, their roles within the JAA are assigned to ensure an appropriate distribution of responsibilities.

Historically, the largest contribution to European civil aviation regulation and safety activities has been made by the United Kingdom and France. In the UK, an Accidents Investigation Branch (AIB) had been established within the Royal Flying Corps as early as 1915. When a Department of Civil Aviation was set up in the Air Ministry at the end of the First World War, the AIB moved to this department and became responsible for investigation of both civil and military accidents. The 1920 UK Air Navigation Act gave the Secretary of State for Air power to make regulations for the investigation of civil aircraft accidents and the first European legislation for this purpose were the UK Air Navigation (Investigation of Accidents) Regulations of 1922. Following the Second World War, the Ministry of Civil Aviation was created and made responsible for all certification and operating requirements, including the activities of the AIB. The AIB was passed to the Department of Transport in 1983 and in 1987 was renamed the Air Accidents Investigation Branch (AAIB).

In the area of safety regulation, the UK CAA and its predecessors have been responsible for the issue of British Civil Air Worthiness Requirements (BCARs). More recently, under the auspices of the JAA, the CAA has also played a key role in the drafting many of Europe's Joint Aviation Requirements (JARs).

Outside of the US and Europe, other nations have played a comparatively minor role in the international development of civil aviation safety, as perceived from a Western standpoint, at least. Former Eastern Block countries have either developed standards independently or aligned themselves with the infrastructure established by the former Soviet Union. Most of these nations, including Russia, together with far East countries such as China, South Korea, Japan and Indonesia are now adopting or are beginning to harmonise their indigenous procedures with FAA/JAA practices.

In the past, British influence has been significant in Canada, India, South Africa, New Zealand and Australia. Transport Canada is now closely aligned with the FAA, with accidents being investigated independently by the Transportation Safety Board (TSB). In Australia, civil aviation falls under the responsibility of the Federal Department of Transport and accidents are handled by Bureau of Air Safety Investigation (BASI), which maintains close links with the UK AAIB.

In spite of the progress that has been made in improving safety regulation and standards around the World, some important black spots still remain. Most notably, these comprise continental Africa and South America. Operating standards in the latter, at least, have recently become the subject of FAA attention, but accident records indicate that much progress still remains to be made in many of the countries involved.

1.2.4 Other Safety Organisations

Increasingly, moves are being made towards establishing greater levels of international collaboration in the regulation of the global air transport industry. On a regional level, the activities of the JAA in Europe have already been mentioned; also, the FAA and Transport Canada are currently in the process of establishing a similar level of integration in North America.

Globally, however, the most universal influence is provided by the International Civil Aviation Organisation (ICAO). This body was formed in 1947 to act as a specialised agency of the United Nations and it is charged with furthering development, co-operation and safety within the global air transport industry. The organisation's influence extends world-wide, across a total of approaching two hundred member states. Some of the roles that are played by ICAO in international air safety will be examined more closely in Chapter 4 of the thesis.

Two other bodies worthy of mention here are the International Airline Pilots Association (IALPA) and the Flight Safety Foundation (FSF). Both of these groups are independent, non-profit making organisations that possess powerful lobbying influence and hold widespread respect throughout the World's aviation safety community.

1.3 The Formulation of Safety Policy & Legislation

1.3.1 Safety Regulations Applying to Airline Operations

All airlines World-wide are required to run their services according to a set of nationally adopted operating rules and procedures. These regulations govern the every-day operation of aircraft in public service and define requirements for flight operations, facilities, inspection, maintenance and training. It has been seen that FAA or equivalent JAA rules covering these aspects of aircraft operations have been widely adopted in Western countries and, increasingly, harmonisation with these standards is beginning to occur in many other areas of the World. FAA legislation is published in the form of Federal Aviation Regulations (FARs), many of which are (or are currently in the process of being) mirrored by directly comparable European Joint Aviation Requirements. For reasons of simplicity, therefore, the discussion in this section will be restricted to the examination of American FARs. Many of the observations made can be taken to be broadly applicable to air transport operations in Europe and the remainder of the World.

When examining almost any aspect of safety in civil air transport, it is necessary to define the scope of interest. Safety issues in associated with wide-body jet airliners are frequently quite dissimilar to those encountered in small piston-engined public charter aircraft. These two categories of airliner operation are governed by different regulations, in terms of aeroplane design, crew training, flight procedures, airport facilities, maintenance, etc. Between these two extremes, many different combinations of safety regulations can apply, depending on the size of the airline operator involved and type of aircraft being flown.

In this thesis, interest lay primarily with the investigation of fire safety issues in large passenger aeroplane types. However, it was not straightforward to choose a suitable cut-off point for the study as several possibilities existed for defining what the minimum size of a "large" airliner might be. In order to illustrate some of the options that were available, the aeroplane size distinctions adopted in FAA air transport regulations will now be examined.

In terms of aircraft operations, FAA rules differentiate between two types of air services; FAR Part 121 applying to the larger Air Carriers and FAR Part 135 for smaller Air Taxi Operators. The former are defined as airlines providing a service

with aircraft designed to carry more than 30 passengers or 7500 lb of cargo. Part 121 carriers are required to adhere to stricter regulations in areas concerning pilots, facilities, maintenance and safety equipment.

In addition to operating rules, the aircraft that airlines fly are universally designed and manufactured according to a set of strict technical requirements. Increasingly, these airworthiness FARs or the equivalent JAR standards are being adopted by aircraft manufactures world-wide, to ensure that their products are able to compete effectively in all global markets. FAA airworthiness standards are divided into two sections: FAR Part 23, applicable to small aeroplanes and FAR Part 25 for large transport category aircraft. These regulations are applied according to the maximum takeoff weight of the aircraft, and its passenger or payload capacity. For instance, small aeroplanes are defined as those with 19 or fewer passenger seats and a takeoff weight of 19,000 lb or less. If a such an aeroplane has more than 10 seats, then it is treated as being a commuter aircraft and the design must meet additional requirements contained within Appendix A of FAR Part 23.

The FAA are also responsible for many areas of economic regulation, including the definition of traffic and financial reporting requirements to be adhered to by all operators of public service aircraft. Economic Regulations Part 217 and 241 apply to operators of aircraft with more than 60 passenger seats, and Part 298 applies to operation of smaller aircraft.

The three main areas of FAA legislation applicable to the US air transport industry are summarised in Table 1.1. It can be seen different distinctions in aircraft

Legislation Category	Rules Applying to Large-Scale Operations	Aircraft Cut-Off Point	Rules Applying to Small-Scale Operations
Operating Rules	FAR Part 121 (Air Carrier)	< 30 passengers or < 7500lb cargo	FAR Part 135 (Air Taxi Operator)
Airworthiness Standards	FAR Part 25 (Large Airplanes)	< 20 seats and < 19,000lb weight	FAR Part 23 (Small Airplanes)
Economic Regulations	FAR Parts 217 & 241 (Certificated Air Carriers)	< 61 passengers	FAR Part 298 (Commuter & Air Taxi Operators)

Table 1.1: Regulations Governing Air Carriers Operating in the USA

size are used in each case, ranging from 20 up to 60 passenger seats. For the purposes of the present study, it was decided to consider only aircraft that possess at least 30 passenger seats, in line with US FAR 121 airline operating rules. The advantage of this particular cut-off point is that it excludes all modern piston-engine aircraft types, but still encompasses the large number of feeder-liner operations that are undertaken with turbo-prop airliners with less than 61 seats.

1.3.2 Formulation of Safety Legislation

The provision of legislation governing airline safety is undertaken by a complex international infrastructure, operating on many different levels. As outlined in the previous section, the oversight of regulators encompasses all sectors of the civil

aviation industry, covering aspects of airliner design, manufacture, operation and maintenance. Rule-makers face a complex and often torturous task when implementing a change in previously established legislation. A seemingly clear-cut case for a new safety improvement in a certain area may become less attractive or even be revealed to be highly undesirable when subject to more detailed consideration. The reasons for this are manifold. New legislation has to be appraised in terms of technical, operational, political and economic feasibility criteria as well on safety grounds. Many promising safety initiatives have been abandoned in the past because they have been proved to be too expensive, impractical to implement, or of limited effectiveness in everyday airline operations.

Safety legislators can rarely act autonomously; policies must be formulated in the context of the air transport industry as a whole. A given rule may result in dissimilar repercussions for different aircraft manufactures, airline operators or even complete regions of operation. The latter implies that prevailing socio-political considerations, at both domestic and international levels may sometimes also need to be taken into consideration.

Safety initiatives can also originate from outside of the formally established legislative infrastructure. Frequently, after a catastrophic incident has attracted a high media profile, a plethora of suggestions are voiced by members of the public, the media, political committees, consumer pressure groups, worker unions, etc. Most of the recommendations provided by these sources can usually be rejected immediately, on grounds ineffectiveness or the impracticality of their consequences. However, some ideas may well demand more detailed consideration, especially if a particular event has highlighted an unforeseen set of circumstances. Legislators therefore need to be seen as being receptive to new ideas and be able to provide clear justification for any policy decisions that are reached.

1.3.3 The Application of Regime Theory to Airline Safety

The process of formulating regulations in the area of air transport safety can be addressed with the application of classical regime theory. This approach involves the analysis of the policy making infrastructure as a complex system, or regime, operating and interacting at multiple levels within the prevailing environment of the airline industry. In general, infrastructures on this scale are too complicated to detail and analyse in anything but the most approximate manner. However, in spite of these limitations, regime theory has been used by some authors in an attempt to provide an insight into the air-safety regulation process. In this section, the some of work undertaken by Golich in this area (Golic, 1989) is presented.

The complexities involved in the formulation, implementation and enforcement of safety policies within the air transport industry may be conveniently illustrated with the use of accident case studies. For example, the circumstances surrounding the 1974 THY¹ Airlines DC-10 crash resulted in media attention being focused on effectiveness of the prevailing safety regime in the air transport industry (Job, 1994; Prince, 1990). In the immediate aftermath of the accident, in which 374 people lost their lives, many accusations were levelled by almost all parties involved. These groups ranged from passenger relatives, the media, THY airlines and

¹ Türk Hava Yollari - Turkish Airlines

McDonnell Douglas, the aircraft manufacturers, through to the European certification agencies, the Federal Aviation Authority and the Turkish government.

Subsequent manoeuvrings resulted in protracted altercations breaking out between several of these parties. The points of contention spanned areas as diverse as the split-second actions of a baggage handler involved in dispatching the aircraft, the integrity FAA certification engineers, through to the influence of military-industrial lobby in the US government and assigning of international liabilities.

In cases as complex as these, the application of regime theory may prove beneficial when attempting to understand how issues in aircraft safety are dealt with. The method can provide a structure through which the system of air-transport safety can be dissected and analysed. Regime theory attempts to recognise that legislative systems may be influenced as much by political and hierarchical considerations as by information derived on a more explicit basis. If insidious influences exist, then they are fully acknowledged and duly incorporated into the model.

Golich's approach to the analysing the air-transport industry's safety infrastructure is to divide the system into domestic, national and international levels. A suite of actors exist in each of these layers, with individuals usually performing in some level of a group hierarchy. Many interactions occur, both within individual hierarchies, and between co-existing hierarchical bodies. Given the overlaps that occur between different layers, many processes have multiple consequences and thus need to be considered at multiple levels within the overall system. It is precisely this innate complexity that regime theory has been designed to address.

All regimes involve players. The regulatory system within the air transport industry is governed by personnel acting at different levels within their organisations. In order to deal with this, three types of participant are commonly differentiated in regime theory. For current purposes, these can be labelled as *micro-actors*, *macro-actors* and *state elites*, respectively.

A close examination of almost any major aircraft accident will reveal existence of connections between system and unit levels of analysis, between micro and macro actors and between scenario variables involved. These relationships begin to tell us something about the process of change in the aviation industry. Such accidents commonly result from linkages between micro actors, corporate engineers and government bureaucrats working within narrowly defined terms of reference, and the larger forces of change in domestic bodies, international organisations, institutions and markets. The prevailing national civil aviation regime, as an intervening variable between international and domestic structures and processes both influences and is influenced by the nature of these linkages.

Golich states that virtually all recent regime literature speaks of the need to develop interactive models that link domestic and international policy issues more closely, since "domestic policy" issues spill over into international politics and "foreign policy" has domestic roots and consequences. The lack of detail in system-level theories has led to poor explanatory or forecasting abilities. By adding domestic dynamics, scholars run the risk of losing parsimony, but potentially stand to gain a more accurate reflection of reality. Trying to understand the reciprocal dynamics taking place in and between both system and unit levels of analysis presents an even greater challenge.

Researchers have identified, at both the system and unit levels, certain key variables that influence actor behaviour. We need to understand how these influence

state elites operating at the "intersection" of domestic and international politics as they select policies designed to serve their conceptions of aviation safety interests.

At the system level, international power play and market structures are critical. Equally important are non-structural variables, such as changes in reigning ideas and knowledge, technological innovation, and shifts in the number and patterns of transitional interactions.

At the domestic level, policy makers are influenced most fundamentally by ideology, which shapes public perceptions about appropriate state-economy relationships and about which and how issue areas should be managed by governments. Wielding special influence, bureaucrats determine the "short list" of feasible policies; they bias policy effects through selective interpretation and by varying policy implementation schedules. Private sector demands and actions are becoming increasingly important. Sometimes influence is exercised consciously and formally by economic interest groups or associations lobbying for special treatment. Policy can also be influenced less consciously, but no less powerfully, when corporations pursue survival strategies which place constraints on or create advantageous opportunities for state behaviour. Finally, policy selection will be a function of the limitations and possibilities inherent in the prevailing regime.

Many scholars have noted that regimes, like many other institutions, resist change. Organisational inertia and the effects of prior policy choices are partially responsible for this phenomenon because state and non-state actors have learned how to operate both internationally and domestically within familiar parameters. Additionally, the positive contribution of regimes to reducing uncertainty and to facilitating global management of a wide-ranging number and type of issue areas means regimes will persist without supervision from a central authority.

Nevertheless change does occur. State and non-state actors adjust to changes in domestic and international environments. They alter their beliefs and actions incrementally as a result of daily interactions or on the basis of new information. They develop knowledge or skill by study or experience, such as feedback about which policies have worked and which failed in the past. Knowledge, "... *the sum of technical information and of theories about that information which commands sufficient consensus ... to serve as a guide to public policy ...*", is affected by changes in reigning ideas.

Communication provides opportunities for state and corporate elites to learn, to redefine interests, and to select new policies. The exchange of ideas, knowledge and technological innovation can lead to regime creation and, later, to new ways of behaving within regime parameters. New rules and decision-making procedures may be adopted. Eventually, critical variables may be so altered that new or modified regimes begin to emerge, guided by different norms and principles. Crises often constitute the necessary catalyst for learning because they force decision maker recognition of structural and non-structural changes occurring in the system.

The process of change never ceases. The daily behaviour of state and non-state actors, guided by regime dictates, creates new constraints and opportunities for international relations which eventually lead to changes in both internal and external environments. The process of constant, incremental adjustment eventually generates such tension between "old" principles, norms, rules, and decision-making procedures and the newly prevailing structural and non-structural limitations and incentives that change is imminent. The incompatibility may not trigger change immediately. Often

some identifiable crisis is the catalyst. Once elites recognise that adjustments are needed, regimes may facilitate the communication leading to their modification, because they “link states together” and shape reciprocal behaviour which “can affect the conceptions of self-interest”. The latter influence the selection and implementation of adjustment policies. Macro-level changes are also affected by the daily behaviour of an aggregate of micro actors. These individuals operate according to domestic and international regime structures which delimit appropriate political and economic action at both levels. The contributions made by micro actors, prevailing ideology and regime influences in policy adoption are depicted in Figure 1.1.

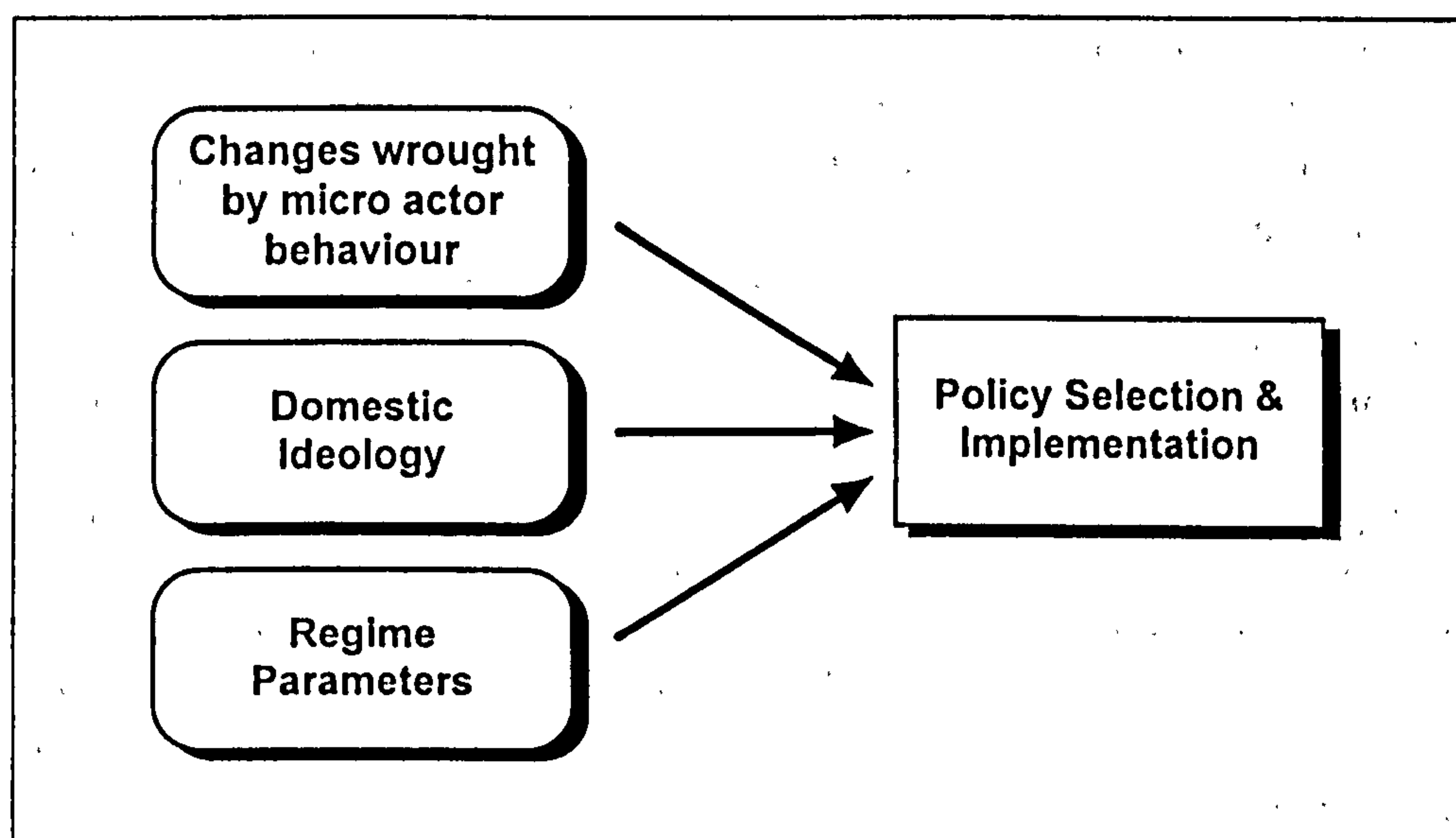


Figure 1.1: Influences in Policy Selection & Implementation

Receptivity is function of ideology and the pressures created by micro-level activity and demands. Adjusting policy selection and implementation adds a dimension of learning. However, we cannot presume that all learning results in the selection and implementation of optimal policies. Government and corporate elites can be misinformed, select myopic, destructively conflicting policies, or implement policies poorly, as well as learning, selecting and implementing “good” policies “well”. Because of the shifting and often conflicting demands to which decision makers must respond, policy selection and implementation can be influenced by “inappropriate” pressures. In the case of the THY airlines DC-10 accident, concerns about declining political, military and economic power have affected decisions about technologically solvable safety problems. Fortunately, actors can learn from such failures as well as from successes.

1.3.4 Knowledge Resources for Improving Safety

If policy makers and airline operators are to be in a position to improve levels of safety within the air transport industry, they must be aware of the types of dangers that are being faced and the best means with which they can be combated. If such knowledge is to be utilised in strategic decision making, it needs to be precisely quantifiable and obtained in a reliable form. Consequently, much scientific research has been performed within the area of aircraft safety with the objective of fulfilling specific information needs. The knowledge gained from these studies will be

examined in detail in the next Chapter. Thus, in this section, only a brief overview of aviation safety research is given.

Most safety research programmes are instigated by national aviation authorities, such as the FAA, CAA, Transport Canada and DGAC. Usually, initiatives are formulated in response to specific accidents, to analyse recently emerging concerns or to investigate new technological developments. In cases where adequate expertise and facilities exist, such work is usually performed in-house by the organisation(s) concerned. However, when specialised capabilities are called for, or no internal research facilities are maintained, other parties are called upon. In the past, these have typically comprised aircraft manufacturers, independent research organisations, military or other government agencies and educational establishments. Increasingly, aviation authorities are co-ordinating their spending on safety research and establishing joint programmes with the above types of organisation under national or regional initiatives.

It is possible to categorise research activities into three broad areas, namely historical, experimental and analytical. Those in the first category involve the examination of past events and production of safety statistics, audits and benefit analyses. This type of research possesses the obvious advantage of being based upon real events, but the findings yielded may be imprecise or statistically unreliable.

In contrast, experimental programmes attempt to quantify at first hand physical or behavioural phenomena that are in some way representative of those encountered in aircraft accidents. High levels of precision and repeatability of results can usually be demonstrated, but test conditions cannot always be made to be adequately realistic.

Lastly, analytical methods such as conceptual modelling and computer simulation are often used when historical information cannot be interpreted in sufficient detail or with adequate reliability and experimental methods prove to be impractical for some reason. These techniques are useful for establishing an understanding of complex phenomena, but are usually difficult to validate to a sufficient degree of certainty.

In addition to the research activities overseen by national aviation authorities, other organisations are actively involved in the study of aircraft safety. Aeroplane manufacturers and systems suppliers obviously possess a very direct interest in the safety of their products. As a result, they frequently undertake work that lies far beyond or is even totally unrelated to that which is strictly required for certification purposes. Unfortunately, information gained from such studies can sometimes be product specific, or is not made freely available. However, as airliners become ever more complex and difficult to certificate, the significance of these voluntary activities may be set to grow in the future.

Some valuable contributions to air safety research have also been made by independent organisations, educational establishments and agencies based in other industries. The latter span areas as diverse as automobile safety, building regulation, the petrochemical production and fire fighting services.

1.3.5 Certification of Aircraft for Accident Safety

The variable nature of aircraft accidents makes it difficult for them to be prepared for in advance. Consequently, current safety measures are designed to address potential dangers at source level and, wherever possible, provide a degree of

redundancy or flexibility to deal with unpredictable scenarios. Preparations for dealing with emergency situations can be grouped into three areas; ground-based precautions, onboard measures and crew/passenger training. In the present study, attention will be directed primarily towards the latter two aspects, i.e. the hardware and “software” components of the aircraft itself. Whilst airport and other ground-based emergency services can occasionally play a significant role in accident survival, arguably, their influence is several orders of magnitude lower than that of precautions taken onboard of aircraft.

The majority of airliners currently in large-scale passenger service World-wide with more than 19 seats have been certificated to FAR/JAR 25 Large Aeroplane Airworthiness Requirements. These standards are intended to ensure that all airliners are as safe and consistent in airworthiness features as it is reasonably possible to ensure. As a result, almost all aspects of aircraft design and construction are addressed with detailed stipulations or recommended practices. Those most directly applicable to aircraft accidents cover the following areas (JAA, 1994):-

Cockpit Crew Provisions

- survival equipment
- pilot compartment view and smoke clearance
- cockpit controls

Passenger Provisions

- doors and emergency exits
- ventilation
- pressurisation
- emergency evacuation

Crash Survivability

- seat strength
- stowage compartments
- ditching

Fire Safety

- provision of fire extinguishers
- protection of lavatory, cargo and baggage compartments
- fire protection of aircraft systems
- flammability, heat release and smoke emission of cabin materials
- lightning and static electricity precautions

Many of these airworthiness regulations have been progressively modified over time, in order to take account of technological advances and insights gained from operational experience. A significant proportion of these changes are not required to be backdated to aircraft types that are already in service, under so-called “Grandfather” exclusion rights. Thus, it should be noted that, technically, only the most modern aircraft in the World’s airline fleet actually comply fully with prevailing certification safety requirements.

1.4 Outline of Thesis

1.4.1 Summary

In this chapter it has been seen that air travel is and almost certainly will continue to remain extremely safe. However, if levels of airline traffic continue to increase and a corresponding reduction in accident rates is not attained, catastrophic events will occur at greater frequencies in future years. The airline industry may then encounter problems with public perception of air safety. In addition to reducing accident rates, this issue can be addressed by increasing the survivability of events when they occur. Study of past accidents indicates that a significant potential for progress to be made exists in this area.

Safety in commercial air transport has been developed progressively over many decades, primarily in the United States and Europe. On a global level, bodies such as the International Civil Aviation Organisation and co-operation through international research programmes are set to maintain advances in safety into the future. However, formulating new policies and implementing change in a complex industry is far from straightforward. Margins remaining for technical improvements to be made are becoming progressively smaller and analysis of safety must encompass many areas onboard the aircraft. In addition to issues of uncertainty about effectiveness of new measures, economic, political and historical constraints may also apply.

1.4.2 Path of the Research

This study attempts to deal with some of the issues now being faced when attempting to further improve levels of safety within the air transport industry. To provide a basis for the work, a wide-ranging review of existing research in the field and an extensive study of past aircraft fire accidents were undertaken. The results of these activities clearly suggested that an integrated and holistic approach to the analysis of aircraft fire safety was needed. The way chosen to achieve this was to construct a computer-based risk assessment model that incorporates a large quantity of information gathered from past accidents, together with results from many areas of scientific safety research. This tool works by generating aircraft accident scenarios and then simulating their outcome in terms of occupant survival rates. Details of incidents being modelled are formulated to vary in a probabilistic manner and be statistically representative of past events.

Perhaps, the key to the work is that all significant aspects of aircraft accidents are incorporated within the analysis in a balanced and integrated manner. Achieving this required that the role of scenarios features, crash effects, fire development and evacuation by surviving occupants in aircraft accidents were closely examined. These four areas were represented explicitly within accident simulations with the construction of interacting sub-models. In consequence, this then enables the effects of new safety measures and the influence of future trends in accidents to be explored. The resulting risk assessment tool was used to undertake four case studies. Each of these demonstrates a different aspect of the programme's usage and provides an indication of how this type of research may contribute to the improvement of airliner safety in the future.

1.4.3 Thesis Map

The structure of the thesis is portrayed in Figure 1.2:-

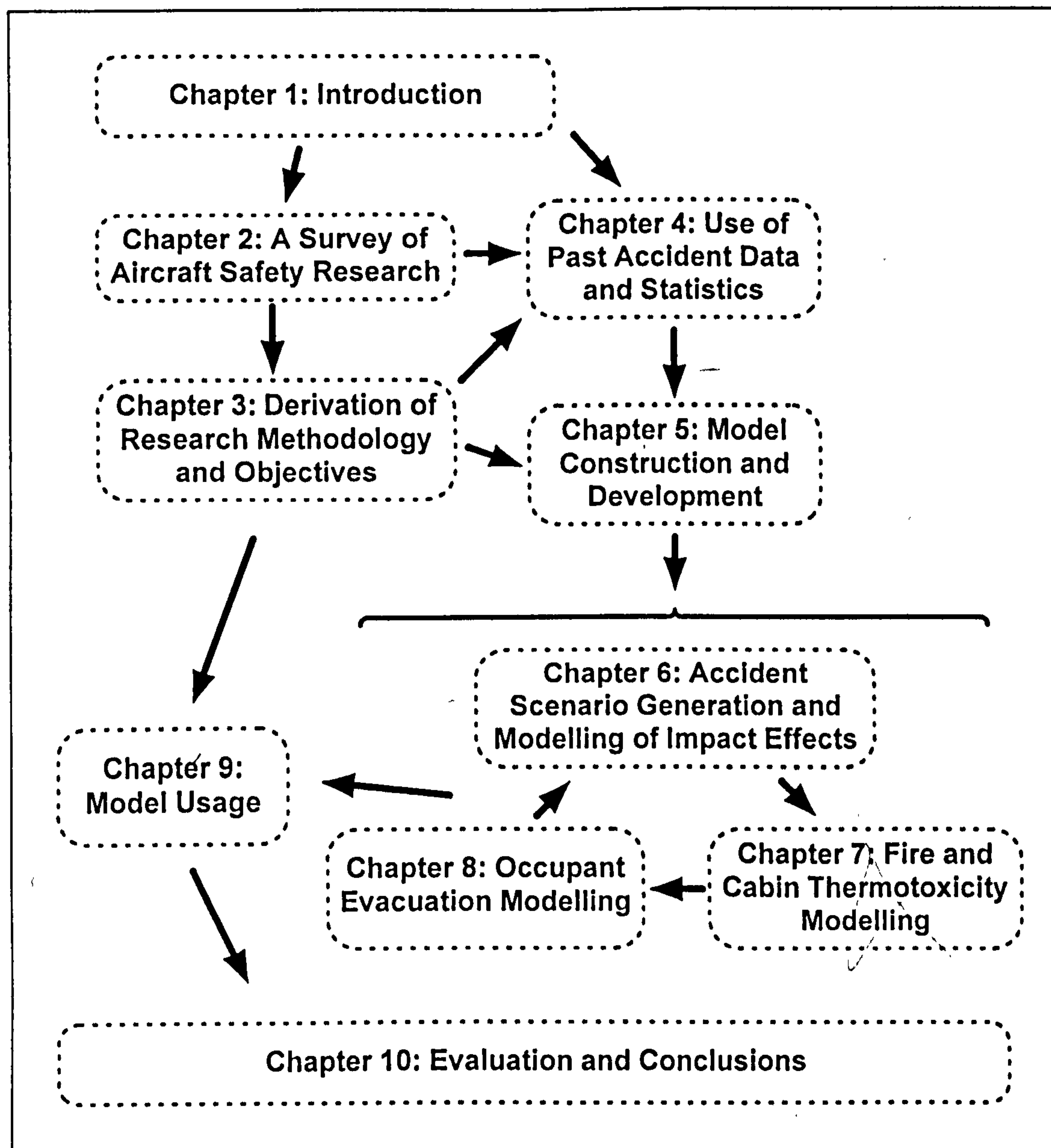


Figure 1.2: Map of the Thesis

Chapter 2: A Survey of Aircraft Safety Research

2.1 Air Safety Research - An Introduction

2.1.1 The Need for Research

It was seen in Chapter 1 that there has been a consistent need to obtain more information about almost all aspects of aircraft accident survival. Those who are responsible for ensuring the safety of air travel require a detailed understanding of what accidents involve in order to formulate new safety measures and minimise the human losses incurred. As a result, knowledge gained can be applied in safety legislation, aircraft manufacture, airline operations and crew training.

The majority of research undertaken to date has been funded by national aviation authorities. Much of this work is directed towards specific problem areas, with the aim of enhancing existing safety legislation. In addition to the obvious humanitarian and economic justification for such research to be undertaken, these organisations bear legal responsibility for safety regulation within their country's airspace. Aircraft manufacturers have also made important contributions in many areas. Although the findings made can sometimes be product or market specific and possibly justifiable on the grounds of quantifying product liability, any research being performed on a voluntary basis should be welcomed.

Smaller-scale research studies are also initiated by independent bodies, such as military or government research organisations, educational establishments and private consultants. The possession a degree of autonomy can sometimes enable research needs to be pursued with more freedom than when investigators are more closely involved with the industry. Finally, important lessons can be learnt in aircraft accident safety from research undertaken other industries. Examples of the areas involved include the quantification of liquid hydrocarbon fires, evacuation from buildings, materials combustion, smoke toxicology and automobile crash dynamics.

2.1.2 Topic Areas Covered

The complex nature of aircraft accidents means that they can potentially involve a range of different survival issues. Consequently, this has meant that research into aircraft safety has evolved in a number of specialised areas. Those which are surveyed in this chapter are:-

- Historical air accident data
- Aircraft crash testing and impact modelling
- Experimental fire tests and fire modelling
- Determining the effects of fire on people
- Aircraft evacuation trials and simulation modelling

Each of these areas will now be dealt with in turn in subsequent sections of the chapter.

2.2 Historical Air Accident Data

2.2.1 Accident Data Collection and Analysis

Since the earliest days of commercial air travel, investigations have been made when accidents involving aircraft have occurred. These enquiries usually result in information being generated and made available for those concerned with air safety. Such data can then be collated and analysed, resulting in an appraisal of current standards and their extrapolation into future trends. This enables the effectiveness of current practices to be evaluated and areas of special concern identified. Armed with this information regulators can prioritise and implement new safety improvements for the air transport industry as they prove necessary.

The quality and the extent of such information can vary enormously. In the fledgling days of commercial air transport, the US Air Mail service kept records of accidents occurring within its fleet of aircraft. However, civil aircraft accidents were not investigated systematically anywhere until the introduction of the US Air Commerce Act of 1926 (Wells, 1991). Since that date, the majority of industrialised countries have instituted a system for the investigation and reporting of air-accidents, in some form or other. This process has not become universal, even amongst nations that are signatories to the Chicago Convention (ICAO, 1994) - many countries choose not report their accidents openly because of cultural, financial or political reasons.

In spite of often incomplete or inadequate data, much work has been performed in gathering information about aircraft accidents. These activities have been undertaken by aircraft manufacturers, national aviation authorities and individual researchers in many countries. Most of the data gathered comes from the official reports issued by the government deemed to be responsible for the investigation of the incident under Annex 13 of the International Civil Aviation Organisation (ICAO) Chicago Convention. In addition, many national authorities allow documents associated with the compilation of the official accident report to be made available on request. Many of the larger airlines and aircraft manufacturers also retain detailed information about accidents incidents, particularly those involving their own aircraft.

2.2.2 The Aircraft Accident Report

The ICAO Chicago Convention Annex 13 recommends a standard format for the writing of accident reports. This is intended to structure the information obtained from an investigation in a logical and concise manner, and ensure that no important omissions are contained in the final publication. Example headings for the main sections of a report include "History of the flight", "Weather", "Injuries to persons", "Damage to aircraft", "Analysis", "Conclusions" and "Recommendations". This standardised reporting format appears to have been widely adopted and has greatly increased quality of information available to those involved in the detailed analysis of such accidents. Inevitably though, some governments still persist in issuing nothing more than the most terse of summaries, even after a major accident has occurred. These often contain little or no useful information, and are usually concerned chiefly with apportioning sole responsibility for the incident to the flight crew.

2.2.3 Compilation of World-wide Accident Data

To date, most of the collection, archiving and analysis of accident data by the world's air safety community has been undertaken in an uncoordinated manner. The

most comprehensive record of commercial aircraft accidents currently available is probably the UK Civil Aviation Authority's *World Airline Accident Summary* (WAAS) (CAA, 1996). This provides basic details and short descriptive summaries of most accidents and serious incidents involving aircraft in passenger or cargo revenue service world-wide. The information is derived from official accident reports or, in their absence, from other sources. WAAS is updated annually and it constitutes a logical starting point for most investigations involving aircraft accident data analysis.

More extensive information on selected accidents occurring between the 1950's and the 1980's can be obtained from the ICAO *Aircraft Accident Digest* series (ICAO, 1980). These volumes contain an edited version of the official report for many of the more serious accidents, conveniently formatted in the ICAO standardised layout. Only a small proportion of all accidents is covered by the publication, usually incidents that are relatively severe, or possess some other special significance. Nevertheless, the digests provide a convenient supplement to the basic WAAS data and make available the contents of many reports that would otherwise be very difficult to obtain.

Other sources of accident summary data include the computer-based ADREPS (ICAO, 1995) and the various national aviation authority incident reporting systems in place around the world. Comprehensive records are also maintained independently by academic researchers, such as Taylor (Taylor, 1991). Some aircraft manufacturers, notably *Airbus*, *Boeing* and *Fokker*, together with organisations associated with the insurance industry, such as the UK-based *Airclaims Ltd.*, also collate accident data.

2.2.4 Data Classification and Analysis

Many of the organisations and individuals who maintain historical records of aircraft accidents are actively involved in the interpretation and statistical analysis of their data. Most published studies adopt one of two approaches; namely the identification of long term trends from categorical data, or alternatively, the undertaking of a more detailed investigation chiefly concerned with some specific aspect of air safety.

Work involving the identification of long term trends usually encompasses more accident cases than investigations utilising the second approach. Typically, these studies encompass hundreds of incidents, drawn from, for example, revenue passenger operations world-wide since the start of the jet age. The sheer quantity of cases requires that the data be coded or categorised in some manner for the undertaking of any meaningful analysis. These classifications might include country of the aircraft's registration, phase of flight during which the event occurred, aircraft age, scheduled or charter service, aircraft size, etc.

The results of these long term studies are usually smoothed and presented with time as an independent variable, so that trends can be reliably identified. Given that the data has been obtained from a high proportion of all aircraft operations, the conclusions of these long term studies are usually assumed to apply to the industry as a whole. The world's largest aircraft manufacturer, Boeing, is particularly noted for the production of these types of study (Murray, 1995).

In contrast, many investigators utilise historical accident data in an attempt to resolve more specific safety issues. An example might be the work undertaken to

judge relative safety of wide-cut aviation fuels¹ in accidents involving aircraft crashes (Taylor, 1991). The requisite data (the proportion of occupants killed by the effects of fire) could only be determined for 49 of the 75 accidents under consideration, but some reasonably clear indications were still obtained.

In order to extract the maximum information for this type of study, accidents can be closely examined and analysed on an individual basis. This may reveal evidence that is essentially anecdotal or descriptive in nature, and thus masked by the use of a strictly categorical method. The additional "background" information can often lend more credence to findings, where the use of a small sample size means that results cannot be guaranteed to be statistically significant. Also, conclusions cannot necessarily be applied in a wider context than from which the basic sample data was drawn, unless a generic applicability can be demonstrated.

2.3 Aircraft Crash Testing and Impact Modelling

2.3.1 Introduction

Most aircraft accidents involve some form of crash (i.e. a rapid deceleration where significant structural damage to the airframe is incurred). Much work has been undertaken to investigate structural deformation and occupant survivability for transportation accidents in general. Experimental crash testing techniques have been predominantly used in the past, but computer-based analytical studies are becoming increasingly common.

A significant proportion of this research has been undertaken by the automotive industry. However many of the findings published in this context are directly applicable to the air transport. In addition to the work by the automotive sector, much work has been performed to specifically investigate occupant survivability and fuel tank integrity aircraft crashes (Thomson, 1984).

2.3.2 Airframe Crash Tests

When an aircraft crashes, large deformation and crushing of its structure can occur, often posing considerable danger to the occupants in conditions that might otherwise be survivable. As a result, numerous experimental trials have been performed to test the response of aircraft structures in crash impacts. The most comprehensive tests utilise a remotely piloted aircraft, complete with anthropomorphic test dummies, carefully instrumented to record impact decelerations and deformations. The crash test aircraft is flown into the ground along a precisely determined flightpath, usually so as to collide with a prearranged set of obstacles. These tests are extremely costly to perform with large commercial aircraft types and they are therefore undertaken relatively infrequently. A well-documented example is the FAA Controlled Impact Demonstration (CID) of 1984, which also involved the fire evaluation of an anti-misting kerosene (Blake, 1985; Hayduck, 1986).

Ground-based impact testing of complete airframes is considerably more straightforward to perform than free flights trials. Typically aircraft are attached to

¹ Wide-cut fuels are more volatile than grades of aviation kerosene currently in widespread use and thus vaporise more easily. Their use was commonplace in the 1960's and 1970's, but they have been phased out since, primarily as a result of concern over their safety.

some form of guidance rail and taxied under their own power into obstacles at high speed. The principal disadvantage of ground-based testing is that it is difficult to produce an adequate component of deceleration in the vertical direction, with some form of hill or up-slope usually being employed (Spicer, 1964). Some of these trials have involved the destructive testing of a large number of airframes and the analysis of fuel fire initiation is a common theme (Pinkel, 1953, 1958).

When researchers are concerned with more detailed aspects of aircraft structural crashworthiness, it may not be necessary to test an entire aircraft. Often, representative sections of cabin seating or fuel tank structure can be tested adequately in isolation. When testing passenger seating for example, the use of three seats rows is common, to determine the effects the seats in front and behind the instrumented test row (Johnson et al., 1988). These small scale experiments are often used for comparative or optimisation studies, where multiple runs are required. The initial development of anti-misting safety fuels was undertaken in this way, with structures built to rupture in a similar manner to wing fuel tanks (Miller and Wilford, 1971).

In recent years, computational methods have been increasingly used to predict the behaviour of structures in crash conditions. Initially, the use of these techniques was restricted to simplified "stick" representations of very basic structural elements or individual occupants. However, non-linear analysis techniques have advanced rapidly and it is now feasible to model complete aircraft configurations or the dynamic interactions between multiple rows of seated passengers (Wittlin and Neri, 1990).

2.3.3 Occupant Impact Testing

The development of passenger seats, together with their occupant restraint systems, has been predominantly influenced by the necessity to provide adequate support and retainment in crash situations. For modest and moderate impact forces, it is possible to use human volunteers as test subjects; the Eiband curves suggest that vertical accelerations of up to 15g (sustained over 0.005 to 0.5 seconds) are tolerable for able-bodied volunteers (Eiband, 1959). However, experience obtained from past accidents and airframe impact testing has shown that accelerations of up to 50g may be encountered in many crash situations. In order to obtain the kinematic responses of occupants in such extreme conditions, it is necessary to resort to the use of anthropomorphic dummies.

These experimental tests have shown that aircraft occupants face three main dangers during severe crash impacts (Snyder, 1976):-

1. Ejection from the seating position
2. Application of excessive forces to the body
3. The occurrence of large relative motions between adjacent body segments (whiplash and flailing)

Occupant ejection and flail injuries have been addressed by the development of improved seat restraint systems, improved occupant bracing positions and the controlled deformation of seats backs.

Peak acceleration forces can be reduced by the use of energy absorbing seats, which spread the deceleration over a longer time interval with the use of collapsing structures (Alforo-Bou et al., 1985). In this way, the kinetic energy of the occupant can be managed so as to reduce the severity of any impact injuries.

2.4 Experimental Fire Tests and Fire Modelling

2.4.1 The Danger of Fire

As well as crash impacts, many survivable aircraft accidents involve a significant fire. The large quantities of fuel, together with flammable cabin furnishings carried by most passenger aircraft provide a significant fire potential even without the occurrence of a crash accident. Historical research suggests that up to three quarters of the fatalities in many survivable fire accidents may be attributable to the effects of the fire (Speitel, 1988). As a consequence, much research has been undertaken by the aircraft fire safety community into understanding, quantifying and reducing the threat of the effects of fire in aircraft. The work can be divided into four categories; namely the fire testing of airframe structures, cabin interiors and aircraft materials, together with fire extinguishment. Each of these is now considered in turn.

2.4.2 External Fuel Fire Tests of Airframe Structures

These are intended to reproduce the scenario of an external fuel fire in the vicinity of an aircraft fuselage. The emphasis of these studies is usually concerned with establishing the characteristics of the fire and its effect on the airframe structure and the development of the environment inside the aircraft cabin. The FAA has contributed most of the published work in this field to date (Sarkos et al., 1991).

External fuel fire tests are usually conducted with actual aircraft structures, modified, if necessary, to represent typical passenger aircraft door configurations or impact damage. Experiments have shown that a typical airliner fuselage will only provide resistance to an adjacent external fuel fire for 30-60 seconds (Sarkos et al., 1991). After the fuselage structure has been breached, fire usually spreads rapidly, aided by high levels of ambient thermal radiation. Other significant conclusions obtained from destructive airframe fire testing include (Sarkos et al., 1991):-

1. An aircraft standing on its undercarriage is more vulnerable to an external pool fire than an aircraft resting on its belly.
2. The wings can provide an effect shield from flames for the fuselage and overwing exits.
3. The presence of flame penetration paths and the effects of acoustic wall linings can play a significant role in fire penetration.
4. The earliest cabin threat from the burnthrough process is smoke obscuration, produced from the pyrolysis of aircraft materials.

These trials obviously involve the airframe being tested to destruction and so they are necessarily expensive to conduct.

When the researchers are concerned primarily with measuring the cabin thermo-toxic environment, as opposed to determining the fire resistance of the aircraft's structure, a different approach may be used. This involves the airframe being lined and insulated to protect it from fire damage, thus preserving its structural integrity during the trial. When the primary mechanism of fire spread is by convection of heat and smoke, this approach can yield convincing results (Hill and Sarkos, 1985). However, the heat reflectance and absorption properties of the protected structure may be quite different to those of the bare airframe. This implies that care needs to be

taken when interpreting the effects of radiative heat transfer in results obtained from tests utilising these non-destructive techniques.

The results of external fuel fire experiments are commonly plotted as time histories of ambient temperature, light transmission and heat flux. Often, marked stratification of the cabin atmosphere is encountered and measurements therefore tend to be recorded at a series of heights above the cabin floor.

The influence of wind strength and wind direction have been shown to play a major role in determining the effects of external fires in many circumstances. This is because the convective heat transfer in the first 90 seconds of a fire will be dominated by wind conditions and fuselage openings (Eklund and Sarkos, 1985). In the most favourable conditions, no fire penetration may occur at all, whilst at the other extreme, convective heat flux may occur through openings to make the cabin rapidly non-survivable.

The effectiveness of cabin water spray systems has been investigated with full scale airframe fire tests (Hill et al., 1992; Whitfield and Whitfield, 1988). The results of these trials have shown that water spray systems have the potential to reduce the rate of fire spread and concentration of fire products within the passenger cabin. Other contributions of full scale testing include the initial demonstration of the value of fire blocking layers in passenger seat cushions (Sarkos et al., 1991) and the investigation of the use of Halon in cabin fire protection (Sarkos, 1975).

2.4.3 Cabin Mock-up Fire Tests

Once a fire has penetrated into the cabin of an aircraft, cabin furnishings and trim quickly pyrolise, ignite and then contribute significantly to the effects of the fire. In order to increase our understanding of these often complex processes, many smaller scale experimental fire tests have been undertaken. Because the focus of these tests lies chiefly with obtaining the fire properties of the cabin contents, as opposed to the fire resistance of the cabin structure, partial cabin mock-ups can be used. These tests are essential to relate the findings of materials fire experiments, conducted in small test chambers, with the comprehensive, but costly airframe fire tests described in the preceding section (Lopez, 1985).

The walls of small scale mock-ups usually incorporate some form of ventilation control and tend to be constructed of steel, for durability in fire (Duskin, 1985). Alternatively, if the testing only involves low ambient temperatures, such as determining visibility in smoke, sections of real aircraft fuselage can be used, with the advantage that cabin seating, lighting and trim are already pre-installed (Madgwick, 1982).

Cabin mock-ups are particularly useful when researchers are interested in some of the more complex interactions that occur when a mixture of cabin materials undergoes simultaneous pyrolysis and combustion. In these circumstances, the fire products may differ significantly in composition in comparison with those obtained when same materials are tested individually (Auvinet and Favand, 1975).

A related area of work involving the use of mock-ups is in the fire testing of cargo compartments (Ball, 1991) and lavatory units (Kourtides et al., 1985). Underfloor cargo bays in passenger transport aircraft may contain large quantities flammable material and are commonly inaccessible in flight. It is thus essential to provide these compartments with adequate fire detection and/or suppression measures.

2.4.4 Fire Characteristics of Materials

Materials intended for application in passenger aircraft have to exhibit adequate fire performance in particularly demanding conditions. The primary difficulties associated with optimising the fire properties of aircraft cabin materials are (Hilado, 1985):-

1. They are highly engineered materials because of the emphasis on minimum weight;
2. They are employed in environments that permit limited or no egress in the event of a fire;
3. They face possible exposure to high heat flux levels because of their proximity to fuel;

As a consequence, airworthiness requirements specify a well-defined list of fire criteria that must be met by materials to be used in the passenger cabins of large aircraft (JAA, 1994). These criteria include burnt rates, self-extinguishment, flame penetration, smoke generation and, in the case of seat cushions, weight loss during flammability testing. Compliance with these requirements is demonstrated with the use small scale materials fire tests.

The fire testing of materials is a mature technology and it has been largely developed outside of the aerospace industry. Many types of standard fire tests have been evolved to measure numerous material parameters in addition to those listed above and they are too numerous to list here. Brief overviews of the fire testing of materials in an aerospace context are provided by Godfried and Hilado (Godfried, 1975; Hilado, 1985).

One area in which aircraft fire safety has contributed significantly to the more widespread use of fire resistant materials is in the application of fire blocking layers to polyurethane foam seat cushions. Polyurethane foam has been widely adopted for seat cushioning in transport and domestic applications; it is cheap, light, resilient and widely available in many tailored grades. However, the pyrolysis of polyurethane based materials in air yields large quantities of many lethal substances, particularly carbon monoxide and HCHO (Spurgeon et al., 1985). In contrast, neoprene (polychloroprene) based foams possess far more favourable fire characteristics, exhibiting high char yields, good ablation efficiency and low smoke emissions (Parker and Kourtidis, 1982). The principal disadvantages of neoprene foams are their higher densities (typically 46 kg/m^3 in comparison with around 24 kg/m^3 for traditional polyurethane foams) and their greater acquisition costs.

The solution adopted by the aerospace industry has been to use cushions constructed from polyurethane foam encased in a neoprene foam fire blocking layer. Fire tests have shown that this form of cushion construction can offer significant improvements in fire protection (Kourtidis and Parker, 1985). Other forms of cushion fire-blocking layers include E-glass, kevlar/nomex mix, and polyacrylonitrile based fabrics.

Most materials fire testing involves the use small samples, a standard method of heat addition and a rigorously controlled test atmosphere. Care must be taken when interpreting the results of these laboratory fire tests; as noted previously, materials can exhibit markedly different behaviour in full cabin trials. Nevertheless, small scale testing is invaluable for the initial screening of materials and it provides a suitable basis for the development of more comprehensive fire-worthiness experiments.

2.4.5 Fire Containment and Extinguishment

The role of fire-fighting services in the event of an aircraft fire is to save life. This is achieved by isolating the effects of the fire from aircraft occupants and by extinguishment of the fire. Given that an aircraft is likely to be damaged beyond use by even a relatively modest fire, little or no priority is assigned to the restriction of material destruction until all those on board have been saved.

In the case of fires that start inside the fuselage of an aircraft, the first intervention may well be by the onboard crew members. Most of these internal fires arise in lavatory or cargo compartments. Although they might be relatively modest in size, the close proximity of internal fires to passenger means that they can represent a considerable threat to life, often within 10-15 minutes of their initiation (Kourtides et al., 1985). The primary method for dealing with these categories of fires has been the introduction of smoke detection, ventilation restriction and Halon-based fire suppression systems. The latter will phased out in the near future as a consequence of the Montreal Convention on halogenated hydrocarbons and the provision of suitable alternatives is being actively pursued (Ball, 1991).

Aircraft fires that involve large quantities of fuel, usually as a result of a crash, provide a quite different set of circumstances. Some of the main problems faced by the emergency fire-fighting services include (Nash, 1975):-

1. There is a very high hazard involved. Modern passenger aircraft may carry up to 600 passengers.
2. Any crash is likely to render helpless a large proportion of the occupants, who nevertheless must be regarded as potential survivors, unless shown to be otherwise.
3. The discharge of large quantities of a volatile liquid fuel in the immediate surroundings usually produces a very rapidly growing and often catastrophic fire situation.
4. The strength of the aircraft structure can never be adequate to withstand the tremendous effects of impact damage.
5. Aircraft payload margins do not allow for the installation of fire-fighting systems capable of dealing with a major fire - even if they were to remain operational after a crash.
6. The location of the accident site cannot be known, at least with any precision, until the aircraft comes to a stop.
7. The time scale of an aircraft fire under the worst conditions and the likely survival time of the occupants are both so short that the changes of fire-fighting services taking effective action in time to save lives are low, except if the accident occurs on the airfield.

Aircraft fires can present two types of extinguishment problem, namely quasi two-dimensional (spilled or pool fires) and quasi three-dimensional (running fuel or jets and spray of fuel) (Fiala, 1982). The most effective media for combating these two categories of aircraft fires are water-based foams and dry powders respectively.

All fire fighting agents work by inhibiting the hydrocarbon-air/oxygen interaction. This can be achieved by three distinct ways; by forming a physical barrier between the reactants, by absorbing heat from the combustion process, or, finally, by chemical means through trapping of free radicals involved in the combustion reaction.

Most agents utilise at least two of these inhibition mechanisms for their effectiveness and it can be difficult to differentiate between the latter two in some circumstances (Fiala, 1982).

Fire-fighting foams work by sealing the fuel from any air/oxygen supply and by heat absorption. They are very good at dealing with large scale spill fires, but are not effective with running fires, such as fuel falling from ruptured tanks to the ground. Foams are generated on demand by aerating a solution of foaming agent in water, resulting in expansion ratios¹ of up to 1000. However, for the extinguishment of large fuel spill fires only “low expansion” foams are used; these are formed with a solution strength of 3-6 percent and expansion ratios in the range of 6 to 30. As a result of their relatively high density and viscosity, these foams can be projected up to 50 meters, are less affected by wind/fire draughts and are more able to penetrate into restricted areas, than mixtures utilising higher expansion ratios (Nash, 1975).

Many post crash fires can be extinguished more efficiently with the use of dry powders or Halon in combination with aqueous foam. Halon and other similar gases work by physical displacement, heat absorption and chemical interference. They can be particularly effective for “mopping up” enclosed areas with limited accessibility, such as underfloor compartments, wing leading edges, undercarriage bays, etc. However, fire-fighting gases are “transient” agents, unsuited to dealing with large open fires. As such, they are used in a secondary role.

Dry powder extinguishers are very effective in dealing with both open spill fires and enclosed compartment fires. Working in a similar manner to gaseous agents, they are only effective whilst being applied, and leave the fire unprotected when application ceases. Powders suffer from the disadvantages that they tend to obscure the fire zone and may have severe choking effects on any survivors (Nash, 1975).

2.4.6 Modelling of Fires

The inconvenience and expense of conducting full scale fire experiments have resulted in considerable effort being applied to the modelling of fires by computational means. Most accident fires are extremely complex in nature, containing many chemical processes and interaction mechanisms that are poorly understood. Their simulation therefore requires that many approximations and simplifications be made in order for a tractable model to be derived.

In most fire models, details of chemical reactions are left unrepresented and an analogy is formulated on a strictly physical basis. This treats the fire as being a form of “black box”, defined purely in terms of its physical interactions with the immediate surroundings. Fire parameters are usually minimal, for example consisting of heat and smoke output levels, together with rates of oxygen and fuel consumption. Typically, fire growth characteristics are either assumed *a priori* or calculated from empirically derived relationships.

Two types of approach have been adopted for the modelling of fire; zone models and field models. These differ primarily in terms of their resolution and degree of reliance on empirically derived approximation.

Zonal fire models have been developed directly from established traditional hand calculation methods (BRE, 1991). The geometry of the fire atmosphere is

¹ Defined as the ratio of the volume of the made up foam to the volume of the solution from which it was made.

represented by a small number of analytical zones, for example the fire core, fire plume, smoke layer and free atmosphere. Interactions between zones and the resulting changes in their geometry are determined from semi-empirical physical approximations or from experimentally derived data. Zone models are dependent on prior assumptions of how a fire and its productions will behave. As such, they are limited to dealing with reasonably well defined situations, where fire behaviour is likely to be consistent with previous experience and experimental findings can thus be applied. Most zone models therefore deal with fires in closed compartments, where fire plume and smoke layer relationships are well understood (Zukowski, 1978).

The simplicity of zone models enables them to be readily extended to consider more complex geometry, such as a complete building, for example (Cooper, 1988). This process can be further continued with the division of zones into smaller sub-zones, to provide an increased resolution of the fire atmosphere, a technique used in the DACFIRE aircraft cabin fire model (Poulios, 1986). Developments in computer technology have enabled the discretisation of the fire domain in ever higher resolutions and when combined with associated advances in Computational Fluid Dynamics (CFD), this has lead to the establishment of field modelling techniques.

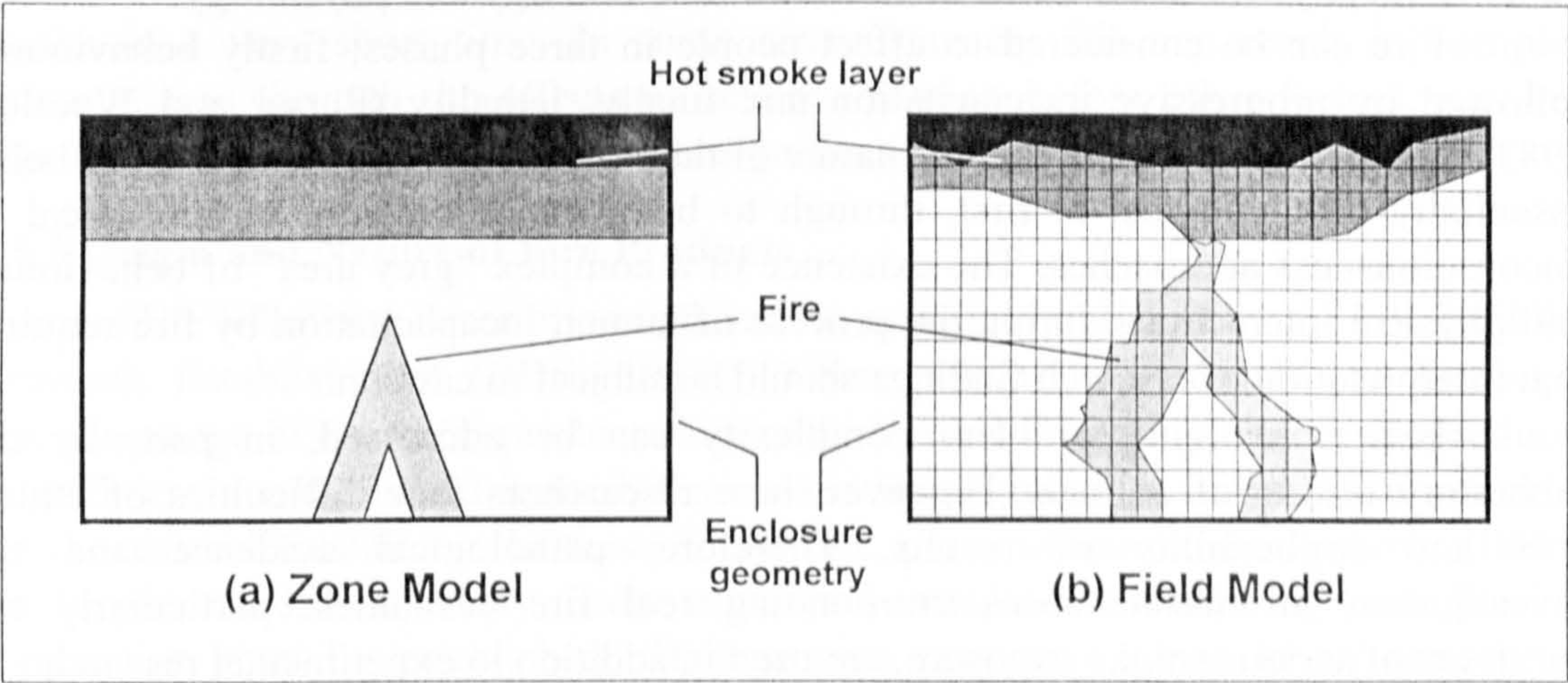


Figure 2.1: Zonal and Field Representations of Fires

Field modelling utilises far fewer assumptions about the nature and behaviour of fire products. It does this by avoiding resort, as far as possible, to established experimental correlation and attempts to return to first principals to solve the basic laws of physics for a general fire domain (BRE, 1991). The approach generally requires that the geometry of the problem be discretised into a grid of small elements or cells. Boundary conditions, together with theoretically derived rules of conservation and equivalence are used to set up a large number of mathematical equations. These are solved numerically by computer to establish a fire solution.

Field modelling techniques do not pre-assume the nature of fire effects. This means that they have the potential to reveal new mechanisms of fire behaviour that were previously unappreciated or only thought to occur in other contexts (Fennel, 1988).

The principal limitation of the field modelling approach is in complexity of problem definition (Thomas, 1985). It requires that fire scenarios are precisely defined in terms of boundary conditions, chemical processes, physical properties, geometrical mesh, etc. This information is often unavailable or else impractical to generate. Thus

resort has to be made to simplifying assumptions, along the lines of zone modelling techniques. For this reason, field modelling has tended to focus on established fire problems, such as the spread of heat and smoke in enclosures, where the problem is concisely bounded and suitable experimental data is often readily available (Galea and Markatos, 1991).

Another significant drawback of field modelling techniques in some contexts is that solution times are often measured in hours, rather than the seconds usually required by zonal methods.

2.5 The Effects of Fire on People

2.5.1 Fire Lethality

Most accidental fires produce large quantities of heat, smoke and toxic gases. These three products are encountered in high concentrations in most fire environments, and each of them can represent a serious threat to human life. Accordingly, much research has been undertaken to investigate the lethality of fire to humans, mostly within the fields of combustion toxicology and physiology.

Fire can be considered to affect people in three phases; firstly behavioural, followed by progressive incapacitation and finally, lethality (Purser and Woolley, 1983). It is pertinent to note that the nature of the influence of fire changes from being essentially psychological at first, through to being predominantly physiological as unconsciousness approaches. The existence of a complex "grey area" of behavioural and physical interactions during the process of human incapacitation by fire requires that interpretation of research findings should be subject to caution.

Issues involving problem complexity can be addressed, in part, by the laboratory testing of animals. However, here researchers face difficulties of ethics, cost and applicability of results. Therefore, pathological evidence and the investigation of circumstances surrounding real fire casualties, particularly the survivors of serious smoke exposure, are used in addition to experimental research.

Most fires deaths occurring in aircraft accidents are attributable not to burns and exposure to heat, but to the combined effects of toxic smoke products (King, 1989). This stems directly from the fact that interiors of modern passenger aircraft are composed predominantly of synthetic polymeric substances, such as PVF, polyamides, epoxies resins, polyurethane and neoprene foams. When these materials are subjected to the effects of heat, they produce a complex mixture of volatile species and combustion products. These toxic gases and smoke are generated in large quantities by almost all types of fire and their effects can be highly lethal, even in modest doses. Consequently, research has been dedicated to quantifying and understanding the effects of combustion toxicity on both human physiology and behaviour.

Much progress has been achieved in the investigation of fire lethality. Researchers possess a basic appreciation of how heat, smoke and toxic gases, when considered individually, constitute a threat to human life. However, current knowledge levels are still rudimentary in areas where different incapacitation mechanisms act in combination. There remains much progress to be made in a hugely challenging field.

2.5.2 Physiological Effects of Fires

The primary products of fire are heat, smoke and toxic gases. Together, these three elements together form the total fire hazard, with its associated fire atmosphere. This fire atmosphere can have a wide ranging effect on people:-

1. High ambient temperatures levels may result in serious burn injuries, especially to the respiratory tract.
2. Smoke particles in the atmosphere restrict vision.
3. Toxic and narcotic gases are usually present, causing rapid incapacitation and death.
4. Ambient oxygen levels may be low, resulting in hypoxia induced behavioural changes and increased respiration of fire atmosphere.
5. The presence of irritants causes painful effects to eyes, upper respiratory tract and lungs.

In most fires, the effects of toxic and irritant gases, together with the presence of dense smoke particles are predominant. The synthetic materials commonly used in aircraft cabin fittings are capable of producing large quantities of highly noxious smoke in a very short time. In some circumstances, this can result in complete incapacitation through the effects of severe irritation before other factors, e.g. heat exposure, narcosis or hypoxia, become significant (King, 1989).

2.5.3 Origin and Nature of Fire Products

(The following description is based on material published by the UK Building Research Establishment (BRE, 1985)) When polymeric materials are heated, a complex range of chemical products is usually formed. If these products are produced in sufficient quantities and ignited, flames and large quantities of heat result, making the process self-sustaining. In these conditions, gases temperatures of above 1000°C can be generated. Conversely, under some circumstances, smouldering (non-flaming) combustion may be established. This process may take place in an atmosphere containing oxygen (*thermal oxidative decomposition*) or in an inert atmosphere (*pyrolysis*). The decomposition products of typical cabin polymeric materials are summarised in Table 2.1.

The presence of flames tends to destroy volatile decomposition products with the formation of a small range of simple combustion products, such as carbon monoxide (CO), carbon dioxide (CO₂) and water (H₂O). If nitrogen is present in the polymer, hydrogen cyanide (HCN) and oxides of nitrogen (NO_x) may also be produced. In many cases, a similar range of these base products has been found to be produced from quite different materials, which simplifies the analysis of combustion toxicology significantly (Woolley and Fardell, 1982).

Elemental Composition	Example Materials	Pyrolysis Products	Oxidative Decomposition Products
CH	polyethylene, polypropylene	hydrocarbons	CO, hydrocarbons, oxygenated species
CHO	wood, polyesters	CO, hydrocarbons, oxygenated species	as for pyrolysis
CHN	polyacrylonitrile	hydrocarbons, amines, cyanides	CO, hydrocarbons, amines, cyanides
CHNO	polyurethanes	CO, hydrocarbons, cyanides, oxygenated species	as for pyrolysis
CHCl	polyvinylchloride	hydrocarbons, hydrogen chloride	CO, hydrocarbons, hydrogen chloride
phosphorus and antimony	numerous polymeric materials	phosphorus and antimony containing products	

Table 2.1: Polymer Thermal Decomposition Products

The thermal decomposition of even a single material can produce a complex mixture of substances. The nature of these products can vary considerably with the prevailing combustion environment, with the concentration of gaseous reactants, ambient temperature and oxygen availability usually being highly significant. When local conditions only provide sufficient oxygen for the partial reaction of gaseous species, incomplete combustion occurs. In these circumstances, decomposition products are not able to be fully broken down into simple base products and complex mixtures of relatively large molecules result. Low-oxygen combustion environments lead to organic compounds producing carbon particles and carbon monoxide, because complete oxidation to carbon dioxide cannot be fully supported. In consequence, incomplete combustion is usually characterised by high levels of smoke production together with the presence of low temperature yellow-orange flames.

2.5.4 Fire Toxicology

As a result of chemical studies of experimental fires and animal exposures to the thermal decomposition products from a wide variety of materials, two fundamental points have emerged concerning the nature of fire product toxicity (Purser, 1988):-

1. Although thermal decomposition of a wide range of materials leads to the formation of a large number of complex chemical products, fire toxicity is dominated by the effects a small number of base products.
2. Toxic effects are dominated either by a narcotic (asphyxiant) gas, such as carbon monoxide or hydrogen cyanide, or by complex mixtures of irritants.

Narcosis is the oxygen starvation of the brain. Its effects are fairly predictable and they can result from the presence of a narcotic gas, high carbon dioxide

concentrations, or from low ambient oxygen levels. The two most important narcotic fire products are carbon monoxide and hydrogen cyanide.

A particularly dangerous characteristic of human narcosis is the relatively short transition time between near-normal behaviour and unconsciousness. This is because the body is able to adapt and compensate for limited doses, leaving the victim unaware. However, further exposure leads to a collapse of this defence mechanism and deterioration is rapid and severe. The symptoms of progressive narcosis are behavioural changes, such as lethargy or euphoria, followed by poor physical co-ordination, unconsciousness and death.

Narcosis levels are quantified with the use of Haber's Rule, which states that the accumulated effective dose from a product is equal to its concentration multiplied by the exposure time (Hartzell et al., 1985). However, in the case of carbon monoxide, both inhalation and excretion by the lungs occur, and the effective dose becomes dependent on the rate of uptake (Coburn et al., 1965). In aircraft fires carbon monoxide exposure times are relatively short (less than one hour) and the effects of excretion can be ignored, thus enabling Haber's Rule to be applied (Stewart, 1973). The effects of most narcotics acting in combination can be assumed to be linearly additive. This implies that the total accumulated dose is given by the sum of the Fractional Effective Doses (FED's) for each individual product present.

The effects of irritant fire products are less well understood and harder to determine than the effects of narcotics. During exposure, the most important form of incapacitation is by sensory irritation. This results in painful effects to the eyes, upper respiratory tract and lungs, but is unlikely to be fatal. These effects occur immediately and their severity is dependent on prevailing exposure levels, although a degree of adaptation can occur with continued exposure. Sensory irritants are classified by Respiratory Depression 50 percent (RD_{50}) values, which is the concentration of irritant required to reduce breathing rate of laboratory rodents by 50 percent.

The second effect of irritants is acute pulmonary response, in the form of lung inflammation and oedema (fluid production). This reaction takes 6-24 hours to occur and it is the main post-exposure cause of fire deaths. The severity of pulmonary irritation response is dependent on accumulated levels of exposure.

In complex atmospheres, as are likely to be encountered in aircraft fires, the effects of irritants appear to be considerably worse than predicted by the addition of individual components. This suggests that interactions or the production of short-lived chemical species with a very high irritancy potential may be occurring.

2.6 The Evacuation of Aircraft

2.6.1 The Fire Evacuation Problem

The need for safe and expeditious movement of large numbers of people within confined spaces can arise in many circumstances (Fennel, 1988). In these situations, the efficiency of the evacuation process may often be dependent on the degree of co-operative and altruistic behaviour exhibited between participants, as well as the nature of the evacuation environment. History has provided many examples of how human tragedies can result when the movement of large crowds breakdown and panic behaviour ensues (Bryan, 1988).

The effects of fire usually serve to exacerbate difficulties in evacuation, blocking escape paths, reducing visibility, restricting aural communication, etc. Many survivors of major fire accidents recount how the dangers of fire can develop in a latent manner, with the perilous nature of the situation not becoming generally apparent until it was too late to take effective action (Fennel, 1988). These problems can rapidly transform a seemingly straightforward evacuation process into an extremely critical matter of escape and survival.

The need for research into the safe evacuation of people from enclosed spaces in fire situations is therefore readily apparent. In consequence, evacuation tests have been undertaken to investigate fire safety implications in widely differing contexts, ranging from high-rise buildings, cinemas, museums and shopping malls through to undersea train-tunnels, passenger ships and aircraft. The results of many of these trials have not been publicly reported in detail, with the notable exception of the evacuations undertaken by the aviation industry. Presumably this is because the testing in other fields has been primarily concerned with the obtainment of one-off fires-safety certificates, rather than being formal research investigations intended for industry-wide dissemination. Given that this thesis is concerned with egress primarily from aircraft, the lack of formally reported evacuation trials in other contexts need not be a matter of concern. However, contributions in experimental evacuation research from other industries could potentially provide a valuable supplement to the aircraft-specific testing that has already been undertaken.

In addition to the experimental approach, the problems associated with large-scale evacuation of people has been investigated with the use of computer simulation programmes. Although work along these lines appears to have been initiated in the 1970's, the computer simulation of evacuation has only become technologically feasible during the last decade or so. Unlike the work in experimental evacuation, computer evacuation models have been developed by the building industry as well as in the context of aircraft safety.

2.6.2 Experimental Aircraft Evacuation Trials

Many types of aircraft accident involve a high probability of a catastrophic fire occurring without the passengers necessarily being disabled by crash injuries. In these circumstances, it is imperative that the occupants of aircraft are able to evacuate themselves to safety in a short a time as is practicably possible. In order to ensure this, much research has been performed to investigate the problems encountered in aircraft evacuation. This work typically involves the use of actual aircraft, or at least high fidelity cabin mock-ups, together with large numbers of volunteers to perform the role of evacuating passengers.

Formal evacuation safety standards are defined in the airworthiness requirements issued by the FAA and JAA (JAA, 1994). These certification standards apply to all large passenger aircraft in public service and stipulate the following:-

"... it must be shown that the maximum seating capacity, including the number of crew members required by the operating rules for which certification is requested, can be evacuated from the aeroplane to the ground under simulated emergency conditions within 90 seconds. Compliance with this requirement must be shown by actual demonstration..."

It is obviously not feasible to reproduce simulate true "emergency conditions", including effects of fire, crash injuries and disorientation. However, efforts are made to incorporate some degree of realism by deactivating half of the total number of emergency exits. The disabled exits are distributed evenly along the length of the cabin and their locations are not indicated to the participants. It is the responsibility of the cabin crew to ascertain the serviceability of exits and redirect passengers accordingly.

Additional realism is added to the 90 second trials by undertaking them in darkness, using only the emergency lighting provided on the aircraft, and by the distribution of loose articles, such as hand baggage, pillows, blankets, etc., throughout the cabin.

Given the risk and unpredictability associated with the conducting of a live demonstration, manufacturers undertake preparatory trials in an attempt to identify and correct any problems that may be encountered in the one-off certification test. The results of these preparatory tests are not openly reported, as they represent commercially sensitive information in the highly competitive aircraft sales market. However, because manufacturer evacuation testing is strictly oriented towards certification requirements, it would possibly contribute little additional information beyond the results provided by the actual qualification trials.

Evacuation testing is notoriously expensive and difficult to perform safely. As a consequence, aircraft evacuation trials are only routinely undertaken by major manufacturers and a few specialist institutions, the latter usually acting under contract to national airworthiness authorities. Minor injuries are common, even when participants are instructed to behave in an orderly manner. The most serious incident to date occurred 1991, when one volunteer was paralysed and 46 others were injured during FAA certification testing of a wide body aircraft (Flight, 1993). The now paralysed woman tripped at a doorway and slid head-first down an escape slide, fracturing her neck. The 405-seat aircraft involved had failed to pass the 90 second evacuation test after two attempts.

The use of emergency escape slides has always been problematic, with typically 5-6 percent of their users being injured on hitting the ground or when colliding with each other (Flight, 1992). To reduce these risks to the absolute minimum, cushioning mats and able-bodied helpers are placed at the bases of slides to aid evacuees in moving away promptly and safely. Since evacuation rates, in general, appear to be determined by conditions immediately inside exits, these obligatory safety precautions have no discernible effects on measured egress times.

The mishaps surrounding the 1991 certification tests resulted in the FAA issuing new guidelines requiring that testing of escape slides be conducted separately from large-scale cabin evacuation trials. Certification trials now require passengers to vacate onto platforms at door level, with the allowable time being reduced from 90 to 62 seconds¹. The troubled wide-body aircraft was able to complete the revised test in 56 seconds during 1992.

In addition to safety problems, large-scale evacuation trials also present many difficulties from a purely experimental standpoint. Some of these include:-

¹ Reportedly, 15 seconds of this reduction is to take account of time previously required for door opening and slide deployment, with the remaining 13 seconds being attributed to the hesitation factor formerly encountered at the top of slides.

1. Large numbers of suitable people must be recruited to act as test subjects
2. Repeatability of evacuation trial results may be poor
3. Test subjects have to be motivated to behave naturally
4. It is difficult to represent the effects of fire in an adequate (and ethically acceptable) manner

The evacuation research trials undertaken on behalf of national aviation authorities are rather different in nature from those performed in certification testing. Typically, research trials involve a smaller number of participants and are used to investigate specific issues in evacuation safety, such as the evaluation of new ideas or the refinement of current procedures. All tests are recorded in detail with video cameras, allowing exit flow rates to be calculated and plotted against time. As the majority of the research is funded by public bodies, the results are openly published. The outcome of such testing can often provide the basis for modification of existing certification rules. Thus, there is usually a requirement for increased realism and the statistical significance of results to be demonstrated. The latter can be achieved by conducting multiple runs, usually backed up with the use of a control case.

Some of the topics addressed by FAA and CAA evacuation testing include:-

1. The effects of non-toxic smoke (Muir and Marrison, 1990)
2. Influence of acoustic signals (Muir and Bottomly, 1992)
3. Seating configurations adjacent to exits (Muir et al., 1989)
4. The effect of passenger motivation (Muir et al., 1989)
5. Influence of cabin crew behaviour (Muir and Cobbet, 1995)
6. Escape of handicapped passengers (Blethrow et al., 1977)

An innovative feature of some of these trials has been the stimulation of motivated behaviour in the participants. This has been achieved by the introduction of a cash bonus payment system, whereby those who are first out immediately receive a modest payment in reward. The effectiveness of the incentive on evacuee behaviour can be startling, with jamming, crushing and clambering over seats becoming significantly more prevalent (Muir et al., 1989). The character of the motivated evacuations corresponds well with the behaviour that occurs amongst passengers when cabin conditions are perceived to become life-threatening in real accidents. Paradoxically, pushing and jamming of passengers serves only to slow down the evacuation process.

Other significant results provided by evacuation research testing include the demonstration of how critical bulkhead door widths and seating configuration adjacent to exits can be. Cabin safety regulations have been modified as a direct consequence of these findings. Recent work has also shown that assertive behaviour by the cabin crews can greatly increase exit flow rates beyond those achieved by undirected passengers (Muir and Cobbet, 1995).

2.6.3 Evacuation in Smoke

A limited number of trials have been undertaken to determine the effects of non-toxic smoke (Muir and Marrison, 1989). They have shown that, in general,

evacuation rates are slowed down and that rates of progress become more dependent on the width of passageways and seat spacing. Ethical constraints prevent trials from being undertaken with toxic smoke in the West.

In contrast, work has been reported by Jin, in Japan, which involves the testing of individual's response to the effects of irritant wood smoke (Jin, 1981; Jin, 1989). Two types of tests were tried; the first involved volunteers moving through a smoke-filled corridor to a door and the second required simple tasks to be performed whilst seated in a room with progressively increasing smoke density. Significant findings included:-

1. Walking speed slowed when in heavier smoke densities
2. Smoke tolerance was higher when subjects were familiar with their surroundings
3. Males tended to feel physiological discomfort, whereas psychological discomfort was more dominant in females
4. Smoke tolerance increased as subjects gradually became acclimatised to conditions with time

2.6.4 Computer Simulation of Occupant Evacuation

2.6.4.1 Background

The limitations and expense associated with large scale evacuation trials have resulted in the development of a range of computer simulation models being developed to represent the evacuation of people. The discipline is still at a relatively early stage in its development, and much progress needs to be made, particularly in the representation of human decision making processes and behaviour. However, indications are that computer-based simulation of evacuation will complement and, in the longer term, potentially replace experimental evacuation trials.

In general, computer-based evacuation research appears to be dominated by applications for the aviation and building sectors, with no work being located, for example, in the offshore, railway or shipping industries. A total of eleven evacuation models was identified, nine of which have been examined in detail. One of the excluded models is currently under development by the UK Building Research Establishment and forms part of an innovative fire risk assessment tool called CRISP II (Phillips, 1992). This work addresses the interactions between occupant behaviour, fire properties and building design in typical domestic house fire scenarios. Unfortunately, further details about the programme could not be released for publication at the time of writing. The two remaining evacuation models were only discovered at a late stage of the current research, and adequate information to enable their inclusion within the survey has yet to be acquired¹.

Brief descriptions of the eight evacuation models are provided in the subsequent sections, followed by a table summarising their main properties.

¹ The two models in question are by Singh, under contract to Transport Canada, and by Marchant at the University of Edinburgh.

2.6.4.2 EXODUS

This a prototype egress simulation that models the evacuation of individuals from an enclosure such as an aircraft, train or cinema type of building (Galea et al., 1993). The path of each individual is represented by movement across a grid and the thermo-toxic effects of fire can also be accommodated. The programme core comprises five interacting components, modelling the local environment hazard and toxicity together with the passengers' movement, behaviour and attributes. EXODUS was originally built within the G2 expert systems software environment, but has been re-coded in C/C++. Key features of EXODUS include:

- Comprehensive passenger characteristics, defined by 22 physical and psychological attributes.
- Hazard and Toxicity sub-models used to model thermo-toxic incapacitation.
- Simple "nearest serviceable exit" escape strategy
- Evacuee seat jumping capability

2.6.4.3 STRATVAC

This model is used to study escape strategies used by passengers evacuating a burning aircraft (Cagliostro, 1984). The movement of individual passengers across a grid is controlled interactively by test subjects. Passengers have identical characteristics and, once the evacuation is under way, their view is limited to only their immediate environment. Movement conflicts can be resolved amicably or by gambling for a contested location. In addition to fire spread and ingress, cabin blockage resulting from debris can also be represented. STRATVAC is programmed in FORTRAN 77 and utilises dedicated graphics software. Key features of STRATVAC include:

- Interactive control by test subjects
- Random fire model
- Evacuees restricted to localised view and have to remember overall cabin layout during evacuation process.
- Random cabin and exit blockages used to complicate evacuation process.

2.6.4.4 EVAC

This model is intended to simulate certification evacuation trials from aircraft as opposed to actual fire evacuations (Parks and Ostrand, 1982). Passenger egress as individuals across a discrete grid, controlled by comprehensive decision models. The latter can take into account factors such as personal choice, established flows and attendant instructions. Performance fidelity is achieved by an explicit micro-modelling approach, i.e. evacuee attributes, movements and actions are modelled in detail. No facilities for simulating of fire or passenger incapacitation are provided. Key features of EVAC include:

- Elaborate behaviour models for determining actions of individual passengers, e.g. fore/aft movement decision based

on boarding entry point, flow bias, exit proximity and queue flow rates.

- Ability to resolve the effects of increments in detailed data, such as seat pitch, aisle width, visibility levels etc.
- Model complexity results in sensitivity to random passenger input data. This leads to quasi-chaotic results, typical of real evacuation trials.

2.6.4.5 TAKAHASHI

Takahashi's model simulates orderly mass evacuations from multi-story buildings (Takahashi et al., 1989). Evacuees are assumed to move in a homogeneous ensemble which is modelled by a fluid flow analogy. Buildings are represented by a network of interconnected volumes, linked by flow controlling exits. A simple behaviour model distributes flows between multiple exits so as to achieve minimum escape times. The assumption of a low hazard level precludes the incorporating the effects of fire and evacuee incapacitation. Takahashi's model is programmed in FORTRAN, and includes the following features:

- Unique fluid ensemble modelling of egress, which implies large numbers of evacuees and orderly behaviour.
- Relatively modest computational requirements.

2.6.4.6 EXITT

This model simulates occupant decisions and actions in residential building fires (Levin, 1989). Evacuees are modelled individually and the building room layout is represented by nodes and links. Evacuee behaviour is modelled by a relatively sophisticated set of heuristics, or they can be controlled interactively by answering simple questions. Occupant characteristics are individually specified by seven coefficients. Their awareness, decision processes and egress are affected by smoke, noise and alarms. Escape route is determined by a shortest path algorithm, with demerits for passing through smoke or windows. The model is programmed in the *BASICA* language. Key features of EXITT include:

- Some unique behaviour models e.g. collection of infants and faster travel after encountering smoke filled rooms.
- Ability to read in smoke distribution data and estimate physical and psychological impact.

2.6.4.7 KOSTREVA

Kostreva's model performs optimal path analysis of the evacuation of individuals from structures which are involved in fires (Kostreva et al., 1991). Evacuees are modelled discreetly and move across a network of nodes. Escape strategies are based on globally optimal egress paths and these are determined with dynamic programming techniques. Features such as blockages and variable link attributes, such as cost and traverse time, are incorporated into the model. Key features of Kostreva's model include:

- Global egress strategies that mimic intelligent decision processes.
- Concept of an egress path composed of optimal links; the dynamic simulation environment means that optimal path may vary with time.

2.6.4.8 EXIT89

This is an evacuation model that simulates the egress of a large population of individuals from a high-rise building (Fahy, 1991). Evacuees are treated individually and they are moved through a network of rooms, corridors and stairwells. All evacuees possess identical (average) attributes and no attempt is made to model behavioural variations. Egress strategy is based on a shortest route rule base, with a strictly local perspective. Exit paths can be blocked by smoke and egress speeds are defined as a function of crowding levels (based on body size) to reproduce queuing effects. The EXIT89 model is programmed in FORTRAN. Key features of EXIT89 include:

- Limited treatment of evacuee characteristics enables large populations and complex buildings to be modelled.
- Ability to read in smoke distributions from external programmes and estimate psychological impact.

2.6.4.9 Colt Vegas

Vegas is an evacuation model developed within the *Superscape* Virtual Reality (VR) package by *Colt Virtual Reality Limited* (Potel, 1995). Evacuees are represented as individuals, with a pre-defined set of attributes and general evacuation scenarios can be constructed. Additional functionality can be created by the use of an in-built scripting language. Key variables can be altered interactively, for example altering the width of an exit, and the effects displayed immediately. Very simple rules are used to determine people's behaviour; such as a fixed speed of movement, and assignment of pre-determined actions according to the output of a random number generator.

The effects of fire are incorporated with a zonal model for heat and smoke flux. To run in real time, in concert with the evacuation simulation, the fire domain is split into five zones. Fire parameters are limited to starting location, size and rate of growth, all pre-determined from user input.

Vegas possesses an impressive three-dimensional graphic display of the evacuation process, which allows the user to view simulation from any vantage point or as one of the participants. As a consequence, however, only can only up to about 500 people can be modelled reliably. Key features of Vegas include:-

- Powerful spatial modelling and graphics display capabilities.
- Very basic evacuee behaviour and fire spread modelling.
- Use of script language to enable programming of new functionality.

2.6.5 Computer Evacuation Models: Conclusions

These eight examples illustrate some very diverse and original approaches to evacuation modelling. However they all possess, in some form or another, the following features:

- 1. A spatial representation of the enclosure(s) being evacuated. This may consist of a discrete grid, a network, a numerical array or simply just a bounded area.
- 2. A clock or other similar type of time accounting system, to give the simulation a time-scale.
- 3. Some form of heuristic evacuee decision making process. This might range from interactive instruction from test subjects through to an evacuee simply aiming for the nearest available exit.
- 4. Representation of evacuees' physical and/or psychological characteristics and status. These may be averaged from sample populations and a "fluid" analogy adopted or the attributes of individuals may be modelled discreetly using a "ball-bearing" approach.
- 5. The existence of an objective or end status e.g. the achievement of egress or incapacitation.

A summary of the features of each model is provided in Table 2.2:-

Simulation Model	Scenario Type	Spatial Representation	Evacuee Representation	Decision Stimuli	Thermo-toxic Incapacitation
EXODUS	aircraft/ general	discrete grid	individuals on grid nodes (one per node)	global + local	yes
STRATVAC	aircraft	discrete grid	individuals on grid nodes (one per node)	global + local	no
EVAC	aircraft	discrete grid	individuals on grid nodes (one per node)	global + local	no
TAKAHASHI	building	continuous volume network	fluid ensemble	local	no
EXITT	building	node network	individuals on grid nodes	global + local	yes
KOSTREVA	building/ general	node network	individuals on grid nodes	global	no
EXIT89	building	node network	individuals on grid nodes	local	no
VEGAS	general	free space	individuals in free space	local	yes

Table 2.2: Classification of Evacuation Simulation Models

The variety of techniques used to implement features within the simulation models are extremely wide-ranging. Some of the differences in method are obviously due to the dissimilar contexts in which the models were formulated. For example, some of the simulations are optimised to represent thousands of individuals moving on different floor levels, whilst others model tens of evacuees passing through a single constriction. However, even when taking such variations of scale into consideration, there appears to be no historical consensus on the best modelling strategy for the analysis of complex evacuation problems. The different approaches possess relative strengths and weaknesses and none appear to be satisfactory in all aspects.

An essential feature of any simulation model is an adequate representation of the evacuees' decision making processes. It is perhaps in this area that the models described show the greatest diversity in methods of implementation. However, it is possible to categorise the evacuee decision processes as being in response to local stimuli, global stimuli or to a combination of the two. The evacuee decisions are inevitably based on *heuristics* or *rule sets*, which can be built up to the desired level of sophistication. The formulation of the evacuee rule sets is of fundamental importance as they determine the dynamics of the simulation. It is apparent that the reduction of an evacuee's complex behavioural characteristics to numerical models is conjectural process. It was noted that several of the authors acknowledged the tentative nature of their evacuee rule sets and they therefore ensured their accessibility for modification, "to accommodate new information as it emerged".

It is thought that the best overall approach for the construction of an evacuation model is to combine features and ideas drawn from the various simulation models that have been examined. The accurate simulation of evacuation from an aircraft cabin necessitates that two conflicting requirements be met. Firstly, the complex and confining nature of the cabin geometry requires that spatial resolution be sufficient to represent the effects of critical gaps and distances. Secondly, the scale of the simulation problem will vary enormously; for example, a small commuter aircraft type might perhaps only have 30 individuals onboard, whilst potential future large aircraft designs could well carry 800-1000 passengers. The compromise in this conflict of resolution and scale is a key characteristic in all of the models surveyed.

The emphasis of some of the modellers lies on the formulation of a relatively simple programme within a commercial simulation package. This allows rapid re-coding and experimentation to be used during the development process, thus helping to nurture ideas and progress in the short term. However, the model will inevitably be subjected to the constraints of its development environment, unless it is translated into a standard computer language at a later stage. Also, there appears to be a danger from the use of superficial modelling practices. These can occur when, for example, the restrictions of in-built routines force compromises in functionality to be made, or when excessive emphasis is placed on graphical display.

Three of the programmes surveyed incorporate some form of mechanism for representing the effects of fire on evacuation process. In each case the associated fire model is either extremely basic, or else is provided by an external programme. However, the value of adding dynamic influences to the evacuation is still clearly demonstrated by the increase in realism provided; for example, exits becoming unusable and evacuees slowing down. The integration of more advanced types of fire models would necessitate the use of a modular programme construction, as proposed by Phillips (Phillips, 1994).

2.7 Evaluation of Research: Implications for the Study

2.7.1 Breadth and Balance of Air Safety Research

The work surveyed in this chapter has been extremely varied, covering numerous and often highly contrasting aspects of aircraft safety. Research ranges from, for example, combustion chemistry on a molecular level through to full-scale crash tests with remotely piloted aircraft, complex numerical modelling and evacuation trials with live volunteers.

In spite of the diversity of the work covered, it is possible to identify essentially three basic approaches to the undertaking of research. These involve historical, experimental and analytical methods, respectively. To date, work involving the first of these approaches has tended to be undertaken independently from that in the second and third categories. Knowledge obtained from past accidents appears to be regarded as useful background information for those concerned with air safety, but historical findings have rarely been utilised directly in scientific research.

In contrast, experimental work and analytical methods have proven to be highly complementary in many disciplines. In combination they can be used to calibrating and extrapolating the other's findings, respectively. These dual-approach techniques have been utilised widely in areas such as crash, fire, toxicology and evacuation analysis.

As well as comparing different modes of research, it possible to examine progress made across different aspects of aircraft safety. Essentially, most of the work described in this chapter can be placed somewhere within main three fields of safety analysis. These are aircraft crash, fire and evacuation research, respectively. Figure 2.2 illustrates an interpretation of the progress that has currently been made across these three areas. Note that a continuous horizontal axis has been used to depict

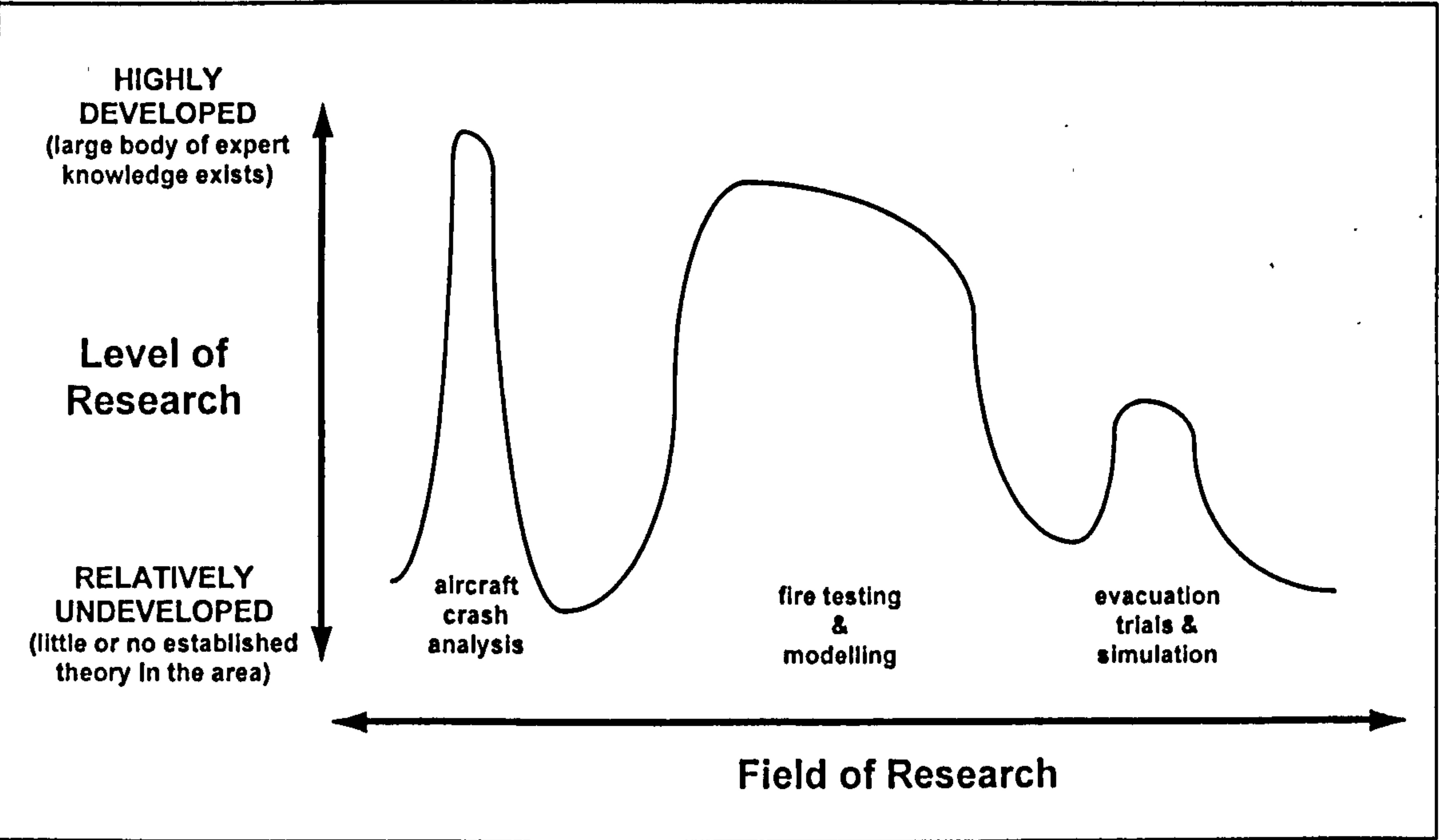


Figure 2.2: Aircraft Safety Research: Current State of the Art

"different" fields of research; this should be taken to imply that all areas of aircraft safety overlap to a significant extent. The vertical axis in the diagram plots the level of development (not necessarily equal to levels of progress) to have been made across each field. It can be seen that three main areas of specialisation occur in safety research, centred on crash analysis, fire testing/modelling and evacuation trials/simulation, respectively. Progressively lower levels of expertise have been attained in each of these three areas; however crash research appears to be highly specialised (i.e. a narrow peak) in comparison with the greater level of diversity found in fire research. Significantly, relatively little overlap was perceived as occurring between these two areas. A greater, but arguably, still insufficient degree of collaboration appears to exist between combustion, human toxicology and evacuation analysis.

2.7.2 Implications for the Current Programme of Research

Study of the work that has been undertaken in aircraft safety indicated that substantial levels of scientific expertise exist in the analysis of crash effects, fire development and passenger evacuation. However, researchers tend to focus their efforts in only one of these areas and then attempt to attain a very high level of knowledge. Inevitably, this has led to voids or gaps in understanding in areas that do not lie within established scientific disciplines, or cannot be dealt with adequately with established methodologies. In contrast, findings established by historical analysis usually span all features of accident safety, as they occurred in the past. Information obtained by this route is, however, less precise and of a lower level than that provided by scientific studies.

Ideally, research into almost any aspect of accident safety needs to combine knowledge from both scientific and historical sources, wherever possible. This is then likely to lead to the production of more balanced and widely applicable findings. However, the task of linking two seemingly dissimilar types of information together appears to be far from straightforward, in either specialised areas of safety research or more general accident survivability studies. As a result, currently, very few examples of these types of approaches to research exist and suitable methodologies have yet to be established in any area.

The current thesis seeks to demonstrate that it is feasible to address these perceived deficiencies in existing aircraft safety research. In Chapter 3, it is described how the research objectives associated with this task came to be derived. The means by which a suitable research methodology was formulated is also recounted in detail.

Chapter 3: Derivation of Research Methodology and Objectives

3.1 Background to the Research

3.1.1 The Formulation of a PhD

This chapter describes the initial planning of the research programme. This process essentially consists of finding a researchable subject, deciding what form the study should take and what type of research issues it would attempt to address. The outcome of these decisions would determine the overall nature of the investigation and establish a fundamental structure for the research activities, around which a more detailed work plan could be developed.

Ideally, the formulation of research in this context should be governed by academic considerations alone. However, external factors can often serve to limit or oppose academic intent and thus shape the research process to some extent. These external influences might include personal relationships, the nature of the research environment, political influence, practical resources and financial constraints. In the case of this thesis some of these factors were significant during formulation of the research plan. Specific examples include focusing the study area down from fire safety in general to fire safety in transport aircraft, and the adoption of a holistic as opposed to a specialist perspective. The first section of the chapter therefore outlines the background to the research and details some of the more important external influences and their effects on the overall direction of the programme.

The process of focusing the research topic was an essential prerequisite before the establishment of individual work tasks and the undertaking of more detailed studies could begin. However, the initial planning stages were of fundamental importance and needed to be undertaken with the possession of a reasonable level of knowledge in the chosen field of study. Therefore, a significant part of the literature survey was required to be in place before any real consideration could be given to choosing the research approach. In consequence, the survey of existing research could be viewed as occurring in two phases, with the decision-making and structuring of the current study occurring around the period of transition between the two stages.

The arguments developed in this chapter were formed predominantly as a product of the preliminary phase of the literature survey. This part of the literature study was deliberately made wide-ranging in extent, in an attempt to provide an overview of all areas of potential interest in the field of fire safety. It was regarded as an exploratory exercise, branching out as far as was possible in order to establish the limits of existing knowledge in the various disciplines of fire safety. As will be seen later in the chapter, this initial research included a limited survey of historical records, in addition to scientific and technical reports. With this information in hand, it was then possible to plan the nature of the current undertaking, providing justification for the chosen approach, where necessary. This resulted in the formal adoption of a computer-based simulation methodology.

The second phase of surveying existing research was more involved than the preliminary work. It partially consisted of acquiring more detailed knowledge in specific areas of research that were judged to be most relevant in the context of

aircraft fire safety. A general overview of this information was provided in Chapter 2. Many aspects of the surveyed fire safety research are also given more detailed consideration in the context of Chapter's 5-8, where they were of direct relevance in the process of constructing the computer model. A substantial proportion of the second phase of the literature survey was dedicated to building a database containing historical information about past aircraft accidents. The need for this information and its significance is explained later in this chapter. The collection, sorting and analysis of this data is recounted in Chapter 4.

The literature survey inevitably formed an ongoing activity throughout the course of the research programme. However, it was found that most of the material describing scientific and technical research was obtained during the first 12 months of the study. In comparison, the compilation of the accident database was a more prolonged process and it was not drawn to a close until the third year.

The final section of the chapter deals with the development of the research objectives. These consist of a series of statements describing the focus of the research and how it would be structured to achieve the overall research aim. As outlined in the next section, the research objects formed the basis from which detailed research design was begun.

3.1.2 The Research Design Process

It was a requirement of the department in which the study was being undertaken to carefully structure the design of the research and to justify the choice of approach at each stage of the process. In addition, the provision of a contribution to knowledge had to be demonstrated and the work placed in context within existing work in the field. In short, the fulfilment of these requirements would ensure that justification could be provided for *what* the research topic should be, *why* it should be studied and *how* it would be investigated.

More formally, this process involves choosing the topic area to be studied, the formulation of the research aim, selection of a suitable methodology and designing the research objectives, leading to detailed research design. For convenience, this procedure can be represented as part of a linearly structured plan of activity (See Figure 3.1). However, it should be appreciated that, in practice, many of these tasks

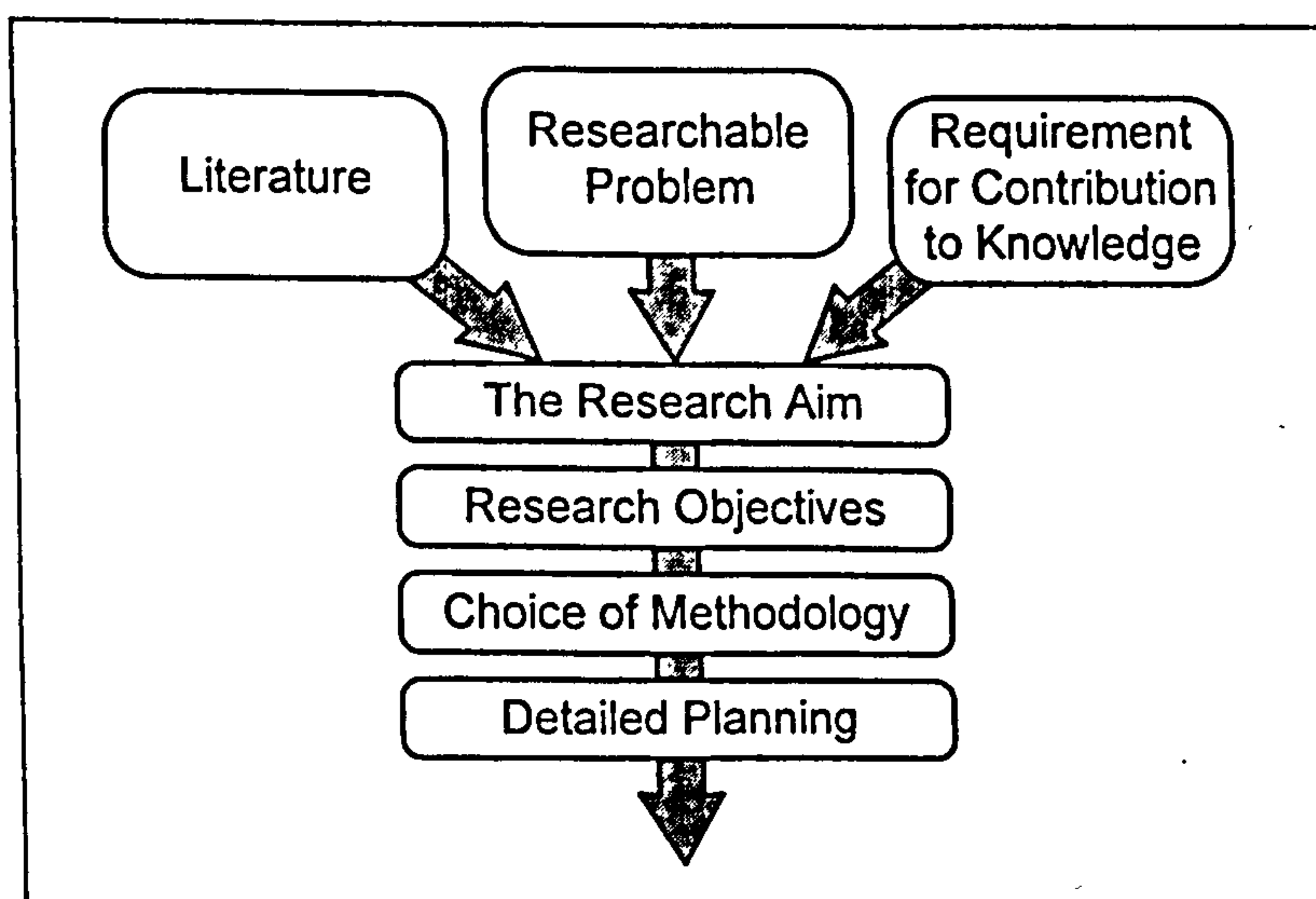


Figure 3.1: The Research Design Process

were carried out in parallel and that significant backtracking may occur.

The first task to be performed in the initiation of any research undertaking is to identify a researchable problem and establish the aim of the activity. Often, the research aim will be communicable in the form a succinct statement, perhaps consisting of only a single sentence. The intended aim in most research is to address a perceived problem. The latter can be obtained from study of the area under consideration and the identification of a difficulty, requirement or issue that requires addressing. Closer examination of the matter and analysis of the requirements of potential knowledge customers will enable a researchable problem to be formulated. In the educational context, a requirement will also exist to demonstrate the originality of the research. This means that if the chosen topic has already been addressed by other researchers, then the proposed study must differ from the existing work in some significant aspect. In most circumstances, genuine research will never be precisely duplicated by independent workers. Thus, in practice, the requirement for original work serves mainly to prevent plagiarism or mis-attribution.

An additional academic consideration is the necessity for research to provide a tangible contribution to existing knowledge. This implies that awareness of work published in the area of study must be demonstrated and the new contribution placed into context within the field. This commonly involves the identification a particular gap or apparent inadequacy in the information provided by existing literature and shaping of the research programme to fill any associated need.

A prerequisite for establishing the aim of a research project is an appreciation of relevant work undertaken by others in the area of activity. A comprehensive knowledge of existing research is particularly essential in an academic environment, where a sufficient degree rigor must be exhibited throughout the programme. This information is usually obtained from the undertaking a survey of published research literature and from previous experience in the area of research. The literature survey can never be completely exhaustive and results obtained will be dependent on the environment and facilities in which it is carried out. The survey will often form an ongoing part of the research effort, in order to include new material as it becomes available. It may often be necessary to cover new subject areas, if changes in the direction of the research dictate.

An integral part of the survey process is the preliminary interpretation of the gathered material and drafting of summary notes for future reference. Much of the information obtained will inevitably prove to be redundant in the longer term, but it may be difficult to gauge the true significance of a piece of work until a reasonable amount of knowledge has been accumulated. It is therefore common practice to instigate some form of cataloguing system to enable convenient return to the required material.

The research objectives stipulate how the aim of the work will be achieved. They consist of series of statements that describe the following:-

- The nature of the research problem and what aspects of it will be considered
- The main tasks that need to be performed to achieve the research aim
- The research methods or other techniques that will be used
- The envisaged outcome or product of the research

In essence, they provide a summary plan for structuring of the research activities, and, in an academic context, the objectives of what the contribution to knowledge will be.

3.1.3 Personal, Departmental & Institutional Influences

The starting point for the entire study was the acceptance of a preliminary research title, provided by the research supervisor. This title was probably intended more for administrative convenience than academic purposes. As such, it was considered to be unrestrictive and open to different interpretations:-

"Dynamic Fire Risk Assessment Models Applied in Transport Contexts"

The title was to be regarded as essentially provisional in nature and open to modification, as changes in the emphasis of research dictated. In consequence, the only historically imposed constraint on work content was the requirement to study some aspect of fire safety in a human context. Initial discussions quickly resulted a consensus that the research should be undertaken with a comparatively holistic outlook, rather than from, say, a purely scientific, sociological, or policy-study standpoint. This decision was a consequence of the multi-disciplinary nature of the research department in which the work was to be undertaken and the preconceived intentions of the author.

The term "*Risk Assessment Model*" can possess quite different connotations in some specific circumstances (Hall, 1991). However, for the purpose of formulating the research, it was provisionally regarded as implying that some form of qualitative risk analysis would be undertaken. Definitions of risk are numerous, but in the context of fire safety, the following seems reasonable (Hall, 1992):-

"Risk refers to (a) a type and degree or peril or loss; (b) the relative likelihood or degree of probability that that type and degree of danger or peril or loss will occur."

Thus, risk assessment is usually associated with some form of probabilistic analysis, where rational objectivity or judgement may often be used to supplement incomplete physical knowledge (Kersken-Bradley, 1988). Once the work had been planned in detail, it still appeared to remain comfortably within the scope of risk assessment modelling. In consequence, the term was retained for the duration of the study.

A significant early influence on the emphasis of work was the existence of two departmental contacts working in the field of fire safety. These researchers were involved in the development of computer-based fire risk assessment models¹ and the undertaking of applied aircraft evacuation research² respectively. For reasons that will become apparent, both of these contacts were destined to become advisory supervisors for the study. The two advisors, together with the personal supervisor, formed a supervisory panel that was to be convened as required throughout the duration of the work.

The availability of information at the host institution together with the aeronautical background of the author quickly resulted in attention being focused on

¹ W.G.B. Phillips, formerly of the Fire Research Station, a department of the Building Research Establishment, UK.

² Professor H.C. Muir, head of the Department of Applied Psychology in the College of Aeronautics, Cranfield University, UK.

the topic of civil aircraft fire safety. It was recognised that many of aspects of research undertaken within seemingly specialised fields of fire safety are applicable in a more general context. For example, initial reading revealed that there appeared to many similarities between fire safety in air transport and the equivalent problems faced in the rail, offshore engineering, shipping and building industries. This suggested that knowledge could potentially be obtained from many branches of fire safety research, even though the thesis would be constructed within the context of aircraft safety. The corollary of this was that the work could probably be adapted or extended to address fire safety concerns in other industries.

These considerations resulted in a distinct honing of the research emphasis, coalescing it down from “*transport contexts*” in general to specifically the study of transport aircraft. In order to reflect this clarification in emphasis of the study, and acknowledge the possession of a degree of ownership by the author, the research title was changed to:

“*Probabilistic Risk Assessment Modelling of Passenger Aircraft Fire Safety*”

It will also be noted that the term “*dynamic*” modelling had been dropped. The phrase could have implied the adoption of a particular type of approach in the research department in which the work was being undertaken. Its omission was therefore a precaution to avoid any confusion or mis-representation concerning the nature research methodology, which still had yet to be determined.

It was not known during the preliminary stages whether or not a computer-based methodology would be adopted. Both the host department and three supervisory staff were remarkably well balanced between those who were conversant in use of computer modelling techniques and those who were not. The author was proficient in the use of a number of complex computer-based applications and operating systems, but had no recent programming experience.

For these reasons, the possibility of constructing a computer-based model was regarded strictly as an open option during early discussions with supervisory staff. However, ideas evolved quickly during the initial stages of the literature survey, when the complex nature of events occurring in aircraft accidents became apparent. The importance of dynamic interactions between aircraft occupants, fire and the local environment clearly required their representation within any meaningful form of safety analysis. This form of modelling could only be undertaken with the use of computer-based approach.

3.2 Initial Findings Obtained from Accident Data and Statistics

3.2.1 The Relevance of Historical Information

Those concerned with understanding the issues surrounding fire safety in commercial passenger aircraft have two main resources of information with which to work from. These consist of historical data about events that have occurred in the past and the findings obtained from scientific investigation. The two classes of material yield quite different, but complementary, types of information. Historical data can generally be taken to be authoritative but it is essentially qualitative in nature and may often be incomplete. In contrast, scientific work is undertaken systematically and provides quantifiable results. However, scientists are usually forced utilise an artificial

experimental environment, which can make it difficult to guarantee the wider applicability of the findings obtained.

The potential value of historical information, in the form of accident reports and studies based on past accidents, was realised at an early stage of the investigation. Initially, the historical material was regarded as merely an adjunct to the scientific literature, rather than as an integral part of the survey. However, as the work progressed, it became apparent that both the quality and the extent of available historical information could be sufficient enough for the material to form a major contribution to the basis of the research.

If accident data were to constitute a significant part of the study, it had to be accepted as being a reliable and authoritative description of actual events. This requires that the publishers of historical documentaries have access to adequate source material and evidence with which to work from. In addition, this information must be gathered, interpreted and reported in an objective and factual manner as possible.

An obvious difficulty in undertaking studies into accidents and human disasters in general is that the nature of these events precludes a researcher from obtaining contemporary evidence during the actual occurrence of an incident. Scientific research into safety matters attempts to reproduce particular aspects of an accident in a controlled and reproducible manner, enabling them to be closely studied at first hand. These experiments can therefore be seen to constitute a form of secondary evidence. In contrast, those responsible for the investigation of accidents can usually gain access to physical evidence at the scene. This primary material has to undergo an interpretation process, yielding information of a secondary level. Equivalent secondary material may often be obtained in the form of witness statements and through the experimental reconstruction of key events. A report resulting from such an investigation must therefore be regarded as a product of secondary evidence.

The objectivity of an accident report is very difficult to either prove or disprove conclusively. In the context of aircraft accidents, perhaps the most reliable indicators are the independent nature of many of the investigatory and reporting organisations, such as the International Civil Aviation Organisation, the US National Transportation Safety Board and the UK Air Accident Investigation Branch. In many instances, nations with an underdeveloped air transport infrastructure have chosen to delegate responsibility for the investigation of an accident to a team of professionals brought in from another country. This arrangement has been provisioned for by amendments to the ICAO Chicago Convention and it has often proven beneficial for all involved parties.

In some countries, the production of accident reports is overseen by government or other official bodies, whose members may possess a vested interest in the outcome of any investigation. This can often lead to undue influence being exerted to exonerate the role played by official institutions, procedures and standards. However, in most circumstances, it is plainly apparent when the content of a report has been prejudiced, usually from the character of the conclusions and the absence of any constructive recommendations. In these circumstances, a thorough investigation of the accident is rarely undertaken and this usually results in little or no useful fire safety information being provided in the report.

The reporting of accidents in many countries falls somewhere between the two previously described extremes. Often, genuinely good intention appears to exist, but inexperience, probably in combination with a lack of resources precludes the

undertaking of a detailed inquiry. Correspondingly, reports tend to focus on factual aspects obtained from the scene of the incident, with less emphasis on the analysis and interpretation of events. In spite of these limitations, reports falling within this category can provide much valuable material for the safety researcher.

These interpretations were formed from the study of a limited number of accident reports in the exploratory stages of the study. However, it was clearly evident that the quality and integrity of information provided in many of the accident reports would be sufficient enough to justify its use as a substitute for primary data. It was also apparent that, given the limitations of scientific techniques, much of the information provided by the historic material would be impossible to obtain by other means.

Where information concerning past accidents was possible to obtain by scientific investigation, the historical material could also form an invaluable basis from which the contributions of scientific research could be evaluated.

3.2.2 The Construction of a Preliminary Accident Database

In the initial stages of collating information from past accidents it became apparent that the order of several hundred reports could be of direct relevance to the study fire safety. These particular accidents would need to be systematically identified from thousands of incidents available on record, according to a set of suitably defined criteria. It was not possible to decide what these criteria should be for the first phase of the data gathering, as ideas concerning the direction of the study had still to be developed. The preliminary phase of the information gathering process was therefore split into stages, each of which served to progressively cut down the number of accidents under consideration and make the analysis more manageable.

The first stage would log the two thousand or so incidents that involved public transport aircraft and were probably serious enough to warrant further investigation. These would then be subjected to a second round of more detailed analysis, in order to ascertain the role played by fire in each case. This acceptance/rejection process would then lead to the formation of a database of key accidents where fire was definitely known to have played a significant role. The preliminary information gathering and classification process is detailed in the first section of Chapter 4.

The purpose of the initial survey was to find out exactly what type of events typical aircraft fire accidents were likely to involve. The intention was to obtain a basic familiarisation with all aspects of the accidents and then identify particular areas which might be suited to some form of analysis. At first sight, the preliminary accident data survey could be regarded purely in terms of an information gathering exercise. However the activity was undertaken in parallel with the literature survey and considerable effort was taken to compare and relate the information being simultaneously accumulated in the two areas of work. The data gathering was thus equally important for its contribution to the gestation of ideas and formulation of the overall research programme.

A key requirement for the preliminary data gathering work was to provide some basic statistical information about historical events. The nature of accidents was found to vary enormously from incident to incident, and completely different outcomes could often result. Specific classes of accident might require the use of a different type of approach in their analysis, or perhaps be of only marginal significance. It was therefore required to obtain some indication of the relative

frequency at which different types of accident had occurred in the past and prioritise them in terms of fire safety issues. This would enable the emphasis of the research to be shaped by historical precedence, rather than it being left exclusively to intellectual propensities.

As the information gathering progressed, it was discovered that many accident reports provided significant quantities of information in the format of a descriptive narration. Most of this material was essentially qualitative in nature and would not be amenable to a straightforward coding or classification process, making it impossible to represent it adequately within the preliminary database. However, provision was made for several lines of descriptive notes to be included in each accident record, thus enabling key anecdotal information to be recorded where necessary.

In consequence, it was appreciated that the second phase of the accident data gathering and analysis would have to include provision for dealing with an appreciable quantity of descriptive evidence. In addition, another adjustment that could be usefully incorporated into the second stage would consist of recording the sources from which information was derived. This would be of potential value in resolving situations where contradictory evidence had been obtained from multiple sources.

In summary, the preliminary data survey had covered the order of 10,000 recorded incidents listed in the World Airline Accident Summary (CAA, 1996) since 1948. Of these, approximately 2000 were considered to be of potential relevance to study and their details were recorded for further analysis. Once the objectives and bounds of the research had been formulated, it was possible to reduce this number down a total of around 200 incidents for inclusion in the second stage of the survey.

3.2.3 The Nature of Past Aircraft Fire Accidents

The preliminary survey of aircraft accidents revealed a large quantity of information, whose content would provide important implications for deciding the overall direction of the research. It should be noted that, at this early stage, the recorded details were relatively basic, much of the data was still incomplete and little statistical analysis had been undertaken. However, ample evidence had been obtained to provide some fundamental pointers as to what real aircraft accidents were likely to involve. These were of sufficient importance to justify the time spent data on the data gathering effort and reaffirm the need for undertaking the second phase of the accident data survey.

The most important revelation to be provided by the preliminary data was that the vast majority of aircraft fire accidents involve some form of impact. The term "crash" was regarded as being generally unsatisfactory or even misleading when used to describe many types of incident. Therefore, as explained in Chapter 4, two terms were formally introduced in order to classify the occurrence and nature of aircraft "crashes". These were *significant impact* and *significant fuselage disruption* respectively. The probability of an aircraft accident involving a significant impact is shown in Figure 3.2.

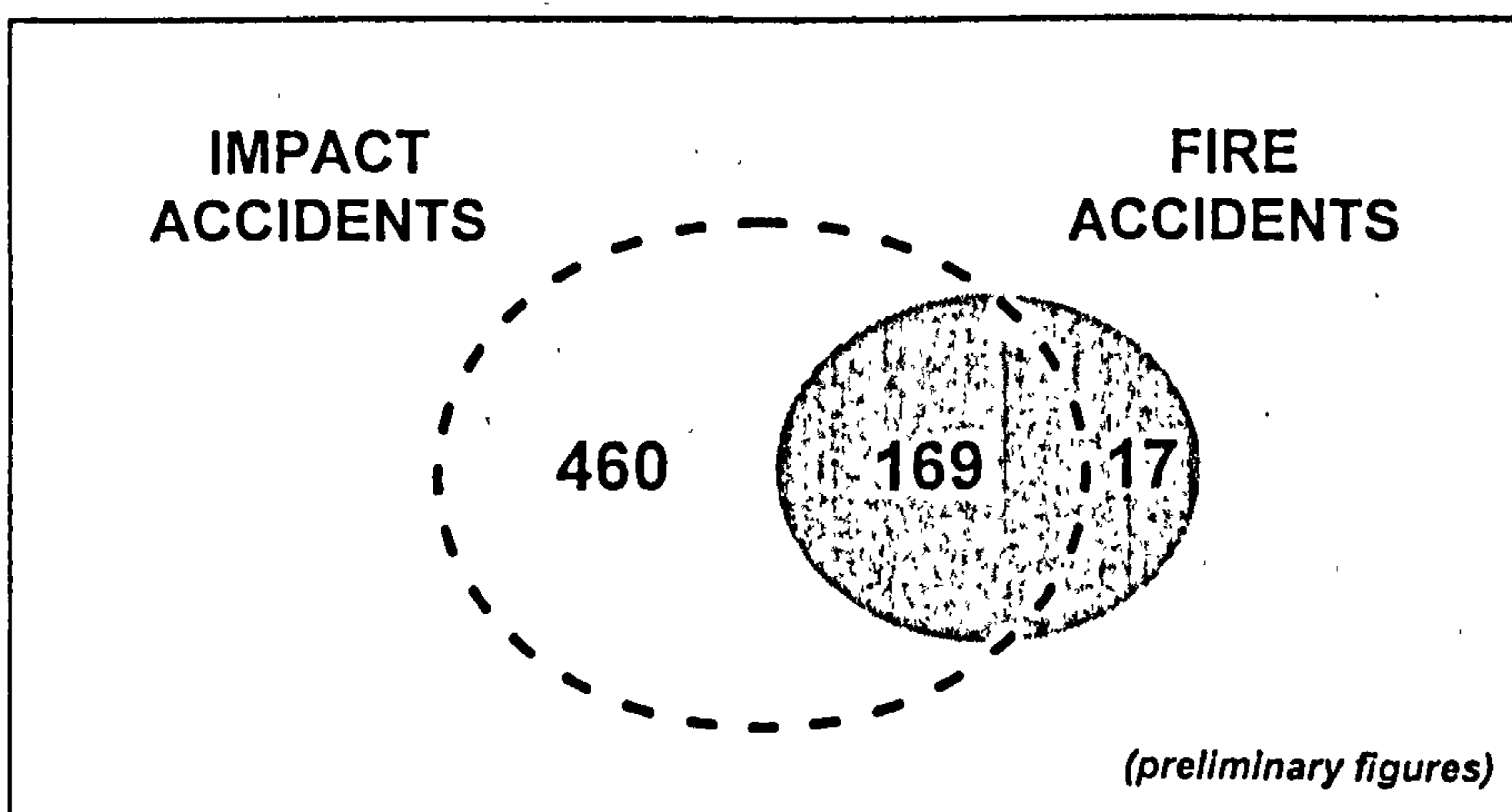


Figure 3.2: The Occurrence of Impacts in Fire Accidents

It was apparent that approximately ninety percent of the fire accidents had involved a significant impact. Effectively, this can be taken to mean that nine out of ten survivable fire accidents will result in the aircraft no longer being supported by its undercarriage. It also was apparent, even from incomplete figures, that passenger injuries and fatalities in most fire accidents were just as likely to be caused by the effects of impact trauma, as from the effects of fire. These early indications were reinforced by results obtained in the second stage of the past accident survey.

3.2.4 The Diversity of Aircraft Fires

The nature and characteristics of fires in the surveyed accidents showed significant variation from one case to another. For example, on some occasions very severe fires have occurred, but they have had comparatively little effect on the aircraft occupants. Conversely, in other instances, smoke products produced from relatively small fires have killed hundreds of passengers. The diversity in effects resulting from different types of fire clearly indicated the need for some form of classification process. This was necessary in order to identify the differences and commonalties between various fire types and establish how these related to the different types of outcomes that had been observed. In the early stages, every accident fire appeared to be almost completely unique, but as the data gathering progressed, some common themes emerged and meaningful categorisation thus became possible.

The first distinction to be made was between those fires that had originated inside the pressure shell of the fuselage and those that started outside the aircraft. (These two categories will subsequently be referred to as *internal* and *exterior* fires respectively.) The dangers associated with these two classes of fire are often quite different in nature, as outlined in the following paragraphs.

Internal fires are most likely to start in galleys, toilet compartments or underfloor cargo holds. Minor galley fires are relatively common, but because of their generally minor nature and the close proximity of cabin staff, they have rarely constituted a serious threat to life. However, when an internal fire starts in an inaccessible and/or unattended part of an aircraft in flight, the consequences can be very serious indeed. The danger stems from the fact that the occupants of the aircraft are trapped with the fire inside a sealed structure and have to remain so until the aircraft can be safely landed. Internal fires have produced some catastrophic results in

the past, but they are comparatively rare, comprising only seven percent of the total number of accidents surveyed. Improvements in operating procedures and the introduction of automatic fire detection and suppression systems in the last decade appear to have largely nullified the threat posed by internal fires.

The vast majority of aircraft accidents surveyed involved exterior fires. These differ from interior fires in that they usually involve the aircraft's fuel and therefore tend to grow rapidly to a larger size, with more destructive consequences. Many accidents involve the aircraft being subjected to a severe impact, resulting in the rupturing of wing fuel tanks and large quantities of fuel being released. If the fuselage structure also happens to have been severely damaged, fire can easily ingress into the passenger cabin, often with horrific consequences. For convenience, it was decided to group these types of incident under the label of *impact* fires. Development of the precise definition of this term is expanded upon in Chapter 4, but for the preliminary survey work, it was taken to mean the presence of a fire in the immediate vicinity of the passenger cabin together with the existence of significant tearing or open dislocation of the cabin structure. The implication of this definition is that *impact* fires are able to enter the cabin rapidly and thus pose an immediate threat to the aircraft occupants. This was found to be the most common type of exterior fire, occurring in just under half of the surveyed accidents.

In circumstances where the fuselage has remained essentially intact after an accident, a limited degree of fire protection may be afforded by the cabin structure. In many instances fire can occur close to an aircraft's fuselage and this measure of protection can be critically important in increasing time available for the egress of passengers. However, flame penetration may usually be expected to occur in a matter of minutes, or even within thirty seconds in the most extreme circumstances. Nevertheless the presence of fuselage structure appeared to make these fires sufficiently different from the *impact* fires to merit separate classification. The title *burnthrough* fires was chosen. This term implies the existence of a fire in close proximity to the aircraft fuselage and which is able to penetrate through to the passenger cabin before the aircraft can be completely evacuated. *Burnthrough* fires were found to be the second most important category of fires, occurring in over one quarter of the incidents.

In many of the less critical accidents, fires have been centred away from the occupied sections of the aircraft, or else they have required significant time to grow to a potentially hazardous size. This can often allow for all surviving occupants to reach safety before the fire effects become potentially dangerous. This fire type was given the label *external* fire, signifying that no substantial burnthrough into the cabin area occurred during the course of the evacuation period. External fires have been comparatively rare, only constituting around one in ten of the accidents surveyed.

The categorisation of each of the accident fires into one of these four classes was initially perceived to be reasonably straightforward process, as the four classes of fire had been defined so as to be quite distinct. However, upon detailed examination, a significant proportion of the accidents could arguably be assigned to more than one category. Thus it became apparent that, in some instances, distinctions would not necessarily be clear-cut. This change in perception prompted a re-examination of the relationships between the internal, impact, burnthrough and external fire categories, which yielded a rather surprising result. Ironically, it was concluded that the association between the fire "categories" should really be regarded as a continuous

distribution. This can be illustrated by considering each fire type in terms of the time required for the fire to ingress into the passenger cabin.

Impact fires are able to gain access around about the time that aircraft comes to a stop, because of extensive fuselage destruction. For the sake of argument we can define this point as time zero. In-flight fires usually have to endure for several minutes before the aircraft can land; thus they can be interpreted as occurring at some negative time before the aircraft stops. In contrast, burnthrough fires require a short (positive) interval before they can enter the cabin area. By definition, external fires take significantly longer to penetrate, or else may not be able to penetrate at all. The latter case may be interpreted as corresponding to an infinite burn-through time. This argument is illustrated in Figure 3.3.

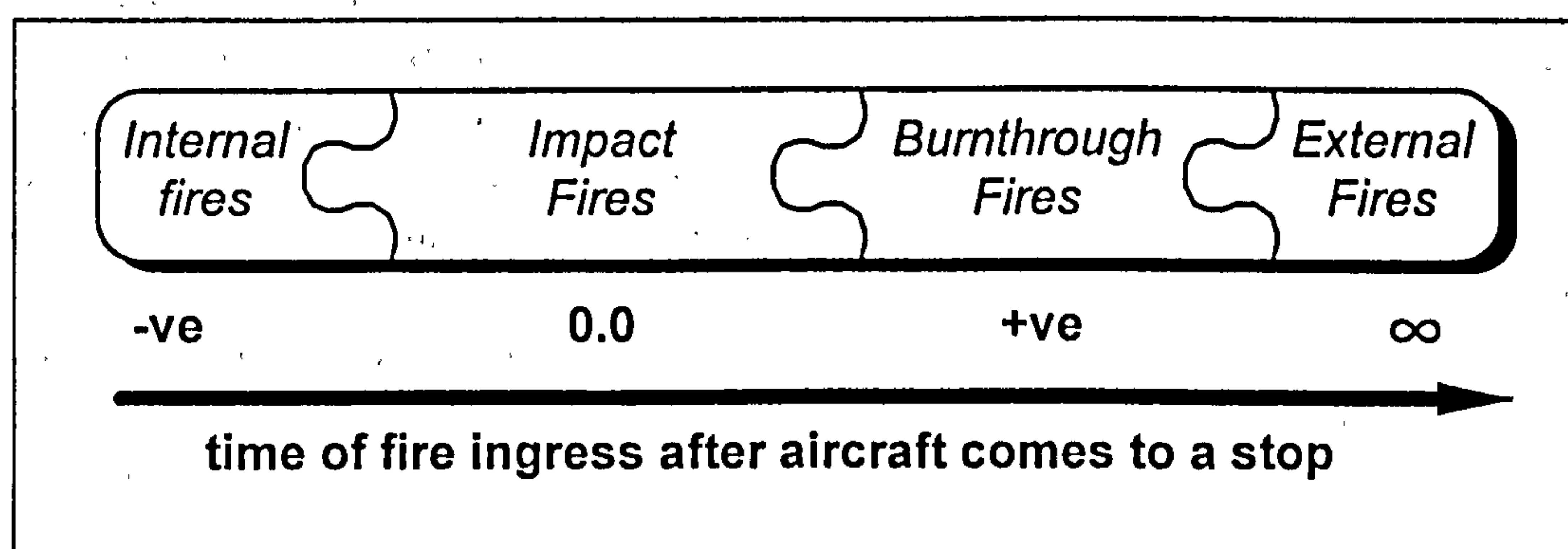


Figure 3.3: Fire Classification as a Function of Ingress Time

In spite of this re-appraisal of the fire classification process, the identification of four fire categories was still considered to be a valuable first step in the analysis of the historical information. Perhaps the greatest single contribution that it would make was to reveal the fact that undertaking an adequate analysis of aircraft fire safety would need to involve far more than merely the study of fire.

3.2.5 Implications for the Modelling of Aircraft Fires

Initial impressions gained from the historical data suggested that the diversity of the characteristics present in each of the four types of accident fire would make their analysis difficult. Ideally, a single general model would need to be formulated, able to deal with all types of aircraft fires in a consistent manner. Alternatives to this included the creation of a family of specialised models, each addressing a specific type of fire scenario, or else restricting the study to consider only one particular class of fire. The universal fire modelling approach was thought to be the most appealing of the three, but it was not immediately obvious if it would be feasible to achieve. In consequence, considerable thought was applied to identifying the most important aspects of accident fires and determining how they might contribute to occupant fatalities. This effort represented an attempt to return to the absolute fundamentals of the fire survivability problem and establish whether or not any substantial common links existed between the various types of fire accidents.

As has already been seen, the first step in the analysis of the accident fires had been to classify each of them into one of four categories. This inadvertently led to the discovery of the first conceptual link between the surveyed fires; their consequences

can, to a large extent, be characterised in terms of the time required for ingress of fire into the cabin.

The value of this finding was threefold. Firstly, it encompassed all types of fire with a single-dimensional parameter (fire ingress time, measured from the point at which the aircraft comes to a stop). Secondly, this variable was known to be reasonably straightforward to ascertain for most incidents. Finally, because the parameter provided classification on a continuous scale, it would be innately more suited to describing those "crossover" accidents that did not fit cleanly into discrete categories.

Another, rather more obvious, feature shared by all the accidents was the significance of the fire size. If all other parameters are held constant, the larger the fire, then the more serious its effects would be on potential survivors. This statement is deceptively simple; however, in order to make quantitative use of it, we need to know precisely just what makes one fire larger than another. In this context, fire "size" should perhaps be taken to mean some undefined measure of the rate of output of the three main products of fire, i.e. heat, smoke and flame. These fire properties are difficult to measure in closely controlled experimental conditions, and practically impossible to quantify accident situations. Even if precise information about heat, smoke and flame production is obtained, it is not known how these characteristics should be combined to produce a single measure of fire size.

To avoid these inherent difficulties in measuring fire size, most fire experiments utilise some form of standard fire source. These are intended to produce reasonably consistent quantities of fire products and be straightforward to replicate. Typical examples of standard fires include a domestic armchair, a rectangular pool of kerosene, oil/gas burners, or cardboard box loosely filled with cotton rags. In large scale aircraft fire safety experiments, the most common types of standard fire source are rectangular pools of aviation grade gasoline or kerosene (e.g. JP-4, or similar). This is presumably because most aircraft fires predominantly involve spilt fuel, in their early stages, at least. The particular advantage of using a pool fire analogy is that it allows for the effective size of a fire to be specified in terms of its ground area. For a rectangular fire, this means the provision of length and width, or, in the case of a circular analogy, simply a fire radius.

Although this solution to the problem of quantifying fires has been developed for the purposes of undertaking fire experiments, it was thought to be of potential use in the analysis of aircraft accidents. It was considered that many reports contained enough information on the size and effects of the accident fire to enable a reasonable estimate of an equivalent pool fire size to be made. This would probably enable most of the incidents involving exterior fires to be quantified with of a logical and consistent measure. However, the pool fire analogy is not applicable to the cases of internal fire, where the source is most likely to consist of interior furnishings and/or cargo. Given that internal fires represented only seven percent of the surveyed accidents and appeared to be becoming increasingly rare, they were thought to represent a low priority. Internal fires were therefore regarded as special cases, that would have to be addressed with a different type of fire model.

The study of research literature indicated that large-scale experimental fire tests always involved fully developed pool fires of a fixed size. However, information about past accidents suggested that the development characteristics of real fires were usually markedly different from those of the test fire cases. Aircraft fires generally do

not grow rapidly to a fixed size and remain centred in one position; rates of growth and direction of spread often differ considerably from incident to incident and emergency services usually intervene. No information on these aspects of accident fires could be located in the literature and it became increasingly apparent that the issue would require addressing. Significant attention was therefore applied to studying the problem of the fire growth, spread and extinguishment.

In terms of accident survivability, we are concerned with the preservation of life and it is this *time history* of a fire during the period of evacuation from the aircraft that is of primary importance. Where surviving occupants have been unable to extricate themselves, they have usually succumbed to the effects of the fire, either during, or soon after the evacuation period. This then naturally leads to the concept of a *survival window*, i.e. the existence of a short period of time after the occurrence of an accident during which potential survivors possess a reasonable opportunity for escape. Historically, this period has typically ranged from one to five minutes, although much longer intervals have been required in a few instances.

The fact that we are only interested in the characteristics of accident fires during a relatively short survival window has two important implications. Firstly, most fires tend to change size significantly during their first few minutes. For example, where impacts produce fuel misting, a large and immediate "fireball" generally subsides into a smaller steady state conflagration. Alternatively, in cases where the fire might initially be quite small, progressive leaking from ruptured fuel tanks can often result in steady growth of a fire. This implies that aircraft fire accidents must be considered as dynamic events, undergoing significant changes in nature within short time intervals.

Also, a short survival window implies that the intervention of emergency rescue services may not have a major role in reducing the number of casualties in most accidents. This conclusion was reached after careful study of historical events; the initial data survey indicated that the arrival of emergency services on the scene occurs, on average, about three minutes after an aircraft comes to a stop. If an additional minute elapses before effective fire-fighting begins, then often little can be done to help survivors in critical situations. Typically, after a few minutes most passengers will either be safe or already well beyond help. Trapped survivors have tended to struggle out unaided, or else be unconscious and/or inaccessible and thus likely to succumb in a very short time.

In comparatively rare instances, a fire can require a significant time to become established after an accident occurs. Emergency rescue services are often then able to play a valuable role in expediting the evacuation process and maintaining the availability of escape routes. However, aircraft can still be destroyed by fire several minutes after having been safely evacuated. This has occurred even when substantial numbers of fire-fighting appliances have been in attendance and such events illustrate the scale of the problem in dealing adequately with a large scale aircraft fire.

The decision was therefore made that it would be possible to ignore the effects of emergency intervention in aircraft fire accidents, at least for a first level of approximation. This would allow for a considerable degree of simplification to be achieved, in that occupants could be treated as self-rescuing and fires could be assumed to behave as if they were unregulated. The latter point was especially valuable in that it allowed for the utilisation of a substantial body of research

undertaken into quantifying the properties of large open hydrocarbon pool fires (Mudan and Croce, 1988).

If this conclusion seems in any way controversial, then it should be appreciated that other researchers have reached the essentially the same verdict; *"In the case of a severe spill fire, the study showed that an equipment response time of 60 seconds or less is required to produce a reasonable probability of rescue"* (Chicarello and Shpilberg, 1976). Subsequent discussions held with specialists in the fire safety industry have served to confirm these findings.

In summary, this section has described the development of ideas concerning the modelling of aircraft fires, based on the interpretation of past accidents. Although the fires were initially perceived as being both extremely diverse and complex, an understanding of the fire problem was gradually developed. This was achieved by identifying some key aspects of fire survival and using these to unify the analysis of past accident fires. In effect, this meant that the most important differences between fires in past accidents could be quantified in terms of three variables. These are:-

1. The position of the fire
2. The time required for ingress of fire into the cabin
3. The size of the fire during the evacuation period

The interpretation of aircraft fires in terms of these parameters would also facilitate the use of a pool fire analogy for modelling the vast majority of accident fires. Much information is available on open pool fires, obtained from both experimental research and theoretical analysis; thus this is the most obvious modelling approach to adopt.

It was observed that the development of accident fires was often very dynamic in nature and this would have to be represented in the fire analysis. Also, it was found that the intervention of emergency fire-fighting services rarely played a significant role in fire survival during the critical first few minutes of an accident. These considerations suggested that a comparatively simple zonal model, incorporating dynamic growth behaviour, would be best suited for the analysis of aircraft fires.

3.2.6 The Importance of the "Total Accident Scenario"

The analysis of historical data showed just how diverse many aircraft fire accidents could be. This was not realised immediately because, at first, attention was confined purely to examining the fire survival aspects of each incident. Thus, the scope of the analysis was restricted to ascertaining the physical attributes of each accident fire and determining how these affected survivors attempting to evacuate from the aircraft. However, as the analysis progressed, it became apparent that far more background information was required in order to characterise the nature of the fire survival problem in many of the accidents. Relevant features could potentially include the aircraft type involved, the nature of the accident site, weather conditions, evacuation details and the consequences of any crash that might have occurred.

Consider, for example, details of the three incidents listed in Table 3.1. The information provided has been taken directly from the results of the preliminary accident survey and describes three accidents that occurred within a period of 18 months during 1984-85. Note that the basic scenario appears to be very nearly identical in each case; all three incidents involved the same aircraft type, included an emergency evacuation in the presence of large scale burnthrough fire and were caused by a catastrophic engine failure whilst the aircraft was on the ground.

Date	Aircraft Type	Location	Killed	Injured	OK	Fire Type	Site	Notes
840322	B-737-200	Calgary (Canada)	0	1	119	Burnthrough	taxiway	Engine failure on ground. Fuel tank penetrated; rapid fire. Evacuated through all 4 rhs & front lhs exits in ~3mins.
840830	B-737-200	Douala (Cameroon)	2	0	116	Burnthrough	taxiway	#2 engine failure during taxi. Fuel tank punctured & fire followed. Evacuated in ~90s.
850822	B-737-200	Manchester (UK)	55	15	67	Burnthrough	taxiway	#1 engine failure on takeoff & fuel tank punctured - aborted. Evacuated through fwd doors & rhs overwing exits in 210s.

Table 3.1: Three Aircraft Fire Accidents

However, in spite of these striking similarities, it can be seen that three very different outcomes resulted in each case. The first incident produced only one serious injury; two fatalities occurred in the second case and the final accident involved 55 deaths. It should be noted that in all cases, casualties were due entirely to the effects of fire. The contrasting fatality rates occurred for very basic reasons¹; however these reasons are not readily apparent from inspection of the rudimentary information gathered in the preliminary accident data survey. It was therefore obvious that the risk-assessment modelling task was going to involve significantly more work than had originally been anticipated.

The highlighting of these inadequacies in the preliminary data analysis lead directly to the concept of a *total accident scenario* being formulated. This was defined as consisting of "the combination of all accident parameters and circumstances that significantly influence the survival prospects of accident victims". The past accident data that had been obtained up to this point clearly suggested that the performing of a satisfactory risk-assessment study would need to involve the analysis of these total accident scenarios. This information should describe precisely how and why aircraft accidents result in casualties, rather than just indicating what has occurred, when, and where. Without this level of knowledge, it would be very difficult to obtain a comprehensive understanding of the many critical features that determine fire survivability in these events. Specialised studies can be performed on specific aspects of aircraft fire safety, but the results obtained from these endeavours then have to be placed into the context of real events if they are to be of significant value in policy formulation.

These considerations implied a need to establish the details of the total accident scenarios for all the incidents collated in the preliminary survey database. The emphasis of this requirement lay with the gathering of significantly greater quantities of descriptive material, in order to provide a more detailed understanding of the incidents. This, then, constituted the primary justification for undertaking the second round of accident data gathering and analysis. Before this work could commence, it was first necessary to decide precisely what categories of additional information would be required and how they should be organised. It was stated previously that detailed interpretation of the accident fires had already been undertaken, as part of the fire classification process. Three other aspects of the accidents were identified for treatment in an equivalent level of detail. These were general scenario details, the effects of crash impact and the evacuation of survivors,

¹ For example differences in wind conditions, rate of fire spread, passenger behaviour and passenger familiarity with the location of emergency exits.

respectively. The remainder of this section discusses these information categories and provides the reasons why they were considered to be relevant to the study. The organisation and recording of this information in the second phase of the accident data survey are detailed in Chapter 4.

In some instances, seemingly minor details can have a major influence the outcome of aircraft accidents. Consider, for example, the growth in size of a pool fire. This usually be governed by the type of terrain present at an accident site; fuel can easily spread to cover large areas on a concrete runway surface, but will quickly be absorbed by a ploughed field. Alternatively, if an aircraft happens to crash into a built-up area, unusual ventilation effects, heat reflection and the combustible remains of buildings may sometimes serve to exacerbate fire development. There have been many cases in which circumstances similar to these combine to produce unusual or unexpectedly severe fire effects. Therefore, an attempt was made in the second phase of data gathering to note any details or general aspects of the accidents that might have had a significant effect in determining fire lethality. This information often included the following items:-

- Local weather conditions at the time of the incident
- Type of terrain present at the accident site
- Quantity and type of fuel being carried
- Accessibility of the aircraft wreckage
- Prevailing wind speed and direction

Given that the role played by these features in the development of fires is, in many cases, poorly understood, their inclusion in the survey was thought to be justified even if their relevance could not be directly ascertained.

An attempt was also made to record some other miscellaneous items of information. These included the type of flight involved, time of day, light conditions and a brief synopsis of events, together with the reported cause of the accident. In the latter case, causal details were not expected to contribute significantly to the study of fire safety. Nevertheless, this information was valued because it helped to portray a more complete picture of events occurring in the accidents.

It has already been shown, purely from the fire classification analysis, that the survival prospects of passengers involved in a fire accident are closely related to the structural integrity of the aircraft's fuselage. Thus, when the cabin structure has been severely ruptured or dislocation of the fuselage occurs, survivors have a significantly higher chance of succumbing to the effects of fire. This implies that the consequences of severe impact damage may be just as important as the effects of fire in determining fire survivability in many incidents. Thus, it was judged that the role of impacts in aircraft fire accidents warranted further investigation.

As well as structural damage, impact forces can produce a host of other dangerous effects. Typically, these include the blocking of emergency exits, displacement of cargo and baggage, significant quantities of debris, loss of cabin lighting and seat failures. Most crash accidents also involve large numbers of occupant injuries and fatalities which occur as a result the effects of impact trauma. Thus, it was apparent that information was needed in order to clarify what proportion of fire accident fatalities could be attributed to the effects of impact forces. This was

obtained by summing the fates met by the 19,405 accident victims accounted for in the preliminary database. The results of this exercise are shown in Figure 3.4.

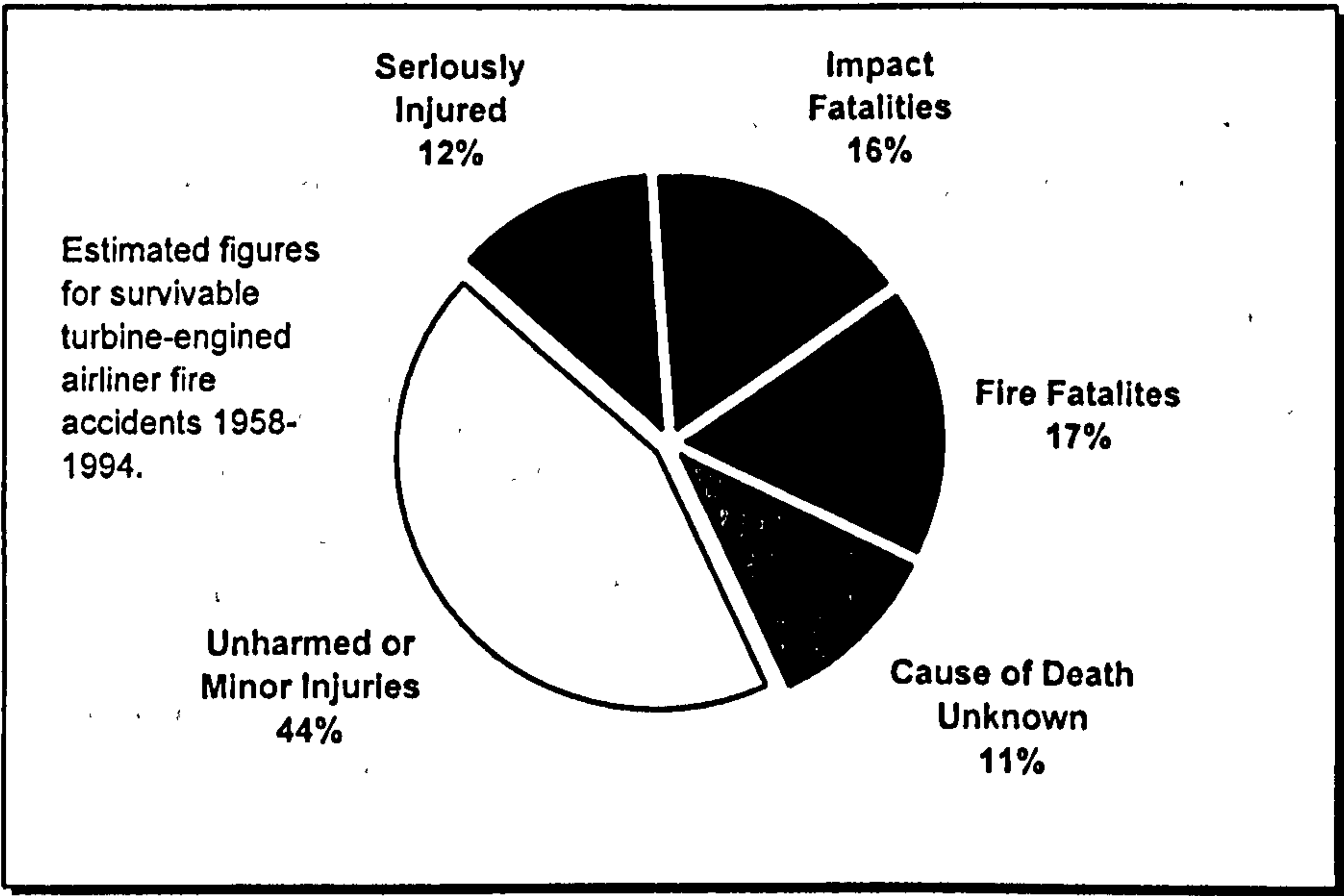


Figure 3.4: Casualties in Aircraft Fire Accidents

It can be seen that the average survival rate in past aircraft fire accidents is around 56 percent. Significantly, deaths are almost equally as likely to result from impact trauma as from the effects of fire. Note also that serious injuries occur in only 12 percent of those involved, which suggests that vast majority of occupants either escape from the aircraft safely, or else they tend to die from the effects of their injuries.

Two interesting points arise from these statistics. Firstly, on average, at least 56 percent of people involved in the accidents have successfully escaped from the aircraft, usually within 2-3 minutes of it coming to a stop. This means that most survivable aircraft fire accidents will have involved some form of large-scale emergency evacuation.

It is also apparent that impact deaths occur almost as frequently as fire deaths. It must therefore be assumed that many of the serious injuries result from the effects of impact forces. In addition, many of those succumbing to the effects of fire are likely to have been previously incapacitated through serious impact trauma injury. These injuries, incapacitation and deaths resulting from impact forces must be considered in any form of aircraft fire safety analysis.

The process of passenger evacuation also plays a critical role in most aircraft fire accidents. It has already been pointed out above that because, on average, over half of an aircraft's occupants are likely to escape without serious injuries, emergency evacuations have occurred frequently in past accidents. However, hidden in these figures is the frequency at which seemingly benign situations rapidly degenerate into desperate struggles of life and death. Indeed, it is not uncommon for passenger incapacitation and deaths to occur within two or three minutes of a serious conflagration breaking out. Historically, in past accidents, 20-25 percent of passengers have probably succumbed to the effects of fire in this manner.

Rates of passenger egress can vary widely from incident to incident. For example, in the three Boeing 737 accidents examined earlier in the section, evacuation times ranging from 1½ to 3½ minutes were achieved. Reasons for this diversity in

performance can be difficult to ascertain, as a large number of factors are usually involved. Some of the most prominent of these include:-

- Passenger attributes and behaviour
- Configuration of the aircraft's cabin
- Availability, usage and effectiveness of emergency exits
- Rapid degradation of the cabin thermo-toxic environment
- Actions of the aircraft's crew members
- Consequences of any crash impact

Given the prominence of occupant egress in the overall fire survival process, it was contemplated that as much information as possible would need to be gathered in this area. Many of these aspects are addressed in accident reports under the heading of "Survival Aspects". However, this information was, in most cases, descriptive in nature, sometimes incomplete, and often too voluminous for straightforward incorporation into a computer database. This implied that such data would be difficult to analysis in a systematic manner and integrate, where applicable, into a quantitative safety analysis.

However, in spite of these difficulties, it was thought essential that a comprehensive understanding of the evacuation aspects of the fire accidents be obtained. This could only be achieved with the possession of a convenient and consistent collation of the all the acquired information. Thus, the second phase of information gathering and analysis included the preparation of summary descriptions detailing evacuation and survival aspects for each of the incidents on record.

In summary this section has described how many features of aircraft accidents combine to determine the number of lives lost due to the effects of fire. Nominally similar accidents may result in highly contrasting fatality rates, as a result of differences in key survival aspects. These effects are often abstruse and can be encountered in crash, fire, evacuation or more general aspects of an accident. It was thus concluded that, wherever possible, more detailed information should be obtained for each of the incidents listed in the preliminary database. This would enable "Total Accident Scenarios" to be formulated and ensure that all relevant safety aspects were integrated within the safety analysis.

These conclusions were to hold some important implications when interpreting the contributions to have been made by scientific research in the field of aircraft fire safety. Some of the issues involved will now be examined.

3.3 A Re-appraisal of Fire Safety Research

3.3.1 The Interpretation of Scientific Work

The undertaking of the historical survey provided a thorough appreciation of the events to have occurred in past aircraft fire accidents. However, in order to construct a meaningful risk assessment model, it was required to combine this knowledge with additional contributions from scientific fire safety research. However, before this would be feasible, had to be ensured that the information obtained from experimental and theoretical activities would be compatible with historical events. This could only be achieved by re-examining the research to have been published by

the fire safety community in light of the conclusions reached in the preliminary accident survey.

It was possible to interpret the research undertaken by fire safety research community from two distinct perspectives. Firstly, the scientific work could be interpreted purely in its own right, without reference to its practical application or relevance to past events. The validity of results then has to be judged on a self-contained and essentially scientific basis. Significant findings can then be incorporated into a safety analysis verbatim in the form of self-contained “black-box” mechanisms, or alternatively, just used to provide a generic insight into real-world processes.

Alternatively, contributions made by scientific research could be assessed in the wider context of actual aircraft accidents. This involves the appraisal of a work’s utility in terms of its degree of correspondence with real events and practical relevance to matters of fire safety, in addition to its scientific integrity. The consideration of all three of these aspects constitutes a challenging test that has only been passed in a few select areas of safety research. However, in fairness, it should be pointed out that these criteria are far more wide-ranging than the limited contexts discussed or envisaged by most safety researchers. If a piece of research is found to be satisfactory in terms of realism, relevance and scientific rigor, then its findings obviously have the potential be integrated into a safety analysis at a fundamental level. In such circumstances, scientific knowledge could be expected to play a very substantial role in contributing to the basis of a risk assessment process. The assessment of scientific fire safety research using these two levels of appraisal will be related in the following two sections.

3.3.2 Evaluation of Research in a Scientific Context

Most of the research undertakings to have been analysed were probably intended to contribute to fire safety research on a purely scientific basis. The first point to be made is that, as far as it was possible to judge, published findings were probably scientifically valid in all cases. However, this does not necessarily imply that they could be incorporated directly into an analysis of aircraft fire safety. Reasons for this are numerous and diverse. In general they include the restricted scope of individual studies, incompatibility of results obtained across different disciplines and inherent limitations in experimental and theoretical methods used.

Traditionally, the scientists and engineers involved in the research activities examined have trained and worked within a single specialised discipline. This can often lead to under-emphasis of the role played by factors that happen to fall outside the investigator’s area of expertise. Alternatively, the significance of these parameters can be acknowledged, but then their values prescribed arbitrarily or determined by experimental capabilities. A prominent example of this has occurred in the fire testing of materials, where “*Most presently available methods are deficient in not providing sufficient heat flux and in not providing one-dimensional heat flux.*” (Hilado, 1985). Similarly, when compiling and evaluating data on past aircraft accidents, statisticians are often forced to shape and interpret information in order to make it compatible with formal methods of analysis. This may involve the over-simplification of complex relationships, the omission of descriptive, “noisy”, statistically insignificant, or other difficult data and the practice of “data dredging”. As a result, the true diversity of a

problem may go unappreciated, key inter-dependencies can be missed or, conversely, spurious relationships warranted undue attention.

In such circumstances, complacency can sometimes result. For instance, until comparatively recently, strength requirements for passenger seats were determined primarily through the application of engineering "judgement". However, as knowledge of human survival capabilities in severe decelerations has become more widespread, anatomical considerations and dynamic behaviour have come to dominate impact testing of aircraft seating. This has resulted in the imposition of far more stringent passenger seat strength requirements.

Several branches of fire safety research have only been established or only risen to prominence comparatively recently. These new disciplines may well eventually make valuable contributions towards the improvement of safety standards in the future. However, in some cases, the true role of the research needs to be established and much groundwork put in place before significant achievements can be made. These facts may not always prevent unrealistic claims being made about current capabilities in developing areas of research. Consider, for example, the use of Computational Fluid Dynamics (CFD) for the modelling of fires¹. The technology of CFD is approaching maturity in some other engineering applications, but the adequate simulation of a typical aircraft fire remains beyond current capabilities. A contributory reason for this is that the direction of fire modelling has largely been predetermined by the availability of software capabilities established and optimised in other fields of CFD. Thus, fire modellers have always been forced to make many approximations and restrict the application of their codes to unrealistically simplistic fire situations. These facts may not always be openly acknowledged in the reporting of the work.

In fairness, it should be pointed out that considerable advances have been made in the computer modelling of impacts and large-scale structural deformations. In many areas, developments in dynamic and non-linear methods have greatly reduced or even eliminated the need for experimental impact testing.

The surveyed research literature encompassed many diverse aspects of aircraft fire safety. Consequently, it was found a wide range of different research approaches and methodologies were used and a number of different scientific disciplines were involved. This obviously enables investigative techniques to be matched to the particular needs of the research in question, but may sometimes lead to the creation of gaps or incompatibilities in knowledge where areas of study overlap significantly. An example of this may be seen in different approaches adopted by experimental psychologists and computer modellers when analysing aircraft evacuations. With social scientists, the emphasis of research lies with interpreting interactions between behaviour patterns, local environment and personal characteristics of evacuees. Trials are usually recorded on video in order to obtain a complete illustrative record of activities, rather than just to facilitate the timing of discrete events. Generally, descriptive observations tend to feature just as prominently as measured evacuation rates in the reporting of results.

In contrast, computer scientists have treated the process of passenger egress in terms of precise micro-analysis of events and their timings. This necessitates that the complexities inherent in human movement and behaviour be reduced to simple

¹ As opposed to combustion modelling - a specialised branch of CFD dealing with the controlled combustion of fuels in engineering applications, such as engines, furnaces, ovens, etc.

mathematical relationships. Diversity in human characteristics can be incorporated by choosing passenger traits from suitable probability distributions. Emphasis lies predominantly with the quantification of evacuation dynamics, rather than with the obtainment of an increased understanding of human behaviour.

These contrasting approaches of analysing problems encountered in the evacuation of aircraft make for an interesting comparison. However, the task of integrating and applying the work of the two schools is far from straightforward. The primary difficulty is that experiments do not deliver results directly suited to computational analysis and that no convenient interface appears to exist between the two. Thus, for example, computer modellers have yet to represent collective behaviour or deal adequately with more nebulous psychological interpretations. Correspondingly, the social scientists have rarely quantified their results in a form compatible with analysis by computer simulation. If some form of synthesis is to be achieved, then either traditional boundaries within the two fields need to be expanded until overlap occurs, or suitable linkages must be forged by inter-disciplinary specialists.

This example of how different disciplines can possess dissimilar outlooks when working in the same area of fire safety research is by no means unusual. It can also be argued, for instance, that equivalent differences exist between experimental fire testers and computational fire modellers, or between materials combustion researchers and combustion toxicologists.

It was revealed in a significant proportion of the research publications that currently established experimental methods are unable to deal adequately with many of the more complex phenomena encountered in the field of fire safety. Practical difficulties can often be encountered in the following areas:-

- Recording of certain types of parameters
- Maintaining control over the test environment
- Dealing with time dependent or random factors
- Establishing representative test conditions
- Ensuring that ethical constraints are satisfied

In many cases, more straightforward experimental errors can be dealt with during the processing of results. However, it is often necessary to add, modify or remove test constraints in order to obtain a tractable experimental procedure that is capable of providing meaningful or repeatable results. Sometimes, this may lead to pertinent aspects of the subject under investigation being masked or their influences being modified in some way. Parameters dealt with in this way are usually those that are either unpredictable or else difficult to control; for example weather, people and fire. Thus, an applied researcher is usually forced to make a compromise between experimental fidelity and practicality in the design of research. Deliberate over-constraint appears most likely to be applied in experiments involving significant safety issues and high costs; such as in full-scale aircraft fire testing and passenger evacuation trials.

More generally, undue reluctance can sometimes be shown for dealing with probabilistic, time-dependent and other “difficult” or inconvenient parameters. These can often be unnecessarily reduced to average, steady-state or discrete values, with the loss of potentially significant information. Examples of these parameters include the

fluctuation of flames, wind, dynamic impact loads and the diversity of materials typically involved in cargo fires.

In conclusion, it is apparent that, within its terms of reference, the scientific research surveyed has made many valuable contributions to the study and analysis of aircraft fire-safety. However, even within well-established disciplines, significant challenges still remain to be overcome in almost all branches of research. This derives from the fact that aircraft fire accidents generally involve many complex, stochastic and extreme phenomena that are not readily amenable to experimental analysis. In some instances, specialists have been shown to be reluctant to consider pertinent aspects of a research problem that happen fall outside their area of expertise.

From a wider perspective, the task of integrating work undertaken across a range of disciplines also appears to be substantial. Even where no gaps in coverage exist between related subject areas, contributions from adjacent field of research may not be compatible with each other. Much gap filling and cross-interpretation is needed before experimental research can begin to provide a more complete picture.

3.3.3 Compatibility with Historical Events

If findings obtained from safety research were going to play a substantial role in the risk analysis, then it would necessary to demonstrate rather more than just their scientific integrity and the general compatibility of their results. Although investigative procedures may appear perfectly valid from a scientific viewpoint, they may sometimes be applied in inappropriate circumstances. This may lead to the obtainment of results that are "scientifically" correct, but unsatisfactory, irrelevant or even misleading in the context of risk assessment. Much of the safety research surveyed appeared to fall into this category. These undertakings are probably justifiable on the basis of their intrinsic scientific merit and potential value in the longer term, rather than in terms of their direct practical utility. It was thus necessary to ensure that any research findings used in the safety analysis were adequately representative of the events known to occur in real aircraft accidents.

The inapplicability of many safety research findings for the purposes of risk assessment is probably a direct result of the catastrophic nature of most aircraft fire accidents. Many of the phenomena encountered can be very extreme, difficult to reproduce, or else impossible to quantify in scientific terms. Consider, for example, the imponderable complexity of events that typically occur in aircraft crashes, accident fires and large-scale passenger evacuations. These are practically impossible to reproduce in an experimental environment or analyse adequately in real accidents. In consequence, researchers are usually faced with challenging problems when attempting to investigate real issues in air safety. Almost inevitably, the use of analogy, approximation and artificial bounding of a problem have to be relied upon to a much greater extent than in most other fields of research. This implies that experimental procedures will be farther removed from real situations and thus results might be expected generally to be less representative of actual events. It was therefore reasonable to anticipate that satisfactory correspondence between the scientific safety and real events could not be taken for granted.

The preliminary accident data survey had revealed that aircraft fire accidents were very diverse in nature. It appeared to be impossible to characterise a "typical" incident, because basic circumstances could often be completely dissimilar from accident to accident. Even when two scenarios appear to be superficially similar, very

different outcomes could sometimes result. The inconsistent nature of real accidents appears to be particularly hard to accommodate in safety research, as one of the primary tenets of scientific investigation is the ability to obtain repeatable results.

In some types of work, the complex nature of the process being investigated yields a natural variation in results. This can occur in spite of best efforts of researchers to enforce the consistency of readings taken in a series of supposedly identical tests. Two examples of this type of research can be found in passenger evacuation trials and ground-based crash testing of aircraft. In both cases, it has proved necessary to undertake multiple tests in order to determine the level of consistency of being obtained. Results are usually plotted in the form of distributions or envelopes and findings given with an associated level of probability or statistical significance. Although this method of analysis is obviously time consuming and expensive, it represents an extremely constructive approach to the scientific investigation of difficult safety issues, such as aircraft impacts, crash fires and passenger evacuation. The more complex features and probabilistic aspects of aircraft accidents are not designed out of the experiment, or merely ignored. Instead, efforts are directed at exploring meaningful problems and designing realistic experiments, in spite of the inconvenience involved. In some circumstances, this will increase the likelihood of inconclusive results being obtained. Although this might be frustrating from a scientific point of view, it may provide a more accurate reflection of the true nature of the real life situation being investigated.

3.3.4 Related Difficulties

In many cases, it is unfeasible to undertake a series of identical experiments to ensure consistency of results, because of financial or practical reasons. With only a single set of results to work from, it is obviously impossible to determine the extent to which probabilistic factors may have influenced the outcome of an experiment. This problem tends to be dealt with in one of two ways; either the issue is ignored or test conditions are constrained to exclude the effects of randomly varying parameters. Examples of the latter include fixing the size and shape of a fire, the use of standard impact deceleration rates and the disabling of one half of available emergency exits. There may sometimes be a danger that these decisions can be made arbitrarily, without due reference to actual conditions that are known to have occurred in past accidents. Consider, for instance, the fact that researchers have reported difficulty in completing a programme of airframe fire tests, because they were waiting for zero wind conditions to occur. This appears to be a case where rigid adherence to test procedures has served to highlight inadequacies in formulation of an experiment.

Sub-scale tests or mock-ups are often used in experimental investigations. This may enable a greater degree of control to be exerted over the experiment, as well as being more convenient and less costly than full scale trials. However, care is obviously required to ensure that real conditions are adequately approximated in the experiment. This has been a problem in fire testing of cabin materials, where marked differences have sometimes been found to occur between laboratory and *in situ* performance in accidents.

In a similar vein, difficulties are encountered in the field of combustion toxicology when attempting to apply results obtained from animal testing to humans. Primates are more representative of humans than rodents, both in terms of behavioural and physiological characteristics. However, their greater cost of upkeep and lower

powers of recovery have resulted in rats becoming the most common species in animal toxicological testing. Extrapolation of findings to humans is problematic because it is rarely possible to ascertain accurate toxicity exposure histories in accident victims. Thus, results obtained from animal testing can only be used for initial screening purposes, or, at the very most, approximate cross comparison of toxic substances.

An obvious problem in undertaking safety research is that only one or two significant aspects of safety can be analysed in a single test. It has been seen how many accidents involve complex interactions between the effects of impact, fire and occupant evacuation. These cross influences can often be impossible to represent adequately in experimental research. However, rather than ignore their potential significance, researchers may sometimes attempt to crudely represent the effects of key interactions. Examples of this practice include the use of cut-outs to represent fuselage rupturing in airframe fire tests, the undertaking of evacuation trials with obstacles and in darkness, and the opening of exits in cabin fire testing. Although these measures are often only approximate in nature, they are usually simple to implement and can serve to increase the realism of a test to a significant degree. Ideally, however, the design of large scale tests in any area of aircraft safety should involve researchers from a number of different disciplines. This might help to ensure that ancillary aspects of the problem area under study are adequately catered for, whenever this is conveniently possible.

Even when research only involves activities a single specialised discipline, the fundamental assumptions used may prove to be unrealistic. This can occur for reasons of experimental convenience, or perhaps because of limitations in analytical capabilities. One example is in the fire testing of materials. Standard fire tests involve rates of incident heat flux that are significantly lower than those commonly encountered in aircraft fire accidents. In consequence, the true fire properties of some materials were not discovered until after they had entered service. As previously mentioned, this may situation may have arisen, in part, because materials scientists responsible formulating the tests were generally unfamiliar with the high intensity of aircraft fuel fires.

In other cases, the scope of research may be deliberately restricted to coincide with analytical, rather than experimental capabilities. For example, computational modelling of aircraft fires appears to have focused exclusively on internal fire scenarios. The preliminary accident data survey showed that these types of fires occur rarely in comparison with cases of burn-through and impact fires. Thus again, through lack of appreciation, research activities can be governed by matters of convenience, rather than by real world data needs.

The extreme nature of many aircraft fire scenarios is impossible to reproduce safely in evacuation trials and crew training tests. The incorporation of non-toxic smoke into evacuations, motivation of evacuees with rewards and forceful behaviour by cabin crew are all extremely beneficial, but these techniques can never recreate a fully adequate level of realism. Trials undertaken with irritant smoke in Japan may provide an accurate insight into human behaviour in truly adverse conditions, but this type of work is unlikely ever to be undertaken in the West. Currently, the most hazardous fire testing undertaken in the UK involves the training of fire fighters. However, these individuals are highly trained professionals and their performance cannot be taken to be representative of aircraft accident victims.

3.3.5 Conclusions

In general, it was concluded that scientific research undertaken in the area of aircraft safety is not always well matched with events that are likely to be encountered in aircraft accidents. Consequently, use of scientific findings alone is not adequate when attempting to analyse issues in accident survival. In order to estimate true levels of risk, research findings about specific hazards must be placed in context by combining them with information obtained about real events. This does not imply that much of the safety research undertaken in the past is inherently flawed or inapplicable. In many cases, the scope of an investigation is deliberately restricted for very sound reasons. Thus, such work is only intended to provide a limited insight into one particular aspect of a complex problem area; the results obtained are useful for indicative purposes, but cannot be applied directly in a wider context.

In some types of research, the results obtained are directly applicable to circumstances met in real accidents, but only a small sub-set of accident scenarios is covered. As a result, it can be difficult to incorporate these partial findings into accident risk analysis, which, in order to obtain balanced results, must treat all scenarios types in an even-handed manner. If results are to be interpolated between different sets of experiments, it is necessary that an adequate range of different circumstances is investigated.

In summary, if research findings are to be applied to assessing issues in aircraft safety, then it is desirable that the work concerned meets a number of criteria. These are as follows:-

- Address issues that are encountered in a high proportion of accidents
- Related work to that being undertaken in associated areas
- Possible to quantify the effects of experimental compromises, where they have been necessary
- Findings are compatible with observations made about real events
- Procedures used are adaptable to deal with different circumstances
- A contrasting range of experimental conditions is covered

3.4 Formulation of a Computer-based Modelling Methodology

3.4.1 Challenges Faced in Improving Aircraft Accident Safety

Many issues in aircraft fire safety appear very difficult to address within the limitations imposed by the use of established scientific methods. The complexity of aircraft accidents necessitates that large quantities of information must be drawn together from different areas of scientific research before meaningful conclusions about human survival can be derived. Significantly, however, much of the knowledge required is steadily being assembled by specialists working in many fields of aircraft safety. Although gaps in understanding still exist in many areas, when identified and prioritised, they may become feasible to bridge in the longer term.

The translation of research findings into new safety policies is also an extremely challenging task. If new measures are to be introduced, their effectiveness must be assessed in the context of risk levels faced in real accident scenarios. Most

incidents involve a combination of crash disruption and large fuel fire. However, the nature of the fire survival problem can differ considerably from accident to accident. For example, a night-time crash occurring a large distance off airport constitutes a quite dissimilar predicament to, say, an uncontained engine fire on takeoff, or an inflight cargo fire. As well as their potential diversity, aircraft fire accidents also tend to involve many complex, highly interactive and dynamic phenomena. These attributes can make it difficult to integrate knowledge obtainable from past events, or plan purposeful research programmes to investigate matters of concern.

Similarly, it is also far from straightforward to perform a satisfactory analysis of the wider effects of either current or proposed new safety measures. In addition to purely objective considerations, those involved in the field of aircraft safety also deal with an highly emotive subject matter. This is occasionally highlighted by the vociferous, but often poorly informed media coverage and public lobbying that can occur in the immediate aftermath of a major accident. These problems are likely to be encountered with increasing frequency in the future. The formulation of safety policy must also take into account the highly cost sensitive nature of the air transport industry, together with possible political implications and the limitations imposed by historical precedence (Transport Committee, 1990).

3.4.2 Identification of a Research Need

Faced with these challenges, those committed to minimising the hazards encountered in aircraft fire accidents need to integrate a large body of information containing many diverse and often seemingly incompatible types of data. In spite of the quantity of knowledge available, appreciable gaps in understanding still have to be dealt with in some areas. Consequently, scientists, engineers and policy makers can routinely be forced to make decisions involving significant factors that lie outside their own areas of expertise and without access to suitable sources of information to refer to. Greater levels of accountability in the policy formulation process also mean that there is increasingly a need to provide clear quantitative justification for many of the conclusions reached in matters of public safety (CAA, 1991).

The addressing of these difficulties clearly requires that maximum utilisation is made of all available information sources in any decision making process. Thus, there exists a need for some form of knowledge framework or decision support tool. This should be capable of combining the many sources of information available in the field of aircraft safety in an explicit manner. The complexity of events typically encountered in aircraft fire accidents clearly suggests that this tool should utilise computer simulation methods, in order to provide an adequate level of analysis. Also, all important features of accident survivability need to be considered, such as fire development, passenger evacuation and the effects of any crash impact.

The use of such a computer simulation tool might then enable findings from more specialised branches of safety research to be integrated within an holistic accident safety analysis for the first time. In the longer term, the development of these techniques could potentially yield a tool capable of supporting a systematic risk assessment analysis of key issues in aircraft accident survival.

3.4.3 Establishment of a Methodology

The primary challenge in constructing such an accident analysis tool is in dealing with the sheer quantity, diversity and intricacy of the information available in

the field of aircraft safety. Obviously, in order to create a tractable computer model, it is necessary to make many simplifications and approximations in the analysis process. In some instances, gaps in knowledge have to be bridged with little more than the application of educated guesswork. In order to minimise the consequences of these difficulties it was decided to formulate a research methodology based upon a combination of historical accident analysis, existing scientific safety research and computer simulation. Given that the work was primarily concerned with assessing survivability of aircraft accidents, these events constituted a logical base unit for the analysis. Thus, the computer model would effectively be designed to generate aircraft accident scenarios and then simulate their outcome in terms of the number of casualties involved.

For the model to be able to fulfil its intended purpose, scenarios of accidents being analysed needed to be representative of those encountered in reality. The information required to ensure this could be obtained by undertaking a survey of aircraft accidents that have occurred in the past. The features and relative likelihoods of different accident types might then be determined and recreated with the use of probabilistic techniques in the analysis model.

The events occurring within accidents needed to be simulated in detail. It has been seen in this chapter that most incidents involve significant crash impacts, large fuel fires and the evacuation of substantial numbers of passengers. This implied that the simulation tool would need to incorporate crash effects, fire development, thermo-toxic incapacitation and occupant egress models. These different aspects of analysis would interact heavily with each other and so needed to be integrated together in a balanced manner. The overall concept of this accident simulation methodology is depicted in Figure 3.5.

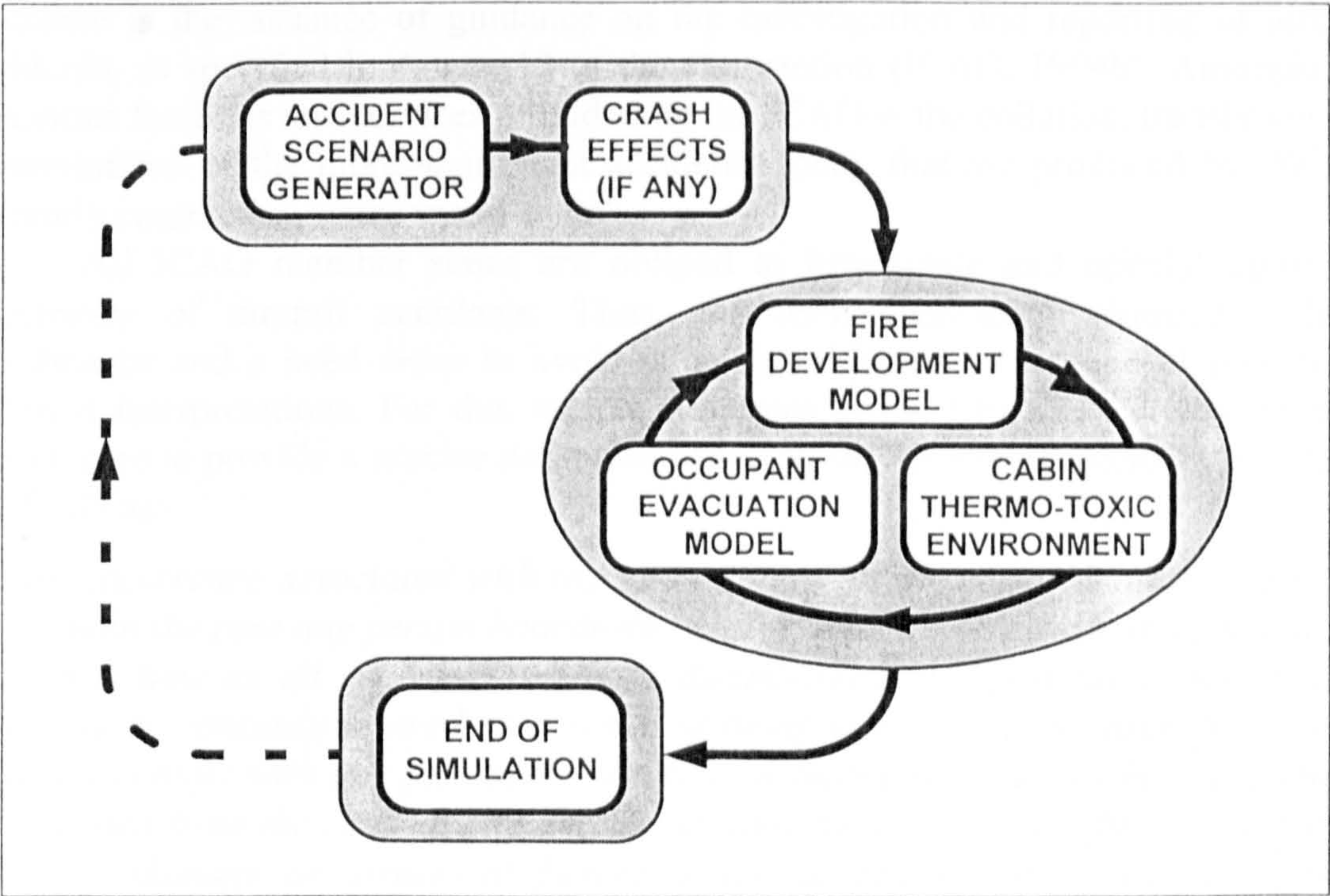


Figure 3.5: Accident Simulation Methodology

3.5 Thesis Aim and Objectives

3.5.1 Research Aim

The aim of this thesis can be defined as follows:-

To create a computer-based simulation and risk assessment tool that can be used to analyse key issues in aircraft fire accident safety in a balanced and holistic manner.

3.5.2 Research Objectives

The objectives associated with this aim were:-

1. *To construct a computer-based risk assessment tool suitable for investigating issues in aircraft fire safety.*
2. *To deal with a fully representative range of accident scenarios as opposed to just those that are more amenable to established methods of analysis.*
3. *To utilise a holistic approach, modelling all factors that influence fire lethality in a balanced and integrated manner.*
4. *To demonstrate that it is feasible to undertake quantitative risk analysis of aircraft accidents, safety issues and safety policies.*

Chapter 4: Use of Past Accident Data and Statistics

4.1 Introduction: Investigation and Reporting of Civil Aircraft Accidents

4.1.1 The Investigation of Aircraft Accidents

The high casualty rates and material losses encountered in catastrophic aircraft accidents provide a powerful incentive for attempting to eliminate their occurrence. Given that this aim of complete prevention will be impossible to achieve within the foreseeable future, equal efforts have also been directed towards reducing the lethality of the incidents when they occur. These mutual approaches to dealing with the challenge of increasing the safety of air-travel can be conveniently labelled as *accident prevention* and *accident mitigation* respectively. A prerequisite for the pursuit of these two objectives is the attainment of a thorough understanding of the problems encountered in past events and determining the implications that they might hold for the future. This can only be achieved through the investigation and reporting of aircraft accidents.

The widespread utilisation of air transport has ensured that almost all nations have been provided with a motive for co-operation in matters of the organisation and safety of air transport operations. As recounted in Chapter 1, this impetus led to the formation of the International Civil Aviation Organisation (ICAO) in 1947, a body responsible for the co-ordination of air transport activities on a world-wide level. The remit of this organisation was largely set in place by the 1944 Chicago Convention, to which 52 nations were signatories (ICAO, 1994a). Included in the ICAO's terms of reference is the issuance of guidance on the investigation and reporting of aircraft accidents, as specified in Annex 13 of the Convention (ICAO, 1994b). Amongst the numerous facilities and services provided by the ICAO is the collation, translation and dissemination of the more significant accident reports that are produced by the 183 currently contracting states world-wide¹.

All ICAO member states are obliged to investigate and openly report the occurrence of aircraft accidents. Thus, the term "accident" acquired a legal significance and a need arose to avoid it being subjected to a range of potentially different interpretations. For this reason, delegates at the Chicago Convention took special care to provide a precise definition of the word. An aircraft accident is defined by ICAO as:-

"an occurrence associated with the operation of an aircraft which takes place between the time any person boards the aircraft with the intention of flight until such a time as all such persons have disembarked in which (a) a person is fatally or seriously injured as a result of being in or upon the aircraft, or by direct contact with any part of the aircraft, including parts which have become detached from the aircraft, or direct exposure to jet blast; or (b) the aircraft incurs damage or structural failure which adversely affects the structure strength, performance or flight characteristics of the aircraft and which would normally require major repair or replacement of the affected component; or (c)

¹ As at 1st January 1995.

the aircraft is missing or is completely inaccessible" (Edwards and Edwards, 1994)

It should be noted that a strict distinction is maintained between the terms "accident" and "incident". The latter should really be used to refer to events that are less serious in nature, where no serious injuries result or only relatively minor damage occurs. Often, this can be taken to loosely mean a "near-accident" (Wells, 1991). The ICAO definition of an incident is (Edwards and Edwards, 1990):-

"an occurrence, other than an accident, associated with the operation of an aircraft which affects or could affect the safety of the operation"

Until recently, states have not been obliged to report aircraft incidents, although many have chosen to do so. In 1994, the ICAO ratified a change to Annex 13, widening the remit for investigating and reporting procedures. This defines a new category of "serious incident", taken to be:-

"... an incident involving circumstances such that an accident nearly occurred"

Although this appears to be a relatively loose definition, the reporting of such events has now been made compulsory (Winn, 1994).

In the case of the present study, we are concerned with both accidents and more serious incidents, providing that significant fire damage occurred. Thus, for the sake of convenience, in the present work, the terms "accident" and "incident" are used interchangeably, unless specifically noted otherwise.

Procedures for the investigation of aircraft accidents are specified in the ICAO *Manual of Aircraft Accident Investigation* (ICAO, 1970). This document includes information about the numerous background activities that are necessary in the event of an aircraft accident, such as notification procedures, general administration and the issuing of information. Of more relevance in the present context, however, is the provision of expert advice on many of the more practical aspects of accident investigation. All potentially significant features of an accident are covered, ranging from details of the site, wreckage and prevailing weather through to the possible role played by sabotage, maintenance actions and human factors.

The broad coverage is intended to ensure that investigators adopt a methodical approach and reduce the chances of important information being overlooked. The latter can be particularly important, since many crucial pieces of evidence may pass unnoticed or their significance not be appreciated by an untrained observer.

Unfortunately, in spite of the general thoroughness of the *Manual of Aircraft Accident Investigation*, many ICAO member states still persist in failing to investigate aircraft accidents to an anywhere near adequate standard. However, the publication has undoubtedly served to improve the efficacy of most inquiries to some extent and has been particularly valuable in increasing awareness of the potential importance of ancillary factors in many accidents. Examples of the latter relevant to the current study include the identification of fire induced deaths, together with the effectiveness of evacuation, rescue and fire-fighting actions.

If information obtained from the investigation and reporting of past accidents were to constitute a significant component of the overall study, it was essential to ensure that the data was accurate. This would obviously be impossible to demonstrate conclusively and so we are forced to rely on the competence, general objectivity and independence of the investigatory body. When organisations conform closely to

ICAO recommended practises; these virtues may usually be taken for granted. If this is not the case, then it is usually plainly apparent from the character of the accident report. This is a direct consequence of the overall purpose of undertaking an aircraft accident inquiry, defined in the ICAO investigation manual as being (ICAO, 1994b):-

“The fundamental purpose of inquiry into an aircraft accident is to determine the facts, conditions and circumstances pertaining to the accident with a view to establishing the probable cause thereof, so that appropriate steps may be taken to prevent a recurrence of the accident and the factors which led to it. An equally important purpose is to determine the facts, conditions and circumstances pertaining to the survival or non-survival of the occupants, and crash-worthiness of the aircraft. The nature of the inquiry into an aircraft accident should not be accusatory as the object is to take remedial rather than punitive action; similarly the assessment of blame or responsibility should not be included in the duties of the accident investigation authority since this function is normally the prerogative of the judicial authorities of the State concerned. Nevertheless, it is unavoidable that acts or omissions, by individual persons or organisations, are sometimes clearly revealed and in such instances it is the duty of the inquiry to say so. Any such statement should not confuse the purpose of the aircraft accident investigation which is primarily to indicate what caused the accident rather than who caused it: this should be rightly for others to decide”

The prominence attached to the no-blame status of the accident investigation is readily apparent. Thus, when the outcome of an enquiry serves to resolutely condemn one or more of the involved parties, immediate scepticism is called for. In these circumstances, the focus of the investigation is commonly directed at the contributory actions of individuals, such as the flightdeck crew, an air traffic control officer or a maintenance engineer. Usually associated with this is the omission of any examination of the possible role played by operating procedures, training, regulation and organisational infrastructure.

In a similar vein, instances where investigators possess inadequate experience are reasonably straightforward to identify. In many cases, reported information may often be accurate, although usually incomplete, but its interpretation may be omitted or perhaps leave much to be desired. A good example of the latter is the mis-attribution of bone fractures frequently encountered in fatally injured crash victims. These breakages can sometimes occur post-mortem, when corpses are exposed to extreme heating, but then erroneously ascribed to result from the effects of impact forces (Hill, undated). This may be sometimes be connected with the fact that authorities may feel obliged to indicate that accident victims died instantaneously rather subjected to a torturous death, for humane reasons.

When errors in official interpretation and judgement are generally perceived to occur, particular accidents may gain a certain air of notoriety. This can often produce intense speculation and re-examination of the event by safety researchers, legal experts, government committees and the media. Even if no general consensus can be reached on all facts and conclusions, more obvious oversights will be corrected, or at least, reasons for possible doubt highlighted.

In some circumstances those responsible for undertaking the investigation of an accident may not be able to issue an accident report without it being subjected to

governmental approval. The official vetting process may result in significant information, conclusions or recommendations being suppressed in the published version of a report (Prince, 1990). Often, in these circumstances, the imposition of such omissions leaks to the media, perhaps via members of the investigatory team, from witnesses or even through alternative official channels. For those concerned with the compilation accident data, the net result of official interference in the reporting process may be similar to cases involving inexperienced investigators. The implication of this is that, for some accidents, the degree of acceptance of the official report in the wider air-safety community and media may need to be examined. Where controversy has arisen, use can often be made of secondary information sources, findings of follow-up investigations and expert opinions.

Three potential sources of inaccuracy in the investigation and reporting of aircraft accidents have been outlined. These consist of the desire to compound blame onto individuals, the inexperience of investigators and the distortion of official reports, respectively. In all three cases, the factual evidence that is reported will generally be accurate. Problems will more usually manifest themselves in the omission and/or distortion of pertinent information, in order to bolster a particular interpretation of events. It is rarely feasible to fabricate or deny the occurrence of factual events without the deception becoming apparent in the longer term; half-truths being easier to sustain than outright falsifications. This implies that the major challenge of interpreting past accident data lies not with the validity of obtained material, but rather with the incompleteness and unavailability of more detailed information.

4.1.2 Aircraft Accident Reports

Annex 13 of the Chicago Convention requires the publication of accident reports in connection with the undertaking of any accident investigation. Four separate formats of report are required; in chronological order of preparation these are (ICAO, 1970):-

1. The Preliminary Report
2. The Final Report
3. Summary of the Final Report
4. The Accident/Incident Data Report

The purpose of the preliminary report is to forward information to all concerned as soon as practicably possible after the occurrence of an accident. Basic factual and circumstantial information is usually available within the first three to four weeks of an investigation and so it is stipulated that a preliminary report should be issued within 30 days of the date of the incident.

The final report constitutes a complete, accurate and finalised record, documenting all aspects of the accident investigation. It is a synthesis of the report compiled by the head investigator and the reports published by the specialist groups within the accident investigation team. To help ensure thorough and complete reporting, ICAO provides a detailed description of the layout required for a final accident report. This structures the account of an investigation into five sections; namely factual information, analysis, conclusions, safety recommendations and

appendices. These sections are sub-divided into further categories, for each of which standardised paragraph numbering and guidance notes are provided.

The publication and distribution of the final report are only undertaken after consultations have held with other nations that possess a legitimate interest in its contents. In addition to the state conducting the investigation, these could include the state which instituted the investigation (if it had delegated the whole of the investigation to the "conducting" state), the state of the aircraft's registry, the state of the aircraft's manufacture and any state providing information relevant to the accident. This consultation process can sometimes lead to disagreements over analysis, conclusions and safety recommendations contained in the report. If these prove impossible to resolve, then the existence and explanation of the dissent may be noted in the final report.

The summary of the final report provides a synopsis of the investigation in a convenient and uniform format. They are only required to be produced in cases where information contained in the final report is of exceptional value to the promotion of aviation safety. This might involve instances showing how new investigative techniques having been successfully employed, or where there is a need for significant preventative action. The summary is not intended to replace the main report, but rather to be of smaller size by cutting down on details that are unnecessary for understanding of the accident. This enables the summary to be incorporated into the ICAO Aircraft Accident Digest (ICAO, 1980), thus permitting dissemination to all ICAO member states world-wide.

The accident/incident data report is compiled from the final report and, together with the preliminary report, is required for inclusion in the ICAO Accident Data Reporting System (ADREPS) (ICAO, 1995). Given that this system is computer-based, the format of the provided information is required to be computer compatible. This allows for the monthly publication of a "Summary of Preliminary Reports", an annual "Digest of Accident Statistics" and for the provision of an accident information retrieval service.

These four categories of accident reports together provide both a convenient and systematic method of distributing information about aircraft accidents. Aspects of particular value to the researcher in air safety are the translation, standardisation of content and the general availability of the publications. These points are invaluable when attempting to collate and understand the implications provided from accident investigations of varying standards.

In most cases, it proved impractical to obtain copies of final accident reports. These documents are often quite large, typically ranging from 100 to 200 pages and could only be retained for a limited period once accessed via inter-library loans. In addition, only reports involving significant British or US national interests were readily obtainable. Thus, full accident reports were only acquired in cases of important British or American accidents where alternative information sources proved unsatisfactory. This represents around ten percent of the 216 accidents included in the main round of data collection and analysis.

The largest contribution of information was obtained from the ICAO Aircraft Accident Digests. As indicated above, these publications provide extended summaries of final accident reports, grouped together and published annually. In most incidents, the sections of the main report that deal with the fire, rescue and occupant survival aspects are reproduced in full. This means that, for the purposes of investigating

aspects of fire safety, the Digests are of comparable value to main accident reports. Typically, they might comprise five to ten pages of condensed text or significantly more in the case of more significant incidents. The quantity of information provided was found to be highly suitable for the purposes of the study. An additional advantage of using the Aircraft Accident Digests was that these publications were readily available at Cranfield.

Use was also made of data obtained from the ADREPS system. This provides a computer-based information retrieval service, albeit with a significantly lower level of information than the ICAO Digests or full accident reports. Printouts were acquired for accidents and serious incidents involving significant fire damage to the aircraft (ICAO, 1995). Several preliminary accident reports were also obtained, but these proved to be of negligible value, given that more recent information was available for all accidents occurring up to and inclusive of 1993.

4.1.3 Other Sources of Accident Data

The starting point for the data gathering study was the UK Civil Aviation Authority's World Airline Accident Summary (WAAS) (CAA, 1996). This provides basic details and a short summary of all accidents involving commercial passenger aircraft in revenue service. A typical WAAS entry is shown in Figure 4.1. The main

18.4.72	SVC10	EAAC	Addis Ababa	Scheduled Passenger	107	Crew Pass	8 35	2 13	1 48	Destroyed
<p>The aircraft was taking off from Addis Ababa for a flight to London via Rome. Just prior to reaching Decision Speed (V_1), a nose wheel tyre was punctured by a light aircraft jacking pad, lying on the runway. The crew immediately initiated the appropriate abandon take-off procedure but were unable to stop the aircraft before it reached the end of the runway. The aircraft dropped heavily on the lower ground and broke up on impact. A severe fire ensued and the aircraft was completely destroyed. 43 passengers and crew were killed; 15 were injured and 49 were unhurt.</p> <p>The report concludes the accident was due to a partial loss of braking effort arising from the incorrect reassembly of a part of the braking system, as a result of which the aircraft could not be stopped within the runway and stopway distance remaining. (Imperial Ethiopian Government Report No A1 11/72).</p>										

Figure 4.1: Example Entry from World Airline Accident Summary

value of the publication is its systematic coverage of all incidents occurring world-wide since 1946. To enable this to be achieved, a loose bound format is used and supplementary updates provided annually. The information provided in the WAAS entries is insufficient to allow for anything but the most rudimentary analysis of the incident. For example, it was found that in many instances the occurrence of a significant fire was not recorded and thus it could not be immediately determined if a given incident would be relevant to the study of fire safety.

The main value of the publication was therefore in the provision of a large listing of accidents which were known to have, or could potentially have involved a significant fire. This list contained approximately 2000 entries, the vast majority of which would be discarded as the survey work progressed. The most common reasons for the dropping of accidents from further consideration were that they were non-survivable, involved a piston-engined aircraft, or no significant fire damage had occurred. The formulation of these inclusion criteria is discussed in the next section.

Other researchers have already undertaken numerous studies of the fire-safety aspects of past aircraft accidents. Perhaps the leading independent authority in the

field is Taylor, who has constructed a comprehensive computer database, logging details about many thousands of incidents. This has been achieved by the accumulation of accident reports and numerous other types of source material over a period of some thirty years. Some of the wide-ranging areas to have been addressed by Taylor include:-

- The relative safety of wide-cut aviation fuels (Taylor, 1975)
- Duration times of passenger exposure to the effects of in-flight fires in past accidents (Taylor, 1990a)
- The proportion of passenger deaths that may be attributable to the effects fire (Taylor, 1975; Taylor, 1990b)
- Historical trends in the nature of aircraft fire accidents (Taylor, 1986)
- Estimation of the potential utility of passenger protective breathing equipment in past accidents (Vant, 1990)

These studies have involved the surveying of large numbers of aircraft and were found to be invaluable for positively identifying many of the incidents suited for inclusion within the database. Acknowledgement must also be given to Taylor for making significant quantities of source material available to the author.

Other individuals have also performed useful research into particular aspects of past accidents. For example, Hill has undertaken important studies in the area of aircraft accident pathology, helping to clarify the role played by fire in numerous incidents (Hill, undated). Private consultants have also regularly produced surveys of accident data, often directed towards the identification of long-term trends in safety (Kapustin, 1993).

Substantial use was also made of safety studies published by regulatory authorities and aircraft manufacturers. The Federal Aviation Authority has undertaken research of past accidents in an attempt to establish the potential benefit of introducing anti-misting kerosene (FAA, 1981) and the provision of passenger smoke-hoods (Speitel and Hill, 1988). Similarly, the UK Civil Aviation Authority has performed historical analyses when addressing the issues of passenger survivability in aircraft fires (CAA, 1991) and in benefit studies of cabin water-spray system (CAA, 1993).

The former Fokker aircraft company was also very active in the analysis of airliner accidents, sharing information readily and maintaining its own independent database. The manufacturer made an important contribution to the research of passenger exit usage in past airliner accidents (Schaefers, 1990).

4.1.4 Inclusion Criteria for Aircraft Accidents

It has already been seen that the initial survey of aircraft accidents yielded a total in the region of 2000 events that could potentially have been relevant to the study. The performing of a detailed analysis on this number of incidents was obviously not feasible within the available time frame. It was therefore necessary to choose some inclusion criteria in order to severely reduce the number of accidents under study. This would enable effort to be concentrated on those incidents that were of most relevance to the analysis of aircraft fire safety.

The most fundamental requirement was that the accident needed to have involved fire to a significant extent. This would obviously have been the case if

passengers happened to be killed or injured by the effects of fire and all such incidents were therefore included. However, many accidents happen to involve substantial fires that represent an immediate threat to the safety of passengers, but fortunately, the fire does not actually harm the aircraft's occupants in any way. A substantial number of these cases provide useful information concerning many aspects of fire safety and thus needed to be included in some way. The most obvious approach to quantifying the threat posed by fire in an accident is to look at the extent to which the passenger cabin may have been damaged; if substantial destruction by fire had occurred then the occupants must have been in danger. The following criterion was formulated to identify the occurrence of a fire accident:-

"Involved, or probably involved passenger fatalities due to the direct effects of fire, or, the passenger cabin was destroyed or severely damaged by the effects of fire."

This definition was very close to the one subsequently found to have been used in an FAA fire study (Speitel and Hill, 1988).

Another basic requirement for the relevance of an accident to the study of fire safety was that it must have been survivable. Many incidents involve all of the aircraft's occupants being killed instantaneously by extreme impact forces, after which a severe crash fire usually ensues. Given that there exists no potential for the saving of life, these cases provide minimal information for the study of fire safety. The terms "survivable" and "partially survivable" accidents have been widely used air-safety researchers in order to differentiate incidents where all or at least one of the aircraft's occupants survives any occurrence of an impact.

A slight departure from the "survivable" criteria of Taylor was made in that accidents caused by in-flight fires are *not* automatically included if the aircraft is subsequently involved in a non-survivable crash.

The size of aircraft to be included in the study also had to be prescribed. Most commercial passenger flights involve medium or large sized aircraft, with two or more engines. Some of the smaller aircraft types currently in service were not designed specifically for revenue passenger use and thus they cannot be classed as airliners. More generally, these aircraft may differ considerably from higher capacity types in terms of their safety features, construction, configuration, performance and mode of operation. This very probably affects the nature of their accidents. It was therefore decided to exclude smaller aircraft designs from the accident data survey. Two logical options existed when setting the aircraft size limit below which accidents would be rejected. In terms of aircraft design, types with 20 or more seats are certificated under FAR/JAR 25 "Large Aeroplane" rules. Alternatively, in operational terms, types with more than 30 seats can only be used in the US by licensed air carriers. The 30 seat limit was eventually adopted for two reasons; to further reduce the number of accidents under consideration and to guarantee that the aircraft was in airline (as opposed to possible air-taxi operator) service.

The type of engines used in the aircraft was considered to be relevant the study of fire safety. Turbine (i.e. jet and turbo-prop) engines are generally more reliable than reciprocating piston engines and they use significantly less volatile grades of fuel. The latter were in universal use before the advent of the jet age, but now tend to be restricted to smaller or specialist aircraft types. Because of the growing obsolescence

and significant differences in the safety characteristics of piston-engined types¹, it was decided to eliminate them from the study. It should be noted that this decision automatically excludes all aircraft accidents occurring before the advent of the first jet-engined airline services on the 2nd May 1952. Analogous reasoning was used to exclude helicopter and other non-fixed wing types from consideration in the study.

The final criterion for inclusion within the accident survey was that the aircraft must have been involved in commercial passenger operations at the time of the incident. Different safety standards and operating procedures apply, for example, to cargo, training, positioning and military flights. This can often adversely affect safety levels and the nature of accidents that occur in these types of operation, making them unrepresentative of typical passenger services. A few special cases may require some clarification:-

- A commercial aircraft has been chartered by military authorities for the transportation of service personnel; inclusion was dependent on the use of an airline flight crew and the allotment of commercial flight code.
- An aircraft was being used in passenger-cargo “combi” operations². All such cases were excluded if the configuration required a separate type certification, implying that some aspect of safety may have changed significantly.

Other researchers have used additional criteria to exclude specific types of accidents. Examples include the occurrence of extreme impact damage, the involvement of aircraft from former Eastern Block countries and fires resulting from mechanical failures in flight. These criteria were carefully considered for application to the current study, but in all cases their adoption would have involved the discarding information from some important accidents. Therefore, their inclusion could not be warranted.

4.2 Initial Analysis & the Formulation of an Accident Database

4.2.1 Data Requirements

In the initial stages of the study, historical information was required primarily to indicate the general nature of aircraft fire accidents and to provide a statistical basis for determining what direction the work should take. This would then allow for the identification of a research need and perhaps suggest the most suitable approach to be adopted for the study.

There was obviously a requirement to compile a substantial quantity of accident data in a short a time as possible, because no substantial planning could be undertaken in the interim. This immediate need could be best fulfilled by performing a preliminary survey, to be followed, if necessary, by a more extended data gathering effort. As has already been mentioned, the initial survey encompassed over 2000

¹ Average fatality rates of 32% for piston-engined aircraft types and 21% for turbine-engined aircraft types have been reported as occurring in accidents world-wide in the period 1955-1974 (Taylor, 1975).

² “Combi” or combined passenger and cargo aircraft are designed to carry both passengers and cargo in the main passenger cabin. Changes necessary for this include the addition of side cargo doors, cargo handling equipment and local structural strengthening.

accidents. When the inclusion criteria had been finalised, it became possible to reduce this total down to 217 cases for inclusion within the study.

The large number of incidents under consideration and the provisional nature of the initial analysis meant that only relatively basic information could be retained in each case. Because of this, at first it was decided to place the emphasis firmly with determining whether or not each incident met the inclusion criteria described in the previous section. However, as the number of accidents under consideration was progressively reduced, it became feasible to record more details in each case.

The first priority was to include sufficient information to enable each incident to be readily identified with the possession of only the minimum of details. Thus, although the accidents were numbered and sorted by their date, the aircraft type, location of the accident and airline details were also noted. This then made it straightforward to allocate fragmentary pieces of information, as often obtained from miscellaneous sources, to the appropriate incidents.

The opportunity was also taken to include additional data describing the general nature of the scenario and indicating the role played by fire in each case. In most instances, this information consisted of basic numerical or categorical variables that were simple to interpret and might later prove relevant to the study of fire safety. However, limited provision was also made for the inclusion of some descriptive text, allowing pertinent observations to be noted. The simplicity of the data ensured that it would be straightforward to handle in a computer spreadsheet and be readily amenable to statistical analysis.

The preliminary data-gathering stage thus resulted in the production of a simple database containing 200 or so accidents that were thought to be relevant to the study. The individual records provided basic information covering a number of different aspects of each accident. This data can be conveniently grouped into five categories, as shown in Figure 4.2.

Identification Details	Occupant Fatalities	General Scenario	Fire and Impact Parameters	General Notes
<ul style="list-style-type: none">• date• aircraft type• accident location• airline• airline nationality	<ul style="list-style-type: none">• killed• seriously injured• minor/unharmd	<ul style="list-style-type: none">• phase of flight• airport distance• visibility/weather• terrain	<ul style="list-style-type: none">• fire type• fire fatalities• significant impact• fuselage damage	<ul style="list-style-type: none">e.g.• cause of accident• nature of egress• crash details• extent of fire

Figure 4.2: Information Categories Used for Initial Data Survey

The definitions of the various information fields, together with reasons for choosing them, are given in the next section.

It should be noted that it was not possible to find out all of the information required for the preliminary database, even by the time that the end of the study was reached. Thus some entries were filled with a “?”, signifying that the data could not be determined. In other instances, data entries might have been uncertain or conflicting information was obtained from differing sources. Attempts were therefore made to indicate possible discrepancies in the general notes and the associated data flagged with a question mark e.g. “2-5 miles?” or “burnthrough fire?”.

At the end of the data gathering effort, one final check of the preliminary database was made, using all the gathered information sources. Increased familiarity with the accident reports and cross comparison of different sources made it reasonable

to estimate some data that had still not been confirmed. This information consisted primarily of the accident fire type and the occurrence of significant fuselage destruction. Both of these could require subjective judgements to be made in some circumstances and thus discrete categorisation was not always possible without the possession of very detailed information. However, fire type and presence of fuselage damage were judged to be key variables in characterising the nature of aircraft accidents by statistical means. Their estimation was therefore thought to be justified in the limited number of cases where absolutely definite indications could not be obtained.

4.2.2 Definitions for Categorical Classifications

The preliminary database contained predominantly categorical or numerical information about each accident. Before embarking on the task of encoding the data, it was necessary to decide what categories of information and accident variables would be recorded. The previous section outlined the two key requirements for the initial survey; the positive identification of the 200 or so accidents under consideration and the provision of a basic statistical indication about the general character of aircraft fire accidents. Given the provisional nature of the survey and the necessity that the information be generated in as short a period of time as possible, it was only feasible to include data that would be directly obtainable from the accident reports. These, then, were the primary considerations when deciding the various classes of information to be included. A brief description of each of the information categories now follows.

The details necessary for the definite identification of each accident were reasonably straightforward to ascertain. They consisted of the date, aircraft type involved, airline and the location of the accident. Although this information was seemingly elementary, care needed to be exercised in some circumstances. For example, slight discrepancies in the specification of an accident date have sometimes occurred between several information sources. These anomalies usually consist of plus or minus a single day and stem from differences in time zones, or cases in which an accident may have occurred soon after the local midnight.

Confusion over the identification of an accident from inadequate data sources can also arise in many other circumstances. For example inconsistencies can often result when an aircraft type has been incorrectly designated, multi-national airlines are involved, certain types of aircraft leasing arrangement were used or the accident has occurred in a defunct country. Thus, in almost all instances, standard ICAO interpretations of accident identification details have been used, as contained in the CAA World Airline Accident Summary.

The one exception has been in the separation of multiple aircraft incidents. In some circumstances more than one aircraft could be involved in a single accident, as in, for example, the infamous collision of two Boeing 747's on the island of Tenerife in March 1977. When (as with this case) the aircraft involved qualify independently for inclusion within the survey, they have been listed in separate entries. Justification for this is given on two accounts; the accident can be considered in more detail and, secondly, occupants of different aircraft may often be subjected to significantly different conditions for survival.

The occurrence of occupant injuries and fatalities are obviously highly relevant in any study of air safety. It should be noted that the term "occupants"

includes the crew of the single aircraft under consideration, but not those aboard any additional aircraft involved that might be involved. Bystanders and emergency personnel on the ground were also excluded from the figures.

The casualty figures are based on the standard ICAO criteria; for example, fatalities must occur within 72 hours of the incident, otherwise they are regarded as serious injuries (that happen to result in death in the longer term). Serious injuries are defined as those that require overnight hospitalisation.

The phase of flight in which an accident occurs has been considered in several air safety studies. In terms of aircraft fire safety, the phase of flight gives a reasonable indication of the aircraft's fuel load. Thus, for example, incidents occurring during takeoff or the initial climb will involve significantly higher fuel loads than those occurring in final approach or landing. The various stages of flight in commercial passenger operations are illustrated in Figure 4.3. Note that standard classifications

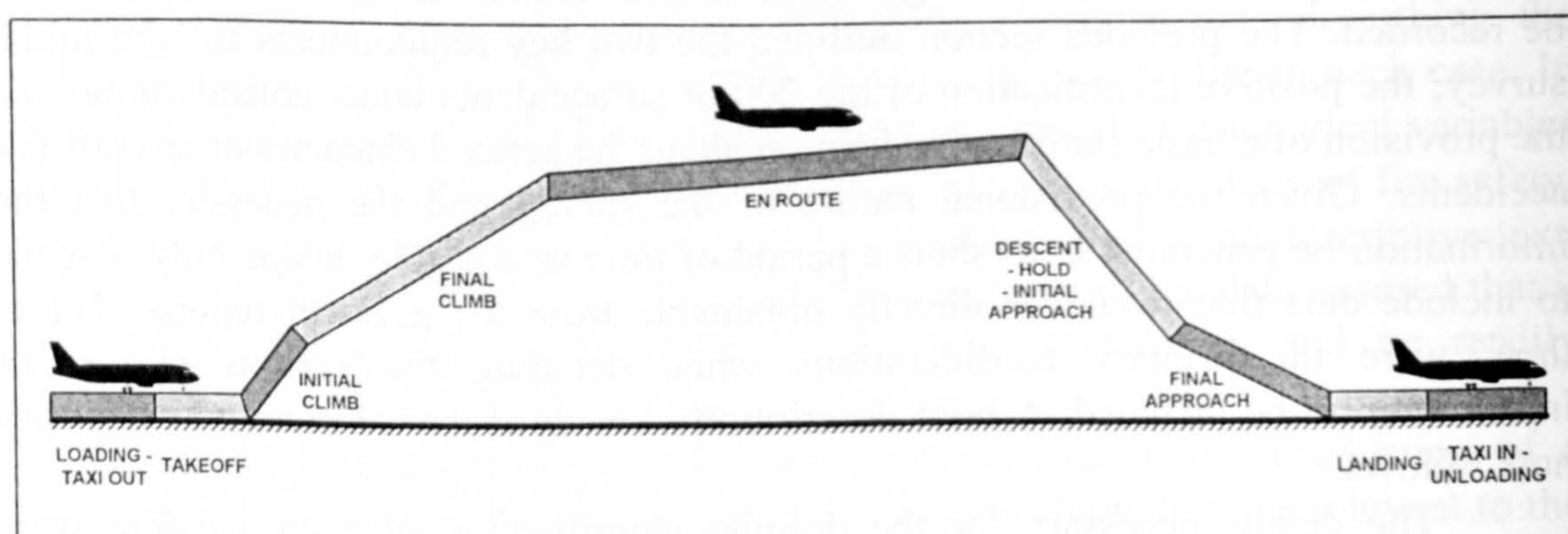


Figure 4.3: Stages of a Typical Airline Flight

have been used in defining the nine phases of flight. Thus, for example final approach is taken to be the period before landing when the aircraft has passed the outer ILS¹ marker, but has still not reached the airfield perimeter fence.

The flight stage can also provide a general indication of the state of readiness and awareness of the aircraft's occupants. Passengers and crew are likely to be most prepared for emergency action during more stressful parts of the flight, such as in takeoff and the final approach. This is probably related to the fact that almost three-quarters of the accidents surveyed were found to occur in the takeoff, final approach or landing stages of flight.

When an aircraft crashes some distance away from its intended landing point, more severe accidents tend to result. This is because the aircraft may have been uncontrollable, or else the crew were unaware of the close proximity of the ground. In addition to airport distance, the prevailing weather or visibility and the type of terrain present at the accident site may also relate to the expected severity of incidents. Thus, all three of these parameters were recorded in the initial survey.

It is notable that the airport distance, visibility/weather and terrain each directly influence the deployment and subsequent effectiveness of emergency fire-fighting and rescue services. For example, an accident site 30 nautical miles from an airport, located on a mountain side in blizzard conditions and darkness, might require several hours to locate, whilst a landing overrun stopping just through the perimeter

¹ Instrument Landing System.

fence will usually be attended within minutes. It was intended to pay close attention to examining these relationships at a later stage in the study.

The classification of the accident fires into categories has already been discussed in section 3.2.4. There, it was related how the fires were initially perceived as being suited to grouping into four distinct types, namely *internal*, *impact*, *burnthrough* and *external* fires. However, the possession of more detailed information and the undertaking of further analysis showed that differentiation between these various classes of fire might not necessarily be clear cut in many instances. Nevertheless, it was decided that a categorical breakdown of fire types would be of enormous value to the study, even if it were necessarily approximate. Thus the effort into classifying the fires by type was maintained and the results included in the preliminary database.

Particular attention was paid to examining the relationship between the effects of any impact and the severity of the fire. Most of the more serious accidents on record involve substantial structural disruption of the aircraft's fuselage and the immediate ignition of large quantities of fuel. The implication of this is that a relatively severe impact must have occurred in such incidents, both to create significant fuselage damage and to rupture the main fuel tanks. Occupants of the aircraft are in especial danger in such circumstances for three reasons. These are the facts that substantial crash disruption and injuries are likely to have occurred, fire growth is often extremely rapid and the fact that the fuselage structure may afford little or no effective fire protection for the aircraft occupants.

As argued in Chapter 3, for a number of reasons, these circumstances appear not to be addressed satisfactorily in most aircraft fire-safety research undertaken to date; yet they have occurred very often in past accidents. For this reason, the definition of an "impact" fire was developed, in order to highlight the frequency at which these types of incidents occur. This definition, as well as those used for identifying the three other fire types, are as follows:-

- *Internal Fire*; where the fire starts inside the cockpit/cabin pressure shell.
- *External Fire*; where the fire starts outside the cockpit/cabin pressure shell and no significant fire penetration occurs before all occupants are able to egress.
- *Burnthrough Fire*; where fire starts outside the cockpit/cabin pressure shell and significant fire penetration occurs before all occupants are able to egress.
- *Impact Fire*; where significant cabin structural disruption takes place and fire occurs adjacent to a ruptured area, so that immediate fire penetration is able to occur.

In many of the accidents examined, significant numbers of casualties have resulted primarily from the effects of fire, rather than from the sustaining of crash trauma injuries. Some reports provide an indication of how many of these fire fatalities are thought to have occurred. In other cases it is possible to deduce the number or obtain estimates from alternative sources. These figures are of key interest primarily because they show the lethality of fire in aircraft accidents. As such, they

indicate the theoretical potential for the saving of lives through the introduction of fire safety improvements.

It should be noted that accident deaths frequently result from a combination of injuries, including for example, acute shock, multiple fractures, severe burns and narcosis. Accident pathologists are instructed, however, to note all contributory factors and also indicate the ultimate cause of death wherever possible (ICAO, 1970). This necessitates that some caution be exhibited when attempting to assess the relative frequency of fire deaths, as distinctions between fire and impact trauma deaths may not always be clear-cut. It has been suggested previously in this chapter that when the primary cause of death cannot be determined conclusively, investigators are likely to err towards declaring the occurrence of an impact fatality, rather than a fire victim. This may be for reasons of compassion, or else through inexperience in aircraft accident pathology. In consequence, the fire fatality rates obtained in the preliminary survey should probably be regarded as conservative estimates.

The term "crash" was judged to be inappropriate for classifying the aircraft accidents because, in general usage, it implies that a violent collision and severe destruction have occurred. However, in reality many "crash" accidents have involved the aircraft coming safely to a stop with nothing more than a series of modest jolts. Often, the undercarriage may collapse, but decelerations remain relatively mild, with the fuselage structure being left essentially intact. For this reason, the terms *significant impact* and *significant fuselage disruption* were formulated to classify whether or not the aircraft came to a stop in a catastrophic manner.

Impact denotes whether or not a *significant impact* was judged to have occurred to the aircraft during the incident. This must have involved one or more of the following:

- Significant cabin structural disruption (e.g. crushing, ruptures or fuselage dislocation)
- The aircraft coming to rest off a runway or off paved airport surfaces
- The aircraft coming to rest in an unusual attitude
- The occurrence of substantial fuel spillage
- Occupant deceleration injuries

It should be noted that accidents in which an aircraft comes to rest off a runway or where passengers are exposed to large decelerations almost always result in the collapse of the aircraft's undercarriage. This stems simply from the fact that aircraft landing gear are designed to withstand the same or lower forces than the rest of the airframe. Also, they are obviously one of the first parts of the aircraft to strike the ground or to hit obstacles in the event of an impact. Thus, with onset of any form of significant structural damage, the undercarriage will almost always be amongst the first structural items to fail. Consequently, it was found that the most convenient way of establishing the occurrence of a significant impact was to ascertain whether or not the aircraft remained standing on its undercarriage when it came to a rest. On this basis, significant impacts were found to have occurred in 86 percent of the accidents surveyed.

Significant fuselage structural damage was found to occur in many of the more serious impact accidents. This was thought to be relevant in terms of occupant

survivability and the ingress of fire into the cabin. Thus, the presence of significant fuselage damage was defined by the occurrence of structural disruption (e.g. crushing, ruptures, seat distortion or door jamming) in cabin or cockpit areas. This was present in 63 percent of the aircraft accidents under study. It was found to be significant that, in the absence of significant fuselage damage, almost all occupant deaths tended to occur primarily as a result of the effects of fire. Also, the fires were found to have slower growth rates and be generally less intense in accidents not involving severe impacts.

The final section of information held in the database consisted of general notes and observations. These did not contain any categorical information and, being of an informal nature, tended to vary considerably in content from incident to incident. They are therefore not discussed here.

4.3 Treatment and the Use of Data in Modelling

4.3.1 Determining the most Relevant Accident Parameters

The data obtained in the early stages of the survey was kept deliberately simple, for speed and convenience. As described above, this resulted in two types of information forming the basis of the initial database; categorical variables and numeric variables respectively. These two classes of information were fundamentally different in nature (the former resulting from discrete classifications and the latter being scalar quantities); thus they required contrasting methods of treatment. Some of these differences will be covered in the next two sections.

However, before any of the information could be incorporated into the computer model, some exploratory work was necessary. It was desired to structure the data within the computer programme in a form that would enable statistically representative accident scenarios to be stochastically generated. This implies that the existence of any key interdependencies must be discovered and then incorporated as appropriate into the computer model.

These statistical relationships within the accident data can be classified into two types; *logical* dependencies and *latent* dependencies. The former mainly exist between categorical parameters and stem directly from the definitions used in the data encoding. Logical dependencies are usually self evident; obvious examples in the present context include the fact that impact fires can only occur in the presence of significant fuselage disruption, or that if no impact occurs then all fatalities will be caused by the effects of fire. For a model to be internally valid, basic logical dependencies must be maintained in all circumstances.

Latent dependencies are considerably more difficult to determine, as they result from the complex interactions that often occur in many accidents. Given that many of the parameters involved occur randomly and are impossible to isolate, most of these relationships are poorly understood. Examples of latent dependencies might include the fact that fires are more likely to start on the right hand side of the aircraft, or the possibility that different types of fire are likely to occur in takeoff (as opposed to landing) accidents. A primary challenge in most forms of risk assessment modelling is the quantification of key latent dependencies that exist between model parameters.

The first task to be undertaken in analysis of the historical data was thus to discover the most important latent dependencies in the accident data. Given that we are concerned with fire safety, this involved determining which simple aspects or features of the accidents most closely corresponded with the occurrence of high fire fatality rates. In order to achieve this, an independent variable was needed for representing the fire fatality rate of each incident. Thus, a figure of demerit (or more accurately, a fire lethality index) was defined:

$$\text{Fire Lethality} = \frac{\text{Number of Fire Deaths}}{\text{Total Number of Occupants Aboard Aircraft}} \tag{4.1}$$

The use of this lethality index allowed the severity of each accident to be quantified in terms of the proportion of occupants who died as a result the fire.

The next step was to examine each of the accident parameters recorded in the initial accident database and discover which ones correlated closely with high incidences of fire deaths. This was achieved by coding the parameters for analysis with *SPSS CHAID*¹ software, a commercial computer application designed to facilitate segmentation modelling of statistical data. The variables found to be most closely associated with high rates of fire fatalities, together with the associated levels of confidence, are shown in Table 4.1.

Ranking	Accident Parameter	χ ² Significance Level
(1)	Fire Type	99%
(2)	Fuselage Disruption	95%
(3)	Phase of Flight	90%
(4)	Airport Distance	90%

Table 4.1: Parameters Associated with High Fire Fatality Rates

It can be seen that fire fatalities depend closely on the type of fire involved, together with the presence of significant fuselage disruption. Less definite correlations were also obtained with the phase of flight in which the incident occurred and the distance of the accident site from the airport.

It was desirable that the computer model generate these four parameters in order of their dominance. This is because when each successive parameter is decided, we are left with a smaller sub-set of historical cases with which to determine the next parameter. Consider, for example, the case of generating an accident scenario involving a burn-through fire without fuselage disruption, occurring after a significant impact on takeoff. This requires the setting of five variables, using the following logic:

1. For determining the fire type, we have a total of 217 cases with which to work from. The historical probability that a burn-through fire has occurred is 60/217.

¹ Chi-squared Automatic Interaction Detector.

2. Assuming that a burn-through fire has been found to have occurred, we are left with 60 cases with which to work from. The historical probability that no significant fuselage damage has occurred is 42/60.
3. Assuming that no fuselage damage has been found to have occurred, we are left with 42 cases with which to work. The historical probability that a significant impact has occurred is 31/42.
4. Assuming that an impact has been found to have occurred, we are left with 31 cases with which to work. The historical probability that the accident has occurred during takeoff is 10/31.
5. Assuming that the accident has been found to have occurred during takeoff, we are left with 10 cases with which to work. This is only just sufficient enough to create a probability distribution for determining the distance of the accident site from the airport.

It will thus be apparent that the numbers used in determining accident scenario parameters become progressively less accurate as smaller branches of the probability tree are reached. This underlines the importance of setting variables in a suitable order, to avoid having to rely on sparse data for determining highly significant interdependencies. Care must also be taken to ensure that logical dependencies are always satisfied in any scenario generation process.

4.3.2 Use of Categorical Data

The categorical information that was gathered mainly consisted of key facts describing the general nature of each incident. Examples include the type of aircraft involved, terrain present at the accident site, phase of flight in which the accident occurred and the type of fire involved. Given both the simplicity and the fundamental importance of this information, it was destined to form the basis for the first round of analysis and enable the first steps to be taken towards formulating the simulation of aircraft fire accidents.

The discrete nature of categorical data lends itself to statistical analysis methods. However, before such techniques could be applied, it was necessary to deal with missing values that existed in some of the information categories. In most cases, data was found to be lacking in only a small number of the 217 incidents that were being studied. In these circumstances, the values of missing entries were assumed to be split in proportion to the breakdown of the data that had been obtained. This then enabled all subsequent analysis to be undertaken with a sample of 217 cases, simplifying calculations and facilitating cross-comparison of results between different information categories.

The only exception to this occurred with the type of terrain present at the accident site. Here, it was found that this information could not be determined in almost a quarter of the accidents being studied. It was known that most of these incidents had occurred a significant distance from the airport. This implied that their terrain details would not be statistically consistent with the other three quarters of the accidents, the vast majority of which had occurred in the immediate vicinity of an airport. It was therefore inappropriate to assign missing values in accordance with data that had been obtained.

As has already been seen, it transpired that the three accident scenario parameters that correlated most closely with high fire fatality rates were all categorical

in nature. Given that categorical information is comparatively straightforward to deal with, this greatly simplified the task of generating the more fundamental details of accident scenarios in the risk assessment model. The approach taken in this aspect of the analysis was to utilise a probability event tree, structured to determine the fire type, occurrence of impact and phase of flight for the accident being simulated. The construction of this scenario event tree is described in Chapter 6.

Overall, it can be seen that, although categorical information about past accidents is inherently simple to deal with, it formed the foundations of the entire simulation analysis. When analysed with care and presented in an appropriate form, this type of data can yield important and often under-appreciated insights into accident safety.

4.3.3 Obtaining Numerical Data

Most accident reports provide a significant quantity of quantitative information about the events they describe. Whenever it is possible for investigators to make measurements or accurate estimations, such data is supplied in numerical, rather descriptive form. Examples of accident variables recorded directly from this type of source included:-

- Date on which the event occurred
- Number of people involved
- Number of fatalities and injuries incurred
- Distance of the accident site from the airfield
- Number of emergency exits used
- Wind direction and strength

In addition to data that can be defined explicitly with numbers, other important features of accidents, although quantitative in nature, can only be described by verbal or pictorial means. Examples of this type of information include the level of structural damage sustained by an aircraft, the extent to which a fire eventually spread and the delay encountered before an exit could be opened. In order to simulate these aspects of aircraft accidents, it is usually necessary to translate descriptions of quantitative parameters into numerical form. When undertaking the accident survey, all such material was recorded fully in its original verbal or pictorial form, wherever practical. The analysis techniques then used to quantify this descriptive information into numbers are covered in Chapters 6, 7 and 8.

4.4 The Accident Data

4.4.1 Two Stages of Information Gathering

The survey of past accidents was effectively undertaken as a continuous process over a period of approximately two years. However, it has been seen that the analysis was performed in two distinct stages, leading to the production of a preliminary and a main database, respectively. These two resources of information were implemented in different forms and designed for the collation of contrasting

types of data. Thus, the two databases complemented each other in use and, as a result both were utilised extensively through to the completion of the research. Brief details of each now follow.

4.4.2 Preliminary Database

The preliminary database was implemented in the form of a computer-based spreadsheet and contained basic summary information on each of the 217 events processed. This made it most suitable for processing of categorical and numerical data and screening out incidents that were not suited for inclusion within the study. Thus, the preliminary database originally encompassed over 2000 accidents; these were gradually reduced in number as more information on each event was obtained, until the final total was arrived at. The primary uses made of the spreadsheet data during model development were:-

- Recording and resolving instances in which conflicting information about an incident had been obtained
- Sorting accidents by different criteria
- Grouping and counting similar categories of accident
- Performing statistical tests
- Plotting graphs

A simplified version of the preliminary accident database is provided in Appendix A.

4.4.3 Main Database

The main accident database was recorded in the form of a paper filing system. Entries were accompanied by copies of original source material wherever this was feasible. An extensive summary was prepared for each of the accidents. Figure 4.4 illustrates a typical example of one of these documents. This procedure enabled information from a wide variety of sources to be compiled and recorded in a consistent format. Source locations were also noted, in case they became required for future reference.

The primary use of the main accident database was in recording descriptive information about the incidents. Separate text fields were used to record scenario, impact, fire, cabin thermo-toxic environment and evacuation details. The information contained in each of these categories could then be collated across all 217 database entries and used to focus on specific aspects of accident scenarios. Some of the results of these activities will be examined in subsequent chapters of the thesis.

References

☒ CAA WAAS

☒ NTSB-AAR-72-12

☒ FAA CT-88/03

☒ Hill Thesis

Date701127

Aircraft TypeDC-8-63

Killed47

Injured49

Unharmed133

Impactyes

Fire Typeburnthrough

Fire Fatalities47

Scenario

	Crew	Fatal	Serious	Minor/None
Passengers	46	43	138	

N4908C, Capitol. Attempted to takeoff on an icy runway at Anchorage International Airport, Alaska with wheel brakes on. The tyres burst and the aircraft failed to become airborne. It slid 3400' off the runway, hitting obstacles, and the fuselage broke in two mid way between the wing and the tail. The aircraft was destroyed by an intense ground fire. The flight was a Military Airlift Command contract flight with military personnel aboard.

17 05 (Night time) Light freezing drizzle

Impact

The aircraft overran and struck a low wooden barrier, an ILS structure and a 12' deep drainage ditch before coming to rest 3400' beyond the end of the runway. One or two jolts were felt before one severe jolt which started the break-up before the aircraft came to a rest. The fuselage broke in two, just aft of the rear "jetescape" door (8 seat rows from rear), with the two sections separating by approximately 30'. The right wing also detached.

Fire

Gross amounts of fuel contaminated the wreckage area, reportedly 6-8" deep. An intense ground fire developed immediately after the crash. The fire started on both sides of the aircraft before it had come to a stop. Several explosions occurred approximately 2 mins after the crash. The airport fire services vehicles arrived at the crash site 3-5 mins after the accident had occurred and were hampered by subsequent explosions. Wide cut fuel.

Thermo-Toxic Environment

The cabin became untenable after spill fuel was set alight by explosions after approximately 2 mins. 46 passengers and one flight attendant died as a result of the fire.

Evacuation

The cabin lights went out during the impact sequence. One man released his seat belt before the final jolt and was thrown approximately six rows forward. A large fire erupted on the right side of the aircraft and some passengers left their seats and attempted to move away from the area. Passengers from forward of the galley reported that people were moving down the aisle before the aircraft had come to a stop. One man stated that most of them were "thrown about pretty bad". Both overhead luggage racks came down on top of the passengers and the aisle was obstructed. Galley equipment came out all over the floor, rendering the forward galley service door unusable as an exit.

The aft galley door was only partially opened by a passenger and the 81 stewardess because it opened against a small embankment. 16 people exited through this door. A stewardess opened the main entry door.

The forward "jetescape" floor level exits were located at the ends of seat row 9. There were no seats 9A and 9F located in front of these exits. Military officers seats next to the exits in seats 9B and 9E, opened them. 19 people exited through the left door and 22 exited through the right door.

The overwing exits were at seat rows 18 and 20. The men in seats 18A, 20A and 20F opened 3 of the 4 exit window hatches. The 18A exit was opened while the aircraft was still moving and flames came in for a short while. 13 passengers used this exit, but others went forward to evacuate, rather than attempt to use it. Six passengers used the 20A exit one used the 20F exit. In addition, 16 more passengers reached using an overwing exit, but did not specify which one. The overwing exit at seat 18F was reportedly jammed.

Eleven passengers in the forward section reported escaping through the break at the rear of the cabin, near row 38. The two rear "jetescape" doors were situated in row 33. A man who was seated in seat 33E next to the right door said that he was unable to open either of them and so he got out through the break. Six other survivors found themselves ejected from the cabin, in-between the two sections of the fuselage. Four of these ejected passengers were still in their seats (36E, 36F, 37C & 37D).

The aft portion of the aircraft at the break was separated from the rest of the aircraft by approximately 30'. 17 reportedly used the break. Flight attendant #1, stationed at the aft entry door, was unable to open her door. She crossed the aisle to the galley and, with passenger assistance, opened the exit, which was against a small embankment. Only 4 people reported leaving by this exit, including the 84 flight attendant, who was carried out by a passenger. This flight attendant had to loosen her seat belt in order to hold loose galley equipment secure. Because of her loosened belt, she was thrown from her seat and knocked unconscious.

Gross amounts of fuel contaminated the entire area. One man from row 8 stated that when he departed the aircraft, fuel had already covered the floor. "I recall that it was deep enough to cover my shoe" he said. "Fuel was also pouring out of the torn section where I exited close to the ground." A man from row 10 who evacuated through the forward left "jetescape" door advised that the fuel was like a river at the end of the chute. A man in row 19 reported that when a window exit hatch in front of him was opened, flames shot in, followed by some fuel or water, causing him to believe that they had landed in water. A man from row 17 reported that he was sprayed with fuel during his attempt to escape. All of these people had their clothes discarded, because they were fuel soaked.

The captain stated that after the aircraft stopped, he opened his cockpit window and yelled to the passengers were leaving through the forward entry door to leave the area. He attempted to go back into the cabin through the cockpit/cabin door, but it was blocked. He then exited through the left side cockpit window, went back to the main entry door and assisted passengers to get out of the aircraft through this exit. When no other passengers appeared at this door, he proceeded to the right side cockpit window and assisted the co-pilot in evacuating the flightdeck and the navigator who had been injured in the crash.

Figure 4.4: Example Entry from Main Accident Database

Chapter 5: Model Construction and Development

5.1 Conceptualisation of the Risk Assessment Model

5.1.1 General Requirements for the Computer Programme

The aim of the research essentially involved the implementation and use of a computer based risk assessment model for the purpose of analysing issues in aircraft fire safety. The central task in this undertaking was the development of a comparatively large computer programme, which was to act as a tool for integrating the considerable quantity of information available on aircraft fire safety. This programme would simulate aircraft accidents and enable investigative studies to be performed into many aspects of air safety. It was thus apparent that conceptualisation of the computer model would play a pivotal role in determining the overall success of the study.

However, before any substantive programming work could begin, it was necessary to give some careful thought as to how the model would be implemented. It had to be ensured that the direction and scheduling of the computing activities were actually matched with the true needs of the research, rather than being left to emerge during the coding process. When the latter approach is taken, there is a significant danger that a loss of direction might occur. This can often manifest itself when computer programming becomes an end unto itself and sight is lost of the primary reason for undertaking the activity. Therefore, in order to avoid this possibility, it had to be determined exactly what was required of the model and what it would be feasible to achieve in the time available. This would then help to ensure that all computing activities were fully justified and that they were regulated on a pre-planned basis.

5.1.2 Matching the Level of the Analysis to Data Quality

One of the primary requirements for the tool was to accommodate the large amount of information obtained from a comparatively wide range of different sources. This data would come in many forms, encompassing crash, fire, evacuation and miscellaneous aspects of aircraft accidents. In some of these areas, the available information was of a very high quality, whereas in others, knowledge could often be relatively sketchy or perhaps incomplete.

An important consideration in the computer modelling was that the overall accuracy of the analysis would be determined by the weakest links in the chain of knowledge used. This implied that the development of individual sub-models to a high degree of sophistication could not be justified whilst other parts of the analysis were still relatively approximate. Thus, efforts needed to be directed towards improving the weakest parts of the overall risk analysis, before detailed refinements were added elsewhere. For example, no information was found to quantify the effect of impact injuries on the mobility of evacuating survivors and yet this linkage may play a fundamental role in determining fire casualties in many aircraft accidents.

Influential mechanisms like these may be omitted or treated inadequately in many sophisticated computer simulation models, because they are inconvenient to address with computer methods. Conversely, excessively detailed methods are

commonly applied in other areas that happen to be more amenable to computational techniques. This may often be despite the fact that adequate data may never be available to enable the full calibration of these complex models.

Consequently, the development of the risk assessment model clearly needed to be undertaken in close conjunction with the analysis of the information from past accidents and scientific research. This would enable the level of the modelling to be matched to the quality of information that was actually available. Efforts would need to be focused in areas where knowledge was relatively poor or computer methods had not yet been established. Modelling techniques could then be optimised to make maximum use of limited information and "over simulation" avoided in other areas of the work. Therefore, in comparison with existing computer simulation models, weaker aspects of the overall analysis would be strengthened and areas of excessive resolution simplified to be more consistent with data availability. This should produce a greater level of consistency between the various sub-models and thus provide a more balanced analysis overall.

5.1.3 Linking of Sub-Models

The computer simulation model was required to deal with a number of dissimilar aspects of aircraft accidents, such as the occurrence of structural damage, fire growth and passenger evacuation. The most logical way of implementing this level of functionality was to structure the programme in the form of a series of individual modules. For example, these sub-models might handle crash effects, fire and evacuation parts of the analysis respectively. This would then provide a basic structure for the programme, allowing specific parts of the model to be isolated and worked on independently, thus easing the task of development considerably.

However, as has been pointed out previously, many of the key processes in aircraft fire accidents comprise interactions occurring between different aspects of the incident. Consider, for example, the role of fuselage structural damage in facilitating the rapid ingress of fire, or the detrimental effects of smoke on occupant evacuation. These interrelationships may often play a large role in characterising the nature of an accident and thus they had to be incorporated into any risk analysis. This obviously implied that there needed to be a significant degree of communication and interaction between the various sub-models of the computer programme.

In practical terms, this meant that a substantial quantity of information would need to be accessible by more than one part of the programme. This shared data might need to be accessed in one of two ways; by "read-only" access or "read-write" access. In the former case, a sub-model would look up information in a passive manner and make no modifications to it. For example, a value for smoke density inside a cabin might be referred to when calculating the speed of a passenger's movement.

In contrast, some sub-models might require read-write access to shared information. This allows a model to look up data, update it and then re-save it for other parts of the programme to work with. Obviously, this involves a bi-directional flow of information and as a result this process may be significantly less efficient or even impossible to implement in some modelling environments. As an example, the need for read-write access might occur when incrementing the temperature of a section of fuselage structure that is adjacent to a fire. The current temperature would be looked up, used to estimate a level of radiative heat absorption and then a new temperature value stored in place of the old one.

The existence of an adequate level of cross communication between sub-models would be of paramount importance to the success of the overall programme. The most obvious way of achieving this would have been to play safe and connect “everything” with “everything” throughout. However, this is a mistake frequently made by inexperienced or undisciplined computer programmers and it usually results in an impenetrably complex programme. Clearly, care would need to be exercised over the implementation of the model, if this type of “tangled spaghetti” structure were to be avoided.

One way of achieving this was to clearly define the inputs and outputs of each sub-model and restrict the numbers of these parameters to the absolute minimum. This tactic can be extended further by gathering together sets of related information into a data group or structure and handling them as if they were a single entity. An example of this technique is shown in Figure 5.1, which shows, for the sake of clarity, a one-

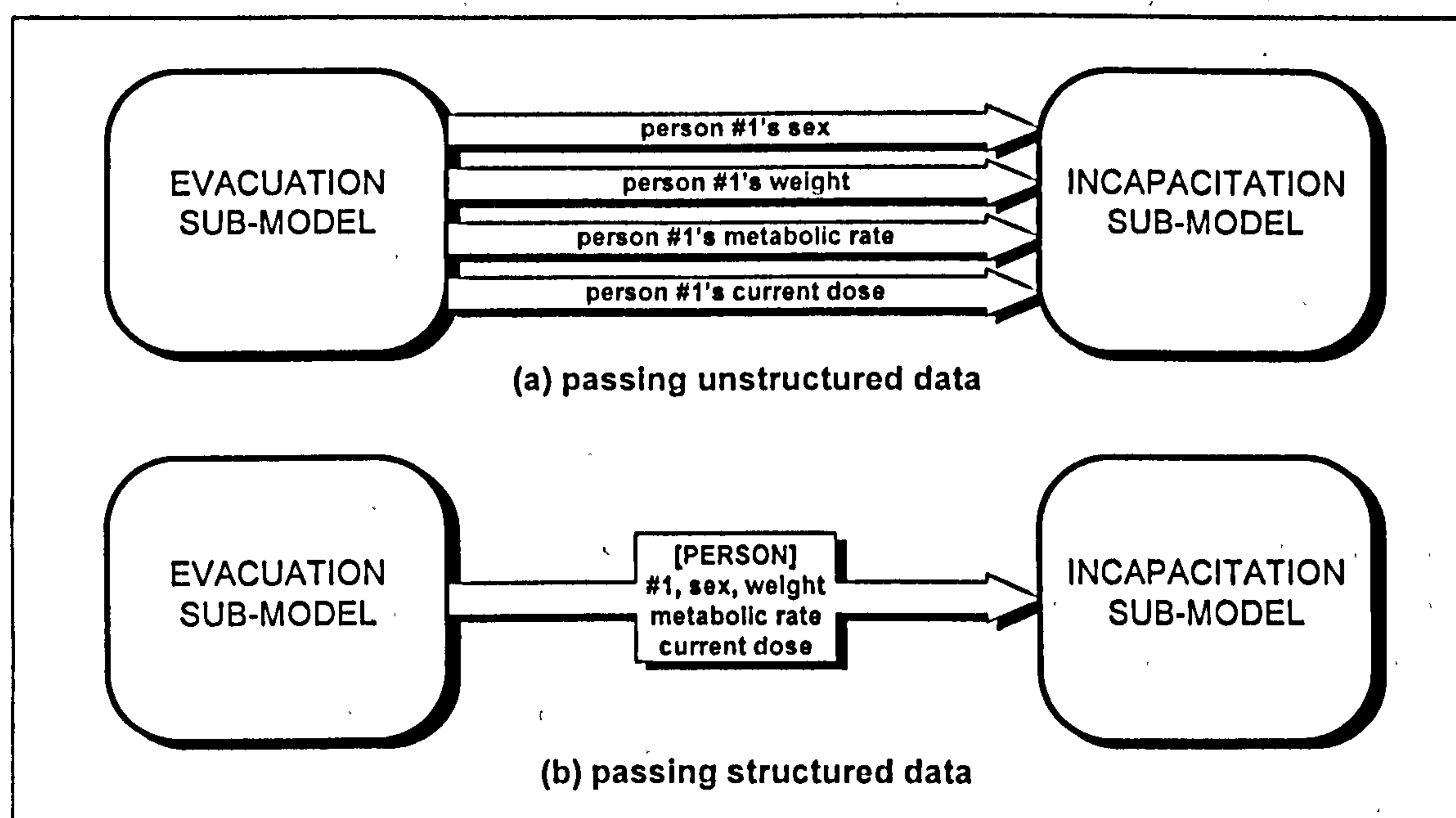


Figure 5.1: Model Simplification Through Structuring of Data

way flow of information between two sub-models. This data consists of a number of characteristics describing the passenger under consideration. Rather than being communicated between sub-models individually, these separate attributes could be grouped together into a “person” and treated as a single object, of pre-defined structure. This then greatly simplifies (and usually speeds up) communication of passenger information between the two sub-models.

5.1.4 User-Interface Requirements

The overriding purpose of the risk assessment was to enable the systematic demonstration, exploration and analysis of the events that occur in aircraft fire accidents. This task had to be achieved in the context of a PhD study and thus it would need to include the definition, planning, researching and writing up of the work. All of these tasks had to be completed within the three year period. It was therefore apparent that the modelling work would have to be directed primarily at meeting the needs of the research. There would be little opportunity for adding extensive refinements or accommodating the requirements of other potential users.

Thus, the end product would consist of a prototype research tool, possibly quite basic and utilitarian in appearance, but with rather more emphasis placed on functionality, adaptability and in-built analysis capabilities.

The first impression provided to an observer when using or demonstrating any computer programme is derived from the qualities of the user-interface. This interface is usually required to perform three main tasks:-

1. provide some degree of control over the programme
2. indicate the current status of the activity being undertaken
3. store and convey the values of any results obtained

In the case of the present study, all three of these functions would be desirable for incorporation into the risk assessment tool. However, because of the research emphasis of the work, rather different levels of priority would be afforded to each of these requirements for the user-interface of the envisaged simulation tool. Accordingly, each of these three aspects will now be considered in turn.

There was obviously a need to provide some form of control over the programme. This would be necessary, for instance, to allow specific types of aircraft accident to be set-up and sensitivity studies or verification work to be undertaken. The most satisfactory way of achieving this would be to have provided an interactive control interface, operating as part of the overall model. This might consist of a series of menus, data entry dialogues or even an advanced windows-based point and click environment.

Alternatively, it was possible to effect control over the programme by directly modifying its source code and the values of input data read from pre-stored files. For example, this could involve fixing decisions, event paths or the values of probabilistic variables, and editing the values of parameters read from input data files. These activities could only be undertaken by a user that was reasonably familiar with internal workings of the model and the language or modelling environment used in its construction. Although this might prove to be unsatisfactory in a more general context, it would be perfectly adequate for the purposes of the PhD study. In the end, time limitations were to force the adoption of the second approach. The inclusion of a comprehensive control interface would have made the tool rather more convenient to use. However, the time required for its construction was better invested in improving other aspects of the programme, as will now be detailed.

The second function performed by the user-interface of many simulation programmes is to show the current status of the simulation process. This allows progress to be monitored and can help to establish how the final outcome of a run was reached. The status of a model may be conveyed by displaying the values of numerical variables, by plotting time-history graphs or perhaps via some form of pictorial animation. The latter can be especially useful for illustrating the role that dynamic behaviour might play in a model, for showing spatial relationships, or in situations where the values of many parameters are changing continuously.

Precisely these kinds of requirements were expected to be encountered in the analysis of aircraft fire accidents. The most obvious case in point is with the simulation of passenger evacuation, where perhaps hundreds of individuals might be moving through a complex arrangement of seating, aisles, galleys and exits. Predictably, many of the evacuation models to have been produced by other

researchers have made use of graphical displays for illustrating the movements of evacuees (Galea 1993; Potel, 1995; Cagliostro, 1984).

Other aspects of the accident simulation could also benefit from presentation in graphical format. For example, fire position and size, the location of cabin wreckage and the cabin thermo-toxic environment each consist of spatial distributions and are thus probably best conveyed in diagrammatic form. All these different outputs of the analysis model could represent a considerable quantity of information and it was anticipated that it might be difficult to portray all of them simultaneously in a single display. Graphical computer interfaces can frequently appear cluttered, gimmicky or confusing when too much information is provided without a clear structure. It now appears to be widely appreciated that over-complicated displays are rarely acceptable, even if a computer application is to be used exclusively by trained specialists (Helander, 1987).

In the case of the current study, it was expected that the computer model would be presented to people from a diverse range of disciplines, such as academics, engineers, psychologists and government officials. Thus it would be necessary to take especial care when designing any graphical display for the model and restrict the information presented to the minimum necessary.

The final, and perhaps the most important, task performed by a simulation programme's user-interface is to display or record the end result of a run. In terms of the current study, these results might consist primarily of the number of occupant fatalities and injuries sustained in an accident, together with their causes and other pertinent details of the accident. This data is relatively concise and could be provided in the form of a text output, written either to the screen or a results file.

At a second level, it would be desirable to obtain causative information, indicating how and why casualties were predicted to have occurred in an accident simulation. This was obviously a far more challenging task, as it would involve the examination of all aspects of the incident, including the roles played by impact disruption, fire growth, exit availability and the progress of the evacuation. One way of achieving this might be to record a series of snapshots from an animated display of the accident simulation. Alternatively, if no graphical display was constructed, then time histories of important parameters, such as fire size, cabin conditions and evacuation rate, could be recorded during the course of a run. These would then be plotted alongside the predicted casualty figures and used to provide a greater insight into the development of events and the factors influencing casualty rates.

In the end, it was decided not to spend too much time pre-planning how the final results of the simulation programme would be presented to an observer. It was anticipated that the user-interface would have to show the progress of a run in reasonable detail, even if only for the purpose of facilitating model development. Thus extensive information would be available throughout the simulation process and it would be relatively straightforward to store whatever data that might be required for analysis purposes. Results could then either be looked up manually, or some form of automatic formatting and presentation could be added, if desired.

Overall, the main requirement for the user-interface of the programme would be to clearly demonstrate the progress and outcome of the accident simulation process. This would be essential for undertaking the detailed analysis of accidents, investigating issues in aircraft fire safety and for programme development purposes. Other aspects of the interface, such as convenience of model use and the provision of

automated analysis and presentation of results were judged to be of only secondary importance.

Thus the final programme would consist of a prototype simulation tool, intended for undertaking exploratory studies in the context of a research environment. It would *not* be suited to use by non-expert users, or for semi-commercial distribution to interested parties.

The task of communicating the simulation process to observers required much consideration. The model could easily be constructed to produce an impenetrable mass of abstruse output data. This information might be decipherable to a computer specialist, but would probably prove meaningless to those possessing a different background. The only alternative to this would be to utilise some form of graphical display for conveying the working of the model, perhaps utilising computer animation techniques.

The primary aim when building the user-interface was therefore to enable ideas to be clearly demonstrated and results presented in a form that would be straightforward to comprehend for a general audience.

5.1.5 Perceived Customers for the Work

It has been stated that the output of the computational work was expected to be a prototype simulation and risk assessment tool, tailored primarily for meeting academic needs. However, given that the study was based upon the analysis of historical information and scientific findings, it was apparent that the tool could potentially be used outside of academia. As a result of this, it was wanted to ensure that the model was capable of being used directly for addressing real-world problems, rather than just for the analysis of theoretical issues that might have been contrived for purely academic purposes. Thus, on occasions, it was found helpful to think in terms of an end "customer" for the risk assessment model, when this was practicable within the constraints of the PhD programme. This could sometimes help to strengthen the sense of direction possessed by the study and assured that the work being undertaken was also relevant in the context of air and fire safety.

Those most immediately involved with the study were the author and the supervisory staff overseeing the research. Although the interests of these individuals were essentially of an academic nature, their scope might well have extended beyond the boundaries of a PhD study. For example, there was a possibility that the work could form the basis for a larger project, be used to complement existing programmes of research, or be continued by other students. In fact, midway through the study, a background agenda evolved, directed towards the securing of further funding to enable continuation of the work beyond the duration of the PhD. This had little direct effect on the direction of the research during the three year study, but it certainly served to focus the mind at times.

In the longer term, customers outside of academia might possibly exist for the work being undertaken. Most obviously, these would comprise those concerned with the analysis of fire safety in passenger aircraft. In addition, it would be comparatively straightforward to extend the study to encompass other modes of passenger transportation, such as coaches, trains and ships. Ultimately, almost any type of enclosed environment that possessed a fire risk could be simulated; for example off-shore platforms, mines, factories, auditoriums or other constricted buildings.

For the purpose of model development, it was assumed that the work would only be applied within the context of commercial aircraft operations. Even with this restriction, potential users existed in a number of different areas and at several levels within the air transport industry. For example, each of the following groups possesses responsibilities or significant interests in matters of aircraft fire safety:-

- Regulatory authorities
- Air safety researchers
- Accident investigation bodies
- Airport Emergency Services
- Transport safety groups
- Aircraft insurers
- Airlines
- Cabin interior outfitters
- Aircraft manufacturers

During the course of the study, presentations were made to individuals representing the first two categories in the list. The detailed questioning that was received from these experts was found to be of invaluable help in refining many aspects of the work.

5.2 Utilisation of the Model

5.2.1 Developmental Usage and Performing Formal Runs

The simulation model would eventually be used in two distinct ways. The first of these consisted of developmental and feasibility testing, undertaken to establish the basic functionality of the tool. This work was performed in conjunction with the analysis of accident and experimental data, and it comprised most of the day-to-day activity in the second and third quarters of the PhD. These runs played a fundamental role in programme development and they constituted the core knowledge building and encapsulation process within the research.

The envisaged use of the completed model was as an integrated tool suitable for undertaking risk exploration and formal risk assessment studies. This was only achievable once all sub-models had been implemented (even if only in a very basic form) and it enabled the overall calibration of the simulation model to be verified. The programme was used in this manner during the second half of the study, usually when giving demonstrations, making final adjustments and obtaining formal results. This mode of operation can be interpreted as a knowledge refinement and exploration process.

The use of the early versions of the model in developmental testing was found to be extremely valuable when interpreting the historical accident records and analysing findings of experimental research. When attempting to integrate this data mentally, it was found to be possible to overlook or underrate the importance of some types of information. This was liable to occur when the material in question was found to be uninteresting, or appeared to be insignificant in the overall analysis. This could potentially have led to a degree of complacency or under-appreciation developing in some areas of the work. However, when attempting to implement and

link certain sub-models, the existence of information gaps and inadequacies rapidly became apparent. These forced a return to the accident database and gathered literature, sometimes with a "shopping list" of data that was actually required for modelling purposes. Often, it was impossible to obtain the level of information that was needed. Sometimes, however, it was found that significant data had been disregarded, or else was possible to derive by some other means. Using the model in this way also forced past accidents and scientific results to be dissected and analysed in a systematic manner. This then helped to ensure that maximum use was being made of all the information resources that were available.

The fact that the data desired could not always be obtained was, in many cases, a significant finding in itself. Some of the weakest areas in current knowledge were observed to be critically important; for example in rates of fire growth, the effects of smoke on evacuee behaviour, or the role of crash disruption in accidents. One particular use of the model in these instances was in testing the sensitivity of findings to variations in the estimated values of missing data. If the influence of these parameters was found to be significant, then efforts could be directed towards maximising the accuracy of estimates used. This might involve resorting to the coding of qualitative information, the factoring of data obtained in a different context, or even to making use of educated guesswork, if circumstances dictate. Although these types of approach might appear crude, acceptable results may often be obtained in cases where it is unfeasible to apply more formal methods of analysis.

5.2.2 Probabilistic Methods and Monte Carlo Simulation

The probabilistic character of aircraft accidents means that a single set of initial circumstances generally has the potential to produce a range of different outcomes. The development of a scenario may often be determined by seemingly insignificant details and through the interactions of many complex phenomena. The paths that events can take may often be very sensitive to the influence of these factors. This can lead to the nature of an accident undergoing a complete change in a very short space of time.

For the purpose of risk assessment, it is usually impossible to quantify or predict these types of characteristics in a deterministic manner. Thus, the behaviour of such a system cannot be accurately established by examining individual incidents in isolation. It is therefore necessary to analyse a range of events, sufficient enough in number to ensure that a representative spectrum of potential outcomes have been considered. Then, in areas where discrete quantification is not practicable or where understanding might be poor, the observed characteristics of a sub-system can be encapsulated in the form of a probability distribution.

In all but the most simple of cases, it is impossible to solve for the effects of these probability functions analytically. However, if the risk analysis is implemented in the form of a computer model, it is possible to run multiple trials and explore the role of probabilistic parameters. Random number generators can be used to initialise values for these parameters automatically from their probability distributions. This then allows a computer model to perform a series of simulations, each one of which produces a different outcome.

Monte Carlo simulation techniques use this type of procedure to numerically solve for the characteristics of probabilistic systems (Kalos and Whitlock, 1986; Kritzman, 1993). They involve the continued repetition of a probabilistic process and

recording of the outcomes obtained. If enough trials are undertaken, the behaviour of the system under study can be mapped out in a systematic manner. The results of Monte Carlo simulations are commonly plotted in the form of frequency or probability density distributions. These show how the relative likelihood of a particular outcome can be dependent on the values of key parameters. Figure 5.2 shows an example of output data obtained from a Monte Carlo simulation of a fire evacuation from a building (Phillips, 1994). Note that, because the method produces results in the form of a discrete series, data fitting and smoothing techniques can often be appropriate.

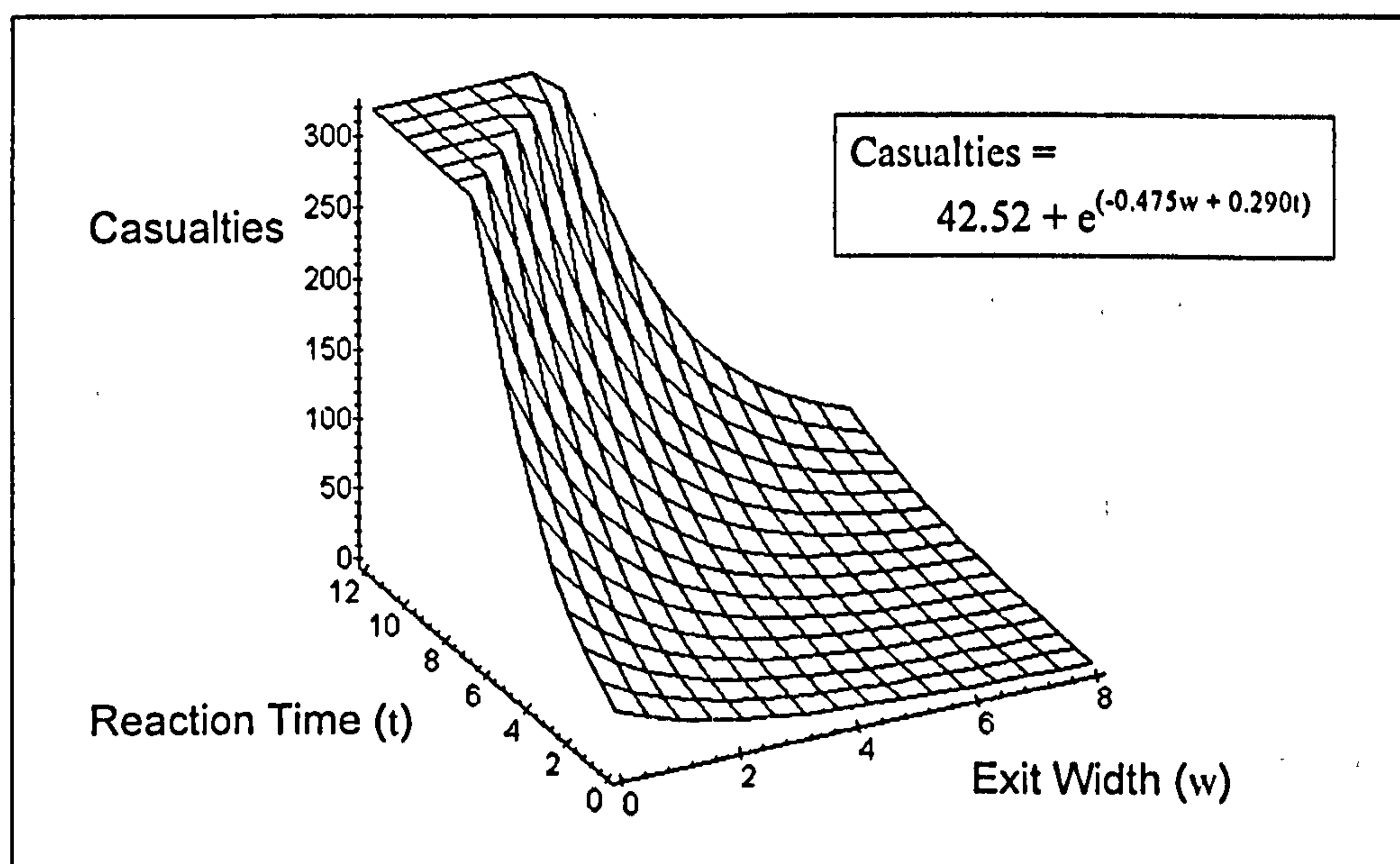


Figure 5.2: Multiple Regression Analysis of Monte Carlo Output

Typically, hundreds or perhaps thousands of runs might have to be performed before statistically reliable results begin to emerge, even for simulations that only involve a modest number of probabilistic variables. This stems from the fact that the number of trials (and thus computational time) needed to obtain an adequate solution increases exponentially with the “degrees of freedom” present in the system (Chorafas, 1965). In consequence, variance reduction techniques and adaptive solution procedures are commonly employed to significantly reduce the number of runs that need to be undertaken (Rubinstein, 1981).

However, it should be noted that systems of practical interest frequently involve too many probabilistic variables for it to be practical to obtain global solution sets to a high order of accuracy. A factor that is also relevant is that it can very difficult to visualise relationships in more than three or four dimensions. Thus, Monte Carlo techniques tend to be employed either for the purpose of undertaking relatively approximate exploratory studies at a global level, or in locally optimising the values of a few key parameters (Phillips, 1994).

It can be essential to perform global exploration in cases where a system has the potential to behave in a non-uniform or otherwise unexpected manner. One example of this in the context of air safety is in the emergency evacuation of aircraft. Figure 5.3 shows an approximate frequency distribution for escape times achieved in 44 past aircraft accidents. It can be seen that about ninety percent of the evacuations were completed within a period of four minutes. However, a distinctive “tail” exists in

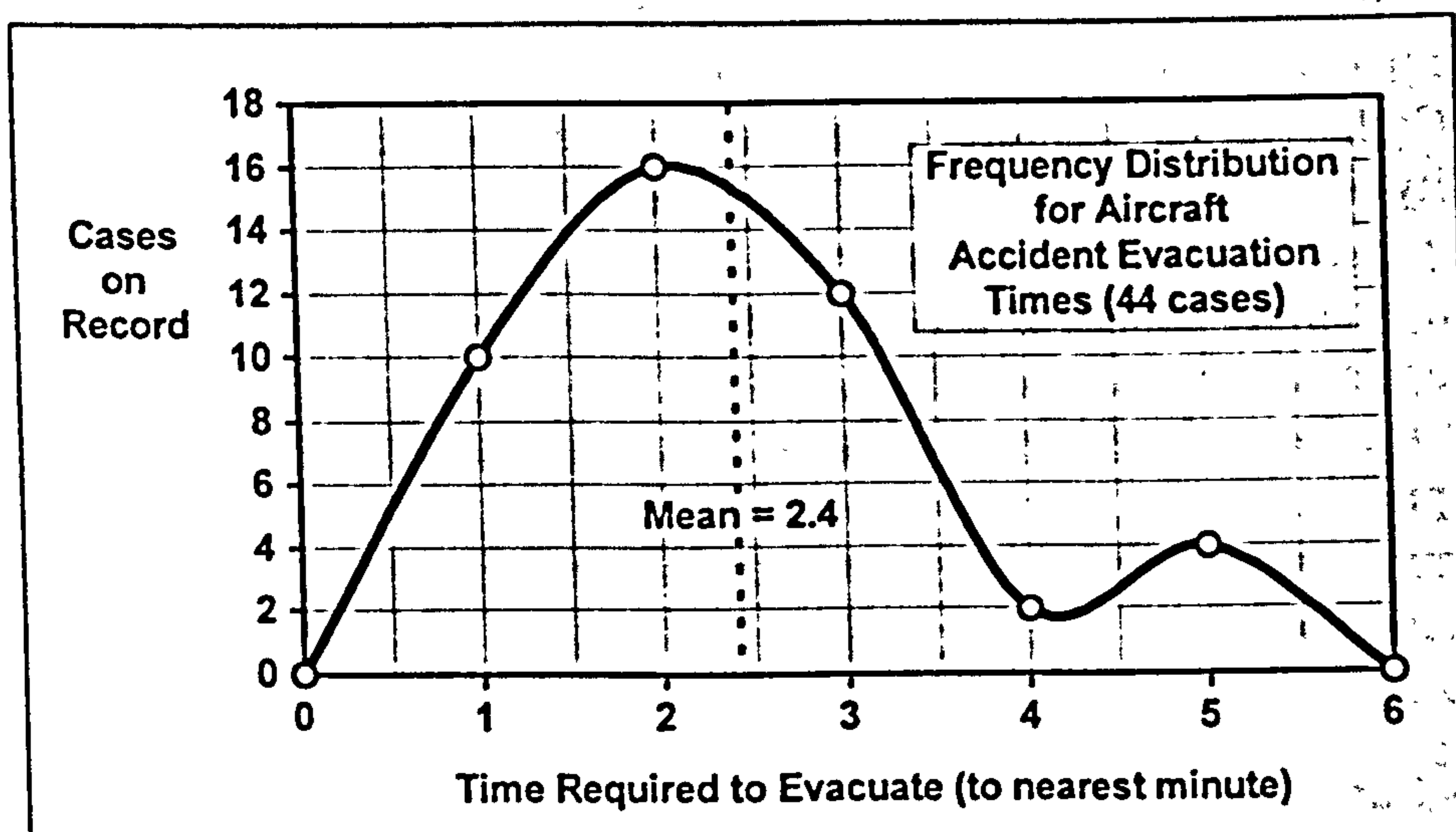


Figure 5.3: Historical Aircraft Evacuation Times

the distribution, centred at around the five minute interval; perhaps hinting at the occurrence of a specific type of difficulty in some of the incidents. Monte Carlo techniques are capable of faithfully revealing this type of anomaly, provided that global exploration is undertaken. In contrast, the use of a deterministic analysis would yield no more than a mean value for a given parameter, perhaps with the provision of estimates for likely error bounds or statistical variance.

5.2.3 Intended Use of the Model

When completed, the simulation model was expected to constitute an integrated risk assessment tool, suitable for the examination of many different aspects of aircraft fire safety. As has been stated previously, the primary customers for this capability were envisaged as being those directly concerned with ensuring the future safety of air transport operations. However, the approach adopted in the simulation analysis would mean that the work would be meaningful to individuals working in specialised aspects of fire safety or perhaps those with a more general involvement in airline operations. Examples of these groups might include researchers in disciplines such as fire modelling, combustion toxicology, behavioural psychology and aircraft crashworthiness, together with aircraft designers, aircrew members and air travellers. This could imply that there might be a requirement for the model to be interpreted on a number of different levels. These could range from stimulating an interest shown by a lay observer, through to the provision an expert with a specific insight into one particular aspect of safety. Although facilitating this range of usage lay outside the formal

In the broadest sense, it would be capable of communicating the true nature of aircraft fire accidents to those concerned with issues in aircraft fire safety. At an intermediate level, the model could be used to examine safety trends and then help to identify and explore areas suited to more detailed analysis. The ultimate use of the tool would be to investigate specific safety issues and the possible effects of introducing new safety policies in an attempt to deal with them. This would almost certainly require the provision of results in a quantitative form and the documenting of all assumptions made, for predictions to possess adequate credibility. Some examples

of the types of topic that could be addressed in this manner are provided in the next section.

5.2.4 Current Issues in Air Safety

Many issues within the area of aircraft fire safety could potentially be addressed by the work undertaken. Currently, some of the more prominent of these include:-

- Quantifying the effects of recent improvements in cabin and fire safety legislation
- The utility of passenger protective breathing equipment (or “smoke-hoods”)
- Fire safety concerns in future Very Large Aircraft (VLA) designs
- The potential for aircraft fire hardening
- The role of emergency services in aircraft fire accidents
- The potential effectiveness of cabin water spray systems
- Training of aircraft crew to deal with fire emergencies
- Fire hazards of new aircraft materials

5.3 Choice of Modelling Environment

5.3.1 Requirements for the Programming Environment

Before embarking on the implementation of the risk assessment model, it was necessary choose the computer environment to be used. The adoption of an inappropriate simulation application or programming language could seriously handicap the programme development process and reduce the utility of the final product. Given that the model was expected to constitute a reasonably large computer programme and that it had to be constructed within a limited time scale, considerable attention was paid to the choice of computing environment. This involved the evaluation both software and hardware aspects of the various options available for consideration.

Excellent computer facilities were provided at the host institution, comprising of at least four different classes of computer platform, each with their associated operating systems and several types of modelling software. Although this range of choice was obviously welcome, it meant that there were up to a dozen or so potential computing environments available. Each of these possessed its own particular set of relative advantages and disadvantages and none could be excluded from consideration immediately. Thus, it was necessary to determine the key priorities in computing needs and then use these to arrive at the most appropriate choice of modelling environment.

Perhaps the predominant computing requirement was a need for ample processing speed. It was anticipated that some parts of the analysis would require many repetitive calculations to be performed, involving different types of mathematical operation. For example, modelling of a cabin's thermo-toxic

environment might require iterative multiplication to an accuracy of many decimal places. In contrast, the simulation of passenger evacuation could entail simple integer pattern matching procedures, although these would probably need to be undertaken many thousands of times. The rate at which these types of calculations could be performed would determine the speed at which the overall risk-assessment model would operate - the "run-time" performance of the tool.

A related, but separate, consideration was the speed at which a computer can interpret or compile programming instructions and create a runnable model - the "compilation" speed. This would be very important in the development process, as it determines the time delay between the making of a change to a programme's code and execution of the programme in order to test the effect of the modification. However, the compilation time has no effect when actually using the tool.

With some of the computing environments under consideration, there was a significant imbalance between these two aspects of processing speed; in some systems, a model could be modified very quickly, but then would only run at relatively slow speed (or vice versa). Clearly, performance needed to be judged on the basis of both the run-time and compilation speeds achieved.

A second aspect of the computing needs was the necessity for a flexible and convenient development environment. Ideally, it should be possible to construct the risk assessment model in the form of a series of separate modules, with clearly defined interactions occurring between them. This would help to ensure that the programme would be clearly structured, thus aiding the development process and making modification more straightforward. Other features that would make model construction more convenient included the provision of adequate de-bugging, error handling and programme editing facilities. There was a need for adequate functionality at a lower level, in terms of numerical handling, availability of mathematical functions, data structuring capabilities and file reading/writing facilities.

The potentially large size of the risk assessment model was recognised as being a significant issue when assessing computing development needs. For example, the evacuation of Boeing 747 aircraft might involve the simulation of over 600 passengers and crew. Each of these individuals might possess many attributes, such as speed, position, direction, chosen route, incapacitation level, etc., which represents a significant quantity of information. The aircraft's cabin configuration would also be relatively complicated and its geometry obviously needs to be represented somehow. All of this information had to be instantaneously accessible or have to be stored within the computer's memory, or alternatively, looked up from a data storage device as it was needed during the course of a simulation run. The latter option would be certain to slow down execution of the model to an unacceptable degree and thus could not be used. Therefore, there was a requirement for the chosen computing system to possess ample memory capacity, or RAM¹, in order for it to cope with the analysis of larger aircraft types.

A growing number of computer programmes now utilise graphical displays to present their outputs. These may range from being indispensable aids for conveying of complex results, through to being gimmicky or even utterly indecipherable distractions. Consequently, this aspect of the modelling activity would need to be approached with clear foresight and disciplined restraint. However, given the potential

¹ Random Access Memory.

complexity of the evacuation modelling work, the use of some form of animated display could well prove to be essential, even if only for the purpose of programme development. Thus, it was considered that the availability of graphical output capabilities should constitute one of the primary requirements in the choice of modelling environment.

The final factor governing the choice of programming environment was the ability to use the risk assessment model on a range of different computers. For example, some of the languages and simulation software packages were only compatible with one particular type of computer platform. Whilst this might not prove to be critical for the undertaking of the PhD study, a requirement for moving the tool to different platforms might arise in the longer term.

5.3.2 Computer Platform Considerations

Three different classes of computer were available for constructing the risk assessment model. In ascending order of capability were IBM compatible Personal Computers (PCs), UNIX workstations and a mainframe supercomputer. The technical characteristics of the machines available from each of these three families are summarised in Table 5.1.

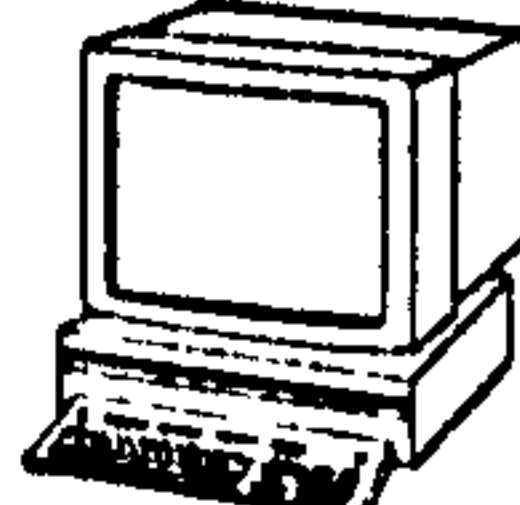
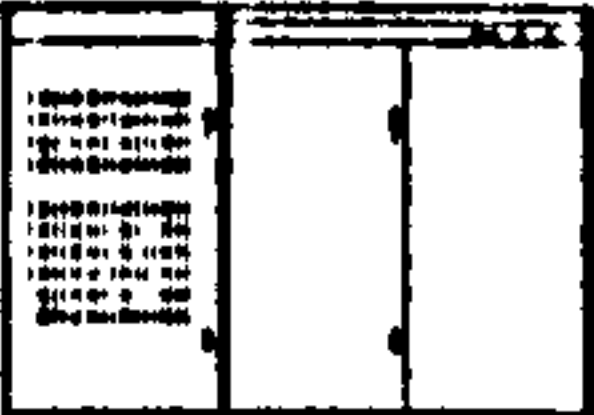
Machine Type	 PC	 PC	 Workstation	 Workstation	 Mainframe
Processor	486DX 66MHz	Pentium 75MHz	Alpha 150MHz	Alpha 175MHz	Cray J (x4) 240MHz
Peformance Index	0.41	0.83	5.2	7.7	10.6
Memory	8Mb	16Mb	64Mb	128Mb	512Mb
Graphics Capability	yes	yes	yes	yes	no

Table 5.1: Computer Platforms Available for Use

It can be seen that there was a large range in the capabilities of the machines on offer. The performance index provides an approximate guide to the relative processing speed for a typical numerical simulation programme. As outlined in the previous section, the installed memory indicates the size of problem that can be handled efficiently.

Although the Cray mainframe computer appeared provide the best overall performance, it was ruled out of contention for the purpose of model development for several reasons. These included the restriction to usage of the Fortran programming language, the inability to run programmes interactively and the lack provision for graphics display facilities. Thus, effectively, the choice of platform lay between PCs and workstations. Both of these machines ran on desktops, possessed a wide-range of software for model development purposes and provided excellent graphics capabilities. Although PCs are in far more widespread use outside of a research

environment, workstations appeared to provide significant advantages in terms of processing speed. The Pentium PCs available possessed adequate run-time performance, but their compilation speed and limited memory capacity might have become marginal as the work progressed.

In consequence, it was decided to perform the development of the programme on a workstation, as this appeared to be by far the best option for meeting the requirements of the research. However, it appreciated that it would be wise to preserve the option of moving the simulation tool across to the rapidly developing PC environment at some stage in the future.

5.3.3 General Purpose Simulation Software

Many types of computer software have been developed specifically to facilitate the construction of simulation and analysis models. Problems encountered in widely differing contexts can sometimes possess a surprisingly similar set of features. In such cases, it may be possible to analyse certain aspects of an issue with the use of a generic computer simulation tool. Examples of frequently encountered simulation software include GPSS, SIMAN, SIMSCRIPT and SLAM (Law and Kelton, 1991). These tools must obviously possess sufficient functionality and flexibility to deal with a considerable range of potential analysis requirements. Features typically provided include:-

- Automated random number generation
- Handling of probability distributions
- Simulation clock facilities
- Decision and control functions
- List or queue handling
- Data collection, analysis and presentation
- Error detection

These built in capabilities can often make model construction more straightforward than with the use of a lower level programming language, such as Basic, Fortran or C. For example, far less (or even no) computer code has to be written, models tend to be automatically structured, changes can be implemented more rapidly and results are easier to interpret. This can result in a more productive work environment, where a greater proportion of efforts are directed at exploring of ideas, rather than struggling directly with a computer's operating system.

The use of general purpose simulation software can also impose some significant disadvantages on the model development process, however. The most significant of these is that simulation software packages are diverse and many in number. This means that knowledge of their proprietary languages are far less widespread than in the case of common programming languages. Also, models tend to possess no stand alone demonstration capability; for a particular machine to run a model, it usually requires the simulation software to have been fully installed on it. High licensing costs tend to inhibit the achievement of wider acceptance in this way. From a technical point of view, general purpose simulation environments are usually less efficient in their use of computing resources (i.e. speed, memory and graphics) than a programming language, providing that the latter is optimally utilised.

The use of a general purpose simulation application was not given prolonged

consideration when planning the modelling activities. The essential reason for this was that no suitable software was installed on any of the computers available for use and no funds available to enable its procurement. However, some time was spent discussing and exploring the two simulation packages in use with other fire safety researchers (Phillips, 1992; BRE, 1995). These were running on computer platforms that were not available for use at the host institution and were called *STELLA* and *NeXTStep Objective C* respectively. In spite of the short time spent on active hands-on testing, it was possible to gain many insights about the relative advantages and disadvantages of these tools. For example, they were very convenient for constructing visually appealing models in a very short time, but ultimately could be restrictive in terms of functionality, the use of computer resources and lack of widespread availability. One particular danger was that too much attention could be paid to graphical presentation aspects and on the provision of a comprehensive user interface, often to the detriment of real modelling activities. Thus, it was possible to create a model that appeared to be very impressive on first impression, but which, in fact, incorporates very few rigorously detailed workings behind the graphical displays.

A series of simple models was constructed in *STELLA* in order to explore its capabilities. This tool was found to be suited primarily for the simulation of continuous systems, represented by building blocks such as “stocks”, “flows” and “converters”. Figure 5.4 shows an example of how a type of continuous flow analogy can be used to determine the type of fire scenario present in aircraft fire accidents. The

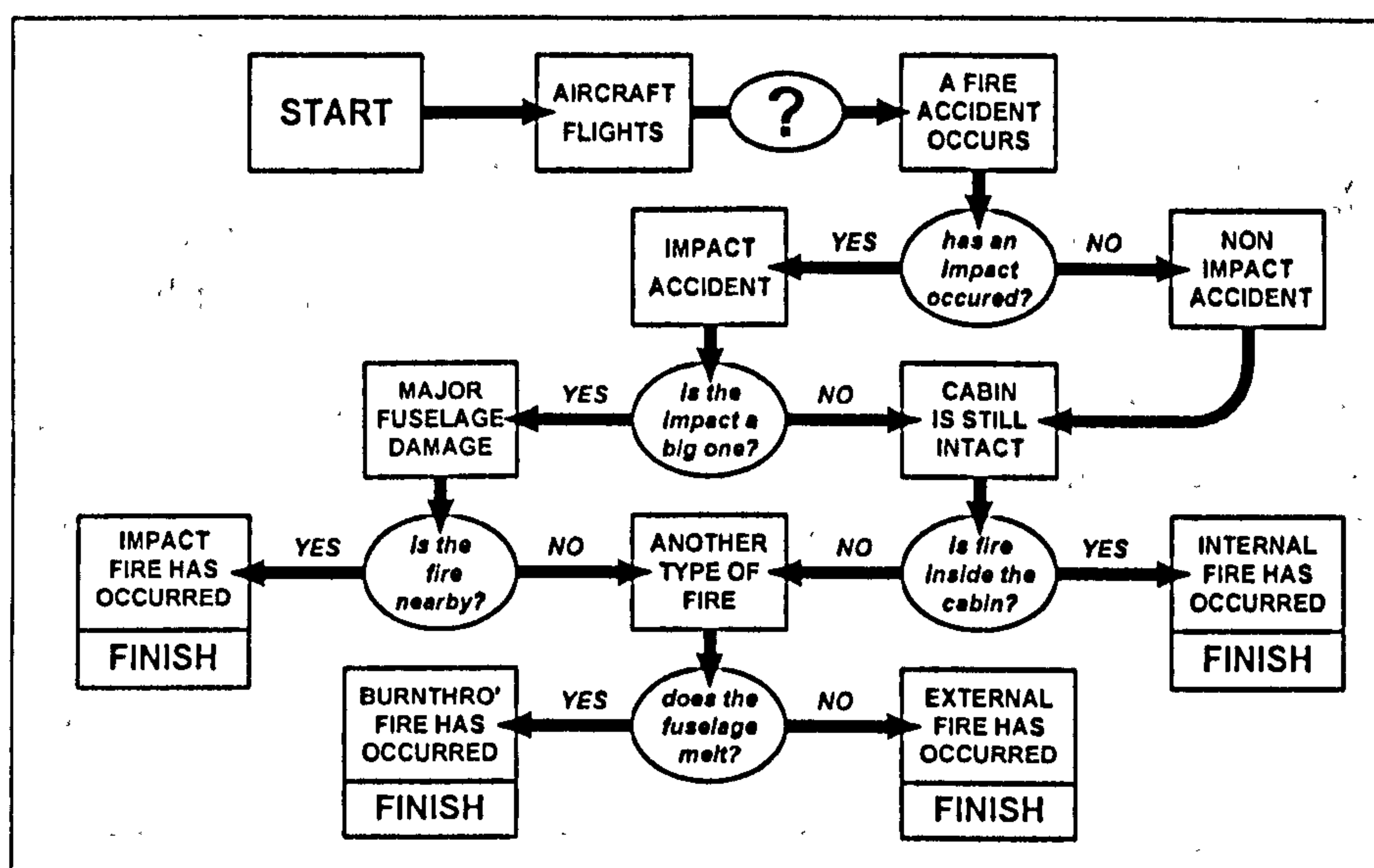


Figure 5.4: Schematic of STELLA Fire Scenario Model

model processes a series of aircraft accidents and, for each of them, traverses the branches of a probability tree and arrives at one of four possible fire scenarios. Ironically, perhaps, this constitutes a discrete decision making process, represented in the form of a continuous system. This serves to illustrate how in-built limitations of “general purpose” simulation software can sometimes be circumvented by using utilising existing capabilities in an innovative way. However, other restrictions in *STELLA* could not be overcome so easily, such as the inability to deal with multi-dimensional arrays and the limited size of problem that it was able to handle.

These types of simulation environments could well have proven useful for development and integration of small scale sub-models or for prototyping the logic of new ideas. However, they were fundamentally unsuited for the task of building of a large multi-module simulation tool.

5.3.4 Programming Languages: Basic, Fortran and C

Many types of computer simulation models are constructed with the use of common computer programming languages, such as Ada, Basic, C, Fortran and Pascal. These languages generally provide a lower level of functionality than general purpose simulation environments, requiring rather more effort to achieve a given task. In the context of the present research, three standard programming languages were available for use, namely Basic, C and Fortran. It would have been possible to construct a satisfactory simulation model with either of these options. However, each language possesses its own particular set of relative advantages and disadvantages; thus it was worthwhile making a careful choice between the three.

Basic is perhaps the most straightforward of the languages to learn and is reasonably flexible, provided that large quantities or complex structures of data do not have to be handled. The time required for programme development is short and widely used extensions to the language enable graphical displays and user-interfaces to be constructed with ease in PC operating systems. Limitations of Basic include its poor numerical efficiency when compared with conventional (i.e. compiled) languages and unavailability on many types of computer platform.

C is becoming the most widely used computer language for general purpose development. It is flexible, efficient and used across almost all platforms. C++ extensions have been created to enable object-oriented code design, which can potentially simplify some types of programming tasks. The primary disadvantages of the language are that graphics and user-interface functions have not been standardised and that it is generally perceived to be difficult or unforgiving for learners.

Historically, Fortran has been the pre-eminent language in scientific and engineering research communities. It is numerically efficient, straightforward to learn and available on almost all types of computers. Before the introduction of the Fortran 90 standard, flexibility was limited and, as with C, establishing graphical displays and constructing user-interfaces can be problematic.

It was decided to adopt the use of the C language when implementing the risk assessment model. The main reasons for this were its flexibility, efficiency and common usage on all types of computer platform. This decision effectively ensured that it would not be possible to create a user-interface for the model in the time available for the study. However, given that this was a comparatively low priority task in the research, the dis-benefit was acceptable. An area of potentially greater concern, however, was ensuring the ability to use animated graphics in the model. This topic is discussed in the next section.

5.3.5 The Need for an Animated Graphics Display

Graphical displays are now frequently encountered in many types of computer simulation modelling (Law and Kelton, 1991). Although these facilities can sometimes be abused, it has been seen how they can be essential when attempting to analyse complex processes. The use of graphics enables large amounts of information to be presented and continuously updated on-screen in a quickly readable format.

Although this can obviously be of great benefit to a programme developer, potentially, it can also aid presentation of work to unacquainted observers and convey dynamic features in a models behaviour.

The type of work being undertaken in the current research suggested that the use of graphical displays would be highly desirable. The envisaged tool would comprise a number of complex sub-models, between which many sorts of interaction could occur. For example, the modelling of passenger egress was required to be capable of representing the movements of hundreds of individuals. Possessing the ability to communicate this aspect of the analysis to psychologists who were currently performing experimental aircraft evacuation trials was likely to be of great benefit to both parties.

However, incorporating graphical capabilities into the model could also have introduced some significant problems. The large computational overheads usually demanded by such features held the potential to slow down the operation of the programme drastically. There was thus a requirement for the ability to switch-off displays when simulating large numbers of accidents.

In terms of programming effort, the creation of displays would also demand significant time. Finally, the graphics routines available for use with C on a workstation would not be portable to other computer platforms.

It was decided that the apparent benefits of using graphical displays for the model would outweigh these potential drawbacks. Thus, it was ensured that adequate graphics facilities were provided in the chosen programming environment. The importance of this decision would come to be underlined when model development was started in earnest.

5.4 Strategy for Model Development

5.4.1 Structuring of the Programme

The range of accident features being represented in the simulation model required careful structuring in order to ensure that programme development remained manageable. This practice would also help to facilitate experimentation and the use of appropriate styles of programming in different parts of the model. A conventional approach taken to this aspect of the work, with key variables, processes and interactions being established in that order. Each of these stages in the conceptual design of the programme will now be examined.

An initial set of simulation variables was straightforward to isolate. The preliminary accident database contained more than sufficient information for a basic description of accident scenarios to be defined. The chosen parameters were then gathered into logical groups (or structures); examples of these included accident scenario features, fire details, aircraft cabin configuration and passenger attributes. In the early stages of programme development, it was not critical what variables were actually contained within each these structures. The point of the exercise was to establish a series of logical groupings which could then be extended, modified, re-arranged or deleted as needed in the development of the work.

The identification of the main processes that required representation within the simulation analysis has been described in Chapter 3. The model would be formulated

to generate aircraft accident scenarios and then determine their outcome in terms of occupant fatalities. The latter can arise from two causes; i.e. from trauma injuries sustained in a crash and from the effects of fire ingress before all occupants are able to evacuate to safety. Consequently, the simulation procedure could be divided into five key processes. These are as follows:-

1. Create an accident scenario for the simulation
2. Determine the effects of any crash impact
3. Model development of the aircraft fire
4. Determine effects of fire ingress into the passenger cabin
5. Simulate the escape of survivors from the aircraft

The basic programme structure used to undertake these procedures is illustrated in Figure 5.5. It can be seen that each of the tasks was assigned to a dedicated module.

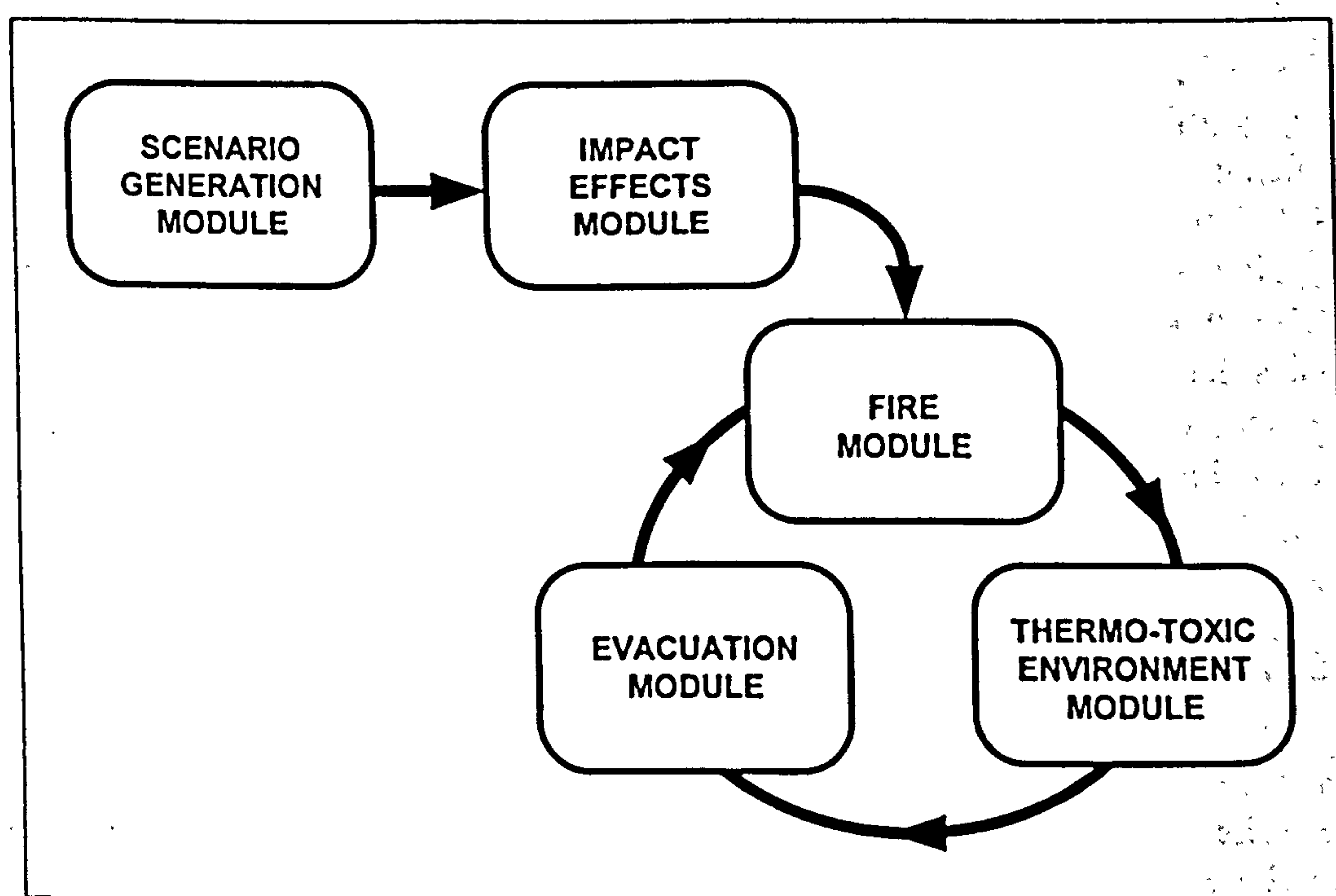


Figure 5.5: Structure of the Simulation Programme

The first two of these, the Scenario Generation and Impact Effects modules are only utilised once per accident simulation. This is because, effectively, they only serve to define starting conditions for the event being analysed and these are not modified by the ensuing calculations. In contrast, the Fire, cabin Thermo-Toxic Environment and occupant Evacuation modules depict a development of events. As a result, these three sections of the programme operate in an iterative manner, regulated by a simulation clock. Thus, these processes can be envisaged as being advanced in a cyclical manner, as indicated by the circular arrows in the figure.

A more detailed version of the above diagram is provided at the end of the thesis in Figure 10.1 (page 240). There it can be seen that a considerable amount of development would be undertaken in each of the five programme modules. A diverse range of techniques was also utilised across the various parts of the programme, ranging from the use of probability trees, tabular look-up, thermal radiation analogy, potential flow theory, finite difference methods and discrete event simulation.

The representation of interactions occurring between different aspects of aircraft accidents was a fundamental requirement for the research. However, such functionality was established progressively as the model development work proceeded. This then enabled the functioning of modules to be verified in isolation and then again as each linkage was subsequently added. As a result, the only preparation required for incorporating interactions between modules was to ensure that the appropriate variables could be accessed by each part of the programme, where required.

5.4.2 Development in the Longer Term

From very simplistic beginnings, the model eventually evolved into a complex and comparatively large computer programme. It was therefore essential to maintain programming discipline and verify that the various parts of the model functioned correctly at all stages. The use of a structured approach to programming helped greatly in the achievement of these tasks. For example, it was usually only necessary to make changes in one or two small sections of C code at any time. This enabled errors to be isolated quickly and allowed for incremental compilation of the programme, both of which resulted in significant reductions in the time required for model development. In addition, this style of programming enabled different variants of a single module to be developed. As a result, the effects of updates or alternative versions could be directly ascertained simply by re-inserting the original code.

However, division of simulation processes into separate programme modules could potentially have resulted in some difficulties. There was a continual danger that excessive effort could be spent in developing one area of the model and, as a result, the overall simulation might become unbalanced. Specifically, in the middle phase of the work, care had to be taken not to divert too much attention to the refinement of the passenger evacuation model. This was perhaps a consequence of the fact that the depiction of evacuation was the most visually appealing and quickly comprehended aspect of the model when seen by casual observers. This possibility was avoided by undertaking the programming progressively, in three separate rounds of development. In each of the rounds, all parts of the model were brought up to an approximately equivalent state of advancement, thus ensuring that no modules became "left behind".

Finally, one extremely important aspect of the development activities was the necessity to ensure that back-up copies of the programme were made at regular intervals. A total of 18 different versions of the model was retained, forming a precise record of progress made at each stage of the work.

112

1. The first part of the document is a list of the names of the persons who were present at the meeting.

2. The second part of the document is a list of the names of the persons who were absent from the meeting.

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Chapter 6: Accident Scenario Generation and Modelling of Impact Effects

6.1 Analysis of Accident Scenarios

6.1.1 Dealing with the Diversity of Aircraft Fire Accidents

It had been found from the study of historical records that past aircraft fire accidents could potentially involve many different types of scenario. These could range from a catastrophic night time crash, occurring a large distance from an airport, though to an uncontained engine failure on takeoff, or, say, an in-flight toilet fire. Usually, many of the features present in a particular incident could be influential in determining the nature of its outcome. Significant contributory factors may be encountered in impact, fire and evacuation aspects of an accident. Typically, these different features will interact and combine in their effects to exacerbate the fire survival problems faced by potential survivors.

The inherent complexity and variability of aircraft fire accidents meant that it would be impossible to define a small but representative sample of “typical” events to base a risk analysis on. Thus, it was concluded that safety issues could only be assessed adequately within the context of real accident scenarios. In computational terms, these scenarios define the starting conditions, internal parameters and external constraints necessary for each accident simulation. However, more generally, this information could be regarded as providing the story lines of possible accidents that might be expected to occur in the near future.

The task of creating the representative details of accidents is undertaken by the *scenario generator* module of the model. The approach taken was to produce the details of incidents stochastically in the form of a Total Accident Scenario. The latter was defined in Chapter 3 as the “*combination of all accident parameters and circumstances that significantly influence the survival prospects of accident victims*”. This scenario effectively characterises the situation that exists immediately after an accident has occurred and sets in place the processes that determine the eventual outcome of the incident. The creation of suitable accident scenarios for the simulation model to process thus forms the very basis of the risk analysis.

The key to constructing a satisfactory scenario generator was to identify, classify, and model the parameters that fundamentally influence survival prospects in aircraft accidents. Obviously, it was only possible to consider accident features that were readily quantifiable and for which adequate historical data was actually obtainable. Many types of information fell into this category and so it was found to be advantageous to sort the gathered data into five different areas to facilitate the undertaking of a methodical analysis. As outlined in Chapter 4, these were:-

1. General Scenario Information
2. The Effects Resulting from any Impact
3. Fire Growth and Fire Fighting Intervention
4. The Cabin Thermo-toxic Environment
5. Evacuation Details

Although the grouping of information into these categories proved to be convenient for gathering, recording and collating historical data, it was not necessarily the best starting point for generating accident scenarios. This was because, in many incidents, significant areas of overlap and interdependency could possibly have existed between the five areas of information. For example, might the type of terrain present at an accident site have influenced the spread of fire?, or did the existence of fuselage impact damage hasten deterioration in the cabin thermo-toxic environment?

Consequently, it was apparent that treating separate categories of information independently from each other did not always accurately reflect the complex nature of real accidents. In general, the outcome of an incident is largely determined by the events that result when crash, fire and evacuation features happen to interact. (See Figure 6.1)

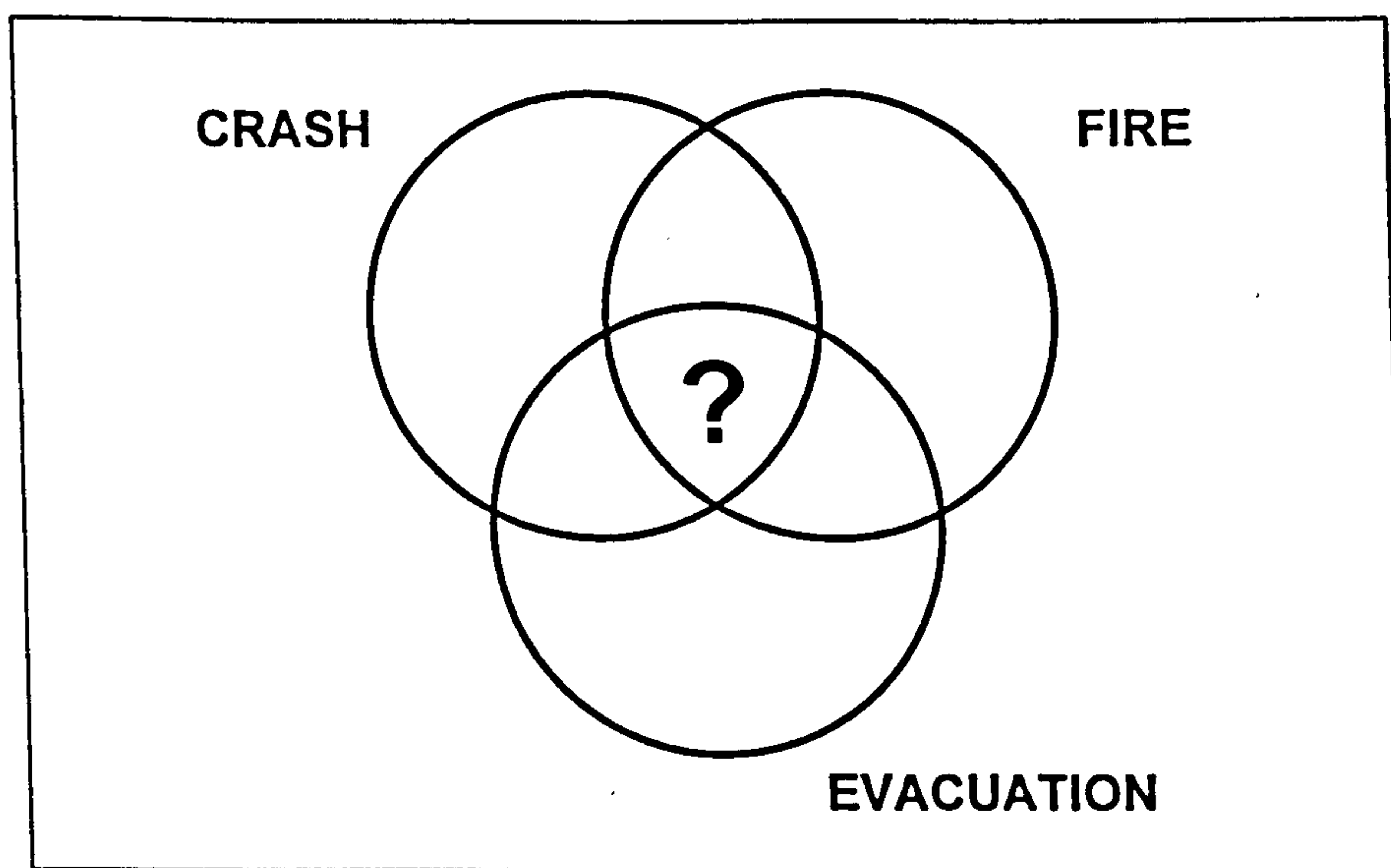


Figure 6.1: The Complexity of Aircraft Accident Scenarios

The implication of this was that some parameters of accident scenarios could not be decided independently of each other. A major task in the formulation of the scenario generator was to decide in what order the details of an incident should be constructed and to incorporate the more significant relationships that were present in the historical data. Obviously, it was not intended to reproduce all correlations precisely, because the only way to guarantee this would have been to store all details of the 217 accidents studied and then retrieve a sequence of these real scenarios in a random order. What was really needed was a method of generating new accident scenarios that were statistically consistent with past events in all important aspects and yet which varied stochastically in content.

The most obvious way of meeting this requirement was to base the analysis on a "probability event tree" approach. This would serve to structure the information obtained from past accidents in a logical manner and ensure that key statistical relationships were preserved in the scenarios provided. Decision points in event paths are resolved by comparing values of randomly generated numbers with fixed probability thresholds. This obviously necessitates the provision of a uniform random (or "pseudorandom") number generator, but this is straightforward to achieve on modern computers (Kalos and Whitlock, 1986). The primary drawback of the method is the fact that calibration data becomes progressively more sparse as smaller branches

of the tree are reached. This meant that, with 217 cases to work with, only three or four levels could be included in the tree before data classifications became statistically insignificant. However, as discussed in Chapter 4, the consequences of this can be minimised by ensuring that events are processed in order of their importance. Regardless of this, no concise or comparably efficient alternative to event tree analysis appeared to exist for dealing with the type of conditional probability analysis that was being undertaken¹. Thus the method formed the basis for deciding the most fundamental features of accident scenarios.

The process of determining more detailed accident scenario parameters was conceptually more straightforward to accomplish. Most of these could be defined independently of each other, usually as functions of fundamental scenario parameters (e.g. degree of cabin disruption present was related to the overall severity of an impact). It was found that some kinds of variables could be treated as being totally independent of all other accident features (e.g. wind conditions and time of day at which the accident occurred). Values for these parameters could be obtained simply by sampling the historical frequency distribution.

To recap, the procedure used in the construction of the accident scenario generator involved the following steps:-

1. Identify which scenario features were most significant in deciding the outcome of an incident, in terms of fire survival.
2. Determine where statistical or logical relationships existed in the occurrences of these “primary” features and quantify the former.
3. Construct a probabilistic “event tree” incorporating these relationships; this could then be used to generate a series of accident scenarios whose primary features would be statistically representative of those occurring in past incidents.
4. Determine “secondary” scenario features independently of each other, based on their historical probabilities and the primary scenario features present.

These activities will be examined in greater detail in subsequent sections of this chapter.

6.1.2 Structuring of the Scenario Generation Module

Conceptually, the scenario module appeared to be relatively straightforward to implement. It was simply required to calculate the values of a set of parameters that together completely define an accident scenario. However, if all of the processes necessary to achieve this were undertaken successively in a linear fashion, a very long and unmanageable piece of code would have resulted. This eventuality was avoided by dividing and sorting the various scenario generation tasks into a series of discrete routines, each of which can be called upon in sequence if or when needed. These then help to ensure that the code possesses a clear and logical structure and provide significant improvements in computational efficiency in some areas.

¹ Some advanced statistical methods for multi-variate data analysis were examined briefly, but were found to be unsuited to the task in hand. These included Analysis-of-Variance (ANOVA) procedures, together with Cluster and Probit Analysis techniques (Norusis, 1993).

As will be seen, the scenario generation module would only come to include three routines that dealt with general accident parameters. The remainder of the initialisation tasks involve more specific types of information, such as calculation of cabin airflow, details of cabin disruption or evacuee characteristics. The routines that handled these parameters were not grouped together within the scenario generator because they are too involved and influence only one of the main simulation modules. Therefore, they have been left as separate components, albeit, for reasons of programming convenience, loosely associated with the main fire, TTE or evacuation simulation module, as applicable. These specialised initialisation routines are described in the following two chapters, in the context of their respective simulation modules, rather than being covered here.

Given that the primary features of an accident scenario were linked by their statistical dependency, they needed to be determined with a single pass through a probability event tree. This process was self-contained and different in nature to the remainder of the calculations being performed in the scenario generation module. Thus it was logical to place this first stage of the scenario analysis in its own dedicated section of code. This part of the model was named "SCENARIO_GEN" and it constituted the first of three components that together comprise the scenario generation module.

The parameters that are set by the event tree process inside SCENARIO_GEN describe whether or not there was a significant impact; the overall magnitude of any such impact; the type of fire present and the phase of flight in which the incident occurred. In addition, the type of aircraft involved and its cabin configuration are chosen independently of the event tree. Although these parameters are few in number, they serve to define the fundamental characteristics of the incident being simulated and form the basis for the calculation many of the more detailed aspects of the accident scenario.

In the early phases of model development, the effects of crash damage were represented by very simple probabilistic functions. The overall magnitude of the impact was chosen from a uniform probability distribution and was defined on an arbitrary scale of 0.0 - 1.0. Values for specific types of impact damage, such as cabin disruption or occupant injuries, were simply set to equal the overall magnitude of the impact, but with the addition of a small (plus or minus) component of random deviation. These values were truncated to remain within the allowable range of 0.0 - 1.0, where necessary. Although this procedure was admittedly rather arbitrary, it served quite adequately to represent the loosely coupled variations in different aspects of impact damage encountered in past accidents. Descriptively, severe impacts *tend* to produce catastrophic consequences, whereas more modest crashes *tend* to lead to less serious effects. However, significant deviations from these apparent norms can frequently occur.

Subsequently, it was found that the task of setting values for impact damage, disruption and injuries became too involved to perform conveniently inside SCENARIO_GEN. Furthermore, these functions did not need to be evaluated in the fourteen percent of incidents where no significant impact would be found to have occurred. Therefore, it was decided to assign the detailed calculation of impact effects to a second component of the scenario generator. This section of the module was called "IMPACT" and would only be called upon in the event of a significant impact occurring. Parameters that are set here include fuselage structural damage, levels of

cabin disruption, exit availability and occupant injury levels. Strong dependencies exist between many of these effects e.g. exit availability is determined by the degree of fuselage structural damage present.

The third and final component of the scenario generation module has been provisionally named “MISC_EFFECTS”. This deals with other miscellaneous aspects of the incident under consideration. At the time of writing, these included the determination of wind conditions, distance of accident site from the airport, type of terrain present, and the time of day at which the accident occurred. The values of all these variables are generated independently of each other, although some are derived from primary scenario parameters, such as the type of fire present or the phase of flight in which the accident occurred.

The structure of the scenario generation module is illustrated schematically in Figure 6.2. Note how primary accident parameters are determined first with the use of the event tree inside SCENARIO_GEN. This information is then fed (if required) into IMPACT in order to obtain more detailed information about the likely effects of any

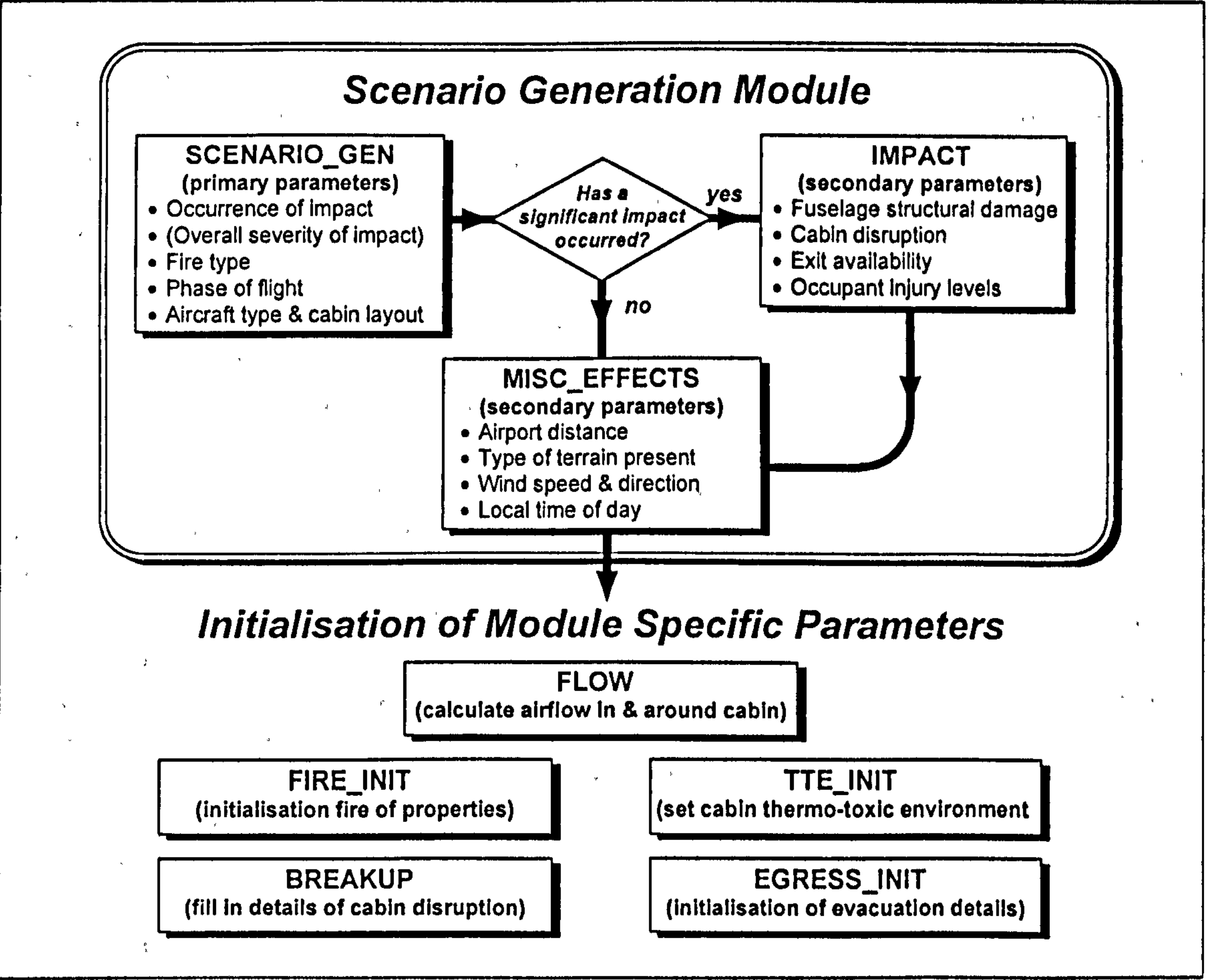


Figure 6.2: Creation of Accident Scenarios

crash impact. Then, other more miscellaneous features are generated by MISC_EFFECTS. Many of these are calculated by taking into account the values of primary accident parameters that have been established previously.

It can also be seen that five other initialisation routines exist outside of the main scenario generator module. These components of the model fill in details of an accident scenario in specific areas, such as cabin airflow, fire properties, the cabin

thermo-toxic environment, cabin impact disruption and data necessary for the simulation of occupant evacuation.

6.1.3 Treatment of Historical Trends in Airliner Fire Safety

Enormous progress has been made in the design and operation of commercial aircraft over the last fifty years. For example, since the introduction into service of the first turboprop airliners in 1953, piston engines, gasoline fuels and radio direction finding aids have all but been displaced in mainstream air transport operations. These have been replaced by turbofan and turboprop powerplants, kerosene fuels and automated flight management systems. Commensurate with these technological advances, much progress has also been made in the areas of crew training, aircraft maintenance, operational procedures and ground-based safety infrastructure.

It is perhaps reasonable to expect that many of these changes will have helped to produce significant improvements in the overall safety of airline operations. This *was* in fact the case, up until the second half of the 1960's. Unfortunately, since then, serious airline accident¹ rates have wavered around the region of one to two incidents per million departures and, in spite of the industry's best endeavours, are showing no consistent tendency to decrease any further (Murray, 1995). Establishing reasons for why this situation has arisen is far from straightforward and the task falls beyond the scope of this thesis. What is more certain, however, is that air travel will probably continue to experience a significant growth in demand in coming years. History shows that the number of aircraft in commercial revenue service has increased at a remarkably uniform rate of about 350 per year over the last three decades. Airline departures flown world-wide have also exhibited a corresponding growth of approximately 400,000 movements per annum in the same period (Murray, 1995).

It may be reasonable to postulate that accident rates experienced over the last thirty years will continue unabated into the future. If this is indeed the case, then growth in the popularity of air travel will ensure that serious aircraft accidents are likely to occur increasingly frequently in coming years. Also, the larger passenger capacities of new airliner designs currently entering service will also tend to produce greater losses of life when they are involved in future incidents. Given that public perception of air safety is probably linked to the frequency at which accidents are reported world-wide, rather than to risk exposure for a given flight, then the air transport industry will clearly have to deal with a growing public relations problem.

These historical trends are of great significance when attempting to analyse future aircraft accidents. Although there can be no guarantee that past events will provide an accurate indication of what should be expected in the future, they constitute a useful starting point from which to work. However, the extremely low occurrence rate of aircraft accidents in the past makes it difficult to predict the frequency at which incidents should be expected to occur in the future. In addition, as aircraft technology, aircrew training programmes and operational procedures advance, there is potential for the character of accidents to change significantly with the passage of time. This then leads us to question whether or not events occurring several decades ago will still be generally representative of today's or tomorrow's incidents.

¹ Where a serious accident is taken to imply hull-loss and excludes sabotage, military action and former Soviet Union aircraft types.

If they are not, then is it feasible to quantify and take account of the differences that have arisen in the intervening period?

As will be seen, it is very difficult to provide definite answers to these questions. Given the complex, random and infrequent nature of aircraft accidents, clear indications cannot be derived from historical records alone. In order to obtain a greater insight into these matters, we must also rely on postulation, reasoning and scientific experimentation. It is precisely the undertaking of these kind of activities that the analysis model was intended to support.

Thus, the main challenges of predicting future trends in air safety are essentially twofold. The first issue lies with establishing at what frequency accidents will be expected to arise in the future. Secondly, it is necessary to ascertain the likely nature and resulting lethality of these incidents when they occur. Thus, we are concerned with estimating both the expected *quantity* and *quality* of future accident scenarios. The remainder of this section examines how these difficulties were dealt with during the formulation of the scenario generation module.

The prediction of future aircraft accident rates from past events has always been problematic because of the sparse and erratic quality of the data available for analysis. In the present context, we are concerned primarily with survivable or partially survivable accidents involving a significant fire risk to the occupants of a turbine engined aircraft. On average, these incidents have occurred at a rate of around 6.0 per annum, as measured over the last three decades. This compares with a mean annual *hull loss*¹ rate of about 15 aircraft per year in all categories of accident during the same period. It should therefore be noted that the fire accidents that have been studied form only a comparatively modest subset of all commercial aircraft losses. Obviously, therefore, the findings obtained here cannot necessarily be taken to apply to other types of accident or airline incidents in general.

With a sample size of around 200 fire incidents available for analysis, it should be reasonable to expect that some form of trend in the number of incidents occurring each year should have begun to become apparent. However, this is not the case, as the annual accident rate has fluctuated wildly since 1958, as indicated in Figure 6.3. It can be seen that the mean rate of 6.0 events per year cited previously is only of limited value when it is associated with a standard deviation of 3.4. The value of the latter corresponds almost exactly to that of a uniformly random distribution.

Some other summary statistics about the accidents show rather more consistency. On average, each of the incidents analysed has involved 91 people onboard the aircraft. Although this figure has increased slightly in recent years, rather surprisingly, perhaps, it has not changed substantially through the decades. This may be because, up until comparatively recently, the introduction of new widebody designs has been balanced by a proliferation of feeder-airline and commuter aircraft types. The mean seating capacity of aircraft involved in the accidents was found to be slightly under 130, which implies an average passenger load factor in the region of 65 to 70 percent.

Researchers have made use of a number of analysis methods in an attempt to identify long term trends in the number of aircraft accidents occurring each year. These techniques usually involve smoothing or coalescing data in order to reduce the

¹ Taken here to mean the complete destruction of an aircraft in an accident, or the occurrence of damage that is too extensive or not economically viable to repair.

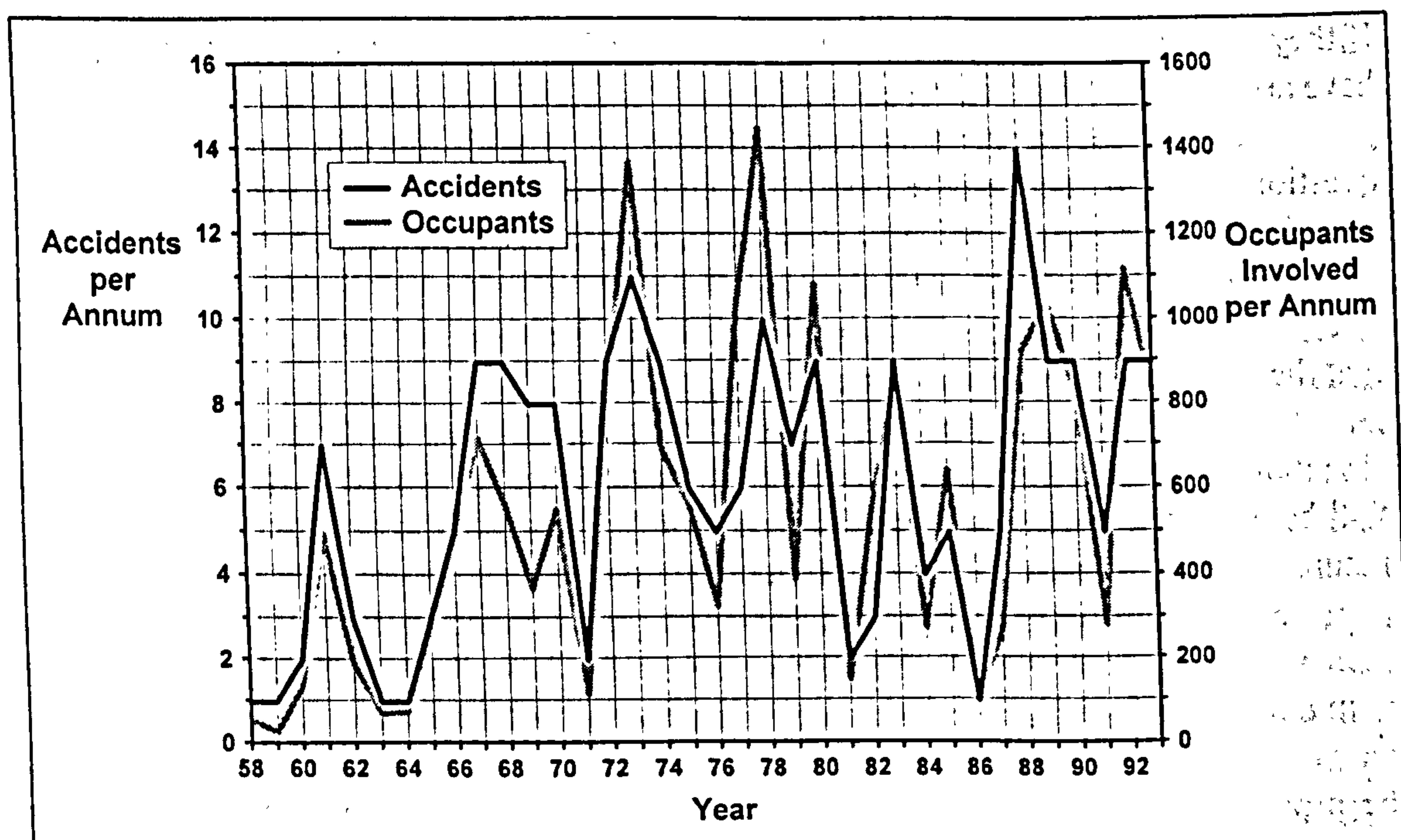


Figure 6.3: Annual Frequency of Airliner Fire Accidents

influence of short term fluctuations. Given that the statistical variance found in accident occurrence rates are effectively eliminated, it was not intended to use the results of any such analysis *directly* in the scenario generator. Any long term trends revealed would need to be modified by reincorporating the random year on year fluctuations that have been so apparent in the past. Thus, the aim is not to predict how many incidents will actually occur in the future, but rather to determine changes in the likelihood of their occurrence. In the context of aircraft accidents, the most commonly employed trend analysis techniques are probably moving average methods and analytical curve fitting; both of these were used on the fire accident data gathered.

It was found that the five year moving average for the annual accident frequencies still showed wide variations from year to year and no clear trend was revealed. In order to obtain a reasonably consistent curve, it was necessary to resort to aggregating data over a nine year interval. Consequently, because of the necessity for a four year leading sample, this technique could not be used to produce any meaningful results beyond 1989. Thus, it was thus judged to be unsatisfactory for the purpose of predicting future (or even current) trends.

The use of curve fitting techniques to reveal trends in the annual accident occurrence rates appeared to offer more potential. Figure 6.4 illustrates the results of applying three different types of "least squares" curve fit to the annual rates. The quadratic approximation appears to offer the best fit to the data, at least in terms of overall statistical deviation. This curve suggests that annual accident rates have peaked in the mid eighties and are now declining steadily. However, it should be noted that correspondence with the last five data points is poor and thus the quadratic fit is in fact rather misleading over the last decade.

The linear and exponential curves indicate a very different trend and suggest that annual accident rates might be increasing steadily, or even rapidly becoming worse. Although their level of fit is less satisfactory overall than with the quadratic curve, they are both more representative in the region of the final 5-10 years of data. Ironically, however, it is apparent that simply assuming that the mean rate of 6.0

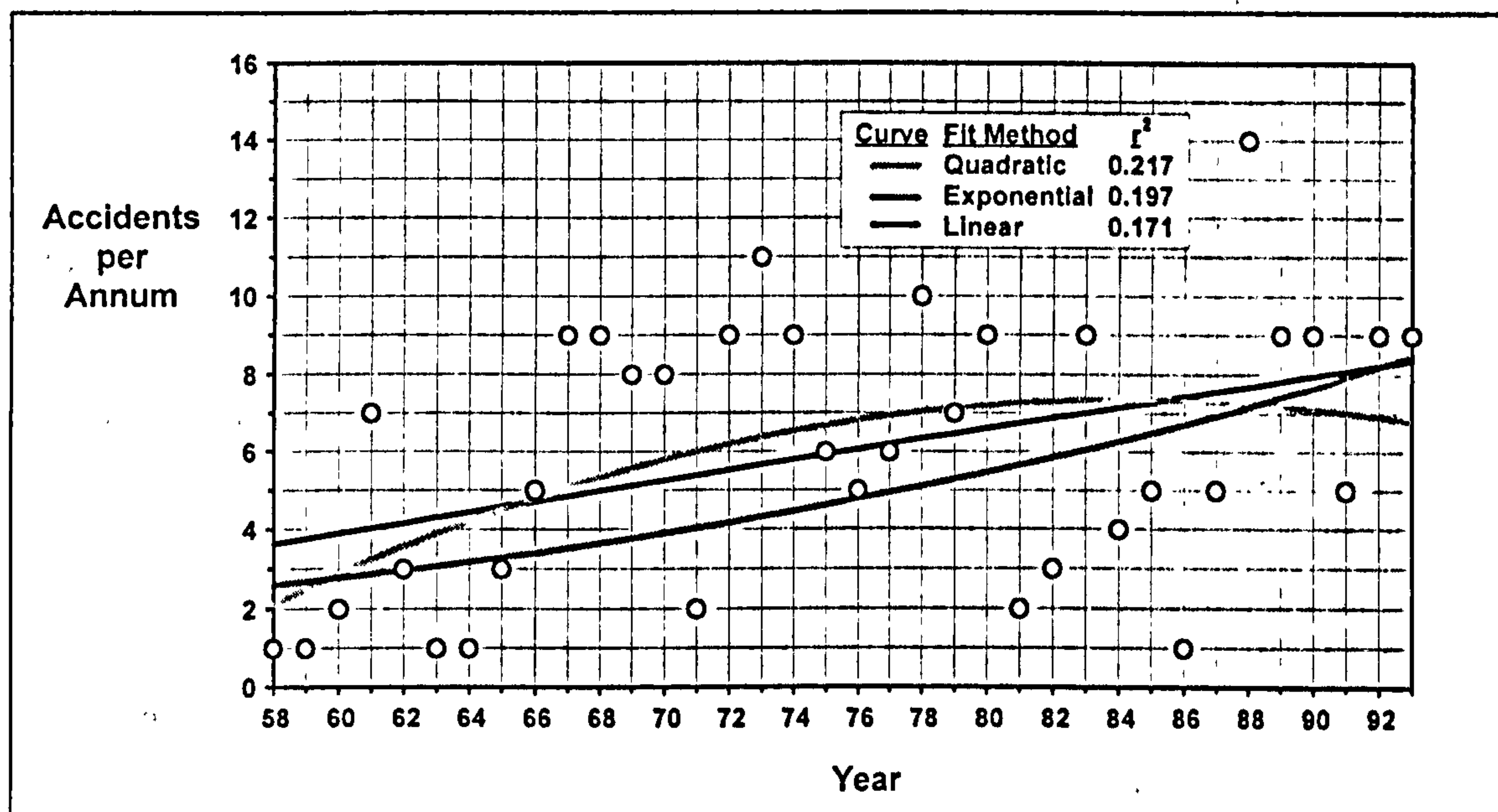


Figure 6.4: Annual Frequency Trends in Airliner Fire Accidents

incidents per year applied during this period would probably prove just as satisfactory as utilising any of the three analytically derived curves.

In the end, none of the curve fit methods investigated were judged to be satisfactory for the purpose of representing overall trends in accident occurrence rates. It can be seen from the three examples given that seemingly contradictory results can easily be obtained when applying such techniques to data that is essentially random. Theoretically, choices of sample intervals, data grouping, numerical smoothing and curve fitting methods can be manipulated to yield almost any trend desired. Clearly, the performing a thorough investigation into frequency trends in aircraft fire accidents demanded much more time than was available in the current study.

These findings held significant implications for the construction of the scenario generation module. Realistically, over the last two decades, no real trend is apparent in the annual occurrence rates of serious aircraft fire accidents. These events appear to occur randomly between one and fourteen times a year, at an average rate of six events per annum. This pattern has been maintained since the first widebody aircraft were introduced into service in the late 1960's.

It was felt that simulating fire accidents on a year by year basis, assuming a mean occurrence rate of 6.0 incidents per annum would be unsatisfactory. This was because such an approach would not be consistent with the highly erratic variations that exist in the occurrence rates of real accidents. Alternatively, incorporating the probabilistic nature of these events within the model in its formative stages would create substantial overheads. All parameters would need to be analysed in terms of probability intervals or expected frequency distributions. Obviously this would add significantly to the internal complexity of the model and severely restrict the scope of the work that could be undertaken in the time available.

The solution eventually adopted was to base the analysis of accidents on levels of risk exposure present per *individual* incident. Thus, issues would be considered in terms of mean loss of life per accident, rather than, say, loss of life per year or decade. This avoids having to deal explicitly with the difficult task of predicting future trends in accident occurrence rates. If necessary, the implications of these "per accident" risk

levels can be quantified simply by factoring them by an appropriate estimate of future accident frequencies. Also, the processing of continuous frequency distributions analytically, in order to calculate the cumulative effects of different types of accident scenario, can be avoided. Instead, continuous probability distributions can be obtained from the simulation of discrete events by Monte Carlo methods. As explained in Chapter 5, this technique involved processing results obtained from many simulation runs to generate probability distributions for various types of outcome.

The strategy for dealing with historical trends in the scenario generation can be summarised as follows:-

1. The scenario generation module was required to produce a series of aircraft accident scenarios.
2. The details of these incidents would vary randomly, but when summed, they still be statistically consistent with past (and probably future) events.
3. The other components of the risk assessment model would then simulate the outcome of these accident scenarios and allow safety implications to be studied.
4. Levels of risk exposure for all types of accident scenario can be obtained systematically by undertaking many accident simulations and making use of Monte Carlo analysis techniques.
5. Predictions of actual casualty levels in fire accidents may potentially be obtained by multiplying risk levels found to be present in individual incidents by estimates of their future rate of occurrence.

As well as dealing with the issue of predicting future accident rates, it was also necessary to consider whether or not the nature of aircraft fire accidents has changed with time. In spite of the vast changes that have occurred in airline operations over the last forty years, the most fundamental aspects of aircraft fire accidents appear to have altered very little. Airliners still operate at comparable speeds, contain large quantities of fuel in relatively fragile wings and carry many passengers in aluminium fuselages. Thus, at first sight, we might expect the events that occur when airliners crash and burn to have remained relatively consistent in past decades.

However, during this period, many new regulations have been introduced relating to the areas fire and cabin safety. These include changes in aircraft fuels, improved fire detection and suppression equipment, more severe crashworthiness requirements, better provision for passenger evacuation and increased crew training. It has been argued that the cumulative effects of these changes have significantly increased passenger survival prospects in aircraft accidents (CAA, 1995). If this assertion is correct, then it would be necessary to take account of the effects of these safety improvements when generating and analysing aircraft accident scenarios.

The most obvious method of quantifying the survivability of past accidents was to ascertain what proportion of those involved in each incident were seriously injured or killed. Because we are particularly concerned with fire safety aspects of these events, an attempt was also made to establish how many fatalities result from the effects of fire, as opposed to the effects of impact or other causes.

The results of this activity were discussed in Chapter 3; briefly, it was found that the proportions of casualties caused by the effects of fire and impact were almost exactly equal and that total fatalities averaged 44 percent of those onboard. Figure 6.5 shows a year by year breakdown of these figures since the occurrence of the first turbine-

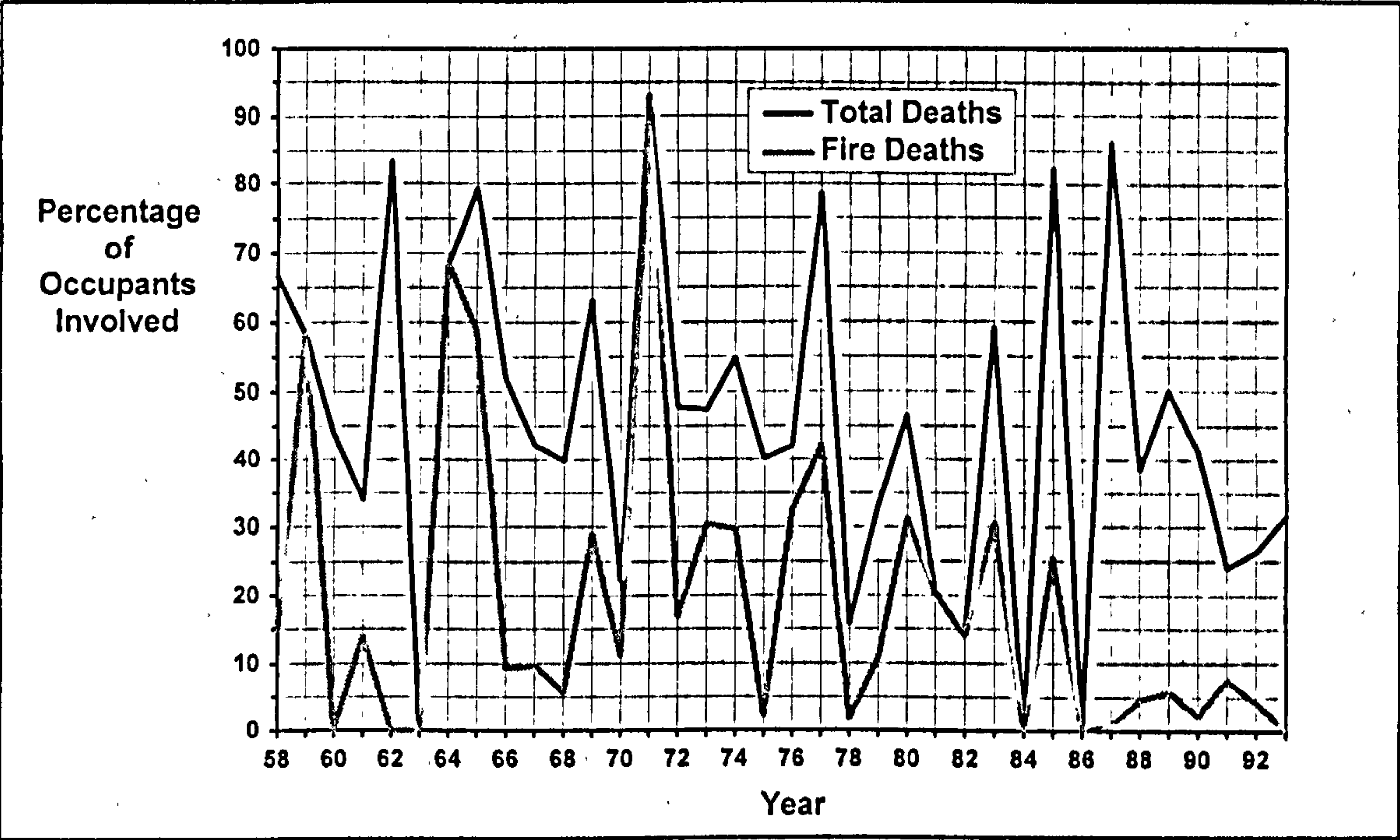


Figure 6.5: Historical Fatality Rates in Airliner Fire Accidents

engined airliner accidents in 1958. The first point to note is the erratic nature of the occupant fatality rates mirror those of the accident occurrence rates discussed previously. In spite of this, it can be seen that, up until 1986, fire deaths accounted for approximately half of all recorded fatalities. Since then, however, the proportion of fatalities that have succumbed to the effects of fire appears to have dropped dramatically to a level of around one in ten. At the time of writing, this finding had not been published by the author, or as far as can be ascertained, any other safety researcher world-wide.

The reasons for this dramatic change are not immediately obvious. Improvements in fire and cabin safety legislation have been introduced progressively throughout the last three decades (Hill and Blake, 1996). Thus it would be reasonable to expect a gradual reduction in fire fatality rates during this interval, rather than the occurrence of any step change. In addition, it should be noted that many regulations apply only to new aircraft types, certificated after a rule change takes effects, or only have to be implemented when an aircraft undergoes major servicing. This lead to a significant time delay before changes are effected in a significant proportion of the world's airliner fleet.

Another relevant factor might be the increasing awareness throughout the airline industry of the threat posed by fire in aircraft accidents. This might especially be the case since the widely publicised incident involving a Boeing 737 at Manchester Airport in 1985, where 55 of the aircraft's occupants were lost due to the effects of fire (King, 1989). However, it might be argued that an increased safety awareness would serve to reduce the likelihood of accidents occurring, rather than altering their lethality significantly.

It is also apparent that, in recent years, the proportion of airline accidents occurring in the Asia-Pacific region and former Eastern Bloc countries has increased rapidly. At present, these incidents tend not to be reported as thoroughly as those occurring in the USA or Western Europe. In effect, this reduces the number of accidents for which publicly available information actually makes a distinction between deaths due to fire and deaths due to impact. Thus, figures for total occupants fatalities are almost always published, but many recent occurrences of fire deaths may be going unreported.

For the purpose of generating accident scenarios, it was decided that no account would be taken of the apparent reduction in fire casualty rates in recent years. In part, the change might be spurious or perhaps attributable to factors that have not yet been identified. However, until the shift in fatality statistics from 1986 onwards could be fully explained, it was considered to be difficult to justify discarding the previous 28 years of data. The scenario generation module was therefore calibrated to reflect fatality rates that have occurred in all the accidents studied.

Similarly, quantifying and taking account the effects of fire safety improvements was judged to be unfeasible on the basis of past fatality rates alone. No obvious relationship appears to exist between the reduction in accident lethality and the years in which changes have taken effect. The inadequate quality of the data available meant that it would only begin to be practical to explore the significance of this issue once the analysis model was in place.

The data output by the scenario generation module may therefore be slightly pessimistic in that it does not differentiate the effects of safety improvements and other changes that have been implemented in the past three decades. Thus the scenarios produced can be only be guaranteed to be consistent with incidents occurring over the last forty years, as opposed to those that can be expected to occur in the present time or near future. However, until we can ascertain what role new safety legislation has made in contributing to the observed reduction in fire fatality rates, no account of them could be made. The passage of time may provide the answer to this question.

6.1.4 Modelling of Occupant Fatalities

The focus of the study lay primarily with establishing how and why casualties occur in aircraft accidents as a result of fire. However it has already been highlighted that approximately half of fatalities in the past incidents studied resulted from impact trauma injuries. It was therefore necessary to take account of casualties resulting from the effects of both impact and fire in any fire accident survivability analysis.

In general, impact injury and fatality levels are predetermined by events that occur during a crash sequence, before the effects of fire become critical. In contrast, fire injuries may take several minutes to arise, during the period in which survivors are usually attempting to escape from aircraft. Thus, for the purpose of analysis, impact casualties can essentially be regarded as playing a passive role in fire accidents, while fire casualties form an active part of the simulation process.

It was therefore logical to assign the calculation of impact injuries to the scenario generation module. Injury levels could then be related to the degree of fuselage damage or cabin disruption present after an impact. It was possible to obtain approximate measures of these impact damage - occupant injury relationships from the historical accident data. Although this type of correlation approach was relatively basic, it was probably unfeasible to establish a more elaborate analysis in the time that

was available. Given that past accidents have shown that the issue of impact survivability is just as significant as that of fire safety, much more effort could justifiably be applied to this aspect of the analysis.

Simulating the occurrence of fire casualties constituted one of the most fundamental tasks of the analysis. They needed to be determined dynamically as a result of interactions occurring between the fire and evacuation modules of the programme. Levels of fire injuries and fatalities are the most logical measures for assessing the severity of occupant exposure to the effects of fire. As such, they would obviously form the one of the most important quantitative outputs of the accident simulations.

6.2 Implementation of Scenario Generator: Primary Parameters

6.2.1 Primary Accident Parameters

The first task to be performed by the scenario generation module is to determine the most basic features of the incident being simulated. As explained earlier in the chapter, these variables determine the overall nature of an accident and form the basis of calculations undertaken in the remainder of the scenario generator. It was therefore essential to ensure that key statistical relationships existing between primary accident parameters were faithfully reproduced in the output scenarios. The most direct way of achieving this was to utilise a simple form of probability event tree. The only real point of concern when adopting such an approach was to ensure that parameters were determined in a logical manner and in order of significance.

Numerous variables were assessed for inclusion within the scenario event tree. Eventually, four parameters were identified; each of these was straightforward to quantify and could potentially play a highly significant role in determining fire casualty rates. In order of their importance, the primary accident parameters were:-

1. Type of fire involved
2. The occurrence of a significant impact
3. Presence of fuselage structural disruption
4. Phase of flight in which incident occurred

It was also necessary to define the type of aircraft to be involved at some point in the scenario generation process. The size and characteristics of aircraft were not found to possess a major influence on fire survival rates in past accidents and so it was assumed that the aircraft type could be set independently of other scenario details. However, in general terms, the aircraft type involved was obviously a very fundamental item of information and it needed to be decided at a comparatively early stage the analysis. Therefore, the task was performed immediately after the scenario event tree and the type chosen was effectively treated as a primary scenario parameter throughout the remainder of the simulation.

6.2.2 Prerequisites for Establishing the Category of Fire Present

Given that the study was concerned primarily with evaluating fire survivability in aircraft accidents, the most obvious place to start the definition of an incident was to choose the type of fire present. It has already been seen in Chapter 3 that four

categories of fire had been defined for the purpose of evaluating past accidents. These were *Internal*, *Impact*, *Burnthrough* and *External* fires respectively. Furthermore, it was then established in Chapter 4 that the type of fire involved correlated more closely with high fire fatality rates than any other scenario parameter tested. However, when we start off by attempting to pick one of the fire categories, a problem arises. This stems from the definition used for the impact fire type, which incorporates the prerequisite for "significant cabin structural disruption" to have taken place. The logical implication of this was that the relative likelihood of a given fire type occurring was critically dependent on the degree of impact damage present. Put more simply, it would be impossible for an impact fire to occur without an impact.

It was therefore apparent that, in order to generate a consistent accident scenario, basic details of the any impact needed to be established before the type of fire could be chosen. Effectively, this changed the order in which the three most influential primary scenario parameters would be evaluated. Once these had then been established, the phase of flight in which the incident occurred could then be decided.

The level of detail required on impact damage before the fire type could be set was comparatively modest; merely establishing the presence of sufficient fuselage structural disruption was adequate. In fact, this task was split into two steps; firstly determining whether or not any type of impact occurred and then deciding whether any such impact would have resulted in gross structural damage. More specific information describing the probable effects of any impact could then be filled in at a later stage in the scenario generation process.

Similarly, the primary parameter "Fire Type" only indicated the broad category of the fire present. Details such as the size, position and growth rate of the fire would be decided at a much later stage. In fact, unlike the impact details, these fire parameters were set outside the main scenario generation module. This stemmed from the fact that they were closely allied with the fire modelling rather than with other aspects of the scenario generator.

6.2.3 Phase of Flight in which the Accident Occurs

The fourth and final scenario parameter that was found to play a significant role in determining fire survivability was the phase of flight in which an incident occurs. For the purpose of correlating with accident lethality, four stages of flight were delineated, namely *ground operations*, *takeoff*, *cruise* and *landing*. These had been reduced down from the nine categories utilised in the accident database.

The reasons for why phase of flight may be of significance were interpreted as being twofold. Firstly, when an airliner takes off from an airport, typically up to one third of its total mass will consist of fuel. As the flight progresses, this fraction gradually decreases until, on landing, only a small proportion of the original fuel load remains. This then implies that accidents occurring during preparatory ground operations or takeoff will be likely to involve larger fuel fires than incidents where smaller fuel loads are present¹.

Also, the severity and consequences of crash impacts may be related to the phase of flight in which they occur. Landing accidents tend to involve more severe impacts than incidents occurring during takeoff or those arising during cruise. This

¹ Taking this argument to extremes, there have been several instances where aircraft have force landed after running out of fuel. In these cases, comparatively little or even no fire damage usually results.

may be because landing accidents are more likely to involve an unchecked rate of descent, higher impact speeds and less occupant awareness. When an aircraft is involved in ground operations, crashes are extremely rare and unlikely to be serious when they do occur.

6.2.4 Construction of Scenario Event Tree

The implementation of first section of the scenario generation module in the form of a probability event tree was straightforward to achieve. Once a suitable sequence for setting the primary scenario parameters had been decided, the 217 scenarios contained the accident database could be broken down in the corresponding order. The resulting figures are listed in Figure 6.6. Note that line widths of various

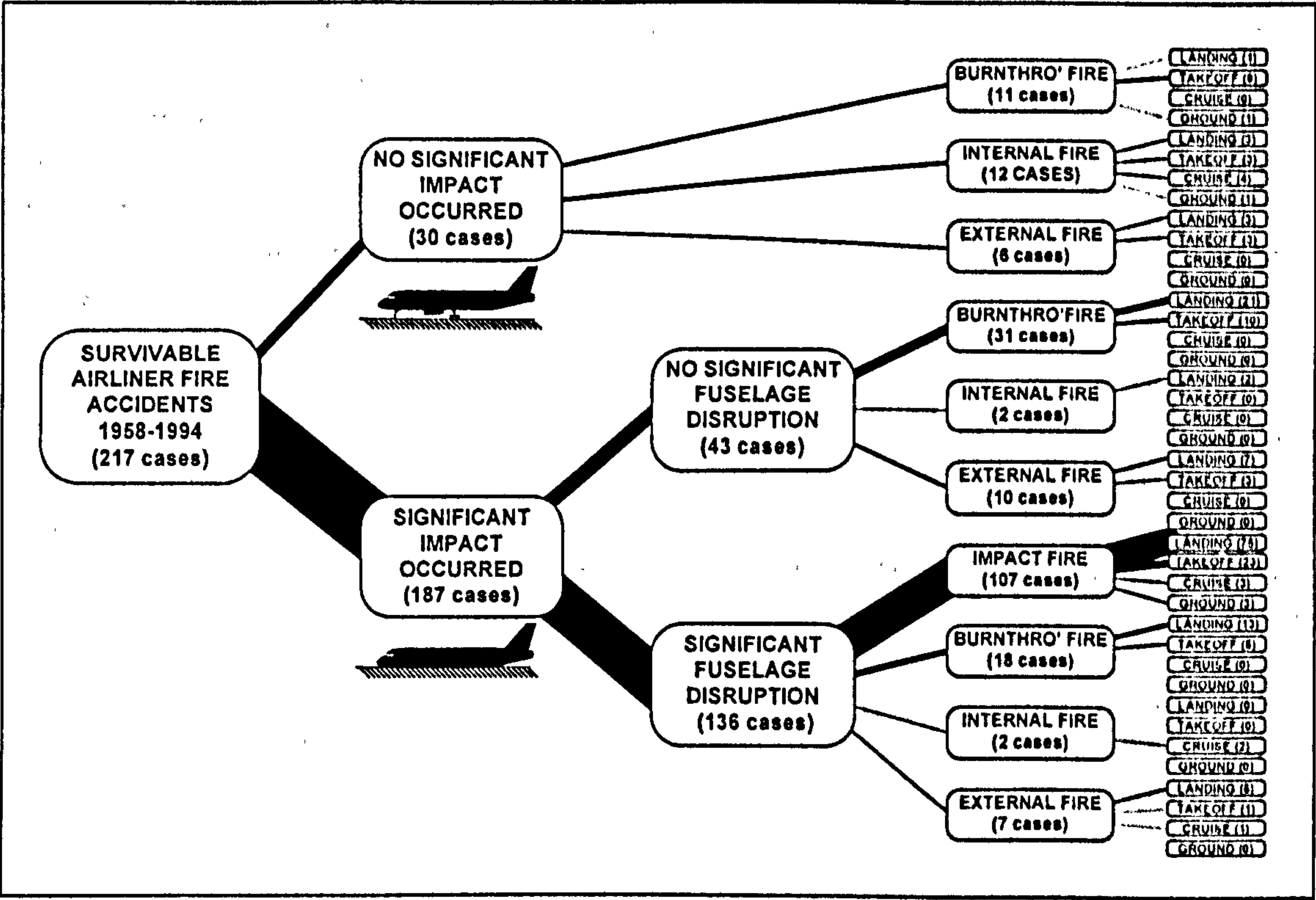


Figure 6.6: Probability Event Tree for Primary Scenario Parameters

branches have been made proportional to the numbers of events involved in each case. The tree is traversed from left to right by choosing four random numbers. At each successive junction, the path to be taken is decided by comparing the value of a random number with threshold probabilities derived from the relative frequency of each branch. Once this process has been followed to the right of the tree, one of forty possible accident scenarios will be obtained.

Two points should be made concerning the derivation of values for probability thresholds from the historical data. Firstly, in cases where complete data could not be obtained, missing values are implicitly assumed to correspond with the known data. Thus, for example, it was established that an impact occurred in 187 of the incidents, but the presence or absence of significant fuselage disruption could only be verified in 177 of these events. Consequently, there is no “fuselage disruption unknown” category and the remaining branch probabilities are assumed to be $\frac{41}{177}$ and $\frac{136}{177}$ as opposed to $\frac{41}{187}$ and $\frac{136}{187}$ respectively.

The other issue of concern was how to deal with types of scenario that could potentially exist, in theory at least, but for which a precedent has yet to occur. These cases are shown as dashed lines in the figure. Two alternatives were possible; it could either be assumed that these scenarios will never in fact occur, or else they could be assigned a small (but arbitrary?) probability of occurrence. It was decided to adopt the former approach and restrict the scenario types to those actually present in the accident database. However, code was put in place to enable all scenario combinations to be generated, in case this became desirable at a later stage.

6.2.5 Type and Configuration of Aircraft Involved

Many parts of the analysis model required information that related specifically to the aircraft type involved in the accident being simulated. For example, these details included fuselage dimensions, exit positions, cabin configuration and passenger numbers. Obviously, these parameters can vary enormously across different designs of aircraft. Thus it was necessary to acquire detailed information for a representative selection of airliner types currently used in passenger service. Then, a specific aircraft type could be chosen by the scenario generator and its design details made available for other parts of the model to access, as they are required.

In general, particular classes of aircraft may tend to be involved in specific kinds of accidents, or be involved in accidents more often. Mean accident rates per departure are generally dependent on the size, age and type of aircraft concerned, as well as the operator and the type of sectors being flown. For a given aircraft type, the expected frequency of accidents will also be directly related to the number of departures being flown by the in-service fleet world-wide. The configuration of an aircraft can also make it particularly susceptible to a particular type of accident¹. Thus engines are more likely to detach if they are wing mounted and fuselage fires are more prevalent in aircraft with that possess underfloor cargo holds.

For the purpose of constructing the scenario generation module, it was not possible to quantify these types of relationships in the time available. This stemmed chiefly from the fact that there are currently over seventy different aircraft types in service with the world's airlines. With only 217 incidents available for analysis, on average, we possess only three accidents per airliner type with which to identify any safety trends that are specific to a particular design. Therefore, aircraft types would need to be grouped into categories, differentiated by age, configuration, operators, types of sector flown, etc. before meaningful trends could be obtained. This task was considered to be beyond the scope of the current thesis and it may not yet have been undertaken in a systematic manner, even by major airline insurance underwriters.

Thus, all aircraft types have been treated equally and are implicitly assumed to be involved in comparable accident scenarios, regardless of their configuration, size or age. As a result, this then enabled efforts to be directed towards the more pressing requirement for representing the details of airliner cabin configurations within the simulation analysis. These configurations comprised data such as passenger numbers, cabin dimensions, seating layouts and exit positions for each aircraft type that was to be analysed. This information is utilised by all three of the main programme modules and was thus an essential prerequisite for undertaking fire survivability analysis.

¹ For example, the McDonnell Douglas DC-9 series of aircraft appear to be especially prone to "back-breaking" in hard landings; at least five such incidents were encountered in the accident survey.

The task of representing cabin configurations was dealt with in three distinct phases in the course of the model development. Initially, two simple cabin sections were used, possessing a single aisle and a double aisle respectively. These are illustrated in Figure 6.7. It can be seen that the cabins contained positions of seats,

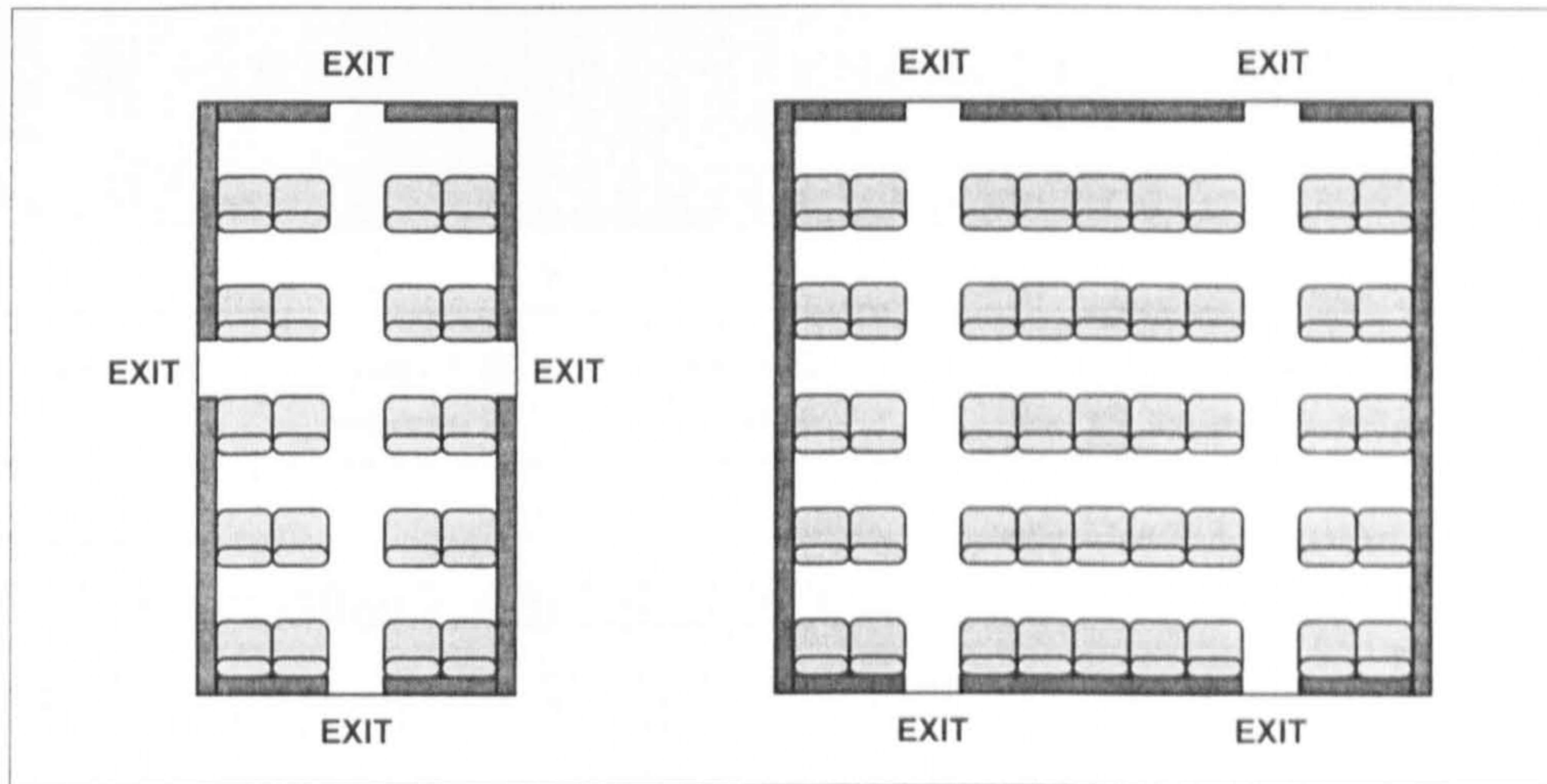


Figure 6.7: Cabin Configurations used in Initial Development

aisles, walls and exits, but were not intended to be representative of any particular aircraft types. The configurations did not include any scale dimensions and lacked features such as overwing exits, cabin divides, toilets and galleys. Essentially, the two initial layouts served only for the purpose of preliminary programme development.

The next step taken was to analyse details of all turbine engined airliner types that have been used in service over the last forty years. This resulted a total of 126 different aircraft, each of which could utilise many different cabin configurations when in passenger service. Rather than attempt to represent the details of many hundreds of configurations explicitly, a single typical in-service seating layout was assumed for each airliner type. Similar cabins were also grouped together where feasible and then treated as a single generic aircraft. This resulted in 34 “homogenised” cabin configurations for use in the analysis. Each generic layout consisted of cabin dimensions, seat spacing across the cabin, number of seat rows and exit positions. Effectively, the preliminary two cabin layouts had been scaled and extended into 34 different configurations, which are representative of those used in airline service world-wide.

The final stage of refining the definitions of aircraft cabins involved modelling aircraft types explicitly. In order for this to be achievable, the 126 aircraft considered previously were reduced down to 72 types *currently* being used for revenue passenger services in significant numbers. Combined passenger and cargo configurations, together with most types possessing less than thirty passenger seats were also ignored. Cabin drawings for each aircraft type were obtained and closely examined. The configurations were translated into a grid format and plotted with a computer-based drawing package. The rationale for using a grid based representation of cabin geometry is covered in Chapter 8. Figure 6.8 illustrates a typical widebody cabin configuration coded in this way. The scale of the cabin grid is drawn uniformly, but in fact varies between 150 and 200 millimetres. Note also that many details are included, such as wider first class seats, toilets, galleys, section divides and cabin crew

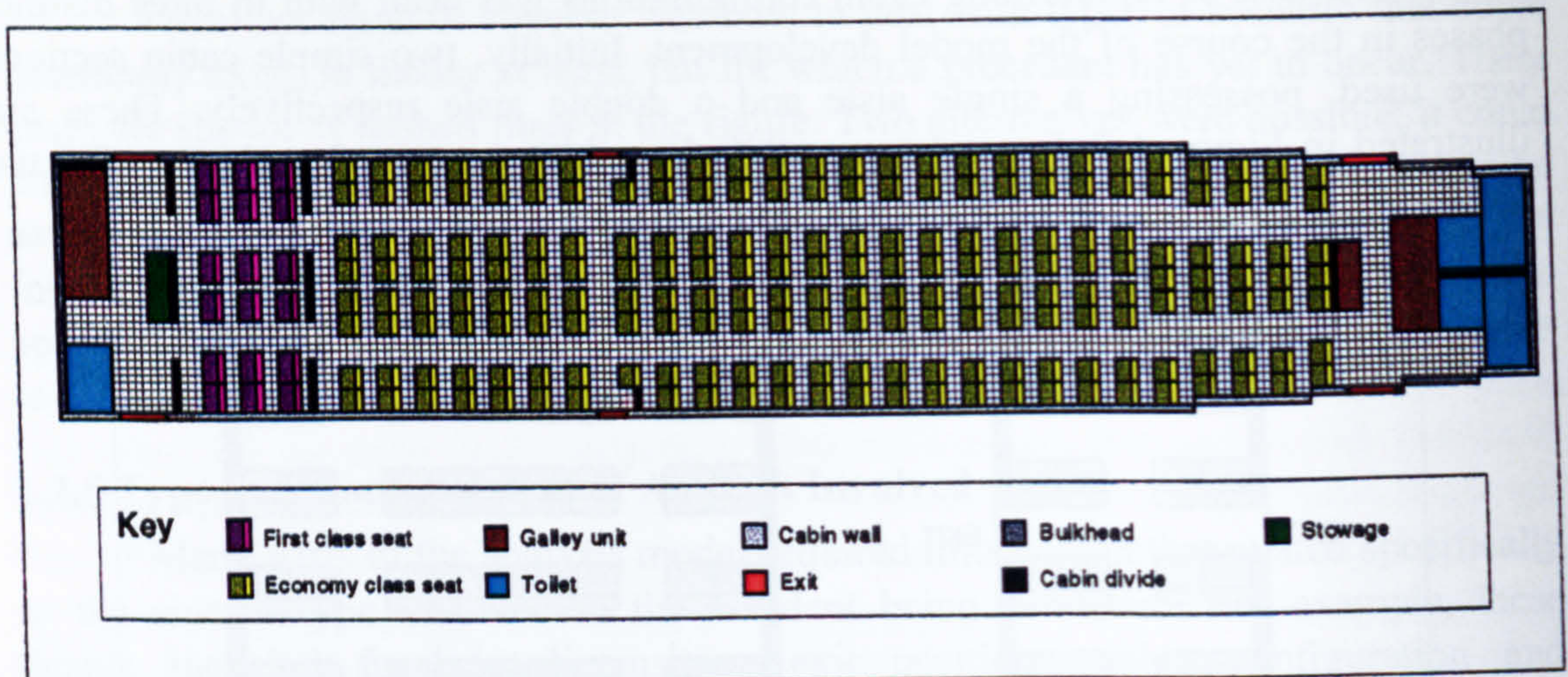


Figure 6.8: Airbus A310 Widebody Cabin Configuration

positions. Appendix B includes diagrams of all 72 aircraft types analysed in this manner.

The first section of the scenario generation module assigns the aircraft type to be used in the analysis at random, or alternatively, can be configured to choose a pre-specified design. In order for the appropriate information to be utilised by the remainder of the programme, it was necessary to store and read data describing each of the 72 cabins in a computer compatible format. The performing of this task is described in Chapter 8.

6.3 Impact Classification & Disruption Modelling

6.3.1 The Nature of Aircraft Crashes

The survey of past accidents showed that almost 90 percent of the incidents analysed involved a significant impact. This meant that the vast majority of survivable fire accidents result in aircraft coming to a stop off a runway and resting on their undersides. Consequently, many of these incidents will result in the aircraft being subjected to considerable deceleration forces, resulting in occupant injuries, structural damage and more general disruption. In addition to producing casualties, these effects will often determine the nature of any subsequent fire and serve to undermine the evacuation efforts of survivors.

One particular feature stood out in many of the accidents that had been analysed. This was that, often, large variations could exist in the consequences of a crash between accidents that outwardly, at least, appeared to be very similar. An aircraft's fuselage can remain relatively intact, even in cases where the majority of occupants may have been killed by impact forces. At the other extreme, on some occasions, survivors have emerged totally unscathed from completely disintegrated wreckage. Thus the overall magnitude of crash forces do not provide a reliable indication as to the extent of structural damage and passenger injury levels.

For the purpose of undertaking a study in fire survivability, we are not concerned with the mechanisms through which impact damage and injuries take place. It was merely required to represent these features at a level of resolution sufficient enough for the requirements of fire and evacuation modelling. This implied that the

past accident data could be quantified at an empirical level for incorporation into the accident simulation. These parts of analysis were grouped together under the label of “impact effects” and dealt with in the second section of the scenario generator.

6.3.2 Research into Aircraft Crashworthiness

Most of the research that had been located in the area of aircraft crashworthiness and impact survivability involved direct simulation, using either an experimental or a computational approach. Whilst these studies were undoubtedly of value for the purpose of investigating complex crash phenomena, they did not fulfil the requirements of the present research. This was due mainly to the fact that the research has been directed towards reproducing the effects of impact forces on aircraft structures, rather than aircraft occupants. Computer based dynamic analysis methods enable physiological forces to be established with a reasonable degree of accuracy. However, it was found to be difficult to relate these findings to real aircraft accidents or establish what level of incapacitation they would correspond to.

A more relevant approach is to study the consequences of past aircraft crashes. This allows the effects of impact forces to be studied in a real environment, including the repercussions for human victims. The primary drawback of undertaking this kind of analysis is that it may often only be possible to estimate the magnitude of impact forces to an approximate degree of accuracy. Nonetheless, if we are concerned only with representing the general effects of aircraft crashes, rather than quantifying the mechanical performance of aircraft structures, this need be of little consequence. Historical crashworthiness studies were known to have been undertaken by the aircraft manufacturer Airbus and by consultants working under contract to the UK Civil Aviation Authority. However, the results of these investigations were unavailable at time of writing. Consequently, FAA crashworthiness programmes constituted the only literature obtained in the area.

The complex nature of aircraft crash scenarios means that it is usually only feasible to classify impact damage on a descriptive basis (Botteri et al., 1979). In terms of fire survivability, the most significant aspects of aircraft crashworthiness are probably engine/undercarriage separation, rupturing of wing tanks and fuselage crushing or disintegration. This is because these are the primary mechanisms for fire initiation, fuel release and entrapment of occupants, respectively. Thus, the study of aircraft crashes usually involves attempting to quantify disruption from these viewpoints. Work published by Boeing has defined the following scale for the purpose of quantifying the severity of aircraft crashes (Horeff, 1982):-

1. *Minor impact damage* - includes engine/pylon damage or separation, minor lower fuselage damage and minor fuel spill.
2. *Moderate impact damage, gear separation or collapse* - includes higher degrees of damage of type 1 and includes gear separation or collapse.
3. *Severe impact damage* - includes major fuel spillage due to wing lower surface tear and wing box damage, but no fuselage break.
4. *Severe impact damage* - includes severe lower fuselage crush and/or Class 1 or Class 2 fuselage breaks, may have gear collapse, but no tank rupture.
5. *Extreme impact damage* - includes Class 1 or Class 2 fuselage breaks with wing separation or breaks, may have gear and/or engine separation.

6. *Aircraft destruction* - includes Class 3 fuselage breaks or destruction with tank rupture, gear and/or engine separation.

where fuselage breaks are: Class 1 - sections break but remain together
 Class 2 - sections break and open
 Class 3 - sections break and move off

These classifications were judged to be unsuitable for use in the present study without modification. They appeared deal adequately with consequences of a crash on an aircraft's structure, as seen from a purely engineering perspective. However, it was considered that more emphasis needed to be placed on how impact forces affect aircraft occupants and their perception of the cabin environment in the immediate aftermath of an accident. From the study of past incidents, it had been concluded that features such as passenger disorientation levels, presence of cabin debris and loss of seat or floor integrity need to be considered in any quantification of crash effects.

As has been stated in the introduction to this section, these "human" aspects of a crash scenario often show little correlation with levels of structural damage present. The implication of this was that the use of two measures for the assessment of impact effects should be used. These were differentiated as "Fuselage Structural Damage" and "Cabin Disruption" respectively. The approach taken was to develop a simple rating scale for both measures. These could then be used to classify impacts that have occurred in past accidents and then generate probability functions for representing these effects within the accident simulation. The difficulties inherent in attempting to quantify the severity aircraft crashes ensured that, in many respects, this would be a subjective exercise. However, the intent was to facilitate the incorporation of impact effects within the overall analysis. Even the most basic of data would suffice for this purpose.

Thus, it can be seen that the research located in the area of aircraft crashworthiness provided a valuable insight into how to approach the problematic task of analysing aircraft crashes. However, the methods that were actually utilised, while essentially being based on existing work, were probably new in many significant respects. It was apparent that the area of research is still relatively undeveloped and potential still remains for much progress to be made.

6.3.2 Fuselage Structural Damage

Before any attempt was made to construct a rating scale for the purpose of assessing structural crash damage, the details of all the incidents held in the accident database were collated and reviewed. It was found that adequate information on impact details was held for 98 of the 187 accidents in which a significant impact was known to have occurred. One outcome of this exercise was to decide that a five point damage scale would provide the best compromise between resolution and ease of implementation. A value of one on this scale would need to correspond with little or no significant effects, whereas five would be used to represent total destruction of an aircraft's fuselage. Thus, effectively, only three intermediate levels of damage were open to definition.

Also, during this preliminary scanning of the accident data, one other important conclusion was reached. Previous studies of this kind had utilised only a single value for representing the degree of structural damage present in each accident.

However, in over a quarter of the 98 cases being assessed, it was apparent that the aircraft's fuselage had completely separated into two or more sections. The level of structural damage (as well as injuries and cabin disruption) present in these different parts of the wreckage could sometimes differ markedly. Thus it was decided to assign individual impact damage ratings to separated sections of fuselage.

The position(s) at which an aircraft's cabin breaks up was judged to be very significant in many of the incidents examined. These locations determine exit availability and risk of immediate fire exposure for groups of occupants remaining in the sections of wreckage. Time was therefore spent recording the position of the fuselage breaks present in the accidents. These locations could then be used to generate probability distributions suitable for determining fuselage dislocation in the impacts effects section of the scenario generation module.

Investigation revealed that, with only a single exception, the portion of an aircraft's fuselage containing the passenger cabin had always split up into either two or three separate sections. There were 16 cases where only a single break was encountered and 10 cases in which two breaks occurred. For reasons of simplicity, it was decided to analyse these two groups of accidents separately. Figure 6.9 shows the

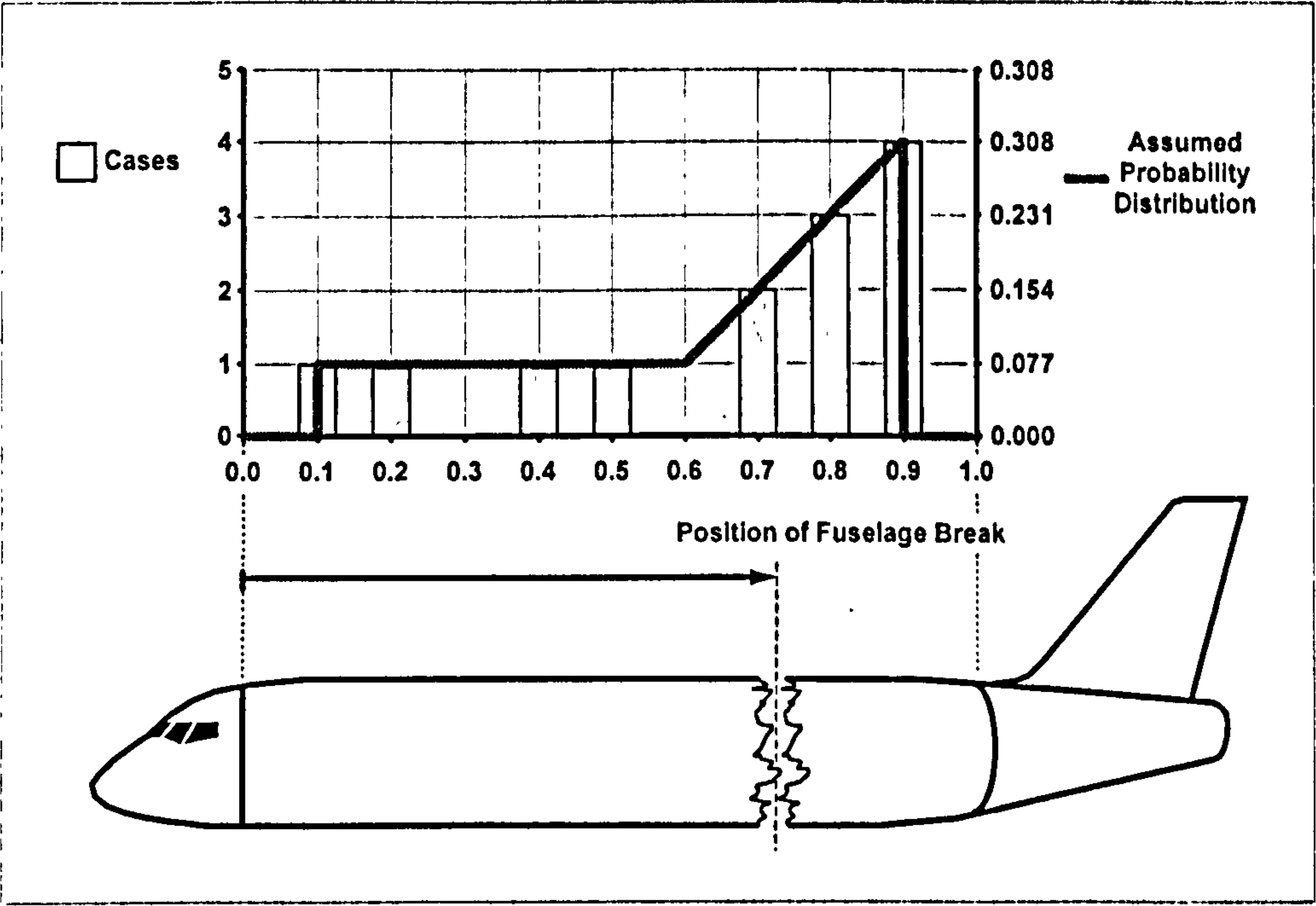


Figure 6.9: Probability Distribution for Determining the Position of a Single Fuselage Break

distributions of breakage positions for cases involving a single fuselage break. The locations have been determined as a fraction of the overall cabin length of the aircraft involved. This distance was defined as running from the cockpit/cabin divide back to the rear pressure bulkhead. It can be seen that fuselages are most likely to split in the region between the rear of the wing and the tail of the aircraft.

The corresponding distribution for cases involving breaks in two or more positions is indicated in Figure 6.10. Here it appears that dislocations occur on either side of the wing position (typically at around 0.4 - 0.5 of the cabin length).

Once it had been chosen to analyse each segment of fuselage on an individual basis, it was possible to finalise the definitions for the categories of structural impact

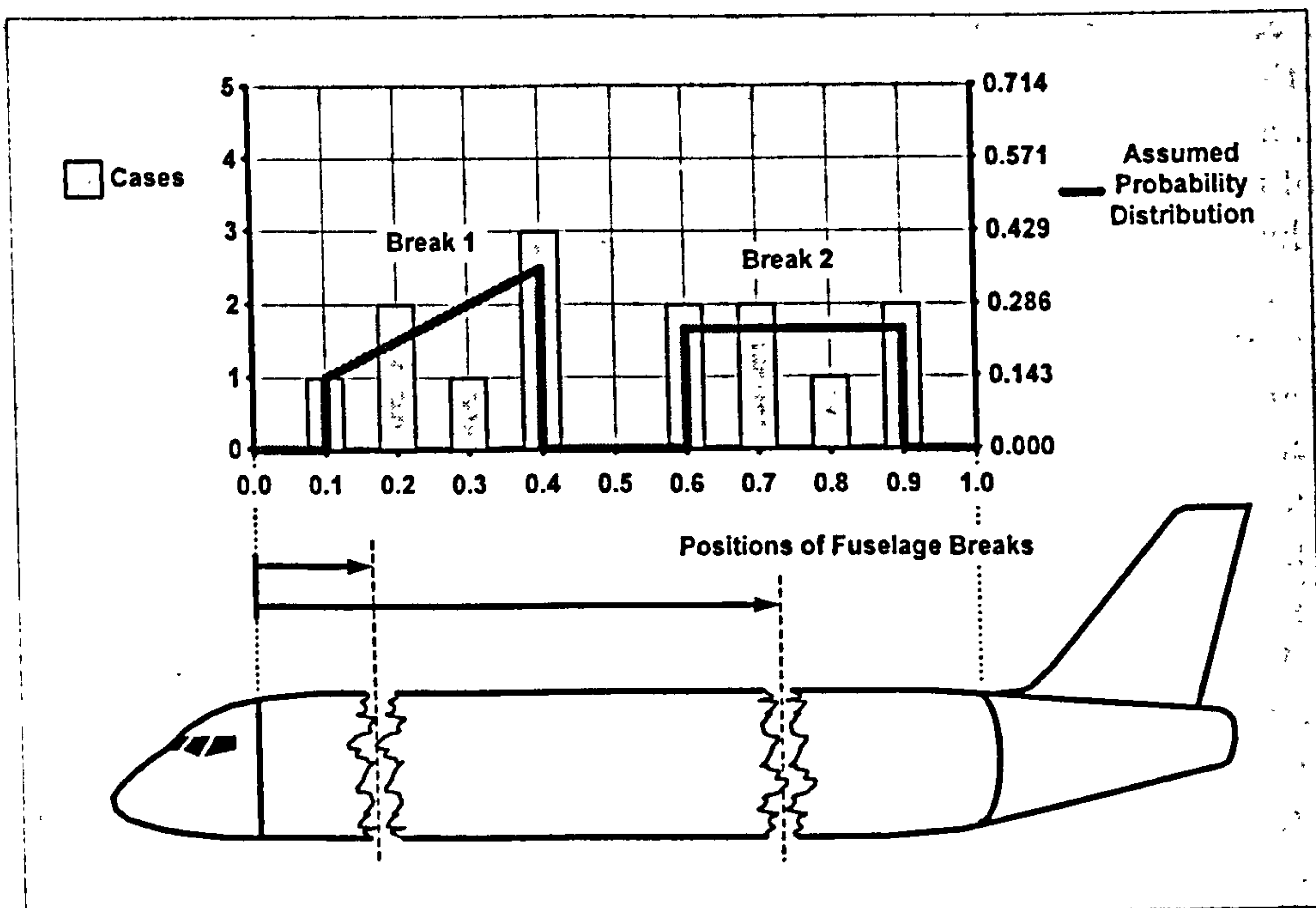


Figure 6.10: Probability Distribution for Determining the Positions of Two Fuselage Breaks

damage. As stated previously, these were graduated into five levels, each of which comprised a brief verbal description of associated damage levels. The five categories were as follows:-

1. *None/negligible* - no significant structural damage from a survival viewpoint.
2. *Modest* - gear collapse or engine separation. Some fuselage distortion or localised underfloor crushing possible, but pressure shell remains intact. Small fuel leaks.
3. *Extensive* - splits, gaps or significant crushing present at cabin level, but fuselage structure remains largely in place. Clean breakages possible. Rupturing of wing tanks or outer wing separation may occur.
4. *Severe* - large holes, crushing or fuselage break-up present. Some sections may be totally destroyed, but structure still remaining largely in place elsewhere. Separation or destruction of wings likely.
5. *Complete* - Little of fuselage remains intact, with multiple break-up or large-scale crushing. Wreckage likely to be contaminated with fuel and virtually unrecognisable.

The structural impact damage present in each of the accidents was graded on this scale. As indicated previously, this was in some respects a subjective process. However, it was found that restricting the number of categories available to five, as opposed to six or more, eased the task considerably.

The results of this activity are provided in Appendix C. Curve fits were obtained from the data were used directly in the scenario generation module for establishing structural damage levels. Note, that for programming purposes, the 1-5 rating scale used to code impact damage was translated into a "Structural Damage Factor", with values between 0.0 and 1.0. Predictably, these distributions show that

damage levels are more likely to be high in cases where a fuselage breaks into two or more sections. In more severe crashes, there appears to be no significant difference in the effects of impact between front and rear sections of an aircraft's fuselage. However, in cases where a fuselage breaks into three, the central cabin area may sometimes experience lower levels of structural damage.

6.3.3 Cabin Disruption

The process used to quantify levels of cabin disruption in the accidents was very similar to structural damage analysis. However, as stated previously, there was a need to integrate both physical and psychological factors when assessing the degree(s) of disruption present in each incident. As a result, the task of differentiating between different levels required rather more interpretation and was thus rather less straightforward to achieve than the grading of structural damage. The five categories of disruption used were defined as follows:-

1. *None/negligible* - apparent normality (most passengers oblivious to the occurrence of any accident)
2. *Slight* - comparable to hard landing, with significant jolting (something out of the ordinary is apparent, crying infants, some confusion present)
3. *Moderate* - minor injuries and personal possessions scattered. Cabin crew struggling to control events (accident is obvious, widespread screaming, panic, jostling and confusion). Emergency exits may be overcrowded or neglected by passengers.
4. *Serious* - seats distorted or stowage bins burst open. Serious injuries present and some of cabin crew may be incapacitated. (Loss of consciousness, disorientation, often with little concern for fellow passengers). Frequent jamming of exits.
5. *Total* - seats and stowage bins detached. Serious injuries and trauma fatalities widespread. Overall loss of control. (No clear recollection of events, behaviour likely to be determined by instinct, even neglecting of spouse or own children). Exits may often be jammed or completely obstructed.

The results of the cabin disruption survey could have been collated and plotted in the same manner as the structural damage data. However, in general, we can obviously expect a strong correlation to exist between the levels of fuselage damage and cabin disruption present in a given incident. Thus, catastrophic fuselage damage tends to be associated with high cabin disruption levels, and similarly, less severe impact damage generally corresponds with a lower degree of cabin disorder. This implied that, for the purpose of generating accident scenarios, impact damage and impact disruption levels could not be treated as independent variables. In consequence, it was decided to prioritise the fuselage damage estimates ahead of the cabin disruption data. This was because the former provided a more direct measure of crash effects and could be estimated more accurately.

The cabin disruption results were therefore analysed with respect to the structural damage present in each case. Figure 6.11 shows the correlation that exists between the two (again, note that the original 1 - 5 ratings have been translated into a 0.0 - 1.0 scale for the purposes of analysis). It can be seen that, on average, cabin

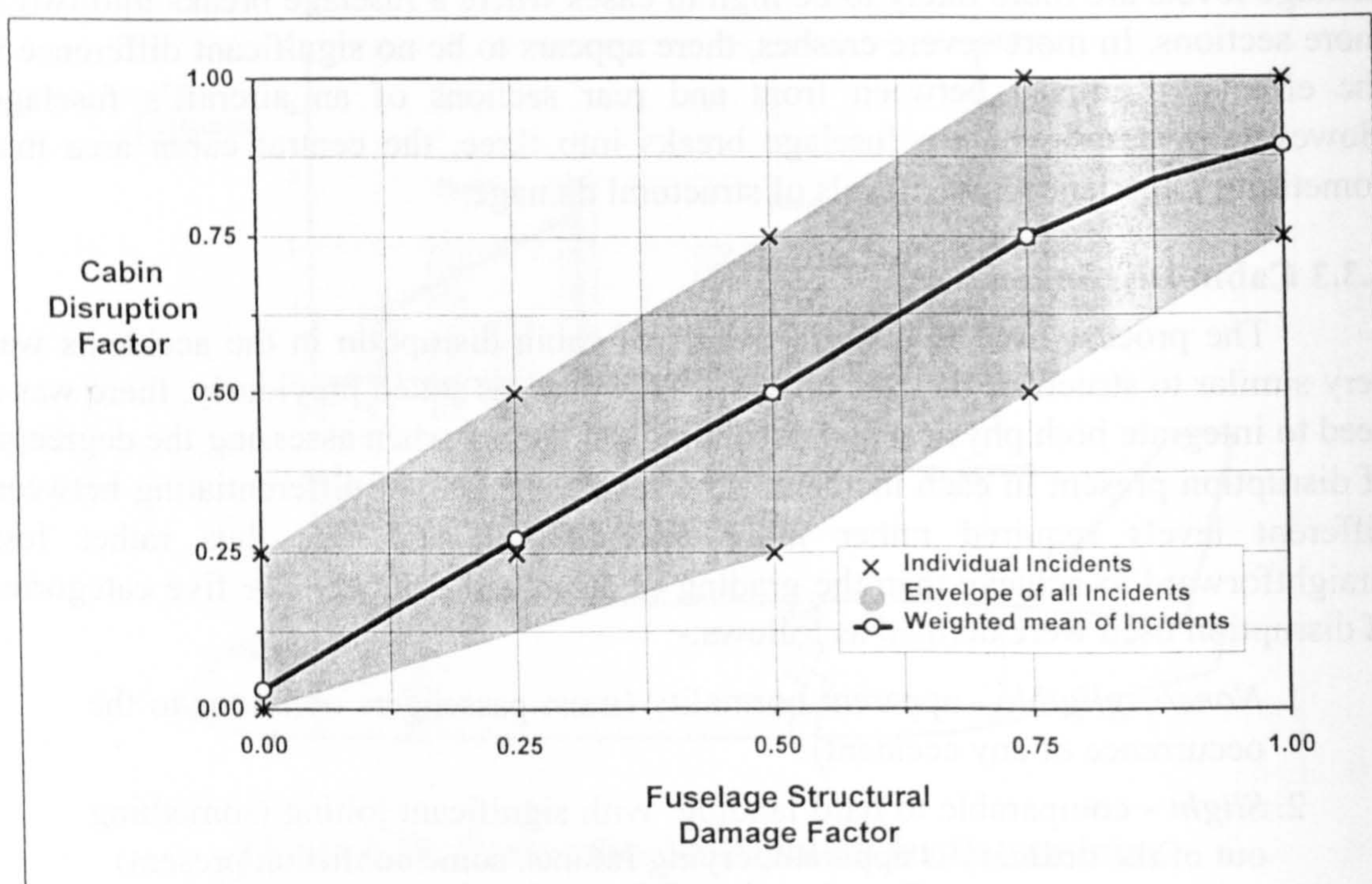


Figure 6.11: Cabin Disruption as a Function of Fuselage Structural Damage Present in an Incident

disruption and structural damage factors are approximately equal. For more severe crashes, disruption values tend to be slightly lower. In contrast, small levels of disruption (0.02 - 0.03) tend to be present even when no significant structural damage has occurred.

For a given level of structural damage, it appears that cabin disruption factor can vary from the structural value by up to plus or minus 0.25. The extent of these deviations is illustrated by shaded envelope in the figure. The resolution of the data obtained does not allow meaningful distributions of these variations to be derived. However, it is probably reasonable to assume that they are distributed symmetrically above and below the mean curve, as far as the 0.0 - 1.0 data limits allow.

The simplicity of this relationship implied that levels of impact disruption could be determined directly from the degree of structural damage present in an incident. This process was implemented within the impact effects section of the scenario generator with the use of simple straight line approximation. Random deviations were applied, assuming an even ± 0.25 distribution, corrected to within the illustrated envelope.

6.3.4 Cabin Orientation and Exit Opening Delays

Additional aspects of cabin disruption to be analysed included cabin orientation, together with the functionality and utilisation of emergency exits. It was observed from past accidents that unusual cabin attitudes can sometimes be detrimental to evacuation or rescue efforts¹. The orientation of a cabin (or particular section of cabin) was classified into one of four categories, as follows:-

¹ This can be especially so when emergency lighting systems fail to activate at night. In at least one of these cases, passengers have struggled to vacate an aircraft without being aware that it was completely inverted.

- level - no tilt mentioned
- upright - up to 45° of tilt
- side - 45° < tilt ≤ 90°
- inverted - tilted by over 90°

Also, in incidents where an aircraft’s fuselage broke into separate sections, an attempt was made to record the relative positions of the portions of wreckage. However, time constraints prevented this data from being analysed and incorporated within the scenario generation module. It was therefore assumed that all cabin sections remain upright and, if breakages occur, adjacent sections will be positioned randomly within a distance of five meters from each other. The results of the cabin orientation survey are summarised in Appendix C.

Exit usage in emergency situations is critical for determining the time required for an aircraft to be evacuated. The number of passengers that utilise a given exit is obviously dependent on the time required for it to be opened, and then, on the rate of egress it is capable of supporting once in use. We can derive values for exit flow rates from experimental trials and by interpolating evacuation times achieved in past accidents. However, obtaining accurate estimates of opening times required for individual exits is considerably more problematic. Numerical values for these delays are given relatively infrequently in accident reports, presumably because they can often be difficult to estimate from conflicting eyewitness reports. Therefore, a need was perceived to exist for translating verbal descriptions of exit opening difficulties into corresponding time delay estimates.

The approach adopted was to assign reported difficulties to one of five exit delay factors. The levels of these ranged from one (exit opened immediately) through to five (exit not used). The approximate time correlations assumed for the delay factors are given in Table 6.1. It should be noted that no distinction was made between different types of exit, such as double-width doors (Type A), overwing hatches (Type III), tailcone or ventral stairway exits. The time values obtained were

Exit Delay Factor	Time to Open (seconds)	Description
(1)	$t < 10$	Immediate
(2)	$10 < t < 30$	Quick
(3)	$30 < t < 60$	Some delay
(4)	$t > 60$	Considerable difficulty
(5)	not opened	Impossible to open or overlooked

Table 6.1: Exit Opening Delay Factors

used to generate probability intervals for exit opening delays at different levels of fuselage structural damage. These are provided in Appendix C. Predictably, it was found that high levels of impact disruption tended to produce greater exit opening delays. Full use of all an aircraft’s exits is rarely made; average utilisation rates appear to lie somewhere in the region of fifty percent. Typically exits remain unopened because they are either ignored, rendered unusable by the effects of fire, or blocked/jammed as a result of a crash.

A thorough investigation of exit usage in aircraft fire accidents has been performed by Schaefer (Schaefer, 1990). This study provided excellent data on exit availability and usage, including the role of aircraft configuration (i.e. the presence of wing or tail mounted engines). However, although passenger utilisation figures per exit were reported, numerical estimation of exit opening times was not undertaken. Thus, the current survey of opening time delays formed a valuable complement to the results of Scaeffers study.

6.3.5 Trauma Injuries and Fire Survival

It has already been seen that occupant fatalities in aircraft fire accidents occur just as frequently as a result of crash injuries as from the effects of fire. Impact trauma injuries can also serve to slow down or even prevent the evacuation of survivors. This can often produce greater levels of fire injury and fundamentally change the nature of an egress process. Thus, the prediction of impact fatality and injury rates for the accident simulations constituted an important requirement for the scenario generation module. The probability functions used to obtain estimates for these figures would have a major role in determining accuracy levels of the survivability analysis.

The modelling of impact fatality rates was relatively straightforward to implement. Casualty figures were available for all of the accidents covered in the historical survey and a large proportion of these cases, causes of death were either known or possible to estimate with reasonable accuracy. Intuitively, we might expect the proportion of occupants that succumb to the effects of impact injuries to be strongly dependent on crash severity. As shown in Figure 6.12, this is indeed the case.

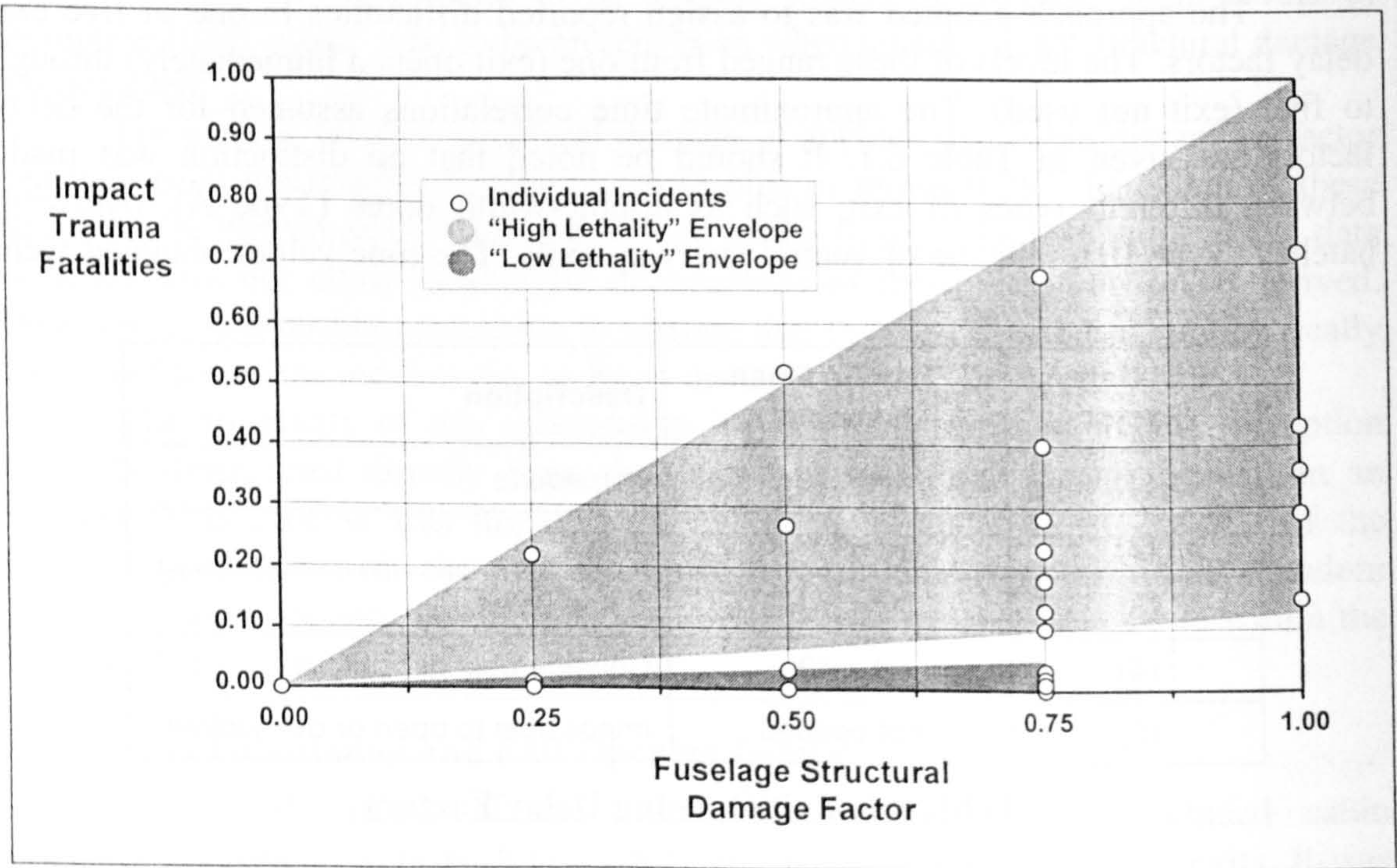


Figure 6.12: Impact Fatality Rates

However, it is apparent that two distinct classes of crash accident might exist. The first of these occurs more frequently and involves high impact lethality rates for a given degree of structural damage. In contrast, accidents in the second category only involve low or moderate levels of damage, and result in far fewer impact deaths. The

different distributions of these “High Fatality” and “Low Fatality” incidents are highlighted with the use of shading in the figure.

Re-inspection of the accidents failed to reveal any clear-cut explanation for the existence of these two classes of crash. The higher lethality cases perhaps might have tended to involve significant crushing of the passenger cabin or greater longitudinal deceleration forces. Alternatively, the apparent differences in impact fatality rates might, to a large extent, be spurious. Nonetheless, a two zone probability distribution was implemented in the scenario generation module. This generated levels of impact trauma fatalities as a function of the fuselage structural damage present.

Variations were assumed to be randomly distributed throughout the two fatality envelopes, apart from cases in which fuselage break-up had occurred. Here, lethality rates were biased to reflect the fact that trauma deaths are far more numerous in the front sections of the wreckage, as shown in Table 6.2.

Impact injury levels were found to be considerably more difficult to quantify than impact fatality rates. Very few accident reports differentiate between serious injuries resulting from impact forces and those caused by the effects of fire. Therefore, it was provisionally assumed that all injuries were, in part, impact related.

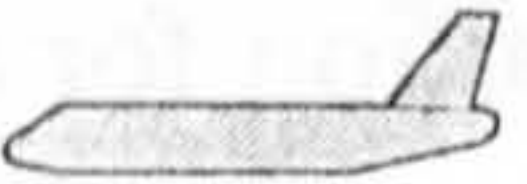
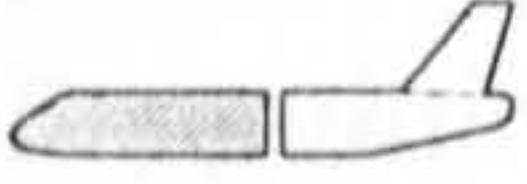
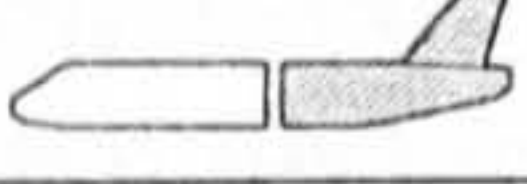
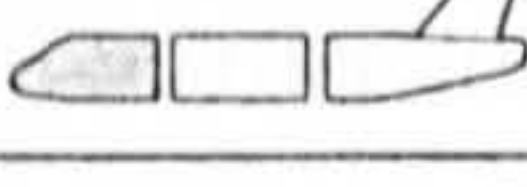
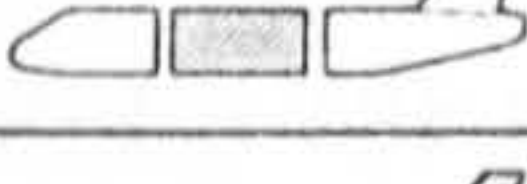
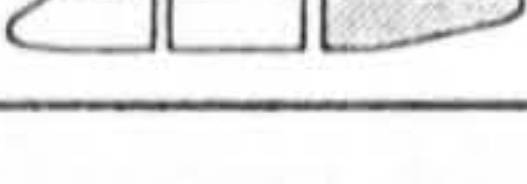
Impact Scenario	Mean Rates			
	Structural Damage	Cabin Disruption	Impact Fatalities	Serious Injuries
 One fuselage section	0.44	0.44	0.10	0.16
 Two fuselage sections (front)	0.84	0.78	0.50	0.06
 Two fuselage sections (rear)	0.80	0.75	0.25	0.22
 Three fuselage sections (front)	0.93	0.90	0.63	0.09
 Three fuselage sections (centre)	0.85	0.88	0.37	0.23
 Three fuselage sections (rear)	0.85	0.90	0.36	0.43

Table 6.2: Impact Casualty Rates

In general, serious injury levels did not appear to correspond with either fire or impact fatality rates. However, significant differences were found in accidents where fuselage break-up occurred, as shown by the figures in Table 6.2. In these incidents, a higher proportion of occupants seated in the rear sections of an aircraft were likely to be seriously injured, rather than killed, by crash forces.

It was decided to analyse the prevalence of serious injuries in terms the total fraction of survivors present in each accident. However, individuals who are killed by the effects of fire will often have sustained impact injuries as well; these cases are obviously not included in reported injury figures. It was therefore necessary to factor the rates obtained to take account of these “hidden” injuries. Fire-victims were assumed to posses the same impact injury rates as accident survivors, although, in fact, they may be significantly higher.

Probability intervals were derived for serious injury rates at different levels of fuselage structural damage. Cases involving one, two and three fuselage sections were analysed separately. Both impact fatalities and impact injuries were applied at random to passengers seated throughout the cabin (or section of cabin).

6.3.6 Psychological Considerations in Aircraft Crashes

The psychological effects of a crash appear to vary widely in different individuals. Accident victims frequently report that they felt stunned, confused or disoriented immediately after an incident had occurred. Aircraft crew members, along with a significant proportion of passengers are usually able to clear their senses and act coherently the instant an aircraft come to a stop. In contrast, other individuals are frequently unable to control their actions in unfamiliar circumstances and panic, inappropriate conduct or even behavioural inaction may commonly result.

Wide variations in behaviour are generally exhibited by individuals, even when they have been subjected to the same accident circumstances. This suggests that these types of issue are related more closely to the personal characteristics of those involved, rather than to details of the events that occur in aircraft accidents. However, psychological effects are unlikely to occur spuriously. Thus, some basic measure of accident "distress" or "unfamiliarity" was needed in order quantify the likely nature and extent of passenger reactions.

As explained previously, the assessment of cabin disruption levels in past accidents was intended, in part, to address this requirement. This survey was undertaken in order to gauge the nature of passenger perceptions about their local cabin environment, as distinct from the degree of physical damage that was actually present. These types of subjective observation were not easy to interpret for many of the accidents and even more difficult to make practical use of in the safety analysis. However, it was felt that the activity could potentially form a useful contribution for a more extended investigation into the subject of aircraft accident psychology. At the very least, cabin disruption levels would provide a basis for determining the occurrence of unpredictable passenger behaviour in the evacuation module.

6.4 Miscellaneous Accident Parameters

6.4.1. The Significance of other Scenario Features

The final section of the scenario generation module was constructed to specify accident details that did not fall under the category of primary scenario parameters or impact effects. In some instances, the role that these variables played in contributing the outcome of an incident could not be quantified from past the accident data. This was due to one of two reasons; either the parameter in question appeared to be relatively insignificant, or else time, time constraints only permitted the undertaking of a brief analysis. Consequently, only four of these miscellaneous accident parameters were considered in detail for incorporation into the scenario generator. These were:-

1. Distance of the accident site from the airport
2. Wind conditions
3. The type of terrain present at the accident site
4. Hour of day in which the incident occurred

The analysis undertaken with each of these variables will now be covered.

6.4.2 Determination of Airport Distance

The distance at which an accident occurs from an airport may provide some form of indication about the time required for emergency rescue services to arrive on the scene. As discussed in Chapter 3, no correlation was found between delayed fire fighting intervention and the sizes or extinction times of fires. Also, in a high proportion of accidents, all survivors are able to escape from the aircraft before the arrival of external help. As a result, the role of emergency services in off-airport accidents is likely to be relatively small.

The analysis of airport distances was broken down by phase of flight in which the crash occurred (i.e. takeoff or landing) and the type of fire experienced. Distances were measured from the appropriate runway threshold, in nautical miles. The resulting distance distributions are provided in Appendix C. Some clear patterns were revealed; for example landing/approach accidents tend to occur at about three times as far from the airport as takeoff/climb accidents. In terms of fire type, burnthrough fires are typically encountered at half the airport distance of impact fires. Although these distributions were incorporated into model and used to generate airport distances for off-airport accidents, this parameter had no influence in the simulation. However, some of the analysis undertaken in this part of study may have important implications for the deployment of airport fire and rescue services.

6.4.3 The Nature of the Accident Site

The type of terrain present at accident sites was recorded in the preliminary data survey. In approximately 90 percent of the cases examined, aircraft came to a stop on runway surfaces, or grass fields on or around the airport. As a result, emergency services are usually able to access accident sites without difficulty. For the remainder of the cases, however, locations tended to vary greatly. Trees and mountainsides are encountered reasonably frequently, but examples of more unusual accident sites include residential buildings, a petrol station, a ravine, swamps, jungle and a car park. In many of these instances, it was impossible for effective intervention to be provided.

The role that prevailing terrain might play in accident survival was briefly explored. However, no clear patterns emerged; fatalities appeared to be determined predominantly by more fundamental features of the accident scenario, such as fire ingress time or crash severity. Interestingly, no significant differences were found in fire properties (such as size and extinguishment time) between runway, grass or miscellaneous accident sites. Consequently, details of accident sites were not incorporated into the simulation analysis.

6.4.4 Effects of Wind and Weather

Wind direction and strength are known to have played a crucial role in fire development in some past aircraft accidents (King, 1989). As a result, the effects of ambient wind conditions needed to be represented in the fire and cabin thermo-toxic environment modules of the simulation programme. For initial purposes, wind direction was chosen randomly and wind strengths were set to vary between 0.0 and 10.0 m/s. However, because information on wind conditions is included in many accident reports, it was feasible to investigate how representative these provisional assumptions were.

Figure 6.13 shows a radial vector plot of wind conditions reported in 54 past aircraft accidents. As far as it was possible to ascertain, no significant correlations existed between wind directions or strength. The fact that vectors are distributed

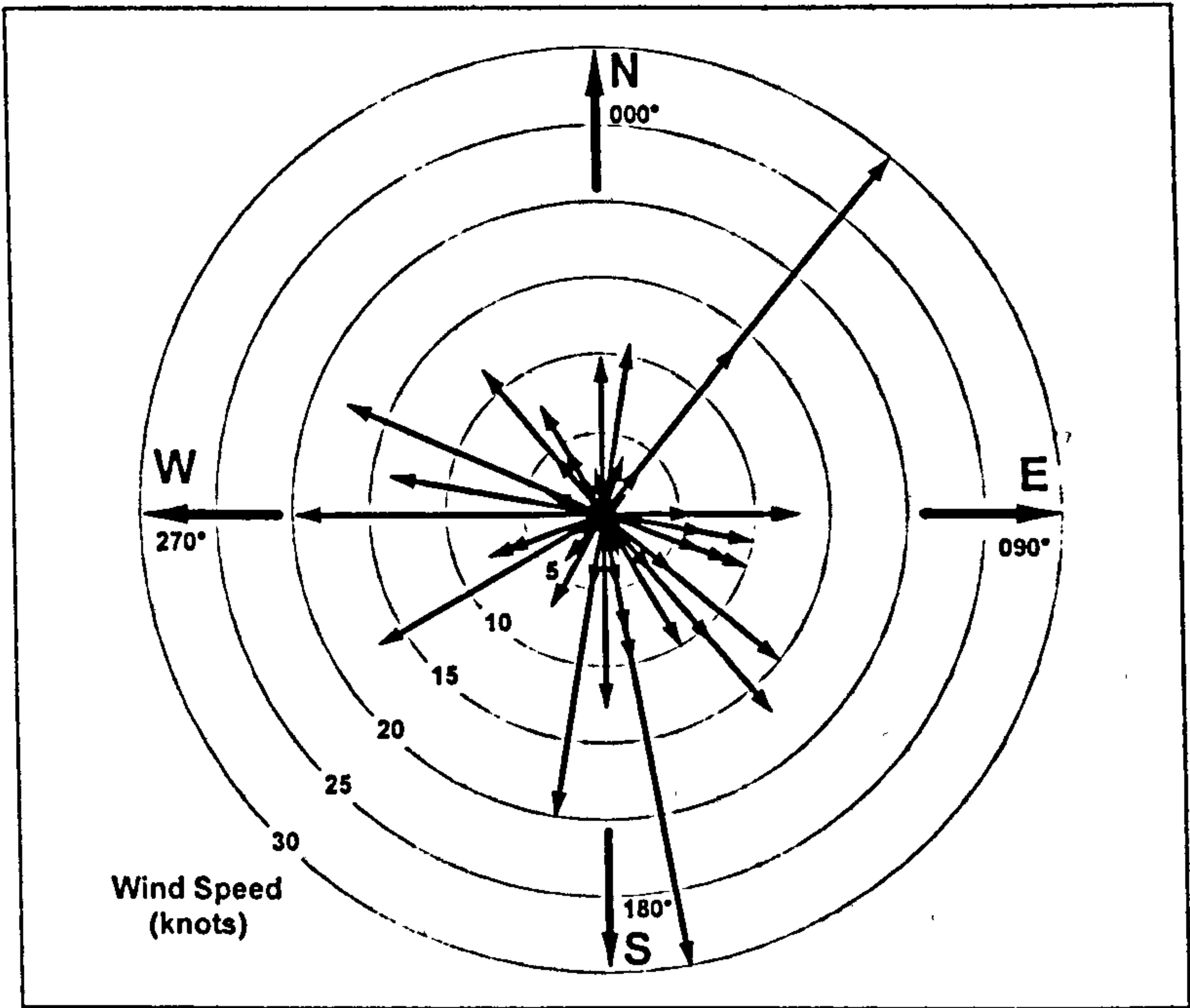


**Figure 6.13: Radial Plot of Wind Velocities
in Past Aircraft Fire Accidents**

evenly around the plot implied that the assumption of a random wind direction was acceptable. However, wind strengths clearly vary up to a speed of about 30 knots (15 m/s) and are not evenly distributed. Consequently, a probability function was derived for winds and incorporated into the scenario generator.

6.4.5 Time of Day at Which Accidents Occur

The local times at which accidents occurred are plotted in Figure 6.14. These hourly frequencies appear to correspond closely with traffic levels experienced at most airports, i.e. peaking during morning and early evening rush-hours. The local

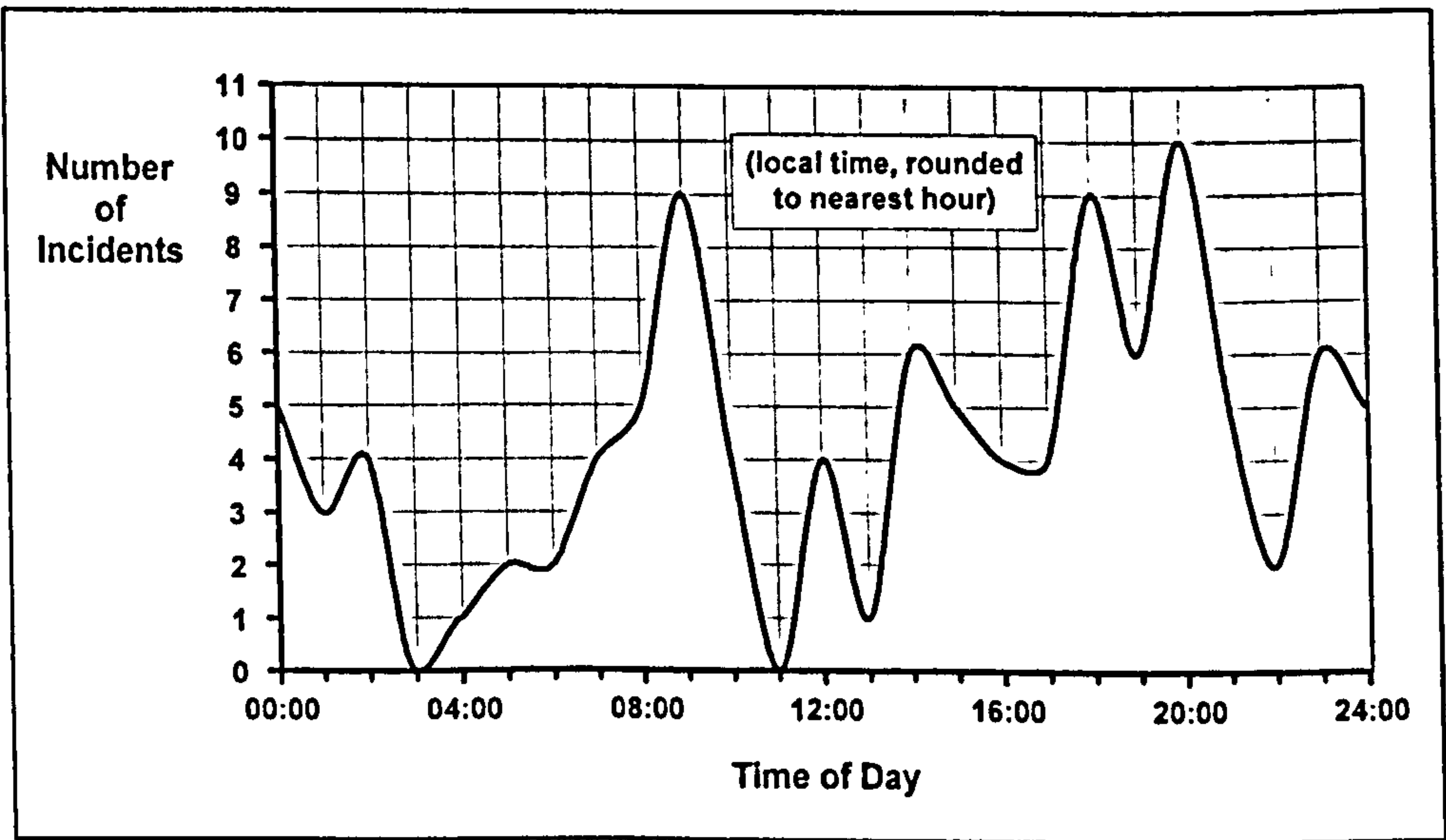


Figure 6.14: Variation in Accident Frequency with Time of Day

time obviously provides an indication of the level of light present at an accident site. Visibility is known to have had an important effect on the efficiency of evacuation and rescue operations; however, time constraints prevented this influence from being modelled in the simulation analysis.

Chapter 7: Fire and Cabin Thermotoxicity Modelling

7.1 The Nature of Aircraft Fires

7.1.1 Introduction

Commercial passenger aircraft carry large quantities of highly flammable fuel in their comparatively fragile wing structures and operate at high speeds. Thus, all commercial flight operations inevitably involve a risk of incurring catastrophic fire accidents. These events can be initiated even before an aircraft has left the ground. Engine failures, static discharges, overheated brakes, electrical faults, dangerous cargo and irresponsible passenger actions have all resulted in serious accidents in the past. However, it has been seen that the vast majority of severe aircraft fires stem directly from the occurrence of a significant crash impact, usually in the takeoff or landing phases of flight.

The nature of aircraft fires varies widely. Crash forces tend to release and spread fuel in an unpredictable manner, and can render an aircraft's wreckage distorted beyond recognition. Often, cargo and cabin furnishings will become involved in a conflagration, creating complex chemical reactions which can produce a multitude of toxic fire products. The effects of melting structures, passenger actions, weather, local terrain and fire-fighting intervention can also serve to influence the properties of a fire substantially.

When all of these factors are considered, it is apparent that we face an extremely challenging task in attempting to analyse and quantify real aircraft fires. For this reason, perhaps, little research appears to have been undertaken in the area. Scientists have tended to focus on more tractable classes of fire problem or restrict the scope of their analysis to cover only a small subset of real aircraft fire scenarios. This situation is certain to be rectified in the longer term, as experimental and particularly computer-based modelling techniques are advanced. However, given current growth trends in the air transport industry, fire accidents appear likely to occur increasingly frequently in the future. Consequently, there is a need for an analysis capable of delivering usable results in the present time scale.

As has been argued previously, the undertaking of a risk assessment study in aircraft fire safety requires that the challenges of dealing with truly representative fire problems are tackled head on. With the limited time available in the current study, this would mean that the fire modelling analysis could only be undertaken at the most basic of levels. However, this was commensurate with the fact that no previous work of this type could be located within the field of aircraft fire safety.

7.1.2 Categories of Fire

The varied nature of aircraft fires created problems when attempting to analyse and classify past accidents. In the early stages of the research, as recounted in Chapter 3, four different categories of fire were eventually identified, namely *internal*, *impact*, *burnthrough* and *external* fires. At the time of the preliminary data gathering activities, these fire types were regarded as being mutually exclusive. However, as a greater understanding of the incidents was gradually developed, it became apparent that the assumption of discrete fire categories could not always be applied

satisfactorily. In some cases, fire characteristics appeared to span more than one category. This discovery then led to the re-appraisal of the fire classification process. It was concluded that aircraft fires could be interpreted more accurately by classifying them in terms of time required for fire ingress after an aircraft comes to a stop. This parameter was comparatively straightforward to obtain for most of the incidents studied and served to link all fires on a continuous scale.

The most prevalent class of fire was found to be the impact type, which was present in 52 percent of the accidents researched. By definition, impact fires enter the passenger cabin area at around about the time that the aircraft stops. This is possible because fuselage structure has been damaged to the extent that it no longer constitutes a barrier to heat, smoke or flames.

Burnthrough and external types were the next most frequent classes of fire, accounting for 29 and 11 percent of incidents respectively. In burnthrough scenarios, sufficient fuselage structure remains in place to significantly delay the ingress of fire. This interval may vary from as little as 30 seconds up to several minutes, depending on details of the structure and fire involved. In instances where a more prolonged delay occurs, such that all occupants are able to escape safely, or the fire fails to penetrate into the cabin at all, an external fire was defined as having occurred.

Conceptually, no sharp delineation's exist between impact, burnthrough and external fire categories. Together, these three classes of fire form a continuous scale, along which incidents can be positioned according to how they correspond with the fire definitions involved. This implied that it might be feasible to construct a single type of model for the purpose of representing over 92 percent of aircraft fires. In the majority of these cases, the aircraft's fuel supply would play a dominant role in feeding and sustaining the fire. The size of fire present thus depends on the area over which the fuel is spread and the rate at which flames can propagate across this region. Because of this, it appeared that an open pool fire analogy might be highly applicable for most accident scenarios. This involves fires being treated as a radiating flame envelope, arising from a circular area of hydrocarbon fuel situated in an open space. As revealed in Chapter 2, much work has been undertaken by the fire protection industry to quantify and model this class of fire.

The fourth category of aircraft fire consists of internal fires. These were defined simply as originating from inside the pressure shell of the aircraft. Internal fires usually involve cargo, toilets, galleys, hydraulics or electrical systems, rather than an aircraft's fuel supply. Consequently, fires of this type tend to have relatively low levels of heat output, but they have the potential to produce complex and highly lethal mixtures of combustion products, especially when oxygen levels diminish. Also, most internal fires arise when a flight is in progress, thus preventing occupants from effecting an escape until the aircraft can be landed and brought to a standstill. Effectively, this positions internal fires at a negative position on the fire ingress time scale discussed above. However, other similarities with impact, burnthrough and external fire types end here. In general, internal fires radiate only limited amounts of heat during the period that cabin conditions remain survivable and tend not to involve significant quantities of aircraft fuel. The hazards of internal fires stem primarily from the fact that heat and combustion products are contained in a closed volume, in close proximity with aircraft occupants. Thus, internal fires constitute a separate class of problem to fires originating on the exterior of the cabin. As such, their representation requires the use of a dedicated model in any simulation analysis.

Given that internal fires comprised only 8 percent of the accidents surveyed and have become increasingly rare in the last decade¹, it was concluded that they could only be afforded a relatively low priority in the study. Time constraints were to prevent the development of two separate classes of fire model. Thus it was necessary to focus the fire analysis to deal predominantly with impact, burnthrough and external fire scenarios. As a stopgap measure, internal fires would only be represented in terms of small fuel fires located within an aircraft's cabin. As will be seen from the information presented in the next two sections, this approach should only be regarded as a very provisional solution to the requirement for dealing with internal fires.

7.1.3 Open Liquid Fuel Pool Fires

When a pool of flammable liquid ignites, a continuous vaporisation and combustion process is established. The thermal energy produced heats liquid at the surface of the pool, which then vaporises and breaks down into a series of pyrolysis products. These are capable of reacting with oxygen, releasing large quantities of energy to sustain the fire process.

Fire produces heat in two main forms; thermal radiation and kinetic energy present in smoke/gaseous fire products. The former can pose a significant hazard and even lead to the spontaneous ignition of materials at large distances from a fire. Gaseous fire products emit thermal radiation at a number of discrete frequencies in the infra-red band. In contrast, radiation by soot particles is continuous over the entire range of the spectrum where heating considerations are significant.

Heat from moderately hot smoke and gases is transferred by convection or conduction processes, involving direct physical contact. Adiabatic flame temperatures for hydrocarbon fuels lie in the range of 1200-1600 K, which are sufficient enough to destroy most aircraft structures in a matter of seconds. Even dense black smoke may possess temperatures in excess of 800 K and thus can pose a major threat to life through burning effects alone.

Fires in open spaces entrain large quantities of surrounding air, some of which is used to burn gases evolving from the fuel source. Most of the air entrained (typically about 90 percent) serves only to dilute combustion products, rather than participating in the chemistry of fire reactions (Delichatsios, 1988). However, given that the entrainment process governs oxygen supply to flammable gases, it effectively regulates the combustion characteristics and burning rate of a fire through physical means.

The air entrainment mechanism is driven by the buoyant upward flow of hot gases, which are replaced by cold ambient air drawn into the fire column. Mixing of flames and air occur as large turbulent eddies emanate from the base of the fire and then roll over to engulf fresh ambient air into the fire. Consequently, the flame envelope tends to oscillate at a natural frequency that decreases with increases in fire size. In general, the comparatively low convection velocities possessed by fire gases mean that the shape and direction of flames are influenced heavily by ambient wind conditions.

The unsteady nature of air entrainment into large pool fires means that oxygen-fuel ratios undergo large fluctuations. This ensures that regions of incomplete

¹ Probably as a result of improvements in automated fire detection and suppression equipment, together with increased crew training and better emergency procedures.

combustion exist at regular intervals throughout a hydrocarbon fuel fire. These result in the production of large quantities of carbonaceous smoke, which can serve to obscure most of the flames present. The presence of thick black smoke around the periphery of a large pool fire can lead to the absorption of a large proportion of the thermal radiation produced in interior regions. Figure 7.1 shows how the proportion of

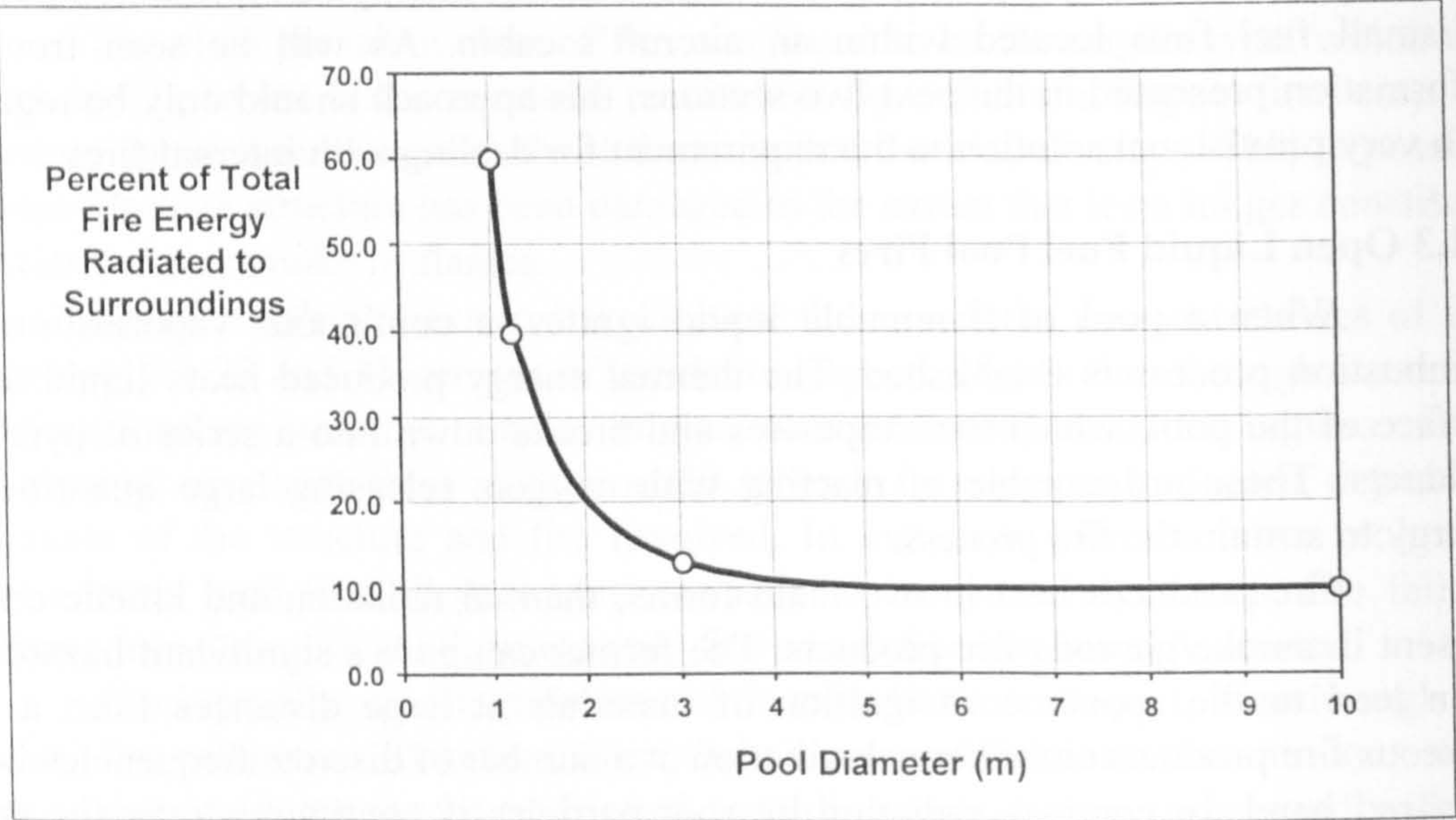


Figure 7.1: Proportion of Energy Radiated from Gasoline Pool Fires

energy radiated to the surroundings drops as the size of a gasoline fire increases (Mudan, 1988). Once a pool fire exceeds a size of about 5 metres in diameter, it appears that only around 10 percent of its total heat output will be released in the form of thermal radiation.

7.1.4 Internal Fires

The fuselages of most modern airliners are designed to provide a sealed, pressure-tight environment, for ensuring the comfort and safety of the aircraft’s occupants. During the course of a flight, pressurisation of the cabin means that potentially hundreds of passengers effectively become locked inside a closed environment. In the event of an emergency situation developing, there is no possibility of escape until the aircraft can be landed and brought safely to a stop.

In normal operations, adequate cabin conditions are only maintained through the carefully regulated application of air conditioning. Consequently, the outbreak of even a small fire inside the pressurised portion of an aircraft can lead to potentially disastrous consequences. This may especially be the case when the point of initiation lies in an inaccessible area, such as in underfloor cargo bays, avionics compartments or behind cabin trim. These types of fire may go undetected for a significant time and be impossible to isolate or suppress effectively whilst an aircraft remains in flight.

Fires occurring in closed compartments have been the subject of considerable research world-wide, particularly in the context of buildings. Much of the work to have been undertaken is probably directly applicable to fires occurring inside aircraft. For example, foam based seating, electrical wiring, plastic fittings and sealed glazing units, directly comparable to those used in aircraft cabins, are likely to be present in most modern domestic sitting rooms. Thus, many of the concepts used in the analysis

of closed room fires can be extended to aircraft cabin fires, or indeed, to many other types of transportation fire scenario. (The following paragraphs have been adapted from a Building Research Establishment Digest publication (BRE, 1991).)

Fires usually start from a small localised source, such as a cigarette or electrical fault. Initially, they tend to grow relatively slowly and this can mean that they may go undetected for a considerable period of time. However, once flames take hold, thermal radiation heats surrounding materials and area of fuel burning may increase rapidly. This, in turn, increases the rate of release of pyrolysis products from the fuel. The hot, buoyant products of combustion rise away from the fuel and, in doing so, entrain air from the surroundings. This mixes with combustion products, both diluting and cooling them, but, as a consequence, also increasing considerably the volume of smoke produced. The destination of the combustion products plays a crucial role in what follows.

In the open, hot smoke and gaseous fire products will usually rise harmlessly away from the source. But, if they are contained within a restricted enclosure, combustion products will threaten any occupants present and potentially cause a dramatic further acceleration in development of the fire. The latter process can often occur suddenly, and consequently is known as “flashover”. This phenomenon usually results when the products of combustion collect in the form of a hot, buoyant layer of smoke and gases under the ceiling of the enclosure. An example of this type of situation inside an aircraft cabin is illustrated schematically in Figure 7.2. Eventually,

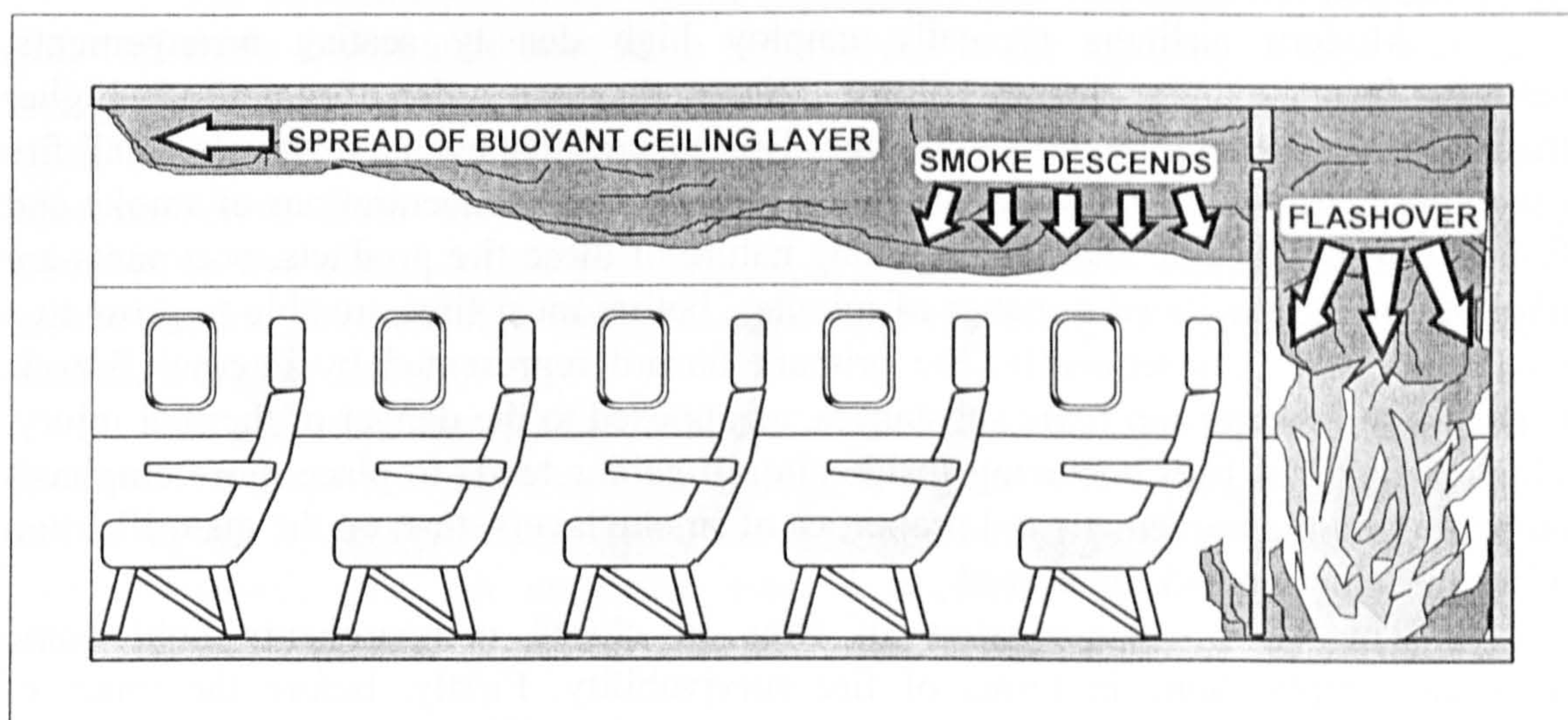


Figure 7.2: Stages in the Development of a Closed Compartment Fire

the hot layer radiates sufficient heat to flammable material remote from the original fire so that it can all ignite almost simultaneously. By now, the fire is likely to require more oxygen for complete combustion than is available. Thus, a large rise in the production of partially oxidised chemical species, such as carbon monoxide occurs and the flames lengthen as unburnt fuel travels outwards to burn in areas where sufficient oxygen is available. The fire is now capable of spreading large distances in a short time. The greatly enhanced kinetic energy in the products of combustion now poses an extreme threat to human survival.

The occurrence of flashover can thus be attributed to a thermal instability, or to the rapid ignition of exposed materials when the level of radiation falling on them reaches a level sufficient for ignition. Flashover is not just an appearance of flame or

the attainment of a particular temperature, but the passing of a fire from one mode of physical behaviour (excess air) to another one (excess fuel) (Thomas, 1985).

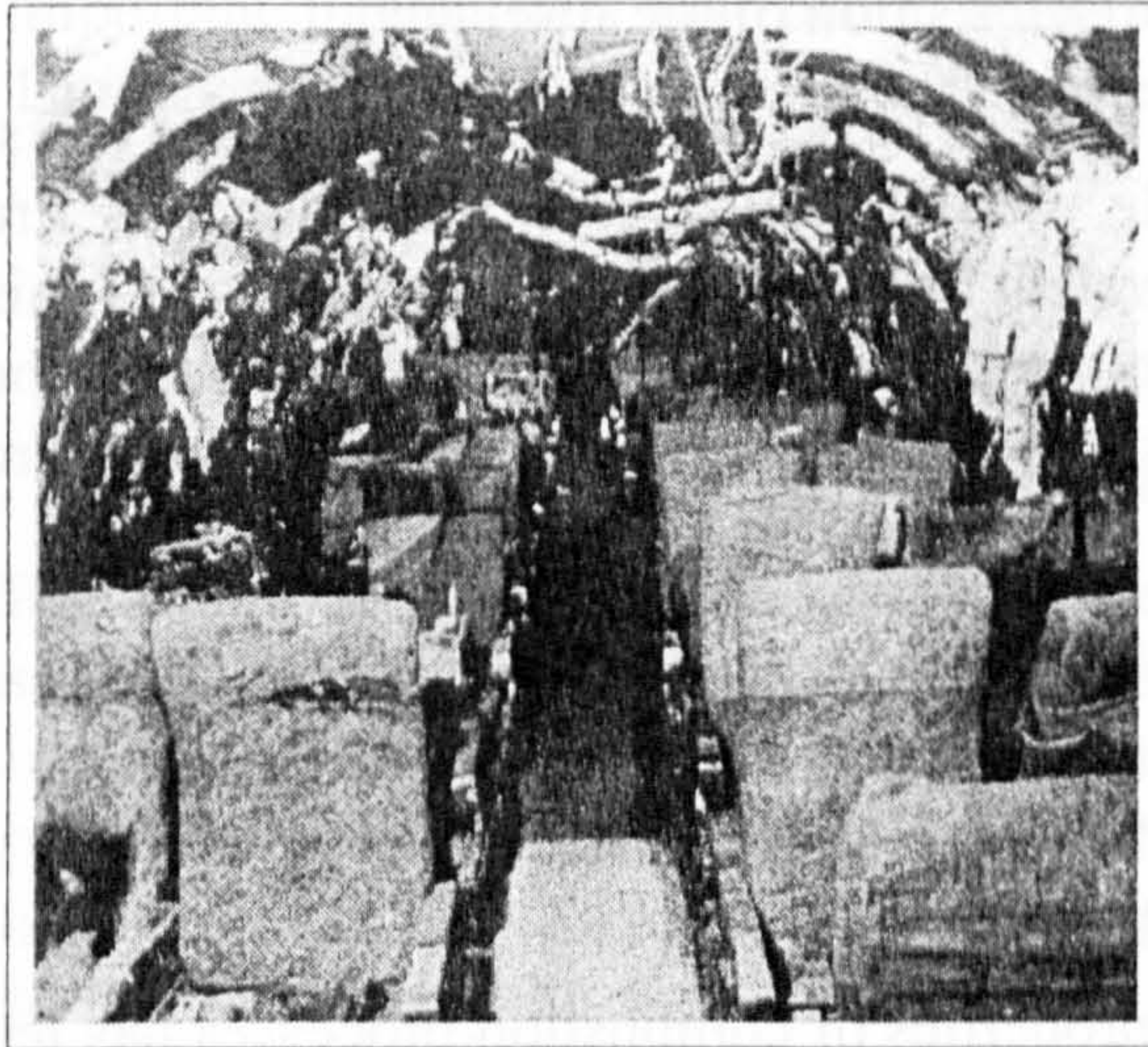
There exists some controversy over the relevance of fire flashover to the assessment of occupant survivability in compartment fires. It is generally accepted that downward-directed radiation fluxes become life-threatening when smoke layer temperatures reach the order of 500 K, or heat flux levels reach the order of 2.5 kW/m² (Cooper, 1988). However, in these conditions, radiant energy feedback is insufficient to have a significant effect on fire growth and spread. Indeed, the potential for flashover to occur only develops once ceiling layer temperatures reach 600-700 K, i.e. well in excess of those deemed to be survivable for those exposed. Consider, for example the fact that in the King's Cross underground fire, few of those who observed the fire flashover survived and most of those who did were seriously injured (Fennell, 1988). Also, in the Manchester accident, conditions were deemed as being unsurvivable once flashover had developed (King, 1989). Therefore, the analysis of flashover might be of more significance in the study of fire spread mechanisms and fire control techniques, rather than for assessing the potential for the saving of life in cabin sized enclosures.

In the case of fires occurring inside aircraft, occupants are often forced to endure the cabin thermo-toxic environment for a significant period before they are presented with the opportunity for escape. This can mean that the rate and manner in which fire products spread through the passenger cabin are critical in determining survival prospects for those trapped inside.

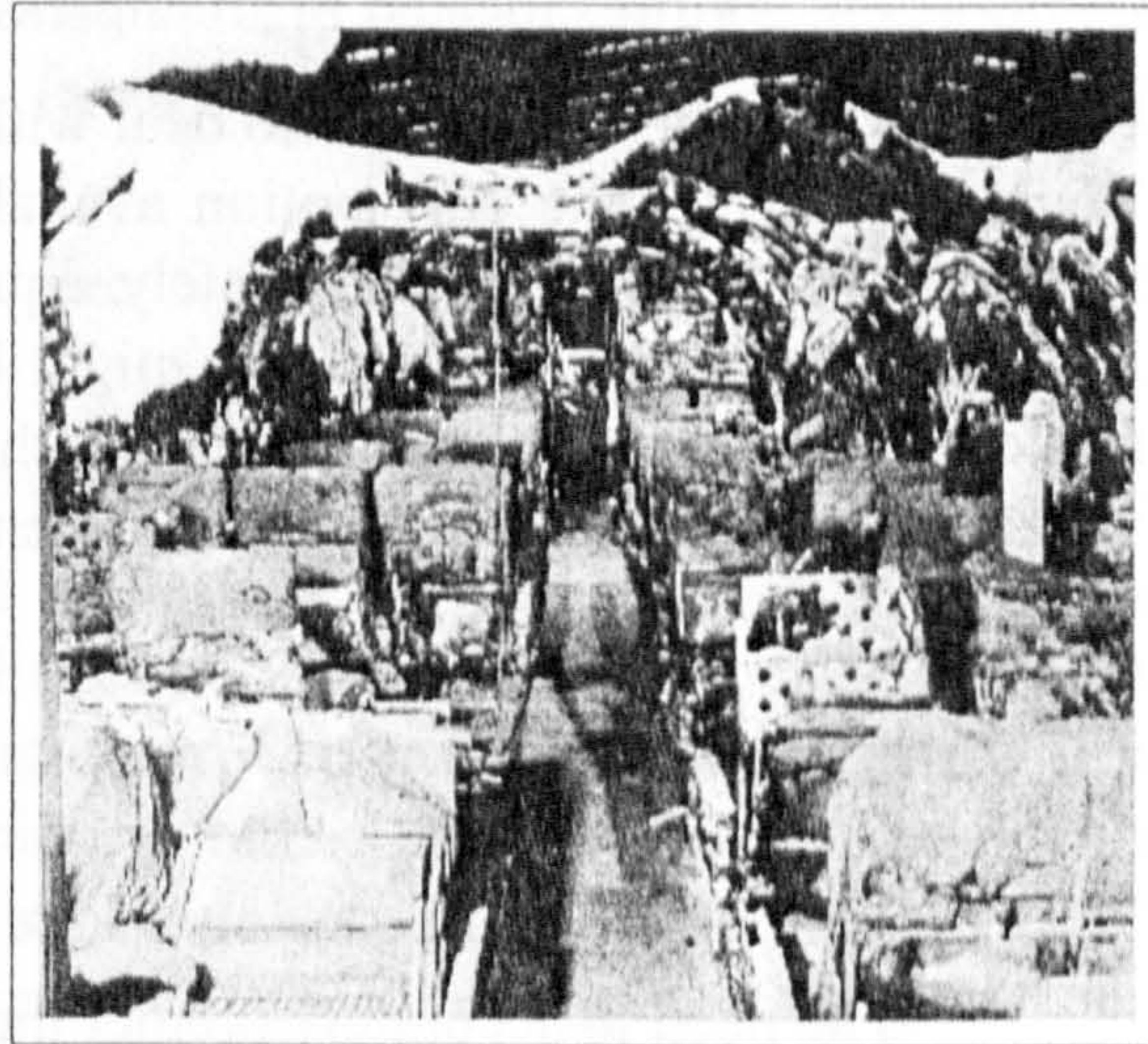
Modern airliners typically employ high density seating arrangements, resulting in occupant/enclosure volume ratios perhaps an order of magnitude higher than those encountered in most buildings. This ensures that even a relatively small fire can expose large numbers of people to dangerously high concentrations of smoke and fumes. Given the toxic and debilitating nature of these fire products, occupants are likely to be incapacitated a matter of minutes, before most fires are able to grow to a substantial size. Consequently, the primary hazard represented by internal fires is exposure to irritants and toxic substances, as opposed to the danger of thermal injury. Thus, analysis of fires occurring inside aircraft cabins tends to place more emphasis on predicting the movement and properties of smoke layers, than on the quantification of heat production and fire spread.

The basic characteristics of fires in closed compartments hold some important implications in terms of fire survivability. Firstly, before the onset of flashover, the majority of fire products are restricted to a comparatively stable ceiling layer, which gradually descends to fill the compartment. This stratification effect is due to the natural buoyancy of the hot smoke and gases. Consequently, many aircraft accident reports contain accounts of how survivors found cabin conditions more favourable when crouched down low near to the floor.

In reality, some mixing and decay of a buoyant smoke layer will generally occur, as a result of cooling, turbulence and diffusion effects. Nonetheless, sharp delineations in local conditions (especially temperature levels), are generally encountered at different heights in a cabin fire (Hill and Sarkos, 1985). Figure 7.3 graphically illustrates the presence of stratification effects in the Boeing 737 accident at Manchester in 1986 (King, 1989). Note how the roof structure and overhead cabin bins were completely destroyed by the fire, even though ventilation was sufficient to prevent a sudden flashover occurring. In contrast, the seat covers are only scorched



(a) view looking aft



(b) view looking forwards

Figure 7.3: Effects of Fire Stratification

and the floor has remained almost unscathed in most areas. The spread of this damage was relatively consistent throughout the forward half of the cabin. These circumstances are typical of a “leaky” (i.e. partially ventilated) compartment fire, even though, in fact, the accident actually involved a large burnthrough fire at the trailing edge of the port wing.

The stratification of the cabin atmosphere had important consequences for some of those unfortunate enough to be involved in the incident. Whilst waiting or struggling to leave the aircraft, they were enveloped by a rapidly advancing “wall” of thick black smoke. After being quickly overcome, they collapsed to the floor in a semi-conscious state. However, it was found that some degree of recovery was possible in the clearer conditions present at a lower level, beneath the most dense smoke layers. This enabled some to make renewed escape attempts and eventually find their way to safety.

In general, even if victims do not regain consciousness of their own accord, they may at least remain alive long enough for there to be a significant chance of rescue by emergency services. Thus, the stratification of an internal fire atmosphere may potentially play an important role in accidents where conditions become marginal.

7.1.5 Miscellaneous Fire Types

Most aircraft fires involve the ignition of large fuel spillages, or, to a much lesser extent, the combustion of solid materials inside the pressurised zone of an aircraft’s fuselage. However, many other classes of fire exist that do not fit conveniently into either of these two categories. For example, some fire incidents might involve the following:-

- onboard oxygen systems
- fully contained engine fires
- fuel tank explosions
- over-heating of wheel brakes
- ignition of ground-based fuels

- fires located in an unpressurised section of the fuselage

Obviously, it was not possible to deal with each of these cases on an individual basis. Thus, realistically the only option available was to analyse such miscellaneous fire scenarios in terms of approximately equivalent fuel spill fires. Consequently, this implied that specific features that might be present in some cases would have to be neglected. The primary justification for this was that either these types of incident are very rare, or else, they tend not to represent a critical threat to life.

7.2 Computer Modelling of Fires

7.2.1 Emergence of Computational Fire Analysis

The need to accurately predict the properties of combustion processes has led to the development of numerous theoretical models that attempt to describe the process or effects of fire. These techniques now encompass an enormous number of approaches, ranging from simple "rule of thumb" estimation methods through to highly elaborate computer simulation methods. However, fires in general, and particularly accident fires, involve highly complex chemical-physical interactions. Many of these phenomena can only be represented adequately by theoretical analogy in certain straightforward and well-defined circumstances. As a result, the analysis of many classes of fire remain well beyond current capabilities and even relatively straightforward problems may require many hours of computer processing to solve. Thus, achievements made to date still only represent a comparatively small subset of what will almost certainly be achieved in the future.

Initially, most fire models had to be implemented with the use of hand calculations and thus they tended to consist of analytical approximations to physical processes. This approach is generally known as "zone modelling". The necessity for relatively simple calculations meant that only certain types of problem could be dealt with the use of this approach. Processes represented in zone models have to be predictable, reasonably well understood and of clearly defined applicability. Typical examples of these kinds of fire include closed compartment fires, torch flames, open pool fires and industrial furnaces. Note that the application of a classical zone-based analogy appears to require that the roles played by the fire environment geometry, fuel source and oxygen supply to the fire can each be accurately quantified by experimental means. In cases where it is possible to confirm that such features can be modelled independently of each other, a fire can be treated in the form of several separate zones. For instance, in a closed room fire, delineations are often made between the fire plume, ceiling smoke layer and the surrounding air (Cooper, 1988; Zukowski, 1978). This then enables a comparatively simple zone model to be derived by empirical means alone.

Often, however, strong couplings exist between different aspects of a fire problem. For example, surrounding structures will absorb heat and often be destroyed by the fire, the availability and composition of fuel can change as a fire spreads and fire fighting intervention, wind or oxygen depletion may affect fire growth rates. Thus, in many practical situations, the fire environment, fuel properties and oxygen supply cannot be treated as being independent of each other. Generally, therefore, a series of differential equations must be used to represent the effects of the more

important interactions that occur between the various aspects of fire development. Thomas states that the main difficulties faced by fire modellers are as follows (Thomas, 1985):-

1. Coupling between fuel and fire
2. Heat radiation from smoke
3. Chemical factors that control the combustion process

Returning to the example of the closed room fire, effects of heat loss to the surrounding structure, air leakages and radiant ignition of remote materials might be incorporated into the model. Often, the magnitude of these secondary effects will be predicted with the use of analytical techniques, rather than by direct experimental measurement. This effectively results in a “semi-empirical” zone model (BRE, 1991). In the past, many of these relationships were obtained from engineering guides and data handbooks. Increasingly, however, developed zonal models are becoming computer-based, which enables calculations to be performed repeatedly for initial scoping purposes.

The move to computer-based implementation also allows more complicated types of fire scenario to be addressed. For instance, the case of a closed room fire can now be extended to cover all room on a single floor, or even an entire building. Alternatively, the computer can be used to provide an increased resolution of analysis for a given problem. This is achieved by splitting previously homogenous fire zones into a series of individual elements, each of which can be solved iteratively in the form of a “miniature” fire zone. An example of this type of approach to dealing with the spread of aircraft cabin fires is provided by DACFIR (Poulios, 1986). Here, zones are segmented along the width, length and height of the cabin and the spread of combustion products from element to element is calculated at a series of time intervals. This represents perhaps the ultimate extension of the zonal fire modelling method and many of the techniques employed are directly analogous those found in CFD based field models (Thomas, 1985).

The analysis of fire with the use of Computational Fluid Dynamics (CFD) techniques is now a rapidly developing field. Most of these numerical methods were originally conceived for the purpose of predicting aerodynamic or other fluid flows. However, advances in the representation of combustion phenomena and enormous performance gain in computer hardware have ensured that the CFD modelling of fires can now be regarded as a separate field in its own right.

Almost all computational flow methods are based around simplifications of the classical Navier-Stokes equations (Allen, 1986). These describe the most fundamental physical-mathematical formulation of fluid flow in terms of velocity, internal energy, shear stress and heat flux. Although the Navier-Stokes equations appear deceptively simple, applying them to problems of practical interest and then obtaining their solution is usually very difficult. Firstly, all but the most simple of geometries are impossible to solve analytically. Consequently, it is necessary to discretise the fire domain into a large number of cells and apply the equations individually to each of these. Typically these “meshes” or “grids” may require tens or hundreds of thousands of elements in order to provide an adequate representation of the geometry under consideration. Then, arriving at a global solution that is consistent across all cell boundaries requires that an iterative solution procedure be adopted.

These tend to be numerically intensive and thus may require hours to converge on even the most powerful of computers.

The second major challenge in applying the Navier-Stokes equations to the modelling of fires consists of dealing with the non-homogenous nature of most of the properties being modelled. Parameters such as turbulence, heat evolution, viscosity, pressure, velocities, chemical composition, etc. can all vary with time and position throughout the fire domain, often down to a molecular level. For instance, the combustion of kerosene is known to involve at least sixteen different chemical species, each of which possesses their own distinct set of physical properties (Allen, 1986).

The solution, or even just the representation of such effects in a numerical form lies far beyond current capabilities. Thus, a series of simplifying approximations has to be made in order to represent the gross effects of many phenomena. The most frequently employed of these include the assumption of steady-state (time-averaged) conditions, dynamic viscosity models, single-phase flows and point sources of heat. In specific applications of combustion modelling, these approximations can be refined until they enable an accurate solution to be achieved. Areas in which the use of this approach has yielded significant results include engine combustion, chimney flows, industrial furnaces and stable gas flames. However, such methods are rarely robust enough to be applied to more general types of fire modelling problem without considerable simplifications being made (Fennell, 1988). Cases in which successes have been achieved tend to involve closely controlled, efficient combustion processes, in a precisely defined environment. These conditions are absent in many fires that are of practical interest, most notably so in the case of aircraft fire scenarios.

7.2.2 Development of Fire Modelling Approach

The examination of research undertaken in the field of computational fire modelling revealed that substantial achievements had been made across many areas. Empirically based techniques appeared to offer efficient solutions for certain, well-defined types of fire problem. These models have the potential to be extended by addition of analytically derived relationships, usually in order to address particular variations in a standard fire scenario. The utility of these empirical or semi-empirical techniques can be greatly increased by implementing them in computer form. For dealing with more general types of fire problem, however, a computational fluid dynamics-based approach may be required. Although CFD techniques are subject to a number of significant limitations, they constitute the only practical method of analysing many types of phenomena, short of recourse to large-scale fire experiments.

However, on returning to the information obtained in the accident data survey, it was far from clear which path forward should be taken. Obviously, it was desirable to integrate the features of real accident fires within the fire modelling analysis, where possible. Generally, however, it was perceived that a gap existed between the capabilities of available fire modelling techniques and the features that were usually present in aircraft accident fires. When taken at face value, established empirical fire models require the application of many assumptions, some of which would be difficult to justify in the context of an aircraft accident. In addition, published empirical methods appeared unable to represent several of the mechanisms or characteristics that can potentially be of overriding importance in aircraft fires. Some examples of these features are illustrated in Figure 7.4. With the exception of

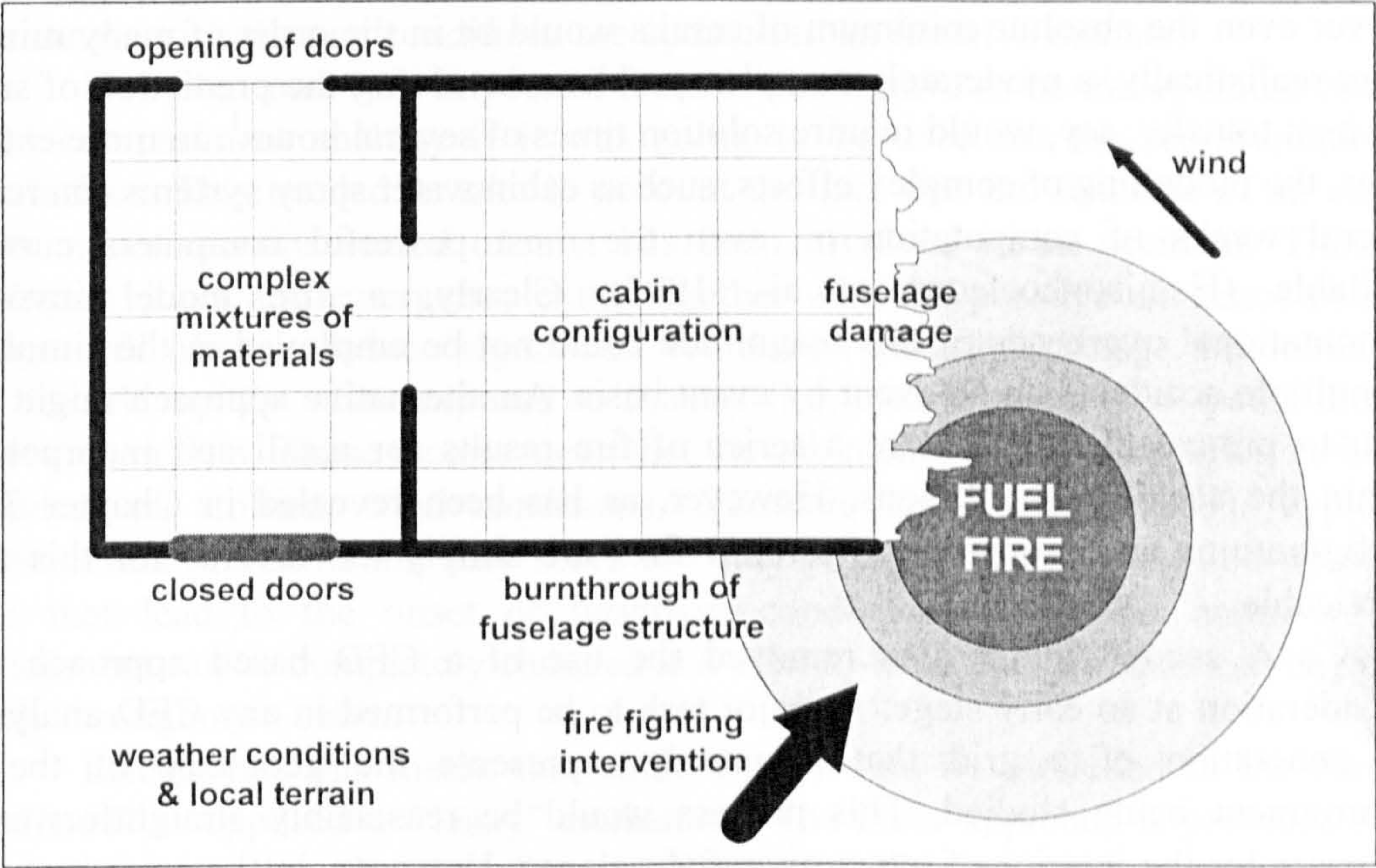


Figure 7.4: Basic Features of Aircraft Fire Scenarios

wind effects and the influence of open doors, none of the factors were dealt in any of the fire modelling studies examined.

Nonetheless, in spite of their inherent limitations, the existing analysis methods were the only real basis from which to start. It was therefore necessary to identify a way in which one or more of the fire modelling techniques studied could be modified or built upon to be more representative of aircraft fires. With this objective in mind, the attributes of the various methods were re-examined in turn, to ascertain precisely what their fundamental strengths were, irrespective of the features that they might happen to lack. It was apparent that the latter would need to be addressed with the addition of new modelling work, whichever fire modelling method was utilised.

Essentially, it was possible to represent the effects of fire within the accident analysis on one of three levels. These options would involve empirical, semi-empirical and CFD field modelling approaches respectively. Each of the three alternatives represented a different compromise in terms of model resolution, data needs and computational processing requirements, as shown in Table 7.1.

Method	Empirical	Semi-Empirical	CFD Field Model
Resolution	low	low - medium	high
Data Input Needs	low	medium	high
Computational Time	< 1 second	seconds	minutes - hours
Usage	"rule of thumb"	scoping purposes	optimisation studies

Table 7.1: Categories of Fire Model Available for Use

It was known from the very start of the study that a CFD field model would be unfeasible to integrate within the wide-ranging analysis being undertaken.

Primarily, this was because the computer calculation times that would be required to deliver even the absolute minimum of results would be in the order of many minutes. More realistically, a moderately complex problem, involving the prediction of smoke and heat transfer, say, would require solution times of several hours¹. In more extreme cases, the modelling of complex effects, such as cabin water spray systems can require several weeks of computation on even the most powerful computers currently available (Hadjisophocleous et al., 1995). Clearly, a fire model involving computational overheads of this magnitude could not be employed in the simulation of multiple accidents on an event by event basis. An alternative approach might have been to pre-calculate and store a series of fire results for recall and incorporation within the accident simulations. However, as has been revealed in Chapter 3, the configurations and properties of aircraft fires are simply too diverse for this to be practicable.

A second factor also removed the use of a CFD based approach from consideration at an early stage. A major task to be performed in any CFD analysis is the generation of a grid that accurately represents the geometry of the fire environment being studied. This process would be reasonably straightforward to automate for the interior of intact aircraft fuselages. However, in the present study it was deemed to be necessary to model the effects of fire occurring both inside and outside the aircraft cabin, including cases in which rupturing or structural break-up of the fuselage had occurred. These features could only be represented adequately with the use of an extremely complex three-dimensional mesh geometry, which would require days, or perhaps weeks of work to construct by hand for a single accident. The only obvious way of automating this task would be to utilise unstructured triangular cells, as opposed to an ordered quadrilateral mesh topology. However, unstructured meshes impose significant penalties in terms of flow solution time and this area of CFD is still at a comparatively early stage in its development.

The insurmountable difficulties associated with the implementation of a field modelling technique effectively restricted the choice of fire model to some form of empirical method. These were potentially capable of providing the basic fire data required for the analysis of aircraft accidents with minimum of computational processing. Most significantly, perhaps, the relative simplicity of an empirical approach would enable fire characteristics to be calculated automatically and made to interact with other modules of the simulation programme. However, as has been described, it was not immediately clear whether or not the features of aircraft fires could be interpreted and translated into processes capable of being represented with empirical modelling techniques. No previously reported activity of this kind could be located in any area of aircraft accident analysis.

It has been seen that simple zonal modelling techniques have been widely utilised to represent the effects of fire in closed compartments. Most of these efforts have been directed towards the analysis of fire safety in buildings, specifically for modelling fire development inside sealed rooms. Given the many similarities involved, it was anticipated that these methods could form the basis for modelling fire spread in the interior of aircraft cabins. The type of analysis envisaged was typified by

¹ For instance, Galea and Markatos have reported 12 hours needed to solve 4200 cells and 62 hours for 20 328 cells in this type of fire analysis (Galea and Markatos, 1991).

DACFIR (Poulios, 1986), where the interior of an aircraft is divided into a moderately large number of cells and conditions are updated in an iterative manner.

However, one very important feature would have to be incorporated into the closed compartment analogy if it was going to be used for the representation of aircraft fires. This needed to take in account the fact that the fuselage of an aircraft almost never remains sealed once it has been involved in an accident. Thus, the opening of doors and emergency exits, together with the possible existence of crash damage will often introduce significant ventilation effects. Fuselage structures also tend to melt rapidly when exposed to intense fire, creating additional paths through which air can flow. These factors mean that the cabin environment can often be highly dependent on ambient wind conditions (Quintiere and Tanaka, 1983). Typically, modest levels of ventilation may serve to delay or even prevent the build-up of fire gases that lead to the onset of flashover conditions. Thus, the nature of fire development can be completely changed and thermo-toxic fire products can be spread rapidly throughout a cabin.

Effectively, this meant that cabin fires would be modelled in the form of “ventilated” as opposed to “leaky” enclosures. The latter approach is provided for in some existing models, but is reliant on the assumption of constant static pressure (Zukowski, 1978), which, in turn, implies negligible airflow velocities. In contrast, conditions inside aircraft cabins may be highly influenced by ventilation effects induced by even the lightest of winds (King, 1989). This implied that internal airflow velocities would need to be considered an integral part of the cabin fire model.

The use of a compartment fire model alone would not fulfil the task of representing fire effects within the simulation analysis adequately. The majority of aircraft accidents involve fuel spillage fires, which start outside the fuselage and then usually ingress into the cabin area. Thus, conditions on the inside of the aircraft are usually determined by the growth and properties of a fire initially located on the exterior. It has already been seen that external fuel fires differ fundamentally in nature from those developing inside a fuselage. Thus, it would not be feasible to analyse both the interior and exterior aspects of a fire with a single fire model. The implication of this was that separate interior and exterior fire models would be required in order to represent most frequently occurring fire scenarios.

The branch of empirical fire analysis most closely related to external aircraft fires is that of open pool fire modelling. In general, pool fire theory is intended to address problems involving accidental spillages of hydrocarbon-based fuels in open spaces. Thus, they are precisely applicable to the analysis of most large-scale aircraft fires. The modelling of open pool fires essentially consists of predicting the size and properties of flames present above an approximately circular expanse of liquid fuel. This flame envelope is then used to derive levels of conductive and radiative heat transfer to surrounding objects by analytical means. Thus, the techniques involved fall into the category of semi-empirical fire modelling.

Perhaps the most fundamental parameter in any pool fire analysis is the diameter of the circle that used to represent the area of a fuel spill. The theory has been developed on the assumption of a fire base that is approximately circular in shape. Obviously, real fires almost never perfectly circular, and so have to be analysed in terms of their equivalent pool fire diameter. Once an appropriate value for this dimension has been decided, the remainder of the fire calculations are comparatively straightforward to perform. Therefore, the main challenge in attempting to apply an

open pool fire analogy to the analysis of aircraft accidents was to interpret past accident fires in terms of their effective pool fire areas. If this translation process could be achieved in a satisfactory manner, then external fire properties could be derived with the use of published theory and standard fire data.

At this stage, it appeared that the task of representing fire properties both inside and outside the passenger cabin in an approximate manner was feasible. However, there were still some significant problems to be overcome in coupling the compartment and pool fire models together, such that they would come to depict the effects of a single ingressing fire. These linkages were a fundamentally important aspect of the entire risk analysis, as they determine how a fire starting outside the fuselage penetrates into the interior to become a critical danger to those inside. The approach taken was to examine the mechanisms through which fire ingress had occurred in past accidents. Then, these basic processes could be quantified and incorporated within the programme in order to link internal fire development to the properties of the external fire. Given the complex nature of fire growth, it was apparent that many approximations would have to be made when attempting to quantify fire spread rates. However, the main purpose of the exercise was to demonstrate that it was perfectly feasible to link two very different empirical models by incorporating the primary modes of fire spread that take place between them. With further development, these intermediary processes might then be refined to a level at least comparable to that of the standalone compartment and pool fire analogies.

It was possible to confirm from the accident reports that most aircraft fires were likely to have spread in a combination of three ways. These were as follows:-

1. Direct flame contact with combustible materials
2. Convection of hot fire products into cabin area
3. Heating of surroundings by thermal radiation

These mechanisms can be interpreted as manifestations of the three fundamental modes of heat transfer; i.e. conduction, convection and radiation respectively. These are shown diagrammatically in Figure 7.5.

The extent of fire spread occurring as a result of direct flame contact is dependent on the spatial relationship that exists between the fire geometry and aircraft's structure. In most instances, a fire must melt or destroy significant portions of the fuselage before flammable cabin materials are exposed to heating effects. This effectively constitutes a thermal conduction/thermal inertia problem, for which a simple analogy could be developed. Often, however, flames are able to access the cabin interior directly, via open exits or through areas where extensive structural damage has occurred. In such circumstances, delays are minimal and fire spread is likely to be extremely rapid.

Most aircraft fires emit a substantial proportion of their total energy in the form of heat radiation. This is absorbed by surrounding objects, which, as a result, increase in temperature and often become spontaneously involved in the fire. This process can play an active role in the spread of both external fuel fires and fires involving the cabin interior, as well as contributing to occupant burn injuries.

In the case of external fires, humid atmospheric conditions can serve to attenuate radiation levels significantly over modest distances. However, the infrared frequencies involved are able to penetrate water vapour at least as well as visible light.

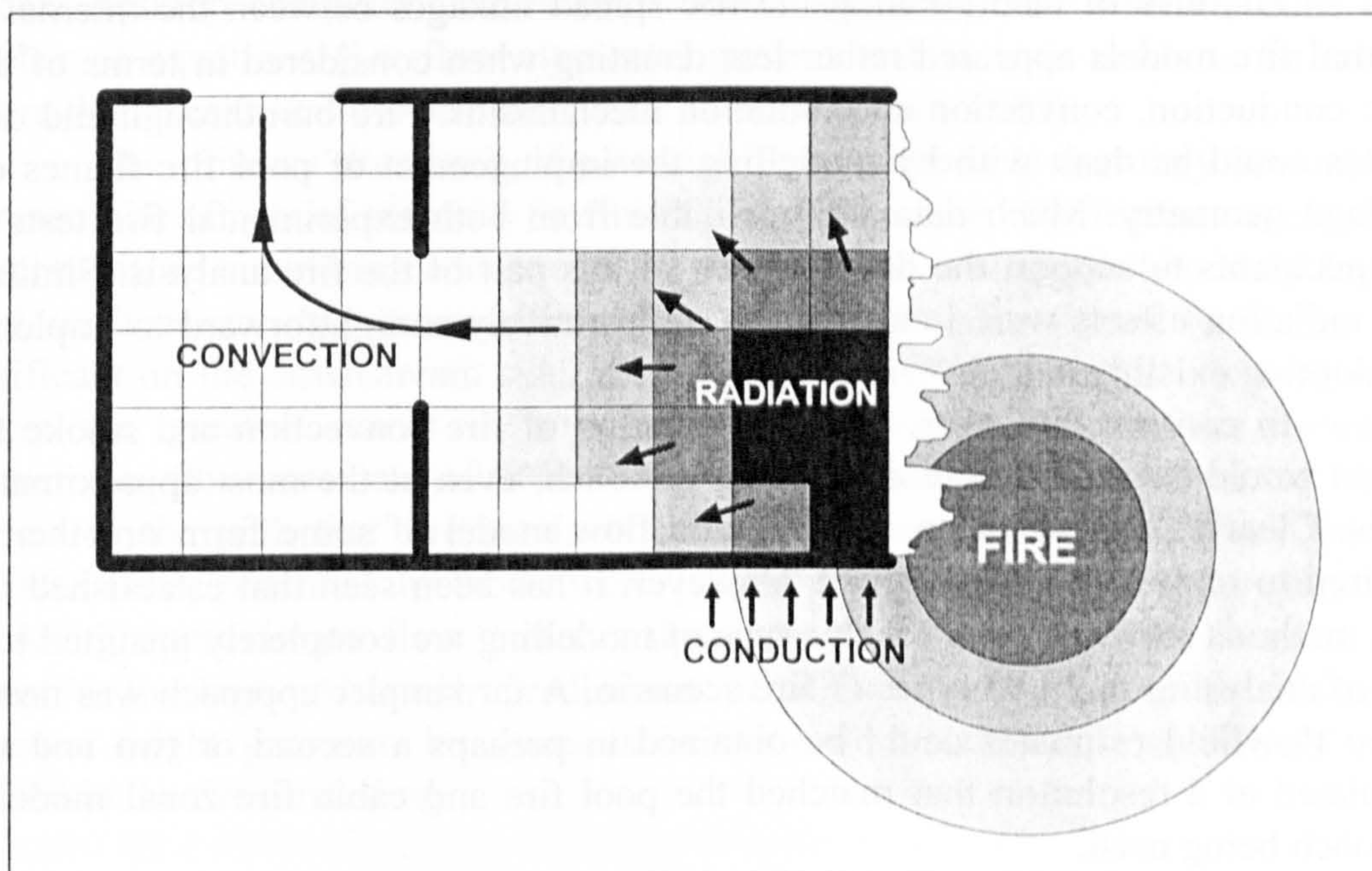


Figure 7.5: Primary Mechanisms of Fire Spread

Thus, fire fighting personnel have reported on one occasion that, in misty conditions, they were able to feel the heat from a large fire before being able to see the flames. Fire spread by thermal radiation effects is dependent on three factors; the intensity of radiation produced by a fire, the attenuation of this energy by the atmosphere and the proportion of the heat absorbed by surrounding materials. These effects are readily quantifiable for the case of objects in the vicinity of an open pool fire. However, their role in the growth of cabin fires is less certain (Poulios, 1986).

It has been seen that, in all but the smallest of pool fires, the majority of the thermal energy produced is contained in the smoke and fire gaseous products evolved. When a fire occurs in open surroundings, all of this energy is vented to the atmosphere in the form of a buoyant smoke plume and it plays no role in fire spread. In contrast, when a fire occurs adjacent to, or inside, an aircraft, a proportion of these fire products will usually flow into the passenger cabin. This inevitably leads to a rapid deterioration in conditions inside, with a reduction in visibility and potentially lethal concentrations of toxic or highly irritant substances. The buoyancy of the hot gases means that cabin thermo-toxic environments tend to be highly stratified. Thus fire spread occurs chiefly in the upper region of the cabin, for example via ceiling panels, cabling ducts and overhead stowage bins.

This mechanism of fire growth is essentially a convection driven process, i.e. it is dependent on the movement of air. These air currents can result from a number of different causes, for instance ambient wind, air entrainment into flames, fire gas production and buoyancy effects. Consequently, the transport of fire products by convective means can often constitute highly complex phenomena. In general, fire flow fields can only be predicted to a moderate level of accuracy with the use of CFD or full scale experimental testing techniques.

In particular, prevailing wind conditions are known to have a potentially important role in fire development. In the case of pool fires, flames and fire plumes can be drawn considerable distances in a downwind direction. This obviously modifies flame impingement and radiation levels for surrounding objects.

The task of incorporating the fire spread linkages between the internal and external fire models appeared rather less daunting when considered in terms of these basic conduction, convection and radiation mechanisms. Fire burnthrough and direct ingress could be dealt with by modelling the impingement of pool fire flames on a fuselage geometry. Much data was available from both experimental fire tests and past accidents to support the development of this part of the fire analysis. Similarly, heat radiation effects were judged to be comparatively straightforward to implement by adopting existing models.

In contrast, however, the representation of fire convection and smoke flow effects would be rather more difficult to establish, even at the most approximate of levels. Clearly, the use of an aerodynamic flow model of some form or other was required to represent smoke spread. However, it has been seen that established CFD field methods currently used for this type of modelling are completely unsuited to the task of analysing multiple types of fire scenario. A far simpler approach was needed, where flowfield estimates could be obtained in perhaps a second or two and were calculated at a resolution that matched the pool fire and cabin fire zonal modelling approach being used.

The only feasible way of fulfilling this requirement appeared to be the use of a potential flow analogy. Potential flow methods utilise analytical functions to represent the most fundamental aspects of fluid flow. The most commonly used flow primitives include a unidirectional flows, flow sources, sinks, doublets and vortices. Some of these basic building blocks are illustrated in the left hand side of Figure 7.6.

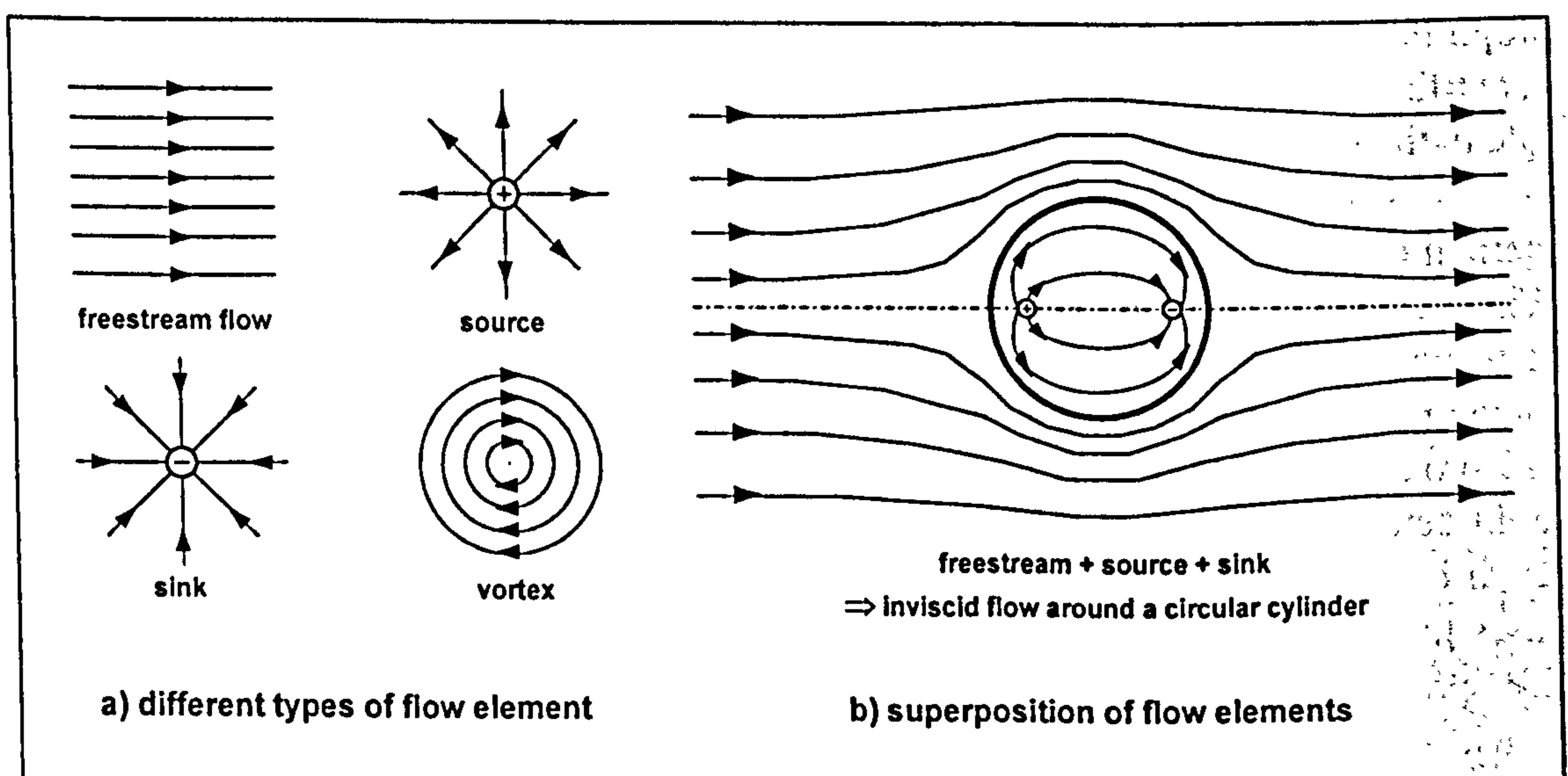


Figure 7.6: The Potential Flow Analogy

Because these functions are all linear, they can be superimposed on each other to build up more complex flow fields. Figure 7.6 shows how three flow elements can be used to represent inviscid flow around a circular cylinder. With larger numbers of flow primitives, it is possible to represent airflow around objects of arbitrary shape. The task of resolving this type of flow problem simply reduces down to that of solving a set of simultaneous equations (one for each flow element being used). Thus, reasonably complex potential flow fields can be calculated in a matter of seconds on a

modern desktop computer¹. However, solution times increase with the cube of the number of equations (i.e. flow elements) present and so care needs to be taken to ensure that excessive flow resolutions are avoided (Press, 1992).

The primary drawback of potential flow methods is that they are unable to represent the effects of viscosity in fluid flow. This means that features such as flow detachment, re-circulating eddies and the existence of a sluggish boundary layer on solid surfaces are not catered for. In general, such effects tend to be far more significant on the downstream side of an object. Consequently, this is where we can expect the greatest errors in a potential flow solution to occur. Fortunately, downstream flow areas are of little consequence in the current study, as we have no interest in the path that fire products take when they are flowing away from the aircraft. Thus, potential methods were judged to be adequate for the purpose of predicting approximate flow patterns upstream and throughout the interior of an aircraft's fuselage. Although predictions of airflow velocities in the downwind direction might prove to be spurious in some circumstances, they would not be utilised in the fire modelling.

7.3 Representation of Cabin Thermo-toxic Environment

7.3.1 Formulation of the Modelling Approach

The rationale for modelling cabin thermo-toxic conditions was to determine the effect that fire might have on the victims of aircraft accidents. It would have been possible to create a highly sophisticated fire spread model for the purpose of achieving this, based on established numerical CFD techniques. However, it was judged that this would be inappropriate for the type of study being undertaken for a number of reasons:-

- It would be difficult to set up a complex model to run autonomously
- Computing calculation times tend to increase exponentially with model size
- The level of calibration data needed was only available for a few types of fire
- The data provided would be too detailed for other parts of the risk analysis

What was really required was the simplest possible cabin fire model that was capable of providing the required resolution of data. Given that the cabin fire model would be created solely for the purpose of determining evacuee incapacitation levels, data needs were effectively defined by the parameters used in published Fractional Effective Dose (FED) incapacitation models. As recounted in Chapter 2, the physiological effects of fire atmospheres can be grouped into main five areas:-

1. High ambient temperature levels
2. The presence of dense smoke

¹ For example, a set of 100 simultaneous equations might require somewhere in the region of 0.5 - 1.0 seconds to solve on a typical engineering workstation computer.

3. Toxic and narcotic gases
4. Low ambient oxygen levels
5. Highly irritant fire products

Fire tests have shown that toxic, narcotic and irritant substances, together with oxygen depletion are generally associated with the presence of smoke. Obviously, the chemical composition of a smoke layer can vary enormously, according to fire properties and types of material involved. However, the complexity of the reactions occurring in fires means that combustion product mixtures are difficult to measure by experimental means and virtually impossible to predict analytically in all but the simplest of cases (Krause, 1996). As a consequence of this, when undertaking fire modelling, the composition of fire gases is either approximated with the use of simple empirical models (Hadjisophocleous et al., 1995), or fixed proportions are assumed.

It was concluded that the latter approach would suffice for the current study, at least for the initial stages of development. Thus, oxygen depletion levels, and concentrations of toxic, narcotic and irritant substances could then be assumed to be proportional to local smoke intensity. Effectively this meant it would be necessary only to obtain predictions of how ambient cabin temperatures (including associated thermal radiation levels) and smoke intensity varied throughout an aircraft's cabin with time.

It was decided at a comparatively early stage in the work that, initially, a two-dimensional (2-D) approach would be used for the cabin fire modelling. Thus values of heat and smoke would be calculated on a plane located at 1.5 m above cabin floor level. This taken to correspond with the average chest height of evacuating passengers and thus be indicative of the air conditions that people would be breathing when standing in an upright posture. In comparison with the 2-D approach, a full three-dimensional analysis would require an order of magnitude more computer calculations to be performed and involve a corresponding increase in the quantity of data being processed. As a result, calculation times would almost certainly be unacceptably slow when attempting to undertake multiple accident the simulations.

However, there were substantial issues that needed to be resolved when attempting to represent complex three dimensional fire phenomena in only two dimensions. It has already been seen that stratification of fire products usually results in the formation of a hot buoyant smoke layer near the ceiling of a compartment. This layer spreads in a horizontal direction and then gradually descends until the possible onset of fire flashover. Thus, the key to the successful modelling of cabin conditions is to encapsulate the basic properties and dynamic behaviour of smoke layer development.

A 2-D fire model would be capable of calculating the growth of a smoke layer in a horizontal plane with little difficulty. This could be achieved by implementing numerical analogies of convection, diffusion and radiative fire spread mechanisms. Effectively, this would then provide a map that shows the extent of the smoke layer, as measured at passenger chest height. The main drawback of attempting this kind of simplified 2-D approach was that no information would be generated on conditions above or below the plane in which calculations were performed. This would prevent the modelling of effects such as evacuees crouching down or crawling on the floor in an attempt to remain below a descending smoke layer.

In spite of the difficulties involved, it was judged that the advantages of obtaining estimates of the cabin thermo-toxic environment in real time far outweighed the limitations inherent in the use of a 2-D analysis. Thus, it was decided to adopt a highly simplified approach to the modelling of cabin fires. It was recognised that there would be much potential for further improvements to be incorporated in this area of the work, once other priorities had been dealt with.

In the short term, the consequences of passengers moving below a smoke layer could be allowed for in the evacuation modelling, if necessary. At a later stage, it would be comparatively straightforward to add stratification effects to the 2-D cabin fire model. One way to achieve this would be to integrate the accumulation of smoke in each section of the cabin over time. Such an approach would involve calculating smoke spread at ceiling level and converting excess concentrations into a smoke layer height, i.e. in the form of an inverted stacking process. This information could then be used to calculate variations in ceiling layer depth throughout the passenger compartment. Because smoke depths would be derived from existing information, this procedure could be implemented extremely efficiently and would not slow the operation of the fire model significantly. In essence, the “extrusion” of 2-D data in this manner constitutes what is sometimes referred to as “2½-D” modelling.

7.3.2 A Note on the Measurement of Smoke Intensity

It is perhaps worthwhile noting here that smoke levels will be referred to in terms of their *Optical Density* per metre (OD/m). This is a dimensional measure of light transmissivity per unit of length of smoke. Predictably, in American and British fire research literature, smoke intensities are usually quoted per foot (OD/ft). Both of these measures are proportional to another frequently used measure, the extinction coefficient. This is defined as follows:-

$$\text{Extinction Coefficient } K = \frac{2.3}{L} \log_{10} \frac{I_0}{I} \quad (7.1)$$

where

- L = light path length
- I_0 = Intensity of incident light
- I = Intensity of transmitted light

Thus:-

$$\text{Optical Density / m} = \frac{K}{2.3} \quad (7.2)$$

and

$$\text{Optical Density / ft} = \frac{K}{7.55} \quad (7.3)$$

7.3.3 Choice of Cabin Fire Effects to be Modelled

As discussed in the previous section, the purpose of modelling fires in the analysis was to determine how they affected the escape and survival of accident victims. Thus, effectively, the only parameters required from the fire simulation module were those necessary for establishing levels of thermo-toxic incapacitation for

individuals still remaining in the aircraft. These fire effects can be categorised into five areas; namely temperature, smoke, narcotic gases, oxygen depletion, and irritants. Each of these aspects of the fire environment will now be considered in turn.

The high temperatures present in the vicinity of fires can possess a debilitating effect on those exposed. Purser makes a distinction between heat convection and thermal radiation when assessing heat incapacitation levels (Purser, 1995). However, the effect of the latter on humans is extremely difficult to quantify and can vary to a large extent from individual to individual (Purser, 1988). Therefore, it was decided that modelling thermal radiation levels in the cabin interior with anything but the simplest of approaches would be unjustifiable. Thus, thermal radiation intensities were assumed to be a direct function of ambient temperature and were not stored explicitly. Consequently, the thermal characteristics of the cabin environment were defined by a single distribution of ambient temperature. This was recorded in the range of 0 to 250 °C or over, on the basis that complete incapacitation by thermal means alone can be expected to occur at a temperature of around 190 °C (Purser, 1995).

The accumulation of smoke in the cabin also plays an important role in determining occupant survivability. Research has suggested that when people are exposed to the effects of irritant smoke, their speed of movement slows, stress levels rise and they may turn back rather than continuing to move forwards (Jin and Yamada, 1989). Movement speed may be reduced to that in complete darkness at smoke optical densities in the region of 0.20 /m. Studies of building fires have shown that, on average, people will turn back to look for an alternative escape route at optical densities of 0.33/m. In case of aircraft fires, however, people may be forced to move through considerably higher concentrations of smoke in order to reach an exit. Thus, it was decided to be conservative and model cabin smoke distributions at levels of up to 1.0 OD/m. Given both the extremely toxic properties and the high temperatures associated with cabin smoke at these concentrations, complete incapacitation will occur almost immediately in such conditions.

The most important narcotic gases produced by fires are carbon monoxide (CO) and hydrogen cyanide (HCN). The presence of carbon dioxide (CO₂) in high concentrations induces hyperventilation, which tends to multiply the effects of any narcotic gas concentrations present. As stated previously, the concentrations of these types of fire products were simply assumed to be proportional to local smoke density. However, it was decided to store individual distributions of cabin CO, HCN and CO₂ concentration. This would facilitate the addition of an empirical smoke composition model at later stage, if so desired. The units used to define these gas concentrations were parts per million (ppm).

Fires consume large quantities of oxygen and, as a result, cabin oxygen levels can often drop significantly in the course of a fire. This induces low oxygen hypoxia effects in those exposed. Oxygen depletion was therefore modelled, albeit at a rather basic level, by assuming depletion levels were proportional to local smoke density. Again, it was chosen to store values explicitly, both for reasons of computational efficiency and because they would be required for any implementation of a smoke composition model.

The final component of the cabin thermo-toxic environment was the level of irritant substances present. The most important irritant gases present in aircraft fires in significant concentrations include hydrogen chloride (HCl), hydrogen bromide (HBr),

hydrogen fluoride (HF), sulphur dioxide (SO₂) and nitrogen dioxide (NO₂). However, in reality, thermal decomposition products evolved in aircraft fires are extremely complex and thus prohibitively difficult to analyse on an individual basis. Thus, an approach involving gas concentrations defined in terms of materials mass loss per unit of cabin volume may be more appropriate, as this avoids the need to identify the composition of the fire products involved. For example, the mass of cabin furnishings decomposed in each cubic metre of air is more straightforward measure to deal with than the equivalent spectrum of HCl, HBr, HF, SO₂ and NO₂ concentrations. Nonetheless, difficulties can arise when attempting to account for the wide range of materials present in aircraft cabins. Another significant factor that has to be taken into consideration is that gases evolved under non-flaming conditions can be more irritant than products arising from flaming combustion by a factor of ten or more (Purser, 1988). Consequently, rather than attempting to deal with these complexities in an explicit manner, irritant concentrations were represented on a generic level with the use of a single cabin irritancy variable. This was defined in terms of a Fractional Incapacitating Dose, where a value of 1.0 represents complete incapacitation by irritant effects. The local degree of irritancy present in the cabin was assumed to be proportional to the prevailing smoke density.

In summary, the fire modelling was designed to generate distributions of seven key parameters that define thermo-toxic survivability levels throughout the passenger cabin. These distributions were two dimensional, time dependent and described the following variables:-

- Ambient temperature
- Smoke density
- CO, HCN and CO₂ levels
- Oxygen depletion
- Irritancy level

7.3.4 Representation of Cabin Geometry

As recounted in the previous chapter, the cabin configurations of passenger aircraft were defined with the use of a coded two-dimensional grid. The resolution of this grid (0.15 - 0.20 m) had been determined by the requirements of the evacuation model. Thus, for example, gaps of these dimensions are typical in situations where passengers might be squeezing past each other in seat rows or narrow aisles. Procedures had also been developed to automatically separate, translate and rotate selected portions of an aircraft's cabin grid. These involve the use of transformation matrices and enable the geometric effects of fuselage break-up and the separation of cabin sections to be represented in accidents that involve severe crashes.

The evacuation grids were the obvious starting point for modelling the geometry of the cabin thermo-toxic environment. However, the resolution that they provided was too high for representing the development and spread of fuselage fires with the empirical modelling techniques being employed. Consider, for instance, a typical Boeing 747-400 seating configuration, coded on an array measuring 325 by 40 cells. This provides a total of 13,000 individual cells that require updating with each iteration of the cabin fire calculations - obviously rather excessive for a "simple" fire model. At this level of resolution, changes in the local environment would be

comparatively small over the distances involved. Thus, realistically, cabin conditions could be modelled perfectly adequately with perhaps an order of magnitude fewer data points. This would also provide the advantage of significantly reducing the time required to perform fire model calculations and to look up local cabin conditions.

The method used to obtain a lower resolution cabin geometry for the thermo-toxic modelling was to sample the evacuation grid co-ordinates at a fixed interval. Thus, for example, cell vertices could be obtained by looking up the co-ordinates of, say, one in three cells of the evacuation grid. This concept is illustrated in Figure 7.7.

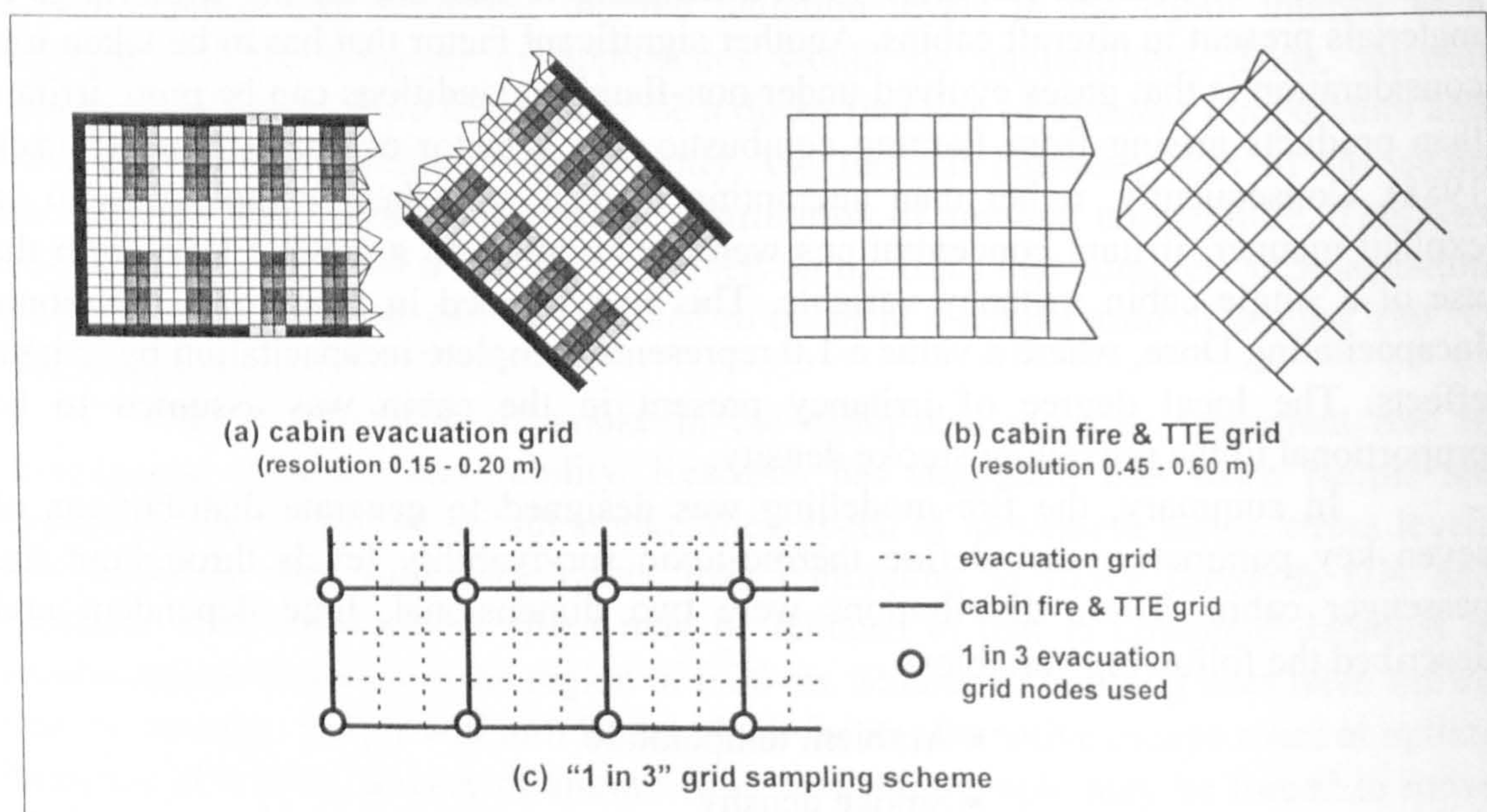


Figure 7.7: Use of Different Grid Resolutions to Represent Fuselage Geometry

Note how obtaining the a low resolution grid in this manner ensures that fuselage breakages and distortion are automatically incorporated into the fire model geometry. It should also be observed that information can be referenced between the evacuation and TTE grids simply by multiplying (or dividing) cell indices by 3. Thus, for instance, a passenger located (n, m) in the evacuation grid will experience the conditions at cell $(n/3, m/3)$ in the cabin TTE model. This feature was used extensively in the simulation programming, for example, to determine levels of thermo-toxic incapacitation in evacuating passengers and to set up the cabin airflow model.

In general, it was found that a grid sampling ratio of 1 in 3 provided the most suitable cell size for the purpose of modelling cabin fires. However, any integer sampling ratio can be used, allowing cabin conditions to be modelled at a higher or lower resolution, if future requirements dictate.

7.3.5 Calibrating Levels of Fire Effects

As stated previously, degradation in cabin conditions was assumed to be proportional to local smoke density. Most of the results obtained from large scale aircraft fire tests indicated that this would be a reasonable first approximation in situations where cabin ventilation was sufficient enough to prevent the occurrence of sudden flashovers. Thus, in spite of the fact that the composition of fire atmospheres could vary widely from experiment to experiment, concentrations of the fire products tend to increase fairly consistently with ambient smoke levels.

Cabin conditions were calibrated with a series of fire test results reported by the FAA (Sarkos et al., 1982). These experiments involved the use of a complete aircraft fuselage, fitted with cabin furnishings representative of those in use in the early 1980's. Exits were left open and a large (8' by 10') fuel fire was located outside an opening intended to be representative of a fuselage rupture. Measurements were taken at a height of 5'6" in the aft cabin area.

The test results indicate that a flashover had begun to develop after approximately two minutes. Mid-way through this process, smoke levels exceeded 1.0 OD/foot for the first time. At this point, cabin conditions were estimated to be as shown in Table 7.2.

Parameter	Measured value at smoke OD of 1.0/foot	Scaled value at smoke OD of 1.0/m
Ambient Temperature	260 °C	122 °C
CO	10,000 ppm	3,000 ppm
HCN	20 ppm	6 ppm
CO ₂	60,000 ppm	18,000 ppm
Oxygen Level	13.0 %	18.6 %
Irritants	2000 ppm (e.g. HF: 1000; HCl: 600)	600 ppm

Table 7.2: Scaling of Cabin Conditions Present During Fire Flashover

The values in the right hand column have been scaled to correspond with conditions at a smoke optical density of 1.0/metre. These are the figures that were implemented in the cabin fire model. Note that the scaled temperature value was actually calculated to be 92 °C. However, cabin temperature rises were generally found to precede increases in smoke density by about 10 - 15 seconds during the fire experiments. Effectively, this smoke hysteresis effect meant that rises in ambient temperature were approximately 30 °C higher than might be predicted with a linear temperature : smoke relationship. Thus, in reality, a smoke level of 1.0 OD/m could be expected to correspond with an ambient temperature of around 122 °C.

Also, the concentration assumed for irritant fire products was derived from the levels of HF and HCl present. Thus, 600 ppm of irritants present at a smoke density of 1.0 OD/m would include 300 ppm of HF and 180 ppm of HCl, with the remainder comprising miscellaneous fire products.

7.4 Modelling of External Pool Fires

7.4.1 Empirical Quantification of Open Pool Fires

Aircraft fires usually involve the release of large volumes of fuel, as a result of damage sustained by wing tanks. Typically, therefore, most accidents entail large open fires, characterised by large, rapidly spreading turbulent flames, thick black smoke and intense thermal radiation. This type of pool fire is also encountered in many industrial environments where there is a requirement to store large volumes of liquid hydrocarbon fuels. Consequently, open pool fires have been the subject of much research by fire safety engineers world-wide.

The primary hazard represented by a large liquid fuel fire is the extremely high intensity of thermal radiation emitted. It has already been seen earlier in the chapter that, for large fires, most of the heat produced will be released in the fire plume. However, if the fire occurs in the open, the majority of these high temperature products will rise away and have little effect on the surroundings at ground level. As a result, radiative heat transfer and direct flame impingement are usually the predominant mechanisms of fire spread. Thus, the modelling of open pool fires by empirical means essentially consists of modelling fire geometry and estimating the levels of heat that are radiated to surrounding materials. Two different approaches are possible when representing heat emissions from a fire; these involve the use of *point source* and *solid flame* radiation models respectively (Mudan, 1987).

At a simplest level, a fire can be considered as a point source of thermal radiation. This implies that heat is emitted uniformly in all directions from a single point and, if the effects of atmospheric attenuation are ignored, heat intensity diminishes with the square of distance. For a given fuel type, the power of the radiation source will be primarily a function of the area of fuel undergoing combustion.

In contrast, the use of a solid flame radiation model enables the effects of flame geometry to be included within a pool fire analysis. This can be particularly significant when flame size is comparable with the distances of surrounding objects, as is obviously the case in most aircraft fire accidents. Flames are represented in the form of a cylindrical envelope, positioned above a circular pool of fuel. Figure 7.8

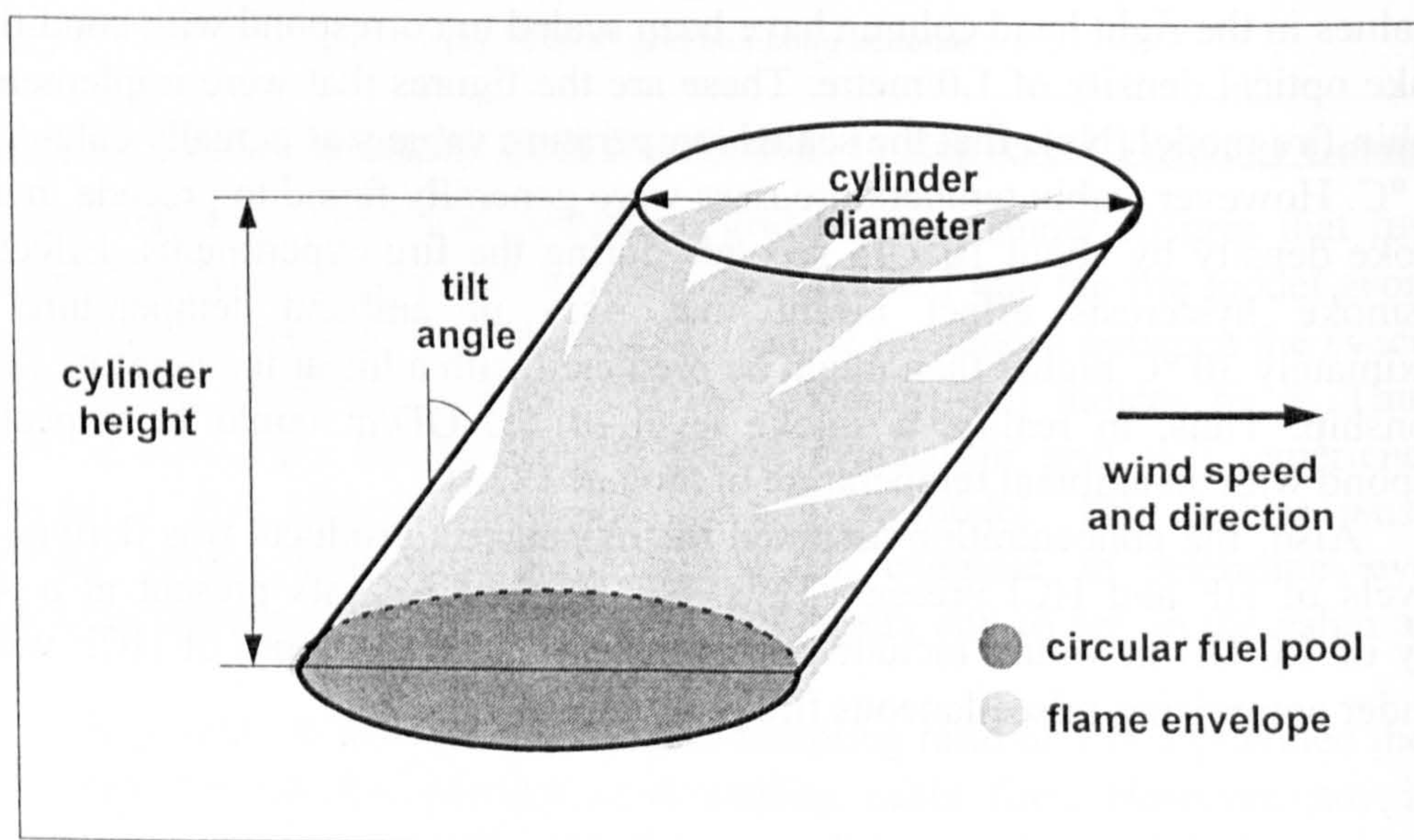


Figure 7.8: Cylindrical Model of Flame Geometry

shows how the effects of wind can be catered for by tilting of the cylinder axis. It is assumed that this flame geometry comprises a uniform grey body emitter of thermal radiation. This then enables the radiative heat intensity at surrounding points to be obtained by a process of geometric integration. The effects of atmospheric attenuation and the surface orientations of exposed objects can also play a significant role in determining levels of heat transfer. Thus, these considerations are frequently accounted for in solid flame model calculations. These and other aspects of the method are covered more fully in Appendix D There it shown that empirical

relationships, derived from the results of fire experiments, and theoretical modelling techniques can be applied to simplify the task of implementing a solid flame model considerably. As result, thermal radiation fields can be obtained with knowledge of comparatively few fire parameters. The data that is typically required consists of the fuel pool geometry, wind conditions, fuel type and atmospheric humidity level.

The preliminary accident data survey had indicated that it was probably feasible to obtain or estimate approximate values for this information in a substantial number of the incidents being studied. This eventually turned out to be the key to establishing a workable pool fire model within the simulation analysis.

Thus, it was discovered that the fundamental characteristics of large open fuel fires can be modelled at an approximate (but, in the current context, perfectly adequate) level by empirical means. Essentially, the analysis required could be broken down into three stages, regardless of the radiation model being used. These are as follows:-

- geometric characterisation of the pool fire
- determination of the radiative properties
- calculation of radiant heat levels at required positions

In the case of aircraft fuel fires, the second and third of these tasks are comparatively straightforward to perform with the use of published data and established fire modelling techniques. However, the major difficulty in attempting to establish a feasible external fuel fire model was to determine the geometric properties of fires that occur in aircraft accidents. Put simply, data needed to be obtained to find out how large aircraft fuel fires actually are; whereabouts, in relation to the fuselage, they tend to start and also, how quickly they are likely to spread.

Seemingly, in spite of the large amount of research to have been undertaken into aircraft fires world-wide, this fundamentally important task had yet to be undertaken by anybody. In general, researchers involved in experimental fire testing or computational fire modelling tend to work with “standard” fire sources, whose properties have been set for experimental convenience. Comparatively little attention has been paid towards determining how these procedures compare with the fires that actually occur in aircraft accidents.

Consequently, it was decided to devote a significant proportion of the time available for the fire analysis to the study and quantification of past aircraft fires. It was noted that, whatever techniques were employed in the fire modelling, the accuracy of the results provided would effectively be limited by the quality of fire data obtainable from past accidents. There would be little point in incorporating a solid flame radiation model into the simulation if the basic data necessary for its calibration had not been obtained. Thus, a simple point source radiation model was used and the resultant time saving used to derive appropriate input data from past accidents, to enable the model to be utilised effectively.

Once this had been achieved, the detailed calibration data would be sufficient to drive almost any type of fire model. Thus, for example, it would be very straightforward to implement a standard solid flame fire model at a later stage, should this be required.

Much of the information about fires that was obtained from the examination of past accidents was almost certainly unique in nature. Therefore, it was attempted to keep the analysis as simple and clear as possible, so that results could readily be

reproduced, augmented and utilised with confidence by other fire safety researchers. Given that, in many instances, numerical data would have to be derived from essentially descriptive information, all interpretations made about the accident fires were carefully catalogued on an individual basis. This then enables the existence of any misinterpretations or points of contention to be identified and, if possible, rectified with better information that might come to light.

7.4.2 Fire Geometry Analysis: Equivalent Pool Fire Areas

The basis of using a liquid pool fire analogy in the analysis of external fires was that the vast majority of aircraft accidents involve large fuel spill fires. In general, empirical models treat these fires in terms of a continuous circular (or rectangular) area of burning fuel, located in an open area. Obviously, in reality, real fires are unlikely to exhibit this degree of uniformity. Fuel will tend to form irregularly shaped pools, the ground may be patchy or undulating, objects may be present in or around the fire and flames may be intermittent. As a result, in empirical modelling, fire sizes tend to be quantified in terms of an *equivalent* pool fire area. This concept attempts to take into account deviations in fire properties and provides a common unit of measurement with which to compare different fuel fires. The assignment of values for equivalent pool fire areas is, to a certain degree, a subjective process, requiring the application of reasoned judgement and common sense. Therefore, the accuracies that we can expect to achieve will be poor. Consider, for instance, that if we are able to estimate the linear dimensions and flame consistency of a fire to within plus or minus 10 percent each, it will only be possible to derive the equivalent pool fire area to an accuracy of plus or minus 30 percent. However, if we are able to study a large number of fires, the effects of any errors are likely to be averaged out to a point where they prove to be acceptable. With this in mind, the assignment, where possible, of equivalent pool fire areas to the aircraft fires was used to form the first stage in the fire geometry analysis.

With information obtained from the accident data survey, it was felt to be feasible to undertake this type of estimation for 72 of the 217 incidents studied. In each of these cases, it was possible to determine where the fire had started and to what proportions it eventually grew to, with a reasonable degree of accuracy. For the purpose of analysis, this information was recorded for each of the 72 accidents in question with the use of an area plot. Typical examples of these plots are shown in Figure 7.8. Note that the aircraft configurations shown are generic and thus should not be taken to be representative of the actual aircraft types involved.

The shaded ellipses represent the estimates of the maximum area over which fire spread in each incident, i.e. equivalent pool fire areas. The use of elliptical fire shapes provided a greater degree of flexibility (and thus accuracy) than attempting to interpret fires as circular areas. From a theoretical standpoint, elliptical pool fires can be analysed by linearly mapping circular pool fire modelling theories.

It should be noted that the fire areas indicate the extent of fire at cabin level. Thus, the masking effect of low set wings was taken into account when estimating fire shape functions. In most instances, fires were able to spread over the top of the wing area, either as a result of wing detachment, the presence of fuel tank rupturing or the effects of wind. Similarly, the estimates of fire areas also include the effects of intervention by fire fighting services, in cases where these were significant.

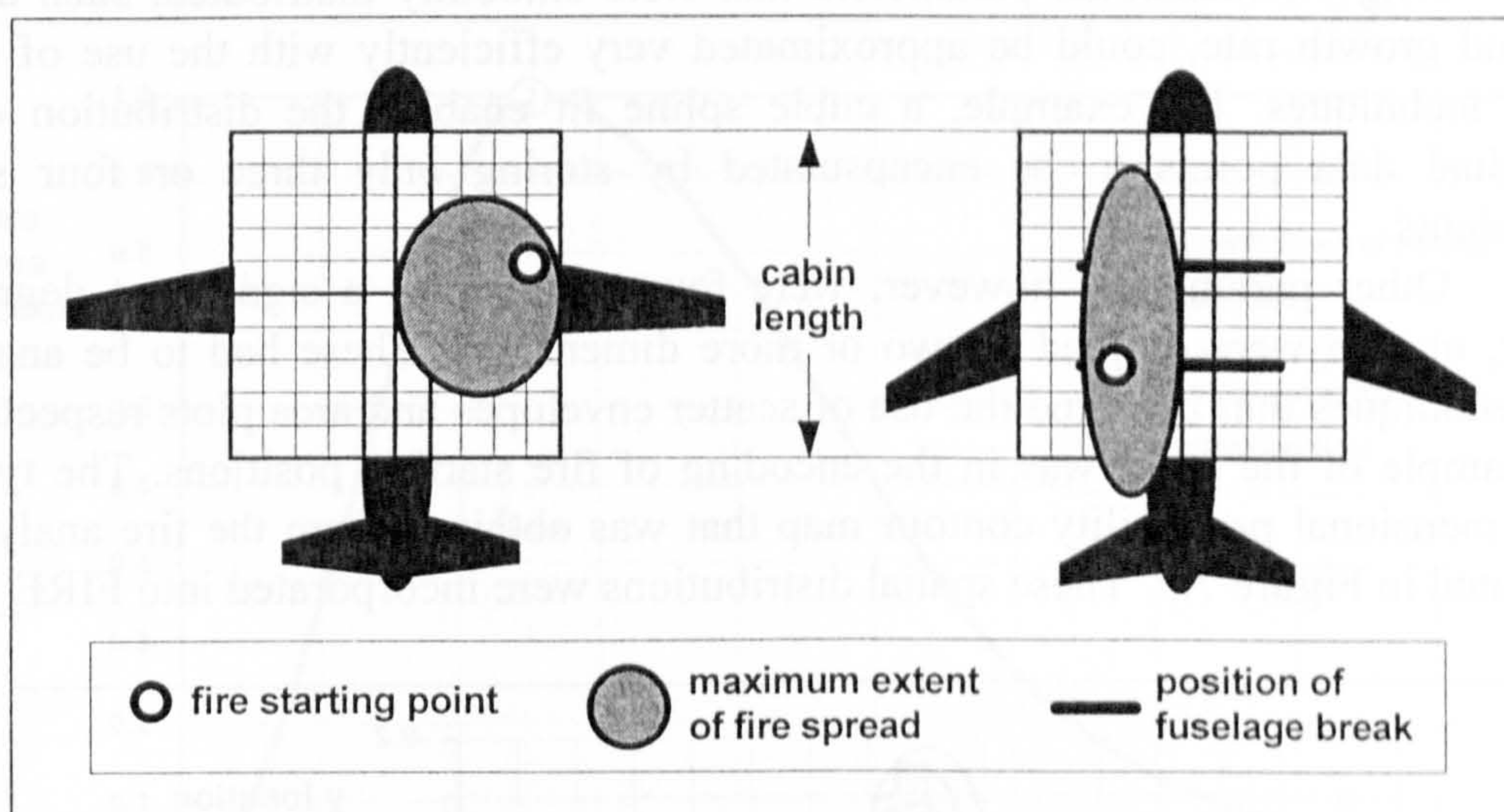


Figure 7.8: Plotting of Fire Location and Spread

The size of the aircraft involved was of relevance in many of the incidents analysed; larger aircraft carry greater quantities of fuel and thus tend to be accompanied by larger fires in the event of an accident. Consequently, this influence was factored out of the analysis by factoring all distances by the cabin length of the aircraft involved. Thus, the scale of the grids shown in the diagrams is one tenth of the cabin length. Also note that the positions of any fuselage breakages were recorded in the diagrams, to aid interpretation with accident reports. The 72 fire spread diagrams are provided in Appendix E.

7.4.3 Modelling of Fire Geometry and Growth Rate

The classification of past aircraft fires in terms of elliptical pool fire areas enabled a systematic analysis of fuel fire characteristics to be performed. The information obtained from this study was of fundamental importance in ensuring that the details of fire scenarios being modelled were both realistic and statistically representative of those encountered in actual aircraft accidents. Without data of this sort, fire properties could only have been prescribed in an arbitrary manner and thus the entire nature of simulated outcomes might have been changed.

The approach taken in the analysis of the 72 fire spread diagrams was to quantify the various parameters that were required for specifying the pool fire model. Probability distributions were derived for each of the following variables:-

- Location of fire starting point(s)
- Variation in fire sizes
- Dependency of fire shape on position
- Movement of fire centre
- Fire growth rate

The procedures used in the analysis and the results they delivered are provided in Appendix F. Probability distributions were obtained in a number of different formats, some of which involved moderately large quantities of data. Thus, there was a need to incorporate this information into the initialisation routines of the fire model (collectively labelled FIRE_INIT) in the most efficient manner possible.

Single dimensional parameters that were smoothly distributed, such as fire size and growth rate, could be approximated very efficiently with the use of curve fitting techniques. For example, a cubic spline fit enabled the distribution of 72 individual data points to be encapsulated by storing only three or four spline coefficients.

Other parameters, however, were found to exhibit a significant degree of scatter, or else were defined in two or more dimensions. These had to be analysed with techniques that involved the use of scatter envelopes and area plots respectively. An example of the latter was in the encoding of fire starting positions. The type of two-dimensional probability contour map that was obtained from the fire analysis is illustrated in Figure 7.9. These spatial distributions were incorporated into FIRE_INIT

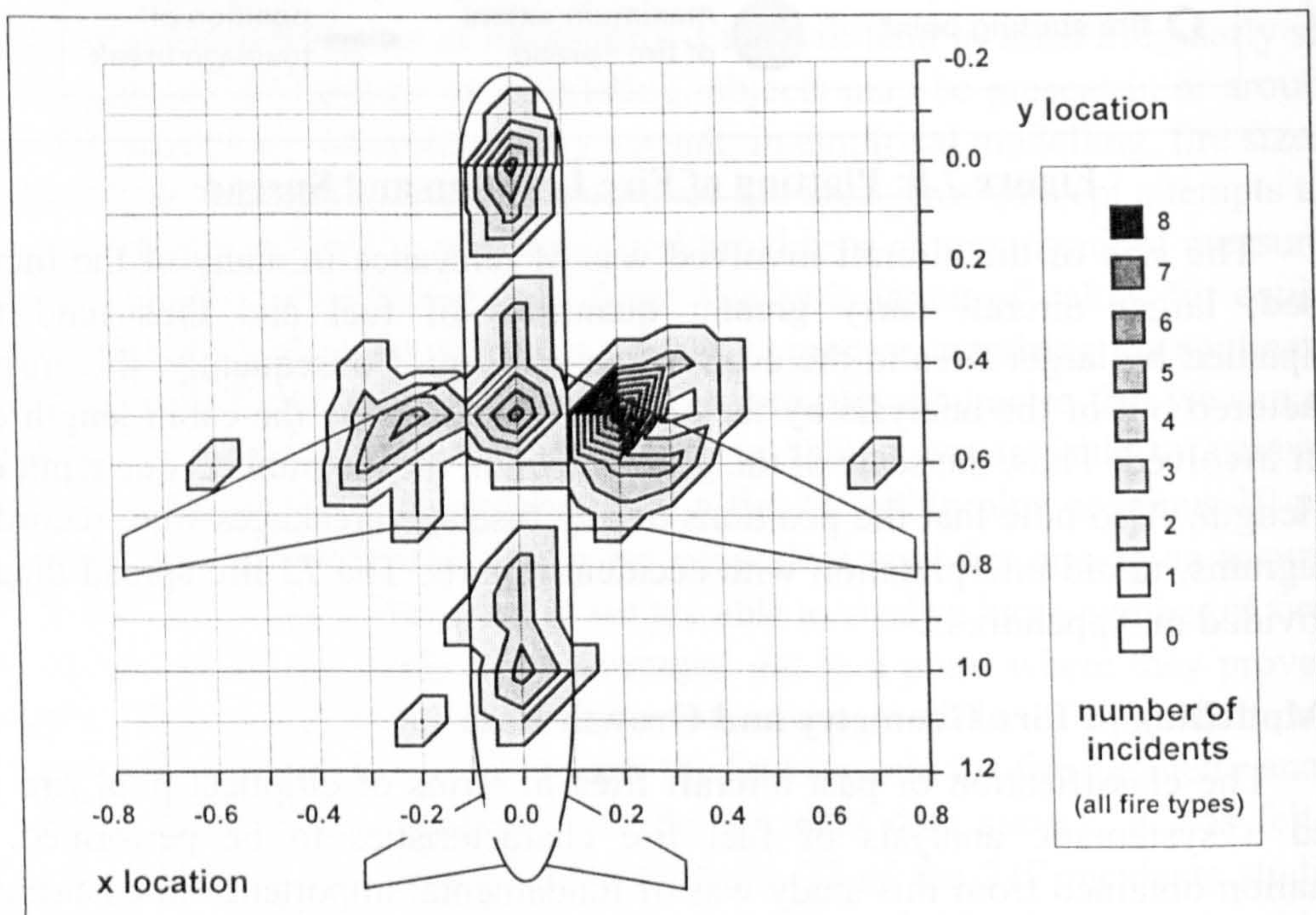


Figure 7.9: Probability Contour Map for Fire Starting Position

in the form of a two-dimensional array of probability values. Fire starting positions are chosen by moving a random distance down and across the array and interpolating between the values of surrounding entries. The use of relatively coarse (14 by 12) arrays in conjunction with data interpolation enabled spatial probability maps to be stored with the use of only 168 integer numbers.

The change in fire size with time was modelled with a generic growth curve. As shown in Figure 7.10, this possessed a classic exponential growth, peak and decay distribution, typical of that encountered in many types of fires. The shape of the curve was defined with cubic polynomials, passing through three control points. Potentially, the positions of these points can be modified to represent effects such as the occurrence of a significant time delay before fire start, fire fighting and sudden fire expansion resulting from explosions. However, for the purpose of model development, a fire growth curve of fixed proportions was assumed, with peak fire size occurring at one quarter of the time required for fire extinction.

Fire areas were comparatively straightforward to derive from probability distributions obtained from the equivalent pool fire analysis. In contrast, the study of fire growth-time histories required a second round of analysis. This involved

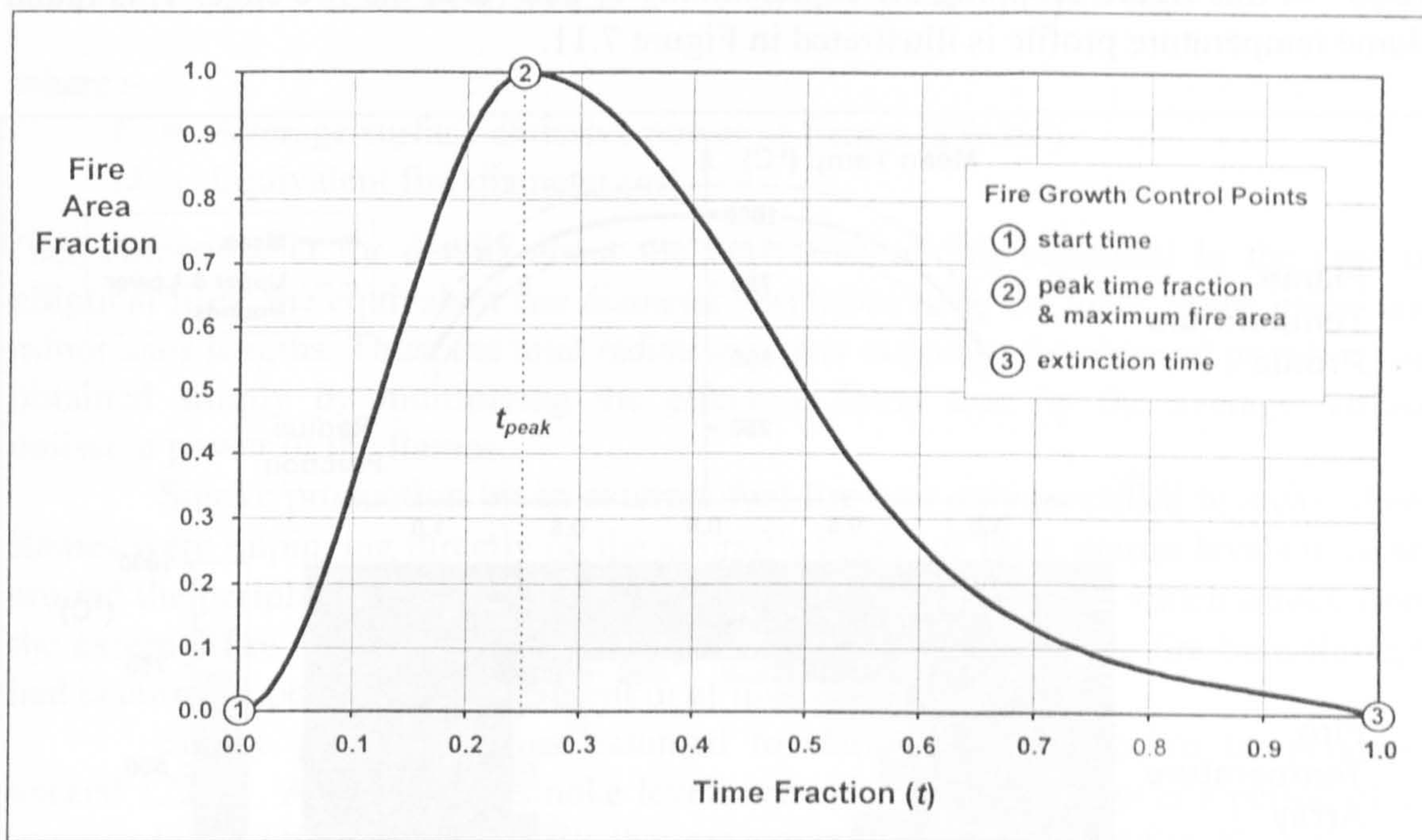


Figure 7.10: Use of Generic Fire Growth Curve

estimating, wherever possible, the following time points for each of the accident fires:-

- start time (after/before) aircraft comes to a stop
- time required for fire ingress in to cabin area
- point at which maximum fire size was reached
- time required for fire extinguishment

The fire start times and fire ingress times obtained are listed in Appendix E. In most cases the information available was insufficient for all four time points to be estimated with any accuracy. However, in spite of the incomplete data, the patterns of fire behaviour observed appeared to fit the exponential growth, peak and decay model remarkably well. In general, the fire extinguishment times tended to be reported the most accurately and these were obtained for 30 of the 72 incidents studied. Thus, these endpoints were used to create probability distributions for the purpose of scaling the horizontal axis of the fire growth curve. This procedure is elaborated upon in Appendix F.

7.4.4 Heat and Smoke Production

Once the geometric properties of the pool fires had been established, the resulting thermal characteristics were comparatively straightforward to model. The parameters that needed to be derived from the pool fire geometry consisted of flame temperature profile, fire radiative power and levels of smoke production.

Flame temperatures at the centre of large hydrocarbon fires are generally in the region of 1400 K, although the intermittent nature of fires means that average temperatures may be somewhat less (Mudan and Croce, 1988). Temperatures also tend to decrease towards the edge of a fire, where flames are smaller in size. Consequently, a simple temperature profile was developed to represent flame temperatures in the pool fires. The temperature at the fire centre was assumed to be

1000 °C, this figure dropping off exponentially to 500 °C at the fire edge. This radial flame temperature profile is illustrated in Figure 7.11.

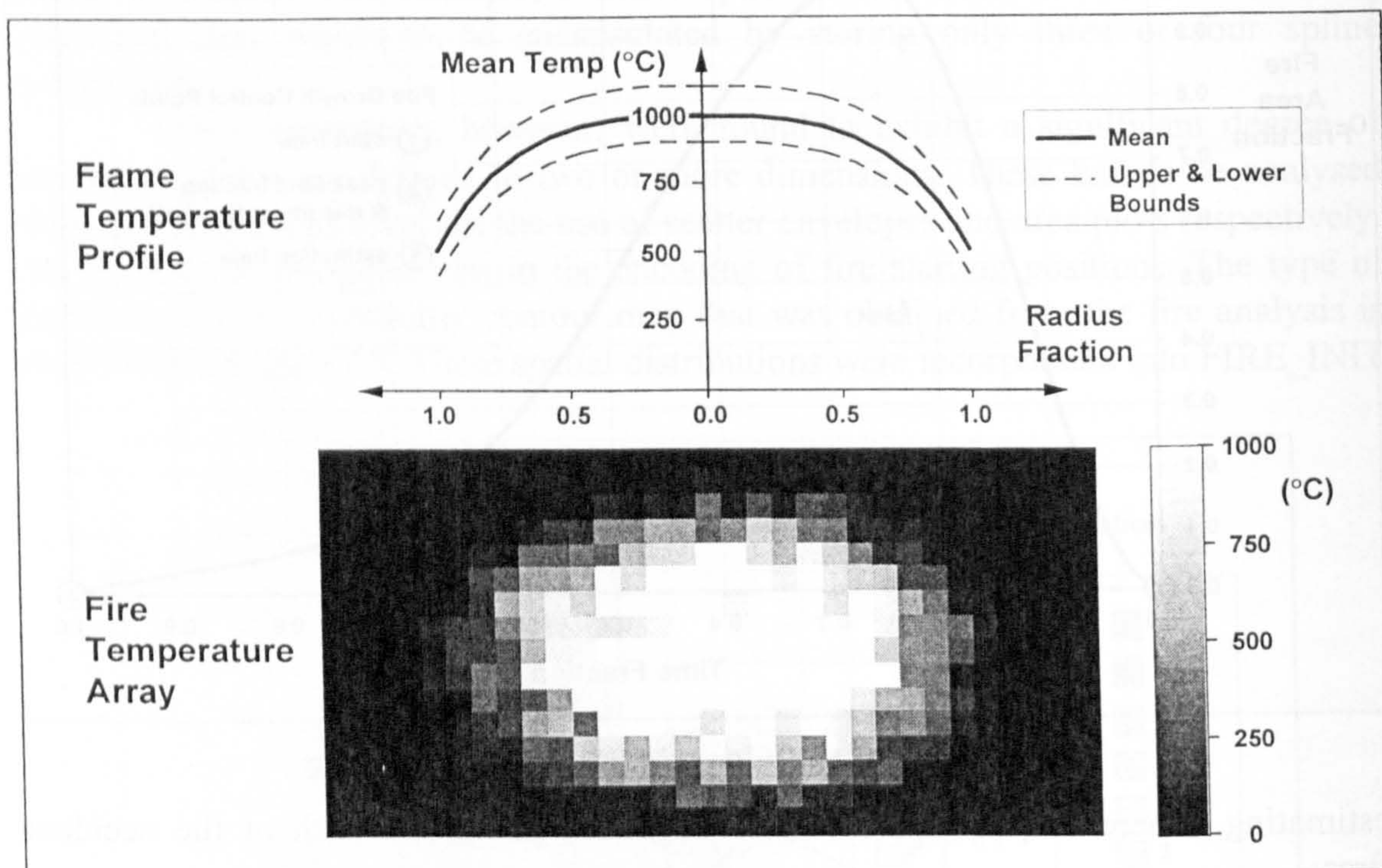


Figure 7.11: Implementation of External Fuel Fire Model

Theoretically, defining the external fires purely in terms of analytical functions would have enabled conditions to be calculated at arbitrary times and positions, as and when required by other parts of the simulation model. However, in order to ensure adequate computational efficiency, it was decided to discretise fire temperature distributions and store pre-calculated values in a two-dimensional array. This enabled local fire temperatures to be simply looked up, rather than having to be re-calculated from scratch every time they were needed. This fire temperature array is illustrated in the lower half of Figure 7.11. Note that a small amount of random noise (± 100 °C) has been added to the cell temperatures, in order to represent fluctuation of flames. The resolution at which fire temperatures are stored and the frequency at which they are updated can be set arbitrarily. Typically, fire temperature distributions were calculated at 10 or 15 second intervals when running accident simulations.

The use of a point source thermal radiation model required that the radiative power of the pool fires be derived from their geometry. The approach taken here was to estimate the effective flame area of a fire and multiply this value by the thermal radiation intensity of the flames present.

The effective area of radiative flames, as seen from any viewpoint, was simply assumed to be equal to the base area of the fire. If a cylindrical flame model analogy was being used, this would correspond with a flame height to fire diameter ratio of $\pi/4$ and large distances from the fire. Although the former figure might appear to be rather low, it should be remembered that no account was being taken of atmospheric attenuation effects and flame view factors. As indicated in Appendix D, taking the latter into consideration can serve to reduce effective flame areas markedly at close proximity's to a fire. The radiative power of fire flames was assumed to be given by:-

$$E = 140 \times 10^3 e^{-0.12D} + 20 \times 10^3 (1 - e^{-0.12D}) \quad (7.1)$$

where:-

E = Average surface emissive power of flames (kW/m²)

D = Equivalent fire diameter (m)

(See Appendix D for details about the derivation of this equation) In the case of elliptical fires, the equivalent fire diameter was taken to be the mean of the major and minor axes lengths. Thus, the total radiative power output of the external pool fire was obtained simply by multiplying the effective flame area by the average surface emissive power of the flames.

Smoke production by an external fuel fire was only modelled in areas where flames were impinging directly on the aircraft's fuselage. Thus, smoke levels were set around the periphery of "open" TTE cells. These were locations at which smoke from the external fire might enter the passenger cabin, e.g. places where fire burn-through had occurred, open exits were present or at fuselage breakages.

Smoke production was assumed to start when local cabin temperatures exceed 122 °C. At this point, smoke levels are increased linearly over a period of 15 seconds to 1.0 OD/m in cabin cells that are exposed to the external fire. Densities are then set to rise in conjunction with cabin temperature up until flashover conditions are reached (3.3 OD/m at 260 °C).

7.5 Cabin Airflow Model

7.5.1 The Requirement to Model Cabin Air Flows

The modelling of airflow in and around the aircraft's cabin formed one of the essential linkages between the cabin and external pool fire models. The rate at which smoke and gaseous fire products spread through a passenger cabin has a critical role in determining how quickly conditions become unsurvivable for those inside. The presence of dense smoke can also serve to block potential escape routes and have a large influence on passenger behaviour. Thus, although factors such as these are extremely difficult to model to any degree of accuracy, their importance demanded that at least a basic representation of smoke spread was incorporated into the simulation analysis.

It has been seen that the only feasible way of incorporating the modelling of cabin airflow within the simulation analysis was to use a potential flow method. In order to make this task feasible within the time available, it was necessary to restrict the flow modelling to two dimensions. The main implication of using this approach was that conditions on the downwind side of the aircraft would not be predicted satisfactorily. However this was of little consequence, as the only airflows being utilised were those on the cabin interior.

Also, all airflow calculations were undertaken separately from the fire analysis. This implies that flow fields are determined entirely from ambient wind conditions, with no account being taken of fire entrainment effects that might be present. The latter can be significant in calm wind conditions (Quintiere and Tanaka, 1983); thus it was necessary to ensure that the analysis could be extended to deal with these effects at a later stage, if required.

The primary advantage of using a method based on potential flow analogy was that results could be obtained in real time. This was essential if the objective of integrating the cabin thermo-toxic modelling with other parts of the simulation analysis was to be achieved. Also, fundamentally important aspects, such as the effects of crash damage, burnthrough of fuselage structure and the opening of exits could be dealt with in a reasonably straightforward manner. Thus, it was possible to automate the flow modelling process for all the types of accident scenarios being analysed.

7.5.2 Potential Flow Modelling: The Panel Method

It has been seen earlier in the chapter that the potential flow methods are based on the superposition of a series elementary flow elements. These flow elements consist of simple analytical functions, whose coefficients are determined by enforcing a set of boundary conditions. Flow elements are positioned and boundary conditions chosen such that the primary features of the flow problem being analysed are accurately reproduced. For a flow solution to be valid, values must be found for all "influence" coefficients that enable all of the boundary conditions to be satisfied simultaneously. Once this solution set has been obtained, flow parameters can be derived at arbitrary positions throughout the flow domain.

Thus, the calculation of a potential flowfield involves three main tasks. Firstly the geometry of the flow problem has to be defined, using suitably chosen flow elements and boundary conditions. Then, this information is used to derive and solve a set of simultaneous equations. Finally, these results are used to scale the contributions of the various flow elements and enable the required flowfield information obtained.

The airflow analysis needed to model flow both inside and outside a hollow body (i.e. an aircraft's fuselage). This task could be achieved with the use of two types of flow element; a single freestream flow and a series of panel sources. The two elements are illustrated in Figure 7.12. The concept of a freestream flow function was briefly introduced earlier in the chapter. It can be used for representing a unidirectional flow at an arbitrary angle i.e. a mean ambient wind velocity.

The source panel element consists of a line, from which flow emanates perpendicularly on both sides. The speed at which the flow moves is defined in terms of flow strength per unit of panel length. Note that source panels may have positive (outwards) or negative (inwards) flow strengths, as indicated in the diagram.

Source panels can be used to manipulate freestream flow conditions, either by repelling or "sucking in" flow in their immediate vicinity, until the desired flow pattern is achieved. The utilisation of potential flow theory in this manner constitutes what is widely known as the Panel Method.

Figure 7.12(d) shows how source panels can be used to approximate inviscid two-dimensional flow around a square. With the use of only 8 panels, the flow pattern obtained is comparatively crude. However, as panel numbers are increased, the flow solution rapidly converges towards an exact analytical representation of the problem being modelled. A point of some significance to the current study is that the flow field inside the closed square is not, as might be expected, predicted to be stationary. This is because the angular sign convention used for evaluating flow contributions from individual panels is only able to enforce compliance with flow boundary conditions on one side of a panel. The implication of this is that we can set sign conventions to

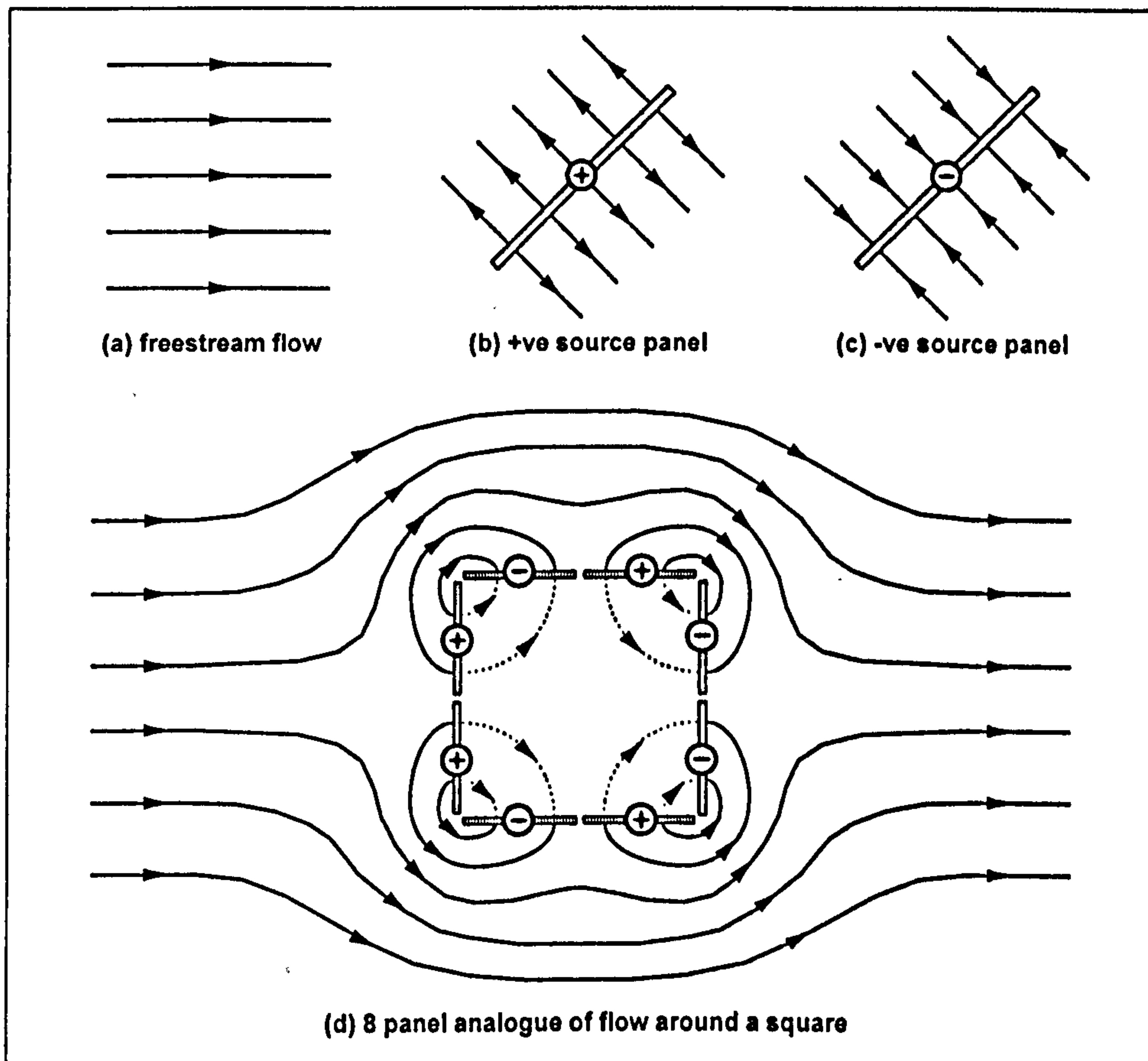


Figure 7.12: The Panel Method

correctly evaluate flow conditions either on the interior *or* the exterior walls of a closed object, but they cannot be made valid on both sides simultaneously. Thus, the illustrated internal flow pattern is a direct result of boundary conditions on the internal walls of the square being left unsatisfied. As such, this “virtual” flowfield is a mathematical idiosyncrasy that has no correspondence with physical flowfields. In order to obtain the real internal flow pattern, panel contributions must be evaluated twice, applying interior and exterior wall boundary conditions in turn.

Apart from its application to internal flow problems, the Panel method implemented was completely standard. The code itself was written from scratch, based on theory widely available in aerodynamics textbooks (Anderson, 1985; Kuethe and Chow, 1986). The source strength equations were solved by calculating matrix determinants and the application of Cramer’s Theorem (Kreyszig, 1988). Although this method was straightforward to understand and quick to implement, it is very inefficient in comparison with more advanced solution techniques, such as Gaussian Elimination or Lower-Upper Decomposition. It was anticipated that the latter method would be introduced at some time in the future, providing a reduction in flow solution times by approximately a factor of three (Press et al., 1992).

7.5.3 Initialisation of Panel Geometries

For cabin airflows to be calculated it was necessary to represent the shape of the aircraft concerned with a series of source panels. These panels needed to define the geometry of the aircraft’s fuselage in a horizontal plane, located at a height of 1.5 metres above floor level, as shown in Figure 7.13. This would mean that both door

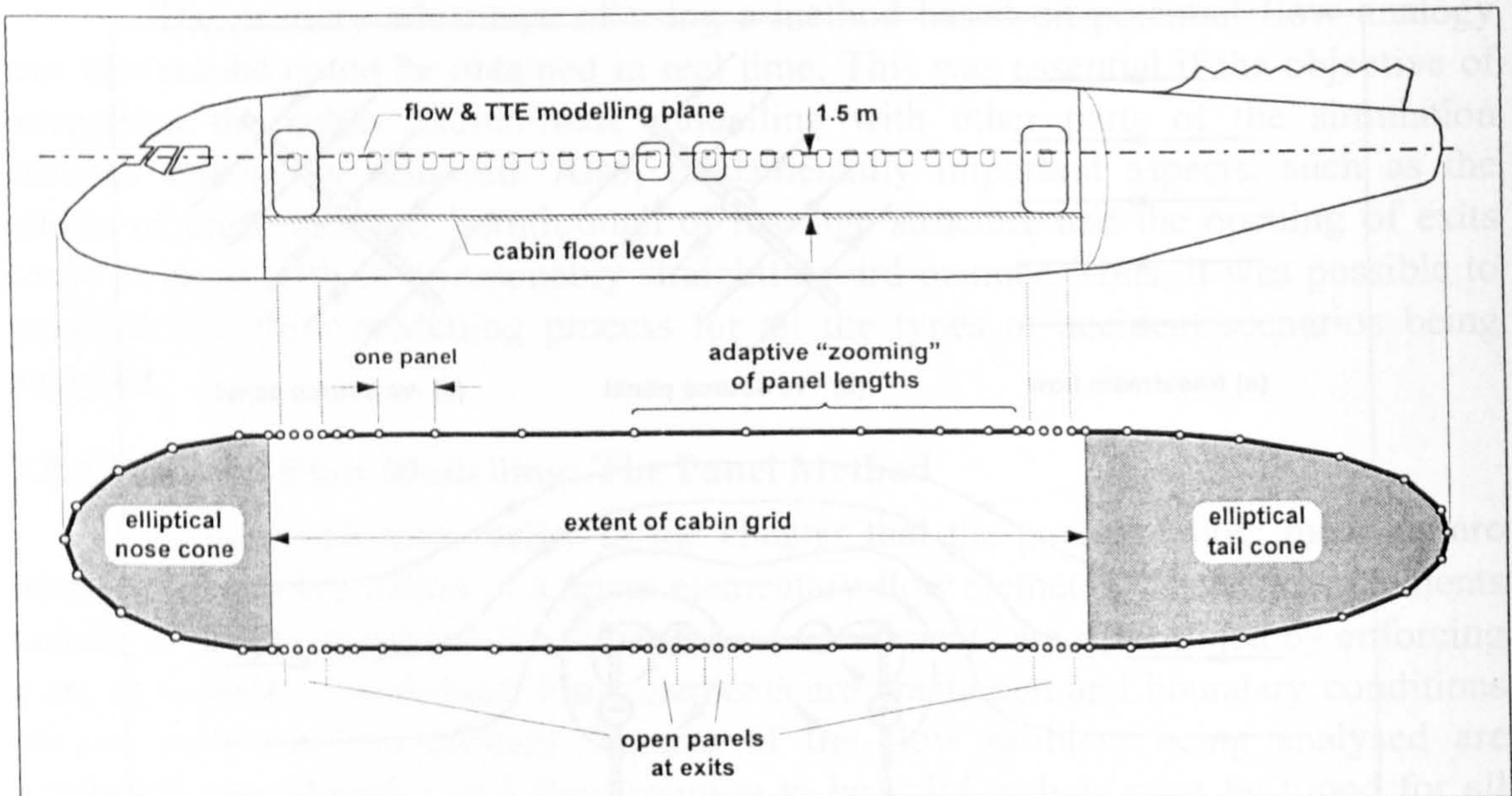


Figure 7.13: Panel Model of Aircraft Fuselage

and overwing hatch exit types were incorporated the panel geometry and ensure that flow solutions could be integrated seamlessly into the cabin TTE modelling.

The most obvious approach to creating the fuselage geometries was to derive the positions of panel end points using co-ordinate data obtained from the evacuation grids. The simplest way of achieving this would have been to calculate panel positions by hand and store panel co-ordinates for each aircraft type being analysed. However, the resulting panel distributions would have been of a fixed resolution and difficult to tailor in order to reflect features such as fuselage break-up and the opening of exits. Therefore, a series of routines was written to automatically produce optimised panel configurations directly from evacuation grid data. The implementation of these enabled fuselage panel models to be generated and updated for all aircraft types during programme run-time. Typically, the panel geometries produced were similar to the generic configuration illustrated in lower half of Figure 7.13.

Some of the considerations that were dealt with in the construction of fuselage panel models included:-

- Clustering or “zooming” of panels into areas where flow properties needed to be modelled at a higher resolution (e.g. open exits, corners and apexes)
- Avoiding the waste of clustering panels around exits that still remain closed
- Provision of the ability to vary the overall density of panel distributions, enabling flow solution time to be traded off against solution accuracy.
- Addition of panels to represent fuselage nose and tail cones at either end of passenger cabins, as these have a large influence on the external flowfield.
- In cases where impact damage was severe, panels needed to track around separated sections of fuselage, possibly in random positions and orientations.

The flow patterns inside an aircraft's cabin are, to a large extent, determined by the size, position and number of emergency exits that have been opened during passenger evacuation. Therefore, it was essential that the effects of exit opening were incorporated within the airflow analysis. This was achieved by omitting flow panels located in the positions of open doors and escape hatches, thus creating a series of gaps or holes in the cabin periphery. Air passes through these open exit positions, establishing a ventilation flowfield in the cabin interior. Cabin flow patterns are determined by the geometry of opened exits and the velocity at which air moves through them.

In order to implement the calculation of internal airflows, it was necessary to take account of the sequence in which exits were activated. Normally, at the start of an accident simulation all exits are closed and cabin airflows are negligible. When aircraft occupants begin to evacuate, exits are opened in an arbitrary sequence, typically over a time period of 30 to 60 seconds. The activation of each additional exit produces a shift in the pattern of cabin airflow, sometimes even resulting in a complete reversal in the overall direction of air movement. These ventilation effects are thought to have been very significant in some past accidents (King, 1989). Consequently, it was apparent that cabin flow patterns needed to be obtained not just once, but possibly every time an exit was opened in the course of an accident simulation. This would then ensure that the effects of transient flow conditions are accounted for within the analysis.

The significance of shifting cabin airflow patterns is illustrated in Figure 7.14. The diagrams show a series of cabin flow solutions for a typical widebody

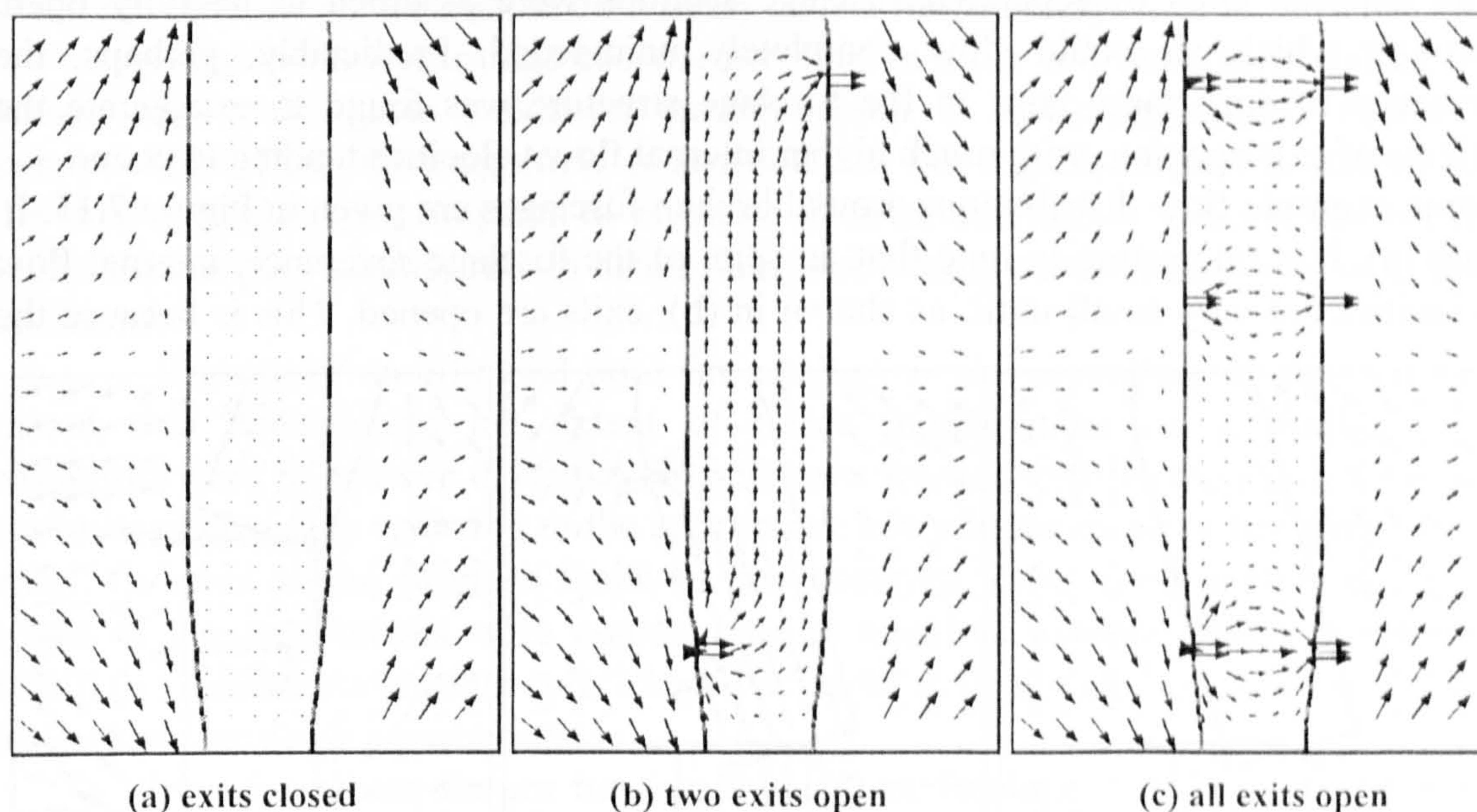


Figure 7.14: Cabin Airflow Vectors Resulting from Exit Opening

aircraft, with different combinations of open exits. The wind is from the left, at a speed of 5.0 m/s and internal flow vectors have been magnified for clarity. Case (a) shows how no internal flows are present when all the exits remain closed. Cases (b) and (c) reveal the changes that can occur when emergency exits are progressively opened. Note how internal flow patterns change markedly when different combinations of exits are activated.

Theoretically, internal flows needed to be re-calculated each and every time an exit was opened in the evacuation simulation. However, in practice, frequently it was found that two or more exits would be opened near simultaneously. Potentially, this meant that intermediate flow patterns might only exist for a short space of time and, effectively, the computational effort required to determine them would be wasted. Therefore, cabin flows were not automatically re-calculated each time an exit was opened. Instead, whenever an exit had been activated, a check was run to determine whether or not any other exits were also just about to be opened (i.e. within a period of three seconds, say). If this were the case, then the flow update would be postponed in order to enable effects of the imminent changes to be included. Typically this procedure was found to halve the number of times that cabin flow fields were calculated and the loss of fidelity was inconsequential.

7.5.4 Impact Damage and Destruction of Cabin by Fire

Cabin airflows may stem from causes other than open exits. In accidents that involve severe crash impacts, significant rupturing or even complete break-up of a fuselage may occur. For the purpose of modelling internal flowfields, holes and gaps resulting from structural damage can be treated in the manner of open exits. Obviously, however, these features will be present from the very start of an accident simulation, rather than being introduced as a result of the passenger evacuation process.

It was ensured that the routines used to create panel geometries were able to deal with fuselages that had been broken into several sections as a result of an impact. The exposed ends of separated fuselage sections were assumed to be fully open, through which air could flow completely unimpeded. Predictably, perhaps, the presence of such large gaps in the fuselage structure was found to exaggerate the effects of exit opening, with much higher internal flow velocities tending to occur. Some example flow distributions around broken fuselages are given in Figure 7.15. In case (a), it is interesting to note that, in spite of the fuselage severance, internal flow velocities are very small until, as shown in (b), exits are opened. This is because the

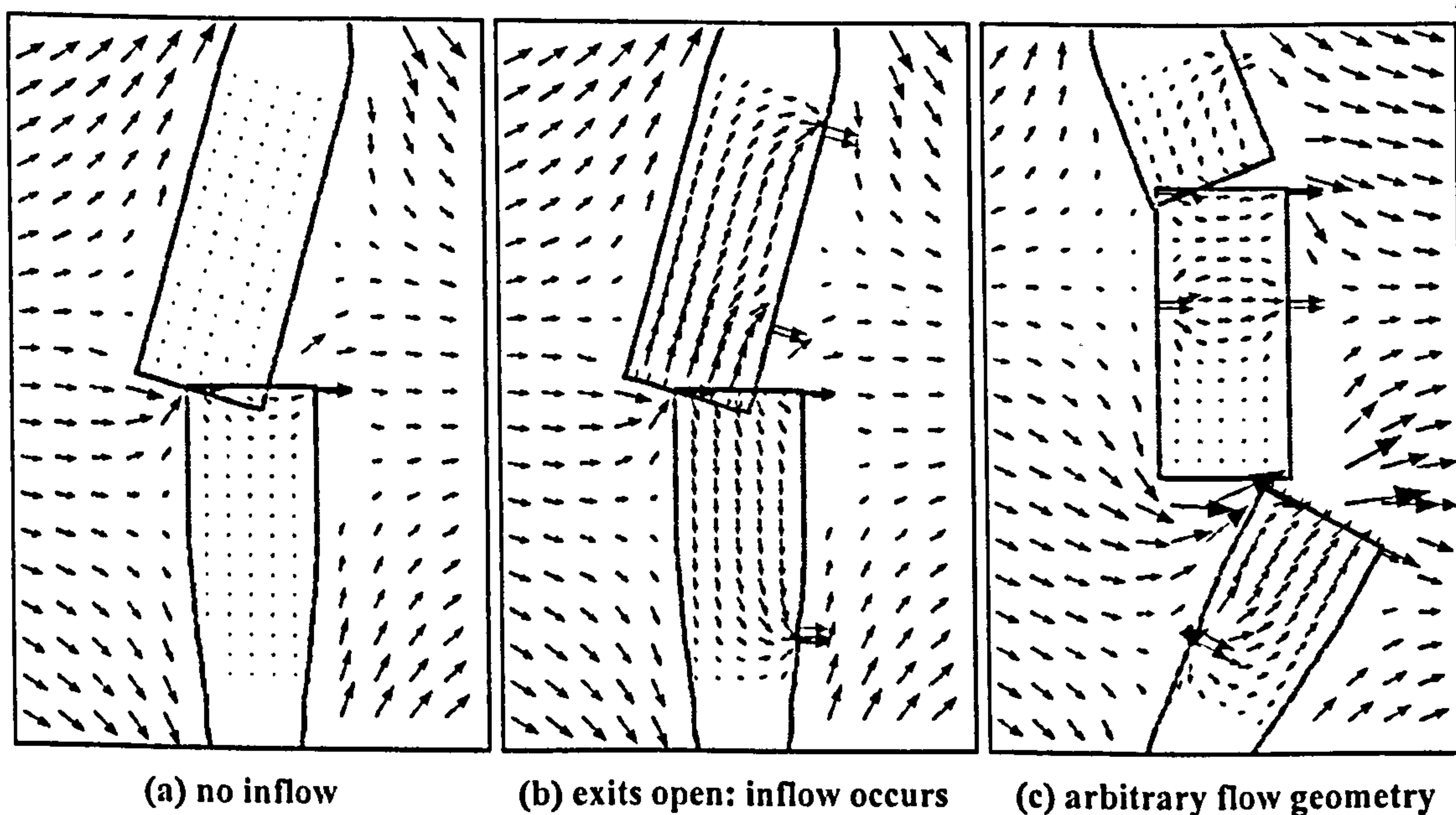


Figure 7.15: Airflow Inside and Around a Broken Fuselage

quantity of air flowing into an enclosure is limited by the size of the outflow paths available. The effects of small scale structural damage, such as rupturing and perforation of the fuselage, was not incorporated into the flow analysis. These features would be straightforward to introduce if information about likely damage distributions is obtained. Time constraints prevented this data from being derived during the of past accident data survey.

Similarly, the destruction of fuselage structure by fire also serves modify cabin airflow patterns locally. However, the modelling of this effect was not afforded a high priority, because, arguably, conditions in the vicinity of these “melt-through” areas are already well beyond being survivable. Thus, changes in flow patterns resulting from the melting of a fuselage were expected to have only a small influence on fire fatality rates. This issue, together with other aspects of fuselage fire hardening, could form the subject of further investigation.

7.6 Cabin Fire Development

7.6.1 Fire Ingress

The primary mechanism of fire spread into the cabin interior in past accidents appeared to be through direct flame contact with the aircraft’s materials. In the most extreme of circumstances, fires are capable of penetrating intact fuselage structures in a matter of seconds (King, 1989). More generally, damage resulting from a crash impact can often leave cabin materials directly exposed to the effects of flames and in these circumstances, fire ingress effectively occurs immediately.

Once cabin furnishings become involved in a fire to a substantial extent, the smoke and toxic gases produced quickly result in cabin conditions becoming unsurvivable. Thus, the magnitude of any delay in fire ingress effectively determines the time available for occupants to evacuate from an aircraft. As a result of this, fire ingress times play a major role in determining the overall survivability rates in aircraft accidents.

The use of an elliptical pool fire analogy in the modelling of external fires meant that determining the extent of flame impingement on a fuselage was straightforward to achieve. External temperatures for wall cells in the cabin TTE grid could be obtained by referring to the appropriate entry in the external fire temperature array. In cases where fuselage break-up had occurred, cabin temperatures along the edges of exposed breaks were assumed to be equal to external fire temperatures. Similarly, conditions in cabin cells located adjacent to open exits could be assumed to be the same as those present outside.

In cases where flames impinged on intact fuselage wall structure, a burn-through mechanism needed to be used. This was based on a simple thermal inertia analogy, where heat is progressively absorbed by the wall cell until the temperature reached is sufficient for melting to occur. A melt-through temperature of 250°C was assumed; this value was intended to take into account the mixture of materials typically used in aircraft fuselage construction, including, for example, light alloy skins, plastic windows, composite panels and fibre glass insulation.

The rate at which wall temperatures increase depend on heat absorption levels and heat capacities of the materials involved. These two aspects were difficult to quantify with any degree of certainty. As a start, conductive heating rates were

assumed to be proportional the temperature difference between the wall and external flames and radiative heat transfer dependent on the levels of thermal radiation intensity present.

However, in reality, many other factors are influential in determining burn-through rates for wall structures. For example, significant complications can include variable material thicknesses, increased heat absorption due to soot blackening, conduction of heat away from heated areas and presence of cargo bay liners. The role of such influences is extremely difficult to ascertain, either by experimental or analytical means and thus very little detailed data was found to be available in this area.

Consequently, it was decided that the only meaningful way to calibrate fuselage burn-through rates was by utilising historical accident data. Estimates of the time required for fire ingress were obtainable for 53 incidents in the accident database. These times were grouped into intervals and the resulting distribution is shown in Figure 7.16. Note that, in almost half of the incidents, fire was observed in the cabin

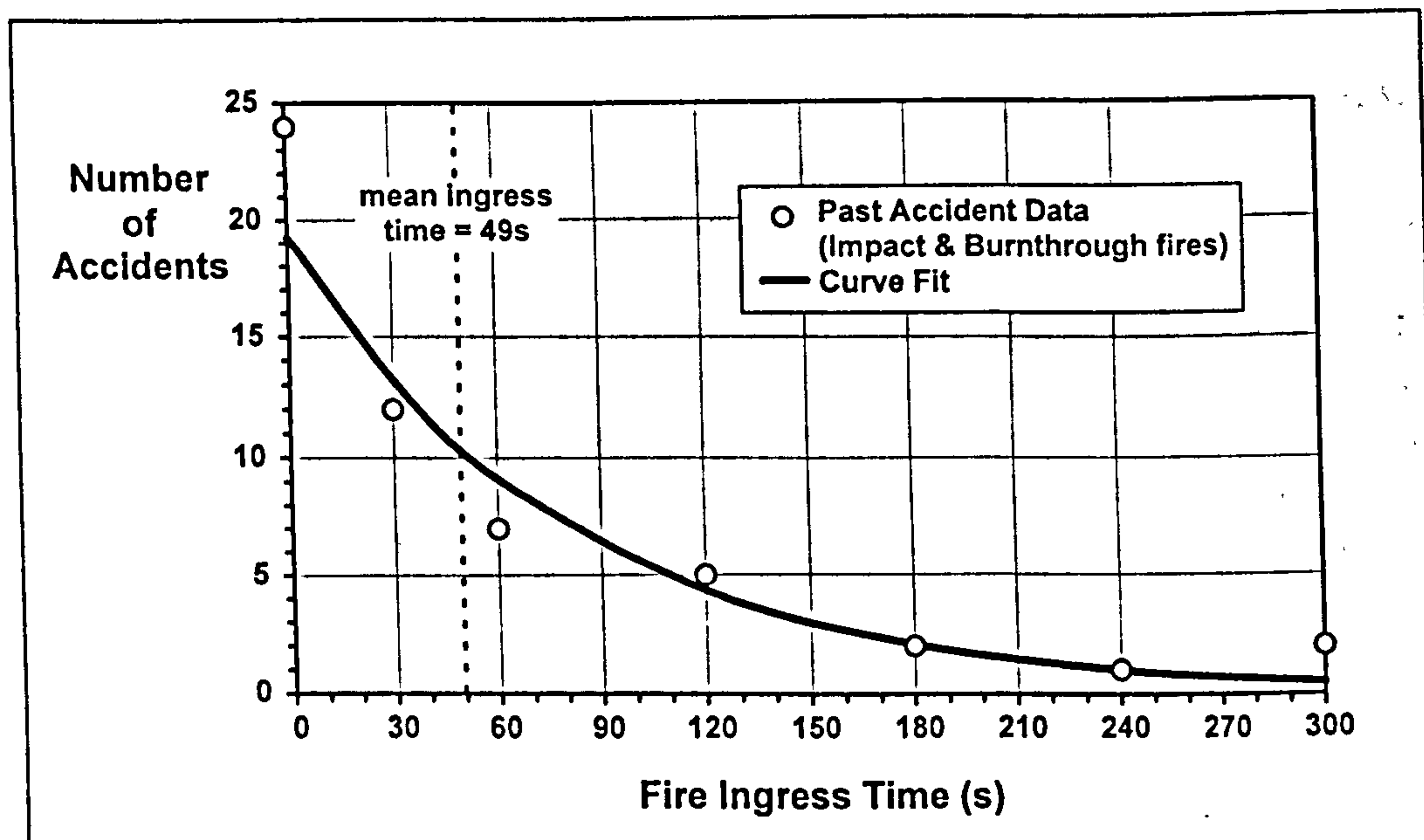


Figure 7.16: Variation in Time Required for Fire Ingress

area immediately after the aircraft came to a stop. It can be seen that the average time required for fire to enter the passenger cabin is 49 seconds. The fire burnthrough mechanism was calibrated to this figure over a series of simulation runs.

7.6.2 Fire Spread inside the Passenger Cabin

Once a fire has entered an aircraft's passenger cabin, smoke and toxic fire products tend to accumulate and rapidly make conditions unsurvivable for those remaining inside. The primary hazard to aircraft occupants in these circumstances is incapacitation by the narcotic and highly irritant effects of smoke, rather than the threat of thermal injury. Thus, the primary task in the fire analysis was to establish the rate at which smoke spreads through an aircraft, as opposed to modelling the extent to cabin materials become involved in the fire. Nonetheless, in order for smoke distributions to be modelled with sufficient accuracy, it was necessary to construct a reasonable approximation of fire development within an aircraft's fuselage.

It has been seen that fires propagate by transferring heat to surrounding materials in three ways, namely by convection, conduction and thermal radiation. The basic physical characteristics possessed by each of these spread mechanisms could be represented within the cabin fire grid with the use of a simple numerical scheme. As with the modelling of fuselage burnthrough, however, the main difficulty in implementing any such analysis lies with establishing the level of the contributions made by the various mechanisms involved. At present, analytical theories can only represent the processes that comprise fire at the simplest of levels. In reality, cabin fire development is controlled by complex interactions that occur between a vast number of physical and chemical phenomena, most of which are still not understood or remain unaccounted for. As a result of this, fire modelling techniques must inevitably involve a combination of analytical and empirical approximation.

The approach used to model fire spread within the cabin was to employ iterative cell diffusion scheme across the TTE grid. A simple first order method was used, equivalent to MacCormack’s Predictor Step (Anderson, 1995). Numerical procedures of this type constitute the basis of computational fluid dynamics and further details concerning their implementation can be obtained from a number of standard textbooks (Abbot and Basco, 1989; Peyret, 1996; Shaw, 1992). Initial conditions of 20 °C and zero smoke density were assigned throughout the cabin. All areas were treated as being homogeneous; i.e. seats, aisles, galleys, etc. were approximated as being a continuous material, through which fire would attempt to spread equally in all directions.

Ingress of the external pool fire was modelled by calculating temperature increases in cells lying around the periphery of each cabin section present. These boundary conditions were usually updated at 5, 10 or 15 second intervals of simulation time. Four distinct penetration scenarios were possible for edge the cells; details of these are given in Table 7.3:

Case	Heat Transfer Mechanism	Burnthrough Time Constant	Resulting Edge Cell Temperature
Pool fire impinging on intact fuselage	Conduction: $q \propto t_i - t_j$	10 s at 1000 K temperature differential	external flame temperature
Pool fire impinging on cabin break	Conduction: $q \propto t_i - t_j$	0 s	external flame temperature
Pool fire remote from intact fuselage	Radiation: $q \propto t_i^4 - t_j^4$	10 s at 100 kW/m ² radiative heat intensity	250 °C → external flame temperature
Pool fire remote from cabin break	Radiation: $q \propto t_i^4 - t_j^4$	0 s	250 °C → external flame temperature

Table 7.3: Pool Fire Penetration into Passenger Cabin

The spread of heat from perimeter cells into the cabin interior through conduction, convection and radiation mechanisms was then calculated. Heat fluxes were assumed to occur only across directly adjacent cell boundaries, with no influence from cells in diagonal positions. These and other cell variables are illustrated in Figure 7.17.

The fire propagation scheme implemented modelled the spread of heat from cell to cell with three terms. The first of these, convective transfer, only spreads heat

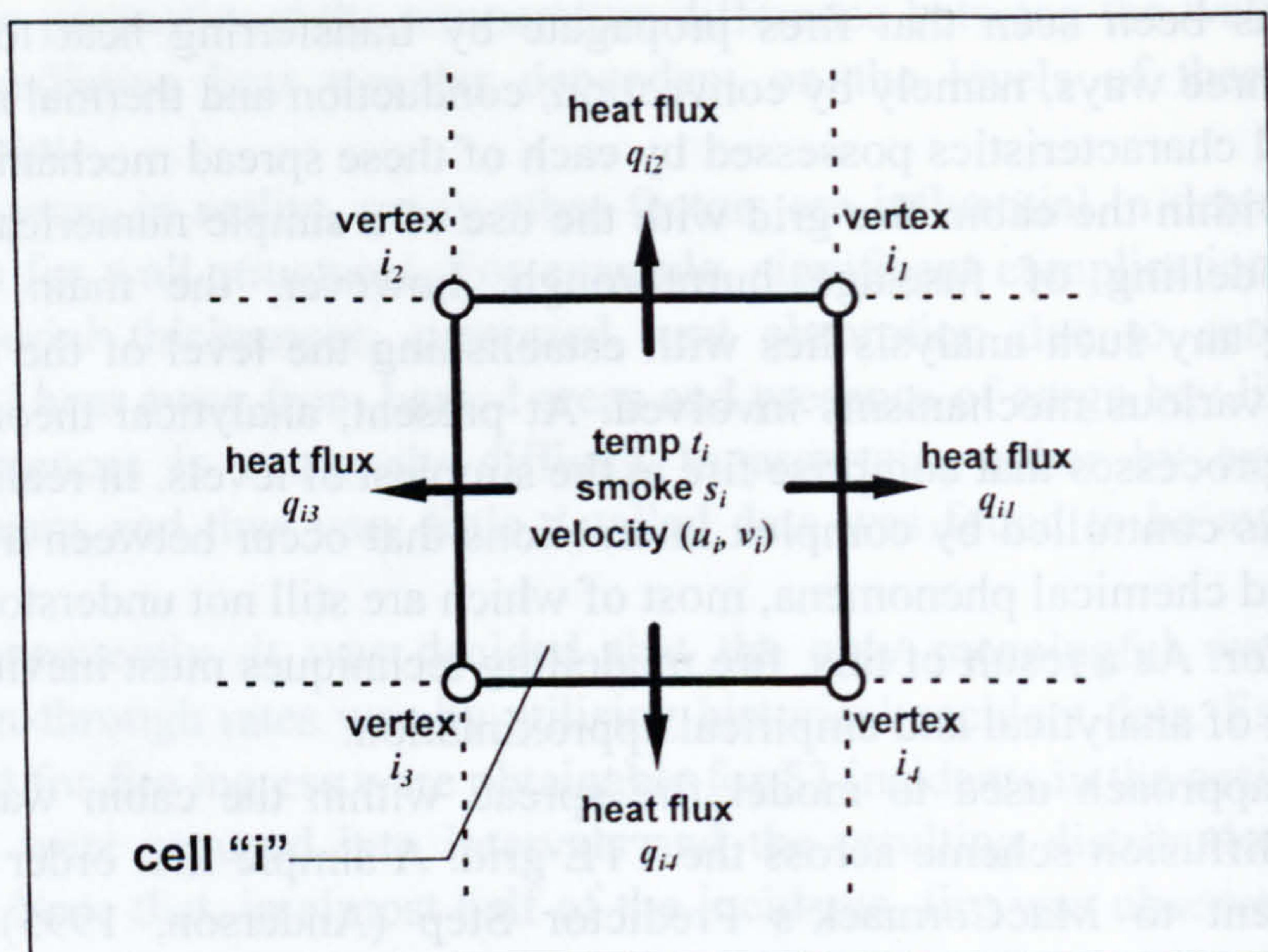


Figure 7.17: Use of Cell-Vertex, Cell-Boundary and Cell-Centred Cabin Fire Parameters

in the direction of the local cabin airflow. Heat transfer rates were made proportional to the temperature differential and the perpendicular component of air velocity present at cell boundaries. Note that cabin grids were not necessarily perpendicular.

In contrast, diffusive transfer could potentially be applied outwards in four directions from hot cells. The magnitude of diffusive heating effects was assumed to be proportional to the temperature difference between two adjacent cells. Similarly, radiative heat emissions were applied to surrounding cells in proportion to the difference in cell temperatures raised to the power of four, i.e. $(t_1^4 - t_2^4)$, in accordance with Planck's Law of radiation (Mudan and Croce, 1988). A term was also used to represent heat radiating from cabin smoke, when the latter was present.

No mechanism was provided for decrementing the temperatures of hot cells in the cabin fire array. Thus, temperature in a given cell increases until equilibrium is established, either with adjacent cells or the with the external fire, at a mean temperature of 1000 °C. This effectively implies that combustion of cabin materials always occurs at a rate that is at least sufficient to maintain a cell's current temperature and that no depletion of the fuel supply occurs as a result of combustion. Obviously, if cabin fires needed to be modelled over extended periods of time, or the effects of fire fighting intervention represented, fuel accounting procedures and mechanisms for cell cooling would need to be incorporated.

Cabin temperature distributions were usually set to be updated every 5, 10 or 15 seconds of simulation time, depending on the trade-off between simulation speed and accuracy desired. Regardless of the update interval used, iterations were performed with 0.5 second time steps. This ensured that CFL numbers were kept below unity (and thus numerical stability retained) for cabin airflow velocities up to a maximum of approximately 1.0 m/s.

These types of heat transfer mechanisms are practically impossible to calibrate to any degree of accuracy in aircraft fires (Poulios, 1986). Fire behaviour is often dependent on factors that are difficult to isolate; thus wide variations in fire characteristics can occur in seemingly identical conditions. In general, results from cabin fire tests appeared to be very sensitive to details of the test set up used and

ambient wind conditions. Similarly, large differences in fire spread rates were noted during the accident data survey. Consequently, it was necessary to set diffusive and radiative transfer rates on a rather arbitrary basis; values were chosen to produce a fire growth speed of 1.0 m/min. This figure appeared to be generally consistent with mean rates observed in past accidents, up until the point at which fire flashover occurs. Beyond this, fire spread rates are of little consequence, as cabin conditions are effectively unsurvivable. However, 1.0 m/min is a somewhat faster growth rate than suggested by the results of most aircraft cabin fire experiments.

The propagation of a burn-through fire inside the cabin of a widebody airliner is shown in Figure 7.18. Note that the fire grows slowly across the width of the

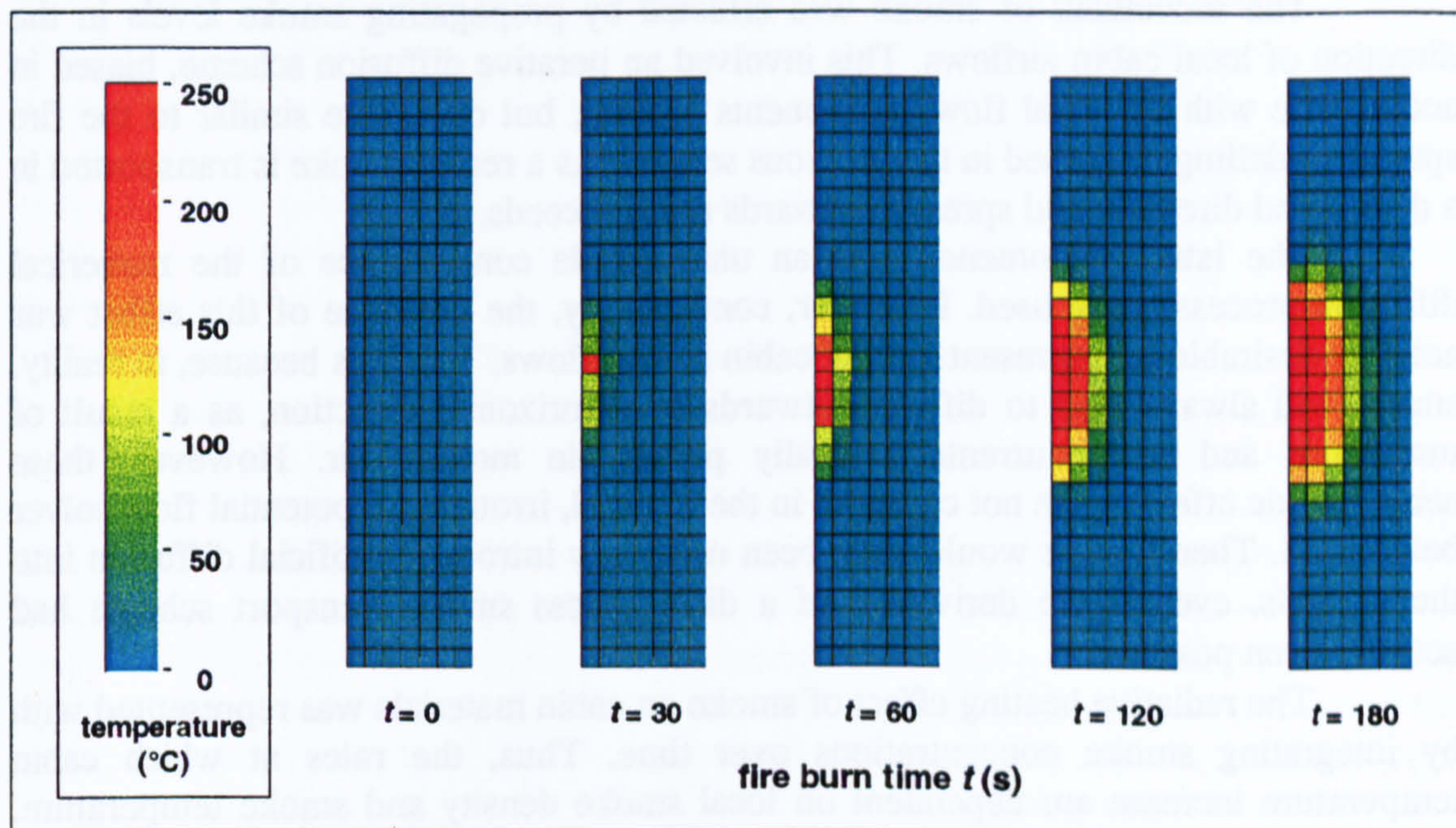


Figure 7.18: Fire Burnthrough and Internal Fire Development

aircraft, but is more extended in the lengthwise direction, as a result of cabin wall involvement. Mean temperatures in the centre of the cabin fire are likely to be approaching 1000 °C, well off the scale illustrated. Because there is no forced ventilation in the cabin, the fire growth illustrated is entirely attributable to the numerical heat diffusion and radiation schemes employed. The role of air movement in the spread of cabin fires is addressed in the next section.

7.6.3 Effects of Airflow on Cabin Fire Development

The development of fire inside enclosed compartments is known to be sensitive to forced ventilation effects. Air currents usually serve to dilute and disperse hot fire products over wide areas, significantly delaying or even preventing the development of flashover conditions (Quintiere and Tanaka, 1983). The rapidity with which smoke can engulf an aircraft cabin means that the primary danger to aircraft occupants is usually incapacitation through toxic and irritant effects, rather than the threat of thermal injury. However, the high temperatures of smoke layers can still make a significant contribution to the total incapacitation levels in those exposed. In addition, considerable quantities of thermal radiation are emitted from hot smoke, resulting in pre-heating of materials in the surrounding environment. This mechanism

is known to play an important role in speeding up the rate of a fire's development and it usually constitutes the trigger for the occurrence of fire flashover (Cooper, 1988).

In consequence, it was concluded that the role of cabin airflow on the internal fire model was essentially twofold. The first and most important aspect that needed to be modelled was the transport of smoke and around the aircraft's interior. This information was needed in order to determine evacuee visibility, toxic incapacitation and irritation levels in the evacuation model. Secondly, it was necessary to represent the heating effects of the smoke dispersed around the cabin. This was because elevated temperatures also contribute to passenger incapacitation and facilitate the spread of fire under hot smoke layers.

The movement of smoke was effected by propagating smoke levels in the direction of local cabin airflows. This involved an iterative diffusion scheme, biased in accordance with the local flow components present, but otherwise similar to the fire spread modelling described in the previous section. As a result, smoke is transported in a downwind direction and spreads outwards as it proceeds.

The later phenomenon was an unavoidable consequence of the numerical diffusion process being used. However, conveniently, the presence of this effect was actually desirable for representation of cabin smoke flows. This was because, in reality, smoke will always tend to diffuse outwards in a horizontal direction, as a result of turbulence and eddy currents generally present in moving air. However, these aerodynamic effects were not captured in the inviscid, irrotational potential flow solver being used. Therefore, it would have been necessary introduce artificial diffusion into the analysis, even if the derivation of a diffusionless smoke transport scheme had actually been possible.

The radiative heating effect of smoke on cabin materials was represented with by integrating smoke concentrations over time. Thus, the rates at which cabin temperature increase are dependent on local smoke density and smoke temperature. The latter was assumed to be proportional to optical density, reaching 122 °C at OD 1.0 /m. Figure 7.19 shows the smoke flow and associated cabin temperature

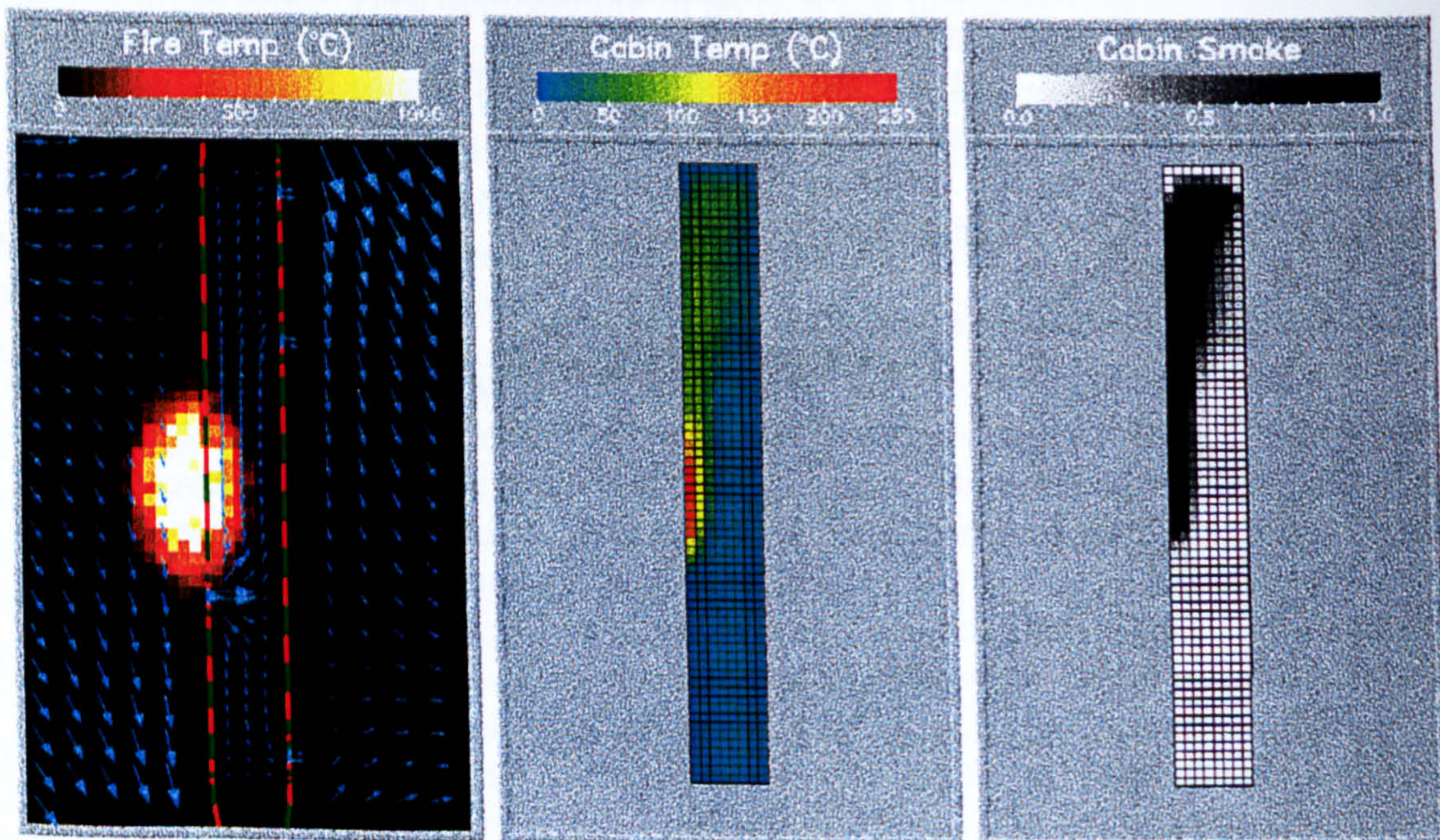


Figure 7.19: Effects of Cabin Airflow on Fire Spread

distribution resulting from a typical burnthrough fire. Note how smoke is carried up the left hand side of the cabin by the internal airflow, away from the area of fire ingress. Diffusion of the smoke stream occurs, before it re-converges and flows out of the forward right exit. The temperature within the denser regions of the smoke layer approach 122 °C.

8.1.1 Conceptualisation of the Evacuation Process

The review of fire evacuation studies in Chapter 2 revealed that two basic approaches were available for representing the egress of survivors from aircraft. These involved representing people either as discrete entities or as a homogeneous ensemble. After considering the relative advantages of the two approaches, it was decided to adopt the former strategy in the current research. This was simply because a study of past accidents had indicated that the process of passenger evacuation tends to be governed by actions performed on an individual level, rather than by group behaviour. For example passengers seated adjacent to each other may often choose different escape routes or exhibit contrasting types of behaviour. These factors possess a fundamental influence on the likely outcome of the evacuation process, and cannot be accommodated if a homogeneous analogy is used.

In addition to the representation of evacuees, the two other features necessary in any evacuation model are some form of geometric definition and a simulation clock. In the present study, the escape of people from aircraft cabins needed to be represented. These structures constitute a very distinctive evacuation geometry, for they can be treated as being two dimensional, non-curved and essentially regular in configuration. These factors suggested that the use of a two dimensionally rectangular grid would be appropriate for the evacuation analysis. The process of passenger movement could then be effected by moving individuals from grid node to grid node, in a series of discrete steps. The order and rate at which these moves are undertaken needed to be carefully regulated by simulation clock. These basic elements were sufficient to form the starting point of the passenger evacuation analysis.

At a higher conceptual level, other features needed to be considered in the evacuation process. Human beings are capable of displaying very complex patterns of behaviour, and typically, computer algorithms struggle to represent even some of the simplest characteristics involved. However, it was necessary to describe in some acceptable representation of events decision-making processes in order for the simulation to function in the desired manner. Many other factors could potentially come to influence occupant evacuation. Most aircraft accidents involve either structural damage, injuries, jamming of exits and/or complete destruction of the fuselage. Fire is also likely to enter the cabin during an evacuation. Smoking escape routes and incapacitating those who are exposed to its toxic effects.

Thus, it can be seen that three main issues needed to be dealt with in the evacuation modelling. Respectively, these were the creation of a suitable evacuation domain, representing the actions and behaviour of individuals and incorporating the major influences of the fire accident scenario.

8.1.2 Integration of the Evacuation Model within the Analysis

The modelling of passenger evacuation required the representation of the geometry and calculation of the cabin structure in order to determine the effect of the major influences of the accident scenario on the evacuation process.

Chapter 8: Passenger Evacuation Modelling

8.1 Modelling Approach

8.1.1 Conceptualisation of the Evacuation Process

The review of fire evacuation models in Chapter 2 revealed that two basic approaches were available for representing the egress of survivors from aircraft. These involved representing people either as discrete entities or as a homogenous ensemble. After considering the relative advantages the two approaches, it was decided to adopt the former strategy in the current research. This was simply because study of past accidents had indicated that the process of passenger evacuation tends to be governed by actions performed on an individual level, rather than by group behaviour. For example passengers seated adjacent to each other may often choose different escape routes or exhibit contrasting types of behaviour. These factors possess a fundamental influence on the likely outcome of the evacuation process, and cannot be accommodated if an homogenous analogy is used.

In addition to the representation of evacuees, the two other features necessary in any evacuation model are some form of geometrical environment and a simulation clock. In the present study, the escape of people from aircraft cabins needed to be represented. These structures constitute a very convenient evacuation geometry, for they can be treated as being two dimensional, are compact and essentially regular in configuration. These factors suggested that the use of a two dimensional rectangular grid would be appropriate for the evacuation analysis. The process of passenger movement could then be effected by moving individuals from grid node to grid node, in a series of discrete steps. The order and rate at which these moves are undertaken needed to be carefully regulated by simulation clock. These basic elements were sufficient to form the starting point of the passenger evacuation analysis.

At a higher conceptual level, other features needed to be introduced into the evacuation process. Human beings are capable of displaying very complex patterns of behaviour, and typically, computer algorithms struggle to represent even some of the simplest characteristics involved. However, it was necessary to formulate at least an acceptable representation of evacuee decision-making processes in order for the simulation to function in the desired manner. Many other factors could potentially come to influence occupant evacuation. Most aircraft accidents involve crashes, which result in structural damage, injuries, jamming of exits and even complete dislocation of the fuselage. Fire is also likely to enter the cabin during an evacuation, blocking escape routes and incapacitating those who are exposed to its thermo-toxic effects.

Thus, it can be seen that three main issues needed to be dealt with in the evacuation modelling. Respectively, these were the creation of a suitable evacuation domain, representing the actions and behaviour of individuals and incorporating the wider influences of the fire accident scenario.

8.1.2 Integration of the Evacuation Model within the Analysis

The modelling of passenger evacuation, together with the representation of fire growth and calculation of the cabin-thermotoxic environment effectively constituted the engine of the accident simulation model. If there were no external influences on

the evacuation process, the results provided would be similar to those obtained in aircraft certification trials. It was therefore necessary for the three programme modules involved to communicate and interact with each other in order for the outcome of accident scenarios to be predicted with any accuracy. For example, the opening of exits would be controlled by parameters from each the modules.

To ensure the provision of this capability, the fire, cabin environment and evacuation modules were designed, constructed and tested in parallel. All accident parameters and simulation variables were made fully accessible to the three modules at any stage of a simulation. Accident features were initialised simultaneously within each module by the Scenario Generator. Fire growth, the resulting cabin environment and passenger movements were also all calculated with a single simulation clock. Consequently, the evacuation process was integrated totally with all other aspects of the analysis from its very conception.

8.2 Spatial Representation of Aircraft

8.2.1 Aircraft Cabin Grids

In order to model the evacuation of aircraft occupants involved in the accident simulation, it was necessary to possess a detailed knowledge of the cabin configuration of the aircraft type involved. The information required covers many areas, including, for example overall dimensions, seating distributions, positions of aisles, exit details, and the existence of constrictions within the cabin. Data at this level of detail is essential for defining the spatial aspects of the evacuation process, i.e. the numbers, distances and relative positions of evacuees with respect to the features that are present in their surroundings. These geometrical criteria play a fundamental role determining in how evacuees interact, both with each other and with their immediate environment, throughout the course of an evacuation.

At the simplest level, an aircraft's interior can be analysed as a collection of objects, many of which possess regular geometries and occur in repeated patterns. In general, modern aircraft cabins possess floor-plans that are approximately rectangular in shape, and the objects within them tend to be densely clustered together. In the context of computer modelling, the most efficient way of encoding this type of information is in the form of a two-dimensional (2-D) rectangular grid. Positions of objects can be defined by coding the contents of individual cells within the grid. Given the regularity of seating patterns, aisle positions, exit locations, etc., very little approximation is necessary when encoding a cabin in this way, providing that an appropriate resolution of grid is used. An example of this translation process shown in Figure 8.1, for a typical section of cabin. It can be seen that the use of a rectangular grid with dimensions in the range of 150 - 200 mm enables cell positions to coincide almost exactly with objects inside the real aircraft. Consequently, grids of these sizes were chosen for the purpose of encoding aircraft cabin configurations.

When full advantage is taken of regularity, pattern repetition and symmetry, a highly accurate representation a cabin can be generated with the storage of the absolute minimum of information. Consequently, it was not necessary to store large quantities of data in an explicit form for each cabin configuration being analysed. Instead, a simple programming language was created for the purpose of defining and storing cabin geometries with a relatively short sequence of commands. These could

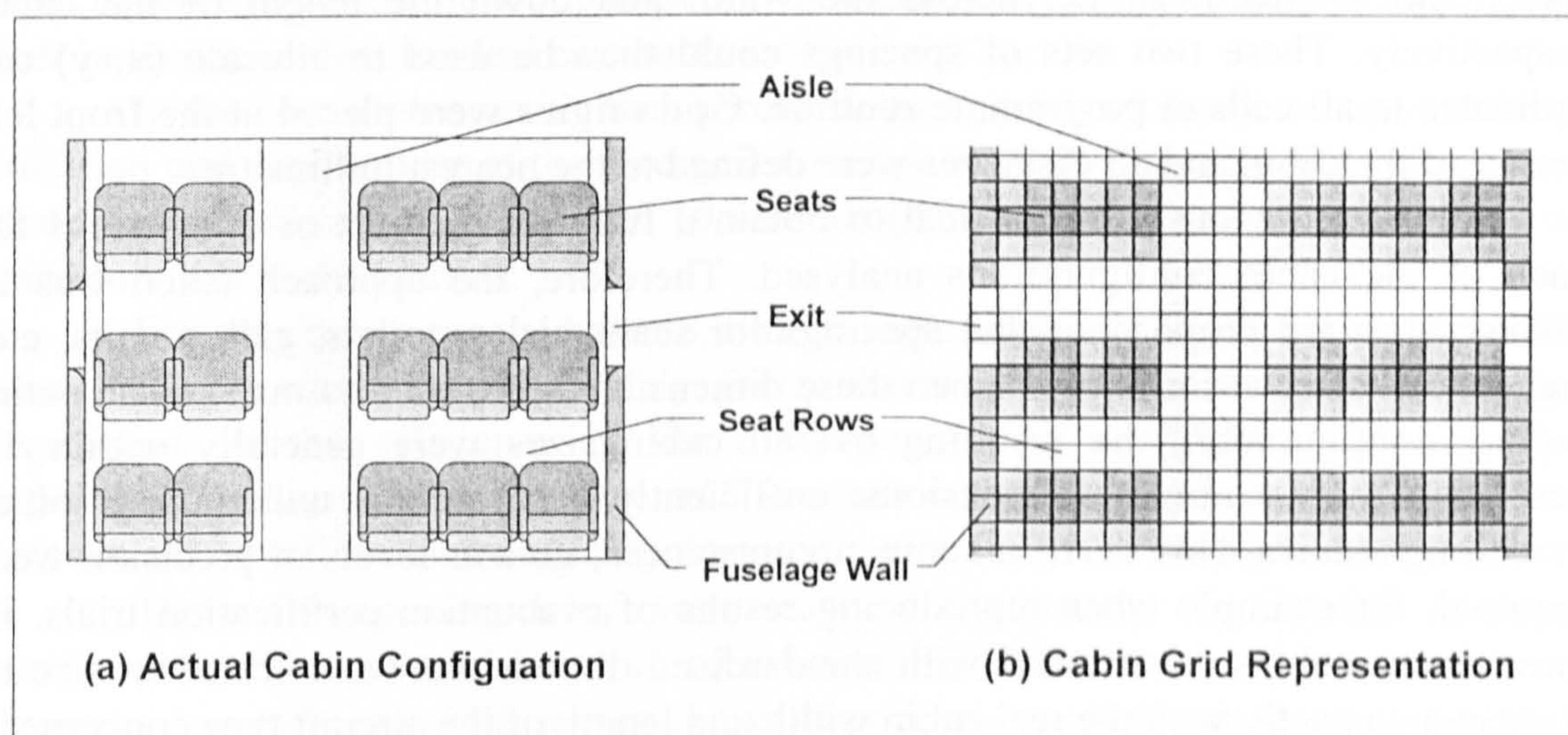


Figure 8.1: Cabin Grid Approximation

be stored in files and interpreted at programme run time in order for the required cabin configuration to be generated. More details of this procedure are provided in Section 8.2.5.

The resulting “map” of the cabin effectively contains two distinct types of information for each cell. These consist of cell vertex co-ordinates, (x, y) , and a numeric code for depicting the cell contents, c , respectively. When programming the evacuation model, it was found to be advantageous to keep these items of cabin data separate. This stemmed from the fact that they were used in two different ways. Cell contents contained categorical information and needed to be referenced repeatedly whilst performing the logic and searching operations that were used to formulate evacuee escape tactics. Consequently, they were stored as a contiguous 2-D array of integers; a very compact and efficient data type.

In contrast, co-ordinate data comprised two continuous variables per cell, did not need to be searched and would only be utilised relatively infrequently, for the purpose of calculating physical distances. Consequently, cell co-ordinates were best stored in the form of a 3-D array of floating point numbers.

The details of cabin configurations differ markedly with aircraft type, and even with different operators of the same type. As a consequence of this, it was perceived to be necessary to represent specific aircraft types on an individual basis within the evacuation model. It was seen in Chapter 6 that 72 different cabin configurations were analysed and coded into a grid-based format, for use within the evacuation modelling. Obviously, this limited selection could never reflect all configurations used by the world’s airline industry. However, the number used was enough to allow typical in-service configurations to be analysed all major aircraft types currently in service. It was anticipated that this would be more than sufficient to reveal the significance of aircraft type in determining accident survival rates and serve as a sample population against which new aircraft types could be compared.

8.2.2 Grid Dimensions

The first stage in defining a cabin configuration was to specify its overall dimensions and the individual sizes of all cells within the grid. Given that cabin grids were assumed to be truly rectangular, effectively this meant defining cell intervals in

the x and y directions, i.e. across the width and down the length of the cabin respectively. These two sets of spacings could then be used to allocate (x, y) co-ordinates to all cells at programme runtime. Grid origins were placed at the front left corner of the cabin and all distances were defined to the nearest millimetre.

It was obviously impractical to obtain a fully detailed set of dimensions for each of the cabin configurations analysed. Therefore, the approach taken was to assume standard proportions and spacings for seats, aisles, toilets, galley units, etc. and set cell sizes accordingly. When these dimensions were used to map out an entire seating configuration, the resulting overall cabin sizes were generally within ± 5 percent of actual aircraft dimensions; sufficiently accurate for undertaking initial modelling studies. However, in some circumstances, greater levels of precision were required, for example when reproducing results of evacuation certification trials. In these cases, cabins constructed with standardised dimensions were scaled in size to correspond exactly with the real cabin width and length of the aircraft type concerned.

8.2.3 Cell Contents

Integer numbers were used to specify the contents of individual cells within the cabin grids. By default, all areas of the cabin were initialised as comprising empty floor space. Details of the cabin configuration were then built up by coding individual cells to represent one of the following cabin features:-

- Fore or aft bulkhead
- Fuselage wall
- Cell on the exterior of the fuselage
- Exit
- Passenger seat
- Cabin divide, internal wall or void area
- Toilet compartment
- Stowage compartment
- Galley unit
- Aisle-way
- Exit traverse row

Once the configuration of the aircraft had been defined, passengers could be assigned to vacant seats. They were distributed randomly across the aircraft, with the probability of any one seat being occupied being equal to the load factor. Cabin crew were not represented in the evacuation simulation. However, the positions of their stations were incorporated in the cabin configurations in many instances, as they would probably be utilised if the model were to be developed further.

8.2.4 Treatment of Exits

The characteristics of doors and emergency exits can often have a fundamental influence over the process of evacuation from an aircraft. Thus, it was necessary to provide detailed information about the size and operability of each individual exit, so that events in their vicinity could be represented accurately. This information comprised exit dimensions and a time estimate for exit opening delay. The latter was

used to represent the time that passes between exit activation and the point at which it first becomes usable, in ideal circumstances. //

In the case of door exits, the opening delay consists of the time required for the inflation and deployment of the emergency escape slide. Evacuation trials have shown that this interval is typically around 10 seconds (Airbus, 1995) and thus this value was used for all floor level exits. //

For emergency escape hatches, time is required for the hatch to be manhandled away from the exit and stowed safely. Given that the speed of this operation is largely dependent on the efficiency of the exit operator, it was difficult to specify a representative time delay. A value of 7 seconds was chosen, on the basis that hatch exits could be utilised more quickly than door exits, in favourable circumstances.

These exit opening delays were assumed to represent the absolute minimum times in which exits could be expected to be utilised. The values were factored in the scenario generation module, to ensure that they corresponded with the delays actually observed in past accidents. In cases where an exit was determined to have been jammed, as a result of damage sustained in a crash impact, an opening delay of 999 seconds was assumed.

8.2.5 Programming of Cabin Data

A large quantity of information was required to define a typical cabin grid configuration in an explicit manner. Consider, for example, the cabin of a Boeing 777 aircraft in a three class seating layout. This required an array measuring 36 by 268 entries to depict in detail, corresponding to a total of 9648 individual cells. Each of these cells possesses x and y co-ordinates, together with an integer code for representing its contents. This means that 28,944 numbers have to be defined in order to completely describe the cabin of a single aircraft type. Whilst modern computer technology might be able to accommodate these quantities of data with ease, the task of deriving and entering the values for cabin grids by hand would have been prohibitively time-consuming.

Consequently, it was decided to construct a simple programming language and command interpreter for the purpose of creating aircraft cabin configurations. The commands were formulated to allow large series of cell co-ordinates or cell contents to be initialised in a single operation. For example, a single command might be used to create an extended row of wall cells, an 11 by 5 cell galley unit, or a large array of passenger seats. Then, instead of storing cabin layouts as tens of thousands of numbers, they could be defined with a comparatively short sequence of commands. The command interpreter can then be used to read in this list of commands at programme runtime and process them to construct a full numeric description of the aircraft's cabin layout. On a modern desktop workstation computer, this interpretation and re-construction process can be achieved in fractions of a second, for even the largest of aircraft types, involving over 15,000 cells. //

The use of this approach enabled complex aircraft cabin configurations to be encoded and tested with the evacuation model in comparatively short time intervals. Returning to the example cited above, the Boeing 777 layout was converted into a grid format, drawn and then programmed in a total time of approximately three hours. // The definition of the 28,944 cells was achieved with the use of only 165 commands.

The implementation of a typical command is shown in Figure 8.2. The function of “seats2” is used to create a rectangular array of business or economy class

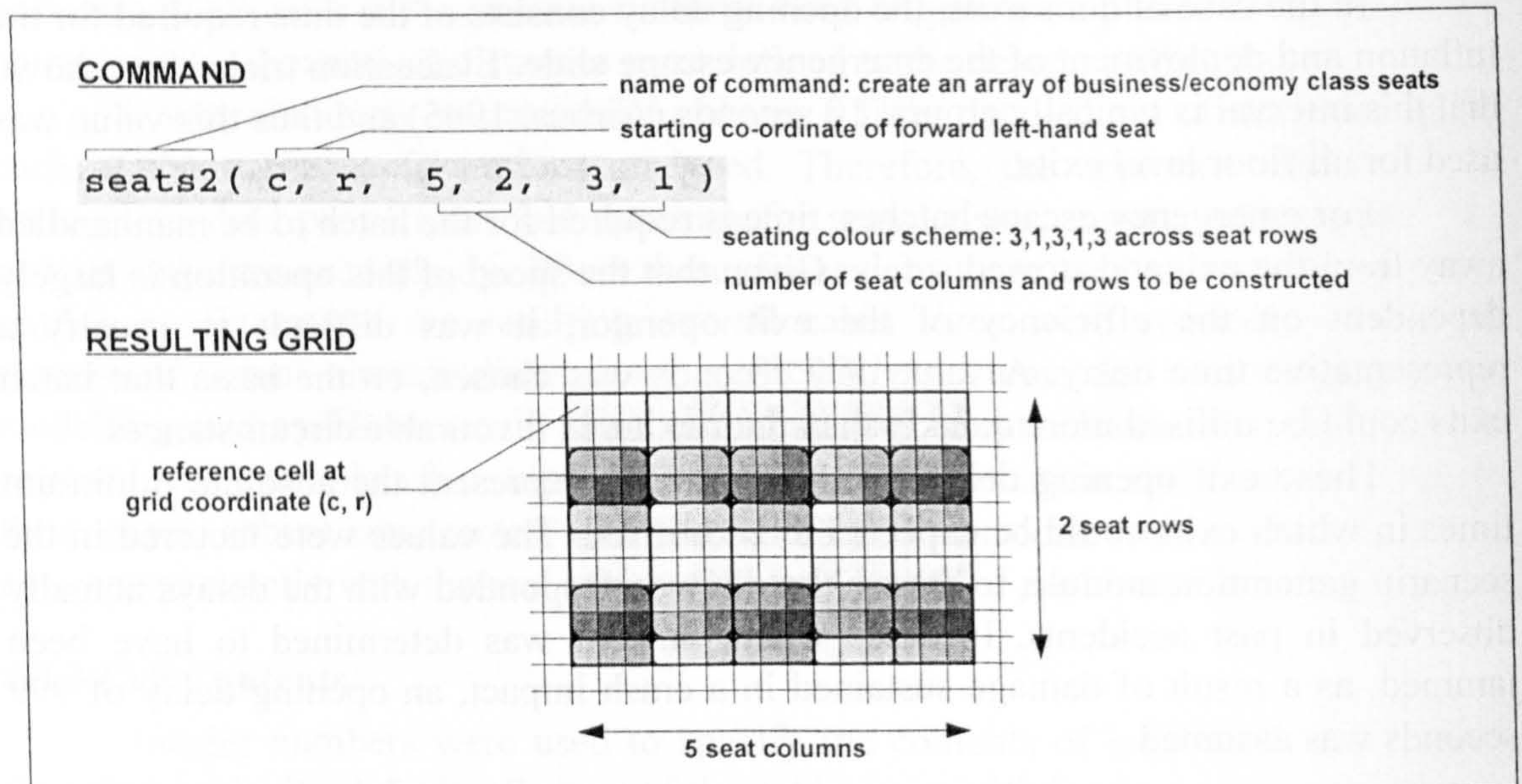


Figure 8.2: Example Grid Construction Command

seats. The parameters that need to be specified by the command are the position of the forward left-hand seat, number of seat columns, number of seat rows and the colours to be assigned to the seats. Each business or economy seat occupies a space of 3 by 5 cells; thus the example shown defines 150 cells in the cabin array with a single command.

A total of eighteen commands was created in order to define all aspects of aircraft cabin configurations. Most of these were used in a manner analogous to “seats2”. One notable exception was the “wings” command which specifies the position of the wings with respect to the aircraft’s cabin, by providing a series of co-ordinates. The use of this and all the other commands necessary for the specification of a complete cabin grid for a small airliner type is illustrated in Figure 8.3. It can be seen that the use of a command interpreter simplifies construction of cabin grids to the extent that a non-specialist would be capable of performing the task. Commands are entered into plain text files, with the use of any word-processing package and then checked by testing them in the simulation programme. The resulting cabin configuration files were collated to form a library of aircraft types for use as required within the modelling analysis.

8.2.6 Structural Disruption & Fuselage Breakages

The cabin grids were constructed to represent aircraft in an intact state, without distortion or breakages that might be present after a crash impact. Before these types of accidents could be analysed, it was necessary to introduce the effects structural disruption into the evacuation model.

It was seen in Chapter 6 that the method used to specify levels of impact damage in the scenario generator involved fuselage segmentation and damage ratings on a 0.0 - 1.0 scale. The latter was straightforward to code into an additional sub-layer of the cabin evacuation grid. However the break-up and separation of a fuselage obviously held far greater implications for the evacuation modelling. As a result, a

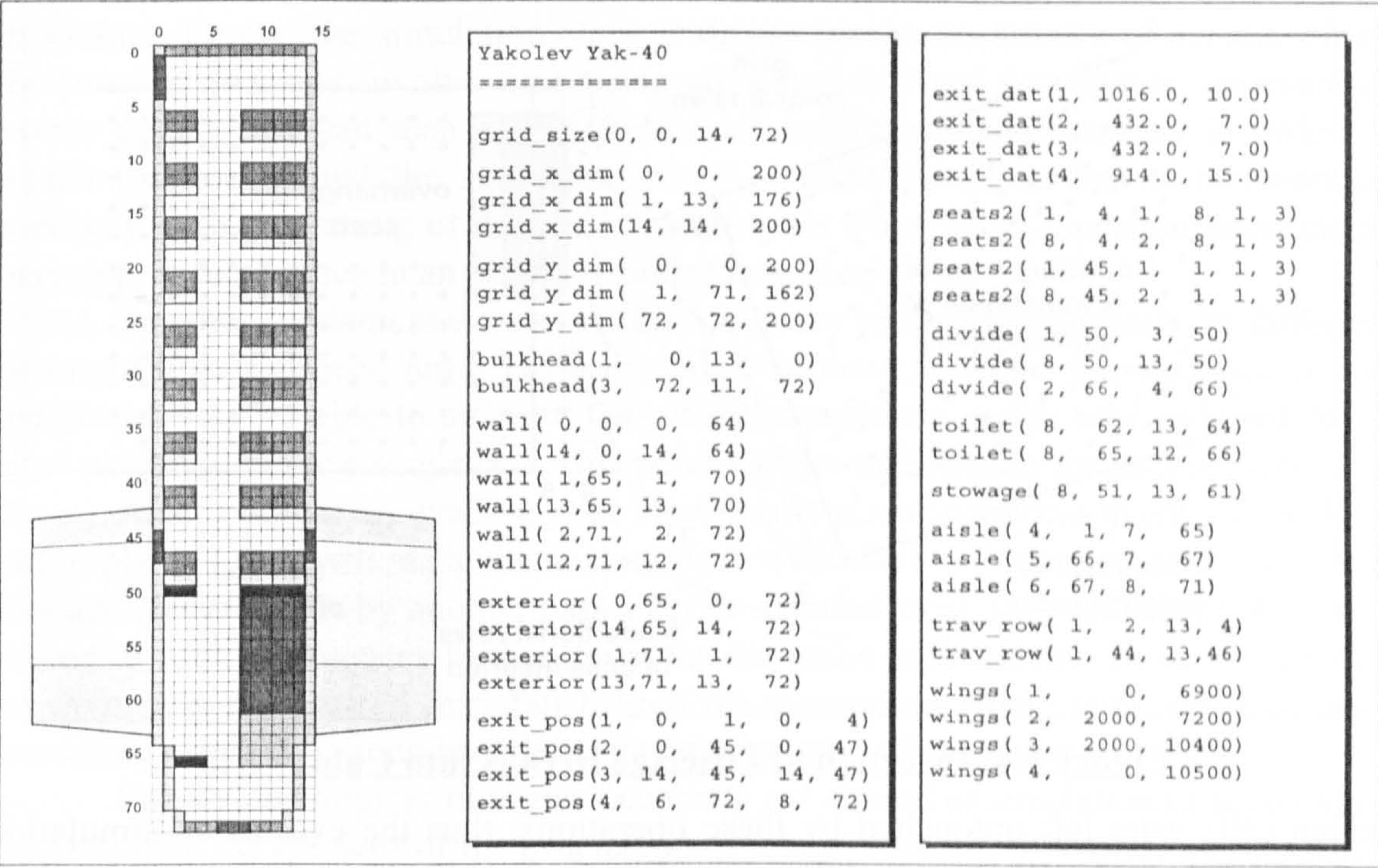


Figure 8.3: Definition of Cabin Grid for a Small Airliner

dedicated section of code, entitled BREAKUP, was created to incorporate the necessary effects into the cabin grids.

The main task that needed to be achieved was to split an aircraft’s cabin into two or three sections and then rotate and translate these pieces into arbitrary positions with respect to each other. Effectively, as far as the evacuation modelling was concerned, this involved breaking a single cabin up into a number of separate units and adding new “exits” at the positions of the severed edges. The classification of these edges as additional exits was prompted by the fact that significant numbers of survivors were known to have escaped by these means in past accidents.

Splitting of a fuselage section in two was achieved by inserting five additional rows of cells at the break positions, as shown in Figure 8.4. It was observed from past accidents that passenger seats located in the vicinity of a fuselage break do not split in two along the break line, but rather, remain attached to one of the fuselage sections, often with a considerable overhang. Two rows of cells were allocated to represent this effect on each fuselage section (rows 1, 2 and 4, 5 respectively). Aisleway cells in rows 2 and 4 were defined as new exits and allocated a slow traverse rate (5.0 seconds), to represent the effects of passengers scrambling across twisted debris.

The central row (number 3) was left to bridge the gap between the fuselage sections and cells were coded as being on the exterior of the aircraft. As such, they played no role in the evacuation simulation and were necessary only for graphical purposes.

Functions were created to translate and rotate separated sections of fuselage into arbitrary positions with respect to each other. These involved simple matrix transformations being applied to grid co-ordinates, introducing a shift (δx , δy) and an angular rotation (θ) around the centroid of the section fuselage concerned. A similar procedure was used to update the locations of external fires, whose positions were defined on the basis of local fuselage orientation. Note that the actual contents of

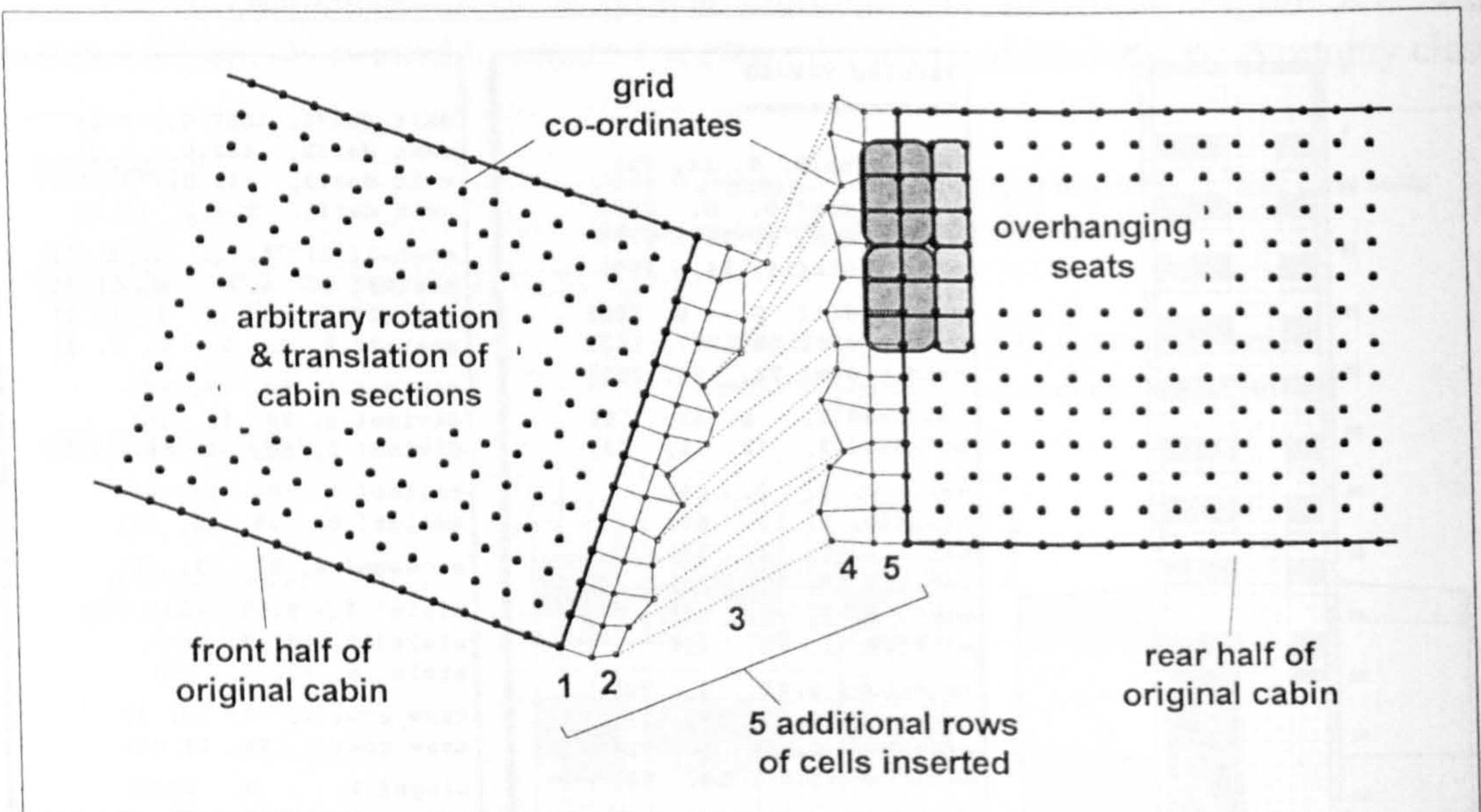


Figure 8.4: Insertion of Fuselage Breaks into Cabin Grid

cabin cells were left untouched by these operations; thus the evacuation simulation would work with cell vectors defined in directions up/down and across the cabin, regardless of the actual physical orientation of the fuselage.

In some instances, fuselage breakages would bisect emergency exits and doors. Given the reinforced structure present in these areas, exits usually remain with one half of the aircraft, rather than being split in two. No correction was applied to represent this effect, as the exits concerned would be likely to have been jammed as a result of structural distortion.

Once the dispositions of cabin sections were known, it was possible to calculate the total envelope of the wreckage and determine an appropriate scale for the plotting of evacuation graphics on screen.

8.3 The Simulation Clock & Passenger Movement

8.3.1 Event Driven Simulation Methodology

The passenger evacuation model was implemented with the use of an event driven simulation process. This involved evacuees performing their moves independently of each other and at any point in time, as opposed to a cell-based or simultaneous movement scheme. To start the process, a completion time for the next movement or action to be performed by each individual is calculated. These events are then sorted into a chronological list, with the most imminent placed at the top. The simulation programme then implements passenger movements based on the order of their occurrence on this list.

When an action is to be effected, the simulation clock is advanced to the time of the event concerned, the action is removed from the event list and implemented. Next, the individual involved chooses their next move in the evacuation and the time required for its accomplishment is calculated. This new completion time is then used to insert the evacuee back into the chronological event list at the appropriate position, effectively making the individual "wait" until it is their turn to move again.

Some important points should be noted about this type of simulation procedure. Firstly, the simulation clock is driven by the occurrence of events. Thus, the process *does not* involve time being advanced in fixed increments, intervening events determined and then executed. Instead, actions are implemented in order in which they occur and the simulation clock is incremented so that it corresponds precisely with the timing of each individual event. As a result, the simulation clock may appear to advance in an erratic or uneven manner.

Another fundamental point is that evacuees move independently at different points in time and need not necessarily take it in turns to move. For instance, a fast individual may be able to advance two or three positions in the time required for a slow person to move a single cell. This point will be amplified in the next section.

Also, because an evacuee is at the top of the chronological event list, it does not imply that they will make the next move in a simulation. If the individual's path is blocked (for example by another passenger or a closed exit), they will be held up and forced to wait as evacuees further down the list make their moves. Thus, the time of an evacuee's next action may fall behind the evacuation clock, until, on their path becoming clear, they jump back into synchronisation with the latest events.

Finally, the number of events occurring per second of simulation time can vary dramatically. At the start of the evacuation of a large aircraft, thousands of passenger movements might need to be processed each second. In contrast, when the last person is leaving the aircraft, perhaps seriously injured or in dense smoke, less than one step might be occur per second of simulation time. Thus, if the computer programme is left to run naturally, processing events at a fixed rate, the evacuation clock will appear to progressively speed up as fewer and fewer passengers remain inside the aircraft. No attempt was made to synchronise the simulation clock to real time in order to hide this "snowballing" effect.

8.3.2 Movement at Different Speeds

As mentioned in the previous section, it was ensured that individuals were capable of moving at different rates within the evacuation simulation. Variations in speed can result from differences in passenger attributes, thermo-toxic incapacitation levels, inter-personal spacing, visibility and the presence of cabin disruption. In consequence, evacuees would be starting off at a range of different speeds and then their rates of movement would fluctuate in accordance with the prevailing conditions.

These speed variations were known to be potentially important in determining egress dynamics; for example, a slow person holding up a queue of faster passengers will result in a significant reduction in the mean rate of progress. Those positioned towards the rear of a slowly moving queue would be more likely to seek an alternative escape route, perhaps causing distribution of exit usage to be modified. Consequently, variation in the speed at which evacuees move not only influences the rate at an evacuation takes place; also the overall pattern of movement may be dependent on the magnitude of the variations present. Thus, in order to obtain a faithful representation of the egress process, it was essential for evacuees to be able to move at their own rates, rather than being forced to synchronise their movements with the fixed cycle of a simulation clock. Effectively, this imposed the requirement for an event driven (as opposed to a clock driven) simulation methodology.

Controlling the rate at which evacuees moved was a task of fundamental importance within the egress analysis. The approach taken was to calculate the time

required for an individual to traverse a cabin cell, based on their current maximum rate of movement. In practice, this speed would rarely be sustained, as evacuees are likely to be slowed in the presence of each other and restrictions in the cabin.

All passengers were assigned a maximum egress speed at the start of the simulation, chosen at random from probability distribution. The later provided values evenly distributed between 0.75 and 1.25 m/s i.e. with a mean of 1.0 m/s and a variation of up to ± 0.25 m/s. This speed range corresponded approximately with the rates observed in video recordings of evacuation trials undertaken by Muir (Muir and Bottomly, 1992). It should be noted that these figures apply to motivated young male volunteers moving through empty aisles; thus they probably represent the upper bounds of passenger speeds likely to be encountered in real accidents.

During the course of an evacuation, the maximum rate at which aircraft occupants can move may be reduced by a number of factors, for example thermo-toxic incapacitation, poor visibility and cabin disruption. It was assumed that the influences of these various effects were independent and multiplicative. Thus speeds were factored in turn by parameters such as Fractional Effective Dose, smoke optical density and cabin disruption levels. In reality, the role of these influences is obviously far more complex than assumed; for example, exposure to light smoke has actually been found to make volunteers move more quickly in experimental tests (Jin and Yamada, 1989).

As has been already seen, the requirement to model evacuees moving at arbitrary speeds was accommodated with the use of an event driven simulation procedure. This aspect of the evacuation modelling is illustrated in Figure 8.5. The two evacuees start at the bottom of the grid and progress upwards at different speeds. Note that the scale of the grid has been enlarged for clarity. Passenger A moves at a rate of one cell per second and will thus cause the simulation clock to be incremented at 1.0 second intervals. In contrast, passenger B only moves at two thirds of this rate and

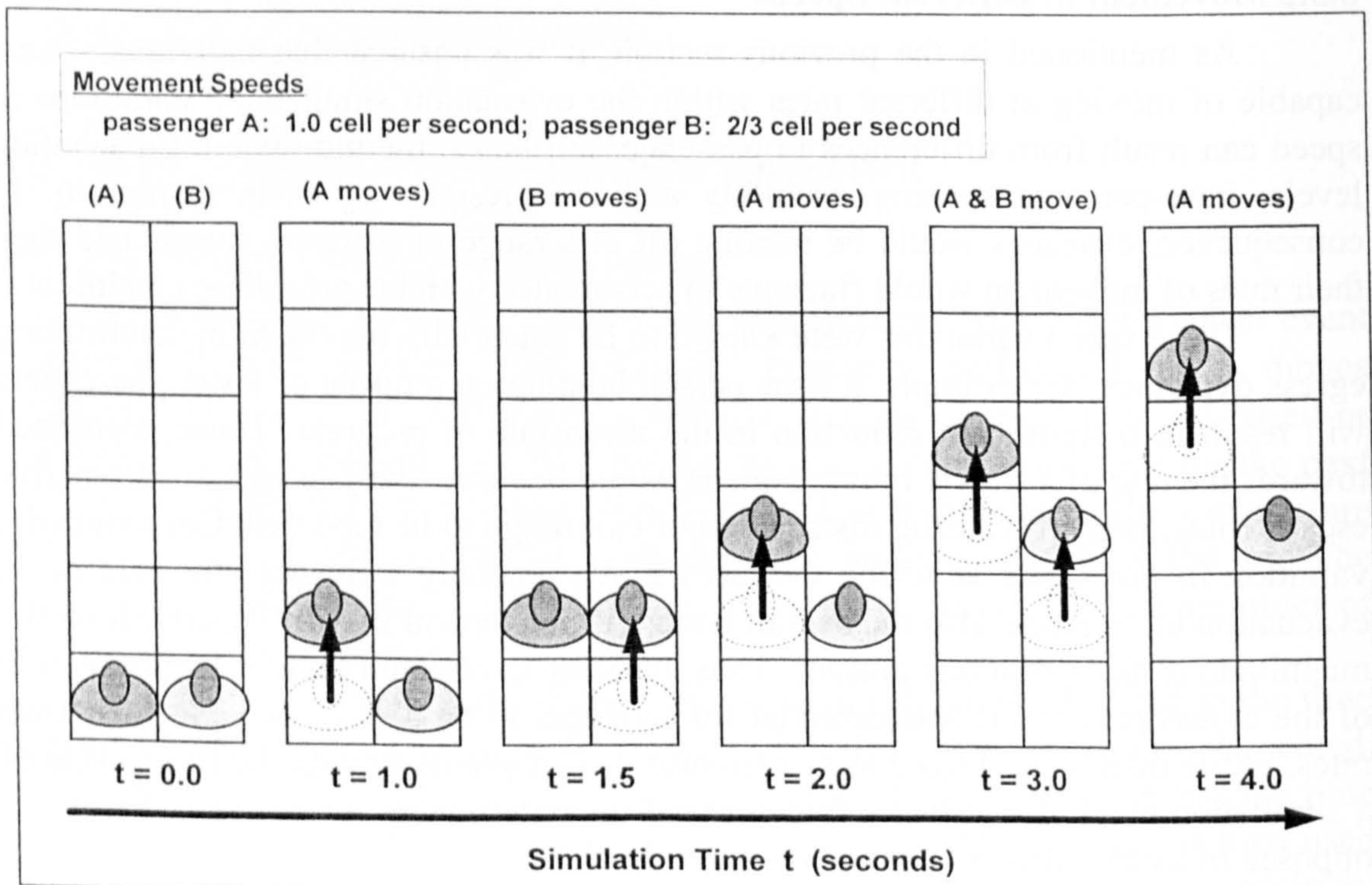


Figure 8.5: Event Driven Simulation of Evacuee Movement

will thus require the clock to be advanced every 1.5 seconds. Driving the simulation clock in accordance with these events produces a repeating pattern of 1.0 and 0.5 second time-steps i.e. a variable time-step process.

It is worth noting that, at a clock time of 3.0 seconds, the movements both evacuees happen to precisely coincide, implying that they both have equal priority the chronological event list. Generally, in this situation, both passengers will be able to make their move in the same time step, with the individual that chances to be in the upper position in the event list getting moving first. Although this eventuality was accommodated for in the simulation programming, in practice it is extremely unlikely to occur. This is because the timings of all evacuee movements involve least one randomly determined component and calculations are performed to an accuracy of sixteen significant figures.

8.3.3 Passenger Crossing and Overtaking

There are occasions during the evacuation of an aircraft when passengers may wish to pass each other in confined spaces. It is possible to distinguish two types of passing manoeuvre; evacuees may wish to pass in opposite directions, or else they may be attempting to move in the same direction. These two cases were classified as *crossing* and *overtaking* respectively.

From a simulation standpoint, both of these interactions could be implemented in a similar manner, as shown in Figure 8.6. Note that the only difference between crossing and overtaking is the direction in which the two passing passengers are facing at the start and finish of the procedure. For the purpose of clarity, the two processes have been illustrated in seven stages. In reality, four of these are actually undertaken simultaneously, which results in a comparatively simple three stage “turn, pass and turn” procedure.

It was decided not to introduce evacuee overtaking in the accident simulations. This was because the manoeuvre was difficult to calibrate and made it a negligible

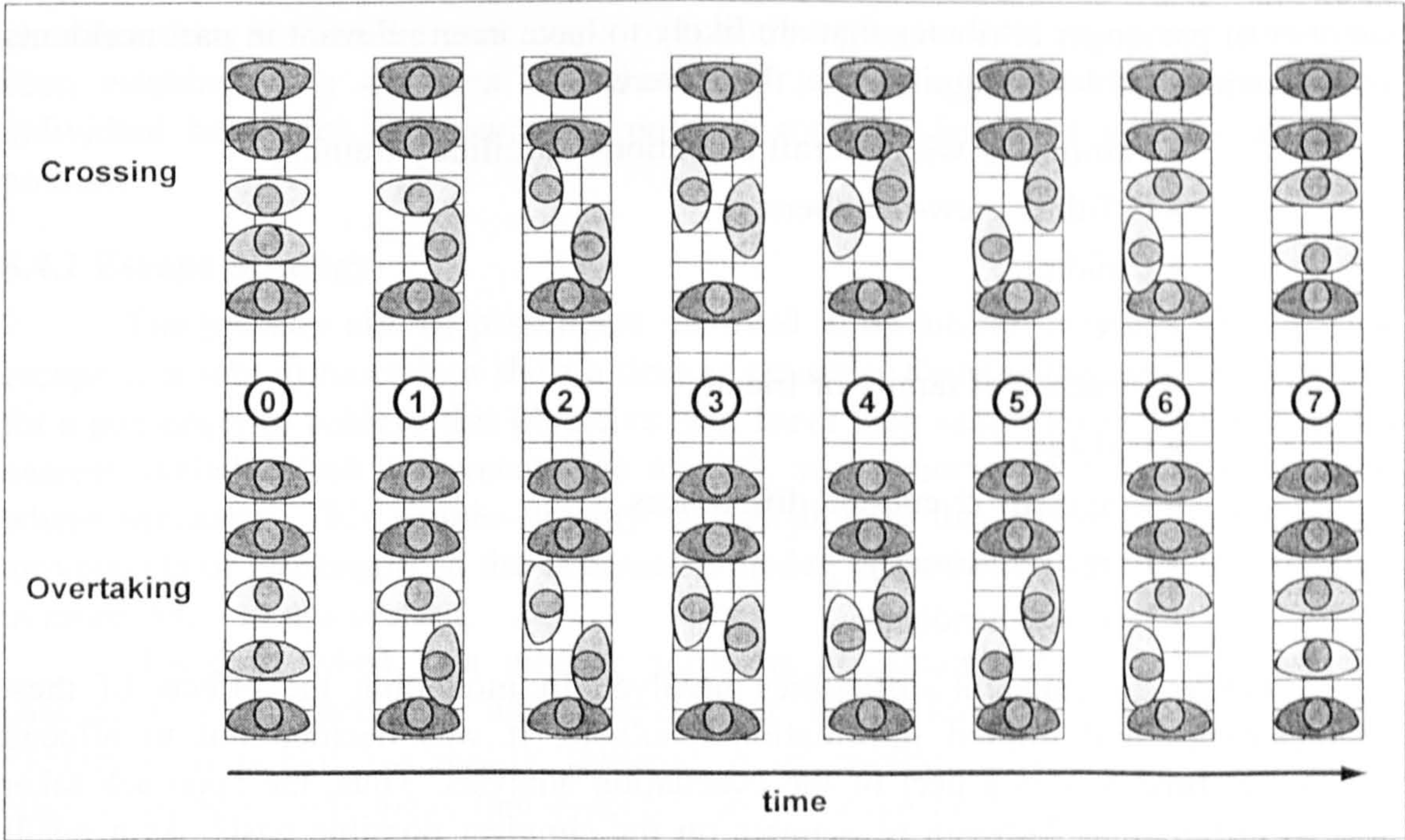


Figure 8.6 : Crossing and Overtaking in a Narrow Aisleway

difference to the outcome of simulations; evacuees just tended to emerge from the aircraft in a slightly different order. In contrast, the use of the crossing manoeuvre was found to be useful for enabling passengers to pass each other when heading in different directions along a modestly wide aisle. This action was assumed to impose a delay of one second on the participants.

8.4 Passenger Decision Making & Behaviour

8.4.1 Representation of Passenger Characteristics

When people are involved in an aircraft accident, they can behave in a number of different ways, some of which contrast strikingly. Reactions can vary from what might appear to be frenzied panic, through to calm purposeful responses or even to complete inaction. Some of these behavioural differences may stem from variations in the circumstances and the local conditions that survivors are exposed to. For instance, several accidents have indicated that individuals located near to a large external fire or fuselage rupture are particularly prone to behavioural inaction. However, the fact that passengers in adjacent seats often react to a situation in completely different manners suggests that behaviour is highly dependent on the characteristics of the individual concerned. As a result of this, it was obvious that provision needed to be made within the evacuation analysis for modelling the attributes of passengers on an individual basis.

A study of evacuations in past aircraft accidents was undertaken, in an attempt to gain an insight into the role of personal characteristics and behaviour in these events. Even with a database of over 200 events to work from, passenger characteristics were specifically cited on only 36 occasions in the accident reports and summaries surveyed. Thus, most of the material was only anecdotal in nature and it was not feasible to determine a statistical significance level for any of the observations made. However, in spite of this, it was least possible to identify a number of passenger attributes that are likely to have been relevant in past accidents. In approximate order of significance, these were:-

- Familiarity with aircraft operations or military training
- Off-duty crew-members
- Children
- Sex
- Presence of family or friends
- Old age
- Linguistic & cultural differences
- Large size/obesity
- Physical handicap

Given the inherent difficulties involved in modelling the effects of these characteristics and limited information available, it was decided not to allocate significant time to this aspect of the evacuation analysis. Thus, the approach taken was to differentiate between passengers on the simplest possible basis. As a result, only two attributes were used; these were passenger reaction time and maximum rate

of movement, respectively. These measures were simple to define, measure and calibrate, as well as being straightforward integrate directly into the evacuation analysis.

It was found that using this minimal set of passenger attributes was sufficient to produce a satisfactory representation of evacuation dynamics. This was because, essentially, the factors noted in the study of past accidents only serve to modify behaviour amongst individuals on very a local scale - for example, the rapid opening of one exit, or the creation of a slow moving restriction in one area of the cabin. Consequently, the net effects of these factors could be accounted for quite adequately by modifying the reactions and rates of movement possessed by certain passengers in the simulation.

Obviously, this means that localised processes arising from detailed differences in passenger characteristics will not be modelled explicitly. However, if the resultant effects on surrounding passengers and the evacuation process as a whole are reproducible by simpler means, this need not concern us. An example of this can be found in the case of handicapped passengers. Trials suggest that, regardless of whether they are blind, paraplegic, obese or mentally deficient, these individuals effectively constitute a slow moving obstruction, behind which faster evacuees are detained (Blethrow et al., 1977). Differences in the rates of movement achievable by these passengers range from 0.82 to 0.19 of those exhibited by unimpaired passengers.

It would have been very straightforward to expand the list of passenger characteristics to encompass almost any conceivable physical or psychological trait. However, without any substantial quantitative information on how such factors might influence behaviour in emergency situations, this exercise would have been meaningless. Although physical parameters, such as age, weight, height and sex are straightforward to measure, determining their significance in realistic evacuation scenarios is far from easy (Jin and Yamada, 1989; Muir et al., 1989). Psychological characteristics, such as patience, aggressiveness or propensity to panic are even difficult to define satisfactorily, short of measuring or making practical use of. These considerations lead to the conclusion that, until a greater level of understanding has been established in the area of behavioural psychology, the characterisation of individual behaviour in computer simulation models should be kept as simple as possible.

8.4.2 Escape Strategy

The primary aim of passengers involved in an aircraft accident should be to escape to a safe distance in a short a time as possible. Perhaps the most obvious way for a passenger to achieve this objective is to leave their seat, move up an aisle to the nearest available exit and vacate the aircraft, accommodating the needs of others where necessary. This simple strategy was to provide the basis for controlling the movements of passengers in the evacuation model; consequently, it will be examined in more detail in this section.

However, when past aircraft accidents are examined, it is apparent that passengers may sometimes utilise less rather straightforward methods of escape. Factors such as exit availability, queuing, novel escape paths and the influence of other passengers may mean that evacuees do not make for their nearest exit. Escape plans and options may also be altered as cabin conditions deteriorate or the

functionality of exits becomes apparent. Some these issues are examined in subsequent sections.

In order for an evacuee to head directly to their nearest exit, it was necessary them to assess the relative distances of the various exits available and choose the shortest. This was achieved within the simulation by making the locations of all emergency exits available to the passengers. Exit choice could then simply be determined by looking up the positions of each exit in turn and calculating the distance involved. There were two possible options for measuring exit distances; they could be evaluated in a straight line i.e. “as the crow flies”, or as the total path lengths that would have to be traversed in order for the exit to be reached. In some situations, significant differences can result from these two options. This point is illustrated in Figure 8.7, which shows a passenger seated in the rear of a DC-9 cabin together with

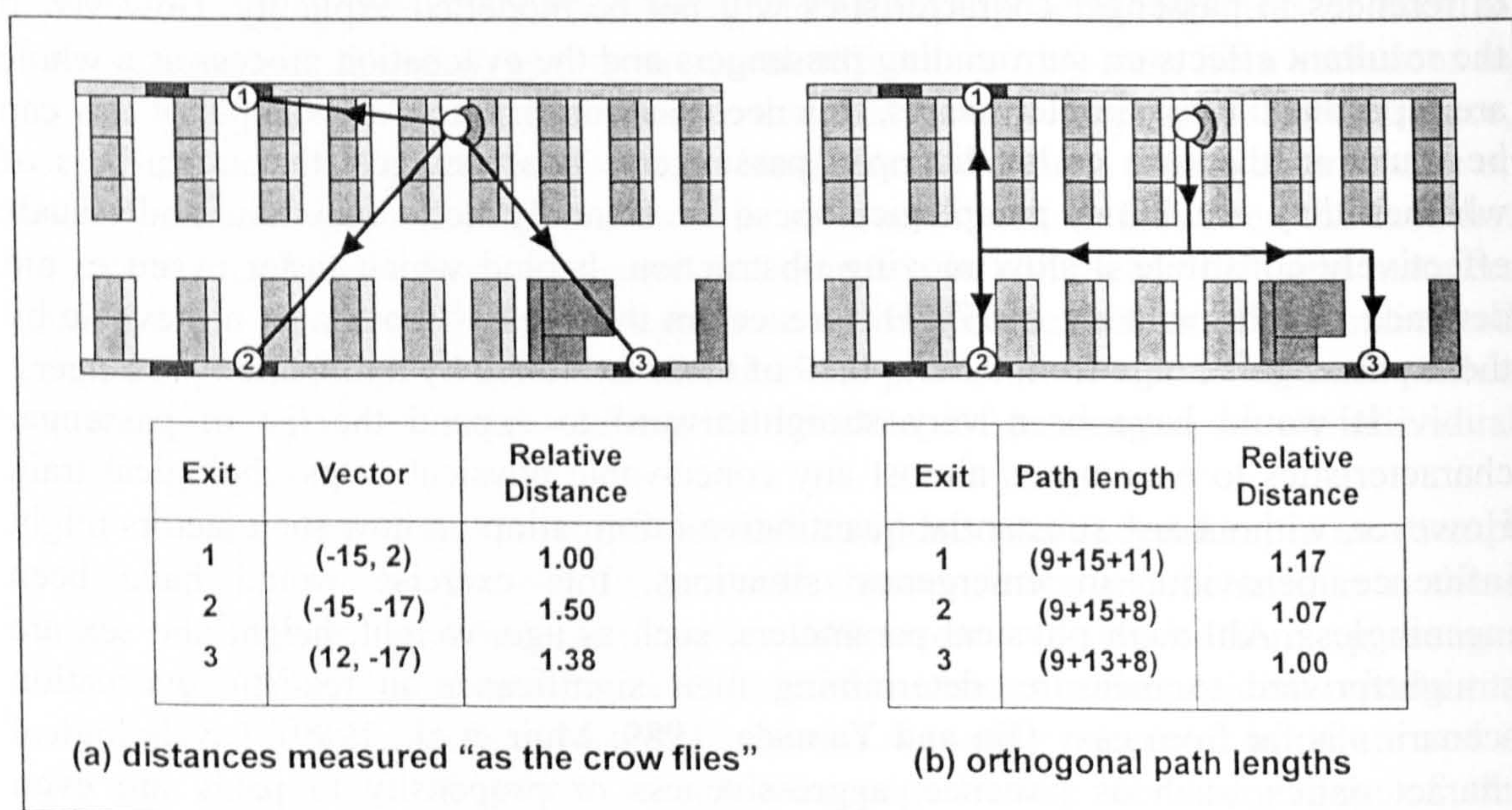


Figure 8.7: Method of Measuring Exit Distances

distances to the nearest three exits. Note how exit 1 appears to be the nearest when straight line distances are compared. However, this exit is actually the furthest away from the passenger when true path lengths are evaluated.

It was not known which of these two possibilities was the better representation of how passengers judge exit distances in reality. Both methods were coded, but the latter tended to be used more often, if only for the reason that path lengths could be evaluated more quickly.

Once the evacuee has chosen an exit, their next move will be dependent on the nature of their current location. This could be one of six cell types; seat, seat row, aisle, exit traverse row, exit or outside the aircraft. The actions that were performed in each of these positions are shown in Table 8.1.

Location	Action
seat	Undo seat belt, stand and move into seat row
seat row	Find and move towards aisle, exit row or exit
aisle	Head in direction of chosen exit, avoiding obstructions. In a widebody aircraft, change aisles if necessary.
exit row	Head towards chosen exit, or else find way out of wrong exit row
exit	Move forwards when clear below
outside of aircraft	Remove from simulation

Table 8.1: Evacuee Actions

It should be noted that, in reality, the task of determining a passenger’s next move is considerably more complicated than this list might appear to indicate. In widebody aircraft, for instance, if an evacuee needed to change aisle, they would be required to move from an aisle back into a seat row. For this to occur, they must be aware that a second aisle exists, know which side it is on and determine whether or not it is advantageous to move across to it. To illustrate this point, Figure 8.8 shows a typical

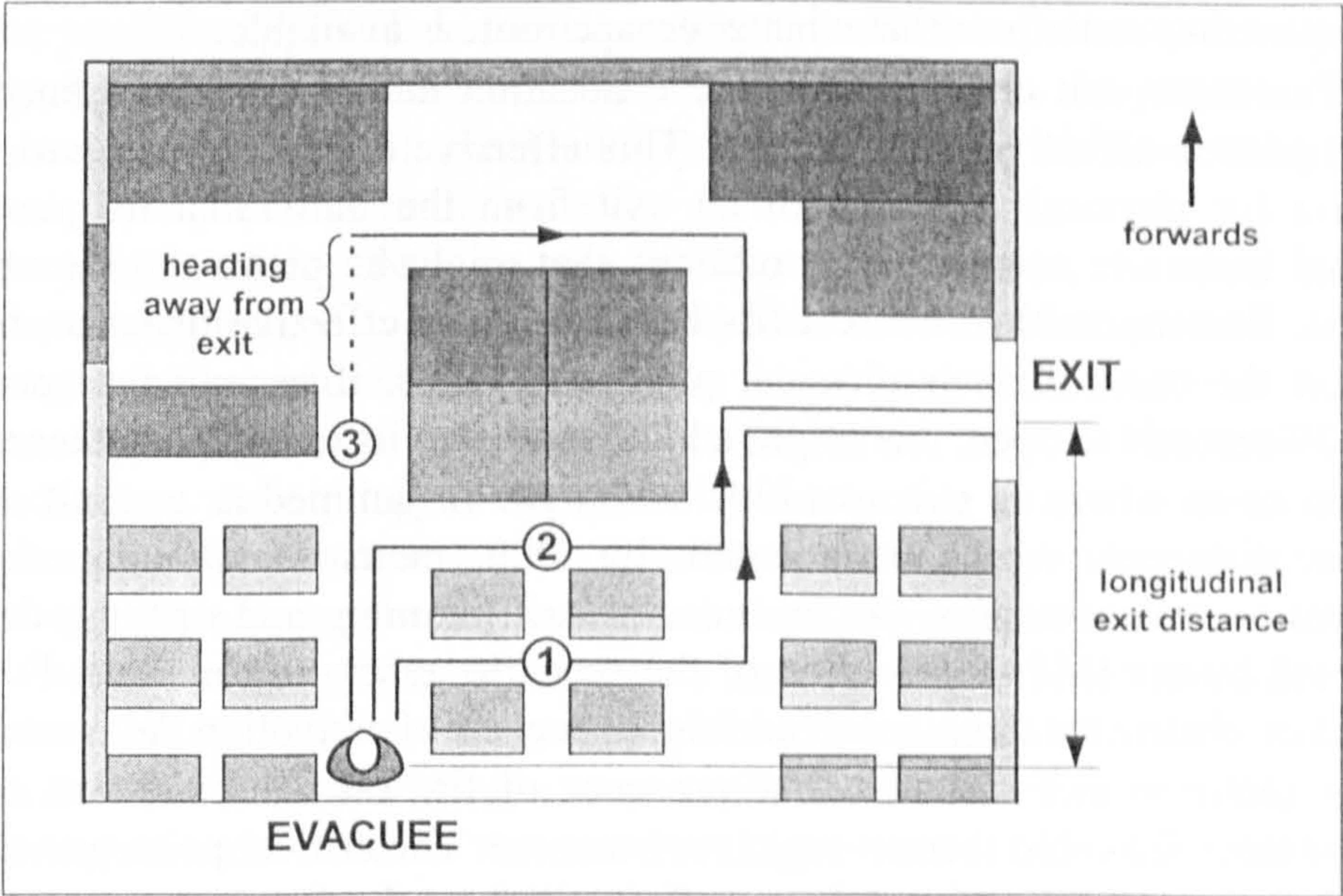


Figure 8.8: Choosing Between Multiple Escape Routes

cabin configuration in the vicinity of a number two exit¹ in a L-1011 Tristar aircraft. Passenger approaching the front of the first class seating in the left hand aisle would be likely to cross seat rows as they neared the exit. This option was programmed into the evacuation model; however, with no source of data to work with, it was assumed that this action might occur at up to five seat rows from the exit. The probability of aisle crossing was made inversely proportional to exit distance, as measured in the

¹ i.e. the first door on the starboard side of the aircraft.

longitudinal direction. Thus passengers would be approximately twice as likely to take route 2 as opposed to route 1 when crossing to the exit.

The figure also illustrates another problem that needed to be dealt with in some aircraft cabin configurations. Occasionally it was necessary for passengers in an aisle to actually move past and head away from the chosen exit before turning across the cabin and to moving towards it. This possibility is labelled as route 3 in the diagram. These kinds of difficulties were dealt with by making passengers perform a series of search patterns when they approached the vicinity of exits. In a manner analogous to playing a game of chess, these search routines enabled all movement options to be explored and "dead-ends" or less favourable routes avoided.

8.4.3 Exit Choice

From both past accidents and evacuation trials, it is known that passengers frequently do not utilise their nearest exit when escaping from an aircraft. It was possible to identify three types of scenario in which this situation might occur. Firstly, there might be a very fundamental reason for not making use of a particular exit; it might have been jammed as a result of impact damage, or blocked by the presence of fire immediately outside. Secondly, evacuees may be unaware of the precise location or even the existence of their nearest exit, particularly in conditions of darkness, smoke or panic. For example, there have been instances where passengers have walked past open door exits and accidentally stumbled into an aircraft's cockpit in heavy smoke. Finally, evacuees may make a positive choice not to use a functional exit because they anticipate that a better escape route is available.

Passenger exit choice within the evacuation model was determined with the use of a pseudo effective exit distance. This effective distance comprised the actual geometric (or physical) distance of an exit from the individual in question, plus additional factors to account for conditions that might be present in the above three scenarios. Passengers then chose exits based on their effective distance, rather than purely on the basis of their physical proximity. Thus, if an exit was perceived to require 30 seconds to open, this might add 20 metres to its effective distance.

In cases where an exit was blocked by fire or jammed as a result of damage, effective distances were incremented by 999 metres, removing them from consideration by passengers. Occurrences of exit jamming and opening delays were determined by the IMPACT section of the scenario generation module. For partially damaged or obstructed doors, each additional second of activation delay was assumed to add 1 metre to exit distance. The presence of fire outside exits was established when updating the cabin thermo-toxic environment. The critical point was assumed to occur when the exit lay within 1.5 mean fire radii from the fire centre. At a later stage, this part of the analysis could be expanded to incorporate the effects of external radiation intensity, smoke levels and wind direction. Theoretically, it would also be possible to predict when escape slides would be likely to have burst as a result of exposure to the effects of fire.

When conditions around an exit become crowded, passengers who are still located at some distance away will usually seek to avoid the congestion and look for alternative escape routes. As a result, evacuees may attempt to distribute themselves more evenly between the available exits, even if this involves traversing greater distances inside the aircraft. Evacuation trials suggest that active encouragement of this behaviour by assertive cabin crew may increase evacuation rates significantly. In

order for this effect to be modelled, it was necessary to compute exit queue lengths and the positions of passengers within these queues. The evacuees were ranked in terms of their path length and only included in the queue of their chosen exit. Each person ahead of the evacuee in an exit queue was assumed to add 1.5 metres to the effective exit distance. This figure was found to produce comparatively responsive passengers, who will attempt to maintain well-balanced exit queues, as might be expected to occur with effective intervention by cabin crew. Reducing the disincentive to values of less than 0.5 metres per queue member produced greater levels of exit crowding. This could be used to depict a breakdown in the objectivity of passengers, perhaps reflecting the absence of cabin crew or onset of panic in deteriorating conditions. As a further refinement, effective exit distances could also be incremented to take account of prevailing passenger flow rates; for example, long queues are likely to be less significant if they are moving rapidly. //

The thermo-toxic environment and visibility levels in the vicinity of an exit are also likely to be a significant factor in passenger decision making. The principle variables influencing an evacuee's decision to move through smoke appear to be recollection of the exit location and ability to estimate the distance that needs to be travelled (Bryan, 1988). However, no data or theory was available to quantify the relationships involved. Evacuee behaviour in past accidents shows wide variations; from passengers blindly feeling their way for considerable distances, through to retreating from advancing smoke until becoming trapped in dead end. As a result of this uncertainty, these influences were not modelled in the evacuation analysis.

One possible approach to implementing the effects of exit obscuration would be to integrate smoke densities along a line running between the position of an exit and the evacuee. The level of exit visibility (or invisibility) obtained might then be used to factor the effective exit distance.

In accidents where break-up of a fuselage had occurred, the open ends of the cabin sections were treated as being new exits. This was intended to allow for the fact that breakages and ruptures are known to have been utilised by a significant proportion of passengers in past accidents (Schaefers, 1990). The main problem encountered when attempting to represent these escape routes was to determine whether or not breakage area would be passable for evacuees, and if so, how inclined passengers would be to use them. Time constraints prevented these issues from being explored when undertaking the accident data survey. Thus, the compromise adopted was to assume that all breakage areas were passable, but then only let evacuees utilise them when no other means of escape were available. As stated previously, the rate at which passengers were able to traverse breakages was set at one person every 5 seconds.

A small (but important) point was that, in crash accidents, it needed to be determined if exits would be unreachable for evacuees as a result of them being positioned on the other side of a fuselage break. In these cases, 999 metres was added to the effective exit distance, thus removing it from consideration.

8.4.4 Effecting Changes in Escape Evacuee Plans

Initially, evacuees were programmed to re-consider their choice of exit and formulate their next action every time they made a move. Whilst this procedure was straightforward to implement and reasonably effective in operation, it was far from being an optimal representation of passenger planning. For example, if the individual

is moving freely through an uncongested area, exits will be re-assessed and their escape plan updated around five times every second. This results in unfeasibly fast passenger reactions and represents a waste of computational resources.

In contrast, when waiting in a large queue, a passenger might be able to move only once every 15 or 20 seconds, meaning that exits are only re-checked at these intervals. This could lead to a scenario where some passengers at the rear of a queue would spot a newly opened exit and, as a result, attempt to change their direction of travel. However, they would frequently be blocked by passengers who remain unaware of new route and are still attempting to move in the original direction.

As a result, evacuee behaviour routines needed to be modified in order to ensure that escape paths were re-checked at more consistent intervals. Realistically, we might expect passengers to become aware of changes in exit status at a rate between extremes in the cases illustrated previously; perhaps at a frequency of every few seconds, or so. Thus, in order to prevent overly delayed reactions, all slowly moving or stationary passengers were made to re-assess exit availability at regular periods throughout an evacuation. The value of this "exit update interval" was set to be once every five seconds since the passenger was last able to make a move.

Nothing was done to slow down the reactions of rapidly advancing evacuees, as any changes would have virtually no effect on the evacuation process. If computational efficiency of the evacuation model needed to be improved, exit scanning could be restricted to a maximum frequency of, say, once per second.

8.4.5 The Role of Passenger Behaviour

Aircraft cabin arrangements are designed to provide all occupants at least one clear path to nearby exits. However, when accidents occur, these routes may not necessarily constitute the most effective means of escape for some passengers. Exit paths may be obscured by damage resulting from a crash, by the effects of fire or be subject to over-crowding by other evacuees. Consequently, accident survivors can often be forced to search for alternative ways of leaving the aircraft, or else face considerable delay.

In these circumstances, passengers may perceive different levels of urgency, or react to a given set of circumstances in dissimilar ways. At the simplest level, it is possible to classify the resulting behaviour into three basic categories:-

1. *Passive*; integrate with other evacuees and queue to leave the aircraft by a conventional route, in a co-operative manner.
2. *Proactive*; adopt own plan of action, perhaps escaping by an unusual route, or actively attempting to influence the actions of others.
3. *Aggressive*; escape as quickly as possible, usually by the most direct route, interfering or displacing other passengers if necessary.

The differences between these three modes of behaviour are illustrated in Figure 8.9, together with some examples of the possible implications for the escape tactics of a passenger. The individual concerned is positioned in a seat row behind a crowded door exit in a Boeing 757 aircraft.

If the person were to behave in a passive manner, they would choose to take a conventional route (1) out of the aircraft, in the prescribed way. Here, this possibly involves waiting to enter the aisle and integrate politely into a queue of passengers.

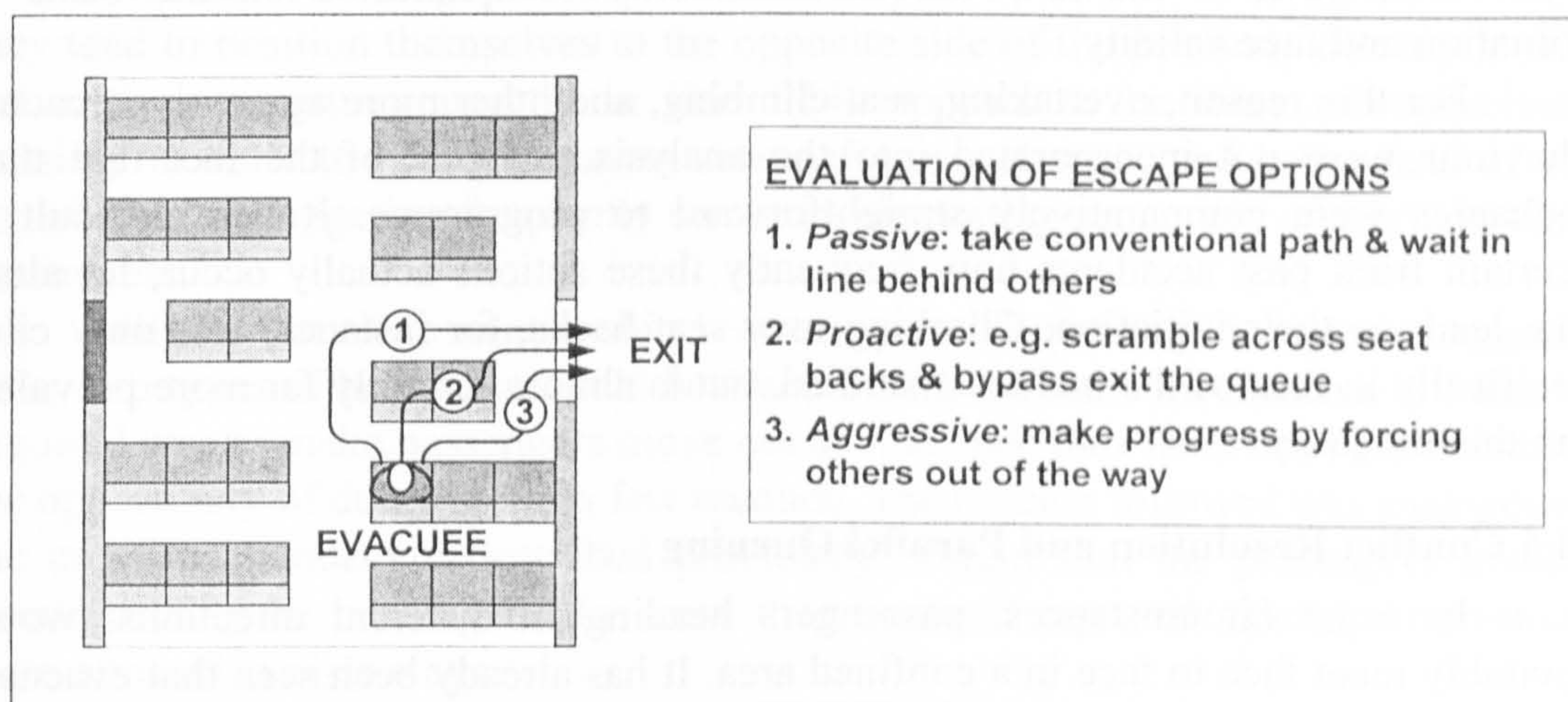


Figure 8.9: Determining Evacuee Escape Options

Adopting this option in crowded cabin conditions would be likely to result in considerable delay.

Alternatively, if the evacuee wished to escape in a shorter time, they might be more proactive and seek an alternative route to the exit. Other passengers could possibly be bypassed, or perhaps encouraged to use a different method of escape. For example, this might consist of clambering over seat backs, opening the door on the left hand side of the aircraft, or moving to an exit located at the rear of the aircraft. The first option is illustrated in the diagram.

Finally, in some circumstances, evacuees may resort to the use of aggressive behaviour. This may be a consequence of them losing control over their actions, or even result from a calculated decision. Other passengers may be forced out of the way or their escape impeded. In the example shown, utilising route (3) could potentially involve displacing two other passengers in adjacent seats and a cabin crew member stationed at the door.

In the evacuation model, evacuees had effectively been programmed to act in a passive manner in most circumstances. This type of behaviour was reasonably straightforward to represent, as processes can be defined with a series of logical rules and simple physical characteristics, such as spacing and speed of reaction. Passengers were found to be particularly likely to act in this way when they are closely supervised in conditions of minor or moderate danger. Thus, even though cabin crew not being modelled in the initial stages of programme development, it can be argued that, implicitly, their effects were partially represented in the modelling of passenger behaviour.

In a small number of situations, proactive passenger characteristics were introduced in order to increase the realism of the evacuation modelling. Examples of this included passengers changing aisles in widebody aircraft, opening closed exits, moving through galley areas and taking account of exit queue sizes. Conflict resolution and parallel queuing, as detailed in the next section, can also be categorised as being proactive behaviour. However, these behaviour patterns tend to involve decision making processes that are subjective, rather than those that are precisely definable physical criteria. As a result, even though proactive passenger behaviour was known to occur frequently in past accidents, many of the relationships involved were difficult or impossible to calibrate from the data sources available. This meant

that most of these behaviour modes could only be quantified on the basis of estimation and face validity.

For this reason, overtaking, seat climbing, and other more aggressive evacuee behaviour were not incorporated into the analysis, in spite of the fact that their mechanics were comparatively straightforward to programme. It was difficult to ascertain from past accidents how frequently these actions actually occur, let alone what leads to their initiation. Climbing over seat backs, for instance, was only cited specifically in four of the incidents studied, but is almost certainly far more prevalent than this in reality.

8.4.6 Conflict Resolution and Parallel Queuing

In some circumstances, passengers heading in different directions, would inevitably meet face to face in a confined area. It has already been seen that evacuees were programmed to co-operate and pass each other amicably in these situations, if space allowed. However, in narrower aisles (less than 0.45 m in width) or in seat rows, it was usually not feasible to perform a crossing manoeuvre. Thus, during the early stages of the evacuation programming, it was found that these circumstances usually lead to a stalemate, with both individuals locked together waiting for each other to make the next move. This situation would then persist until one of the passengers decided to reverse their direction of escape, perhaps as a consequence of fluctuations in exit queue lengths or other exits being opened.

These “conflicts” were dealt with by making the opposing passengers reconsider their exit choices immediately upon meeting. When exit options were compared, a consensus would usually result and one of the individuals would then turn around. As a result, the situation would be resolved, with both passenger moving off in the same direction.

However, in some instances (for example, where speeds of passenger movement were highly dissimilar), agreement might still not be reached after exit options have been reconsidered. Effectively, neither passenger wishes to back down, corresponding with the occurrence of an argument. In this eventuality, the faster of the two evacuees was assumed to be the more domineering, meaning that the second passenger would be forcibly turned around under protest. As a result of this, the later would be slowly hustled in the reverse of their intended direction until, either, they changed their mind, the faster person turns off in another direction, or a less constricted area of the cabin is reached.

Another feature of evacuee behaviour that needed to be refined at an early stage was the tendency for them to remain in uniform single-file queues when moving into less constricted areas of the cabin. This prevented the build-up of passenger congestion to realistic levels and generally meant that double-width door exits were left under-utilised unless they were fed by two separate queues of passengers.

In contrast, it was observed first hand in competitive evacuation trials that evacuees tend to congregate and squeeze two or more abreast whenever wider areas are reached. This behaviour often involves a significant proportion of passengers turning and shuffling sideways in their direction of movement. Frequently, these tactics lead to jamming in situations where passengers reach an exit or narrow bulkhead opening. Consequently, it was judged to be necessary to incorporate side-stepping movements and “parallel queuing” into the evacuation analysis.

In a similar vein, when evacuation trial participants move along narrow aisles, they tend to position themselves to the opposite side of the person in directly in front, rather than remaining exactly in line. This appears to be done sub-consciously, possibly in order to obtain a greater sense of personal space and better field of view ahead. Queue staggering frequently results in alternating sequences of left/right biased passengers.

Given, the close relationship between parallel queuing and queue staggering, these two types of behaviour could be created with the same mechanism. All that was required was to make passengers move out of line once they have been presented with the opportunity of doing so for a few seconds. The process followed was analogous to the crossing manoeuvre described previously, except that the passengers involved would usually be heading in the same direction and repeated sideways movements were allowed in aisle ways.

In constricted spaces, this behaviour results in the staggering of passenger lines and intermittent shifting from side to side in a realistic fashion. The effect of this enhancement can be seen by comparing the distributions of passengers shown waiting in aisles of an A310 aircraft in Figure 8.10. Similarly, when more space is available

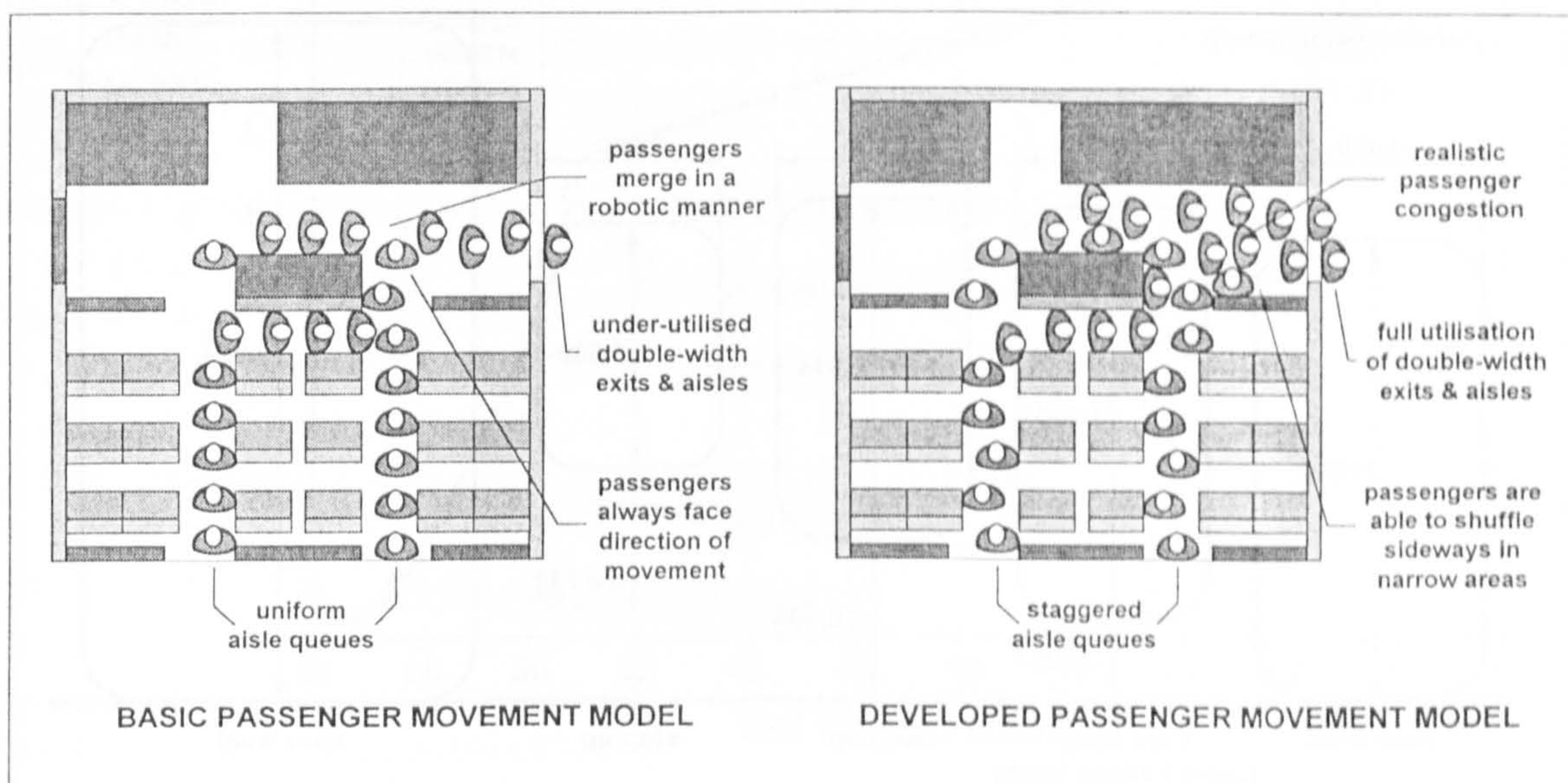


Figure 8.10: Refinement of Passenger Movement Capabilities

for evacuees, successive sideways movements lead to the development of parallel queues and sideways oriented passengers. These features produce a more realistic depiction of congestion in exit areas and ensure that double-width aisles and exits are more fully utilised. The greater passenger densities that result from the introduction of these improvements can be seen in the diagram.

8.5 Exits & Stairways

8.5.1 Exit Types

For historical reasons, aircraft exits have not been standardised across different airframe manufacturers. As a consequence of this, the means of escape from aircraft encompass a wide range of different shapes and forms. Three basic categories of exit exist; floor level doors, escape hatches and ventral/tailcone, each of which can present

quite dissimilar characteristics in an emergency situation. Even within a single category of exit, major variations can exist. For example, a door exit may possess any combination of the following attributes:-

- designed to be operated by cabin crew or by passengers
- positioned amongst cabin seating or in a partitioned off area
- single-width or double-width
- possesses an escape slide or situated above a wing
- symmetric or staggered configuration about aircraft centreline

/// In an attempt to deal with these complexities, airworthiness requirements classify all cabin emergency exits as being equivalent to one four types, namely Type I, II, III and A Exits (JAA, 1994). For certification requirements, ventral exits “*must allow at least the same rate of egress as a Type I exit with the aeroplane in the normal ground attitude, with landing gear extended*”. The configuration and the minimum sizes stipulated for each of these is shown in Figure 8.11. Note that Type A exits are

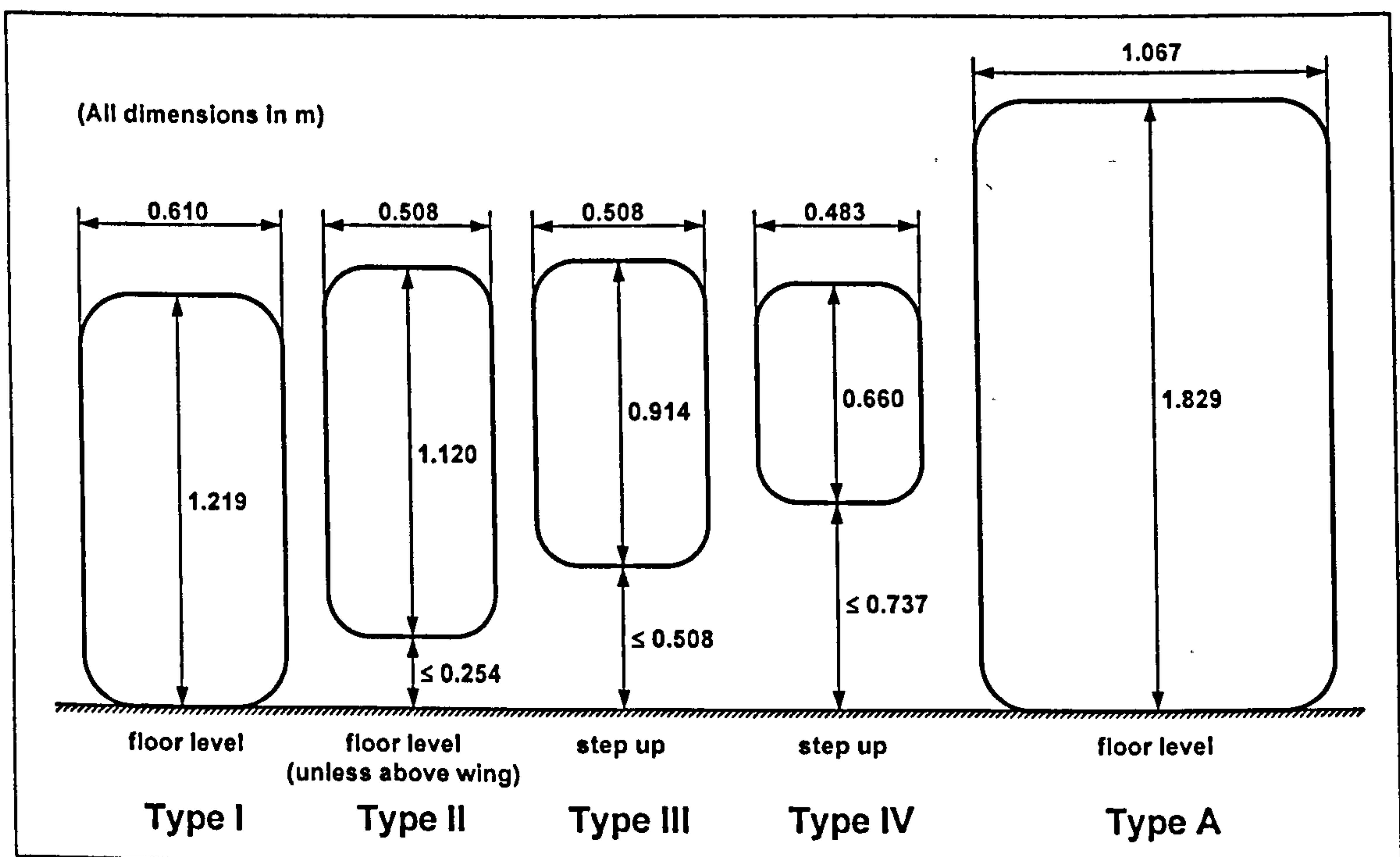


Figure 8.11: Categorisation of Aircraft Exits

used exclusively on widebody aircraft and allow for the passage of evacuees two-abreast. Most other airliner types utilise combinations of Type I exits for normal doors and Type III hatches in overwing positions. There are many rules governing the design and operation of aircraft exits; for these, the reader is referred to the relevant aircraft airworthiness requirements (JAA, 1994).

/// For the purpose of modelling the exits in the evacuation analysis, the distinctions between exit types were kept as simple as possible. Thus, all exits were represented as being either doors or hatches and evacuee flow rates were calculated as a function of their width. The approach taken is outlined in the following two sections.///

8.5.2 Door Exits

Door exits were classified as being placed at, or near floor level, i.e. Type I, II or Type A exits. In general, doors were assumed to possess inflatable escape slides. This assumption is obviously incorrect in cases of ventral and overwing door exits. However, the additional time allowed for slide deployment would correspond reasonably well with the delays associated with stairway activation and passengers finding their way off the wing in these two instances. A minimum opening delay of 10 seconds, including time required for the inflation and deployment of the slide, was used in all cases.

Evacuee flow rates for door exits were calibrated with data obtained from evacuation trials. Variations in these rates were assumed to be dependent on the width of an exit, with no account being taken of door accessibility from the cabin. The derivation of the flow rate relationship is shown in Figure 8.12. Note that the data

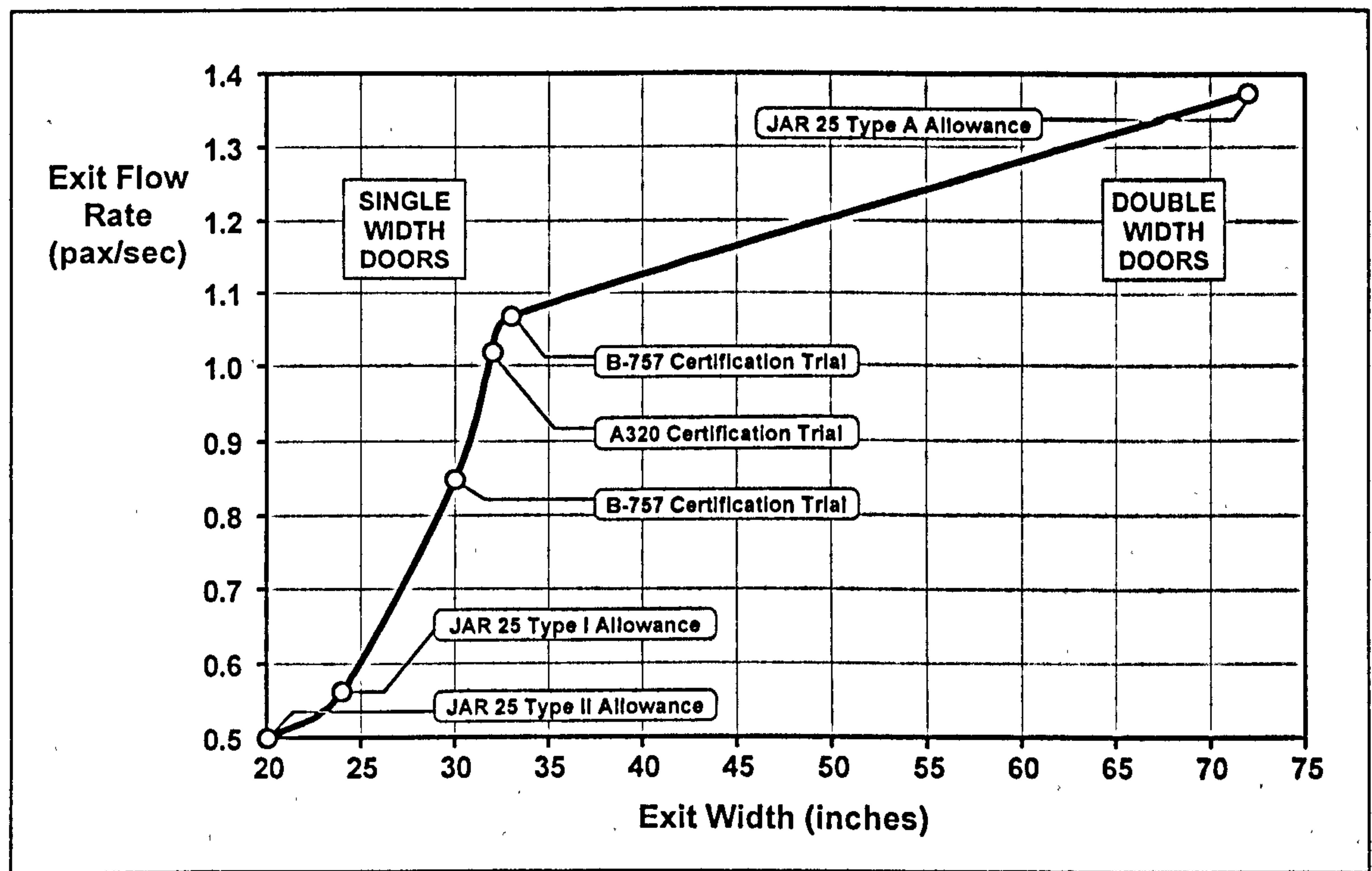


Figure 8.12: Calibration of Exit Flow Rates

used suggests that passenger flow rates for double-width exits are significantly less than that might be predicted from the figures for single-width exits. This suggests that some form of interference effect occurs when evacuees move side by side through a Type A door, perhaps, for example, pausing to jump onto the slide in alternate turns.

8.5.3 Escape Hatches

These consist of Type III and Type IV exits, both of which are usually intended for operation by passengers located in adjacent seats. An obvious problem that occurs with hatch exits is that the hatch itself must be dealt with once it has been removed from the exit. Passengers are instructed to throw the hatch back out through the open exit, but past accidents have shown that they are frequently laid down inside the aircraft, often forming a serious obstruction for escaping passengers.

Another feature of hatch exits is that they are located a considerable distance above cabin floor level and thus require the use of a step-through action or crouching

down low when standing on adjacent seats. This results in rather lower passenger flow rates than are achievable with door type exits.

An opening delay of seven seconds was assumed for all hatch exits and the use of a maximum potential flow rate of 0.55 passengers per second was based on evacuation trial results for a typical Type III installation (Muir et al., 1989). It should be noted that these figures are probably representative of favourable conditions and do not include the effects of unsatisfactory exit hatch disposal.

8.5.4 Stairways and Double-Deck Aircraft

Provisions were made throughout the evacuation modelling for the analysis of multiple-deck airliner designs. Egress from upper and lower levels was depicted as taking place independently, with no attempt being made to represent the use of stairways or the occurrence of interactions between exits on different levels. Passengers were assumed to be more prone to pausing in exits when leaving from an upper cabin, due to the additional 2 - 3 meters of height to the ground.

The use of this simplified approach was partially a consequence of the extremely limited information available on evacuation from two-deck aircraft. The only airliner type currently in commercial service with two passenger decks is the Boeing 747 series. However, experience gained with this aircraft provides little relevant data work with. Earlier versions of the Boeing 747 are certificated to carry up to 32 people in their upper cabins, representing only 6 - 11 percent of the maximum passenger load. Because no upper level passenger exits are provided, these people are required to descend a spiral staircase to the lower cabin in order to leave the aircraft.

More recent 747 variants are able to accommodate up to 69 passengers in their upper cabins and provide a straight stairways down to the main deck. However, a significant difference with these aircraft is that certification requirements dictate that upper-level Type A exits are provided and also that passengers could not use the stairs during the 90 second evacuation demonstration.

As a result of this, Boeing 747 evacuation trials undertaken to date have never provided passengers with a choice between the use of upper level exits or traversing stairs to escape via the lower deck. Similarly, experience with evacuation tests from upper level exits in realistic conditions is extremely limited and also no detailed information was obtained from the study of past accidents.

However, one significant point did emerge in the area of multi-deck aircraft - the fact that spiral staircases are unlikely to be certificated for the purpose of passenger evacuation again in the future. One Boeing 747 accident has occurred in which *"Two of the flight attendants were found with the body of a very large man, who was reportedly drunk, alongside the collapsed circular stairway"* (Speitel and Hill, 1988). Consequently, most projected future large aircraft designs that possess multiple decks illustrate the use of two or more straight stairways.

8.6 Evacuee Injuries & Incapacitation

8.6.1 Fractional Incapacitation Approach

An important aspect of the evacuation simulation was the representation of passenger injuries and fatalities. It was seen in the analysis of past accidents that casualties can result from both impact trauma injuries and the thermo-toxic effects of

a fire. Frequently, accident victims can be subjected to a combination of these injury types. However, impact injuries are sustained before the aircraft comes to a stop and their level essentially remains constant during the course of any escape attempt. In contrast, the effects of thermo-toxic incapacitation are initially absent, but then tend to build up rapidly if any degradation in the cabin environment occurs. In consequence, it was logical to use two parameters for the purpose of representing passenger incapacitation in the evacuation analysis. These were defined as a Fractional Injury Factor and Fractional Effective Dose respectively.

It was described in Chapter 3 how the thermo-toxic effects of fire progress from being essentially psychological at first, through to being purely physiological as unconsciousness is approached. In between these states, there exists a complex grey area, where both the mental and physical aspects of fire incapacitation are of significance (Purser, 1988). A similar analogy can probably be drawn in the case of impact trauma injuries, the effects of which can vary from mild shock through to complete disablement.

In spite of these considerations, it was decided not to attempt to incorporate psychological aspects of passenger incapacitation into the evacuation analysis. This was a consequence of the challenges that had to be dealt with when attempting to model even the simplest facets of human behaviour. Arguably, much progress still remained to be made in this area of the analysis before it would be feasible to introduce any further complexities. Thus, for the time being, utilisation of the incapacitation modelling was restricted to representing degradation in the physical capabilities of evacuees, i.e. reductions in their achievable rates of movement. This was effected by multiplying passenger's maximum speed by their current level of incapacitation.

The concept of a Fractional Effective Dose (FED) has been established by researchers working in the area of fire toxicology. It was seen in Chapter 2, that the use a FED-based approach enables the cumulative effects of narcotic fire products quantified. More recently, this type of analysis has been extended to include the effects of irritant fire products and high ambient temperatures (Purser, 1995).

The derivation of these FED relationships inevitable involves many simplifications and approximations in what is a highly complex area of human physiology. However, the resulting equations are straightforward to utilise, appear to provide acceptable results and are the only method available for quantifying thermo-toxic incapacitation effects. Thus, Purser's FED equations were applied directly in the evacuation model.

8.6.2 Irritant Effects

Determining the effects that highly irritant chemical species have on humans is perhaps the most difficult aspect of a fire incapacitation analysis. Irritant substances cause intense pain in the eyes, upper respiratory tract and lungs, followed, after several hours, by lung inflammation and oedema. Difficulties arise, however, because the effects of a given concentration of irritant often appear to be inconsistent from individual to individual. Also, as noted in Chapter 2, the effects of complex mixtures of irritant fire products may be considerably worse than might be predicted by adding the effects of individual components acting in isolation.

Given the nature of the effects of these irritant substances, it is obviously not possible to perform fully realistic experimental trials with human test subjects in this

area. Thus, the majority of information available is based on information obtained from victims of building fires and animal experiments, neither of which are entirely satisfactory. Significantly, however, Jin has managed to undertake a series of trials with human volunteers moving through irritant wood smoke (Jin and Yamada, 1989). Results from these indicate that the movement speed of test subjects tends to reduce to that in darkness (i.e. approximately 0.3 m/s) when they are exposed to irritant smoke with a density of 0.2 OD/m.

Purser provides irritancy FED relationships for five types of gas and also for non-specific mixtures of organic species. The former are based on gas concentrations present, measured in parts per million (pmm), whereas irritant organic species are quantified in terms of smoke optical density OD. Table 8.2 shows highly irritant and lethal concentrations for each of these substances. These values can be scaled to obtain Fractional Incapacitation Doses (FID) and Fractional Lethality Doses (FLD) for a given smoke atmosphere. It can be seen that with the smoke composition assumed in the cabin fire modelling, optical densities of 1.0 /m are extremely irritant, but unlikely to be fatal.

GAS TYPE	Assumed level in smoke of 1.0 OD/m	Highly Irritant Concentration (FID = 1.0)	30-min Lethal Concentration (FLD = 1.0)	FID in smoke of 1.0 OD/m	FLD in smoke of 1.0 OD/m
HCl	180 ppm	200 ppm	3800 ppm	0.90	0.047
HBr	40 ppm	200 ppm	3800 ppm	0.20	0.011
HF	300 ppm	120 ppm	2900 ppm	2.50	0.103
SO ₂	20 ppm	30 ppm	400 ppm	0.67	0.050
NO ₂	60 ppm	80 ppm	375 ppm	0.75	0.160
Organic Species	1.0 OD/m	0.5 OD/m	3.0 OD/m	2.0	0.333
TOTALS				7.02	0.704

Table 8.2: Incapacitation and Death from Irritant Fire Products

The FID values imply that the smoke will become highly irritant when its density approaches 0.14 OD/m, a figure that compares reasonably with Jin results.

With the assumption of a fixed smoke composition, these figures result in the following smoke : lethal irritancy dose relationship:-

$$FED_{irr} = 0.704 \cdot Smoke\ OD / m \tag{8.1}$$

This was used to obtain the contribution that irritant substances make towards the incapacitation of evacuating passengers.

8.6.3 Narcosis

The effects of narcotic fire products are reasonably straightforward to estimate by integrating the levels of passenger Fractional Effective Doses that are accumulated during the evacuation process. Purser identifies six main factors to be taken into consideration when analysing narcosis effects:-

$$FED_{IN} = (FED_{Ico} + FED_{Icn} + FED_{irr}) \cdot VCO_2 + FED_{Io} \text{ or } F_{Ico2} \tag{8.2}$$

Where

FED_{IN} = fraction of an incapacitating dose of all narcotic gases;
 FED_{Ico} = fraction of an incapacitating dose of CO;
 FED_{Icn} = fraction of an incapacitating dose of HCN;
 FED_{irr} = fraction of an irritant dose contributing to hypoxia;
 VCO_2 = multiplication factor for CO₂ induced hyperventilation;
 FED_{Io} = fraction of an incapacitating dose of low oxygen hypoxia; and
 FED_{Ico2} = fraction of an incapacitating dose of CO₂.

Each of these terms can be calculated as follows:-

$$FED_{Ico} = (8.2925 \times 10^{-4} \cdot ppm CO^{1.036}) \cdot \frac{t}{30} \quad (8.3)$$

$$FED_{Icn} = \frac{t}{e^{(5.396 \times 0.023 \cdot ppm HCN)}} \quad (8.4)$$

FED_{irr} = fractional irritant dose calculated in Equation 8.1 above

$$VCO_2 = \frac{e^{(0.1903 \cdot \% CO_2 + 2.0004)}}{7.1} \quad (8.5)$$

$$FED_{Io} = \frac{t}{e^{(8.13 - 0.54(20.9 - \% O_2))}} \quad (8.6)$$

$$FED_{Ico2} = \frac{t}{e^{(6.1623 - 0.5189 \cdot \% CO_2)}} \quad (8.7)$$

where

t = exposure time (minutes)

8.6.4 Heat

Convection of heat from air or smoke at high ambient temperatures can also play a significant role in fire incapacitation. At low to moderate temperatures, effects are predominantly irritant in nature, with progression to skin pain. Exposure to extreme temperatures results in burns and rapid incapacitation. The onset of the latter can vary widely with individual and the circumstances concerned, but Purser provides the following relationship for guidance.

$$FED_{heat} = \frac{1}{e^{(5.1849 - 0.0273 \cdot temp)}} \quad (8.8)$$

where

$temp$ = ambient temperature (°C)

The effects of exposure to high levels of radiant heat are even less certain. However, it is reasonable to assume that skin pain and burns occur rapidly at intensities above 2.5 kW/m^2 . No attempt was made to quantify this effect in the simulation analysis.

8.6.5 Impact Trauma Injuries

Levels of serious injuries amongst surviving passengers were estimated in the impact effects model. For preliminary purposes, it was assumed that injured individuals would only be capable of moving at half their normal rate. It might be feasible to represent this aspect of accident evacuation in more detail by utilising a measure such the Injury Severity Score (Baker et al., 1974), developed for use in the automotive industry.

Chapter 9: Model Usage

9.1 Undertaking Simulation Analysis

9.1.1 Use of the Simulation Model

The computer model that has been constructed is suited to analysing issues in aircraft safety in a variety of ways and on range of different levels. Usage could vary from investigating a single aspect of a specific accident scenario, through to performing comprehensive risk-assessment studies across a broad spectrum of incidents involving many different aircraft types.

The work that has been undertaken with the model was deliberately formulated to demonstrate contrasting modes of utilisation. At the simplest level, certification-type evacuation trials have been modelled. With the inclusion of impact and fire effects, the analysis was then extended to cover fully representative accident scenarios. Multiple runs were then undertaken, enabling outcomes of hundreds of incidents to be quantified in the form of probability distributions. It is then shown how such analyses can potentially be used to investigate issues in aircraft fire safety in a systematic manner.

These various modes of operation are illustrated with the inclusion of four case studies in this chapter. The example runs cover the following areas:-

1. The representation of certification evacuation trials
2. Evaluation of a particular accident scenario
3. Undertaking of multiple accident analysis
4. Implications of introducing a new very large aircraft design

The first two studies involve the simulation of specific types of accident scenario. Consequently, they allow for the workings of the model to be examined in some detail. A contrast can also be drawn between the efficiency of passenger egress achieved with and without the effects of rapid fire burn-through being present.

The third study illustrates preliminary results obtained from the simulation of a large number of accidents for specific aircraft types. Here, the details of individual incidents have been formulated to vary randomly, on the basis of historical probabilities built into the scenario generation module. Because outcomes are weighted to reflect the relative probabilities of all different kinds of accident scenarios, these types of results can be used for risk-assessment purposes.

Finally, some fire safety aspects of two new very large aircraft designs are explored. Results of accident simulations involving an aircraft in this category of are compared with those obtained for aircraft types currently in service.

Given the partially developed status of the model, these example studies provide only a preliminary indication of what is likely to be achievable with the undertaking of further development. For example, the process of performing multiple runs has yet to be automated. Thus, for this type of study, hundreds of simulations were run on an individual basis and all output analysed by hand.

Although provisional in nature, the results presented here appear to be very encouraging and are consistent with characteristics noted in past accidents, from both a qualitative and quantitative standpoint. However, a proviso should be made that,

even when in possession of the best information obtainable, verification of many of the key relationships within the various sub-models is presently impossible to perform. Compounding this difficulty is the fact that, in many respects, much of the work presented in this chapter is most probably unique and being undertaken perhaps for the first time. Consequently, in some of the areas that the model addresses, little knowledge or no clear consensus exists amongst specialists in the field. Thus, it is usually necessary to appraise output by checking for consistency with past events or experimental data where possible, as is done in the first three case studies. Only then is it feasible to extend the analysis to encompass new areas in aircraft fire safety, such that considered in the final study.

In spite of the difficulty of many of the challenges encountered, the work presented here demonstrates that it is feasible and highly desirable to perform a holistic simulation analysis in the area of aircraft fire safety. This use of this type of approach enables attention to be directed towards aspects of accidents that are critical for establishing a true understanding of aircraft fire safety. Some of these issues discussed in the course of this chapter include the significance of fire location, thermo-toxic incapacitation, fuselage damage and levels of exit availability. The fact that many of these areas are difficult or impossible to analyse by alternative means has arguably led to their comparative neglect within the field of air-safety research. As a result of this, many of the insights provided are likely to be both new and of significant interest to those working in the area.

9.1.2 Analysis Approach

A large quantity of information has been encapsulated within the model during the process of its construction. It has been seen how this data derives from many areas, such as the study of past accidents, experimental research, analytical analogies and statistical modelling. Most of the information obtained in this manner was comparatively low-level or basic in form. Nonetheless, a high proportion of this material has not previously been published and thus its significance in forming the foundations of the work should not be overlooked.

The main objective of the work, however, was to create a simulation tool capable of integrating and building upon these basic components of knowledge, so that all important aspects of accidents could be taken account of. This infers a shift in attention away from the representation of comparatively simple, low-level details towards analysing the overall outcome of complex incidents. Subsequently, the model might then be set up to automatically run and process the results from thousands of these incidents, in the style of Monte Carlo analysis. Findings could then be obtained in the form of probability distributions and long term trends that would be applicable in a global context. This progression in the scope of analysis, from micro to meso and then to macro levels, can be structured into the following areas of focus:-

- specific details, as represented by workings inside of a single sub-model
- more general details, such as impact effects, fire development or aircraft evacuation, modelled on the level of a complete sub-model
- Influences that such aspects of an incident can have on each other, i.e. interactions that can occur between different sub-models.

- The overall outcome of an incident, in terms of survivability levels, evacuation time, end-state conditions, etc., obtained from the analysis of a complete accident.
- Trends apparent from the simulation of a large number of incidents, involving either similar aircraft types or a fixed accident scenario.
- Global implications across all types of aircraft and accident scenario.

The case studies presented in this chapter are intended to demonstrate usage of the model all but the last of these categories. //

Many trial runs and tests were performed with the model during the course of its development. Initially these activities were directed towards examining and verifying aspects of a single sub-model during any one run. As the development of the simulation work progressed, attention was gradually turned towards testing the interactions that occurred between different pairs of sub-models. In the later stages of programming, the effects of changes were integrated and verified across all aspects the analysis. Most of the runs undertaken as part of this development process did not produce statistically balanced results. This was because it was desirable to bias simulation variables to yield scenarios that would involve particular interactions being worked upon. Thus, for example, when developing a function to calculate passenger impact fatalities, accident scenarios were deliberately biased to ensure that they would involve severe impacts.

As a consequence of this “scenario rigging”, fully balanced runs were only performed extensively during the very final stages of programme development. Thus, the work presented in this chapter effectively represents the very first round of substantive output obtained from the model. This means that no adjustments or refinements have been incorporated into the simulation analysis as a result of undertaking preliminary experimentation. All results presented should thus be interpreted on this basis.

9.1.3 Presentation of Simulation On-Screen

// It has been seen in previous chapters that many aspects of the simulation model were presented on screen with a graphical display. These graphics routines required substantial effort to programme; however their use was almost mandatory if aspects such as airflow and evacuation modelling were to be verified. Figure 9.1 shows a typical screen display during an accident simulation and provides a key to the various types of information presented.

At the top left of the display, basic details are provided about the accident scenario being simulated. This information consists of the aircraft type involved, how many passengers are present, location of the accident site, its distance from the airport and the phase of flight in which the accident has occurred.

An evacuation progress plot is located immediately below the accident scenario details. The plot shows the number of evacuee escaping from the aircraft as the simulation progresses. Utilisation of individual exits, together with the total number of people to have left the aircraft, is shown with the use of different coloured lines in the graph. Note that passengers escaping through fuselage breaks are not plotted with a separate line. However, these individuals are included in the total evacuees, plotted both graphically with a white line and numerically on the y axis. //

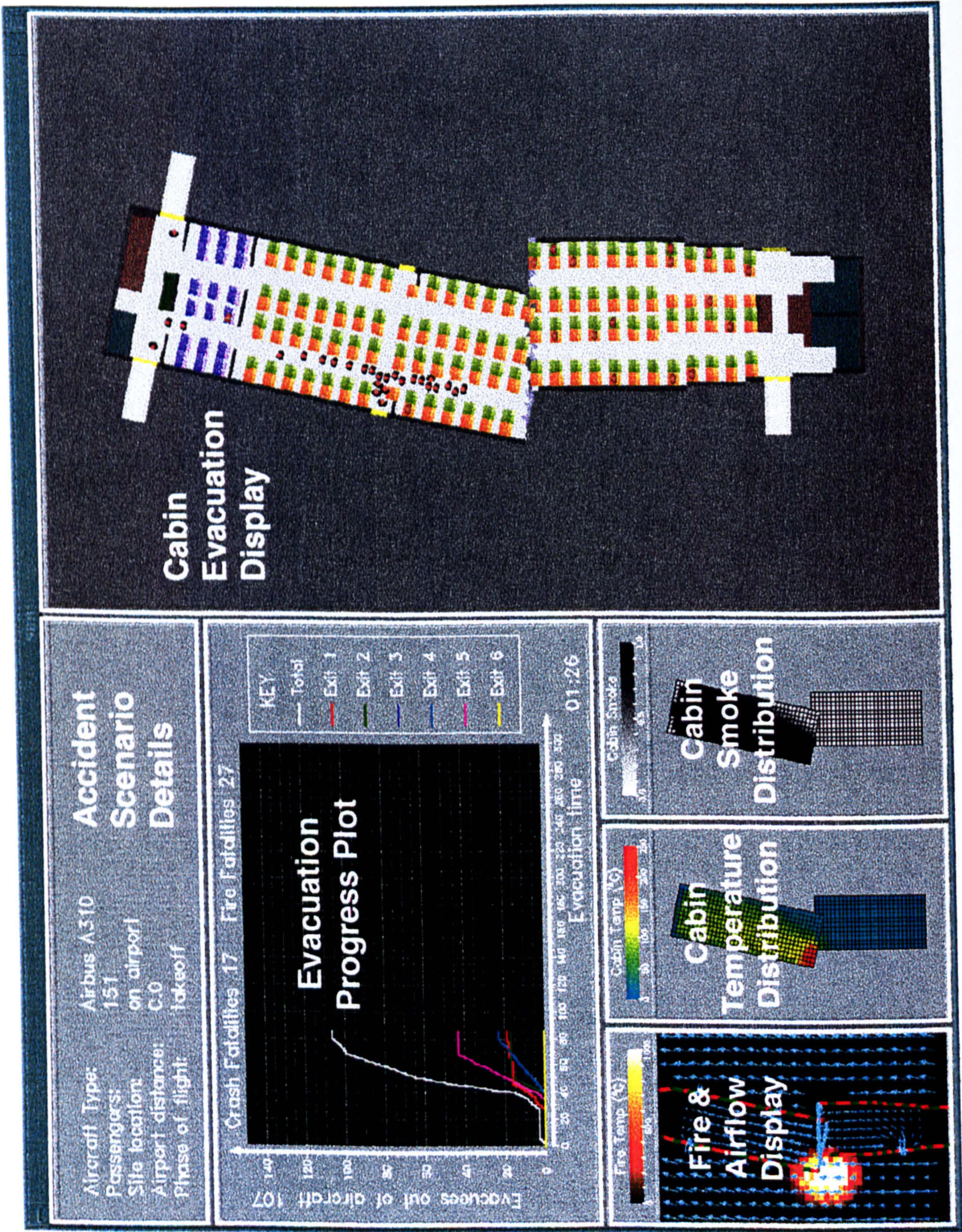


Figure 9.1: On-screen Presentation of Simulation Model

Simulations are usually set to run for a period of up to 5 minutes, with the current simulation time being shown to right of the x axis. Both of the axes are automatically sub-divided and numbered to provide suitable scales.

Above the graph, numbers of fatalities are shown. Those resulting from impact trauma injuries (i.e. "Crash Fatalities") are pre-determined at the start of a simulation. In contrast, the number of fire deaths climbs when passengers are overcome during the course of a run.

The development of fire and thermo-toxic conditions inside the aircraft are shown on the bottom left of the screen. The first diagram shows the area and temperature of the pool fire, together with local airflow vectors. This display is updated every time a new flow solution is calculated, as a result of exits being opened or significant areas of fire burn-through occurring. External fire temperatures are shown on a scale of 1 - 1000 °C and flow vectors are normalised with respect to wind speed, to ensure that they remain visible.

The final two thermo-toxic environment plots show distributions of temperature and smoke levels throughout the interior of the aircraft. As with the fire/airflow display, these are updated at regular intervals throughout the simulation in order to graphically illustrate deterioration in cabin conditions. Interior temperatures and smoke densities are plotted up to levels of 250 °C and 1.0 OD/m respectively.

The remainder of the screen is assigned to the cabin evacuation display. This shows the cabin configuration of the aircraft involved, together with the positions of all those remaining onboard. Evacuee movements and events such as the opening of exits and deployment of escape slides are shown in animated form. Able-bodied individuals are shown with white bodies and those fatally injured as a result of impact injuries are plotted in red. As evacuees are progressively overcome by the thermo-toxic effects of fire, their colour is gradually changed from white to grey to black, and their movements slow to a standstill. Thus, at the end of the simulation, all fatalities are coloured either red or black, according to the nature of their death.

The on-screen display of the simulation model was optimised for a monitor resolution of 1280 by 1024 pixels, using a total of 256 colours. Given that these are above average specifications for some types of computer, it was ensured that the graphics could readily be scaled down to match lower capability devices.

9.1.4 Model Output and Presentation of Results

Information about the progress of simulation runs was provided in two different formats. These consisted of an on-screen graphical display and text-based information sent to the user's terminal, respectively. These two modes of information output were quite different and each possessed their own distinct advantages. Both were used extensively throughout the course of model development and usage.

The design of the graphics display window was covered in the previous section. This form of output was suited to presenting a large quantity of complex and constantly changing information. The ability to convey the effects of interactions occurring between different parts of the model as they happened in real time was of particular importance. Also, the end state of an accident could be clearly presented, with scenario details, cabin conditions, evacuation progress and the positions of fatalities all being available in the form of a concise, pictorial snapshot.

In contrast, only a very limited quantity of information could be conveyed clearly in text format whilst a simulation was in progress. However, it was

straightforward to restrict scope of text output to obtain precisely the information being sought. Thus, for example, the changes in a single variable might be tracked over time or the occurrence of discreet events flagged (such as exits being opened, the occurrence of fire burn-through, passengers being overcome, etc.). This level of control over text-based output was invaluable for the purpose of dissecting accident simulations in detail, as well as in programme development and testing activities.

In addition, information in a text-based format could be saved to a file and analysed once a run (or many runs) had been completed. This greatly facilitated the post-processing of results for studies that required multiple simulation runs to be undertaken. Typically, accident parameters that were output and dealt with in this way included the overall time required for evacuation of the aircraft, together with the numbers of fire fatalities, impact fatalities and survivors left at the end of a simulation.

Frequently, the results of simulation runs needed to be presented in the form of a graph or probability distribution. In cases where interest lay with events in a single accident, the on-screen display of the evacuation progress plot could be used. On other occasions, however, it was necessary to construct graphs from data that involved the simulation of many accidents. This was achieved by importing text-based output obtained from individual runs into a computer spreadsheet package. Because the preliminary work described in this chapter only involved series of up to a 100 accidents each, such a procedure was feasible to undertake by hand. However, if more extensive Monte Carlo style runs were to be undertaken, requiring the simulation of thousands of accidents, post-processing would need to be automated.

Another point that should be noted was that the on-screen display of the cabin environment and evacuation modelling comprised five animated windows, running simultaneously side by side. The sheer quantity of information provided in a single accident simulation is thus difficult to present concisely on paper. For instance, the movements of smoke and passengers may change markedly as successive exits are opened; this can often be difficult to convey in only three or four snapshots of the on-screen display. The strategy adopted has been to attempt to concentrate on only the most important aspects of the simulations presented in detail. Also, illustrations of on-screen displays have been provided at standard (i.e. 30 second or one minute) intervals wherever possible.

Compounding this difficulty, was the fact that it was not always feasible to pause an accident simulation for capture at precisely the time desired. Consequently, most of the time values provided in this chapter should only be regarded as valid to an accuracy of approximately plus or minus two seconds.

9.2 Certification Evacuation Trials

9.2.1 Introduction

Perhaps the most straightforward case-study to undertake with the simulation model was the analysis of aircraft certification evacuation trials. As indicated in Chapter 2, most new airliner types must undertake these tests in order to qualify for use in passenger service. The aim of these trials is generally perceived to be the provision of a common standard to which all aircraft must comply, rather than to test a type's performance in fully realistic "emergency conditions". Consequently, accident

features such as the debilitating effects of fire, extensive structural damage and crash injuries are not represented in certification tests. This means that, for present purposes, these types of evacuation trial can be simulated entirely within the evacuation sub-model of the programme. Therefore, the results obtained in such tests provide a useful check on the more elementary aspects of the evacuation modelling.

Results of certification trials are treated confidentially by certification authorities and aircraft manufacturers. However, information suitable for constructing detailed comparisons has been publicly released for two modern airliner types (Airbus, 1995). These aircraft, the Boeing 757 and the Airbus A320, respectively, form the basis of the simulation studies presented here. In addition, the performances of two newer designs are also examined; these are the Airbus A321 and the still to be flown Boeing 737-800 series.

9.2.2 Model Set-up

Each of the four aircraft's cabins was configured in a maximum density seating arrangement and a full passenger load assumed. Passenger attributes were defined to correspond with a "representative load of persons in normal health", as prescribed in Appendix J of the FAA/JAA certification requirements (JAA, 1994). Relevant parameters included a reaction time of between 0.0 and 5.0 seconds and maximum speed of movement of between 1.4 and 1.6 m/s, i.e. corresponding to a fast walking pace.

Evacuees were made to head for their optimum exit at all times, without interfering with the movements of others or jumping over seat backs. Choice of exit was based on the geometric distance of each exit from the passenger, with the addition of a 0.5 metre disincentive for each person positioned in an exit queue ahead of the chooser. This high level of discernment might be taken to imply the presence of effective supervision by cabin crew members together with responsive, motivated passengers.

In accordance with certification requirements, half of the emergency exits were made available for the passengers to use, distributed evenly on either side of the fuselage. Opening times of 10 seconds for door exits and 7 seconds for hatch exits were applied. In the case of door exits, this time delay was measured from the start of the evacuation process, rather than from the point at which a passenger first reaches the door. This was done in an attempt to take into account the fact that, in reality, these exits are activated by cabin crew members before they are reached by passengers.

9.2.3 Discussion of Evacuation Trials Results

On-screen displays from a typical certification evacuation simulation are shown in Figure 9.2. In the upper half of the diagram, a cabin view illustrates the distribution of passengers 15 seconds after the start of the simulation. Below this, an evacuation progress plot provides a complete history of the run up until its completion, which occurred after 75 seconds.

The cabin view clearly shows how exits constitute bottlenecks in certification evacuations. It was found that queues of passengers formed and stabilised around all exit positions in the first 10-15 seconds of each trial undertaken. The rate of evacuation attained thereafter is governed predominantly by the exit flow rates that are achieved. Passengers at the rear of queues are provided ample time to change their

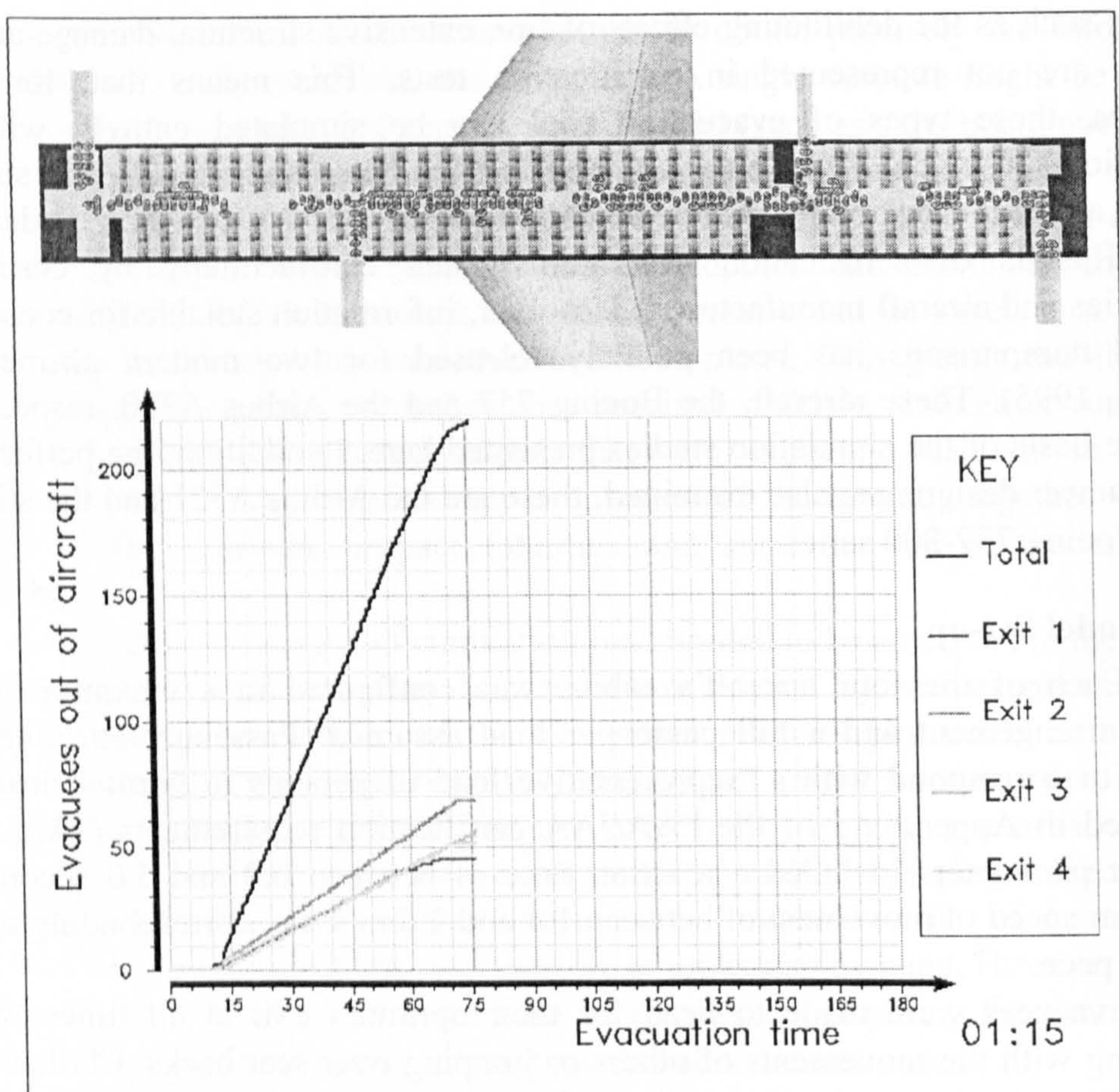


Figure 9.2: B-757 Certification Evacuation Trial

choice of exit as the evacuation develops; this means that their speed of movement becomes unimportant.

Exit flow rates can be gauged by the gradient of the curves in the evacuation plots. In the Boeing 757 example shown, the number 2 door (ahead of the wing) is wider than the other three exits and it thus enables passengers to disembark more rapidly. As a result the number 2 door was the busiest exit, being used by a total of 68 evacuees. In contrast, the plot shows how exit number 1 at the front of the aircraft tended to be under-utilised and only received one passenger during the final 10 seconds of the trial.

Remaining with the Boeing 757 example, the last 6 passengers to leave the aircraft all left via the narrow number 3 door, located aft of the wing. This exit, therefore, appears to be the critical one in determining the certification of the Boeing 757 cabin configuration shown. It may be pertinent to note that Boeing has chosen to locate two galley units adjacent to the number 3 door (these are shaded dark grey in the diagram). Effectively, this removes 9 seats from the vicinity of the critical exit and appears to reduce the overall evacuation time for the aircraft by approximately 6-8 seconds. Without the galley units in this position, certification of aircraft might have proved to be difficult.

It was found that evacuation times achieved for a given aircraft varied significantly from run to run. This meant that it was necessary to undertake many simulations in order to ascertain the true performance of the four aircraft types under test. Figure 9.3 shows the variation in times that were obtained in 100 simulation runs of an Airbus 320 evacuation. For the particular set-up tested, the mean time achieved

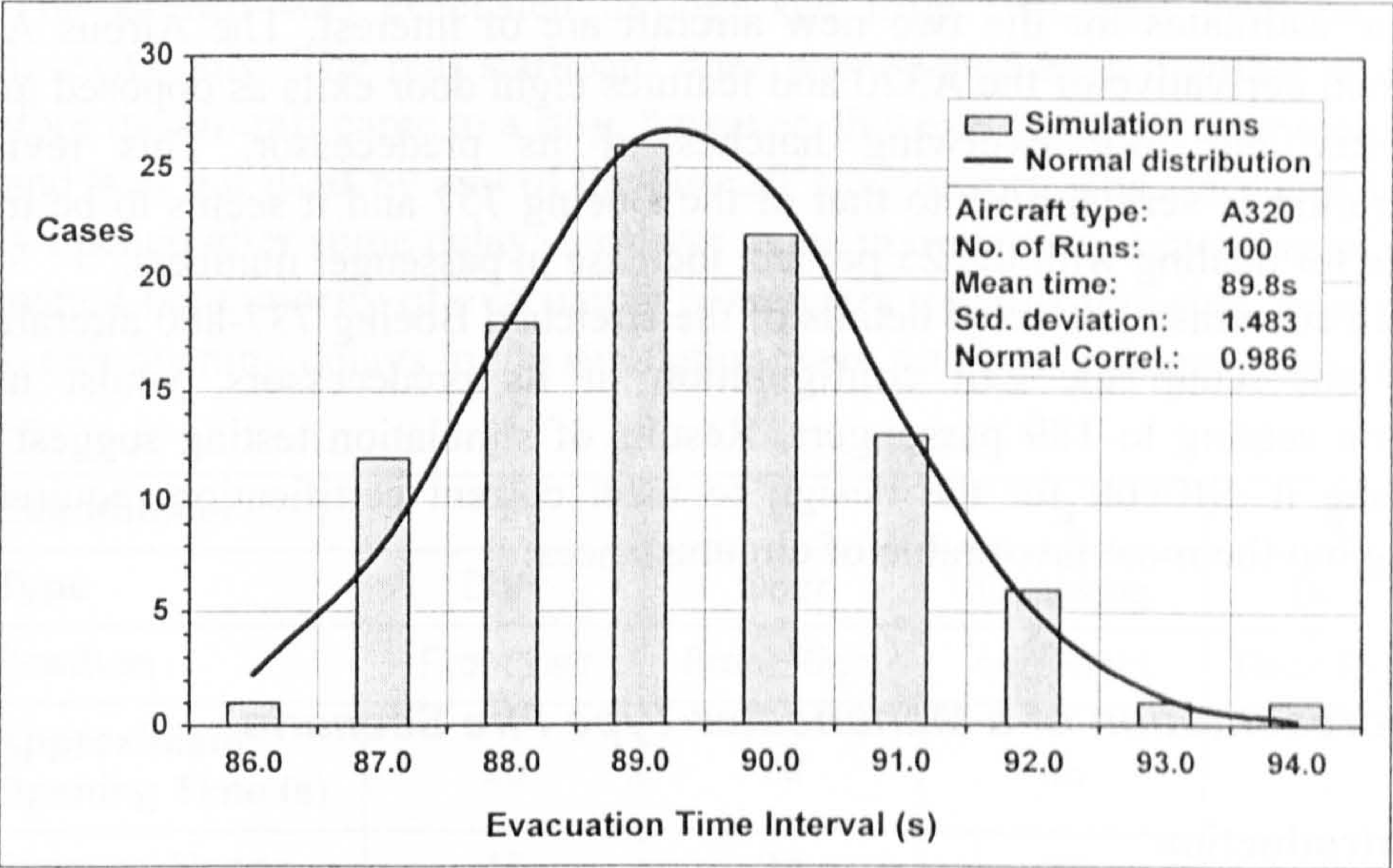


Figure 9.3: Distribution of Evacuation Times Achieved in 100 A320 Trials

was found to be 89.9 seconds, with a standard deviation of 1.483 seconds. The results appear to be normally distributed, with the fit shown implying a single-tailed 95 percent confidence interval of approximately 2.44 seconds - a seemingly tight error margin.

Differences in the results obtained from individual runs were due to random variations in passenger characteristics, such as reaction times and maximum rates of movement. Exploratory testing revealed that, if average levels of performance remain constant, greater levels of variation in passenger capabilities tends to result in slower evacuation times overall. This finding is simple to account for; slower movers will usually inhibit the progress of many other evacuees, whereas faster movers are unable to hasten the movements of surrounding passengers to any significant extent. The net result of this is that groups of dissimilar passengers move at the speed of the slowest individual present.

Table 9.1 shows the mean evacuation times obtained for each of the four aircraft tested. In the case of the Airbus A320 and Boeing 757 aircraft, results of actual certification tests are also provided for comparison. It can be seen that the simulation results compare reasonably with the real outcomes of the evacuation trials. Although the simulation figures are 6-8 percent higher, the relative performance of the Airbus and Boeing types appears to be predicted accurately.

Aircraft Type	Number of Seats	Evacuation Time Achieved in Certification Test	Mean Evacuation Time Achieved in Simulation Tests
Airbus A320	179	79.0 s	85.1 s
Boeing 757	219	73.5 s	77.8 s
Airbus A321	224	NA	81.2 s
Boeing 737-800	189	NA	91.8 s

Table 9.1: Results of Certification Trial Simulations

The time estimates for the two new aircraft are of interest. The Airbus A321 is a lengthened derivative of the A320 and features eight door exits as opposed to the four door exits and four overwing hatches of its predecessor. This revised exit configuration is very similar to that of the Boeing 757 and it seems to be more than adequate for dealing with the 25 percent increase in passenger numbers.

In contrast, projected details of the stretched Boeing 737-800 aircraft indicate that it will retain the exit configuration of its predecessors, whilst increasing maximum seating to 189 passengers. Results of simulation testing suggest that this may make it difficult for the design to meet current certification requirements in anything but the most favourable of circumstances.

9.3 Representation of a Manchester-Type Fire Scenario

9.3.1 Introduction

On the 22nd of August 1985, a Boeing 737 aircraft suffered a catastrophic engine failure whilst attempting to takeoff from Manchester International Airport, in the UK. The aircraft was brought to a halt on a runway turnoff but, in spite of prompt attendance by the airport emergency services, was quickly destroyed by fire before 55 of those on board were able to evacuate.

The incident is now infamous throughout the world's air-safety community and subsequently has been the subject of much analysis. Arguably, the accident (which has already been mentioned in Chapters 3 and 5) is notable chiefly on two accounts. Firstly, the rapidity with which the external fuel fire was able to penetrate through into the fuselage interior was a revelation to many observers, even those familiar with previous accidents of a similar type. Secondly, the event was the subject of an extensive inquiry, which led to the publication of a report of unprecedented detail and scope (King, 1989). The latter has been described as a watershed in the analysis and reporting of aircraft accidents by experts in the field (Taylor, 1996).

In this section, the use of the model to investigate the circumstances of the Manchester accident is demonstrated. This is achieved by reproducing features of the incident as closely as possible and examining the accuracy with which the outcome can be predicted. In addition, the significance of exit usage in the accident is explored by simulating some alternative scenarios that result in some very different outcomes.

9.3.2 Model Set-up

The fire in the Manchester accident was effectively a pool of burning fuel located under the trailing edge of the port wing. Although the fire started whilst the aircraft was midway through its takeoff run, the aircraft sustained almost no fire damage whilst it was in motion. However, upon stopping, ambient wind conditions were such that smoke and flames from the fire were deflected back towards the aircraft. As a result, the rear fuselage was immediately enveloped and burn-through occurred within one minute.

This fire scenario was represented with a 15 m^2 pool fire, with an ellipticity of 0.5 and positioned to overlap the rear fuselage mid-way between the overwing and rear door exits. The burnthrough time constant for the fuselage was set to equal 30 seconds at 1000°C . Wind direction was set to a relative heading of 295° , at a strength of 7 knots.

The aircraft was evacuated through the front two door and the starboard overwing exits only. The rear starboard door was opened by a member of the cabin crew before the aircraft came to a stop; however, this exit quickly became obscured by smoke and was not used by any of the aircraft’s occupants. The starboard front door was only opened after some delay; however, once in operation, a member of the cabin crew directed the majority of evacuating passengers towards this side, away from the fire. The exit opening delays in the simulation were set up to produce this sequence as follows:-

Exit Number	1	2	4	6
Type	Door	Door	Overwing	Door
Position	Front Left	Front Right	Mid Right	Rear Right
Approximate Opening Time (s)	25	70	45	0
Evacuee Usage	17	34	27	0

Table 9.2: Exit Details in Manchester Fire Accident

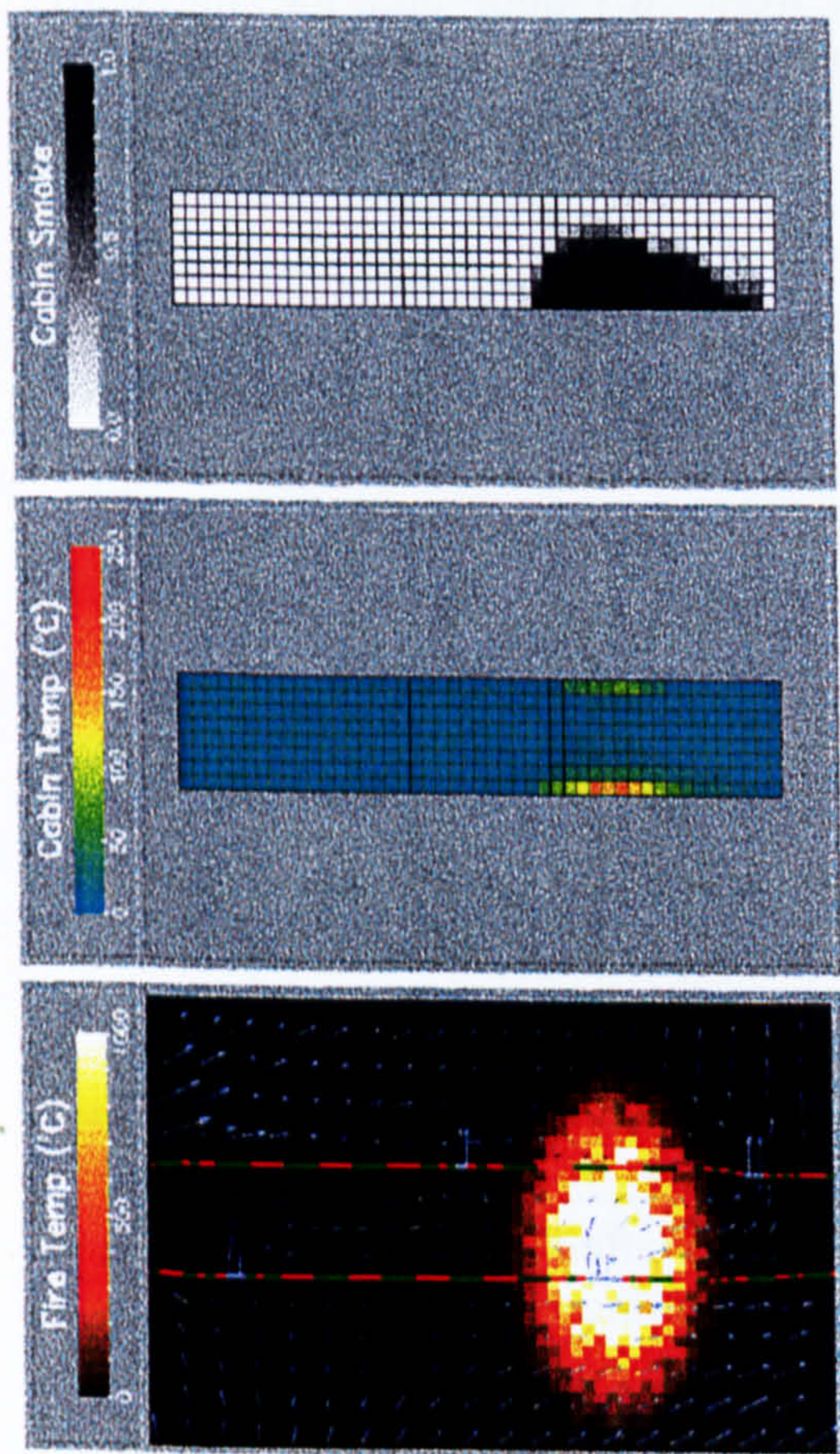
The aircraft seating configuration was a high density layout, with all but two seats being occupied. With the addition of a child and a lap-held infant, this resulted in a total of 131 passengers and there were also four cabin attendants onboard. For the purposes of simulation, the cabin configuration was reproduced exactly and all seats were assumed to be occupied by one passenger, giving a total of 130 evacuees. The two cabin attendants who succumbed to the effects of fire at the rear of the aircraft, together with the two surviving attendants stationed at the front exits were not represented in the simulation.

9.3.3 Discussion of Accident Features

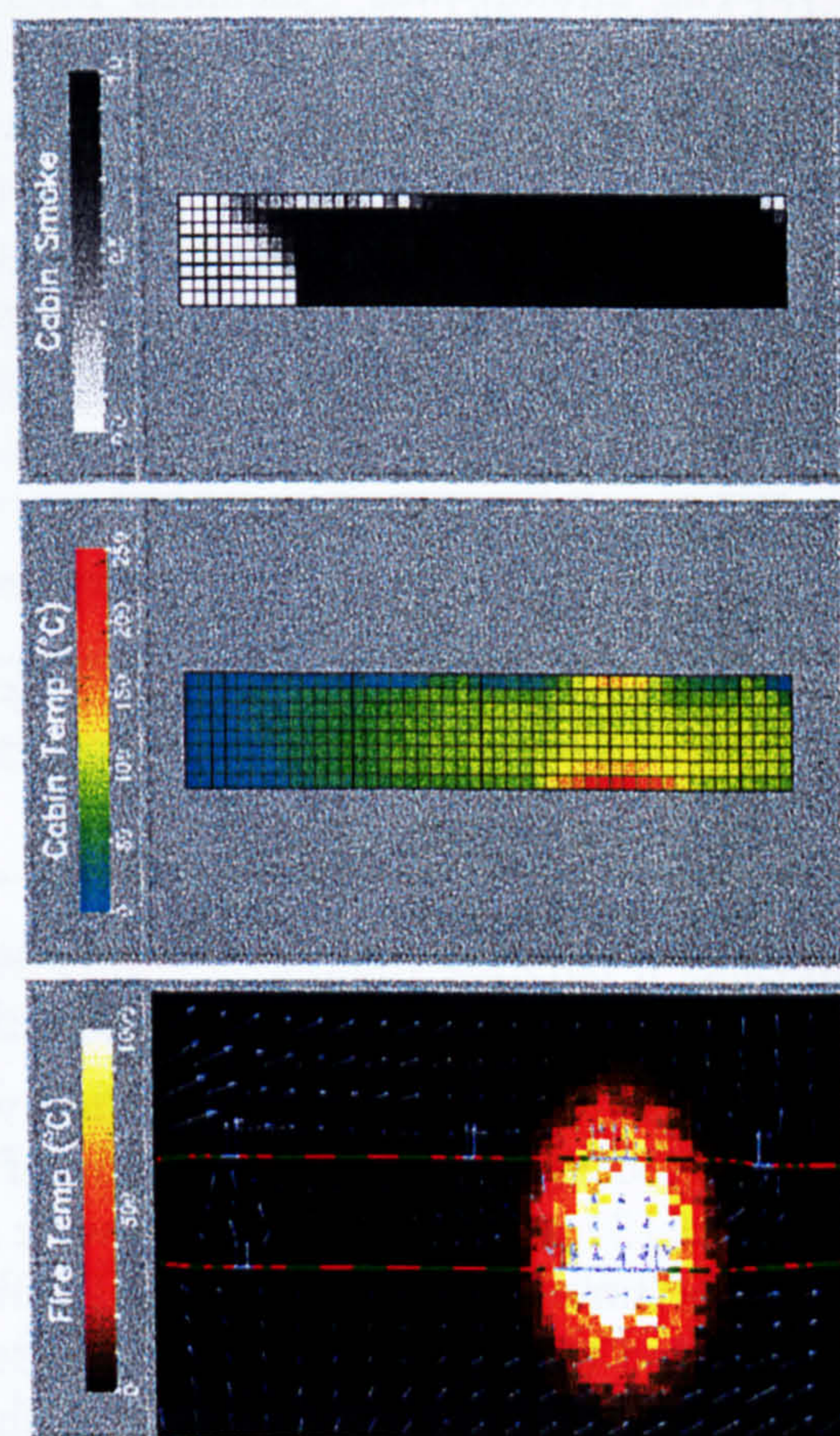
The prediction of fire development inside the aircraft is shown in the sequence of images contained in Figure 9.4. The four snapshots show conditions at 30, 60, 90 and 120 seconds after the start of the simulation. After 30 seconds, the external fire is just beginning to penetrate the left hand side of the aircraft’s fuselage. At this time, exits 1 and 6 are open, setting up an airflow through the interior of the aircraft in a rearwards direction. This then causes smoke to flow backwards, as shown in diagram (b), and block the rear escape route after about 1 minute 15 seconds.

After one minute, a significant portion of the fuselage burnt through and the overwing exit has been opened. These two events modify the pattern of air movement inside the aircraft such that the entering smoke is spread across the full width of the cabin. This observation may explain the “wall of smoke” advancing rapidly up the aircraft, as reported by survivors of the accident.

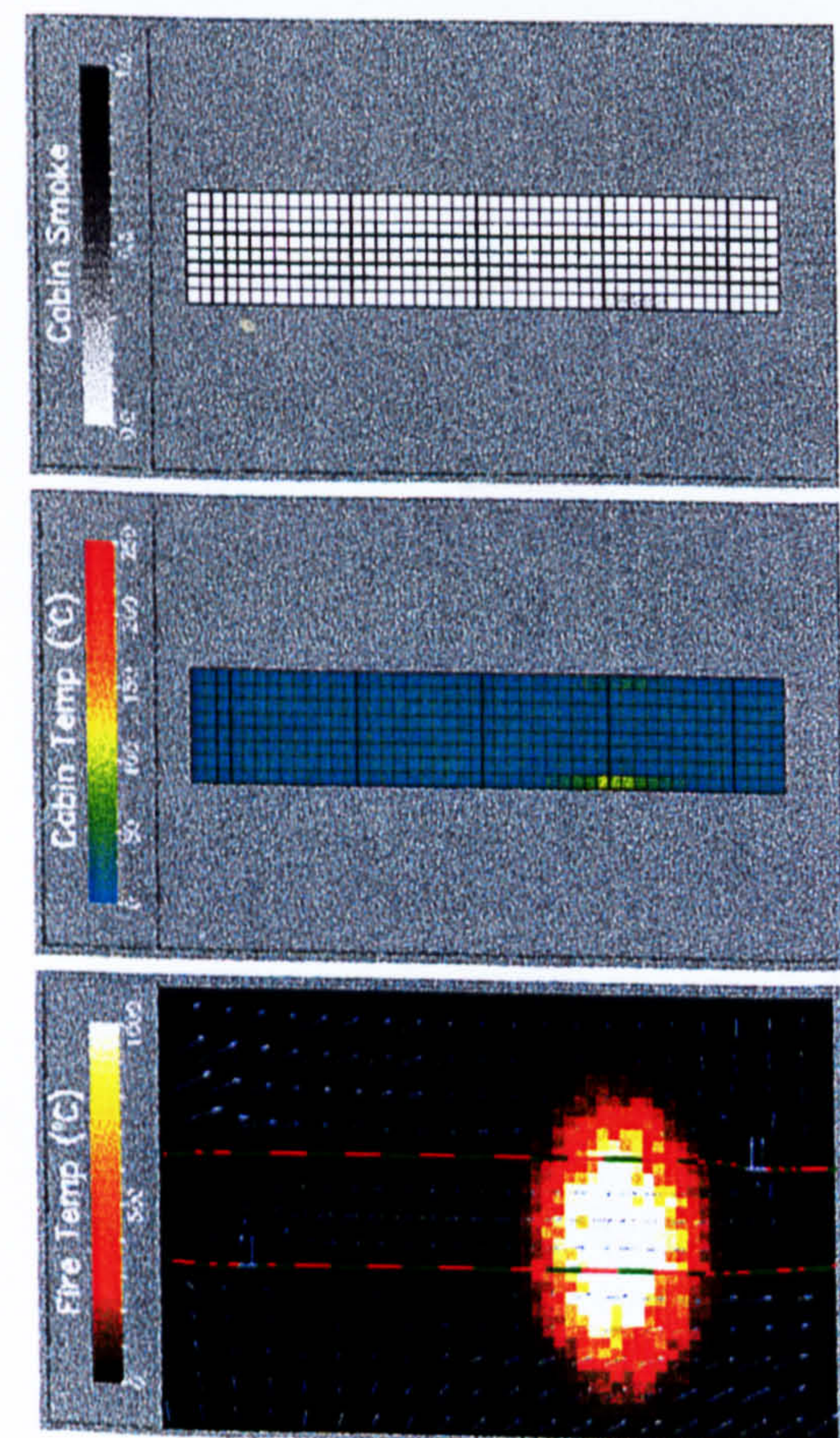
At 1 minute 30 seconds the second forward door has been opened, causing the airflow in the forward half of the cabin to reverse in direction and advance rapidly towards the front of the aircraft. The consequences of this can be seen in diagram (d); smoke reaches the forward exit after approximately two minutes and conditions in the remainder of the cabin are completely untenable. At this point, both sides of the aircraft have burnt through, leading to the entire tail section of the aircraft dropping to the ground.



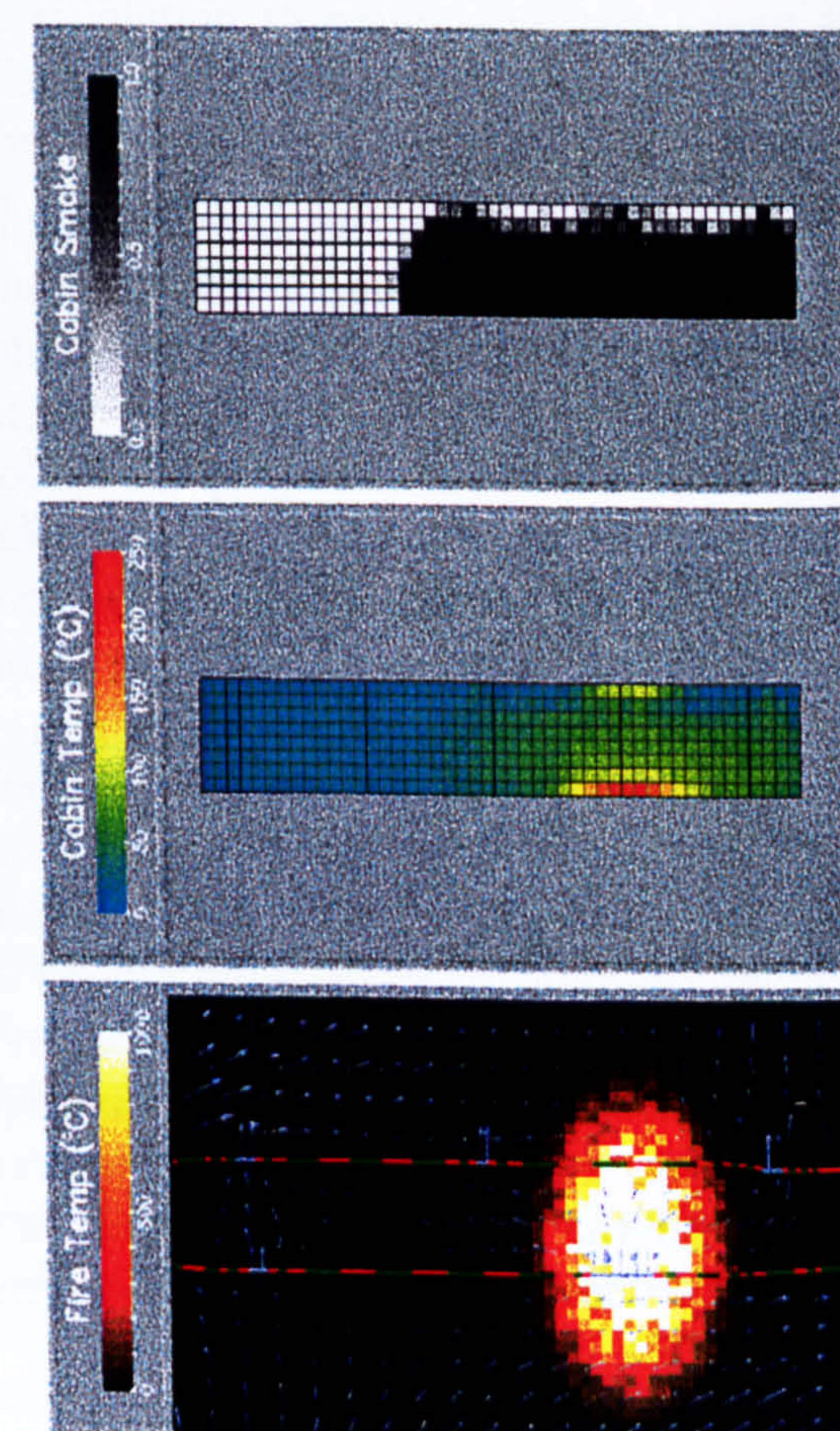
(a) time = 0:30 s



(b) time = 1:00 s



(c) time = 1:30 s



(d) time = 2:00 s

Figure 9.4: Development of Cabin Thermo-Toxic Environment

Details of the evacuation simulation are provided in Figures 9.5 and 9.6. The positions of passengers are shown at the start, mid-way through and near the end of the accident. After one minute, those still remaining in the rear of the aircraft are starting to succumb to the influx of dense smoke. This is indicated on-screen by a gradual darkening of these passengers. At this stage, both the number 1 and number 4 exits have been opened and are being used by passengers. Egress through the former is somewhat erratic, as it is affected by the heat radiating from the fire. This means that only 5 people are predicted to leave from the front of the aircraft during the first minute of the egress.

At this point, many passengers are congregating around the jammed number 2 door, which has still to be freed. Once this is achieved, queued passengers are able to escape rapidly and the exit sustains the second half of the evacuation process. After 2 minutes 10 seconds, the last passenger is able to struggle out, leaving a total of 53 others still onboard the aircraft.

Quantitatively, results of the particular simulation run discussed above compare very closely with the known details of the Manchester accident. However, simulation results were found to vary slightly from run to run, due to random variations in passenger attributes and their seating positions. Therefore, in order for the model's performance to be evaluated properly, results needed to be averaged from a series of runs. To obtain this data, a total of 15 Manchester runs was performed and mean results were calculated. Table 9.3 compares details of the Manchester accident with these simulation results:-

Case	Actual Manchester Accident	Mean Value Achieved in 15 Runs	Standard Deviation in 15 Runs
Exit 1 Usage	17	17.2	2.0
Exit 2 Usage	34	30.9	2.0
Exit 4 Usage	27	25.7	2.4
Total Fire Fatalities	53	56.1	2.2
Total Evacuation Time	3:30 s	2:09 s	5.1 s

Table 9.3: Results of Manchester Accident Analysis

It can be seen that figures for exit usage and fatalities are predicted to within an accuracy of 5-10 percent. These error margins are comparable with the standard deviation figures from across the 15 runs, indicating that the outcome of the real incident lies well within the envelope of simulation results.

The prediction of total evacuation time appears to be less satisfactory. A discrepancy of 81 seconds represents an error of approximately 39 percent - well outside of the observed standard deviation of 2.4 percent. This result clearly indicates that passenger evacuation rates and/or fire incapacitation effects are overestimated in the representation of the Manchester accident. Two suggestions are made to account for the magnitude of this deviation:-

Firstly, circumstances of the Manchester accident were unusually severe in comparison with similar incidents, as discussed in Chapter 3. Specifically, many of the passengers involved had comparatively little experience of air travel, which lead to an unusually high incidence of confusion, delay and inappropriate behaviour. The

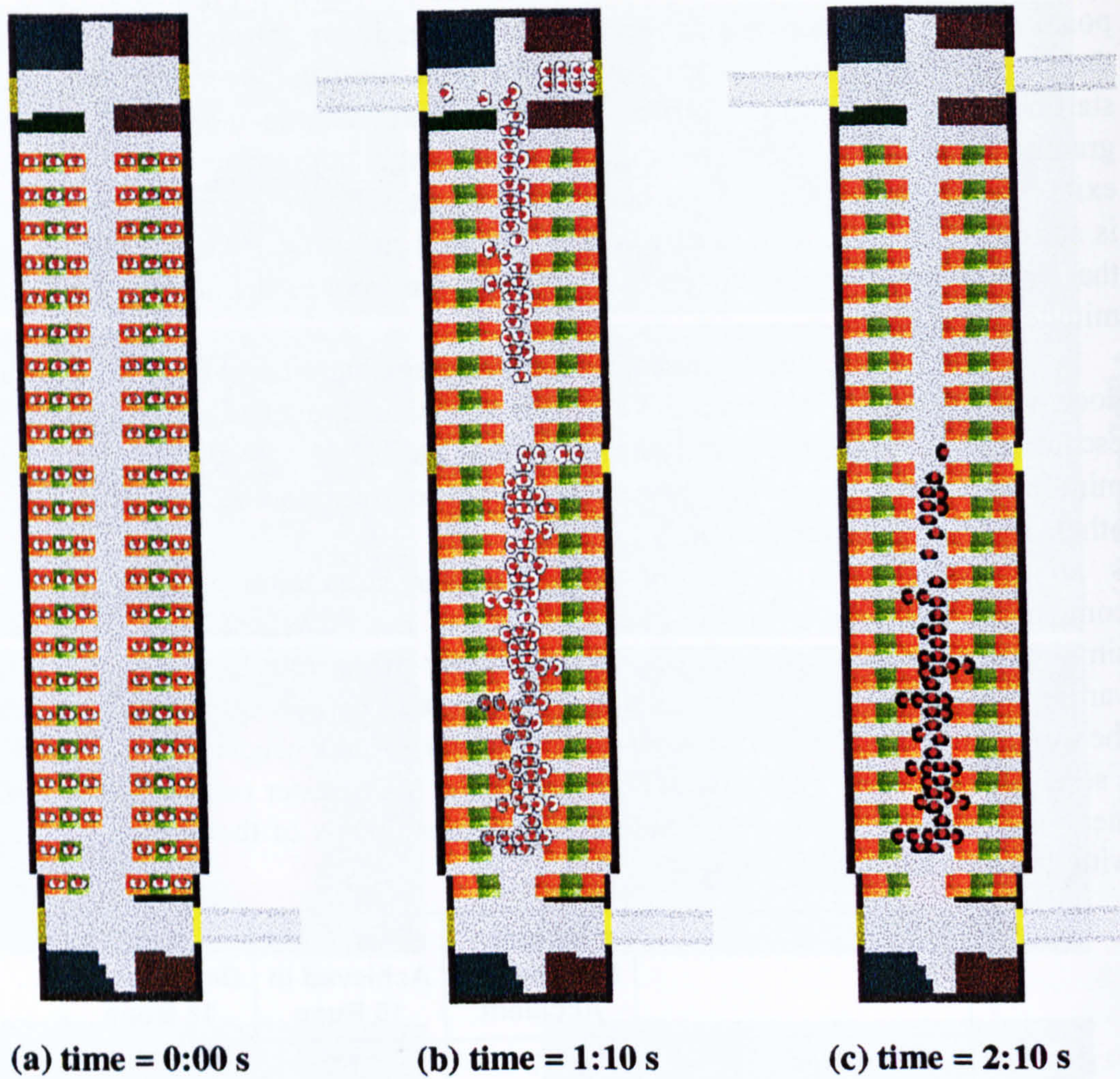


Figure 9.5: Passenger Evacuation Sequence

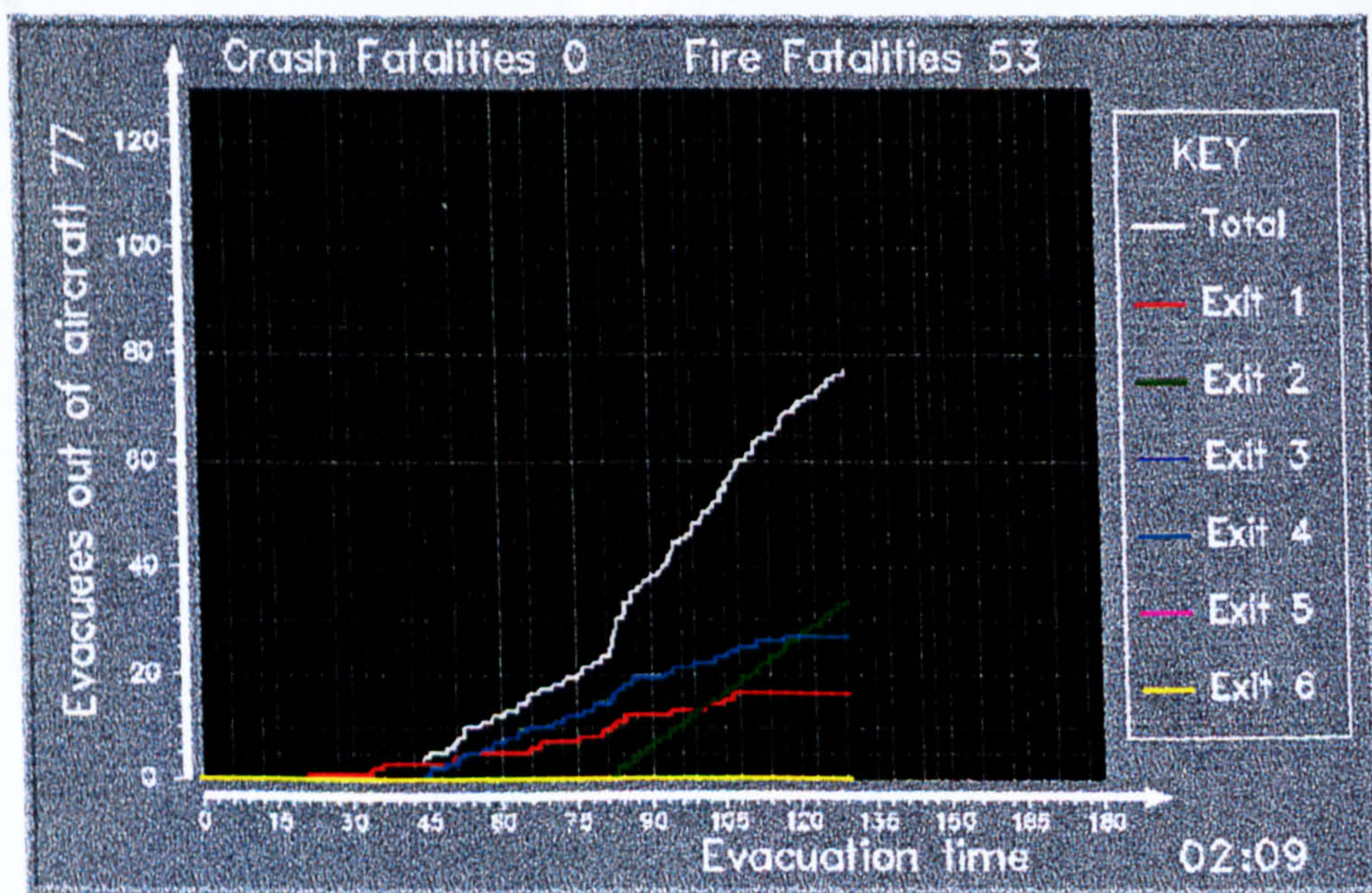


Figure 9.6: Evacuation Progress Plot

rate of evacuation achieved was therefor rather lower than might normally have been expected. Consequently, the “typical” passenger characteristics used in the simulation produced significantly shorter evacuation times than that occurring in the real case.

Secondly, the margin of error involved may not be as significant as it first appears. The explanation of this lies with the fact that the progress of an evacuation in an aircraft accident can be highly non-linear. For example, when passengers have not received crash injuries, evacuation rates tend to be comparatively high until a substantial deterioration in cabin conditions occurs. At this stage, those still remaining inside an aircraft are likely to suffer severe incapacitation within a short space of time, which causes their rate of egress to slow dramatically. Consequently, only the most determined then stand any chance of survival and these few that manage to do so will require significant time to struggle free. In such accidents, the bulk of survivors escapes in a few minutes, but the final few “stragglers” effectively prolong the duration of the evacuation by a substantial margin. Evidence of this tailing-off process is clearly visible with the last five survivors to emerge from exit 4 in the evacuation progress plot. However, the duration of the evacuation tail-off may have been underestimated by a substantial margin.

It is precisely these aspects of thermo-toxic incapacitation and survival capability in extreme conditions that are impossible to analyse or quantify by ethical means. However, results from the analysis of the Manchester accident suggest that the assumption of a simple linear relationship between FED and movement capability might be unduly pessimistic.

9.3.4 Simulation of Alternative Outcomes

The opening and subsequent utilisation of exits in the Manchester incident have been the focus of much attention. Potentially, the most effective means of escape appeared to be the number 2 and number 6 door exits, located on the right-hand side of the aircraft. However, the number 2 door jammed on opening, causing cabin crew at the front of the aircraft to divert their attention to activating the door on the left-hand side. As a result, the malfunctioning exit was not freed until approximately 70 seconds after the aircraft had stopped. Despite the delay in its opening, more passengers eventually managed to leave the aircraft through the number 2 door than by any other exit. This suggests that many lives might have been saved if the first attempt to activate the right-hand door had been successful.

In contrast, the number 6 exit at the rear of the cabin was seen to be open with a successfully deployed at around the time that the aircraft came to a stop. However, the presence of dense smoke outside the door caused a stewardess to direct passengers away from the exit, towards the front of the aircraft. Given the prevailing circumstances, this decision was entirely reasonable and in accordance with the training given to cabin crew-members. With the benefit of hindsight, however, it might be postulated that more people (including both stewardesses at the rear of the aircraft) might have survived if the open rear door had been utilised in the evacuation.

It is possible to identify a number hypothetical scenarios in which emergency exits could have been utilised more effectively in the Manchester accident. For example, if no difficulties had been encountered with any of the exits utilised, what outcome might then have resulted? It was decided to investigate three Manchester scenarios of this type, in each of which exit utilisation differed from that in the original incident in one of the following three ways:-

1. The number 2 exit was opened without difficulty and its slide deployed successfully within 10 seconds of the aircraft coming to a stop.
2. Passengers seated in the back of the cabin were directed towards (rather than away from) the open door exit at the rear of the aircraft.
3. All four of the exits activated were opened promptly and then utilised to the maximum possible extent.

The simulation results for these three scenarios are compared with those for the actual Manchester accident in Table 9.4.

Case Simulated	Mean Evacuation Time	Mean Number of Fatalities
Actual Manchester scenario	2:09 s	56
Hypothesis 1: #2 exit opened without any delay	1:46 s	41
Hypothesis 2: Passengers directed to use open rear door	2:06 s	23
Hypothesis 3: All four exits function to maximum potential	1:16 s	0

Table 9.4: Modification of Exit Usage in Manchester Accident Scenario

Testing of the first hypothesis indicated that the 70 second delay in opening the front right door exit may have prevented about 15 passengers from leaving the aircraft and added 23 seconds to the overall evacuation time. The magnitude of these differences was lower than anticipated; the reason for this is that with immediate activation of the right hand door, effectively the left hand door was made redundant at an earlier stage in the evacuation.

When passengers were left free to use the open rear door, a substantial reduction in the number of fatalities occurred. It was interesting to observe that in such circumstances the rear door tended to be the most heavily utilised exit in the evacuation. Ironically, however, because most of the additional survivors would otherwise have been amongst the first to succumb to the fire, there was little improvement in the overall evacuation time achieved.

Simulation of the third hypothesis, indicated that passengers would begin to exit from the aircraft in substantial numbers within 15 seconds of it stopping on the taxi-way. The resulting evacuation is similar to the certification trials examined in the previous section. Although many of those seated in the rear half of the cabin are severely affected by smoke, usually all manage to escape in an average time of only 76 seconds.

Results obtained from testing of the three hypotheses underline the finely balanced nature of some aircraft fire scenarios. The speed with which a fire is able to penetrate the fuselage of a modern airliner frequently leaves those onboard with few options and very little time with which to effect an escape. In addition, seemingly minor features often have the potential to influence events occurring on a much larger scale. Frequently, these features occur randomly or are impossible to control in the circumstances that typically prevail in the midst of a serious aircraft accident. Consequently, it is usually very difficult to predict what the best course of action

might be, especially since survival prospects are likely to be dependent on the actions of others, over which there can never be a guarantee.

9.4 Multiple Accident Analysis

9.4.1 Introduction

The first two case studies have each been concerned with the detailed analysis of a single accident scenario. However, a major objective of the research was formulate a model that would be capable of simulating all types of aircraft fire scenario. Then, when accident features are chosen randomly from appropriate probability distributions, many runs can be performed in order to obtain a fully representative sample of accident simulations. Results obtained from this type of study can thus be utilised for the purpose of risk assessment, as opposed to the hazard analysis demonstrated in the first two examples.

It was just about feasible to undertake multiple accident analysis by hand at the completion of the study. To keep matters as simple as possible, these runs were restricted to a series of 100 accident simulations, involving the same aircraft type. However, each of the accidents is unique in terms of scenario details, crash effects, fire characteristics and the passenger evacuation process. The outcome of each simulation had to be recorded by hand and results processed with the aid of a computer spreadsheet.

9.4.2 Model Set-up

The aircraft type used in analysis was an Airbus A310, configured with 219 passenger seats in a typical two-class arrangement. This cabin plan has been illustrated previously in Figure 6.8. A mean load-factor of 70 percent was assumed. All simulation parameters were determined randomly by using the probability functions built into the simulation model. The characteristics and derivation of each of these functions have been covered in previous chapters of the thesis. Thus many of the accident scenario features can be taken to be statistically representative of those that have been experienced in aircraft fire accidents occurring over the last 40 years. Obviously, the scenarios obtained with the model are not necessarily an accurate reflection of those that we might expect to occur with A310 aircraft flying today.

The following results were recorded for each event simulated:-

- Total number of passengers onboard
- Number of impact trauma deaths
- Number of fire deaths
- Number of series injuries
- Time required for completion of evacuation

A total 100 accidents were run for the case study. Ideally, it was desirable to have undertaken a significantly larger number of simulations; however the results obtained are sufficient to demonstrate the feasibility of this type of work. In the longer term, runs encompassing 1000 or more accidents would enable outputs to be provided in the form of continuous probability distributions.

9.4.3 Findings and Discussion

The mean casualty rates and mean evacuation time achieved in the 100 accidents are compared with historical figures in Table 9.5. It can be seen that the impact trauma death and serious injury rates match very closely; this is to be expected, as the accident scenario generator merely reproduces historical variations in these data. Fire fatalities were found to occur at a rate of 14 percent of those onboard, compared with an historical average of 23 percent. Given that we might expect the A310 to be more easy to escape from than older narrow-body types, this difference need not necessarily represent a cause for concern. However, this area obviously demands further investigation; perhaps more of the seriously injured survivors should be succumbing to the effects of fire.

	Result Achieved	Historical Average
Impact trauma deaths	21 %	22 %
Fire deaths	14 %	23 %
Serious Injury rate	15 %	12 %
Evacuation time	2 mins 16 s	2 mins 19 s

Table 9.5: Summary Results of 100 A310 Accident Simulations

The prediction of mean evacuation times appears to be promising. However, in reality, the A310 might be likely to perform significantly better than most other airliners and so the accuracy of simulation results is very difficult to judge. A more satisfactory indication can be obtained about this aspect of the analysis by comparing variations in achieved evacuation times. Figure 9.6 illustrates this distribution for the 100 runs and that for 44 accidents in which times are known. Note that the two

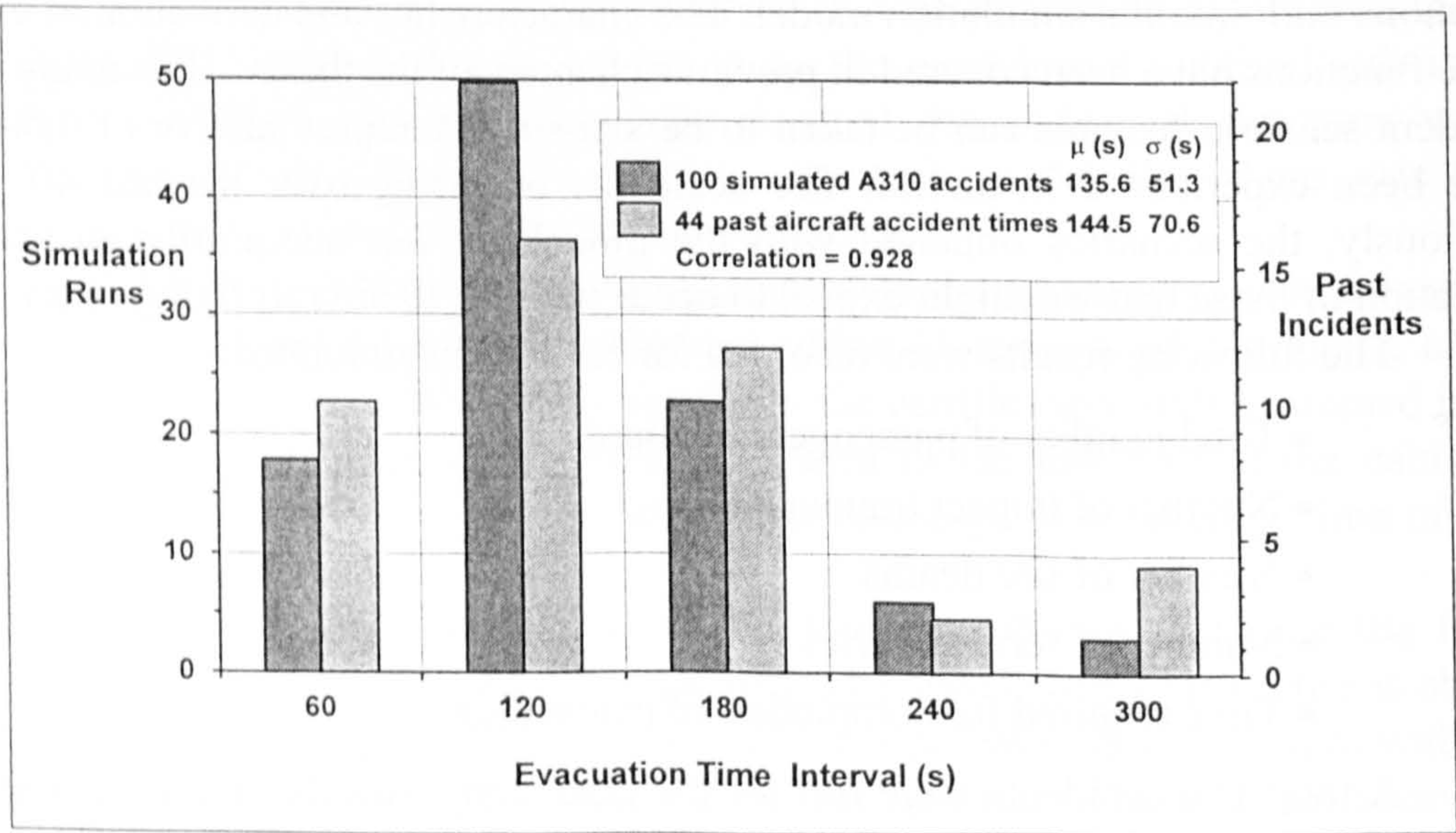


Figure 9.7: Evacuation Times Achieved in 100 A310 Accidents

vertical axes have been scaled differently to enable a direct comparison to be made. It can be seen that the characteristics of passenger evacuation times have been captured reasonably well. The historical distribution is spread more widely, with less of a peak;

this might be expected as it has been compiled from accidents involving many different aircraft types. The distribution of simulated times makes an interesting comparison with that obtained for certification-type evacuation trials, illustrated in Figure 9.3.

In summary, this case study has demonstrated that it is feasible to analyse the outcomes of aircraft accidents with what may be acceptable accuracy. However, the results presented are of a very preliminary nature and it is difficult to make quantitative comparisons with historical data. Consequently, much potential exists for further work to be undertaken in this area.

9.5 Safety Implications of New Very Large Aircraft Designs

9.5.1 Introduction

Over the last decade, major aircraft manufacturers have been undertaking feasibility studies into the development of a new design of large airliner. Attention has been focused both on “stretching” existing types and on the more expensive alternative of instigating a completely new design of aircraft. In the latter case, some very innovative aircraft configurations have been explored, covering alternatives such as fuselages with horizontal ovoid cross-sections, flying wings and even twin bodied aircraft. However, these seemingly radical projects now appear to have been dropped from further consideration, leading to the emergence of two rival Very Large Aircraft (VLA) programmes. Both of the aircraft involved are essentially conventional in design and are projected to be generally comparable in their performance.

Currently, the largest airliner in service is the Boeing 747-400, which has been certificated for the carriage of up to a maximum of 624 passengers. At the time of writing, Boeing in partnership with McDonnell Douglas, appeared to have decided upon the option of launching a programme to re-wing and lengthen this aircraft in order to meet projected market demand in the early years of the next century. As a result, the new stretched aircraft is projected to be capable of accommodating around 800 passengers in a high density seating configuration.

In contrast, Airbus Industries is now appears to be committed to an entirely new “A3XX” Ultra-High Capacity Airliner (UHCA) programme, possibly to be launched sooner than its projected American competitor. This design is likely to have a maximum seating capacity of 854 seats, over forty percent of which will be located on an upper cabin deck.

Undertaking the certification of an airliner in the VLA class will present many new challenges in the area of aircraft safety. Cabin crew will be responsible for co-ordinating larger numbers of passengers, using more emergency exits. These aircraft may possess more than two aisles and, for the first time, a substantial proportion of occupants will be required to evacuate from upper level exits.

This case study investigates passenger evacuation issues in two VLA designs. Firstly, an incarnation of an Airbus A3XX design is subjected to a certification-style evacuation trial and the performance of the upper and lower deck is compared. Then the evacuation from the lower deck of a Boeing VLA design study that possesses three passenger aisles is examined in detail. Both of these investigations yield some interesting results.

9.5.2 Model Set-up

In both the Airbus and Boeing runs, the simulation model was configured to undertake certification style evacuation tests. Half of the total number of exits was made available for use in each aircraft and a full complement of passengers was assumed. For the A3XX, two runs were necessary; one each for the upper and lower passenger decks. Both cabin were configured in a high density arrangement, seating 349 and 489 passengers, respectively. Use of inter-deck stairways by evacuees and interference between escape slides were not represented. All exits were assumed to be identical in effectiveness and were set to become available for use 10 seconds after the start of each test.

Two simulation runs were also undertaken with the lower deck of the Boeing VLA design. In both cases, a two class seating configuration with three aisles was assumed, providing a total of 405 passenger seats. For the first evacuation test, the aircraft's cabin was left unmodified in its published form. For the second run, a minor modification was made to one of the galley units situated in the rear half of the aircraft. This was intended to demonstrate how comparatively small details in the design of a large cabin can have a major influence on the efficiency of passenger evacuation.

9.5.3 A3XX Upper and Lower Deck Comparison

Evacuation from the decks of the A3XX aircraft is illustrated in Figure 9.7. It can be seen that four exits are available for use on the upper deck and five on the

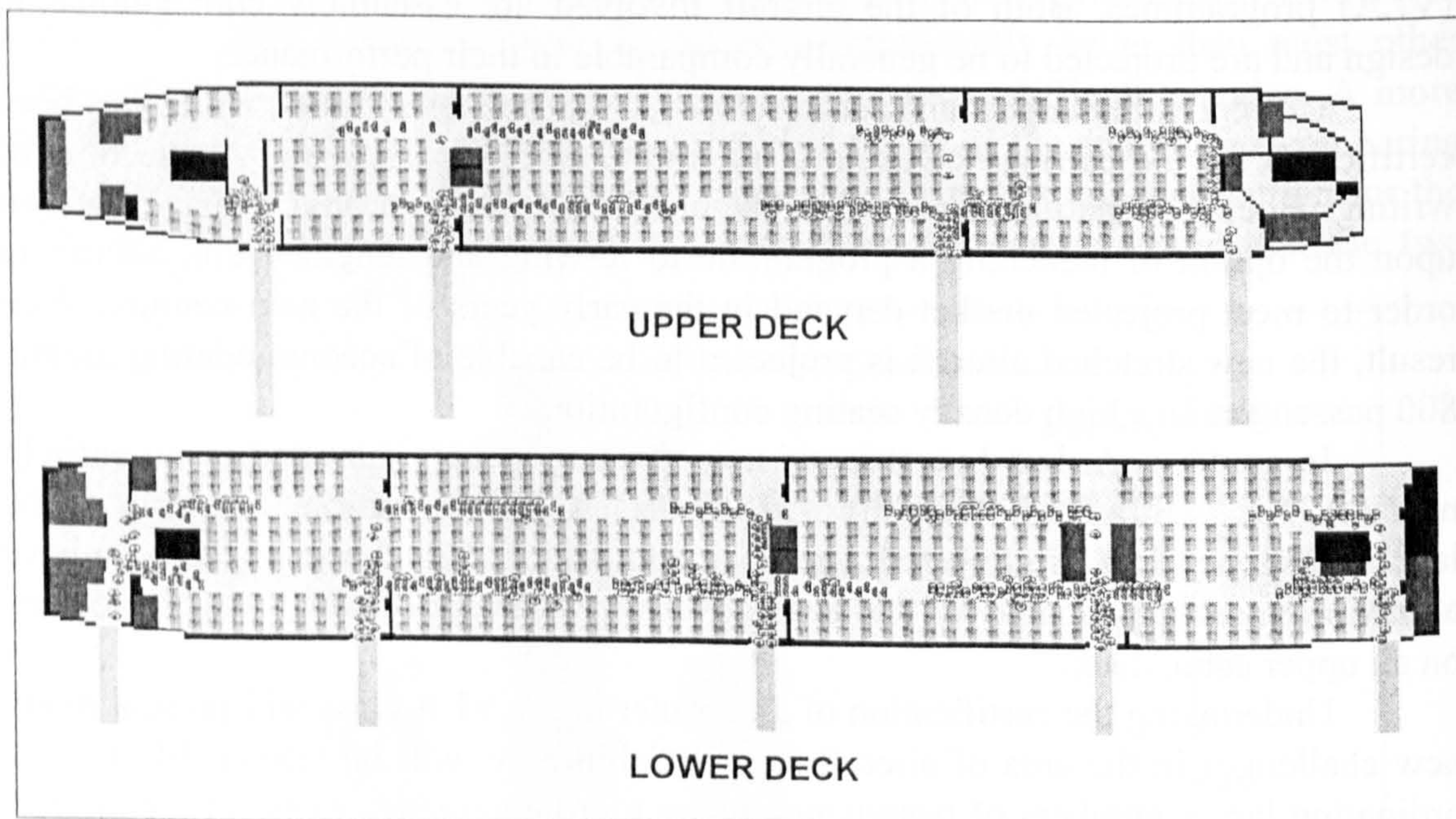


Figure 9.8: Progress of Airbus A3XX Evacuation

lower. Passengers delaying at exits and constrictions in aisles result in the formation of queues in both cabins after a period of approximately 20 seconds. Subsequent to this, the total time required for completion of the evacuation is governed by the number of passengers choosing to queue at each exit and the exit flow rates that can be achieved. With passengers heading for their nearest available exit, doors positioned at the front and rear extremities of the aircraft are under-subscribed on both decks. It

is thus probably not a coincidence that these are the positions in which stairways have been chosen for location by Airbus.

The mean evacuation times together with other details of the upper and lower A3XX decks are compared in Table 9.6.

Deck	Passenger Seats	Number of Exits	Seats per Exit	Mean Evacuation Time
Upper	349	4 (×2)	43.6	57.1 s
Lower	489	5 (×2)	48.9	75.2 s

Table 9.6: Evacuation Details for A3XX Upper and Lower Decks

With the assumptions used in the analysis, it is apparent that the upper deck of the aircraft can be evacuated in about three-quarters of the time required for the lower cabin. This difference is primarily due to the lower passenger to exit ratio present in the upper cabin. It is also worth noting that the use of stairs by evacuees would further accentuate the difference in evacuation time between the two decks.

In reality, it may not be realistic to expect the longer upper-level escape slides to deploy in the same time as those on the lower deck; also the significantly greater height of the upper exits will be more likely to produce passenger hesitation in doorways. The above simulation figures imply that an average pause of only 0.41 seconds per upper deck passenger would be sufficient to equalise the evacuation times of the two decks. Only time may tell if this magnitude of safety margin is sufficient.

9.5.4 Experimentation with Boeing VLA Design

The unmodified cabin configuration of the Boeing VLA design was found to evacuate in a time of 77.7 seconds. This figure compares reasonably with many existing airliners, but is not up to the standard of some widebody types, such as the Boeing 747-400 series for example. The key to this mediocre performance by the design was quickly discovered to be the fact that it utilised three passenger aisles in areas of high density seating. This particular feature need not be detrimental to evacuation performance, provided that adequate escape paths are provided for passengers unfortunate enough to find themselves in a central aisle. However, in the case of the Boeing VLA cabin configuration used in this study, problems were found to occur in the area of a galley positioned near the rear of the aircraft.

The top diagram in Figure 9.8 illustrates the overall configuration of the aircraft concerned. Picture (a) details the congestion that was typically found to occur in the region of the number 4 door on the starboard side of the aircraft. It can be seen that evacuees emerging from the central door are forced to queue behind a row of seats in order to move towards the side of the aircraft. This has the effect of constraining the flow of passengers reaching the number 4 door, thus preventing the exit from being used to its fullest extent.

The most obvious way remove this bottleneck in the evacuation was to remove a portion of the galley unit positioned at the end of the central aisle. This modification is depicted in diagram (b) of Figure 9.7. The effect of the change on the overall evacuation performance was startling. Table 9.7 shows that the revised evacuation time was only 69.1 seconds. This level of improvement could be accounted for entirely in terms of increased utilisation of the number 4 door. Observation of the

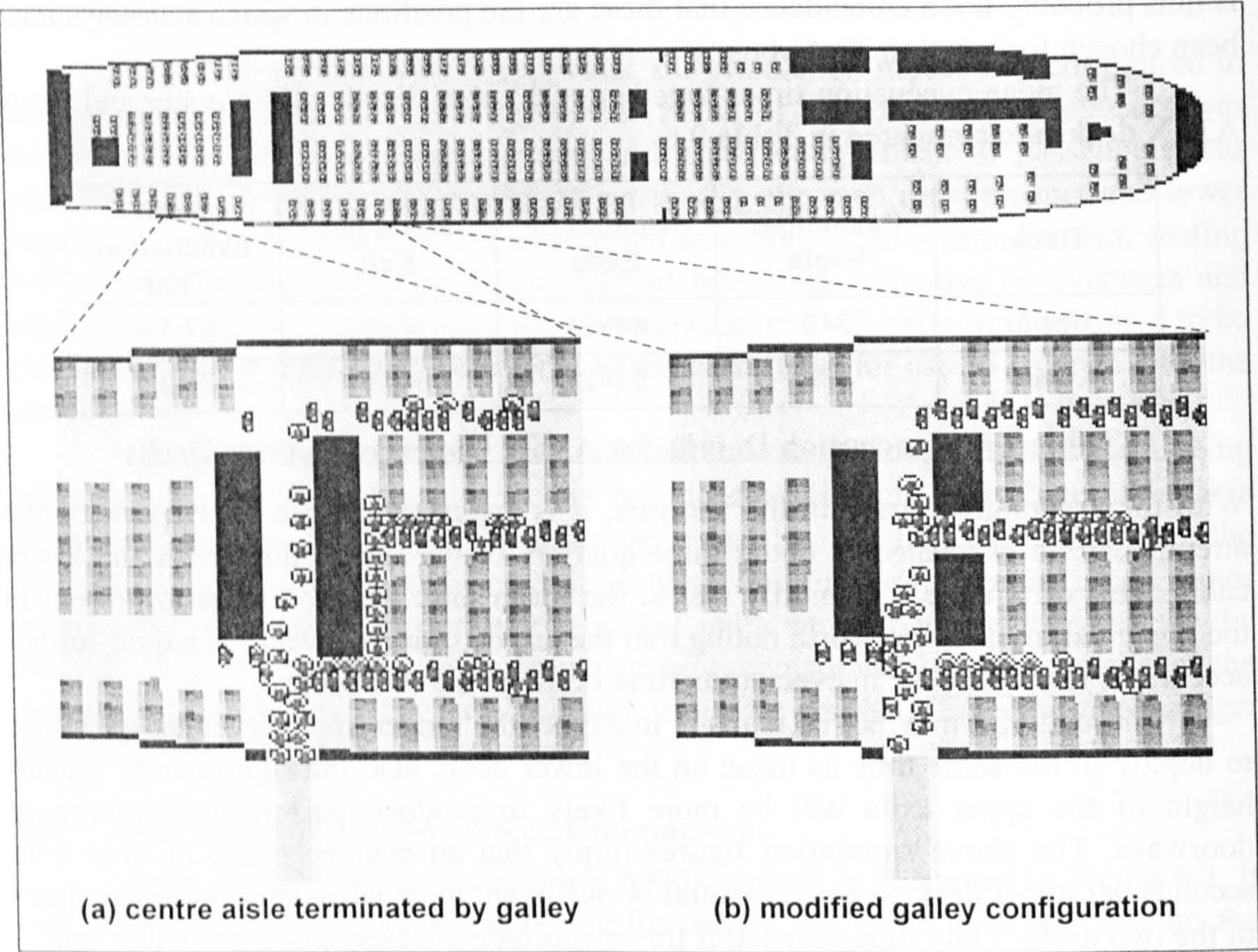


Figure 9.9: Modification of Boeing VLA Design

evacuation runs revealed that a significant proportion of the passengers travelling through the galley cut-out actually chose to turn right and then make for the idle number 5 door at the back of the aircraft. Effectively, the modification spread passengers more evenly throughout the rear section of the aircraft, and improved the utilisation of two exits.

	Original Galley Configuration	Revised Galley Configuration
Mean Evacuation Time	77.7 s	69.1 s

Table 9.7: Effect of Revision to Galley Configuration on Time Required for Passenger Evacuation

This example demonstrates the potentially critical effects that small design changes can have on the evacuation of aircraft. The value of the simulation tool for undertaking these types of preliminary exploration study has thus been clearly underlined.

Chapter 10: Evaluation and Conclusions

10.1 Evaluation of Research

10.1.1 Attainment of Research Objectives

The primary objective of the study was to construct a computer-based risk assessment tool suited for the investigation of issues in aircraft fire safety. The research programme was completely successful in attaining this goal. The tool operates by generating details of aircraft accident scenarios and then simulating their outcomes in terms of the number of fatalities incurred. Many complex aspects of accident survival needed to be considered in this analysis. The main components of the model and the interactions that occur between them are depicted in Figure 10.1. The computer model can be configured to control any aspect of the accidents being simulated and has been shown to deliver accurate results. These capabilities enable quantitative risk assessment studies to be undertaken in almost any aspect of aircraft fire safety.

A second requisite for the research was to provide the ability to deal with a fully representative range of aircraft accident scenarios, not just those that are more amenable to established methods of analysis. This was required because, in order to undertake true risk assessment studies, it is necessary to estimate what the outcome of different types of accident will be and also take account of the relative frequency with which these accident scenarios can be expected to occur. Thus, if findings are to accurately reflect the risks faced in everyday operations, all accident types that are likely to be encountered must be dealt with.

It was ensured that this requirement would be satisfied by undertaking an extensive survey of past aircraft accidents and carefully formulating the scope of the research to match the findings obtained. This led to the identification of a key parameter in the analysis being undertaken - the time required for fire to ingress into the passenger cabin. Many factors influence this ingress time, such as the type of fire involved, its rate of growth, the level of crash damage sustained by the aircraft, wind conditions, etc. These details were found to vary widely from incident to incident; thus the requirement for risk assessment implied that it would be necessary to simulate many accidents in order to obtain statistically valid results. Consequently, from a practical standpoint, the computer model needed to be capable of processing accidents autonomously and at a rate that was comparable to that of real time.

Arguably, one class of accident was not dealt with adequately by the simulation model; those which involve internal fires. As outlined in Chapter 7, the decision to neglect internal fire scenarios was based on two accounts. Firstly, findings from the historical survey clearly indicated that fatal incidents this type have become near to being eradicated in the course of the last two decades. The second factor was that the analysis of internal fires was better suited to ordinary computational fire modelling techniques, rather than the hybrid fire type of model being formulated. Thus, the effective outcome of this decision was to prevent attention being diverted unduly towards accident scenarios that were becoming increasingly unrepresentative of contemporary events.

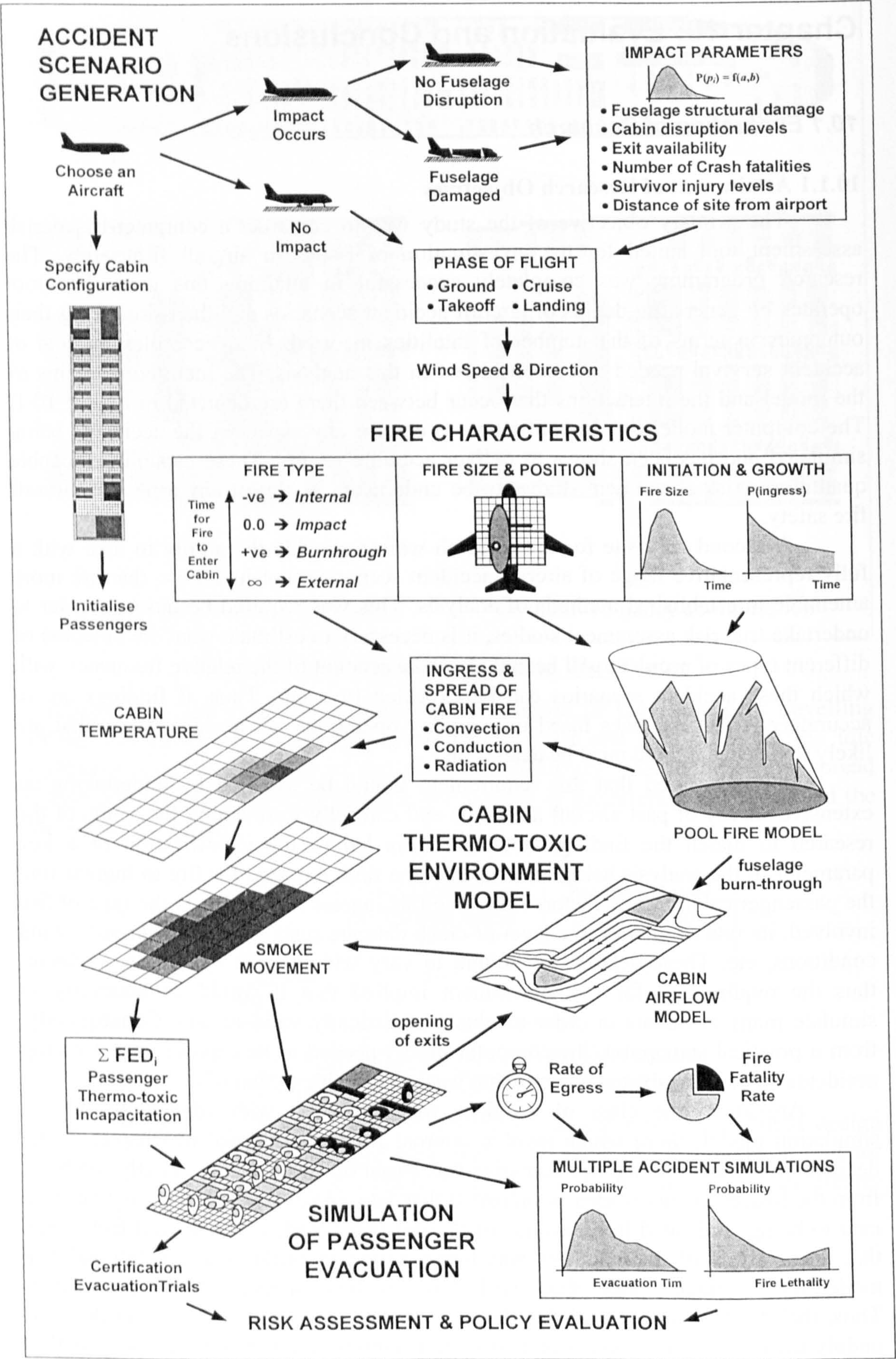


Figure 10.1: Main Features of the Risk Assessment Model

The analysis of fire lethality in aircraft accidents is a complex task, because influences as diverse as crash details, fire development and progress of the passenger evacuation usually need be taken into account. Frequently, powerful interactions can occur between these different aspects of an accident, which prevents them from being analysed on an independent basis. As a consequence of this, a further objective of the research was to utilise a holistic approach in the analysis, modelling all factors that have the potential influence fire lethality in a balanced and integrated manner.

Before these factors could be modelled, it was necessary for them to be identified. This was achieved by performing correlation tests with scenario data obtained from the accident survey. An important result of this activity was the revelation that the level of structural damage sustained by an aircraft was a better indicator of fire lethality than the size of fire present or the speed of evacuation achieved. This finding implied that as well as the modelling of fire development and occupant evacuation, wider details of accident scenarios needed to be taken into consideration.

Because a high degree of integration was necessary, the validity of the resulting model would be limited by the weakest aspect of the analysis that it contained. Therefore, a suitable balance needed to be achieved between the modelling of crash, fire and evacuation aspects of accidents. Throughout the process of model construction, this balance was frequently governed by quality of calibration data obtainable from past accidents and experimental research.

The final objective of the research was to demonstrate that it is feasible to undertake quantitative risk analysis of aircraft accidents, safety issues and safety policies with the tool that was being constructed. Each of these aspects has been covered at preliminary level in the case studies provided in Chapter 9.

As far as the analysis of accidents is concerned, it has been shown that the model can be used to focus down onto the details of a specific incident. Alternatively, levels of risk can be computed across a representative spectrum of accident scenarios, possibly involving many different types of aircraft. This then introduces the capability to explore effects that result from changes of safety policies, or examine issues such as the introduction of new designs of aircraft.

10.1.2 Limitations in the Work

10.1.2.1 Dealing with Difficulties

The trans-disciplinary nature of the work performed in the research made it inevitable that there would be many areas of compromise. Most of the difficulties that were encountered involved analysing aspects of safety that were either dealt with in a different way or else considered to be out of bounds by other researchers. As a result of this, there was usually no obvious way to circumvent problems that arose by recourse to published theory or alternative sources of information.

In most areas, however, the presence of difficulties can be anticipated and then allowed for in the planning of the research. In the short-term, this usually involved the establishment of an approximate stop-gap solution, or temporarily bypassing the need for the relevant part of the model to be used. This then enabled the basic structure of the model to be established and its overall functionality confirmed. Subsequently, however, these fixes needed to be resolved by replacing them with a more substantive analysis. Generally, this was achieved in one of four ways:-

- Adapt techniques that are used in another discipline or in a different context (e.g. the application of potential flow theory to model the movement of smoke)
- Develop new methods to specifically fit the circumstances (e.g. use of fire spread plots and simulating details of occupant evacuation)
- Adopt empirical approach, involving the look-up of statistical data (e.g. modelling the effects of crash impacts)
- Resort to stop-gap estimation or educated guesswork when little or no information is available (e.g. evacuee mobility in dense smoke)

The most important limitations in the analysis involved quantifying the relationships that occur between people, crash effects and fire. Inevitably, these “weak links” occurred as a direct consequence of being forced to adopt the last of the above approaches during model construction. Significantly, it can be that the interactions involved link all parts of the model, rather being located in one particular area. This fact is consistent with the attainment of a holistic and balanced analysis, one of the main objectives of the research.

A discussion of the areas involved now follows.

10.1.2.2 Modelling of Evacuee Behaviour

The task of formulating a realistic representation of human behaviour is a challenge that has to be dealt with in many types of computational simulation analysis. Given that aircraft accidents typically involve people acting in unfamiliar and hazardous circumstances, modelling of their behaviour becomes especially difficult. The main inadequacies in the evacuation analysis consist of predicting occurrences of irrational behaviour, planning of escape strategy in a complex environment and incapacitation by the effects of fire and trauma injuries.

Many examples of seemingly irrational behaviour were encountered in the accident data survey. At the simplest level, cases might be apportioned into three categories, crudely labelled here as “submissive inaction”, “ineffectual panic”, and “exaggerated altruism” respectively. Some instances of behaviour that fall into the third category are explainable in terms of an individual’s next of kin being present in the accident. These effects could therefore probably be represented within the evacuation modelling by some form of group behaviour mechanism and defining suitable passenger attributes. Other categories of exaggerated behaviour, such as uncooperative actions, seat climbing and exit crowding might also be dealt with in an analogous manner. In contrast, occurrences of panic and inaction appear to be much harder to quantify. One possible inroad into this area might be that these reactions appeared to occur more frequently when people are exposed suddenly to large fires or seated near to breaks in a fuselage. Possibly, the best way to incorporate these aspects of behavioural modelling into the analysis is via a statistical approach.

When people are tasked with evacuation from an aircraft, they are usually able to formulate a suitable plan of escape, even in the most confusing or unfamiliar circumstances. Because this task can be performed sub-consciously in a very short space of time, evacuees can adapt and update their escape strategies to take account of changing circumstances and the availability of new information. When examined in detail, these capabilities appear to be very complex and consequently are almost impossible to represent concisely within a computer programme. It was therefore

predictable that determining passenger's escape strategies would be an area of significant compromise in the model.

Orderly certification-style evacuations are reasonably straightforward to approximate. Paths to exits are simple to determine and passengers can be made to take account of queue lengths, behaviour of others, exit flow rates, etc. without difficulty. Many complications arise, however, when the effects of fire and crash disruption are introduced into the evacuation scenario. The decision making analogy must then take account of far wider range of influences, such as cabin visibility, obstruction of aisles, egress via breakages, progress of fire, etc. It would have been possible to allocate major portion of the available research time for the writing a knowledge-based algorithm able to fulfil these demanding requirements. Realistically, however, time constraints and the need to simulate the movements of hundreds of individuals in real time meant that this solution was not feasible. Even when evacuees are assumed to retain their full capabilities, the complexity of the situation was such that only the simplest of rules could be implemented to deal with each eventuality.

The task of calibrating even this basic decision-making model was problematic. The best insight into the area can probably be obtained from survivor accounts of past accidents, especially if a reason or explanation for observed behaviour is required. However it is then usually very difficult to structure these processes or quantify them numerically. For example, it is known from study of past accidents that the possession of relevant training or experience can be a very important factor in determining evacuation performance. Do we attempt to model this type of attribute explicitly or should it be translated into qualities that can be defined more meaningfully, such as speed of movement, rate of reaction and rationality?

Video recordings of experimental evacuation trials were found to be valuable for quantifying simpler behavioural parameters, such as reaction speeds, rates of movement and exit flow rates. Videos also provide a useful qualitative insight into more detailed aspects of the evacuation process. A significant drawback of using such data, however, is that results obtained from experimental trials cannot generally be taken to be representative of real accidents. Thus, it was necessary to apply correction factors to account for anticipated differences in evacuee behaviour and performance in real accidents.

Researchers have interviewed trial participants in an attempt to explore their perceptions of an evacuation and elicit reasons for choosing certain courses of action. The information obtained in this way is likely to form an interesting comparison with the experiences of real accident victims and a combination of these two resources appears to constitute the best basis from which to advance the evacuation analysis.

One particular aspect of passenger behaviour that might have been more feasible to address within the shorter term is utilisation of stairways during egress from future double-deck aircraft designs. People are almost certainly less willing to jump from upper floor exits and stairways are likely to constitute bottlenecks if used by many passengers. Although the former issue was investigated in one of the case studies, time constraints prevented the effects of stairways from being incorporated into the analysis. Given that provision was made for this facility within the model, it should be reasonably straightforward to implement and would enable some interesting optimisation studies to be undertaken. Currently, experience with obtained with existing Boeing 747 aircraft and experimental evacuation trials is insufficient for

quantifying these issues. As a result, effecting the capability to analyse large aircraft constitutes one of the more immediate priorities in the development of the model.

One of the most difficult aspects of modelling passenger evacuation is dealing with the effects of trauma injuries and fire incapacitation. Significant knowledge exists on the physiological effects of fires, but there is very little coverage of psychological aspects. In addition, virtually nothing appears to be known about levels of debilitation that result from crash injuries. It is obviously impossible to undertake experimental research in these areas and thus anecdotal evidence from past accidents is the only information available to work from. The implementation of fractional scales to represent smoke incapacitation and injury levels within the model were found to be convenient and these concepts have already been established in the building fire safety and car safety industries. However, in spite of the fact they appear to deliver reasonable results, the applicability of these scales to aircraft accidents has not been verified. Similarly, the psychological effects of smoke were represented as being just a linear drop in speed with increasing smoke density. This was a consequence of there being only one set of experimental data to work from in this area.

One final aspect of the evacuation modelling that warrants discussion is the exclusion of aircraft cabin crew from the simulation. This was done to simplify the analysis and avoid the need to accommodate more than one type of evacuee. Whilst the decision was clearly justifiable in the earlier stages of the work, the effects of cabin crew actions might need to be incorporated in detail when performing some types of analysis. For example, experimental evacuation trials have shown that assertive behaviour by cabin crew can produce a significant increase in the flow of passengers through door exits. It might be desirable to test the implications of this finding across a range of different accident scenarios.

10.1.2.3 Analysis of Crash Effects

In addition to the modelling of passenger evacuation, a substantial portion of the research was concerned with representing the effects of crash impacts in aircraft fire accidents. Impact disruption was incorporated in terms of structural damage suffered by the aircraft, levels of cabin disruption and resulting occupant trauma deaths or injuries. In the case of structural damage and levels of cabin disruption, acceptable statistical relationships were obtained with the use of a simple categorical 1-5 scale of severity. Whilst this methodology was suitable for quantifying the consequences of crashes at a general level, it does not allow for more specific details to be determined, such as floor integrity, failure of seat attachments or littering of aisles, for instance. The occurrence of each of these features tends to affect accident survivability in a slightly different way, but such considerations are not reflected in the level of resolution incorporated into the impact effects model.

Given that the interest of the research lay primarily with the analysis of fire lethality rather than crash survivability, the level of compromise adopted in this aspect of the work is probably acceptable. However, the use of a simplified approach tends to preclude the effects of recent crash-safety initiatives from being modelled in detail. Examples of safety improvements that may need to be taken account of in this way include detailed improvements in crash-worthiness of aircraft structures, introduction of 16 g rated passenger seats, precautions for those seated facing solid surfaces, and

strengthening of overhead stowage bins. If any of these considerations is to be dealt with, their interactions will need to be facilitated at an appropriate level.

Prediction of occupant injury levels in the crash effects modelling is also relatively simplistic. Both the numbers and severity of injuries are quantified on a statistical basis, being classified as either fatally injured, seriously injured or unharmed. Again, this approach was probably appropriate for the type of work being undertaken, but potential exists for substantial improvements to be made in this area of the analysis. As seen in Chapter 3, a significant amount of work has been performed in the area of quantifying human trauma injuries. Potentially, many of the methods used are applicable in the analysis of aircraft accident victims and could therefore be incorporated into the current research.

However, even if the nature of impact trauma injuries could be classified and predicted with accuracy, the problem of determining what the resulting effects on occupant evacuation capabilities will be still remains. Quantifying these factors satisfactorily with information gained from past accidents is likely to prove extremely difficult, as the evidence available is patchy and anecdotal in character. One source of data that might prove complimentary to this material are results of evacuation trials undertaken with handicapped passengers. In the context of evacuation from aircraft, the constraints imposed by common physical and mental disabilities appear to bear a close resemblance to those that result from typical trauma injuries. If it were possible to establish some equivalence relationships between the two, an important aspect of aircraft fire survival could potentially be made accessible to analysis for the first time.

10.1.2.4 Approach to Fire Modelling

The third main component of the simulation model was the representation of accident fires and the resulting thermo-toxic environment inside the passenger cabin. The choice of approach in this part of the analysis was governed by the unusual requirement to model the key interactions and approximate effects of a fire, incurring the absolute minimum of computational overheads. As a result, a hybrid scheme was formulated, which comprised a two-dimensional cabin fire model used in combination with an external pool fire analysis. The two were linked, in part, with a two-dimensional potential flow solver that was efficient enough to update cabin airflow each time an exit was opened or a significant portion of cabin wall burnt through.

The main shortcomings of the fire analysis stem both from the philosophy behind its construction and limitations imposed by time constraints in the research. It is acknowledged that modelling the development of even a comparatively simple aircraft fire scenario is an extremely difficult task. The best way to analyse this type of fire problem is with the use of a computational fluid dynamics (CFD) method. However, the time needed to set up boundary conditions and obtain just a single solution is typically of the order of several weeks and the quality of results obtained can never exceed that of the input data available. Effectively, these limitations ruled the use of CFD out of consideration, leading to the search for a simpler and more practical alternative. It was aimed to create a fire model that would match and integrate fully with other parts of the safety analysis, working with a higher level of simplification. The quality of the results provided needed only to match the requirements of the thermo-toxic incapacitation analysis rather than providing new insights into the development of fires.

As a consequence of this philosophy, many compromises needed to be made in the fire modelling. Most of the simplifications were justified on the basis that certain features were fundamentally incompatible with the primary objectives of the analysis being undertaken. However, some omissions were the result of time constraints associated with the research, as opposed to arising from technical considerations. Arguably, the three most important of these were lack of smoke modelling outside the aircraft, omission of the effects of fire fighting operations and the failure to incorporate three-dimensional smoke stratification effects inside the aircraft's passenger cabin.

The theory of open pool fire modelling deals predominantly with estimating the extent and radiative power of flame envelopes. An important assumption in the methods used is that smoke rises or is blown rapidly away from the flames and it thus has little or no influence in fire development. This then allows fire properties to be calculated as being purely a function of fuel details and ambient wind conditions.

Whilst the use of this approach appears to be acceptable for modelling the vast majority of aircraft fuel fires, it ensues that smoke movement outside an aircraft plays no part in the fire analysis. Significantly, however, the spread of external smoke can sometimes reduce the availability of exits in adverse wind conditions. An example of this was encountered in the Manchester case study, where an open rear exit on the opposite side of the aircraft to the fire was effectively blocked by smoke flowing around the exterior of the rear fuselage. In other circumstances, external smoke may enter an aircraft from the outside if fuselage damage has occurred or if an inappropriate exit opened. A related point is that the large volume of gaseous products generated by fires will tend to modify airflow patterns on the exterior of an aircraft.

These considerations are not dealt with in the fire modelling, but clearly they could be influential in some accident scenarios. The movements of external smoke would be relatively straightforward to predict on an approximate level, given that the necessary fire, wind and fuselage geometry are already available in the analysis. The phenomenon of fire-induced distortion of airflows would also be simple to represent by locating a suitably sized potential source element at the centre of the fire. Consequently, this work forms one of the more immediate options for undertaking further improvements in the fire modelling.

Another significant area of omission in the analysis of fires is the lack of representation of intervention by fire fighting and rescue services. Although justifiable in the initial development phase of the research, this issue might need to be addressed at a later stage. Information on the significance of fire fighting and rescue actions was gathered during the survey of past accidents and possible linkages with fire survivability rates were explored. It was found that the outcomes of incidents in which emergency forces had attended promptly did not differ significantly from those where no intervention had occurred. This finding was the primary justification for choosing not to incorporate any fire suppression mechanism within the simulation.

However, study of past incidents clearly indicated that effects of intervention were undoubtedly significant in some types of accident scenario. Unfortunately, the resulting improvements in fire survival rates appear to be too small to be readily quantifiable from the analysis of simple summary statistics. A complicating factor in this area is that emergency services are more likely be able to attend landing accidents that occur on-airport. Thus, rescue crews are predisposed towards dealing with

scenarios that tend to involve higher than average fire fatality rates, effectively swamping out any savings of life made.

Consequently, in order to determine the role that emergency services play in aircraft accidents, incidents need to be analysed on a case by case basis. The main mechanisms for saving of life appear to be as follows:-

- Fire containment and suppression of smoke
- Opening of emergency exits
- Clearing evacuees away from escape chutes
- Cutting wreckage and rescue of trapped survivors
- Administering of emergency medical treatment

The task of quantifying the effects of each of these actions in typical fire scenarios is extremely difficult. Evidence from past events can provide isolated examples of where these factors are known to have been significant, but the data available is generally insufficient for purpose of calibrating their simulation. Consequently, the effects of intervention by emergency services can only be predicted with simple estimation analysis, used in conjunction with findings from experimental trials, in areas where applicable work has been undertaken. Because of the levels of uncertainty associated with these procedures, this work constitutes a longer term priority in the development of the research.

One final aspect that might have been dealt with in the fire modelling was the representation of three dimensional stratification effects in a cabin's thermo-toxic environment. In Chapter 7, it was seen that, initially, hot smoke tends to spread through the interior of an aircraft at ceiling level, as a result of buoyancy effects. As a result, conditions near the floor of a cabin can remain survivable for a considerably longer period than those encountered at head height. For example, this factor was known to be significant in the Manchester incident, where survivors reported that they found themselves recuperating slightly after collapsing to the floor.

The decision to use a two dimensional model to represent an aircraft's cabin atmosphere clearly prevented these stratification effects from being taken into consideration in the analysis. The consequences of this are that rates of evacuee incapacitation are likely to be over estimated when dense smoke moves steadily through a largely intact fuselage in a level orientation.

It was anticipated that it would be a simple task to incorporate stratification effects into the cabin thermo-toxic environment model; the provision of this facility was a prominent consideration when this aspect of the analysis was being formulated. Currently, conditions are depicted in a horizontal plane, located at 1.5 meters above floor height. The most obvious way to extend this analysis to three dimensions is to calculate similar distributions at heights of, say, 0.5, 1.0 and 2.0 meters above the floor. Rates of smoke transport and diffusion constants would be reduced at lower levels, producing a progressive filling of the cabin from the ceiling downwards. The stratified cabin environment could then be incorporated into the evacuation analysis, interpolated between different layer heights if necessary. Given that this task comprises a relatively simple extension of existing work, it could be undertaken in a short time scale.

10.1.2.5 Implementation Issues

In addition to the limitations inherent in the formulation of the risk assessment model, some points might be raised about the way in which the work has been implemented as a computer programme. Although the study strictly only needed to produce a tool capable of fulfilling research requirements, it might have been desirable to construct a model that was more suited to hands-on utilisation by other users. Effectively two issues needed to be addressed if this requirement was to be met; the provision of an interface to facilitate setting up of simulation runs and transfer of the programme to a more widely used computer environment.

When using the model, all accident simulations were performed individually and the results obtained processed by hand. In circumstances where specific types of scenario needed to be tested or certain parameters adjusted, the original source code was edited and then re-compiled into an executable programme. Achieving this task requires specialist knowledge, together with appropriate software and requires several minutes for each modification to be effected. Whilst being perfectly acceptable to an author in the process of developing a programme, this procedure is too involved to be practicable for other users to achieve. Consequently, in the longer term, some form of user-interface is needed to make the functionality of the model more accessible. Such an interface would have required considerable effort and time to develop; because of this the task was not feasible attempt in the time available. However, as the emphasis of the work shifts from away from development and towards usage of the model, the provision of a user-interface would be expected to become an increasingly higher priority. Provision of the capability to automatically run and process the results of many accident simulations would also serve to emphasise the unique approach adopted in the work.

A second factor that makes the simulation model less accessible to other users is that it has been developed in a UNIX environment, running on specialised engineering workstation computers. To offer increased flexibility, it desirable for the programme to be ported to run on Personnel Computer (PC) machines. Potentially, this move introduces issues concerning computational speed and memory constraints. However, given the rapid increases in PC capabilities seen during the course of research, this should no longer be an area for concern.

10.1.2.6 Limitations Inherent in the Use an Holistic Approach

At a more general level, the work that has been performed is intended to address the area of risk assessment, rather than be suited to performing more specialised hazard analysis in specific areas. Thus, accidents are represented at a level of detail that allows for a full range of accident types to be covered with the relative probability of different scenarios being faithfully represented. However, two of the case studies presented in the last chapter have demonstrated that it is feasible to examine aspects of aircraft safety, such as evacuation trials and analysis of real accidents, in a resolution that is greater than strictly necessary for the purposes of risk assessment. Although undertaking these more specialised kinds of activity was not a central emphasis in the work, the holistic approach adopted in the research meant that potential capabilities of this type existed across many areas. It is possible to foresee that the interests of some end users might focus upon only a relatively small part of the analysis and, as a result, they probably require more detail to be added in one particular area. How feasible might this be to achieve?

Obviously, the use of an holistic approach made it impossible to deal with all aspects of aircraft fire safety in great levels of detail. However, because the model has been implemented in a general purpose programming language, its functionality can be extended or refined in any area that is desired. The key difficulties in this respect usually comprise lack of understanding or usable data about some of the more complex phenomena being modelled, rather than the existence of any limitations built into the model. Thus, if a point of particular interest can be faithfully conceptualised or at least measured with an acceptable degree of accuracy, it should be possible to address its affects within the simulation.

Arguably, a reasonable guideline to adopt when extending the analysis in this way is to only model details at a level that is sufficient to resolve the phenomena being investigated. If features are represented in at a lower level than this, unnecessary complexity and the potential for additional errors are introduced into the model.

An example of an issue that could have dealt with in this manner is the utilisation of stairways in the evacuation of VLA designs. Undertaking a thorough investigation of this area requires more functionality to be added to the evacuation model. However, the details of movements that individual evacuees make within a staircase are not necessary for the purposes of such an analysis. Effectively, all that is required is the rate at which individuals are able to enter a staircase and the time that they then take to descend to the lower deck. The latter information could be obtained by implementing a simple queuing process, as opposed to a more complex iterative scheme that reproduces step by step movements of each evacuee.

10.1.3 Implications for Design & Implementation of Research

Overall, the adoption of an holistic approach for the analysis of aircraft fire safety has been shown to be feasible and capable of delivering insights that are difficult to obtain by other means. Consequently, it is perhaps a little surprising that so little of this type of work has undertaken in past. However, when such a task is embarked upon with limited time and resources, many difficulties are soon encountered. These can range from simple practical details through to a more general lack of precedents or established expertise in the field.

Perhaps the most significant challenge to be faced, however, is the requirement for several disciplines to be spanned in any such programme of research. Specifically, the current study involved a fairly even division of effort between historical survey, safety research analysis and computer simulation activities. This required a high degree of flexibility to deal with and careful appropriation of available resources. Also, given the diversity of the areas involved, significant preparatory efforts are required before substantial achievements begin to emerge. This work occupied a period of approximately two years in the study - a major proportion of the total time available. In comparison, restricting the scope of safety research to a single more specialised area is likely to lead to far more immediate results.

It is perhaps a combination of these and other issues that has held back development of holistic research methodologies suitable for dealing with complex issues in aircraft safety. Regardless of the difficulties involved, however, arguably not enough examples of these types of analysis exist. As a consequence of this, many techniques and areas of knowledge had to be developed from first hand experience. Some of the more detailed observations made during implementation of the work, together with their possible implications are now discussed.

In order to construct holistic analysis in the area of aircraft safety, it is essential to have a thorough knowledge of aircraft accidents. It was found that study of past events induced significantly different emphases to those found in existing research and legislation in the area of aircraft fire safety. Even when it is unfeasible to use historical data in order to quantify specific issues of interest, the background knowledge obtained from these sources is likely to prove invaluable when designing programmes of experimental research.

Undertaking detailed simulations of aircraft fire accidents is difficult, as it inevitably involves analysis of areas in which little or no quantitative information exists. The task of formulating and implementing a computer model forces the practitioner to be explicit in all details modelled, regardless of the quality of data available. Thus, the methods used in construction cannot be concealed or fudged; all weaknesses and assumptions present in an analysis are laid bare. As a result of this, models may appear crude or overly simplistic; however there is still much potential for valuable new information to be gained. This knowledge is likely to accrue both during the process of researching the construction of the model and from end use of the completed tool.

Typically, it was found that as much effort was expended in setting up boundary conditions and probability levels within the model as spent formulating and solving equations. Arguably, this balance between practical implementation and underlying theory is rarely present in established categories of air safety research. Experimental trials tend to involve a pragmatic approach, with concern for measurement and statistical reliability of results taking precedence over theoretical explanation of the observations made. In contrast, the emphasis computational-based investigation tends to be concerned more with establishing generic capabilities and validating them in simplified test cases than with spending time in attempting to replicate more complex real world scenarios. Thus, although the main product of the research is likely to be interpreted as being merely another category of computer simulation, the scope of the work is rather wider than other computational studies in the area of aircraft safety.

When undertaking a wide-ranging investigation in a complex area, matching the level of analysis across all areas being studied often forces difficult compromises or trade-offs to be made. The researcher faces issues of having to spread available resources thinly and of working beyond boundaries of existing data. Effectively, the reliability of findings is governed by characteristics of weakest links present within the analysis. However, it can be argued that these same limitations are present when attempting to apply any type of research to real events; they just happen to be excluded from explicit analysis. In contrast, with an holistic approach, such links no longer constitute unstated or concealed unknowns; they form an integral part of the analysis. Potentially, this then allows for more accurate assessments to be made and safety margins assigned more appropriately.

Revealing the boundaries of existing knowledge also forces the presence of gaps to be highlighted. Given that other areas are usually covered in more than adequate detail by existing research, it is possible to interpret the existence of "islands of knowledge", between which very little additional information exists. Consequently, this means that holistic research is likely to involve a large proportion of time being spent working at a low level in areas that have received little or no attention from other researchers.

Generally, analysis of issues within aircraft fire safety is constrained by the quality or applicability of available data. This can mean that advances made some areas of research are seemingly redundant as they are impossible to apply in a practical context. Alternatively, the influence of the issue under study can sometimes be completely overshadowed by ancillary factors, about which very little is understood. Consequently, when performing research into specialised areas, it sometimes appears to be possible to overlook the ultimate reason why the activity is being undertaken. This implies that, when undertaking applied safety research, it is not always necessary or even desirable to analyse complex phenomena in the maximum attainable level of detail. Instead, if the focus of a study is restricted to a level that is just sufficient to resolve features of interest, the husbanding of resources that results may enable the scope of the work to be extended to obtain a wider applicability.

Finally, when attempting to simulate and understand complex interactions occurring simultaneously between many processes, computer graphics can constitute an invaluable aid. For the developer of a model, their use enables large quantities of dynamic information to be presented on-screen simultaneously. This allows problems to be quickly isolated and makes it possible to spot unpredicted interactions and behaviour patterns occurring on a larger scale. Graphical displays also help unacquainted observers to quickly assimilate the main features of model. Consequently, however, the true complexity of the analysis actually being undertaken can sometimes be belied. Another factor that needs to be taken into consideration is that graphics are likely represent a substantial overhead, both in terms of the effort required in their programming and the computational processing demands imposed when a simulation is being run.

10.1.4 Implications at Policy Level

The conflict between holism and depth of analysis constitutes an interesting trade off when planning research in aircraft fire safety. Researchers are currently working to quantify a multitude of issues, covering many aspects of fire survival. However, the task of combining the findings obtained from these various undertakings and using them to guide policy formulation appears to have been paid comparatively little attention. Given the diversity in scope and approaches that have been adopted across different research studies, it appears difficult to prioritise or systematically evaluate all the information that available from these sources. In addition, the implications of research findings cannot be interpreted merely in their own right; they need to be integrated with knowledge that is obtainable from the examination of past events. Information of the latter type is usually very different in nature to that provided by scientific analysis, further compounding the difficulties of those responsible for overseeing matters of air safety.

The work described in this thesis may represent one of the first attempts to address these issues. The problem of information complexity has been dealt with through the construction of computer-based simulation model. The use of this methodology enables a large quantity of knowledge to be drawn together and implemented in the form of a single tool. Widely differing types of data can be matched with each other and almost all aspects of aircraft safety integrated in a balanced and thorough manner. Where gaps in understanding exist, it is possible for them to be clearly identified and then the effectiveness of improvisatory solutions

tested. The research has also been based upon the analysis of both past aircraft accidents and scientific safety research studies.

As a result of undertaking these activities, it has been possible to compare the work that has been undertaken by others in different areas of aircraft fire safety. The approaches used and findings obtained in these studies has also been related to the events that are known to have occurred in past accidents. Many of the observations made, together with the advances to have been contributed by the current study, hold implications that lie beyond those that need to be considered when implementing a single programme of research. Some of these issues will now be discussed.

The first and perhaps most obvious point to note is that there appears to be very few examples of holistic analyses in any area of aircraft survivability. Those that have been published are all produced by national aviation authorities (i.e. the FAA and CAA) and involve extremely basic analysis of past accidents. As a result, a large gap exists between these generalised risk assessment studies and more specialised scientific research being undertaken to quantify specific aspects of aircraft safety.

The work presented in this thesis has shown that it is feasible to bridge this void with a computer-based simulation analysis that integrates statistics obtained from past accidents with knowledge derived from scientific research. Use of this approach enables a full range of accident scenarios to be considered in a level of detail that is compatible with the scope of scientific analysis. Just as significantly, perhaps, the use of holistic computer simulation appears to make it feasible to evaluate safety issues in *future* accidents, as opposed to just mapping the effects of recent safety developments onto past events.

It was also apparent that, in many areas of aircraft safety research, knowledge that is potentially obtainable from past accidents is being under-utilised. This is probably a consequence of traditional delineations that exist between different scientific disciplines. These divides tend to mean that individuals and research departments build up expertise in one particular mode of research, such as experimental testing, computer simulation, or volunteer trials. Unfortunately, whilst this situation may help to nurture scientific advancement, it does not facilitate the analysis of more complex multi-disciplinary areas, such as fire-safety engineering. This has meant that little awareness or expertise has been established in the area of interpreting information from past aircraft accidents. As a result, whilst information about these events is generally accepted as being useful and anecdotes are often cited for the purpose of reinforcing scientific arguments, the potential significance of historical data is under-appreciated. Consequently, performing detailed analysis of past accidents is regarded as being an unwarranted or merely a peripheral activity by most safety researchers.

Compounding this situation is the fact that, for those tasked with formulating air safety policies, scientific findings are likely to be more appealing than indications derived from historical analysis. The reasons for this are numerous; results of scientific investigation appear more consistent, more rigorous and easier to interpret than findings from accident surveys.

In spite of this apparent neglect within the scientific research community, information on past accidents is gathered and utilised by aviation authorities, aircraft manufacturers and consultancy organisations. These endeavours are usually undertaken either for the purpose of examining detailed technical aspects of aircraft safety, or for establishing global statistical trends. As a result, the levels at which

information is processed tend to fall on either side of that which is required to complement scientific safety research. Whilst there have been some isolated exceptions to this generalisation (Schaefers, 1990), this situation appears to represent a lost opportunity in the advancement of aircraft safety. The current research has demonstrated that by analysing a substantial number of accidents with the explicit purpose of quantifying safety issues, information can be obtained in a form that is compatible with the needs of scientific studies.

When surveying the work that has been published in aircraft safety, it became apparent that the emphasis and direction of research were not always well matched to the type of events that are known to occur in aircraft accidents. Practical constraints obviously limit the degree of realism that can be achieved in trials that involve human volunteers. However, these types of restrictions do not apply when investigating aircraft crashworthiness or patterns of fire development. It is therefore difficult to accept the unrealistically conservative approaches frequently adopted when performing tests in these areas. Arguably, there sometimes appears to be a reluctance to reveal the catastrophic consequences that can result when parameters such as deceleration forces, structural dismemberment, radiant intensities, fire size and position, etc. are represented at more realistic levels.

Given the adverse media coverage that has been attracted by some aircraft crash fire testing, this reluctance is understandable and, if undermining of public confidence results, perhaps even justifiable. However, when considered exclusively in terms of the data actually needed for undertaking survivability analysis, there is a requirement for more information that corresponds with more severe accident scenarios.

Another point that became very apparent in the study of past safety research was the comparative rarity of cross-disciplinary studies. For example, in many cases, the effects of aircraft crashes and fires can be highly interdependent, but in recent decades there has been a trend to separate these two areas of analysis. This may be a consequence of the increasing levels of specialisation and consequent narrowing of awareness within the safety research community mentioned previously.

Admittedly, experiments involving more than one substantive aspect of analysis are not straightforward to set up and typically only a very restricted set of variables can be explored in each of the areas encompassed. This can make it difficult to decide experimental priorities and integrate results obtained across different parts of the test. However, the current practice of obtaining detailed knowledge about certain features of aircraft accidents when present in isolation, but then having little idea how they may interact in combination is not entirely satisfactory. When full consideration is given to the potential benefits, feasibility and cost of undertaking tests, there may be opportunity for greater levels of integration in safety research.

The use of a computer simulation tool to analyse aircraft accidents opens up many new possibilities in the development of aircraft safety. For the first time, it may be feasible for safety features of a new airliner to be optimised on the designer's desktop. At present, aircraft are certificated to common safety standards that cannot (and are not intended to) be representative of true accident scenarios. Many years of service usage, usually involving a number of accidents, then have to occur before safety features and operating procedures can be developed to their fullest extent. By using some of the techniques developed in this thesis, in the future it may be possible

to advance the analysis of aircraft fire safety to levels of efficiency comparable with those currently found in aerodynamics, structures and systems design.

10.2 Suggestions for Further Research

10.2.1 Improvement of the Model

The time constraints imposed by the study left ample opportunities for undertaking further development of the model. Detailed refinements that could be implemented in a relatively short time scale include:-

- Model the presence of cabin crew and the effects of their actions in aircraft accidents.
- Represent the stratification of cabin thermo-toxic environments in three dimensions and integrate this information with the evacuation modelling.
- Provide the ability to analyse simultaneous evacuation from two decks, including the use of stairways by passengers.
- Quantify the role that advances in safety may have had in recent decades and factor these effects into the analysis explicitly.
- Transfer the model to a PC Windows-based environment.
- Creation of a simple command interface to enable simulation parameters and multiple runs to be set up by other users.

In the longer term, more substantial work on the development of the model could be performed. Revisions might then be made in the following areas:-

- Extending accident data to include more recent years and updating of probability functions within the model to reflect any changes.
- Modelling the effects of crash disruption and occupant injuries in substantially more detail, using some form of injury severity scale.
- Use of three dimensional flame envelope and solid flame emissivity calculations for external fire model. This could then be used to model fuselage burnthrough more accurately in three dimensions.
- Analyse the possible significance of aircraft design configuration in accident survivability and modify generation of crash effects and fire characteristics, if appropriate.
- Introduce airline fleet information, aircraft utilisation levels, accident rates and their anticipated rates of change to enable analysis of future safety trends on a global level.

10.2.2 Safety Studies that could be Undertaken with Model

Potentially, many issues within aircraft fire safety could be investigated with the analysis model. Currently, the most important areas in which further knowledge is needed are interpreted as being:-

- Studying implications associated with the future introduction of new very large aircraft designs.
- Quantifying the expected benefits of fire safety improvements that are gradually being applied to the world's airline fleet over coming years.
- Examining the safety potential that exists for introducing fire hardening materials and associated improvements in the detailed design of airliner fuselages.
- Determining the role that airport fire and emergency rescue services might be expected to play in future aircraft accidents.
- Evaluating the potential consequences of making Type III overwing exits more straightforward for passengers to operate.
- Re-examining the effectiveness of cabin water mist sprays, in the light of the search for a suitable replacement for Halon in engine and cargo hold fire suppression systems.

10.2.3 Research within the Field of Aircraft Safety

In addition to suggestions for further work in the current study, it is possible to make some recommendations for activities to be undertaken in associated areas of research. Some of the more important of these include:-

- The establishment of a unified database of aircraft accident information and statistics, based on standard definitions and made available to qualified researchers world-wide.
- Development of a technique suitable for quantifying the approximate severity and associated consequences of aircraft crashes.
- The making of greater moves towards integrating experimental research being undertaken into different aspects of aircraft accident survivability.
- Formulation of better methods and quantitative tools for performing risk assessment analysis in the area of aircraft safety.
- The undertaking of experimental investigations into evacuation of passengers from wide body aircraft and exits located on upper decks.
- Investigation of injury types that are received in aircraft crashes and their effects on the faculties and mobility of accident victims.

10.3 Conclusions

The main points to have emerged from the study can be summarised as follows:-

- (1) The work described in this thesis has led to the creation of a computer-based risk assessment model, suitable for the purpose of analysing key issues in aircraft fire safety.
- (2) The direction that the research took was largely determined by findings obtained from the undertaking of an extensive survey of past aircraft fire accidents.

- (3) The historical study indicated that fire survivability tends to be governed by the interactions that occur between crash effects, fire ingress into the passenger cabin and the efficiency of occupant evacuation.
- (4) Consequently, it was necessary for each of these three factors to be considered in a balanced and integrated manner within the risk assessment analysis.
- (5) Experimental research undertaken in the area of aircraft safety can provide valuable insights into many aspects of accident survival; however, the emphasis of scientific studies does not always match circumstances that were found to be most likely to occur in real incidents.
- (6) Many features of aircraft fire accidents are extremely difficult to quantify or understand. As a result of this, it is usually far from straightforward to determine the effectiveness of either current or proposed new safety policies.
- (7) In order to deal effectively with these problems, knowledge must be combined from across all available sources, including the study of past events, experimental investigation, analytical simulation and expert judgement.
- (8) A computer-based simulation methodology was adopted in order to construct this type of holistic analysis. The resulting tool functions by stochastically generating aircraft accident scenarios and determining their outcomes in terms of occupant survival rates.
- (9) The use of this approach resulted in an analysis that is both explicit in detail and systematic in coverage. Consequently, where gaps in understanding are revealed, they are clearly identifiable and forced to be positively accounted for.
- (10) In order to encapsulate the most significant features of aircraft fire accidents and represent the relationships that exist between them, it was necessary to formulate the analysis in a lower level of detail than is typically used in scientific applications of computational simulation.
- (11) Because of the number and complex nature of the interactions being modelled, the use of an animated graphical display was found to be invaluable, both during programme development and for conveying the workings of the model to unacquainted observers.
- (12) It was also concluded that a full range of accident types needed to be processed if the undertaking of risk assessment studies was to be feasible. This then implied that it was necessary for simulations to run in near to real time, if the tool was to fulfil its intended purpose.
- (13) Initial testing of the model has clearly demonstrated that it is possible to create statistically representative accident scenarios and then predict with reasonable accuracy how casualties are likely to be incurred as a result of the effects of fire.
- (14) By quantifying trends in the outcomes of large numbers of accidents, the tool can be used to test the significance of new developments or changes in policy within the area of aircraft fire safety.
- (15) The model can also be configured to investigate a particular type of accident scenario, specific details in one aspect of the analysis, or related areas of safety such as certification evacuation trials.

(16) Overall, the study has contributed a new approach to the analysis of aircraft fire safety, integrating much of the best information that is currently obtainable from across the various research disciplines involved in the form of a single holistic risk assessment tool.

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Appendix A: Preliminary Accident Database

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DATE	AIRCRAFT TYPE	LOCATION	COUNTRY	AIRLINE	NATIONALITY	NUMBER KILLED	NUMBER INJURED	MINOR/NHARMED	PHASE OF FLIGHT	AIRPORT DISTANCE	VISIBILITY	TERRAIN	FIRE TYPE	FIRE FATALITIES	SIGNIFICANT IMPACT	FUSELAGE DISRUPTION	OTHER NOTES
580809	VISCOUNT 748D	BENINA	LIBYA	CENTRAL AFRICAN	RHODESIA	36	18	0	INITIAL APPROACH	6	DARK	HIGH GROUND	BTHROUGH	8	YES	YES	HIT GROUND AND CRASHED ON APPROACH. CLOUDY.
590217	VISCOUNT 794D	GATWICK	UK	THY	TURKEY	14	9	1	FINAL APPROACH	3	FOG	WOODED	IMPACT?	14	YES	YES ?	CRASHED INTO WOOD DURING FINAL APPROACH. FOG. TURKISH PRIME MINISTER WAS ONE OF SURVIVORS. NO TECHNICAL FAULTS FOUND.
600107	VISCOUNT 802	HEATHROW	UK	BEAC	UK	0	0	59	LANDING	0	FOG	AIRPORT	BTHROUGH	0	YES	NO	NOSEGEAR COLLAPSED IN HARD LANDING IN POOR WEATHER. FIRE DESTROYED FUSELAGE.
600914	L-188A	NEW YORK LA G.	USA	AMERICAN	USA	0	0	76	LANDING	0	CLEAR	AIRPORT	EXTERNAL	0	YES	YES	HIT DYKE ON LANDING. INVERTED & WING TORN OFF. EVACUATED IN THREE MINUTES THROUGH 3/5 EXITS. FIRE BTHROUGH OCCURRED AFTER EVACUATION. GOOD DETAILS
610119	DC-8-21	NEW YORK IDLEWILD	USA	AERONAVES MEXICO	MEXICO	4	28	74	TAKEOFF	0.2	SNOW FOG	MARSHY FROZEN SNOW	BTHROUGH	4	YES	NO	OVERRAN AFTER ABANDONED TAKEOFF. HIT AIRFIELD BARRIER
610612	L-188C	CAIRO	UAR	KLM	NETHERLANDS	20	16	0	FINAL APPROACH	2.6	FINE	HILL	IMPACT	15	YES	YES	CRASHED ON APPROACH (PILOT INATTENTION). FUSELAGE BROKE INTO 3 ON HILL GROUND; REAR SECTION ONLY IN FIRE.
610615	B-707/328	USBON	PORTUGAL	AIR FRANCE	FRANCE	0	0	103	LANDING	0	FINE	RUNWAY	BTHROUGH	0	YES	NO	HARD LANDING. NOSE GEAR COLLAPSED & FIRE. SPREAD TO HOLD #1 & FUSELAGE. ALL EVACUATED SAFELY. FIRE CREW REACTION NOT AS RAPID 'AS MIGHT HAVE BEEN EXPECTED'. ONE EXIT JAMMED
610711	DC-8-12	DENVER	USA	UNITED	USA	17	12	86	LANDING	0	FINE	AIRPORT	BTHROUGH	16	YES	NO	LEFT RUNWAY ON LANDING. ALL FIRE DEATHS. EVACUATION DETAILS. 3-6 EXITS USED
610712	IL-158	AKFA	MOROCCO	CESKOSLOVENSKE	CZECHOSLOVAKIA	72	0	0	INITIAL APPROACH	8	FOG	?	BTHROUGH	24	YES	YES	HIT POWER CABLES AND CRASHED INTO GROUND ON LET DOWN. FUSELAGE WHOLE BUT INVERTED. FIRE DEATHS OCCURRED
610923	F-27-100	ANKARA	TURKEY	TURKISH AIRLINES	TURKEY	28	0	1	DESCENT	11	?	HILL	IMPACT?	13	YES	YES ?	CRASHED INTO HILL AFTER USING INCORRECT APPROACH PROCEDURE. FOKKER STATED 13 FIRE FATS. ALL 28 FATS BURNT. ONE PAIR ESCAPED WITH MINOR INJURIES

DATE	AIRCRAFT TYPE	LOCATION	COUNTRY	AIRLINE	NATIONALITY	NUMBER KILLED	NUMBER INJURED	MINOR/DAMAGED	PHASE OF FLIGHT	AIRPORT DISTANCE	VISIBILITY	TERRAIN	FIRE TYPE	FIRE FATALITIES	SIGNIFICANT IMPACT	FUSELAGE DISRUPTION	OTHER NOTES
611221	COMET 4B	ANKARA	TURKEY	BRITISH EUROPEAN	UK	27	6	0	TAKEOFF	0	CLOUDY SNOW	SHALLOW SLOPE	IMPACT	21	YES	YES	STALLED ON TAKEOFF. INSTRUMENT FAILURE
620603	B-707-328	PARIS ORLY	FRANCE	AIR FRANCE	FRANCE	130	2	0	TAKEOFF	0.4	FINE	LEVEL	IMPACT	0	YES	YES	OUT OF TRIM TAKEOFF ABORTED AT HIGH SPEED. STRUCK OBSTACLES DURING OVER RUN
620708	VISCOUNT 812	AMARILLO	USA	CONTINENTAL	USA	0	0	16	TAKEOFF	1.4	FINE	LEVEL	BTHROUGH	0	YES	NO	HIT RUNWAY AFTER TAKEOFF. ENGINE FIRES & ABORTED. PILOT DISTRACTION
620722	BRITANNIA 314	HAWAII	USA	CANADIAN PACIFIC	CANADA	27	13	0	LANDING	0.2	FINE	LEVEL	IMPACT?	14?	YES	YES	ATTEMPTED GO AROUND AFTER ENGINE FAILURE. LOST CONTROL & CRASHED. FUSE BROKE IN TWO. ALL FATS IN FWD SECTION (FROM FIRE & IMPACT).
630703	CARAVELLE 6N	CORDOBA	ARGENTINA	ARGENTINAS	ARGENTINA	0	0	70	INITIAL APPROACH	4.4	CLOUDY	LEVEL	BTHROUGH	0	YES	NO	HIT TERRAIN ON FINAL APPROACH, KILLING 3 ON GROUND. WING FIRE. 2/4 EXITS JAMMED FIRE SPREAD "MINUTES LATER". EVACUATED SAFELY.
641123	B-707-331	ROME	ITALY	TWA	USA	50	19	4	TAKEOFF	0.2	FINE HAZY	?	BTHROUGH	50	YES	NO	REVERSE THRUST FAILURE ON ABORTED TAKEOFF. FUEL SPILLAGE & TANKS EXPLODED DURING EVACUATION. 3/6 EXITS USED. 17 FATS FROM THREE EXPLOSIONS.
650520	BOEING 720B	CAIRO	UAR	PAKISTAN	PAKISTAN	121	6	0	INITIAL APPROACH	4.4	FINE DARK	LEVEL	IMPACT	108	YES	YES	DESCENDED & CRASHED WHILST IN CIRCUIT. CAUSE UNKNOWN. WRECKAGE INVERTED. PIA FIRE FATS FIGURE.
651108	B-727-23	CINCINNATI	USA	AMERICAN	USA	58	4	0	FINAL APPROACH	2	POOR	WOODED HILLSIDE	IMPACT	14	YES	YES	CRASHED ON VISUAL APPROACH IN DETERIORATING WEATHER. FUSELAGE BROKE UP
651111	B-727-22	SALT LAKE CITY	USA	UNITED	USA	43	35	13	LANDING	0	FINE	LEVEL	BTHROUGH	43	YES	NO	RAPID DESCENT ON FINAL APPROACH. CRASH LANDED & FUEL LINES BROKEN. EVACUATED THRO' 4/5 EXITS. 3 TRAPPED IN TAIL FOR 23 MINS.
660215	CARAVELLE 6N	DELHI	INDIA	INDIAN AIRLINES	INDIA	2	14	64	LANDING	0	FOGGY	LEVEL	BTHROUGH	2	YES	NO	UNDERSHOT DURING ILS APPROACH. CRASHED ON AIRPORT & FIRE BROKE OUT IMMEDIATELY. ALL EVACUATED SUCCESSFULLY BEFORE FIRE CREW INTERVENTION AFTER 2-3MINS. (ONE OF "FAA 75")

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660304	DC-8-43	TOKYO	JAPAN	CANADIAN PACIFIC	CANADA	64	8	0	FINAL APPROACH	1	VERY POOR	LEVEL	IMPACT	8	YES	YES	64 FIRE FATS? MISJUDGED APPROACH IN POOR WEATHER. HIT SEA WALL AT AIRPORT. FUSELAGE BREAKS USED FOR EVACUATION. (ONE OF "FAA 75")
660422	L-188C	ARDMORE	USA	AMERICAN FLYERS	USA	83	15	0	FINAL APPROACH	1.5	LIGHT RAIN	SLIGHT SLOPE IN FOOTHILLS	IMPACT	12	YES	YES	PILOT INCAPACITATION DURING APPROACH (HEART ATTACK). ALL IMPACT FATALITIES? (FAA) 1.5NM FROM AIRPORT. (ONE OF "FAA 75")
660901	BRITANNIA 102	LJUBLJANA	YUGOSLAVIA	BRITANNIA	UK	98	19	0	FINAL APPROACH	1.2	GOOD	WOODED	IMPACT	22	YES	YES	LANDING UNDERSHOOT INTO WOODED AREA DUE TO MIS-SET ALTIMETER. 2.5KM FROM AIRPORT. FUSE BROKE. EVACUATION DETAILS - SOME EJECTED. (ICAO DATE)
661224	DC-8-51	MEXICO CITY	MEXICO	AERONAVES DE MEXICO	MEXICO	0	8	101	FINAL APPROACH	1	FOG	DRY LAKE	BTHROUGH?	0	YES	NO?	CRASH LANDED ON DRY LAKE DURING APPROACH. 8 PAX SERIOUSLY INJURED & AC DESTROYED.
670216	L-188C	MENADO	INDONESIA	INDONESIAN AIRWAYS	INDONESIA	22	12	58	LANDING	0	LIGHT RAIN	AIRFIELD	BTHROUGH	22	YES	NO	UNDERSHOT ON LANDING. GEAR COLLAPSED. STOPPED ON AIRFIELD. EVACUATED THROUGH 2 EXITS IN ~ 2MINS. PAX TRAPPED IN REAR CABIN. MAIN DOOR COULD NOT BE OPENED. PICTURES (ONE OF "FAA 75")
670228	F-27-100	BASAK	PHILIPPINES	PHILIPPINE AIRLINES	PHILIPPINES	12	7	0	FINAL APPROACH	0.9	FINE	LEVEL	IMPACT	0	YES	1	CG AFT OF LIMITS DURING LANDING. ALL IMPACT DEATHS. 7 SURVIVING PAX RECEIVED RANGE OF INJURIES.
670305	DC-8-33	MONROVIA	LIBERIA	VARG	BRAZIL	51	23	16	FINAL APPROACH	1	LIGHT FOG	LEVEL	IMPACT	28	YES	NO	45 FIRE FATS? UNDERSHOT & HARD IMPACT, KILLING 5 ON GROUND. 1NM FROM AIRPORT. FUSELAGE SPLIT & FIRE ENTERED. EVACUATION DETAILS: IN ~ 3MINS. 2/6 EXITS USED. (ONE OF "FAA 20")
670419	BRITANNIA 313	NICOSIA	CYPRUS	GLOBEAIR	THAILAND	126	4	0	FINAL APPROACH	1.8	LOW CLOUD THUNDERSTORM	HILLS	IMPACT	0	YES	YES	HIT TERRAIN DURING LOW APPROACH. FEW IMPACT/FIRE DETAILS
670427	F-27 200	MALAYBALAY	PHILIPPINES	PHILIPPINE AIRLINES	PHILIPPINES	19	0	0	INITIAL CLIMB	0.8	FAIR	HILLS	IMPACT	19	YES	YES	DEMONSTRATION FLIGHT. FOKKER FIRE FATS FIGURES. 2/19 DIED IN HOSPITAL.
670901	DC-9	OSAKA	JAPAN	KOREAN AIRLINES	SOUTH KOREA	0	0	72	DESCENT	0	.	AIRPORT	INTERNAL	0	NO	NO	TOTAL ELECTRICAL FAILURE & AVIONICS FIRE WHEN STARTING DESCENT. DENSE COCKPIT SMOKE (WINDOW OPENED). LANDED SAFELY ~ 10MINS AFTER 1ST WARNING.

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670909	B-707	FRANKFURT	FRG	PACIFIC WESTERN	USA	0	0	174	TAKEOFF	0	-	AIRPORT	EXTERNAL?	0	NO	NO	#3 ENGINE DISINTEGRATED ON TAKEOFF. EXTENSIVE DAMAGE & FUEL FIRE.
671106	B-707-131	CINCINNATI	USA	TWA	USA	1	10	25	TAKEOFF	0	FINE	AIRPORT	BTHROUGH	0	YES	NO	COLLISION ON TAKEOFF. EVACUATED 420' OFF RUNWAY. 3/8 EXITS USED. MAJOR FUSELAGE DISRUPTION IN ICAO DIG? (ONE OF "FAA 75")
671120	CV-880	KENTUCKY	USA	TWA	USA	70	12	0	FINAL APPROACH	1.4	LIGHT SNOW	TREES / PASTURE LAND	IMPACT	0	YES	YES	UNDERSHOT NIGHT TIME VISUAL APPROACH. HIT TREES & STOPPED 6900' SHORT OF RUNWAY. EVACUATION; AT LEAST ONE PAX USED FUSELAGE BREAKS.
680109	B-7208	BEIRUT	LEBANON	ETHIOPIAN	ETHIOPIA	0	?	?	LANDING	0	?	RUNWAY	EXTERNAL?	0	NO	NO	CAUGHT FIRE AFTER NOSEWHEEL COLLAPSED ON LANDING. 49 ON BOARD. (ONE OF "FAA 75")
680207	B-707-138B	VANCOUVER	CANADA	CANADIAN PACIFIC	CANADA	1	?	?	LANDING	0	?	AIRPORT	EXTERNAL?	0	YES	?	81 ON BOARD? LOST CONTROL ON LANDING, HITTING LIGHT AC AND A BUILDING. 1 AIRPORT EMPLOYEE FAT. SEE TRANSPORT CANADA SOURCE.
680216	B-727-92C	TAIPEI	TAIWAN	CIVIL AIR TRANSPORT	HONG KONG	21	42	0	INITIAL APPROACH	8	CLOUDY	?	IMPACT	21	YES	YES	IMPROPER APPROACH. STRUCK TREES & STOPPED 8NM FROM AIRPORT. FUSELAGE BROKEN.
680408	B-707-465	HEATHROW	UK	BOAC	UK	5	38	84	INITIAL CLIMB	0	CLEAR SUNNY	RUNWAY	BTHROUGH	5	NO	NO	NO.2 ENGINE FAILURE ON TAKEOFF. ENGINE DETACHED DURING APPROACH. EVACUATED ON RUNWAY; IN ~3MINS. 5 EXITS USED. FUEL TANK EXPLOSION INCREASED EXTENT OF FIRE DURING EVACUATION. (ONE OF "FAA 20")
680420	B-707-344C	WINDHOEK	SOUTH AFRICA	SOUTH AFRICAN AIRWAYS	SOUTH AFRICA	123	5	0	INITIAL CLIMB	3.5	FINE NIGHT	?	IMPACT	0	YES	YES	CONTROLLED FLIGHT INTO TERRAIN AFTER NIGHT TAKEOFF. BROKE UP & 2 SEPARATE FIRES.
680612	B-707-321	CALCUTTA	INDIA	PAN AM	USA	6	0	57	FINAL APPROACH	0.7	RAINY NIGHT	?	BTHROUGH?	6	YES	?	680613? SERIOUS INJURIES? UNDERSHOT DURING NIGHT LANDING IN RAIN. HIT TREE, CRASHED & CAUGHT FIRE. STOPPED 2000' SHORT OF RUNWAY & EVACUATED IN ~2MINS. (ONE OF "FAA 75")
680802	DC-8-43	MILAN	ITALY	ITALIA	ITALY	13	0	82	INITIAL APPROACH	7.5	THUNDER STORMS	?	IMPACT?	?	YES	?	SERIOUS INJURIES? HIT TERRAIN IN POOR VISIBILITY WHILST POSITIONING FOR APPROACH. SMOKE & FIRE PROBABLE.

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680810	FH-227B	CHARLESTON	USA	PIEDMONT	USA	35	2	0	FINAL APPROACH	0.1	DENSE FOG	AIRFIELD PERIMETER	IMPACT	0	YES	YES	FOG-BOUND UNDERSHOT APPROACH. HIT 30 DEGREE. SLOPE BEFORE COMING TO REST ON AIRFIELD BOUNDARY. 5 PAX THROWN CLEAR. 3 DIED IN HOSPITAL THE NEXT DAY. (ICAO DATE)
681224	CV-580	BRADFORD	USA	ALLEGHENY	USA	20	27	0	FINAL APPROACH	1.9	LIGHT SNOW	SHALLOW SLOPE TREES	IMPACT	0	YES	YES	UNDERSHOT NIGHT TIME VISUAL APPROACH
690105	B-727-112	GATWICK	UK	ARIANA	AFGHANISTAN	48	14	0	FINAL APPROACH	1.5	FREEZING FOG NIGHT	LEVEL TREES	IMPACT	41	YES	YES	62 ON BOARD. STRUCK TREES APPROACH. STOPPED ~ 1.5NM SHORT OF AIRPORT. PAX EVACUATED THROUGH BREAKS & FWD WINDOW IN ~ 3MINS.
690106	CV-580	BRADFORD	USA	ALLEGHENY	USA	11	17	0	FINAL APPROACH	4.7	LIGHT SNOW NIGHT	TREES GOLF COURSE	IMPACT	7	YES	YES	UNDERSHOT APPROACH. CRASHED ON GOLF COURSE, INVERTED. GOOD ESCAPE DETAILS.
690407	VISCOUNT 757	SEVEN ISLANDS	CANADA	AIR CANADA	CANADA	1	7	7	INITIAL CLIMB	0	-	RUNWAY	BTHROUGH	0	NO	NO	ENGINE WHEEL WELL FIRE AFTER TAKEOFF. AC DESTROYED BY FIRE AFTER LANDING. TRANSPORT CANADA SOURCE. LOST CONTROL OF #1 ENGINE & BRAKE FAILED. AC CIRCLED & ONE PAX RUN OVER. 20 OTHERS ON BOARD.
690726	CARAVELLE 6N	BISKRA	ALGERIA	AIR ALGERIEE	ALGERIA	35	2	0	EN ROUTE	-	?	?	INTERNAL	1	YES	YES	IN-FLIGHT 'EMERGENCY' (ELECTRICAL COMPARTMENT FIRE). ATTEMPTED LANDING & CRASHED ~18MINS AFTER 1ST WARNING. ~3NM FROM AIRPORT. 32 FIRE FATS? EVACUATED IN ~ 3MINS. FRANK TAYLOR HAS FRENCH REPORT. (ONE OF "FAA 75")
690817	BAC 1-11 320	HANOVER	FRG	LAKER	UK	0	0	89	EN ROUTE	-	FINE	RUNWAY	INTERNAL	0	NO	NO	IN-FLIGHT FIRE DURING CRUISE AT 25,000'. PROBABLE ELECTRICAL DISCHARGE IN VICINITY OF RADIO ANTENNA LEAD. COCKPIT SMOKE RESULTED IN EMERGENCY LANDING AFTER 10MINS. PAX OXYGEN SYSTEM BURNED THROUGH & CONTRIBUTED TO FIRE.
690912	BAC 1-11 402	MANILA	PHILIPPINES	PAL	PHILIPPINES	45	2	0	FINAL APPROACH	2	?	HILL	IMPACT	07	YES	YES	HIT HILL DURING APPROACH. CRASHED & CONSUMED BY FIRE.
690917	CV-580	CAMPBELL RIVER	CANADA	PACIFIC WESTERN	USA	4	11	0	FINAL APPROACH	3	CLOUDY	TREES HILL	BTHROUGH	2	YES	YES	CRASHED INTO HILL & FUEL FIRE. FUSELAGE SEPARATED & REMAINED INTACT. COCKPIT CRUSHED; 2 FIRE DEATHS. PAX EVACUATED THROUGH REAR EXITS.
691120	VC-10 1101	LAGOS	NIGERIA	NIGERIA AIRWAYS	NIGERIA	87	0	0	INITIAL APPROACH	8	FOGGY	TREES	IMPACT	62	YES	YES	44 FIRE FATS? HIT TREES DURING APPROACH. CRASHED & BROKE UP 8NM FROM AIRPORT. FIRE CONSUMED MAIN PART OF FUSELAGE.

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700331	CARAVELLE III	CASABLANCA	MOROCCO	ROYAL AIR MAROC	MOROCCO	61	21	0	INITIAL APPROACH	6	?	?	?	?	YES	?	82 ON BOARD. 62 FAT? 700401?
700419	DC-8 62	ROME	ITALY	SAS	DENMARK	0	12	53	TAKEOFF	0	?	RUNWAY	EXTERNAL?	0	NO	NO	65 ON BOARD. UNCONTAINED ENGINE FAILURE ON TAKEOFF. EVACUATED IN 31-60S. ALL EXITS USED. (ONE OF "FAA 75")
700506	VISCOUNT 785D	MOGADISCIO	SOMALIA	SOMALI AIRLINES	SOMALIA	5	11	14	FINAL APPROACH	0	-	RUNWAY	INTERNAL	5	YES	NO	UNDER FLOOR FIRE DURING APPROACH. LOSS OF CONTROL -2MINS AFTER 1ST WARNING; HEAVY CRASH LANDING ON AIRFIELD. BURNT OUT. EVACUATED. MAIN AFT DOOR USED. (ONE OF "FAA 75")
700509	F-27-100	ILLIGAN	PHILIPPINES	PAL	PHILIPPINES	1	32	0	TAKEOFF	0	ZERO VISIBILITY	AIRPORT	BTHROUGH?	0	YES	?	33 ON BOARD. EVACUATED BEFORE AC DESTROYED BY FIRE.
700818	TU-124	ZURICH	SWITZERLAND	CSA	CZECHOSLOVAKIA	0	0	20	LANDING	0	?	RUNWAY	EXTERNAL?	0	YES	NO?	LANDED WITH UC RETRACTED (CREW FORGOT TO EXTEND). "FIRE BROKE OUT".
701127	DC-8-63CF	ANCHORAGE	USA	CAPITOL INTERNATIONAL	USA	47	49	133	TAKEOFF	0.7	LIGHT FREEZING DRIZZLE	EMBANKMENT	BTHROUGH?	47	YES	YES	229 ON BOARD. UNSUCCESSFUL TAKEOFF ON ICE WITH WHEELS LOCKED. WING ROOT FIRE. TANKS EXPLODED DURING ~3MIN EVACUATION. 6 EXITS USED (1 ONLY PARTIAL OPENED). FUSELAGE BREAKS AT ROWS 6 & 37, OTHERWISE INTACT. 3400' OFF RUNWAY (ONE OF "FAA 20")
701228	B-727 200	ST THOMAS	VIRGIN ISLANDS	TRANS CARIBBEAN	USA	2	12	41	LANDING	0.1	FINE	HILLSIDE	BTHROUGH	2	YES	YES	BOUNCED ON LANDING. EVACUATED IN ~60SECS. 300' OFF RUNWAY. 2 EXITS USED + 31 PAX BY FUSELAGE BREAK. 2 PAX BURNED TO DEATH & 1 TRAPPED. SMALL FIRE TOOK SEVERAL MINUTES TO DEVELOP INTO GENERAL CONFLAGRATION. (ONE OF "FAA 20")
701231	F-27-200	SHAMSHER-NAGER	PAKISTAN	PIA	PAKISTAN	7	28	0	FINAL APPROACH	?	?	?	BTHROUGH?	7	YES	?	SERIOUS INJURIES? FOKKER SOURCE. WAAS: 'CRASHED OUT & BURNED ON LANDING'. STOPPED SHORT OF RUNWAY. PIA SOURCE STATE 11/18 KILLED.
710523	TU-134A	RIJEKA	YUGOSLAVIA	AVIOGENEX	YUGOSLAVIA	78	0	5	LANDING	0	HEAVY RAIN TORRENTS	AIRPORT	BTHROUGH	78	YES	YES	CRASHED AFTER ATTEMPTED HEAVY LANDING IN POOR WEATHER AT 260KM/H. RIGHT WING BROKE OFF & AC OVERTURNED. AC BURNT OUT IN THE ENSUING FIRE.
710607	CV-580	NEW HAVEN	USA	ALLEGHENY	USA	28	3	0	FINAL APPROACH	0.8	ADVERSE WEATHER CONDITIONS	NEAR BEACH	BTHROUGH	27	YES	NO	STRUCK BUILDINGS ON APPROACH. BULK OF FUSELAGE REMAINED INTACT. EVACUATED IN ~30SECS. 1 OVERWING EXIT USED. FUEL EXPLOSIONS. (ONE OF "FAA 20")

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720418	SUPER VC-10 1154	ADDIS ABABA	ETHIOPIA	EAST AFRICAN	ETHIOPIA	43	15	49	TAKEOFF	0.1	FINE	AIRPORT	BTHROUGH	43	YES	YES	BRAKE FAILURE AFTER ABANDONED TAKEOFF. HIT OBSTACLE & FIRE EVACUATION 100M OFF RUNWAY. "LH EXITS JAMMED BY IMPACT, RH BLOCKED BY FIRE." ALL PAX USED FUSELAGE BREAK; COMPLETED IN ~3MINS. 33 FIRE FATS? (ONE OF "FAA 75")
720518	DC-9-31	FORT LAUDERDALE	USA	EASTERN	USA	0	0	10	LANDING	0	HEAVY RAIN	ON RUNWAY	BTHROUGH?	0	YES	YES	HARD LANDING. UC FAILED & TAIL SECTION SEPARATED. 1 EXIT USED. AC DESTROYED BY SUBSEQUENT GROUND FIRE.
720614	DC-8-53	NEW DELHI	INDIA	JAS	JAPAN	82	4	1	FINAL APPROACH	?	HAZY	RIVER BANK	IMPACT?	0?	YES	?	CRASHED ON APPROACH, KILLING 4 ON GROUND. JAL LETTER (FRANK TAYLOR)
720813	B-707	NEW YORK	USA	JAT	JAPAN	0	0	186	TAKEOFF	0	?	AIRPORT	EXTERNAL?	0	YES	NO?	OVERRAN AFTER ABANDONED TAKEOFF. PORT WING & ENGINE DAMAGED BY FIRE. SUCCESSFUL EVACUATION. FIRE CREWS INTERVENED AFTER ~4MINS & EXTINGUISHED FLAMES.
721128	DC-8-62	MOSCOW	USSR	JAS	JAPAN	62	14	0	INITIAL CLIMB	1	?	AIRPORT	IMPACT	54	YES	YES	ENGINE FAILURE OR INADVERTENT SPOILER DEPLOYMENT AFTER TAKEOFF. BROKE UP & CAUGHT FIRE. LITTLE DETAIL IN WAAS. JAL'S OWN FIRE FATS. ESTIMATE.
721208	B-737-222	CHICAGO MIDWAY	USA	UNITED	USA	43	12	6	FINAL APPROACH	1.5	OVERCAST	RESIDENTIAL AREA	BTHROUGH	27	YES	YES	STRUCK BUILDINGS ON APPROACH. STOPPED 1.5NM FROM RUNWAY FUEL FIRE AT CENTRE SECTION. EVACUATED THRO AFT SERVICE DOOR + 6 PAX USED FUSELAGE BREAKS. TOOK ~3MINS; 1 PAX HAD TO BE EXTRACTED. (ONE OF "FAA 20")
721220	DC-9-31	CHICAGO O'HARE	USA	NORTH CENTRAL	USA	10	10	25	TAKEOFF	0	FOG	RUNWAY	BTHROUGH	10	YES	NO	RUNWAY COLLISION IN POOR VISIBILITY. DC-9 BURNT & EVACUATED ON AIRPORT IN ~90SECS. FWD & 2 FWD OVERWING EXITS USED. 2 PAX FOUND IN TAIL SECTION (1 FATAL). CV-880 DAMAGED. (ONE OF "FAA 20")
721223	F-28-1000	OSLO	NORWAY	BRAATHENS	NORWAY	40	5	0	FINAL APPROACH	?	?	FOREST	IMPACT	20?	YES	YES	45 ON BOARD. 6 SURVIVORS THROWN OUT OF FUSE BEFORE FIRE STARTED (FOKKER). FRANK TAYLOR'S FIRE FATS ESTIMATE.
721229	L-1011-1	MIAMI	USA	EASTERN	USA	99	77	0	INITIAL APPROACH	18	CLEAR	SWAMP	IMPACT	0	YES	YES	CRASHED ON APPROACH AT NIGHT. CREW DISTRACTED BY MINOR FAILURE. GOOD IMPACT DETAIL
730122	B-707 320C	KANO	NIGERIA	ALJA	JORDAN	176	0	26	LANDING	0	?	AIRPORT	BTHROUGH?	176	YES	NO?	SERIOUS INJURIES? UC FAILED ON LANDING. AC SWERVED OFF RUNWAY. AC CAUGHT FIRE & WAS DESTROYED. EVACUATED THRO FWD LEFT & AFT GALLEY EXITS IN ~ 60SECS. (ONE OF "FAA 75")

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730219	TU-154	PRAGUE	CZECHOSLOVAKIA	AEROFLOT	USSR	66	18	16	FINAL APPROACH	0.3	LIGHT SNOW	OFF AIRPORT	IMPACT	51	YES	YES	CRASHED ON FINAL APPROACH. CAUSE UNDETERMINED. FIRE & IMPACT DETAIL
730410	VANGUARD 952	BASIL	SWITZERLAND	INVICTA	UK	108	36	1	INITIAL APPROACH	9.5	HEAVY SNOW SHOWER	WOODED HILL	IMPACT?	5	YES	YES	SERIOUS PAX INJURIES? HIT HILL AFTER TWO UNSUCCESSFUL APPROACHES. SEE AAR 11/75.
730531	B-737-200	PALAM	INDIA	INDIAN AIRLINES	INDIA	48	0	17	FINAL APPROACH	1.1	?	?	IMPACT?	24	YES	YES	SERIOUS INJURIES? UNDERSHOT ON APPROACH. CRASHED INTO TREES 1.8KM FROM AIRPORT. DESTROYED BY IMPACT & POST IMPACT FIRE. (ONE OF "FAA 75")
730621	DC-8-63	BANGOR	USA	OVERSEAS NATIONAL	USA	0	3	247	TAKEOFF	0	?	RUNWAY	EXTERNAL	0	NO	NO	TYRE FAILURE & UC FIRE ON TAKEOFF. PORT SIDE OF FUSELAGE & WING SEVERELY DAMAGED. 3 PAX SERIOUSLY INJURED DURING EVACUATION.
730711	B-707-345C	PARIS ORLY	FRANCE	VARIG	BRAZIL	123	11	0	FINAL APPROACH	2.7	?	?	INTERNAL	116	YES	NO	IN-FLIGHT FIRE IN TOILET COMPARTMENT. CRASH LANDING ~6MINS AFTER 1ST WARNING, 5KM SHORT OF RUNWAY & SLID ON BELLY FOR 500M. EVACUATED THRO 2 FWD EXITS. 122 (+ADREPS) (ONE OF "FAA 20")
730723	FH-227B	ST LOUIS	USA	OZARK	USA	39	6	0	FINAL APPROACH	2.3	THUNDERSTORM	TREES	IMPACT	0	YES	YES	45 ON BOARD. DOWN DRAUGHT ON APPROACH. CRASHED INTO TREES 2.3NM FROM AIRPORT. ALL IMPACT DEATHS? SURVIVORS EJECTED & RESCUED. SCATTERED SMALL FIRES. (ONE OF "FAA 75")
730731	DC-9-31	BOSTON	USA	DELTA	USA	88	1	0	FINAL APPROACH	0	FOG	AIRPORT	IMPACT	44	YES	YES	CRASHED INTO SEAWALL AFTER UNSTABILIZED & NON-STANDARD APPROACH. STOPPED ON AIRPORT. NO FIRE FATS? POOR WEATHER
731217	DC-10-30	BOSTON	USA	IBERIA	SPAIN	0	4	164	FINAL APPROACH	0	RAIN & FOG	AIRPORT	EXTERNAL	0	YES	YES	HIT APPROACH LIGHTS DURING LANDING. UC SHEARED OFF BY EMBANKMENT & AC SKIDDED OFF RUNWAY. EVACUATED THRO 4/8 EXITS; 4 USED BREAKS & 1 PAX HAD TO BE RESCUED.
731220	B-707-3308	NEW DELHI	INDIA	LUFTHANSA	FRG	0	3	106	FINAL APPROACH	?	HAZE/FOG	?	BTHROUGH?	0	YES	NO	731219? UNDERSHOT & HIT MIDDLE MARKER HUT. FUEL FIRE IN LEFT WING. EVACUATED. RHS EXITS USED. (ONE OF "FAA 75")
731223	CARAVELLE 6R	MANAUS	BRAZIL	CRUZEIRO	BRAZIL	0	7	51	LANDING	0	?	EMBANKMENT	EXTERNAL?	0	YES	NO?	OVERRAN AFTER LATE TOUCHDOWN & AQUAPLANING. RAN DOWN SLOPE 15M BELOW RUNWAY.

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740101	F-28-1000	TORINO	ITALY	ITAVIA	ITALY	38	1	3	FINAL APPROACH	2	FOG & RAIN	?	BTHROUGH	38	YES	YES	CRASHED ON POOR WEATHER APPROACH. PORT WING CAUGHT FIRE. CAME TO REST INVERTED 2NM FROM AIRPORT. INTACT FUSELAGE BURNT THROUGH. EVACUATED THROUGH FUSELAGE BREAKAGES + PAX EJECTED.
740116	B-707-131B	LOS ANGELES	USA	TWA	USA	0	8	55	LANDING	0	FOG	AIRPORT	BTHROUGH	0	YES	NO	NOSEGEAR COLLAPSED DURING NIGHT LANDING. ALL EVACUATION INJURIES. 6/6 EXITS USED; FUSELAGE DESTROYED BY FIRE.
740126	F-28-1000	CUMAOVASI	TURKEY	THY	TURKEY	66	7	0	TAKEOFF	0	MIST	AIRPORT	IMPACT	50?	YES	YES	STALLED ON TAKEOFF. ICING ON WINGS. BROKE UP ON IMPACT ON AIRPORT. PAX EJECTED & EVACUATION THROUGH FUSELAGE BREAKS. 2 DOORS DETACHED. SURVIVORS BADLY BURNT. FRANK TAYLOR'S FIRE FATS ESTIMATE.
740130	B-707-321B	PAGO PAGO	AMERICAN SAMOA	PAN AM	USA	96	5	0	FINAL APPROACH	0.8	HEAVY RAINSTORM	UNEVEN GROUND	BTHROUGH?	96	YES	NO	UNDERSHOT INTO TREES 3900' FROM AIRPORT. EXTERNAL FUEL FIRE ON STARBOARD SIDE. EVACUATED THROUGH LEFT OVERWING EXIT ONLY. (ONE OF "FAA 20"). 1 CREWMEMBER USED HOLE. CROWDING PREVENTED EXIT OPENING?
740315	CARAVELLE 1083	TEHERAN	IRAN	STERLING	SWEDEN	15	0	81	TAKEOFF	0	-	RUNWAY	BTHROUGH	15	YES	NO	UC COLLAPSE DURING TAKEOFF TAXI. RIGHT WING FUEL FIRE. EVACUATED THROUGH 2 LHS EXITS ONLY IN ~2MINS. (ONE OF "FAA 75")
740907	F-27-600	BRANTI	INDONESIA	GARUDA	INDONESIA	33	3	0	LANDING	0	HEAVY RAIN	BUILDING	IMPACT?	?	YES	?	FOKKER SOURCE STATES 28 FATS. HIT BUILDING WHILST ATTEMPTING TO LAND IN BAD WEATHER.
740911	DC-9-31	CHARLOTTE	USA	EASTERN	USA	70	11	1	FINAL APPROACH	3.3	FOG	TREES	IMPACT	39	YES	YES	UNDERSHOT INTO TREES 3.3 NM FROM AIRPORT. FUEL FIRE. EVACUATED THROUGH FUSELAGE HOLES IN ~60SECS. SOME WERE EJECTED. (ONE OF "FAA 75")
741105	DC-9-31	BOSTON	USA	ALLEGHENY	USA	0	0	38	FINAL APPROACH	0	-	RUNWAY	INTERNAL	0	NO	NO	ELECTRICAL FIRE DURING APPROACH. EMERGENCY LANDING AFTER 8 MINS. CABIN PRESSURE PREVENTED DOORS FROM BEING OPENED FOR 2 MINS BY EMERGENCY SERVICES. EVACUATION DETAILS. (ICAA SUMMARY)
741120	B-747-130	NAIROBI	KENYA	LUFTHANSA	FRG	59	54	44	TAKEOFF	1	?	?	BTHROUGH	16	YES	YES	STALLED AFTER TAKEOFF WITH SLATS RETRACTED. IMPACT & FIRE. STOPPED 1NM OFF RUNWAY. EVACUATION DETAILS. 2 RHS EXITS USED. SOME EJECTED & OTHERS USED HOLES. TOOK ~3MINS. (ONE OF "FAA 75")
750624	B-727-225	NEW YORK JFK	USA	EASTERN	USA	113	11	0	FINAL APPROACH	0.1	VERY STRONG THUNDERSTORM	STREET	IMPACT	13	YES	?	HIT APPROACH LIGHTS AFTER WINDSHEAR. STOPPED 700' BEYOND RUNWAY. FUSELAGE DESTROYED. ALL SURVIVORS RESCUED.

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750830	F-27B	ST LAWRENCE	USA	WIEN ALASKA	USA	10	3	19	INITIAL APPROACH	0.8	SEA FOG	MOUNTAINS/DE	IMPACT	0.8	YES	YES	CRASHED INTO MOUNTAIN IN BAD WEATHER. DESTROYED BY IMPACT AND POST CRASH FIRE. (ONE OF "FAA 75")
750924	F-28-1000	PALEMBANG	INDONESIA	GARUDA	INDONESIA	25	0	36	FINAL APPROACH	1.2	FOG	TREES	IMPACT	1.1	YES	YES	SERIOUS INJURIES? STRUCK TREE ON APPROACH & CRASHED. SMOKE & FIRE PROBABLE.
751112	DC-10-30	NEW YORK JFK	USA	OVERSEAS NATIONAL	USA	0	2	137	TAKEOFF	0	-	RUNWAY	BTHROUGH	0	YES	0	ENGINE BIRD INGESTION ON TAKEOFF. ABORTED & UC COLLAPSED. EVACUATED. RIGHT WING FIRE. RH FRONT EXIT USED. INCLUDED IN CAA ANALYSIS.
751130	DC-9	PRAGUE	CZECHOSLOVAKIA	?	?	76	?	?	?	?	?	?	?	0	YES	?	120 ON BOARD
751222	B-707-331	MILAN MALPENSA	ITALY	TWA	USA	0	9	116	LANDING	0	FOG	FIELD	EXTERNAL	0	YES	YES	MISSED RUNWAY WHILST ATTEMPTING TO LAND IN FOG. ENGINES & UC TORN OFF.
760405	B-727-81	KETCHIKAN	USA	ALASKA AIRWAYS	USA	1	32	17	LANDING	0.1	LOW VISIBILITY	RAVINE	IMPACT	0	YES	YES	OVERRAN INTO RAVINE 700' BEYOND RUNWAY ON LANDING. SLOW FIRE SPREAD. EVACUATED. MAIN DOOR, PORT WING EXITS & 6 USED FUSE HOLES. (ONE OF "FAA 75")
760427	B-727-35	ST THOMAS	VIRGIN ISLANDS	AMERICAN	USA	37	22	29	TAKEOFF	0.2	ADVERSE WIND CONDITIONS	AGAINST BUILDING	IMPACT	22	YES	YES	OVERRAN 1000' ON LANDING. RIGHT WING FIRE ENTERED CABIN THROUGH FUSELAGE BREAKS. EVACUATED IN 1-1.3MINS. LH OVERWING EXITS + MANY USED FUSELAGE BREAKS. (ONE OF "FAA 75")
760604	L-188A	GUAM	GUAM	AIR MANILA	PHILIPPINES	45	0	0	TAKEOFF	1	?	RESIDENTIAL AREA	IMPACT	34	YES	YES	ENGINE FAILURE ON TAKEOFF. CRASHED INTO HIGH GROUND 4900' FROM AIRPORT. 34 PAX KILLED BY SMOKE & BURNS. (ONE OF "FAA 75")
761116	DC-9-14	DENVER	USA	TEXAS INTERNATIONAL	USA	0	0	86	TAKEOFF	0	?	RUNWAY APPROACH LIGHTS	BTHROUGH	0	YES	NO	REJECTED TAKEOFF. LEFT WING FIRE. ALL EVACUATED IN 2MINS. ALL 5 EXITS EXCEPT LH OVERWING USED. (ONE OF "FAA 75")
761225	B-707-366C	BANGKOK	THAILAND	EGYPTAIR	EGYPT	52	0	0	FINAL APPROACH	1.2	BROKEN LOW CLOUDS	FACTORY	IMPACT	49	YES	YES	CRASHED INTO FACTORY ON APPROACH, 2KM FROM AIRPORT. 19 KILLED ON GROUND. SURVIVABLE?

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770302	B-707-320	BAGHDAD	IRAQ	IRAQI	IRAQ	0	0	60	LANDING	0	SANDSTORM	RUNWAY	EXTERNAL?	0	NO?	NO	LANDED IN BAD VISIBILITY. #4 ENGINE STRUCK RUNWAY. RH WING FIRE. ALL EVACUATED SAFELY. (ONE OF "FAA 75")
770327	B-747-121	TENERIFE	SPAIN	PAN AM	USA	335	59	2	TAKEOFF	0	LOW CEILING & FOG	RUNWAY	IMPACT	192	YES	1	KLM HIT PAN AM DURING UNAUTHORISED TAKEOFF. FIRE DEATHS: 192 (OR 322?). IMPACT: 135. EVACUATED THROUGH 2 FUSE BREAKS IN 1 MIN. (ONE OF "FAA 20")
770327	B-747-206B	TENERIFE	SPAIN	KLM	NETHERLANDS	248	0	0	TAKEOFF	0	LOW CEILING & FOG	RUNWAY	IMPACT	196	YES	1	KLM HIT PAN AM DURING UNAUTHORISED TAKEOFF. FIRE DEATHS: 196 (OR 245 ?). IMPACT: 52. (ONE OF "FAA 20")
770404	DC-9-31	NEW HOPE	USA	SOUTHERN	USA	63	22	0	EN ROUTE	-	THUNDER STORM	HIGHWAY	IMPACT	29	YES	YES	BOTH ENGINES STALLED IN HEAVY PRECIPITATION. SUMMARY NOTE. CRASHED INTO PETROL STATION. SMOKE & BURNS: 20 FATS. BURNS & IMPACT: 9. REMAINDER: IMPACT ONLY. EVACUATION & RESCUE THROUGH FUSELAGE HOLES ONLY. (ONE OF "FAA 75")
770927	DC-8-62H	KUALA LUMPUR	MALAYSIA	JAL	JAPAN	34	42	3	FINAL APPROACH	4	?	HILL	IMPACT?	17	YES	YES	UNDERSHOT & HIT HIGH GROUND 6NM FROM AIRPORT. PAX ESCAPED THROUGH HOLES IN FUSELAGE; TOOK 12MINS. MODERATE DAMAGE FORWARD; SEVERE AFT. (ONE OF "FAA 75")
771119	B-727-282	MADEIRA FUNCHAL	PORTUGAL	TAP	PORTUGAL	131	33	0	LANDING	0	HEAVY RAIN SHOWERS	EMBANKMENT	IMPACT	?	YES	YES	OVERRAN ON POOR WEATHER LANDING. HIT THRESHOLD LIGHTS & PLUNGED DOWN STEEP BANK 750' FROM RUNWAY. EXPLODED ON IMPACT & FUSELAGE WAS ENGULFED IN FLAMES. PAX EJECTED & USED FUSELAGE BREAKS. (ONE OF "FAA 75")
780211	B-737-275	CRANBROOK	USA	PACIFIC WESTERN	USA	42	5	2	LANDING	1	SNOW	DEEP SNOW	IMPACT	23	YES	YES	THRUST REVERSER DEPLOYED DURING ATTEMPTED GO AROUND. CRASHED 1NM BEYOND RUNWAY. MORE DAMAGE IN FWD SECTION. EVACUATED THROUGH RH REAR DOOR & BREAKS IN FUSELAGE IN ~ 5MINS. 11 FIRE FATS?
780215	B-707-329	TENERIFE	SPAIN	SABENA	BELGIUM	0	0	195	LANDING	0	?	AIRPORT	BTHROUGH?	0	YES	NO?	UNDERSHOT & HARD LANDING SHORT OF RUNWAY. NOSE UC COLLAPSED & AC DESTROYED BY FIRE.
780301	DC-10-10	LOS ANGELES	USA	CONTINENTAL	USA	2	31	167	TAKEOFF	0.1	RAIN	AIRPORT PERIMETER	BTHROUGH	2	YES	NO	MULTIPLE TIRE FAILURE ON TAKEOFF. STOPPED 850' OFF RUNWAY. FUEL FIRE & EVACUATION DETAILS. ALL 4 RH EXITS USED; FIRE BLOCKED 3 RH-S EXITS. EVAC. TOOK 3MINS. (ONE OF "FAA 20")
780303	DC-8-63	SANTIAGO	SPAIN	IBERIA	SPAIN	0	52	170	LANDING	?	RAIN	AIRPORT	BTHROUGH?	0	YES	?	OVERRAN ON LANDING DROPPING INTO A HOLLOW 20M DEEP & CAUGHT FIRE. AQUAPLANING? (ONE OF "FAA 75")

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780521	B-727-100	KENTUCKY	USA	AMERICAN	USA	0	3	101	LANDING	0	?	RUNWAY	EXTERNAL	0	NO	NO	#1 ENGINE FIRE AFTER TAKEOFF. LANDED SAFELY. 1:59 EVACUATION. ALL EXITS & SLIDES USED. SLIDE COLLAPSED (BIG PASSENGER). PAX OPENED WING & REAR EXITS & JUMPED OFF WING (14 INJ). "PANIC DURING EVACUATION" - (ADREPS)
780803	B-707-351	BUENOS AIRES	ARGENTINA	LAN	ARGENTINA	0	0	63	FINAL APPROACH	1.5	?	?	BTHROUGH?	0	YES	NO?	HIT TREES WHILST ON FINAL APPROACH. GENTLE DESCENT & AC DESTROYED BY IMPACT & FIRE.
780824	B-737	BUENOS AIRES	ARGENTINA	AEROLINEAS ARGENTINAS	ARGENTINA	0	0	105	LANDING	0	NIGHT TIME	RUNWAY	EXTERNAL	0	YES	NO	LANDING AT NIGHT WITH UC RETRACTED. ENGINE FIRES EXTINGUISHED BY FIRE CREWS. PAX EVACUATED; 6 RECEIVED MINOR INJURIES INCLUDING ONE WITH 2ND DEGREE BURNS.
781001	DC-9-40	OITA	JAPAN	TOA DOMESTIC	JAPAN	0	1	112	EN ROUTE	-	?	RUNWAY	INTERNAL	0	NO	NO	PASSENGER STARTED TOILET FIRE WITH LPG GAS. CABIN SMOKE & EXTINGUISHED. PAX BREATHED THROUGH WET TOWELS. SAFE EMERGENCY LANDING. (ADREPS)
781115	DC-8-63CF	COLUMBO	SRI LANKA	LOFTLEIDER	ICELAND	183	0	79	FINAL APPROACH	1	LOW CLOUD & THUNDERS TORMS	?	IMPACT?	?	YES	?	SMOKE & FIRE PROBABLE. CRASHED DURING NIGHT TIME APPROACH 1NM SHORT OF RUNWAY. MIS-SET ALTIMETER & DOWNDRAUGHTS. NO CRASH DETAILS IN WAAS.
781217	B-737-200	HYDERABAD	INDIA	ALIA	JORDAN	1	15	116	TAKEOFF	2	?	OVERRUN AREA (FIELD)	BTHROUGH	1	YES	YES	DESCENDED AFTER TAKEOFF WITH SLATS RETRACTED. CRASHED 2NM FROM RUNWAY. FUEL FIRE UNDER REAR FUSELAGE. EVACUATED THROUGH FORE & AFT MAIN DOORS. marginally COMPLETE. (ONE OF "FAA 75")
790124	NORD 262	BECHER	ALGERIA	AIR ALGERIE	ALGERIA	14	9	0	INITIAL APPROACH	9	?	?	IMPACT?	?	YES	?	STRUCK GROUND DURING APPROACH, 15KM FROM AERODROME. NO CRASH DETAILS IN WAAS.
790313	B-727-200	DOHA	QATAR	JORDANIAN	JORDAN	44	16	4	INITIAL CLIMB	0	THUNDERSTORMS	AIRPORT	IMPACT	20	YES	YES	DOWNBURST DURING GO AROUND. CRASHED ON AIRPORT & BROKE UP. EVACUATED THROUGH OAW EXITS & FUSELAGE BREAKS. FIRE & IMPACT DEATHS. (ONE OF "FAA 75")
790329	F-27	QUEBEC	CANADA	QUEBEC AIR	CANADA	17	6	1	FINAL APPROACH	0.8	?	?	IMPACT?	3	YES	?	UNCONTAINED ENGINE FAILURE & FIRE AFTER LIFTOFF. CRASHED AFTER ~72SECS. 4200' OFF RUNWAY. INTENSE FIRE BROKE OUT ON IMPACT; CONSUMED FLIGHT DECK & PARTS OF WINGS.
790426	B-737-200	MADRAS	INDIA	INDIAN AIRLINES	INDIA	0	8	59	EN ROUTE	-	?	FIELD	EXTERNAL?	0	YES	YES	BOMB EXPLOSION DURING DESCENT. FAST LANDING & OVERRUN. WING FIRE. EVACUATED THROUGH FORE & AFT MAIN EXITS. (ONE OF "FAA 75")

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790826	F-28-4000	BROMMA	SWEDEN	LINJFLYG	SWEDEN	0	0	10	INITIAL CLIMB	0	?	RUNWAY	BTHROUGH	0	NO	NO	FUEL LINE FIRE AFTER TAKEOFF. LANDED ~ 10MINS LATER. AFT GALLEY FIRE & CABIN SMOKE. SAFE EMERGENCY EVACUATION.
791007	DC-8-62	ATHENS	GREECE	SWISSAIR	SWITZERLAND	14	0	140	LANDING	0	LIGHT RAIN	PERIMETER ROAD	BTHROUGH	14	YES	NO	OVERRAN ON LANDING; STOPPED ON AIRPORT. RH WING ROOT FUEL FIRE. EVACUATED THROUGH FRONT EXIT. LEFT SLIDE FAILED AFTER 40-50 PAX. TOOK 3 5-4.5MINS. FUSELAGE BROKE(ONE OF "FAA 20")
791223	F-28-1000	ANKARA	TURKEY	THY	TURKEY	41	4	0	FINAL APPROACH	3	?	HILL	IMPACT	5	YES	YES	HIT HILL DURING APPROACH, 3NM FROM AIRPORT. MAINLY IMPACT INJURIES. SURVIVORS IN REAR FUSELAGE EVACUATED THROUGH FUSELAGE BREAKS. 36 IMPACT DEATHS (HILL)
800121	B-727-86	TEHERAN	IRAN	IRAN AIR	IRAN	128	0	0	INITIAL APPROACH	18	?	MOUNTAIN	IMPACT	7	YES	YES	CRASHED INTO MOUNTAINS 18NM FROM AIRPORT DURING APPROACH. VERY SEVERE IMPACT; SURVIVABLE? EXITS JAMMED.
800123	F-27J	YACUMA	BOLIVIA	LLOYD AEREO	BOLIVIA	0	0	18	TAKEOFF	0	?	DITCH	EXTERNAL?	0	YES	NO	RAN OFF TAXIWAY BEFORE TAKEOFF. NOSE WHEEL WENT INTO A DITCH. PROPELLER FAILED & DAMAGED A FUEL TANK. FIRE RESULTED; SUBSTANTIAL DAMAGE.
800227	B-707-320	MANILA	PHILIPPINES	CHINA AIRLINES	TAIWAN	2	0	133	FINAL APPROACH	0	FINE	AIRFIELD	BTHROUGH	2	YES	NO?	SERIOUS INJURIES? UNDERSHOT. TWO ENGINES SEPARATED & AC CAUGHT FIRE. EVACUATED ON AIRFIELD IN ~2MINS. 2 PAX DIED FROM SERIOUS BURNS. AC DESTROYED.
800427	HS-748 2	BANGKOK	THAILAND	THAI AIRWAYS	THAILAND	44	9	0	INITIAL APPROACH	8	THUNDER STORM	RESIDENTIAL	IMPACT?	?	YES	?	CRASHED INTO RESIDENTIAL AREA DURING POOR WEATHER APPROACH. 46 SEAT FAILURES. SLIDES NOT USED.
800602	F-27J	YACUMBA	BOLIVIA	LLOYD AEREO	BOLIVIA	13	0	0	?	13	POOR	?	IMPACT?	12	YES	?	CRASHED DURING POOR WEATHER APPROACH. SURVIVABLE?
800819	L-1011-200	RIYADH	SAUDI ARABIA	SAUDIA	SAUDI ARABIA	301	0	0	FINAL CLIMB	?	FINE	RUNWAY	INTERNAL	301	NO	NO	CARGO FIRE, SECTION C3. LANDED SAFELY 21MINS AFTER 1ST WARNING & TAXIED FOR ANOTHER 3MINS. ALL ASPHYXIATED WITHIN INTACT FUSELAGE. AC DESTROYED BY FLASHOVER (SEE ADREPS + REPORT) (ONE OF "FAA 20")
801104	B-737-200C	BENGUELA	ANGOLA	TAAG	ANGOLA	0	0	134	LANDING	0	SUNNY	GRASS	EXTERNAL	0	YES	NO	UNDERSHOT BY 4M. UNDERCARRIAGE COLLAPSED. STOPPED 20M OFF RUNWAY. FIRE IN #1 ENGINE & RIGHT WING. EVACUATED SUCCESSFULLY. (ONE OF "FAA 75")

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801119	B-747-200	SEOUL	SOUTH KOREA	KOREAN AIRLINES	SOUTH KOREA	15	4	207	FINAL APPROACH	0	CALM WITH FOG PATCHES	RUNWAY	IMPACT	15	YES	YES	UNDERSHOT. NOT A FUEL FIRE? EVACUATED ON AIRPORT. ALL LHS EXITS USED? 2-3MINS. FUSELAGE DISRUPTION? (ONE OF "FAA 20")
801121	B-727-92C	YAP	W CAROLINE ISLANDS	AIR MICRONESIA	USA	0	3	70	FINAL APPROACH	0	FINE	JUNGLE	EXTERNAL	0	YES	NO	UNDERSHOT. RAN ON FOR 1700'. OFF RUNWAY & INTO JUNGLE. UC FAILURE. FIRE 'ERUPTED' ON RHS. EVACUATED THRO LHS WING EXITS. COMBI (CARGO IN FWD COMPARTMENT). CREW IGNORANT OF TAIL DOOR OPERATION. THREE PAX MINOR INJS. (ONE OF "FAA 20")
810727	DC-9-32	CHIHUAHUA	MEXICO	AERO MEXICO	MEXICO	30	1	35	LANDING	0	STRONG SQUALLS & SHOWERS	AIRPORT	IMPACT	30	YES	YES	LANDED 150M TO RIGHT OF RUNWAY & BOUNCED. FUSELAGE BROKE IN TWO & FIRE STARTED AROUND CABIN. EVACUATED IN 5MINS ON AIRPORT. SLIDES USED & EMERGENCY LIGHTING. 30MINS FOR FIRE INTERVENTION. (ONE OF "FAA 75")
811021	TU-154B	PRAGUE	CZECHOSLOVAKIA	MALEV	HUNGARY	0	2	79	LANDING	0	?	RUNWAY	EXTERNAL?	0	YES	YES	FUSELAGE BROKE AFTER HARD LANDING; TAIL DRAGGED. ALL EVACUATED. CHUTES & LIGHTING EFFECTIVE. (ADREPS)
820320	F-28-1000	TANJUNGPANG	INDONESIA	GARUDA	INDONESIA	27	0	0	LANDING	0.4	HEAVY RAIN	FIELD	IMPACT?	27	YES	YES	OVERRAN 700M DURING POOR WEATHER LANDING. "BURST INTO FLAMES" NO CRASH DETAILS IN WAAS. ALL FIRE DEATHS?
820826	B-737-200	ISHIGAKI ISLAND	JAPAN	SOUTHWEST	JAPAN	0	3	135	LANDING	0.1	CROSSWINDS	TREES	EXTERNAL	0	YES	NO?	OVERRAN 140M INTO TREES ON LANDING. 75MINS FOR LAST PAX TO BE RESCUED. AC "CAUGHT FIRE & WAS DESTROYED". (ONE OF "FAA 75")
820913	DC-10-30	MALAGA	SPAIN	SPANTAX	SPAIN	50	40	294	TAKEOFF	0.7	LIGHT WIND	EMBANKMENT	BTHROUGH?	50	YES	NO	ABORTED TAKEOFF & OVERRAN 1200M. HIT OBJECTS & RIGHT WING TORN OFF. FUEL SPILLAGE & FIREBALL. BTHROUGH NEAR TAIL & SMOKE ENTERED THROUGH TEAR IN UPPER PART OF CABIN. (GOOD EVACUATION DETAILS; TOOK ~3MINS. 5/8 EXITS USED (ONE OF "FAA 20")
830116	B-727-200	ANKARA	TURKEY	THY	TURKEY	47	?	?	FINAL APPROACH	0	SNOWSTORM	GRASS	IMPACT?	?	YES	YES	67 ON BOARD. UNDERSHOT IN WINDSHEAR. BROKE UP & CAUGHT FIRE 50M FROM RUNWAY. (PAGE MISSING IN WAAS)
830311	DC-9-32	BARQUISIMETO	VENEZUELA	AVENSA	VENEZUELA	23	?	?	LANDING	0	?	?	IMPACT	22	YES	YES	50 ON BOARD. BOEING STATE 20 NOT 23 FATALITIES. HARD LANDING; NOSE & PORT GEAR COLLAPSED. ENGINE FED FUEL FIRES. EVACUATED THROUGH BREAKS IN FUSELAGE. (ONE OF "FAA 75")
830602	DC-9-30	CINCINNATI	USA	AIR CANADA	CANADA	23	3	20	EN ROUTE	0	?	RUNWAY	INTERNAL	23	NO	NO	TOILET FIRE (PROB. ELECTRICAL). EMERGENCY LANDING ~18MINS AFTER 1ST WARNING & EVACUATION. FLASH FIRE OCCURRED AFTER ~75S. (ADREPS) EVACUATED THROUGH FRONT EXITS & 3 OVERWING EXITS IN ~90SECS. FRANK TAYLOR HAS REPORT. FULL DETAILS. (ONE OF "FAA 20")

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830611	B-727-200	CHICAGO O'HARE	USA	UNITED	USA	0	?	?	TAKEOFF	0	?	RUNWAY	?	0	NO	NO	142 ON BOARD. #1 ENGINE FAILED DURING TAKEOFF. ABORTED. ALL EVACUATED SAFELY. (PAGE MISSING IN WAAS) (INCLUDED IN CAA ANALYSIS)
830711	B-737-200	CUENCA	ECUADOR	TAME	ECUADOR	118	0	0	FINAL APPROACH	1.8	FOG	HILL	IMPACT?	11	YES	YES	STRUCK HILL DURING APPROACH IN FOG. 3100M FROM AIRPORT. SURVIVABLE?
831127	B-747-283	MADRID	SPAIN	AVIANCA	SPAIN	181	11	0	INITIAL APPROACH	?	NIGHT	?	IMPACT	128	YES	YES	HIT TERRAIN 12 KM FROM AIRPORT ON APPROACH. FUSELAGE BROKE INTO 5 PARTS. 9 PAX EJECTED & 2 ESCAPED FIRE INDEPENDENTLY. 201 FATS?
831128	F-28-2000	ENUGU	NIGERIA	NIGERIAN AIRWAYS	NIGERIA	53	9	10	FINAL APPROACH	1.8	FOG & MIST	?	IMPACT	26	YES	YES	SMOKE & FIRE PROBABLE. SANK DURING APPROACH & CRASH LANDED 1.8 NM FROM RUNWAY. (UC FAILURE PREOCCUPIED CREW?) NO CRASH DETAILS IN WAAS. EVACUATED THRO FWD WIN & R O/W EXITS IN ~3MINS. 1 EJECTED; BREAK NOT USED.
831207	B-727-200	MADRID	SPAIN	IBERIA	SPAIN	51	30	12	INITIAL APPROACH	?	THICK FOG	RUNWAY	IMPACT	46	YES	1	51/93 KILLED. 727 HIT DC-9 ON TAKEOFF. B-727 REAR FUSE UNDAMAGED & PAX EVACUATED THROUGH BREAK + DOORS. (TWO OF "FAA 75")
831218	A-300B	KUALA LUMPUR	MALAYSIA	MALAYSIAN AIRLINES	MALAYSIA	0	0	247	FINAL APPROACH	0.7	BAD WEATHER & DUSK	?	EXTERNAL	0	YES	NO	UNDERSHOT & HIT TREES. EVACUATED 1200M SHORT OF RUNWAY. FWD MAIN DOORS & 1 OTHER EXIT USED. SLIDES & LIGHTING EFFECTIVE. FIRE INTERVENTION AFTER 10MINS. (ONE OF "FAA 75")
840310	DC-8-63PF	NDJAMENA	CHAD	UTA	FRANCE	0	0	23	TAKEOFF	0	?	TERMINAL AREA	INTERNAL	0	NO	NO	CARGO EXPLOSION DURING LOADING (PROBABLY A BOMB). EVACUATION. AC DESTROYED. BOMB? (ONE OF "FAA 75")
840322	B-737-200	CALGARY	CANADA	PACIFIC WESTERN	USA	0	1	119	TAKEOFF	0	?	TAXIWAY	BTHROUGH	0	NO	NO	ENGINE FAILURE ON GROUND BEFORE TAKEOFF. FUEL TANK PENETRATED. RAPID FIRE. EVACUATED THROUGH ALL 4 RH & LH FRONT EXITS. (ONE OF "FAA 20")
840830	B-737-200	DOUALA	CAMEROON	AIR CAMEROON	CAMEROON	2	0	116	TAKEOFF	0	?	TAXIWAY	BTHROUGH	2?	NO	NO	118 ON BOARD. #2 ENGINE FAILURE DURING TAXI. SOME REPORTS MENTIONED A BOMB. FUEL TANK PUNCTURED & FIRE. EVACUATED IN ~30SECS. (ONE OF "FAA 75")
841013	B-707-1208	LARNACA	CYPRUS	CYPRUS AIRWAYS	CYPRUS	0	0	10	TAKEOFF	0	?	TAXIWAY	INTERNAL	0	NO	NO	FWD HOLD FIRE WHILST ON GROUND. EVACUATED THROUGH ENTRY DOOR. FIRE EXTINGUISHED BY FIRE SERVICE. (ONE OF "FAA 75")

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850121	L-188A	RENO	USA	GALAXY	USA	70	1	0	TAKEOFF	1.5	FINE	?	IMPACT?	27	YES	YES	VIBRATION 1MIN AFTER TAKEOFF. CRASHED 1.5NM FROM AIRPORT WHILST ATTEMPTING TO RETURN. LACK OF CREW COORDINATION. IMPACT & SUBSEQUENT FIRE. AC DESTROYED & 1 PAX EJECTED. 27 FIRE FATS?
850415	B-737-200	PHUKET	THAILAND	THAI AIRWAYS	THAILAND	11	0	0	FINAL APPROACH	1.8	?	MOUNTAIN	IMPACT?	9	YES	YES	HIT MOUNTAIN 3KM FROM AIRPORT DURING APPROACH. SURVIVABLE?
850802	L-1011-385	DALLAS	USA	DELTA	USA	134	15	14	FINAL APPROACH	1.2	THUNDERSTORM	AIRPORT	IMPACT	20	YES	YES	MICROBURST DURING APPROACH. HIT CARS & WATER TANK. AC DISINTEGRATED APART FROM REAR FUSELAGE & TAIL SECTION, 6000' SHORT OF RUNWAY. SEVERE FIRE STARTED DURING IMPACT SEQUENCE. EVACUATED THROUGH BREAKS, EJECTED & RESCUED. 10 FIRE FATS?
850822	B-737-236	MANCHESTER	UK	BRITISH AIRTOURS	UK	55	15	67	TAKEOFF	0	FINE	TAXIWAY	BTHROUGH	55	NO	NO	#1 ENGINE FAILURE ON TAKEOFF & FUEL TANK PUNCTURED. ABORTED. EVACUATED THROUGH FWD DOORS & RH OVERWING EXIT (3/8) IN 210SECS. (ONE OF "FAA 20")
851212	DC-8-63CF	GANDER	CANADA	ARROW AIR	CANADA	256	0	0	TAKEOFF	1.5	FREEZING SNOW	?	IMPACT	51	YES	YES	CRASHED SHORTLY AFTER TAKEOFF, 1.5NM BEYOND RUNWAY. MILITARY CHARTER FLIGHT. WING ICING OR BOMB?
860702	TU-134A	SYKTYVKAR	USSR	AEROFLOT	USSR	54	40	0	EN ROUTE	-	?	FOREST	INTERNAL	0	YES	YES	BAGGAGE HOLD FIRE; FLAMMABLE SUBSTANCE. FORCED LANDED IN FOREST.
870103	B-707-320C	ABIDJAN	IVORY COAST	VARIG	BRAZIL	50	1	0	INITIAL APPROACH	12	?	FOREST	IMPACT	?	YES	YES	#3 ENGINE FIRE ON CLIMB OUT. CRASHED INTO FOREST 12 MILES FROM LANDING.
870404	DC-9-32	MEDAN	INDONESIA	GARUDA	INDONESIA	28	?	?	?	?	HEAVY RAIN & WINDS	?	?	?	YES	?	45 ON BOARD. HIT OBSTACLES DURING APPROACH & CRASHED. CAUGHT FIRE. HEAVY RAIN & WINDSHEAR? (PAGE MISSING IN WAAS)
870508	CASA 212	MAYAGUEZ	PUERTO RICO	AMERICAN EAGLE	USA	2	0	4	FINAL APPROACH	?	FINE	?	BTRHOUGH?	0	YES	NO?	UNDERSHOT, HIT OBSTACLES & CAUGHT FIRE. REPORT MENTIONS SEAT FIRE BLOCKING.
870804	B-737-200	CALAMAS	CHILE	LAN CHILE	CHILE	1	1	31	LANDING	0	FINE	RUNWAY UNDER REPAIR	IMPACT	2	YES	YES	870805? 33/35. UNDERSHOT ONTO RUNWAY UNDER REPAIR. GEAR FAILED. AC BROKE IN TWO & CAUGHT FIRE.

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870816	DC-9-82	DETROIT	USA	NORTHWEST	USA	154	1	0	TAKEOFF	1.2	?	?	IMPACT	0	YES	YES	STALLED AFTER LIFTOFF. FLAPS & SLATS NOT EXTENDED & WARNING SYSTEM FAILED. BROKE UP & FIRES ALONG WRECKAGE TRAIL 8000' BEYOND RUNWAY. 4 YEAR OLD SERIOUSLY INJ. (EJECTED) & 2 OTHERS KILLED.
880119	METRO III	BAYFIELD	USA	CONTINENTAL EXPRESS	USA	9	1	7	FINAL APPROACH	?	SNOW	TREES	IMPACT?	?	YES	?	STRUCK TREES DURING APPROACH THROUGH SNOW. CAPTAIN USED COCAINE BEFORE FLIGHT. FIRE NOT MENTIONED IN WAAS.
880203	MD-83	NASHVILLE	USA	AMERICAN	USA	0	7	120	LANDING	0	?	RUNWAY	INTERNAL	0	NO	NO	CARGO FIRE (HAZARDOUS CHEMICALS). SMOKE IN CABIN. NORMAL LANDING (1-8MINS LATER) & EVACUATION. AC SUBSTANTIALLY DAMAGED.
880227	TU-134A	SURGET	USSR	AEROFLOT	USSR	20	30	1	LANDING	0	CLOUDY NIGHT	RUNWAY	IMPACT	19	YES	YES	UNDERSHOT. BROKE UP & BURNED. WITHIN AIRFIELD PERIMETER.
880523	B-727-100	SAN JOSE	COSTA RICA	COSTARRICENCES	COSTA RICA	0	1	25	TAKEOFF	?	?	HILL	BTHROUGH?	0	NO	NO	SCHEDULED PAX FLIGHT. AC WOULD NOT ROTATE AFTER V1 ON TAKEOFF. OVERRAN, HITTING A FENCE, DITCH & A HILL. AC DESTROYED BY FIRE. CG AFT OF LIMITS.
880626	A-320	HABSHEIM	FRG	AIR FRANCE	FRANCE	3	36	97	LANDING	0.1	FINE	TREES	BTHROUGH	3	YES	NO	125 PAX. AIR DISPLAY FLIGHT. HIT TREES WHILST ATTEMPTING GO AROUND. CRASHED 250M OFF AIRPORT. SEE ANONYMOUS REPORT. EVACUATION IN 1.5-2MINS. 2/6. EXITS USED.
880706	CL-44J	BARANQUILLA	COLOMBIA	LINEAS AEREAS	COLOMBIA	3	5	0	TAKEOFF	?	FINE	?	?	?	YES	?	SCHEDULED PAX FLIGHT. UNCONTAINED #4 ENGINE FAILURE & FIRE. ATTEMPTED TO RETURN. LOST CONTROL & CRASHED SHORT OF RUNWAY. NO CRASH DETAILS IN WAAS.
880802	YAK-40	SOFIA	BULGARIA	BALKAN BULGARIAN	BULGARIA	25	12	0	TAKEOFF	0	?	AIRPORT	IMPACT?	?	YES	?	CRASHED ON TAKEOFF, WITHIN AIRFIELD PERIMETER. REPORTED ENGINE FIRE.
880831	B-727-200	DALLAS FORT WORTH	USA	DELTA	USA	14	26	28	TAKEOFF	0.6	?	?	IMPACT?	14	YES	YES	STALLED AFTER LIFTOFF. 3200' BEYOND RUNWAY. PARTIALLY DEPLOYED/UNDEPLOYED FLAPS. EVACUATED THRO LF & LMID EXITS + BREAKS, IN ~ 270SECS.
880909	TU-134A	BANGKOK	THAILAND	HANG KONG VIETNAM	VIETNAM	76	14	0	FINAL APPROACH	5	HEAVY THUNDERSTORM	RICE PADDIES	IMPACT?	?	YES	?	CRASHED ON FINALS 5NM FROM RUNWAY IN HEAVY THUNDERSTORM & STRONG WINDS. NO FIRE MENTIONED IN WAAS.

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880915	B-737-200	BAHIR DAR	ETHIOPIA	ETHIOPIAN	ETHIOPIA	35	27	42	INITIAL CLIMB	6	?	OPEN TERRAIN	IMPACT?	6	YES	YES	ENGINE FAILURE FOLLOWING BIRDSTRIKE. LOST POWER TO BOTH ENGINES. FORCED LANDED WITH UC RETRACTED IN OPEN TERRAIN 10KM FROM AIRPORT. BROKE IN TWO 17-35 FIRE FATS?
881017	B-707-338C	ROME	ITALY	UGANDA AIRLINES	UGANDA	32	20	5	FINAL APPROACH	1	FOG	BUILDINGS	IMPACT?	16?	YES	YES	CRASHED DURING APPROACH IN FOG. 1NM FROM AIRPORT. SOME SURVIVORS WERE RESCUED. (CLIPPED BUILDING ON PREVIOUS ATTEMPT) AC DESTROYED BY IMPACT & FIRE.
881019	B-737-200	AHMEDABAAD	INDIA	INDIAN AIRLINES	INDIA	124	5	0	FINAL APPROACH	2.8	HAZE	TREES	IMPACT?	?	YES	YES	HIT ELECTRICITY MAST & TREES ON APPROACH IN POOR VISIBILITY. CRASHED 5 MILES FROM AIRPORT. AC DESTROYED BY IMPACT & FIRE.
881025	F-28-1000	JULIACA	PERU	AERO PERU	PERU	13	57	0	TAKEOFF	1.2	?	?	IMPACT	?	YES	YES	CRASHED WITH NOSE IN ATTITUDE SOON AFTER TAKEOFF, 2KM FROM RUNWAY. EVACUATED. NO EXITS OPENED. SURVIVORS FROM AFT SECTION EJECTED & FWD SECTION BREAKS USED.
881102	AN-24V	RZESZOW	POLAND	LOT	POLAND	1	?	?	FINAL APPROACH	?	FINE	FIELD	BTHROUGH?	?	YES	?	29 ON BOARD. FORCE LANDED IN FIELD AFTER ENGINE FAILURE. SUSTAINED DAMAGE & CAUGHT FIRE.
890203	F-27-600	RANGOON	BURMA	BURMA AIRWAYS	BURMA	26	2	1	INITIAL CLIMB	0.1	FOG	TREES	IMPACT?	?	YES	?	HIT TREE AFTER TAKEOFF IN FOG. FIRE BROKE OUT, DESTROYING AC. EVACUATED THROUGH RH REAR EXIT.
890310	F-28-1000	DRYDEN	CANADA	AIR ONTARIO	CANADA	24	19	26	TAKEOFF	0.6	SNOW	TREES	IMPACT	15	YES	YES	CRASHED 960M BEYOND RUNWAY AFTER TAKEOFF IN SNOW. EVACUATED THRO 2/7 EXITS IN ~60SECS. 47 USED BREAKS.
890607	DC-8-62	ZANDERIJ	SURINAM	SURINAM AIRWAYS	SURINAM	177	8	2	FINAL APPROACH	1	FOG DARK	TREES	IMPACT?	?	YES	YES	CRASHED ON FINAL APPROACH IN DARKNESS & FOG. NO FIRE MENTIONED IN WAAAS.
890617	IL-62MK	BERLIN SCHONEFELD	GERMANY	INTERFLUG	GERMANY	21	29	63	TAKEOFF	0	?	AIRPORT	BTHROUGH?	11	YES	NOT	113 ON BOARD. FAILED TO BECOME AIRBORNE DUE TO JAMMED CONTROLS. WING STRUCK WATER TANK & FIRE DESTROYED AIRCRAFT. PAGE MISSING IN WAAAS
890719	DC-10-10	SIOUX CITY	USA	UNITED	USA	111	185	0	LANDING	0	FINE	AIRPORT	IMPACT	35	YES	YES	296 ON BOARD. #2 ENGINE FAILURE. LOST ALL FLIGHT CONTROLS. CRASH LANDED UNDER ENGINE THRUST CONTROL. SKIDDED, BROKE UP & CAUGHT FIRE. PAGE MISSING IN WAAAS.

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891014	B-727-232	SALT LAKE CITY	USA	DELTA	USA	0	0	20	?	0	?	AIRPORT	INTERNAL	0	NO	NO	OXYGEN BOTTLE CAUGHT FIRE WHILST ON GROUND & BURNT THROUGH FUSELAGE. EMERGENCY EVACUATION. AC DESTROYED.
891021	B-727-224	TEGUCIGALPA	HONDURAS	SAHSA	HONDURAS	127	16	3	INITIAL APPROACH	9	LOW CLOUD	HILL	IMPACT?	?	YES	YES	FORCE LANDED ON HIGH GROUND 15KM FROM AIRPORT AFTER TAKEOFF & BROKE UP. STRONG WINDS & LOW CLOUDS.
891121	AN-24	TYUMEN	RUSSIA	AEROFLOT	RUSSIA	32	8	0	FINAL APPROACH	0.5	LOW VISIBILITY & SNOW	TREES	IMPACT?	?	YES	?	CRASHED WHILE LANDING IN POOR VISIBILITY. STRUCK TREES & CRASHED 800M FROM THRESHOLD. FIRE STARTED AFTER IMPACT.
891125	F-28-4000	SEOUL	SOUTH KOREA	KOREAN AIR	SOUTH KOREA	0	6	42	TAKEOFF	?	FOG	?	BTHROUGH?	?	YES	YES	THE AC WOULD NOT CLIMB AFTER TAKEOFF. WING ICING REDUCED ENGINE POWER. TAKEOFF ABORTED & AC OVERRAN. NOSEGEAR COLLAPSED & FIRE STARTED. EVACUATED THRO 1/4 EXITS. FUSELAGE BREAK OBSTRUCTED.
900105	F-28-4000	VILLA GESELL	ARGENTINA	AEROLINEAS ARGENTINAS	ARGENTINA	0	0	90	LANDING	?	?	?	BTHROUGH	0	NO	NO	OVERRAN. AC BURNT OUT AFTER FUEL TANK RUPTURED
900113	TU-134A	PERVOURALSK	RUSSIA	AEROFLOT	RUSSIA	25	0	47	EN ROUTE	-	?	MOUNTAINS	IMPACT?	?	YES	?	ENGINE FIRE. CREW INITIATED EMERGENCY DESCENT. CRASH LANDED IN URALS.
900214	A-320	BANGALORE	INDIA	INDIAN AIRLINES	INDIA	92	22	32	FINAL APPROACH	?	?	EARTHEN BANK	IMPACT	85	YES	YES	56 EVACUATED IN ~ 2MINS; 2 DIED LATER. UNDERSHOT & BECAME AIRBORNE AGAIN. CRASHED INTO TREES & EARTHEN BANK OFF AIRPORT. HEAVY IMPACT & BROKE UP. REAR & O/W EXITS + FUSE BREAKS USED. FRANK TAYLOR HAS REPORT. PAGE MISSING IN WAAS.
900511	B-737-300	MANILA	PHILIPPINES	PHILIPPINE AIRLINES	PHILIPPINES	8	30	87	TAKEOFF	0	?	AIRPORT	BTHROUGH?	7	NO	NO?	FUEL TANK EXPLOSION WHILST BEING TOWED. EVACUATED THROUGH ALL AFT EXITS + RH PART OF TIME. TOOK ~ 90SECS. (ELECTRICAL FAULT?) PAGE MISSING IN WAAS.
900914	YAK-42	SYVERDOLOVSK	RUSSIA	AEROFLOT	RUSSIA	4	37	87	FINAL APPROACH	?	?	TREES	EXTERNAL?	?	YES	NO?	CRASHED ON FINAL APPROACH AFTER SUSPECTED ENGINE FAILURE. HIT TREES. AC DESTROYED.
901002	B-737-247	GUANGZHOU	CHINA	CAAC	CHINA	114	0	0	LANDING	0	?	AIRPORT	IMPACT?	?	YES	YES	IN-FLIGHT HUAC ATTEMPT; BOMB DETONATED ON FINAL APPROACH. CRASHED ON LANDING AND VEERED OFF RUNWAY. STRUCK A B-757 (SEE BELOW) & CONTINUED ONTO A GRASSY AREA, CAUSING FIRE.

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901002	B-757	GUANGZHOU	CHINA	CAAC	CHINA	78	7	7	.	0	?	AIRPORT	?	?	YES	YES	HIT BY CRASHING B-737 (SEE ABOVE) WHILST BOARDING PASSENGERS.
901024	YAK-40	SANTIAGO	CUBA	CUBANA	CUBA	10	21	0	FINAL APPROACH	?	POOR WEATHER	WOODLAND	IMPACT?	?	YES	?	CRASHED INTO HIGH WOODLAND DURING APPROACH. POOR WEATHER. AC DESTROYED.
901203	DC-9-14	DETROIT	USA	NORTHWEST	USA	8	10	26	TAXI OUT	0			IMPACT	8	YES	YES	TAXIED ONTO ACTIVE RUNWAY IN FOG. HIT BY LANDING B-727. EVACUATED THROUGH FRONT DOORS & LH O/W EXIT. NO FIRE MENTIONED IN WAAS. NO ONE ON 727 INJURED.
910201	B-737-3B7	LOS ANGELES	USA	USAIR	USA	22	10	48	LANDING	0	FINE	RUNWAY	IMPACT	21	YES	YES	B-737 STRUCK METRO DURING LANDING. 89 & 12 ON BOARD. 737 EVACUATED THROUGH FWD LH DOOR, 2 OVERWING EXITS & AFT RH DOOR IN ~ 90SECS. SEE D.H. KOCH LETTER - EXIT USAGE DISAGREES. B-737 BODIES FOUND ADJACENT TO EXITS - RAPID BUILDUP OF DENSE SMOKE.
910323	AN-24B	TASHKENT	USSR	AEROFLOT	RUSSIA	31	0	25	LANDING	0	?	AIRPORT	IMPACT?	?	YES	?	AC VEERED OFF RUNWAY WHILE LANDING & HIT A PILE OF LARGE CONCRETE BLOCKS. NO FIRE MENTIONED IN WAAS.
910903	SKYVAN 3	SARAWAK	MALAYSIA	ADTEC	MALAYSIA	14	6	0	FINAL CLIMB	.	?	JUNGLE	IMPACT?	?	YES	YES	CRASHED INTO JUNGLE AFTER BOTH ENGINES LOST POWER. NO FIRE MENTIONED IN WAAS.
910928	MD-80	BOSTON	USA	CONTINENTAL	USA	0	2	121	TAKEOFF	0	.	TAXIWAY	INTERNAL	0	NO	NO	COCKPIT ELECTRICAL FIRE. EMERGENCY LANDING & EVACUATION (2 INJURIES).
911025	HS-748-272	ANTICOSTI IS.	CANADA	AIR QUEBEC	CANADA	0	0	?	?	0	?	RUNWAY	EXTERNAL	0	NO	NO	ENGINE FIRE. AIRCRAFT DESTROYED BY FIRE AFTER LANDING.
920120	A-320-111	STRASBOURG	FRANCE	AIR INTER	FRANCE	87	5	4	INITIAL APPROACH	12	FOG & LOW CLOUD AT NIGHT	MOUNTAIN	IMPACT	2	YES	YES	HIT HIGH GROUND DURING APPROACH. FIRE. SITE TOOK 5HRS TO LOCATE IN SNOW, FOG & DARKNESS.
920209	CV-640	KAFOUNTINE	SENEGAL	GAMBICREST	GAMBIA	31	13	15	FINAL APPROACH	?	AT NIGHT	SWAMP	IMPACT?	?	YES	YES	PILOT MISTOOK ROAD LIGHTS FOR RUNWAY. HIT TREE & CRASHED INTO A SWAMP. AC BROKE INTO THREE.

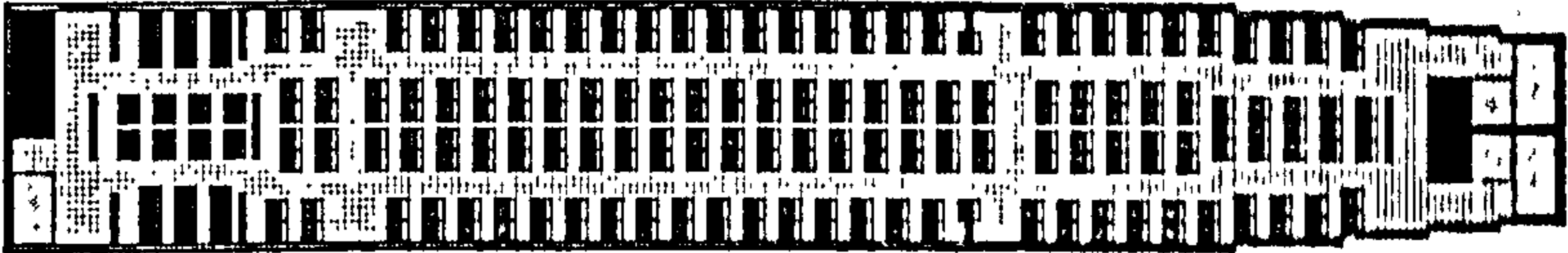
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920513	YAK-40	CHARDZHEV	TURKMENISTAN	TURKMENAVIA	TURKMENISTAN	0	5	33	FINAL APPROACH	0	THUNDER STORM	AIRPORT	BTHROUGH	0	YES	NO?	WING STRUCK RADIO MAST DURING GO AROUND IN THUNDERSTORM. AC LANDED BESIDE RUNWAY & BURNED. AC DESTROYED BY FIRE.
920730	TRISTAR 1	NEW YORK JFK	USA	TWA	USA	0	18	274	TAKEOFF	0.1	FINE	AIRPORT GRASS	BTHROUGH?	0	NO	NO	ABANDONED TAKEOFF AFTER ROTATION - ATC REPORTED FIRE IN REAR OF AC. HARD LANDING & OVERRAN THROUGH A BARRIER. EMERGENCY EVACUATION SPAR FAILURE & FUEL FIRE DESTROYED AC.
920731	YAK-42B	NANJING	CHINA	CHINA GENERAL AVIATION	CHINA	106	0	20	TAKEOFF	?	?	AIRPORT	IMPACT?	?	YES	YES	OVERRAN AFTER ATTEMPTED LIFTOFF. STRUCK A WALL AND "EXPLODED".
920910	F-27 500	BELLAVISTA	PERU	ESSPRESSO AEREO	PERU	1	24	11	LANDING	0	?	AIRPORT GRASS	IMPACT	1	YES	YES	LANDED ON NOSEWHEEL; IT FAILED & AC SPUN, BROKE IN THREE & CAUGHT FIRE.
921030	AN-8	CHITA	RUSSIA	AVIA	RUSSIA	14	1	0	FINAL APPROACH	1	?	?	IMPACT?	?	YES	?	CRASHED 1 MILE SHORT OF RUNWAY. AC DESTROYED. NO FURTHER DETAILS KNOWN
921121	B-737-300	SAN LUIS	ARGENTINA	AEROLINEAS ARGENTINAS	ARGENTINA	0	0	113	TAKEOFF	?	?	AIRPORT	EXTERNAL	0	YES	YES	TYRE BURST ON TAKEOFF. OVERRAN; GEAR & ENGINES RIPPED OFF. FIRE FOLLOWED EVACUATION.
921221	DC-10-30F	FARO	PORTUGAL	MARTINAIR	NETHERLANDS	54	106	180	LANDING	0	THUNDER STORMS	RUNWAY	IMPACT	46	YES	YES	LOST CONTROL ON LANDING IN A STORM. LEFT RUNWAY, BROKE UP & BURNED.
930109	BAe 748 2	SURBAYA	INDONESIA	BOURAO INDONESIA	INDONESIA	16	21	?	FINAL APPROACH	?	HEAVY FOG	SWAMP	IMPACT	?	YES	YES	ENGINE FAILURE AFTER TAKEOFF. CRASHED ON AIRFIELD BOUNDARY IN A SWAMP. AC OVERTURNED, BROKE IN TWO & CAUGHT FIRE.
930109	TU-154B-2	DELHI	INDIA	INDIAN AIRLINES	INDIA	0	7	158	LANDING	0	THICK FOG	RUNWAY	BTHROUGH	0	YES	YES	LANDED OFF RUNWAY. OVER TURNED & BURNED.
930305	FOKKER 100	SKOPJE	MACEDONIA	PALAIR MACEDONIA	F.Y.R. OF MACEDONIA	81	16	0	INITIAL CLIMB	?	ICING CONDITIONS	?	IMPACT?	?	YES	YES	97 ON BOARD. STALLED AT 1200' & CRASHED AFTER TAKEOFF IN ICING CONDITIONS. "EXPLODED"

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930418	DC-9-41	HANAMAKI	JAPAN	JAS	JAPAN	0	0	77	LANDING	0	STRONG CROSS WINDS	RUNWAY	BTHROUGH	0	YES	YES	WING STRUCK RUNWAY IN CROSS WIND LANDING. WING FIRE, UC COLLAPSE & FUSELAGE BROKE IN THREE.
930426	B-737-200	AURANGABAD	INDIA	INDIAN AIRLINES	INDIA	55	16	47	INITIAL CLIMB	4.2	HOT	FIELD	IMPACT	?	YES	YES	FAILED TO CLIMB AFTER OVER LOADED TAKEOFF AT HIGH TEMPERATURE. HIT TRUCK & POWER LINES & CRASHED. AC BROKE INTO THREE SECTIONS & CAUGHT FIRE.
930701	F-28-3000	SORONG	INDONESIA	MERPATI NUSANTARA	INDONESIA	41	2	0	?	?	HEAVY RAIN	HILL & ROCKY BEACH	IMPACT?	?	YES	YES	UC STRUCK A HILL AS THE AC DESCENDED IN HEAVY RAIN. FUSE BROKE IN TWO & FRONT SECTION CRASHED ONTO A ROCKY BEACH.
930726	B-737-500	KOKPO	S. KOREA	ASIANA	S. KOREA	68	42	0	?	?	HEAVY RAIN & STRONG WINDS	CLIFF	IMPACT?	?	YES	YES	HIT HIGH GROUND IN FOURTH POOR WEATHER APPROACH ATTEMPT. AC DESTROYED.
930906	B-727-200	SANTO DOMINGO	DOMINICAN REPUBLIC	DOMINICANA DE AVIACION	DOMINICAN REPUBLIC	0	0	105	FINAL CLIMB	0	?	AIRPORT GATE	INTERNAL	0	NO	NO	SMALL IN-FLIGHT FIRE SPREAD THROUGH FUSELAGE AFTER LANDING.
930914	A320-200	WARSAW	POLAND	LUFTHANSA	GERMANY	2	9	59	LANDING	?	HEAVY RAIN & STRONG WINDS	?	BTHROUGH	1	YES	YES	70 ON BOARD. OVERRAN ON LANDING. HIT EARTH BANK & CAUGHT FIRE.

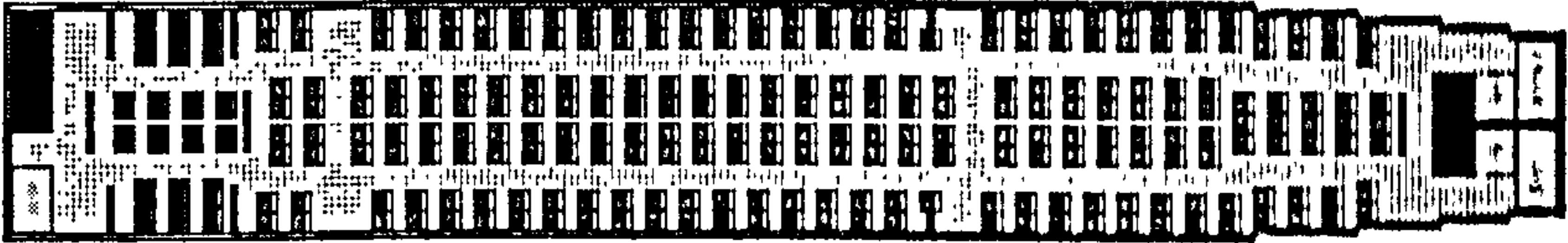
Appendix B: Airliner Cabin Configurations

100

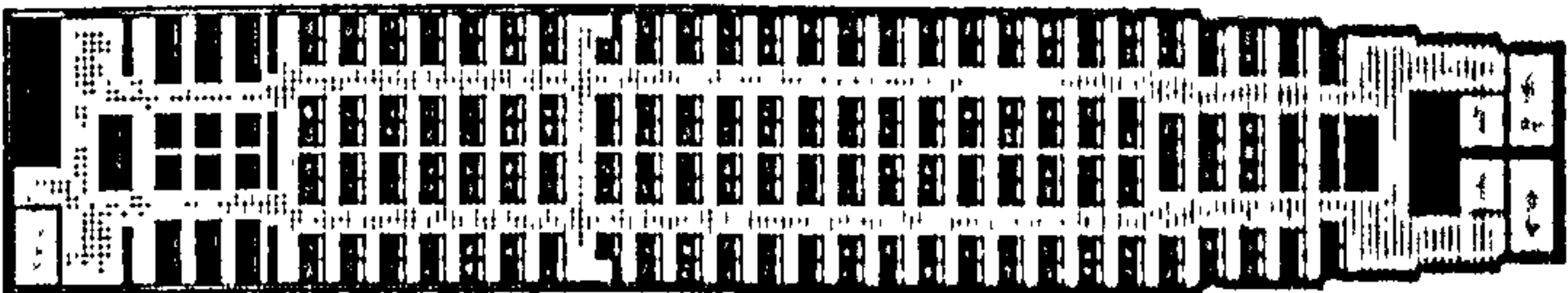
Airbus A300B



Airbus A300-600



Airbus A310



Airbus A319



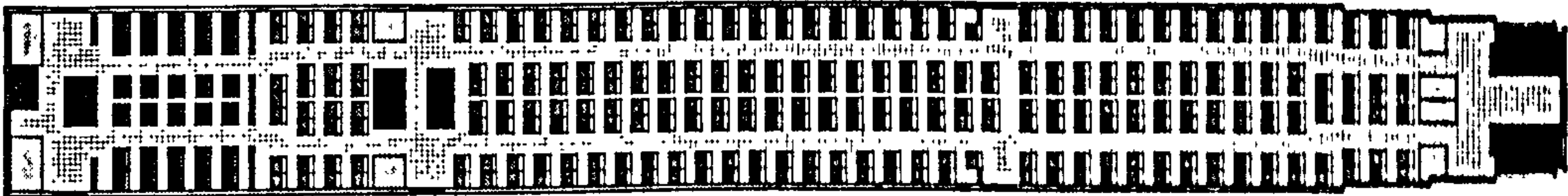
Airbus A320



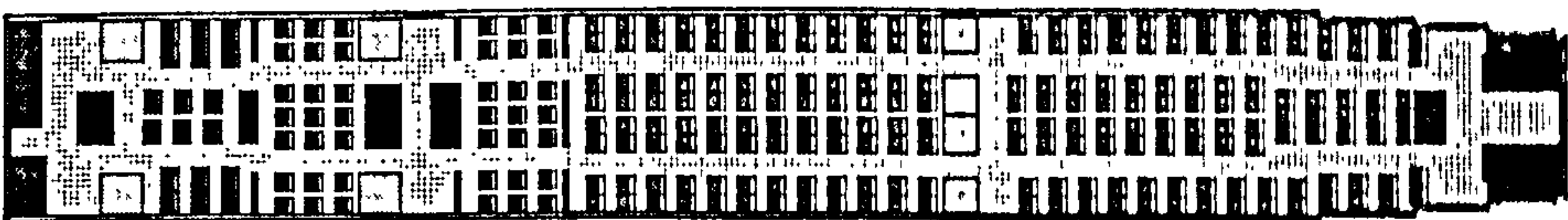
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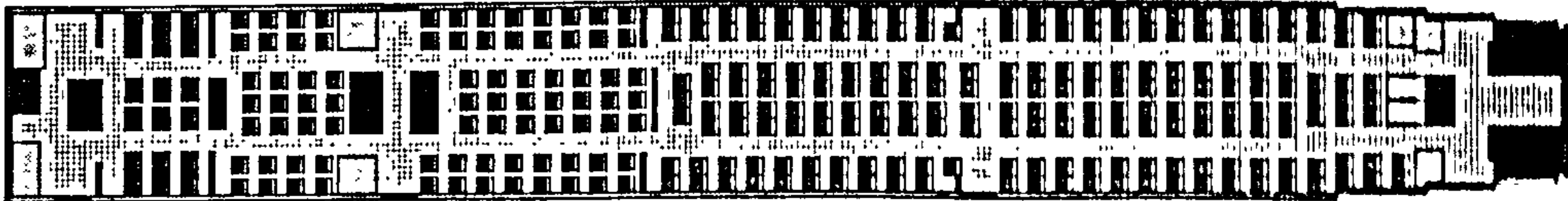
Airbus A330



Airbus A340-200



Airbus A340-300



Antonov An-24



ATR 42



ATR 72



Avro RJ70/BAe 146-100



Avro RJ85/BAe 146-200



Avro RJ100/115/BAe 146-300



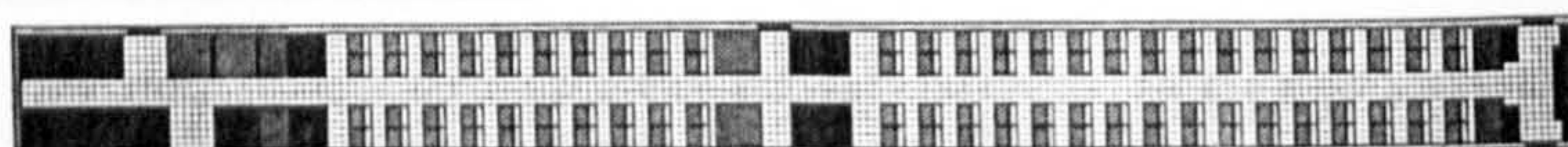
BAC 1-11 2/3/400 Series



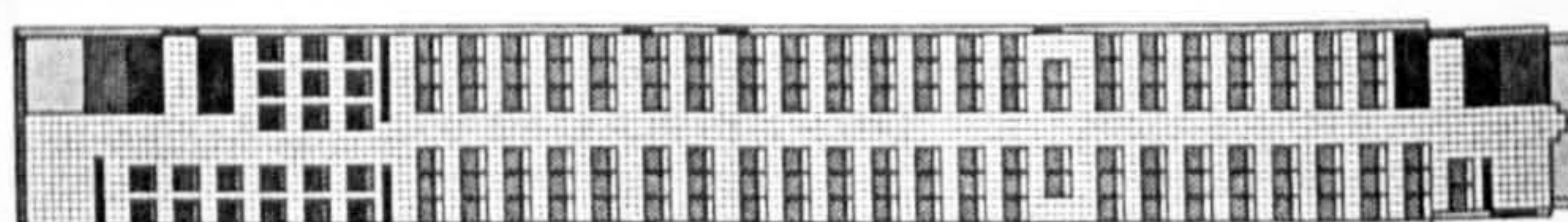
BAC 1-11 500 Series



BAC/Aerospatiale Concorde



Boeing 707-3/400



Boeing 727-100



Boeing 727-200



Boeing 737-100



Boeing 737-200



Boeing 737-300



Boeing 737-400 (two class)



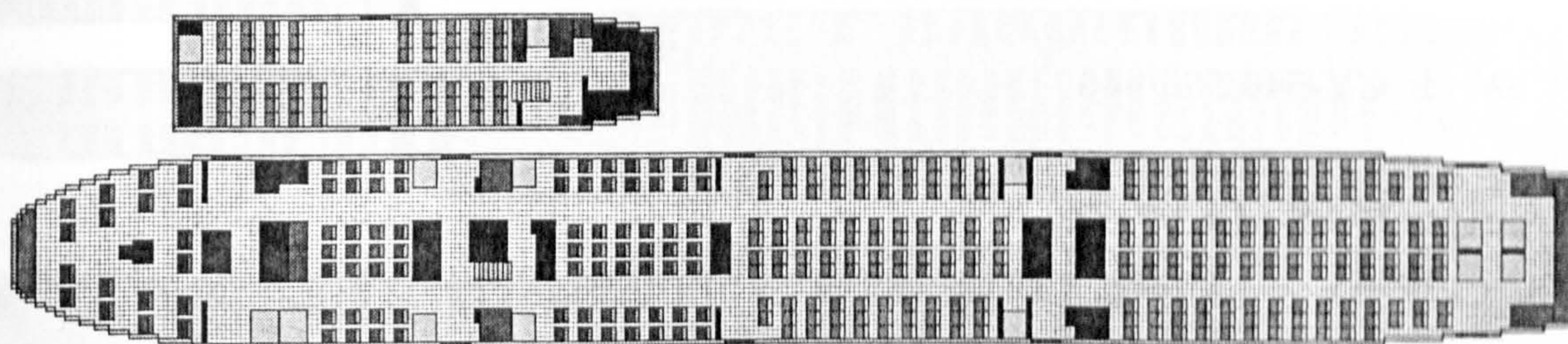
Boeing 737-400 (single class)



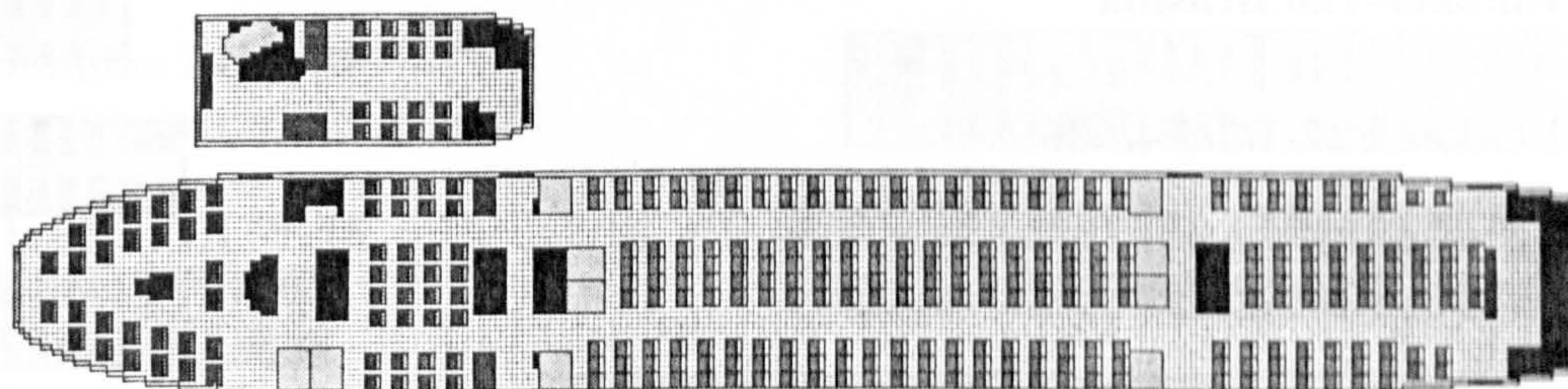
Boeing 747-100



Boeing 747-400



Boeing 747 SP



Boeing 757



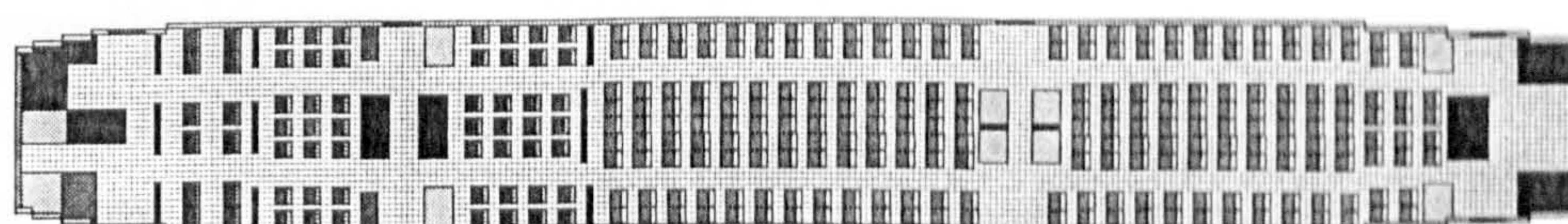
Boeing 767-200



Boeing 767-300



Boeing 777



BAe ATP



CASA 212-300



CASA-ITPN CN-235



Canadair Dash 7



Canadair Dash 8 Series 100



Canadair Dash 8 Series 300



Canadair Regional Jet



Convair CV-540/580/640



Douglas DC-8-61/63/71/73



Embaer-120 Brasilia



Fokker F27-1/2/3/4/600



Fokker F27-500



Fokker F28-1/3/5000 Series



Fokker F28-2/4/6000 Series



Fokker 50



Fokker 70



Fokker 100



Hawker Siddely 748 Series 2



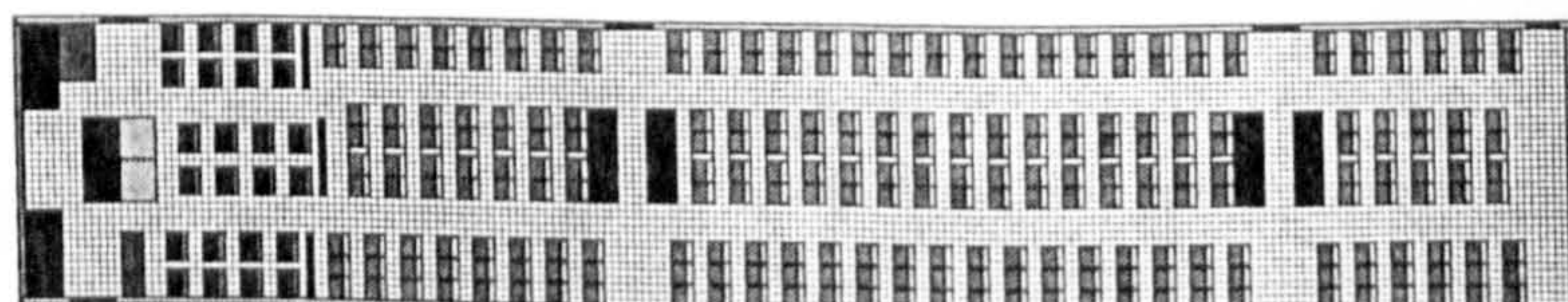
Ilyushin Il-18



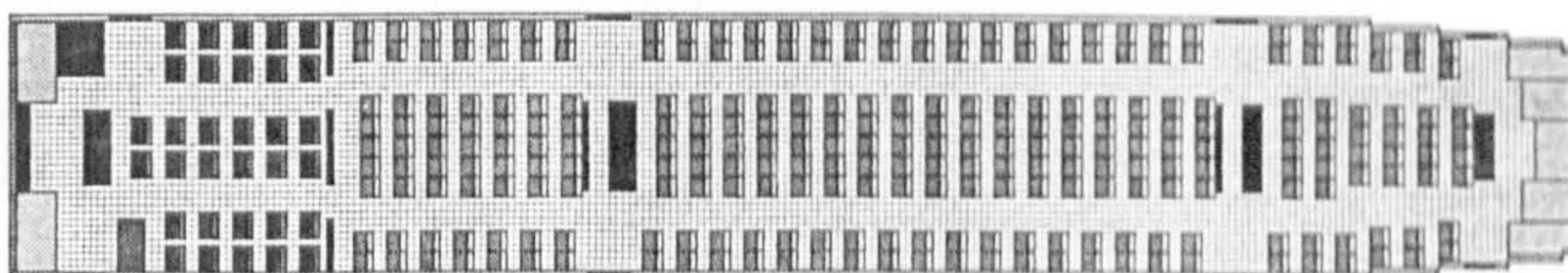
Ilyushin Il-62



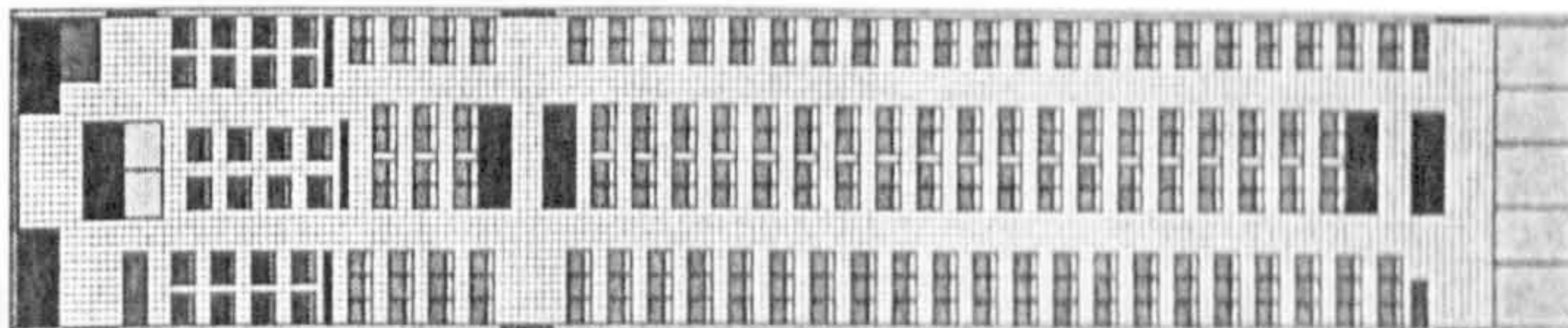
Lockheed L-1011-200 Tristar



Lockheed L-1011-300 Tristar



Lockheed L-1011-500 Tristar



McDonnell Douglas DC-9-30



McDonnell Douglas DC-9-40



McDonnell Douglas MD-81



McDonnell Douglas MD-82/83/88



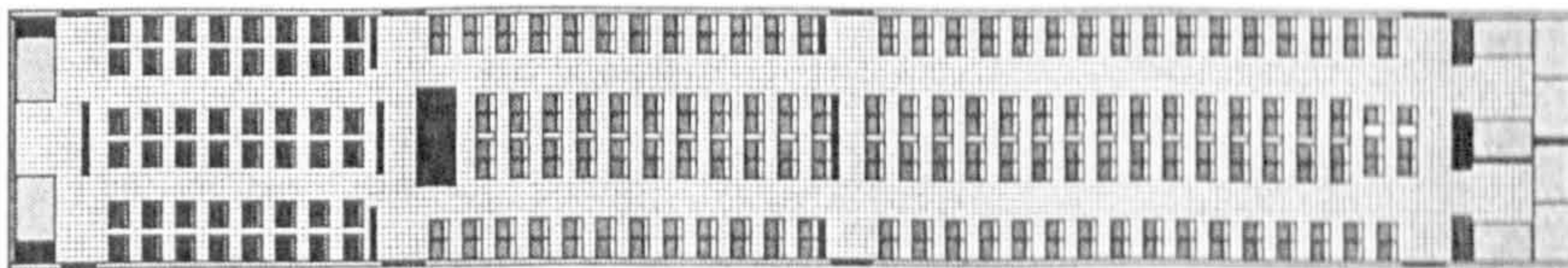
McDonnell Douglas MD-87/DC-9-50



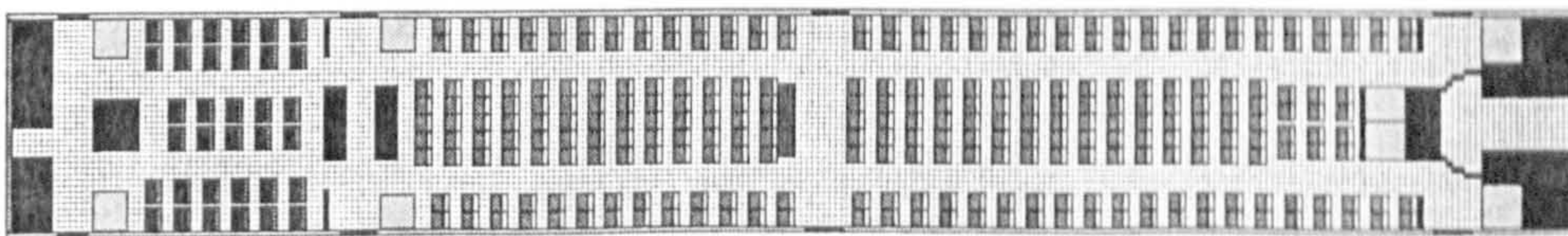
McDonnell Douglas MD-90



McDonnell Douglas DC-10



McDonnell Douglas MD-11



NAMC YS-11



Nord 262



Saab SF-340A



Saab SF-340B



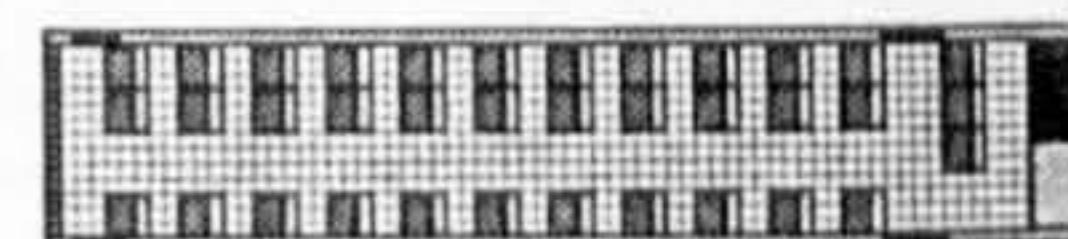
Saab 2000



Shorts 330



Shorts 360



Tupolev Tu-134



Yakovlev Yak-40



Appendix C: Crash Scenario Analysis



Figure 1.1: Graph showing the relationship between Time (ms) and Force (N).



Figure 1.2: Graph showing the relationship between Time (ms) and Force (N).



Figure 1.3: Graph showing the relationship between Time (ms) and Force (N).

C.1 Variation In Fuselage Structural Damage Levels

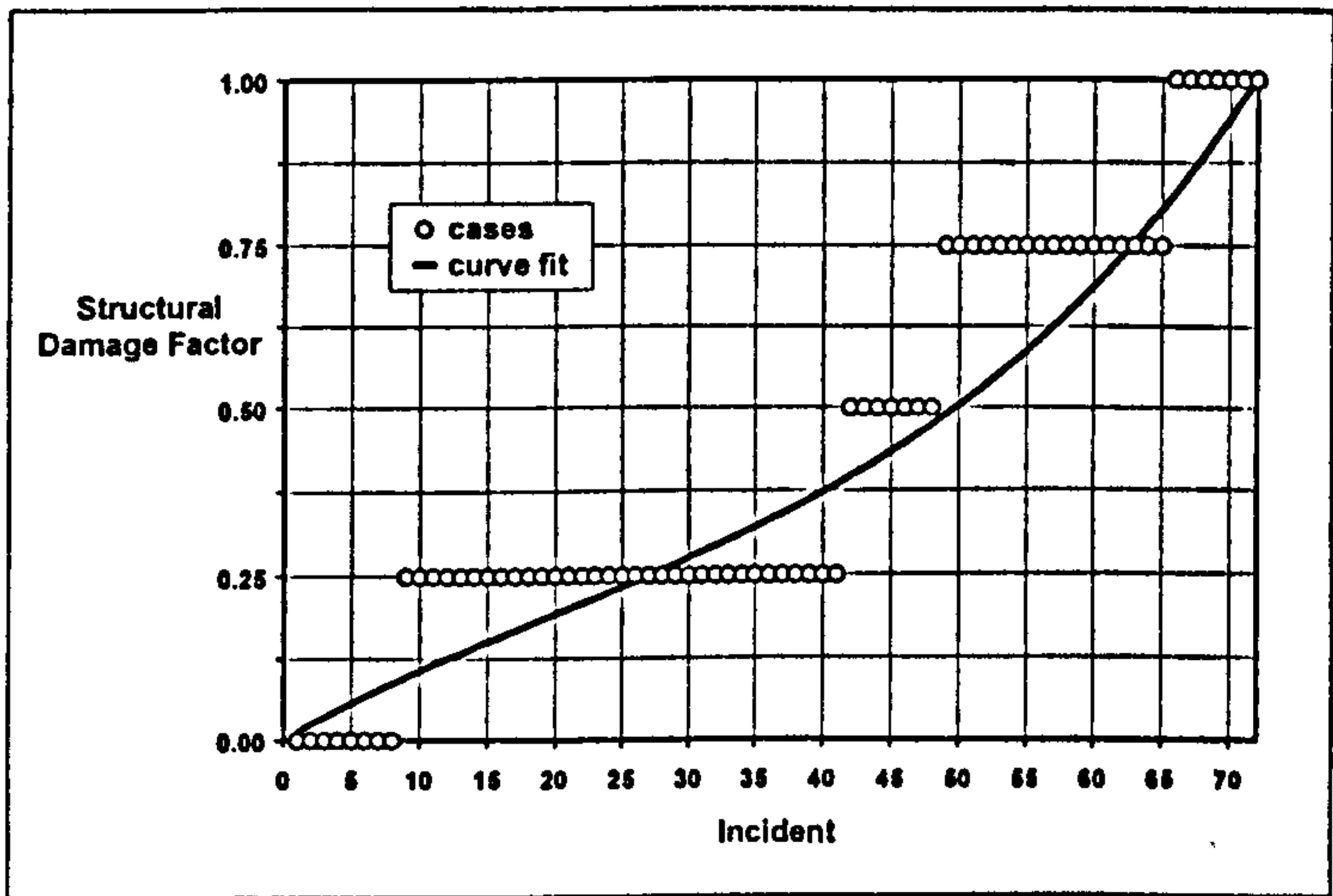


Figure C.1: Fuselage Structural Damage Levels
(Fuselage in one Piece)

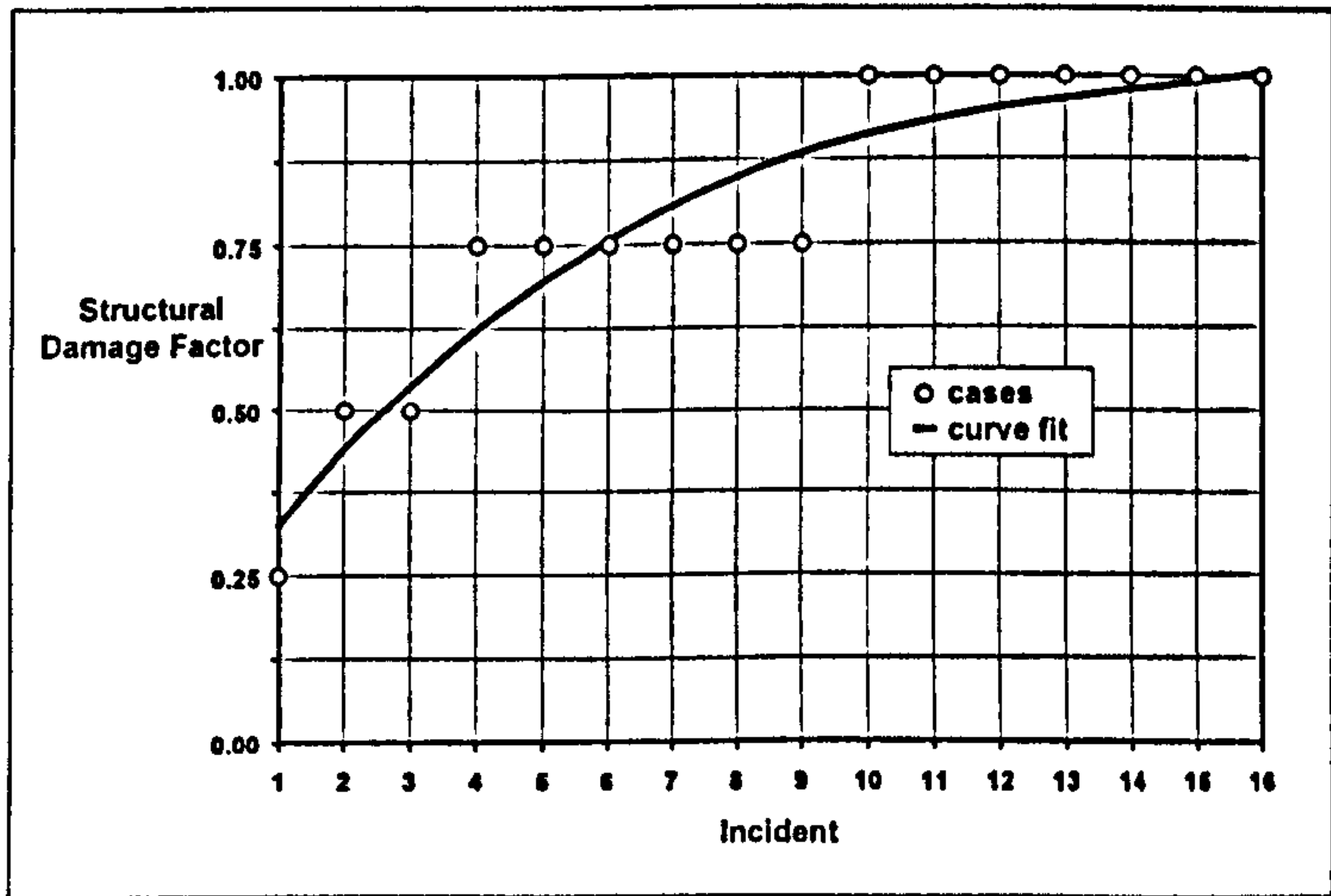


Figure C.2: Fuselage Structural Damage Levels
(Fuselage in Two Pieces: Front Section)

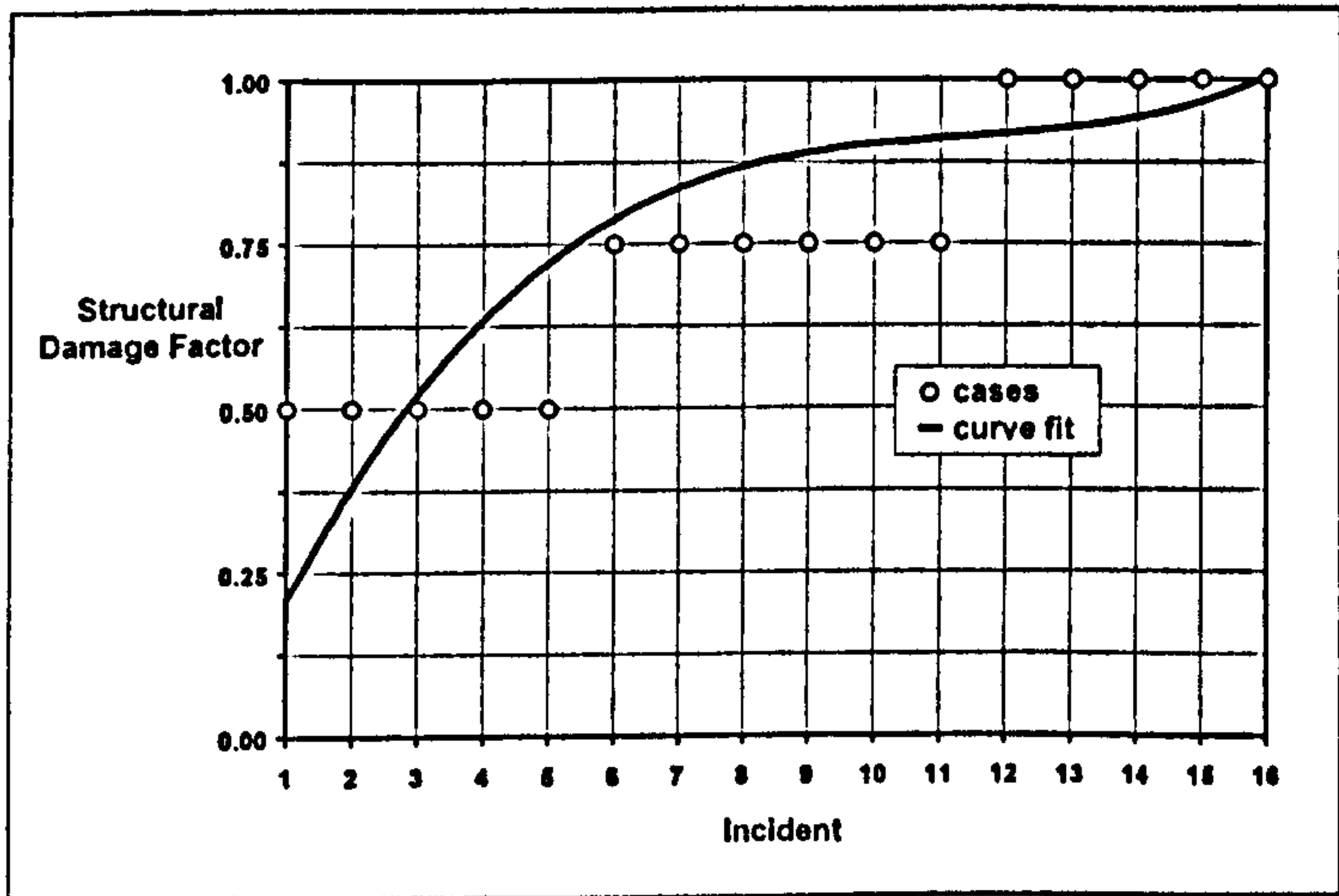


Figure C.3: Fuselage Structural Damage Levels
(Fuselage in Two Pieces: Rear Section)

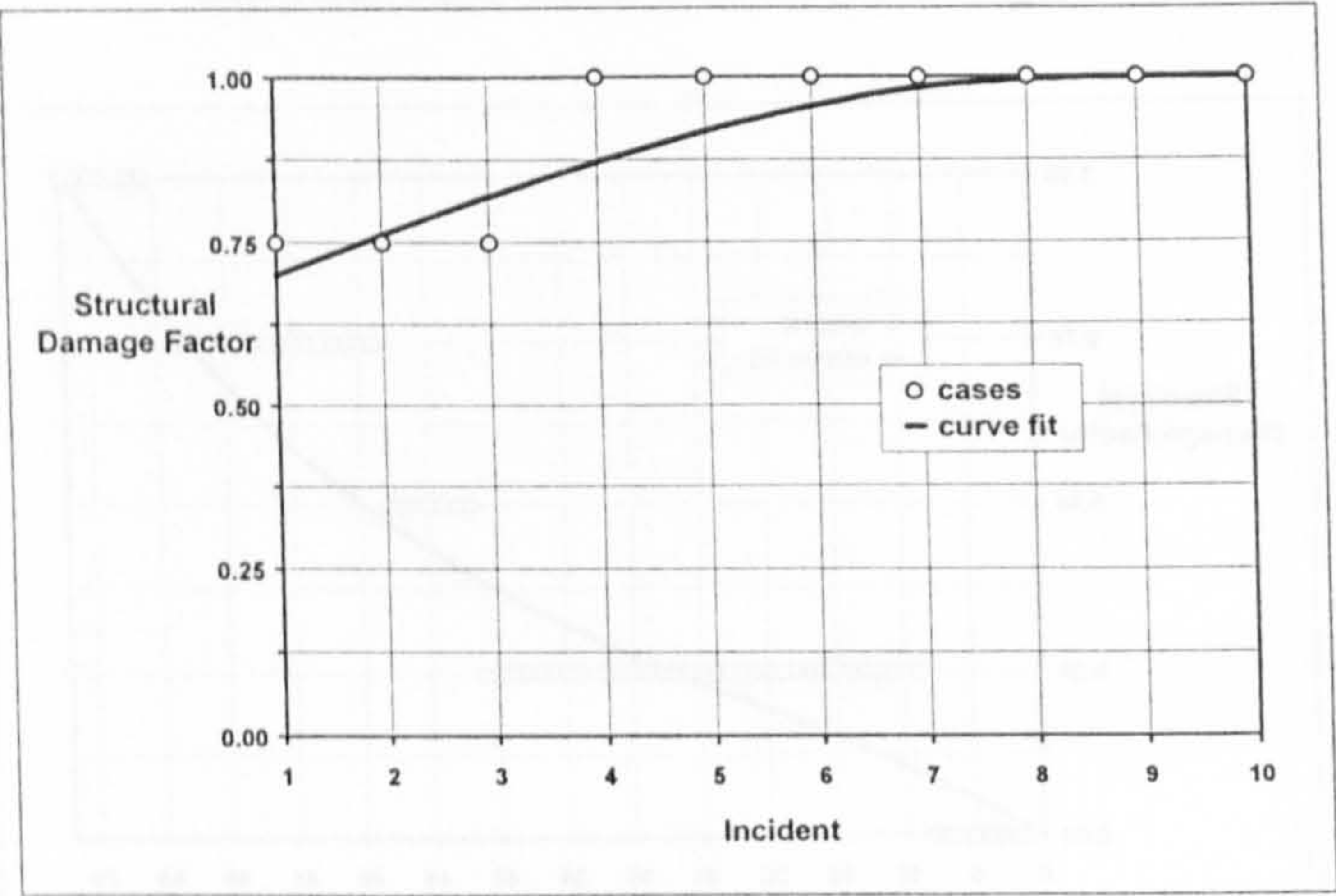


**Figure C.4: Fuselage Structural Damage Levels
(Fuselage in Three Pieces: Front Section)**



**Figure C.5: Fuselage Structural Damage Levels
(Fuselage in Three Pieces: Centre Section)**

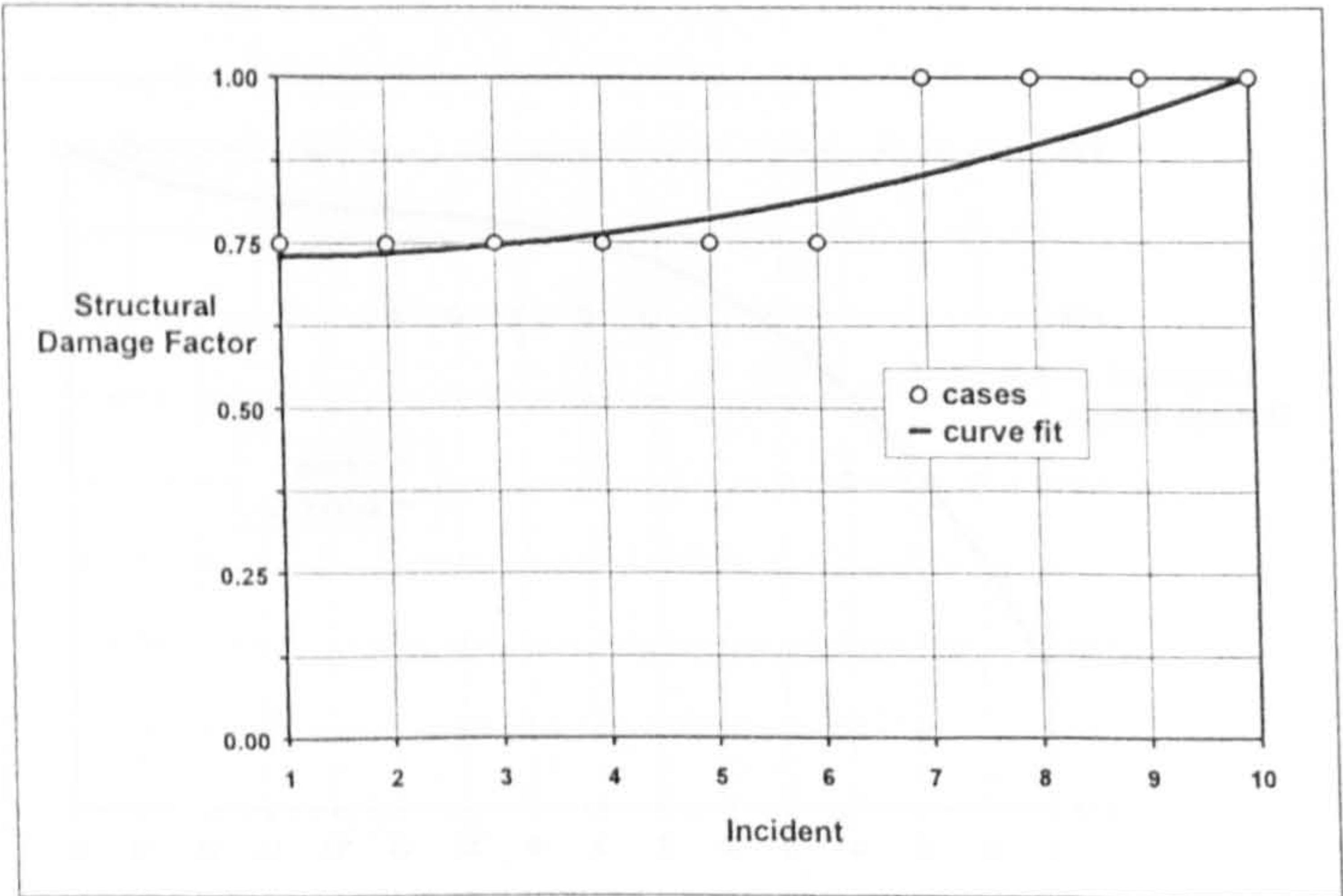


**Figure C.6: Fuselage Structural Damage Levels
(Fuselage in Three Pieces: Rear Section)**

C.2 Cabin Orientation at Different Levels of Structural Disruption

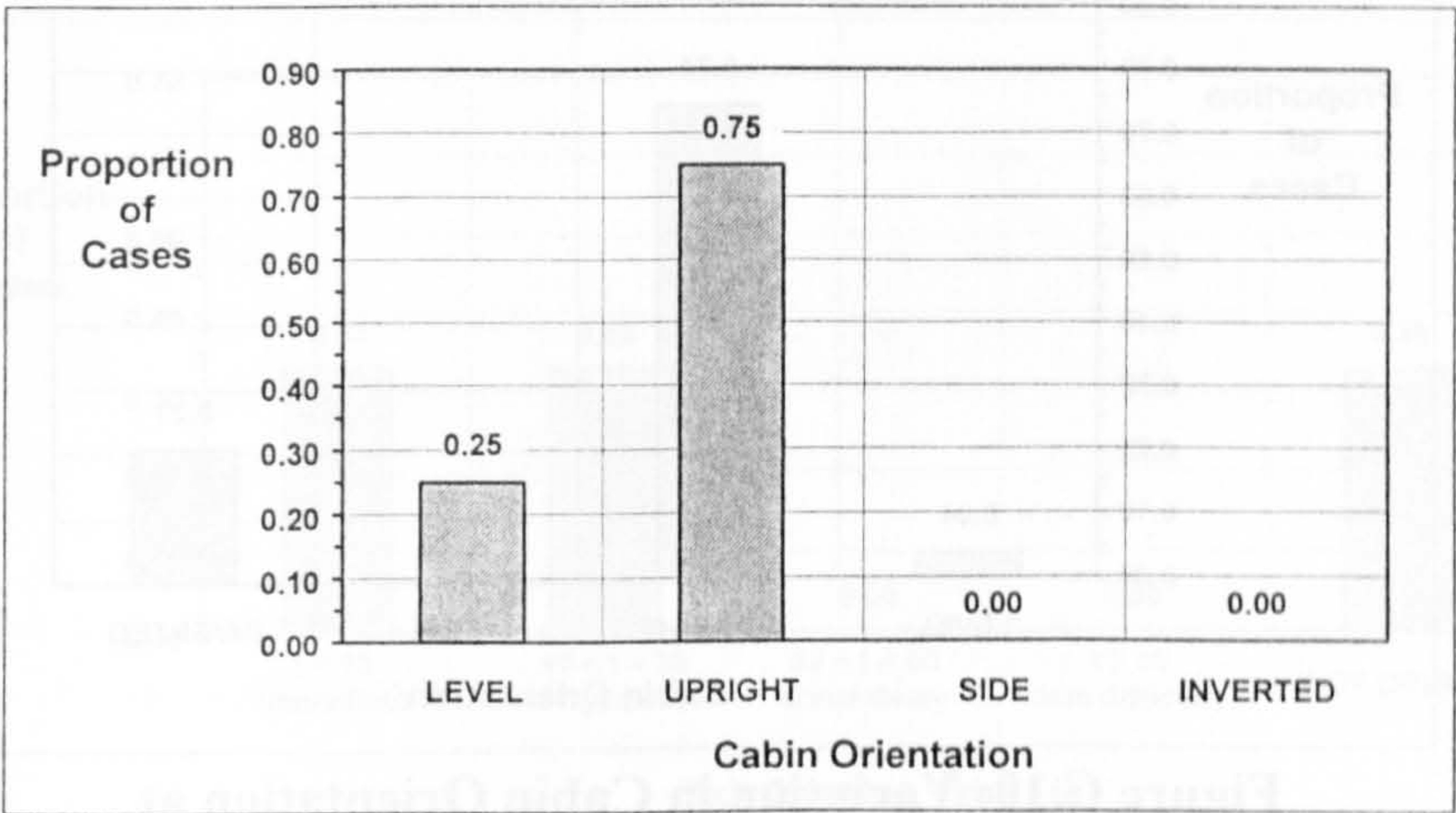


Figure C.7: Variation in Cabin Orientation at Structural Disruption Level of 0.00

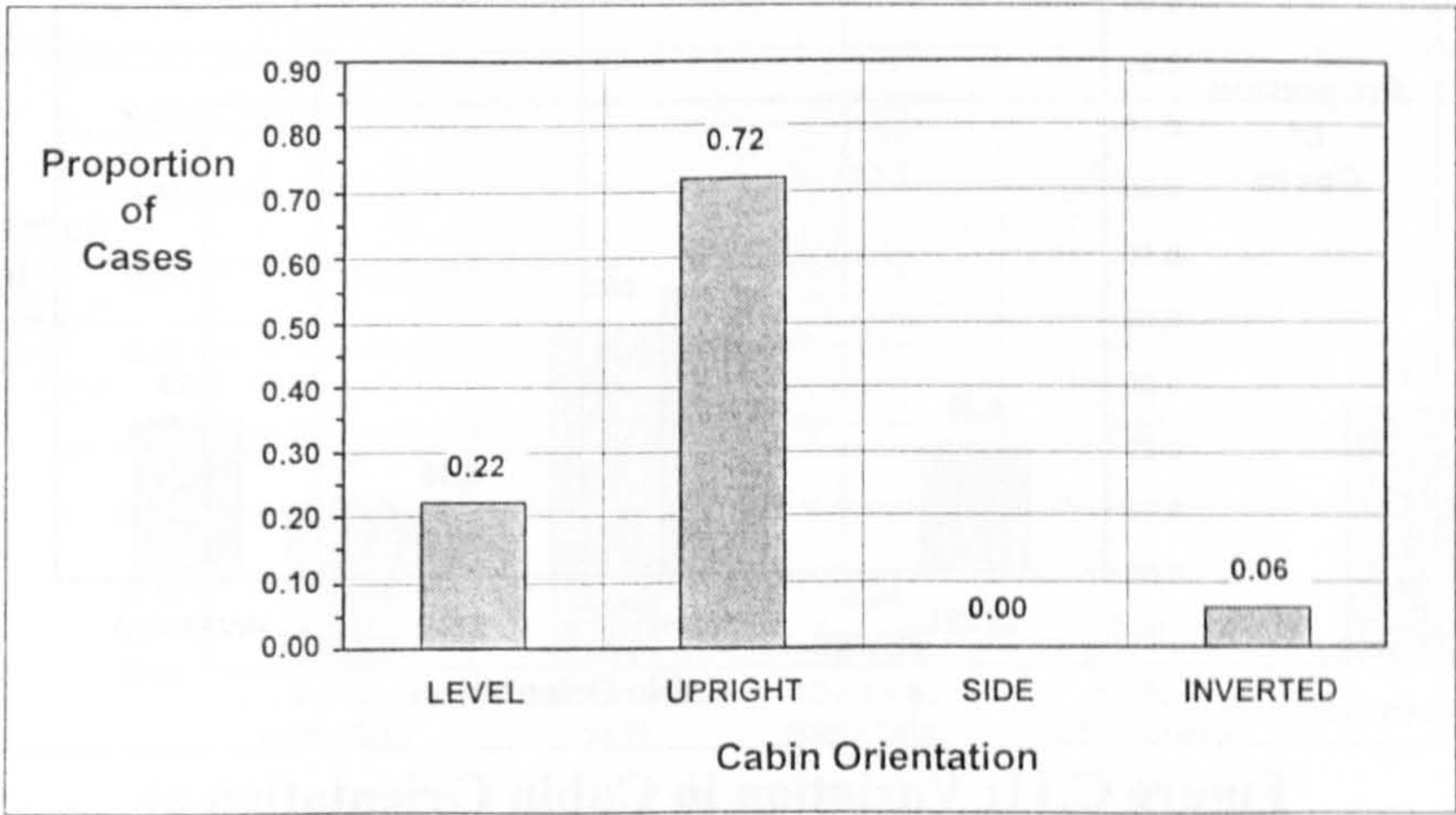


Figure C.8: Variation in Cabin Orientation at Structural Disruption Level of 0.25

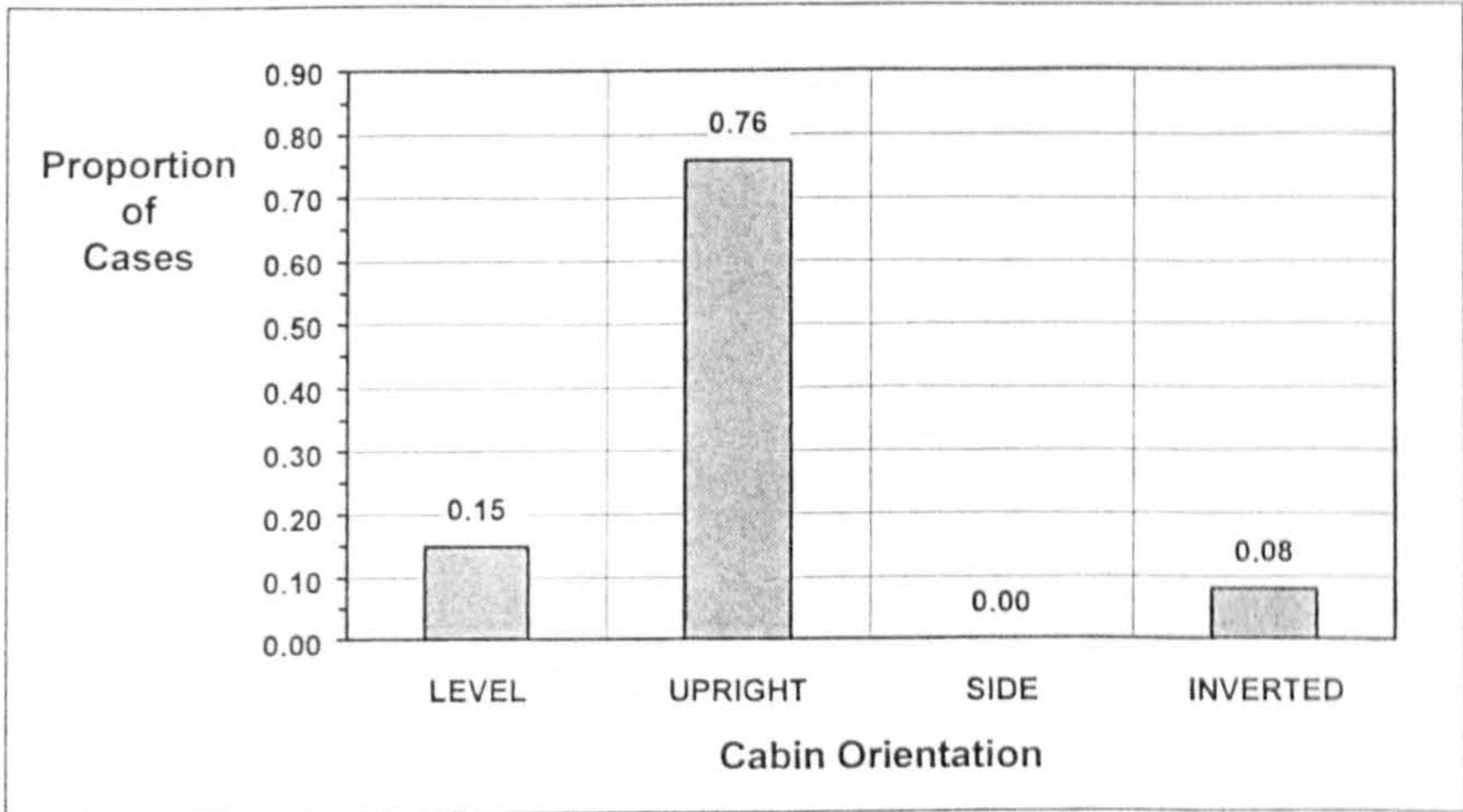


Figure C.9: Variation in Cabin Orientation at Structural Disruption Level of 0.50

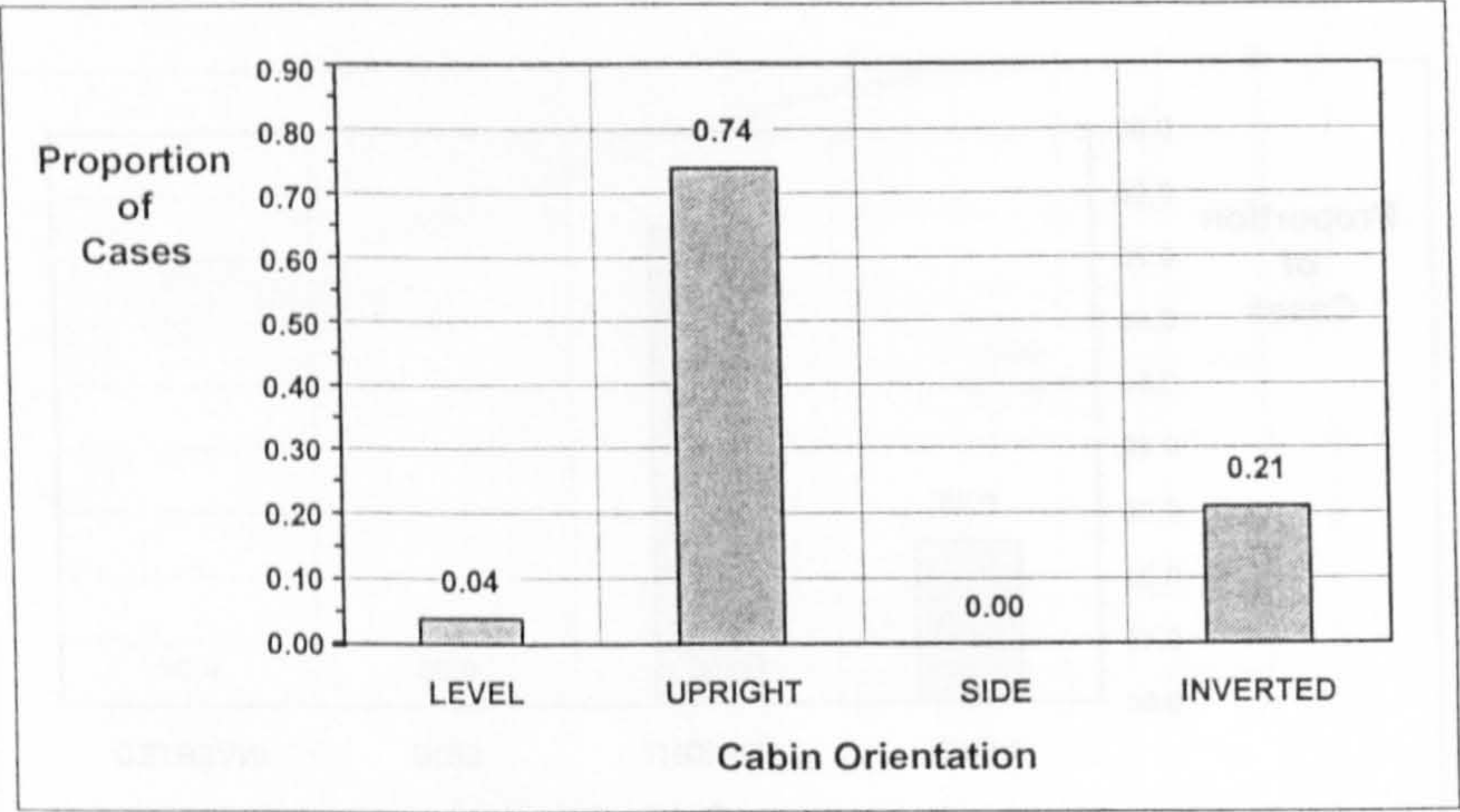


Figure C.10: Variation in Cabin Orientation at Structural Disruption Level of 0.75

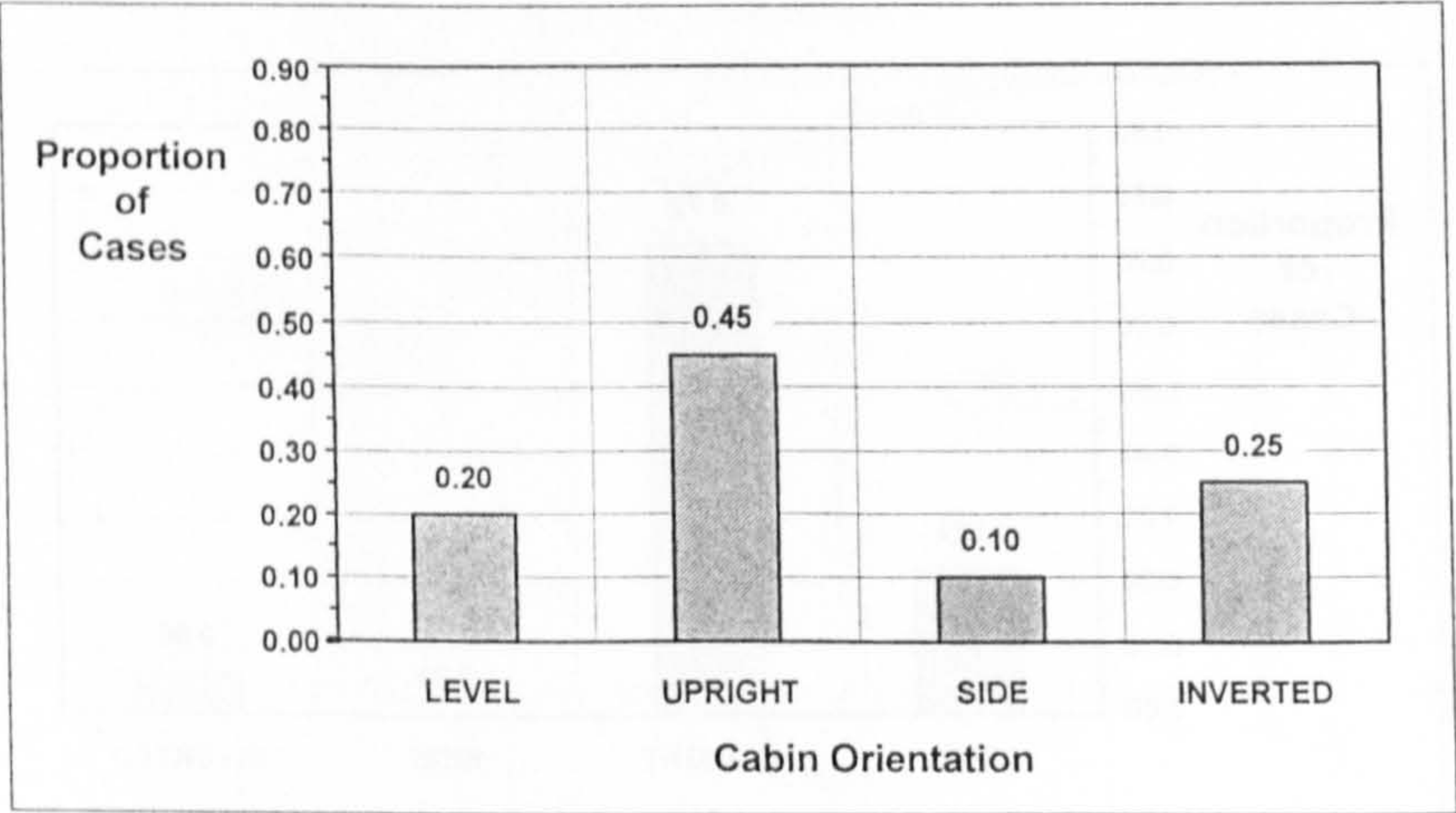


Figure C.11: Variation in Cabin Orientation at Structural Disruption Level of 1.00

C.3 Exit Opening Times at Different Levels of Structural Disruption

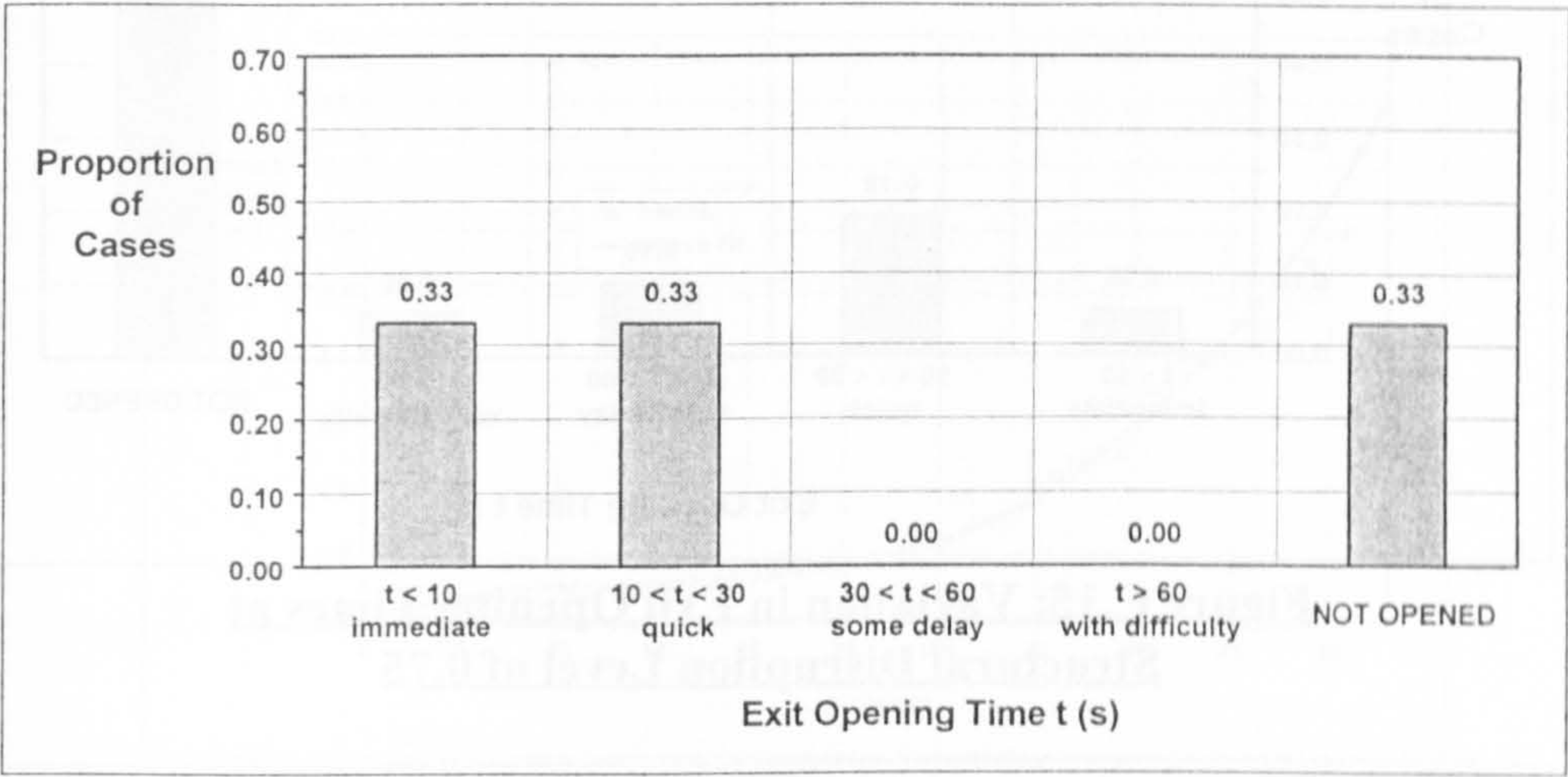


Figure C.12: Variation in Exit Opening Times at Structural Disruption Level of 0.00

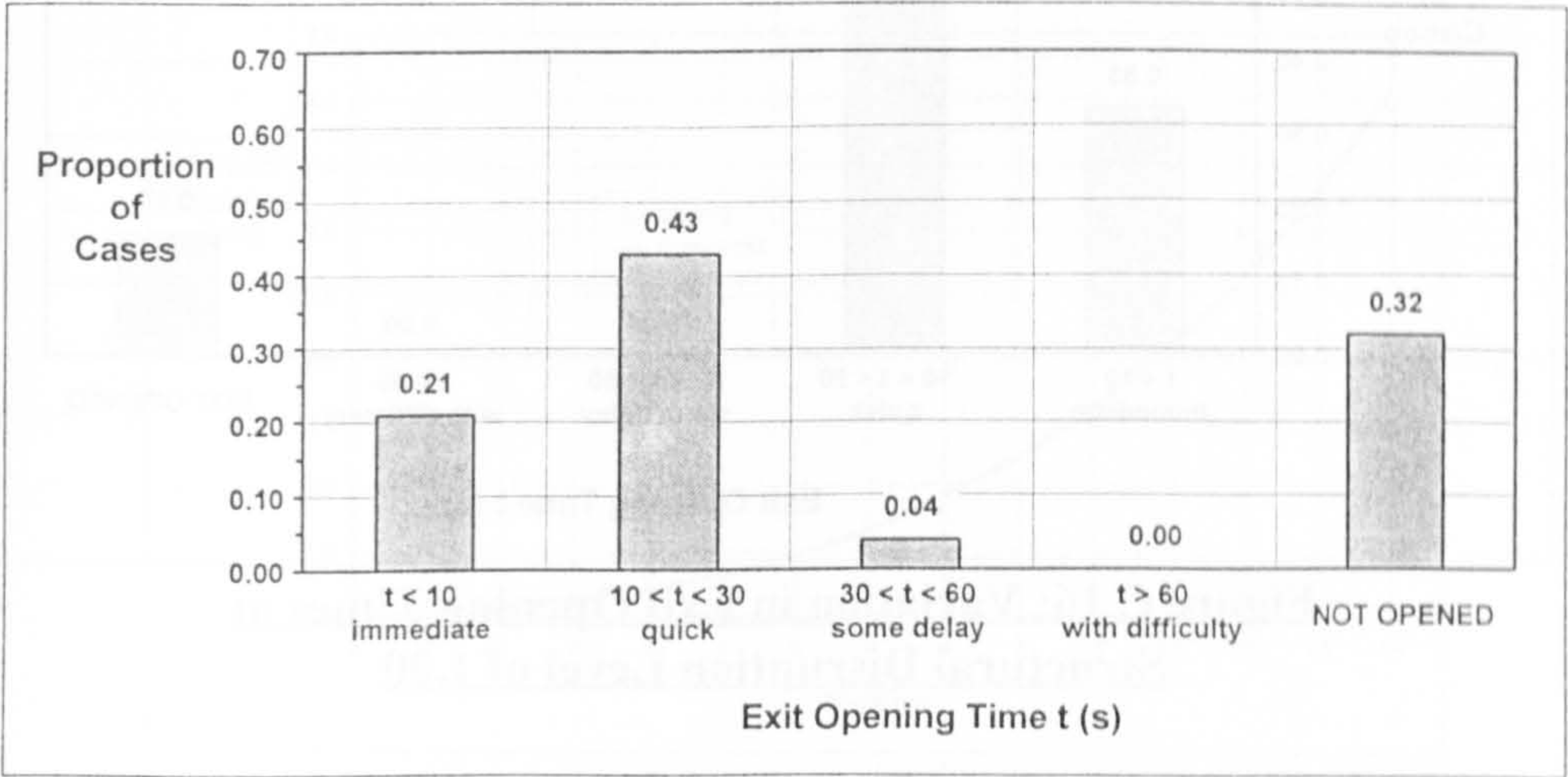


Figure C.13: Variation in Exit Opening Times at Structural Disruption Level of 0.25

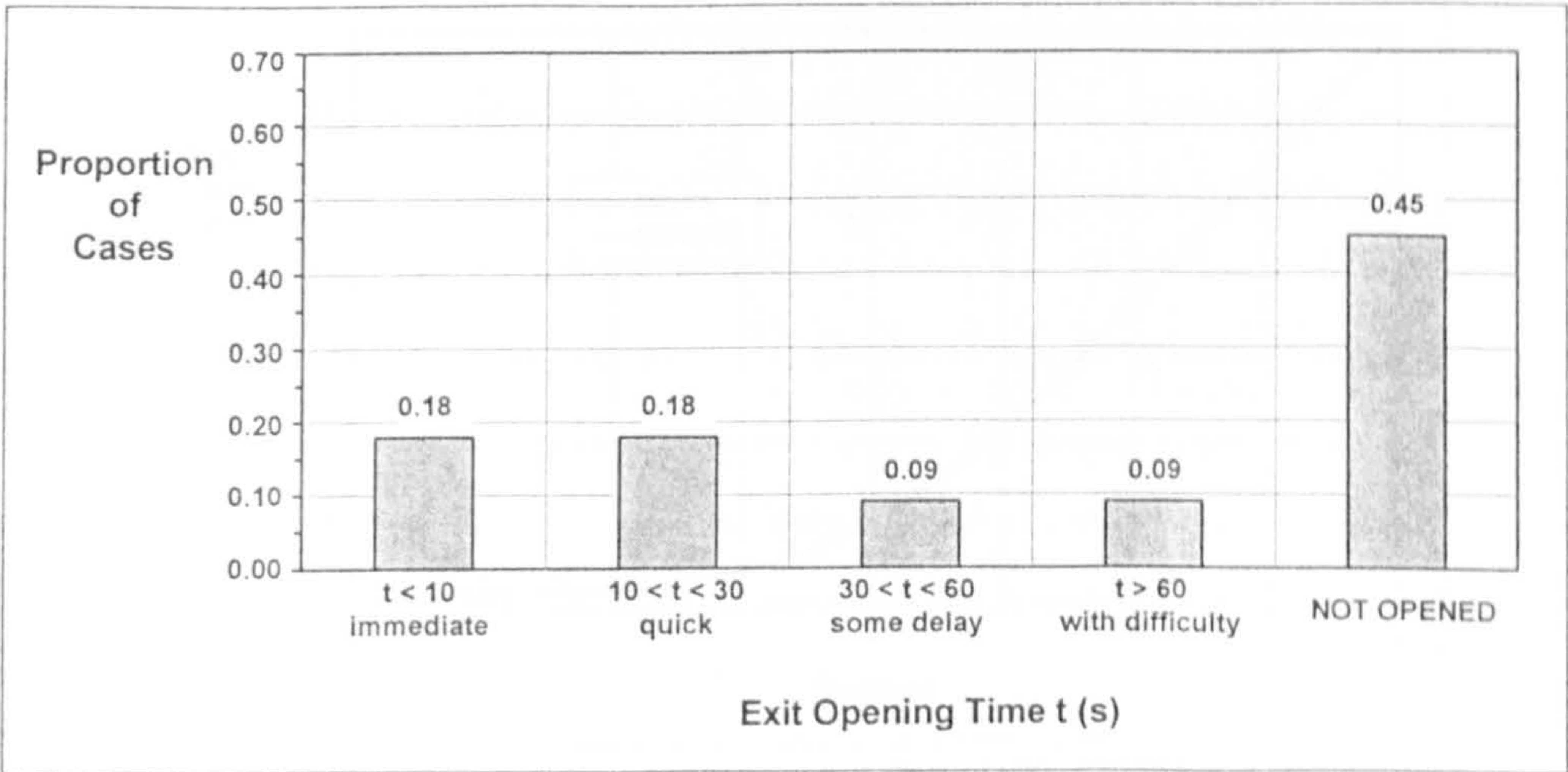


Figure C.14: Variation in Exit Opening Times at Structural Disruption Level of 0.50

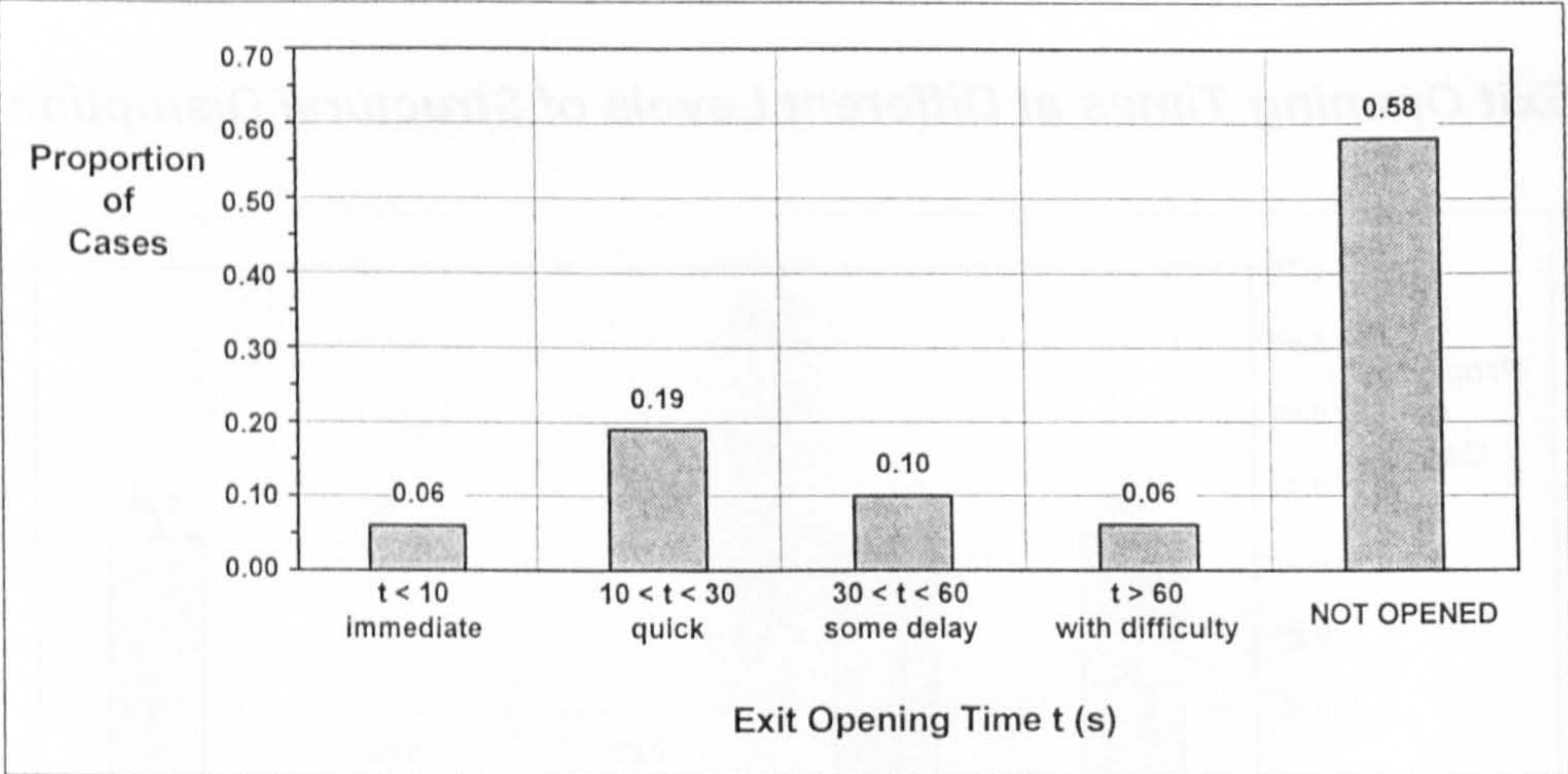


Figure C.15: Variation in Exit Opening Times at Structural Disruption Level of 0.75

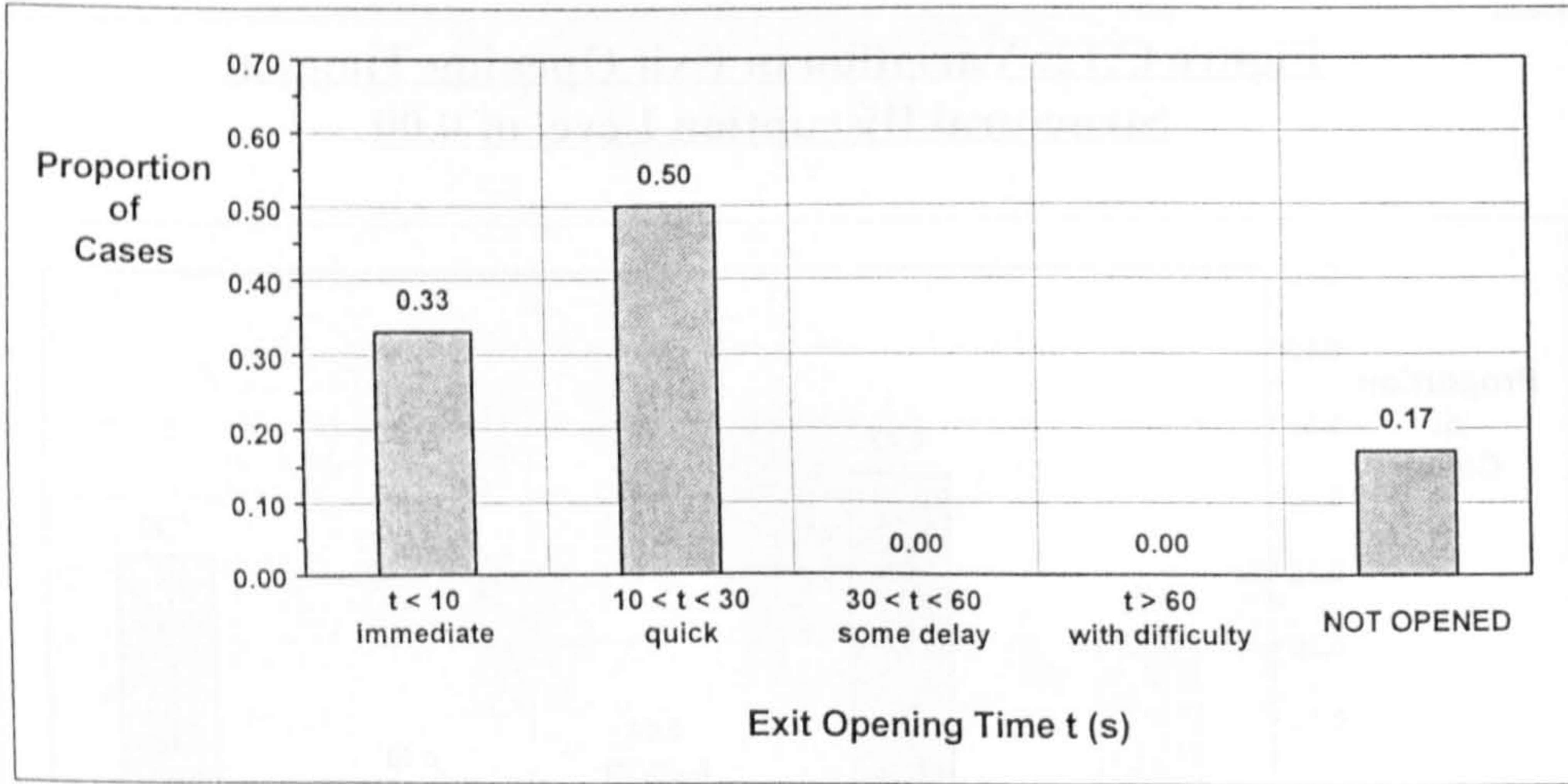


Figure C.16: Variation in Exit Opening Times at Structural Disruption Level of 1.00

C.4 Distance of Accident Site from the Airport

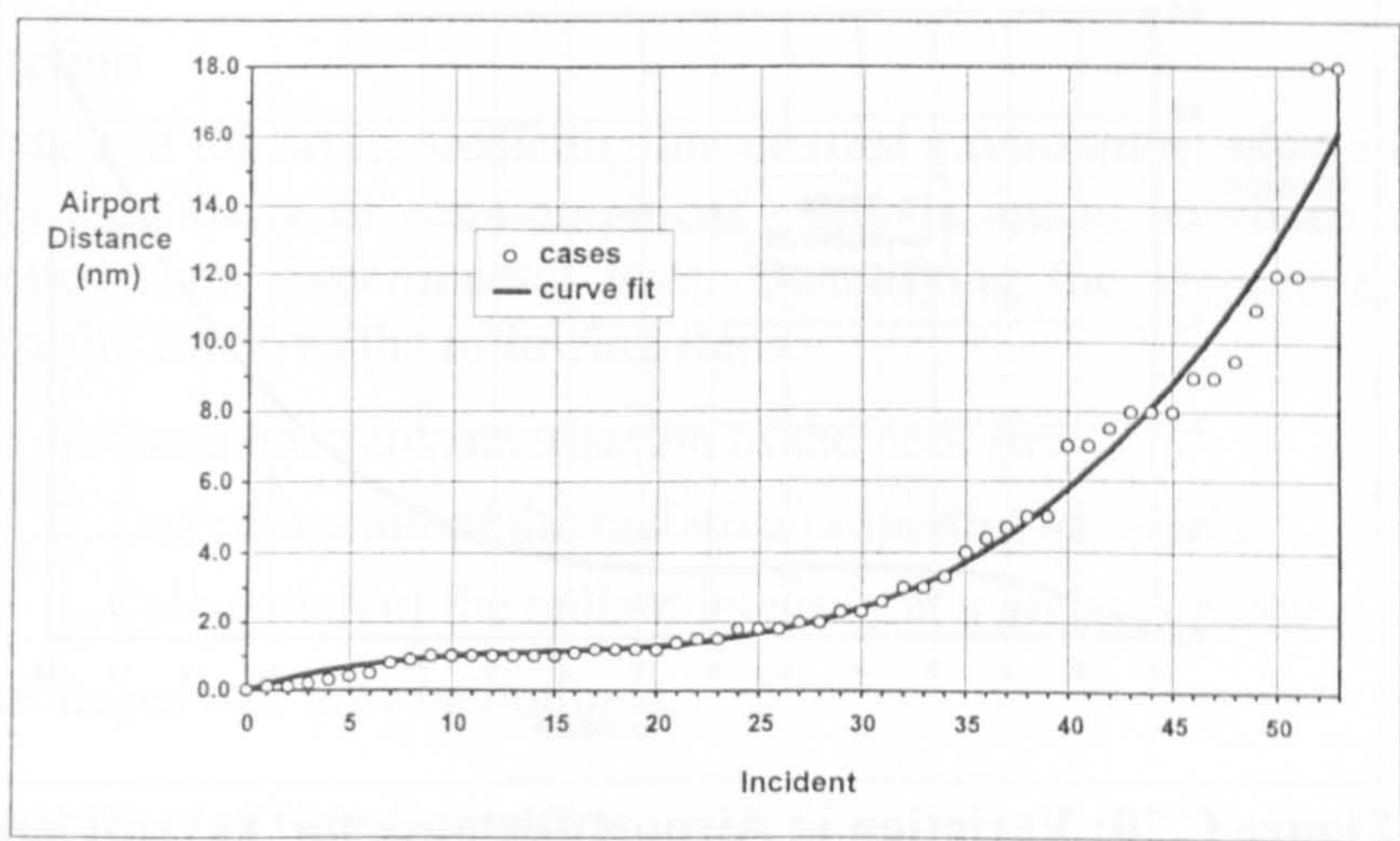


Figure C.17: Variation in Airport Distance for Landing and Approach Accidents Involving Impact Fires

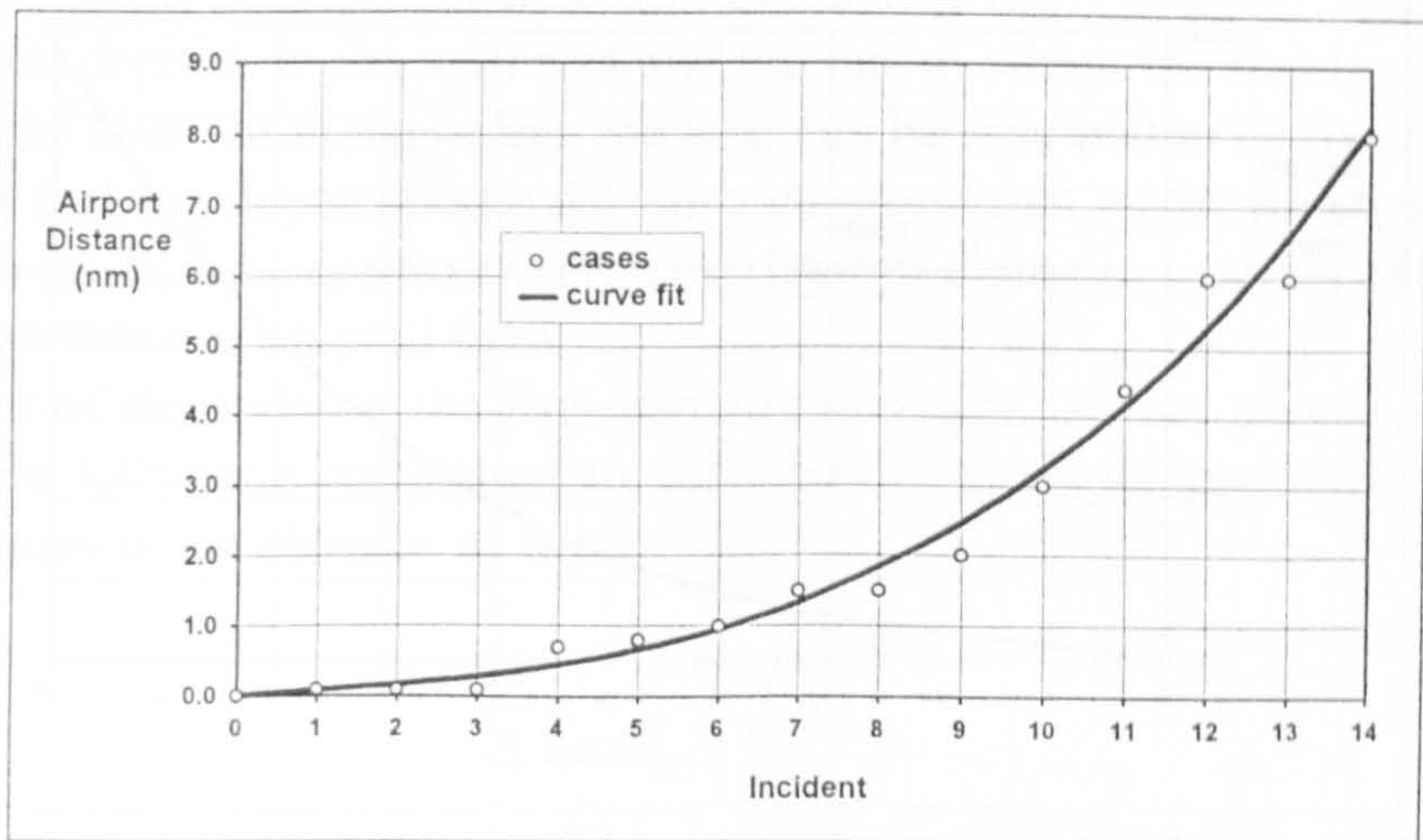


Figure C.18: Variation in Airport Distance for Landing and Approach Accidents Involving Burnthrough Fires

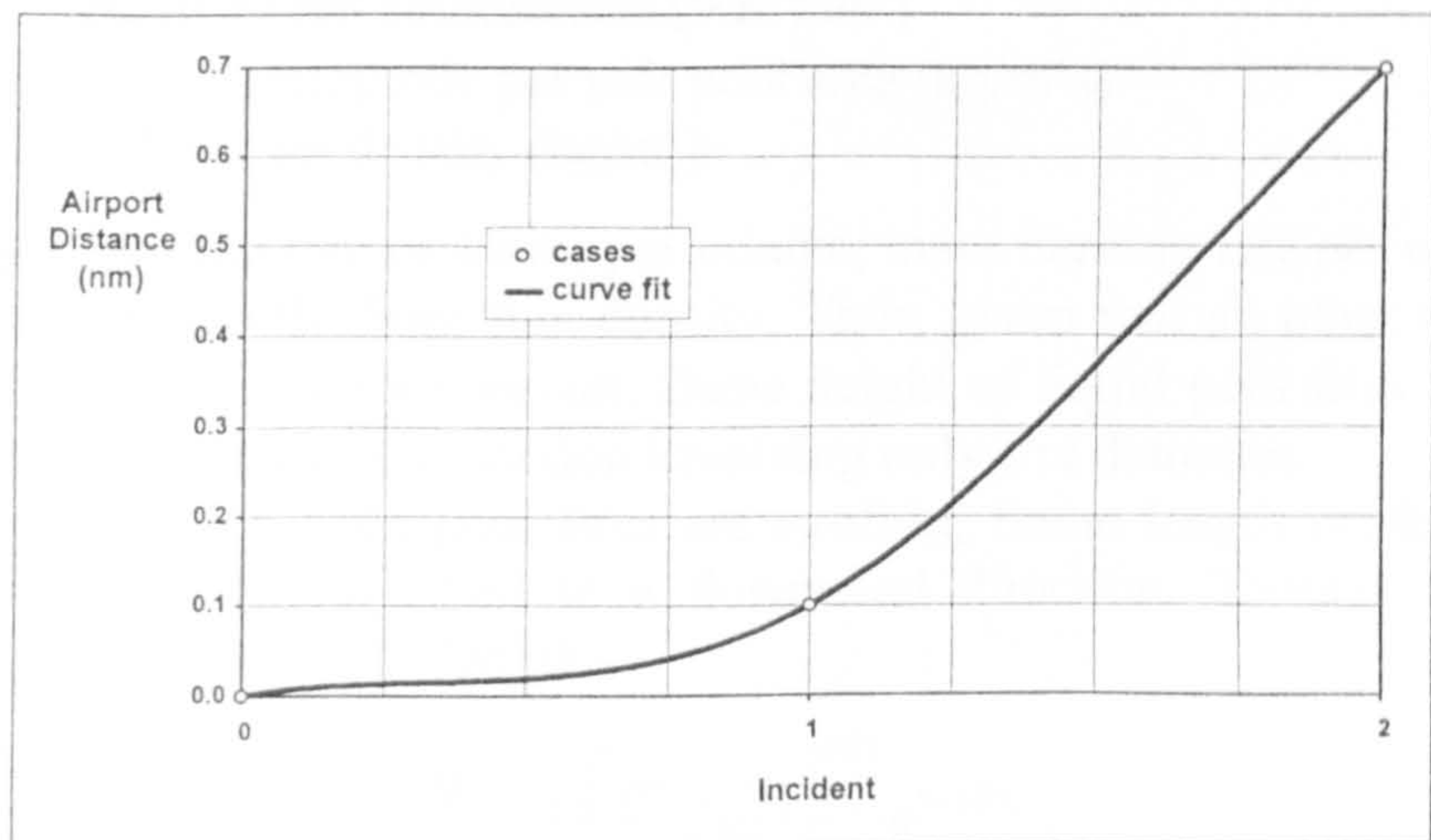


Figure C.19: Variation in Airport Distance for Landing and Approach Accidents Involving External Fires

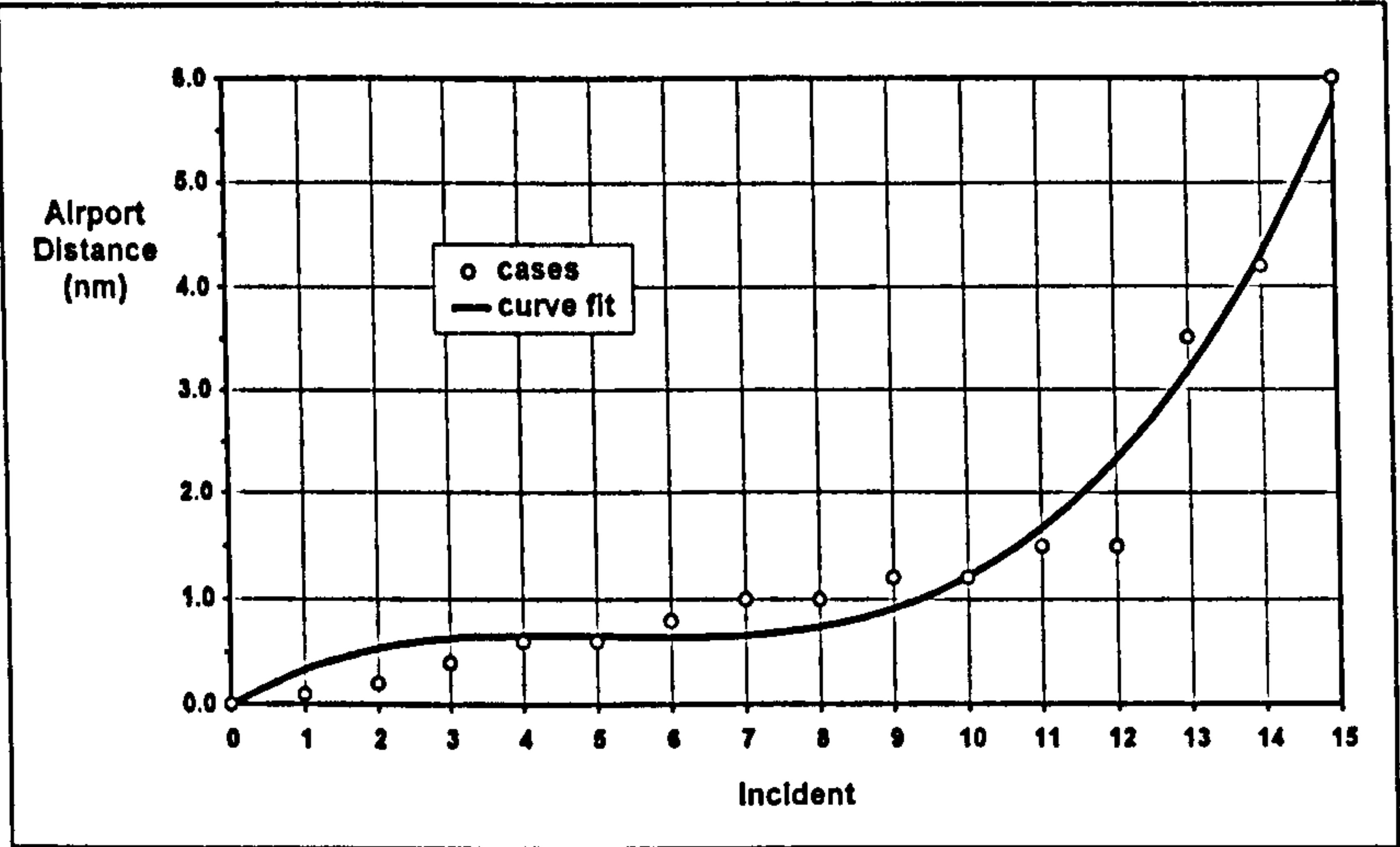


Figure C.20: Variation in Airport Distance for Takeoff and Climb Accidents Involving Impact Fires

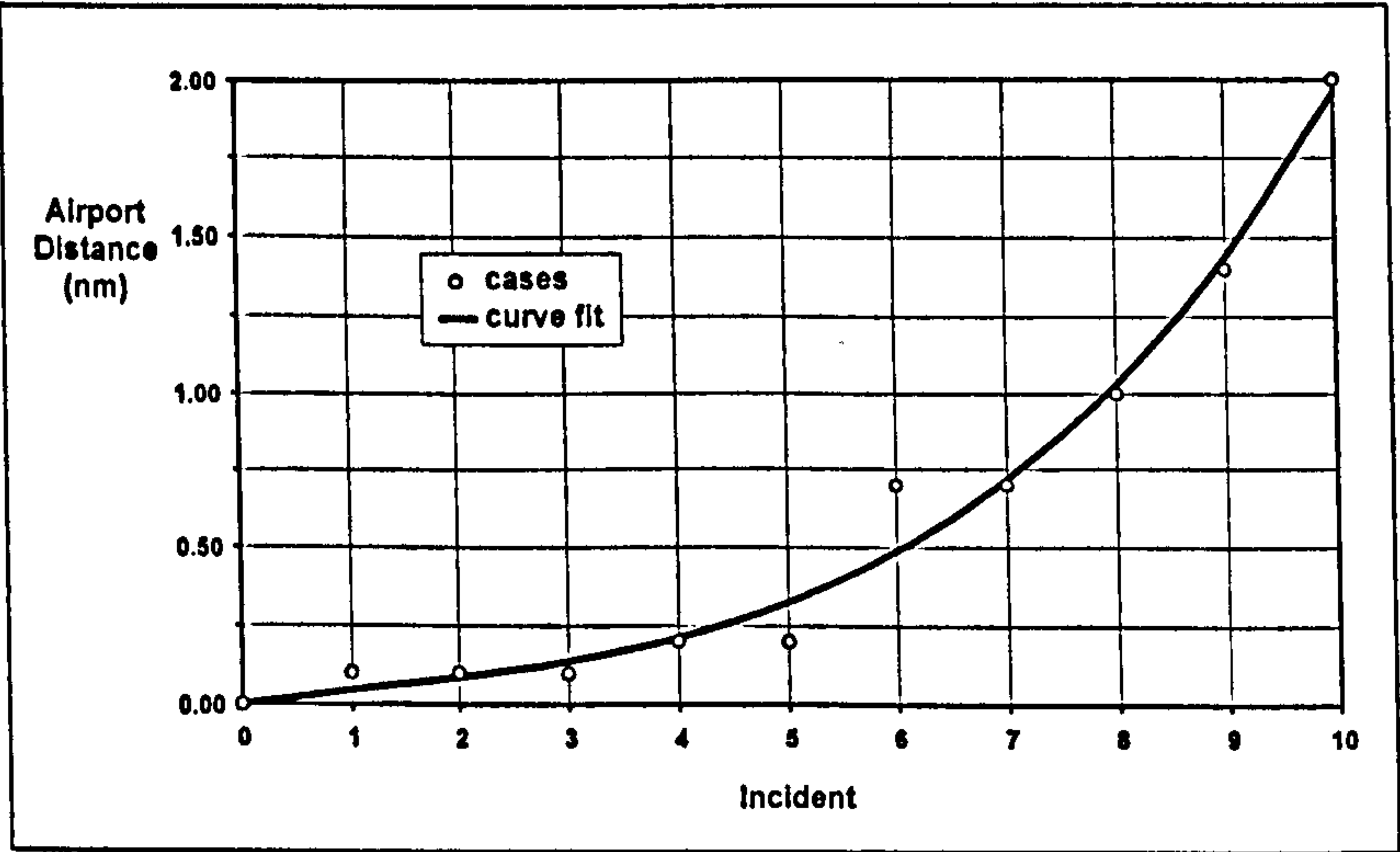


Figure C.21: Variation in Airport Distance for Takeoff and Climb Accidents Involving Burnthrough Fires

Appendix D: Thermal Radiation from Open Pool Fires

D.1 Introduction

The state of the art in predicting the thermal environment of hydrocarbon spill fires consists essentially of semi-empirical methods, many of which are based on results obtained from experimental tests. Quantifying the thermal radiation field surrounding a fire involves the following steps:-

1. Geometric characterisation of the pool fire
2. Determination of the radiative properties of the fire
3. Calculation of the radiant intensity at a given position

Each of these stages will now be outlined.

D.2 Representation of Fire Geometry

The geometry of fire consists of the average size of the visible flame envelope. Generally, this is approximated by assuming that flames are a solid grey emitter and form a well defined shape, such as a right circular or tilted cylinder. The diameter of flames present depend on the spill size and the rate at which the fuel burns. For larger fires (i.e. those over 1m in diameter), the later can be assumed to be fixed at a value of about 4 mm fuel depth per minute for most common fuel types. This enables simple differential models to be constructed to describe fire diameter in terms of original spill size, fuel flow rate and elapsed time.

Flame height of depends on the fire diameter and type of fuel present. Thomas has developed the following correlation to describe the mean visible height of turbulent diffusion flames in the absence of wind:-

$$\frac{H}{D} = 42 \left[\frac{\dot{m}}{\rho} \sqrt{gD} \right]^{0.61} \quad (\text{D.1})$$

where

H = flame height (m)

D = flame diameter (m)

g = gravitational acceleration (9.81 m/s^2)

$\dot{m}$ = mass burning rate per unit pool area ($\text{kg/m}^2\text{s}$)

ρ = ambient air density (kg/m^3)

By assuming a burning rate of 4 mm per minute, mass burning rate per unit pool area can be calculated directly from fuel density. Thus, given that all other terms can be assumed to be approximately constant, flame height of liquid pool fires in zero wind conditions can be reduced to a function involving only fire diameter.

The effects of wind on open pool fires are twofold; flame length is altered and the vertical axis of the fire is tilted in a downwind direction. Thomas provides the following correction for flame length:-

$$\frac{H}{D} = 55 \left[\frac{\dot{m}}{\rho} \sqrt{gD} \right]^{0.67} u^{\star -0.21} \quad (\text{D.2})$$

where is $u^{\star}$ the non-dimensional wind velocity given by

$$u^* = u_w / \left(\frac{g \dot{m} D}{\rho} \right)^{\frac{1}{3}} \quad (\text{D.3})$$

where u_w is wind velocity in m/s.

The American Gas Association provide the following expression for determining flame tilt in wind:-

$$\cos \theta = \begin{cases} 1 & \text{for } u^* \leq 1 \\ 1/\sqrt{u^*} & \text{for } u^* \geq 1 \end{cases} \quad (\text{D.4})$$

where θ is the angle of tilt from the vertical, as measured in the downwind direction. Equations D.1 - D.4 enable the geometry of open pool fires to be modelled in the form of a sheared circular cylinder, as shown in Figure D.1. For a given fuel type, the

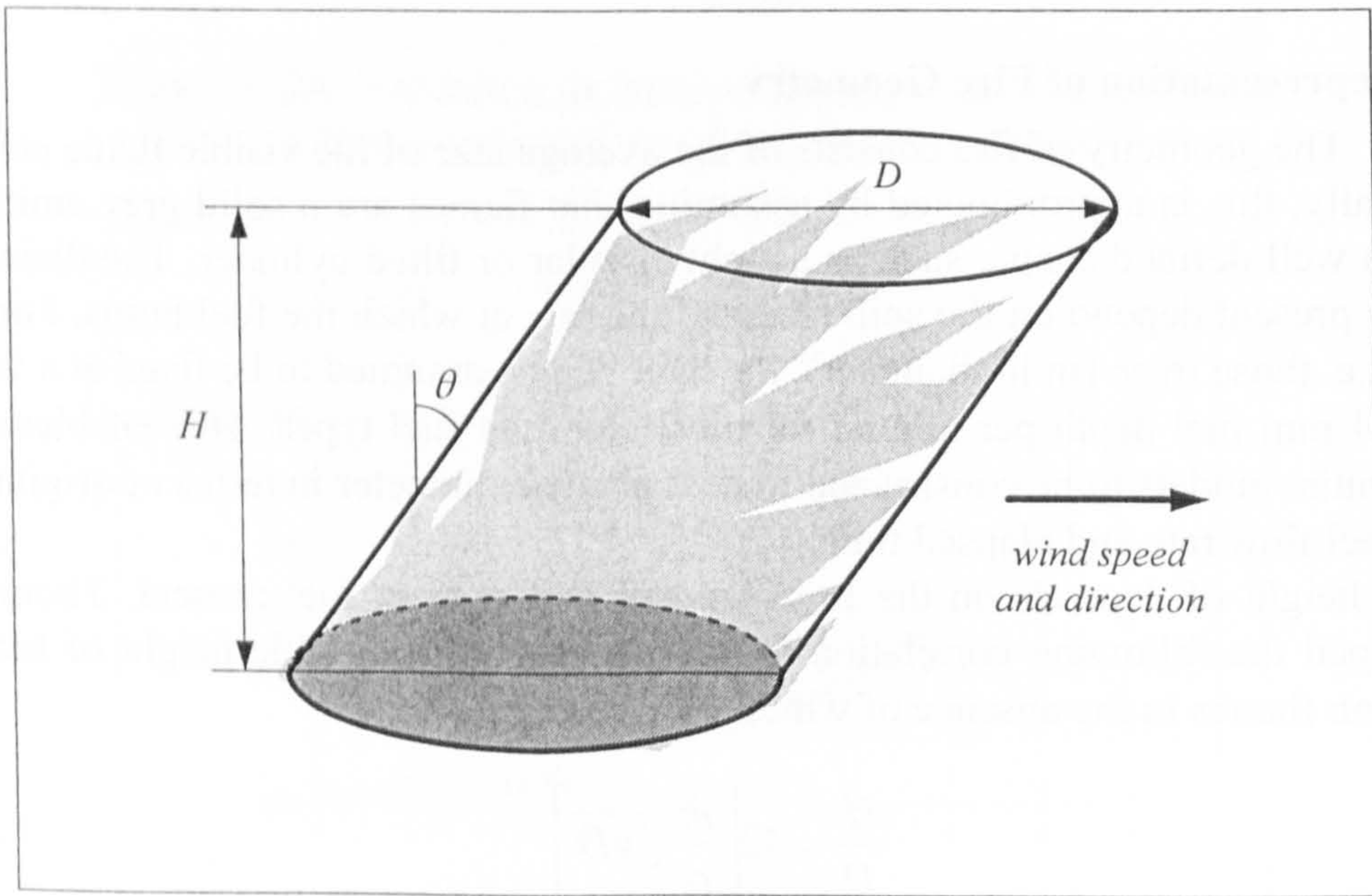


Figure D.1: Cylindrical Model of Fire Geometry

proportions of this cylinder are effectively determined by only three variables, namely equivalent flame diameter, wind speed and wind direction.

D.3 Radiative Properties of Pool Fires

The thermal radiation properties of pool fires can be estimated by two methods. The first of these is the point source model, which takes no account of the geometric size of a fire. Consequently, it can be formulated on the basis of the following three assumptions:-

1. The flame can be represented by a small (point) source of thermal energy;
2. The energy radiated from the flame is a specified fraction of the total energy released during combustion; and
3. The thermal radiation intensity varies proportionately with the inverse square of the distance from the source.

Although this model is elegant in its simplicity, it possesses two important limitations. Firstly, it is not possible to derive the fraction of combustion energy radiated by a fire to its surroundings by theoretical means. Experimental tests show that this fraction can vary greatly with fuel type and fire size. For example, in the case of gasoline fires ranging from 1.0 to 10 meters in diameter, the fraction of energy radiated varies from 60.0 to 10.1 percent respectively. The second limitation of the point source model is that values of thermal radiation intensity are overestimated at locations close to the fire. This is because near field radiation levels are influenced significantly by flame size, shape and tilt, of which no account are taken.

The solid flame thermal radiation model is based on the proposition that thermal radiation emissions are proportional to the size of the visible flame volume. This implies that non-visible gases do not emit significant quantities of radiation, a fact that has been confirmed by experimentation. The thermal radiation intensity, $\dot{q}$, to an element outside of the flame envelope is given by the equation:-

$$\dot{q} = \tau EF \tag{D.5}$$

where τ is the atmospheric transmissivity, E is the average emissive power of the flame and F is the view factor present. The estimation of these three parameters will now be addressed.

D.4 Atmospheric Attenuation

The transmission of thermal radiation through air varies primarily as a function of the distance (or path length) involved. Radiation is attenuated by absorption and scattering, chiefly as result of water vapour and carbon dioxide present

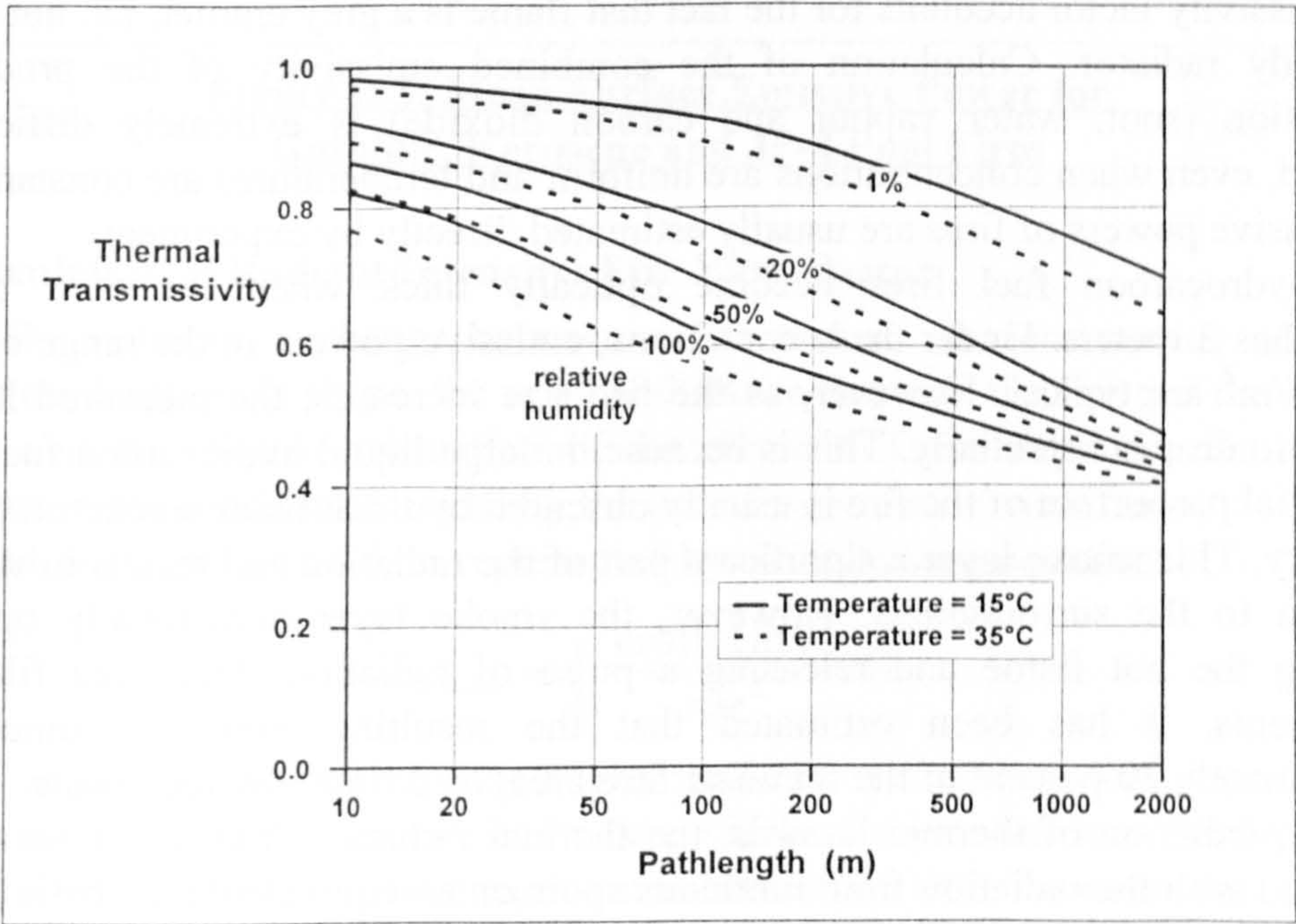


Figure D.2: Atmospheric Transmissivity for a 1400 K Thermal Radiation Source

in the atmosphere. This process occurs at a number of discrete absorption frequencies, the bandwidths of which must be integrated in order to obtain the total level of attenuation present. Results of this type of transmissivity calculation are illustrated in Figure D.2 for a continuum source possessing a temperature of 1400 K, typical of a

large hydrocarbon pool fire. It can be seen that attenuation levels vary widely with atmospheric water vapour content (a function of ambient temperature and relative humidity levels).

D.5 Heat Emission from Flames

The emissive power of a flame is most important parameter in the solid flame model. The thermal radiation from a fire emanates from both gaseous species, such as water vapour, carbon dioxide and carbon monoxide as well as from luminous soot particles. Gaseous species emit radiation in discrete spectral bands, whereas the soot radiation is continuous over the entire spectral range of importance.

The emissive power of a large turbulent fire is often approximated by the following expression:-

$$E = E_b \epsilon \quad (D.6)$$

where E_b is blackbody emissive power (kW/m^2) and ϵ is emissivity. If the mean radiation temperature of a fire is known (which is significantly less than the adiabatic flame temperature), it's irradiance can be obtained from Planck's law of radiation:-

$$E_b = \sigma (T_f^4 - T_a^4) \quad (D.7)$$

where

T_f = radiation temperature of the flame (K)

T_a = ambient temperature (K)

σ = Stefan-Boltzmann constant ($\text{kW/m}^2\text{K}^4$)

The emissivity factor accounts for the fact that flame is a grey emitter, i.e. not an ideal blackbody radiator. Calculation of the combined emissivity of the products of combustion (soot, water vapour and carbon dioxide) is extremely difficult and involved, even when concentrations are uniform and temperatures are constant. Thus, the emissive powers of fires are usually estimated directly by experiment.

Most hydrocarbon fuel fires become optically thick when their diameter approaches 3 meters. Under these conditions, emissive powers in the range of 110 to 130 kW/m^2 are typical. However, as the fire size increases, the measured heat flux appears to drop substantially. This is because, in large liquid hydrocarbon fuel fires, a substantial proportion of the fire is usually obscured by thick black smoke on the outer periphery. This smoke layer absorbs a significant part of the radiation and results in very little emission to the surroundings. However, the smoke layer occasionally opens up, exposing the hot flame and releasing a pulse of radiation. From the filming of experiments, it has been estimated that the resulting luminous zones cover approximately 20 percent of the flame surface area, on a time averaged basis.

For the prediction of thermal hazards, the thermal radiation from black soot can be combined with the radiation from luminous spots on an equivalent area basis to arrive at an average emissive power for a fire. The following correlation has been derived from experimental data for determining the average emissive power of large, sooty hydrocarbon fires:-

$$E_{average} = E_m e^{-SD} + E_s (1 - e^{-SD}) \quad (D.7)$$

where

E_m = maximum emissive power of luminous spots (approximately 140 kW/m²)

E_s = emissive power of smoke (approximately 20 kW/m²)

S = a parameter determined using experimental data (0.12 m⁻¹)

This function is illustrated in Figure D.3, together with results from the fire tests used for its calibration. Note that the experimental data has been obtained from a combination of gasoline, kerosene and JP-4 fire tests.

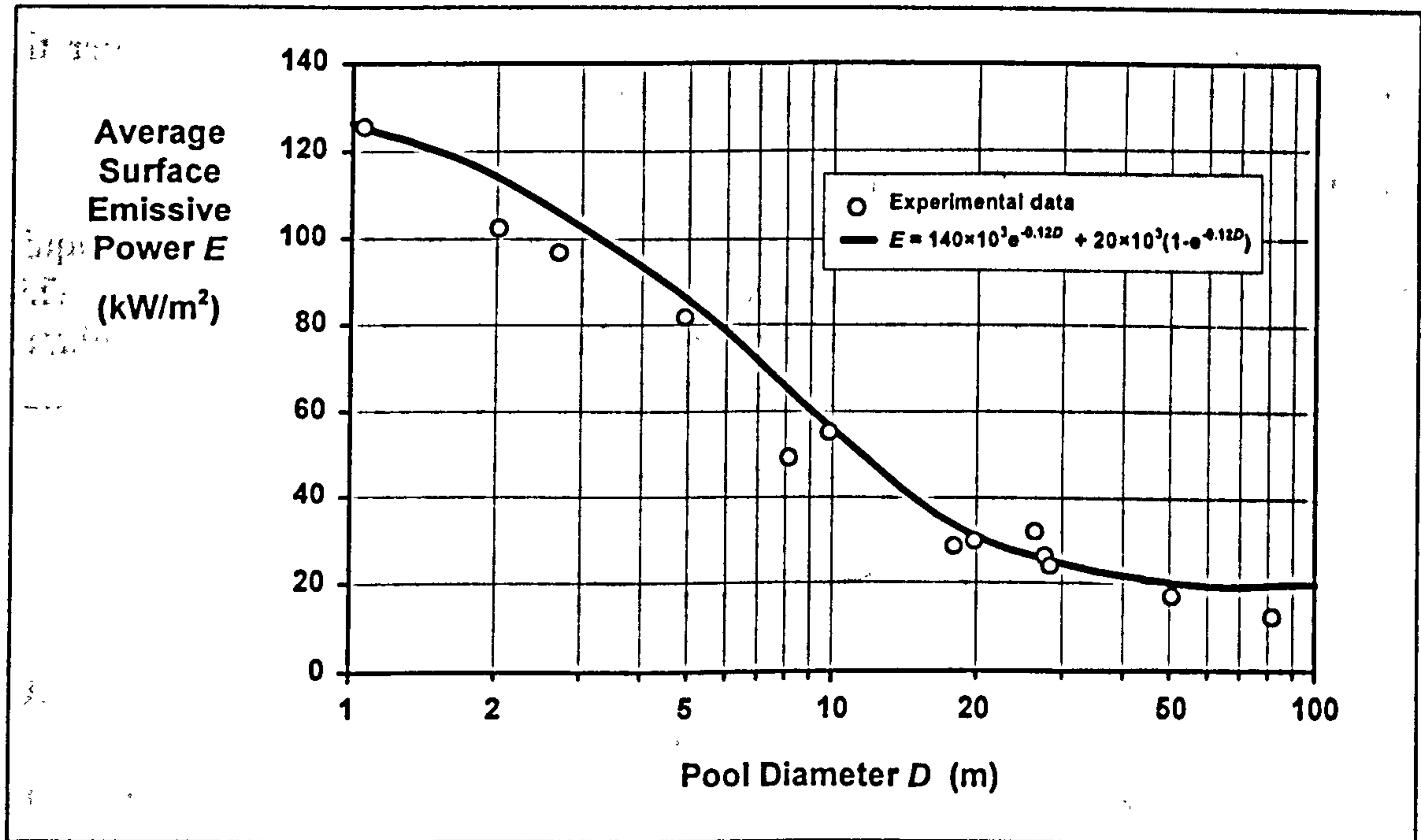


Figure D.3: Mean Surface Emissive Power for Gasoline, Kerosene and JP-4 Pool Fires

D.6 Calculation of Radiant Intensity: Fire View Factor

The radiation exchange between a fire and an element outside of the fire depends on the flame's shape, the relative distance between the fire and the receiving element and the relative orientation of the element. These dependencies are taken account of in the solid flame model by the use of a geometric view factor.

In general, the view factor, F , is represented by the following equation:-

$$F_{A_1 \rightarrow dA_2} = \oint_{A_1} \frac{\cos \theta_1 \cos \theta_2}{\pi r^2} dA_1 \quad (D.8)$$

where 1 and 2 are, respectively, the angles made by the normals and dA_1 on the fire and dA_2 on the receiving element; and where r is the distance between the fire element and the receiving element. The integration is carried out over the entire surface of the flame (A_1). In the case of a sheared cylindrical model of flame geometry, this integral can be evaluated analytically for any receiving element orientation.

In general, a maximum view factor will experienced when an element is angled somewhere between horizontal and vertical positions. This corresponds with the peak radiation intensity that can be expected to occur at some point on a rounded surface. The magnitude of the maximum view factor simply equals the vectorial sum of horizontal and vertical view factors, i.e.:-

$$F_{\max} = \sqrt{F_{\text{vertical}}^2 + F_{\text{horizontal}}^2} \quad (\text{D.9})$$

Mudan has employed a contour integral approach to determine closed form equations for view factors from a slanted cylinder of arbitrary length and radius (Mudan, 1987). These enable solid flame model view factors to be determined for a receiving surface at any orientation. Expressions for horizontal and vertical view factors for a slanted cylinder follow.

At locations very close to a fire, the maximum view factor experienced at ground level is not very sensitive to flame height. In contrast, flame cylinder tilt angles are highly significant at all distances from a fire.

D.7 Cylindrical Flame Geometry

It was seen in section D.2 that the flame geometry of an open liquid hydrocarbon pool fire can be represented by a cylinder of radius r and height h . This cylinder may be slanted through an angle θ to take account of the effects of wind, as

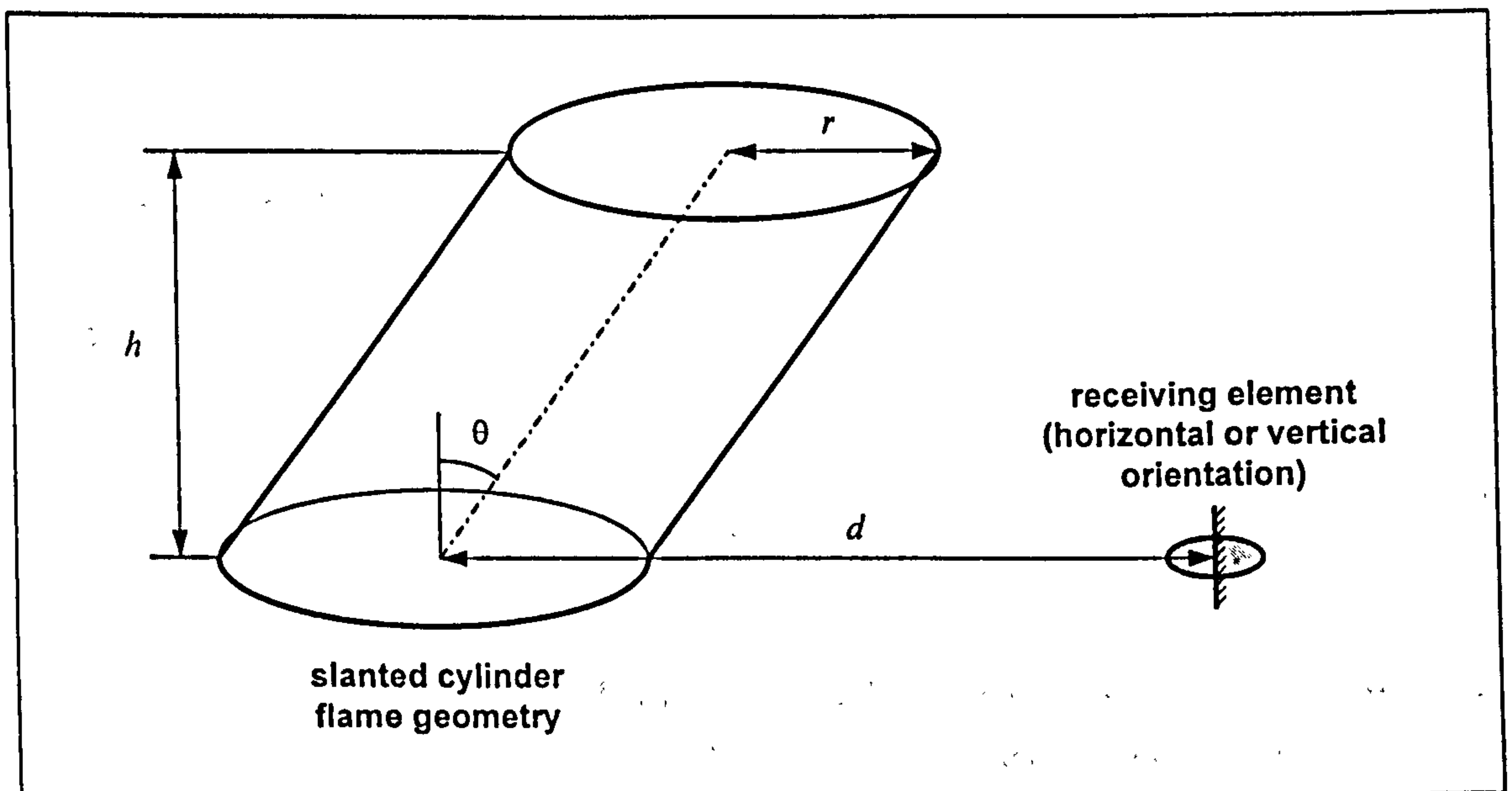


Figure D.4: Notation used in Cylindrical Flame Model

shown in Figure D.4. For the purpose of calculating the radiant properties of this flame envelope, as experienced by a receiving element positioned at ground level, two parameters need to be calculated. These are a height to radius ratio and a scaled distance of the receiving element from the fire, respectively.

The height to radius ratio of the cylinder is defined as follows:-

$$a = \frac{\text{flame height } h}{\text{flame radius } r} \quad (\text{D.10})$$

Similarly, the non-dimensional distance of a receiving element from the flame axis is defined to be:-

$$b = \frac{\text{element distance } d}{\text{flame radius } r} \quad (\text{D.11})$$

D.8 Geometric View Factor for a Vertically Inclined Element

The view factor, F_v , experienced by a vertically inclined element, situated at a distance d from the fire centre is given by the following expression (Mudan, 1987):-

$$\begin{aligned} \pi F_v = & \frac{a \cos \theta}{b - a \sin \theta} \frac{a^2 + (b+1)^2 - 2b(1 + a \sin \theta)}{\sqrt{AB}} \cdot \tan^{-1} \sqrt{\frac{A}{B} \left(\frac{b-1}{b+1} \right)^{1/2}} \\ & + \frac{\cos \theta}{\sqrt{C}} \left[\tan^{-1} \frac{ab - (b^2 - 1) \sin \theta}{\sqrt{b^2 - 1} \sqrt{C}} + \tan^{-1} \frac{(b^2 - 1) \sin \theta}{\sqrt{b^2 - 1} \sqrt{C}} \right] \\ & - \frac{a \cos \theta}{(b - a \sin \theta)} \tan^{-1} \sqrt{\frac{b-1}{b+1}} \end{aligned} \quad (D.12)$$

where

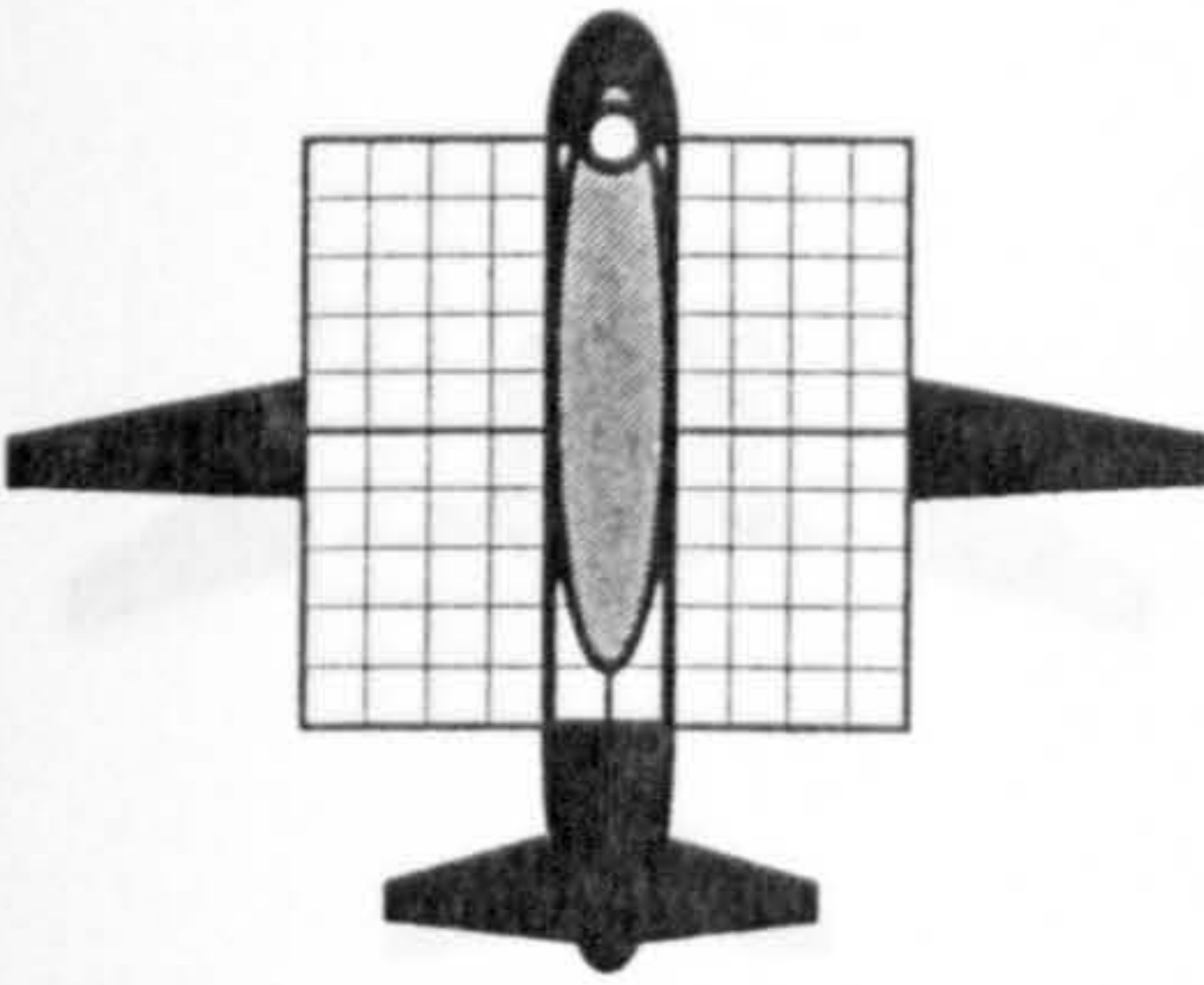
$$\begin{aligned} A &= a^2 + (b+1)^2 - 2a(b+1) \sin \theta \\ B &= a^2 + (b-1)^2 - 2a(b-1) \sin \theta \\ C &= 1 + (b^2 - 1) \cos^2 \theta \end{aligned}$$

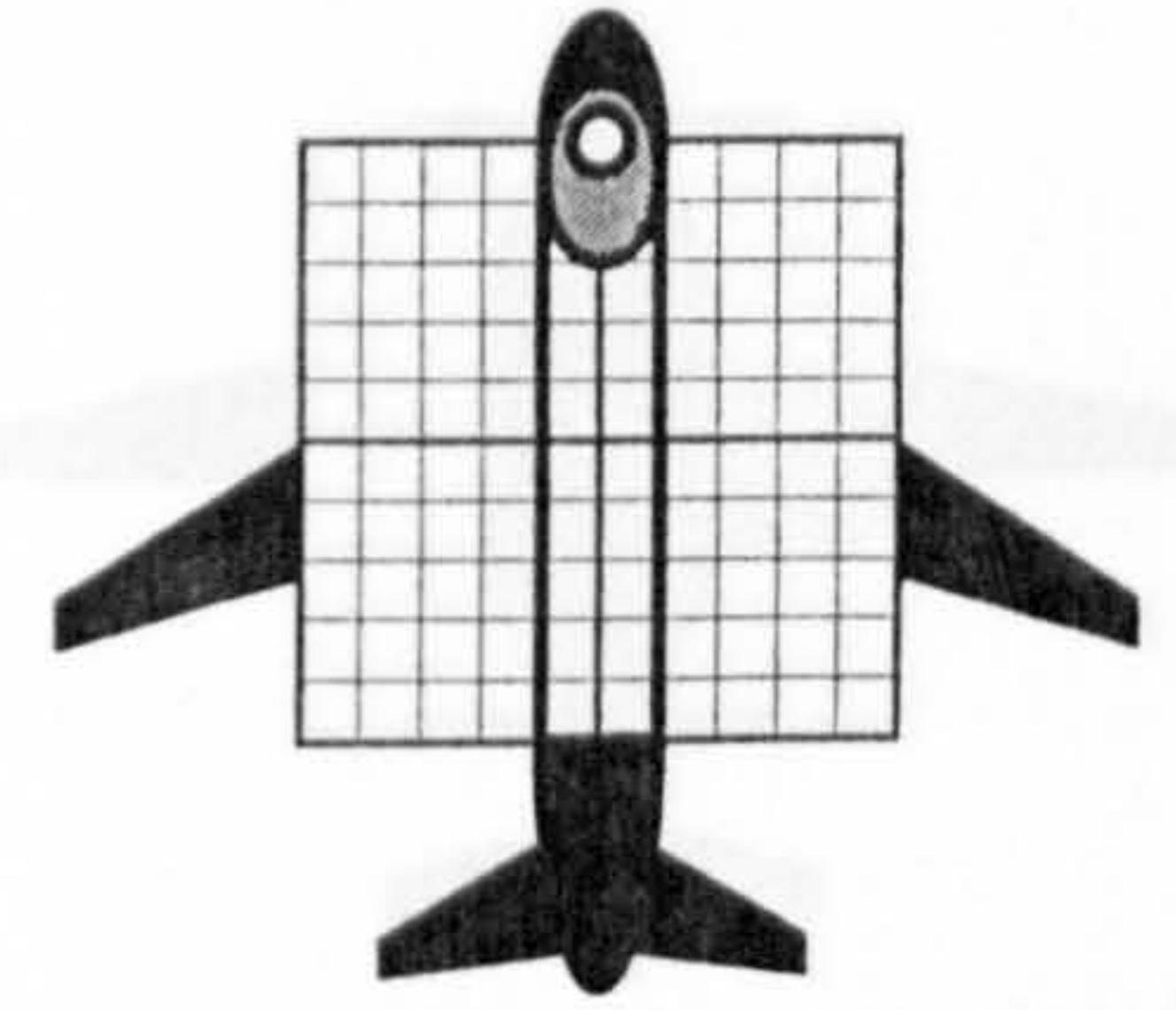
D.9 Geometric View Factor for a Horizontally Inclined Element

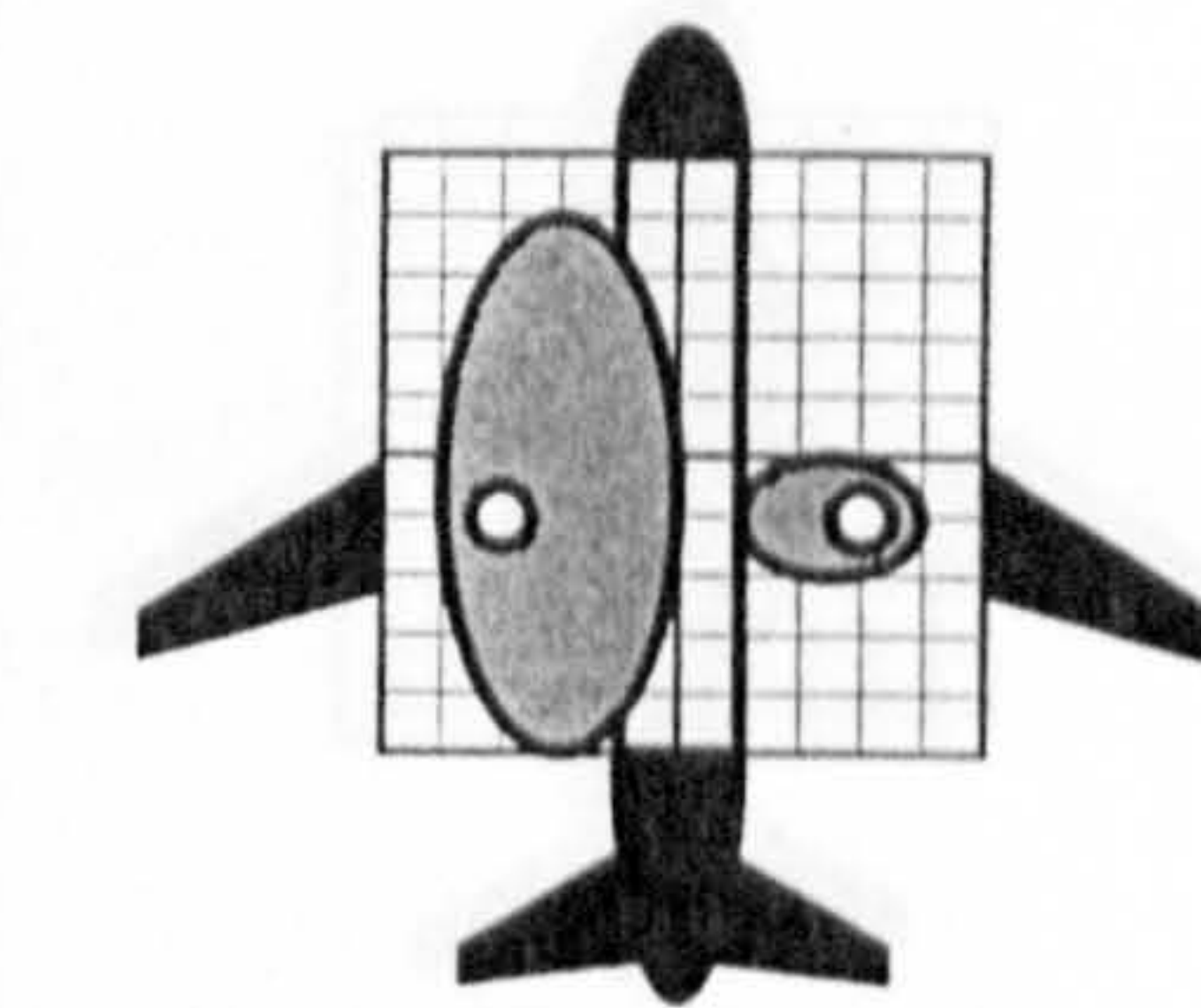
Similarly, the view factor, F_h , experienced by a horizontally inclined element at the same location is given by:-

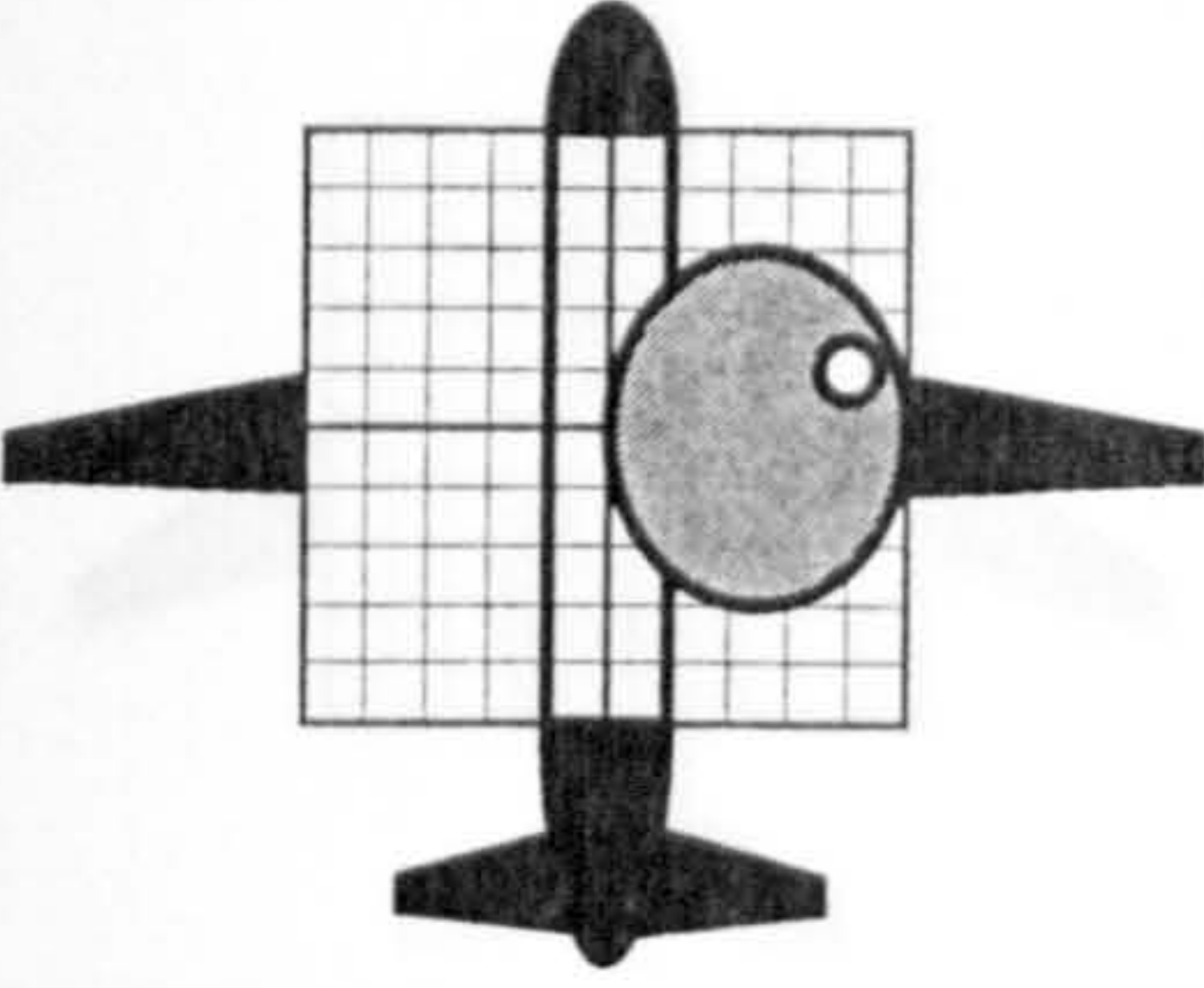
$$\begin{aligned} \pi F_h = & \tan^{-1} \sqrt{\frac{b-1}{b+1}} \\ & - \frac{a^2 + (b+1)^2 - 2(b+1 + ab \cos \theta)}{\sqrt{AB}} \cdot \tan^{-1} \sqrt{\frac{A}{B} \left(\frac{b-1}{b+1} \right)^{1/2}} \\ & + \frac{\sin \theta}{\sqrt{C}} \left[\tan^{-1} \frac{ab - (b^2 - 1) \sin \theta}{\sqrt{b^2 - 1} \sqrt{C}} + \tan^{-1} \frac{(b^2 - 1)^{1/2} \sin \theta}{\sqrt{C}} \right] \end{aligned} \quad (D.13)$$

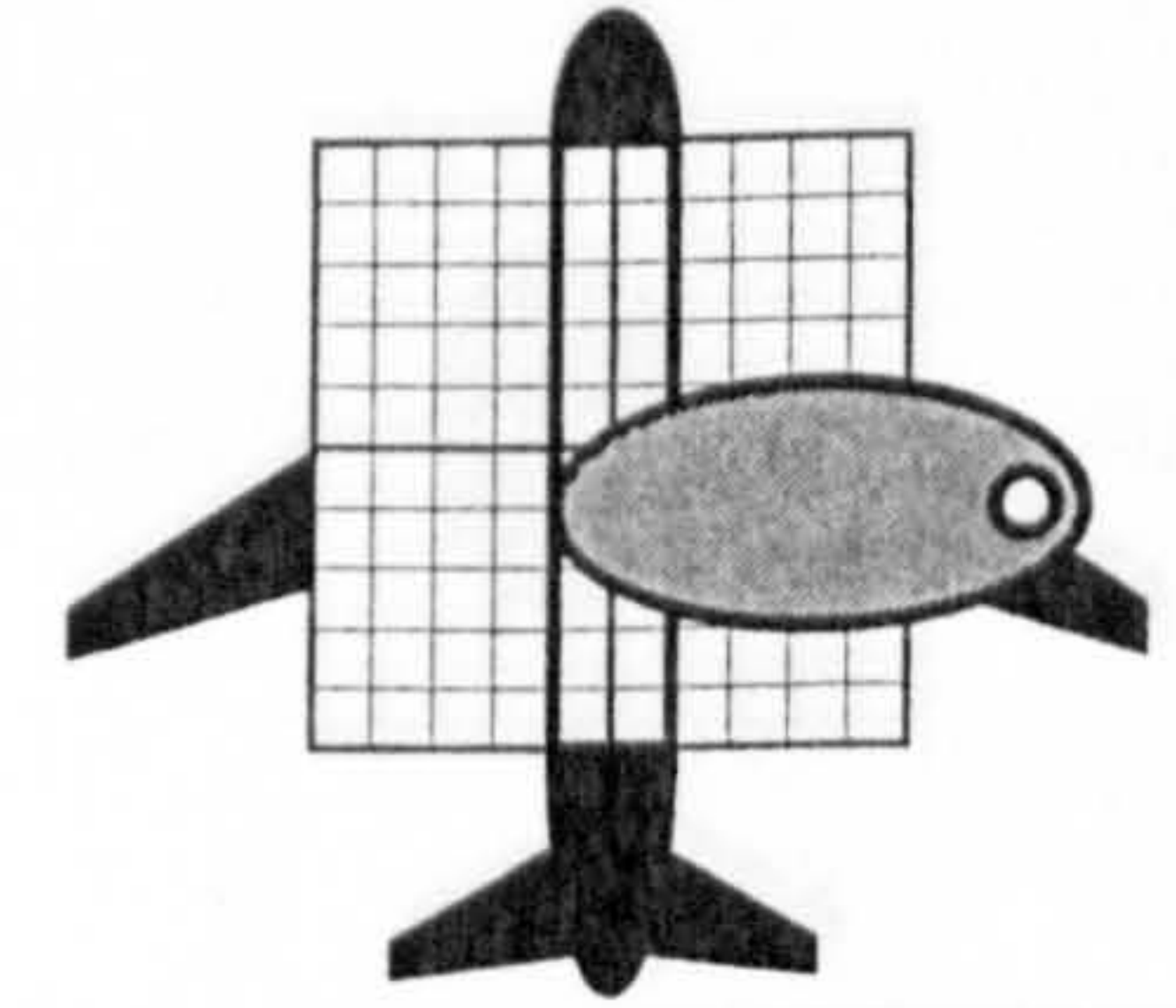
Appendix E: Fire Spread Diagrams

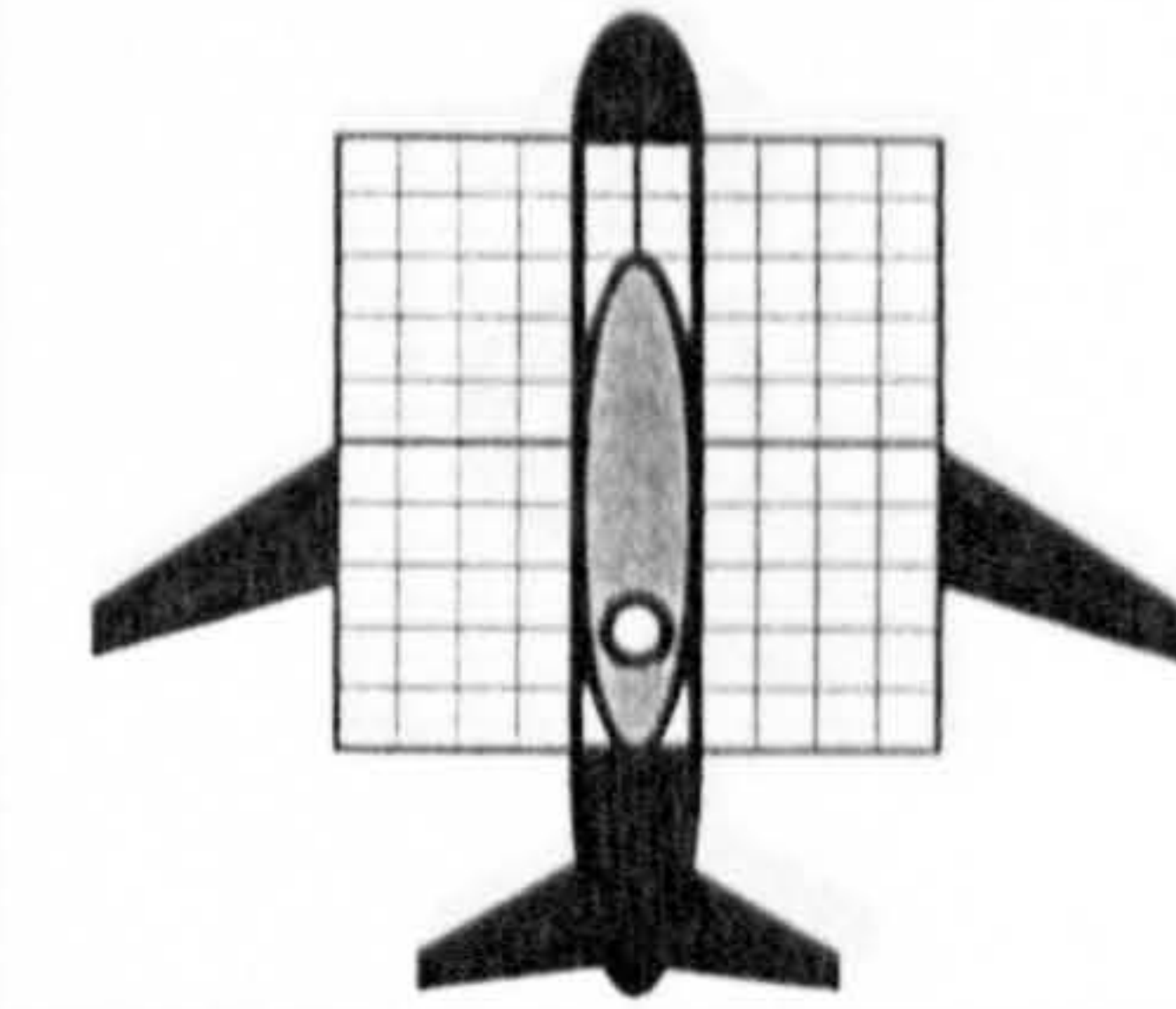
600107 (Burnthrough)	
	
Aircraft	Viscount
Scenario	nose-gear collapse
Starting point	nose-gear bay
Initiation time	0:00
Burnthro' time	(2:00)
Cabin damage	completely destroyed
Fire fatalities	0.00

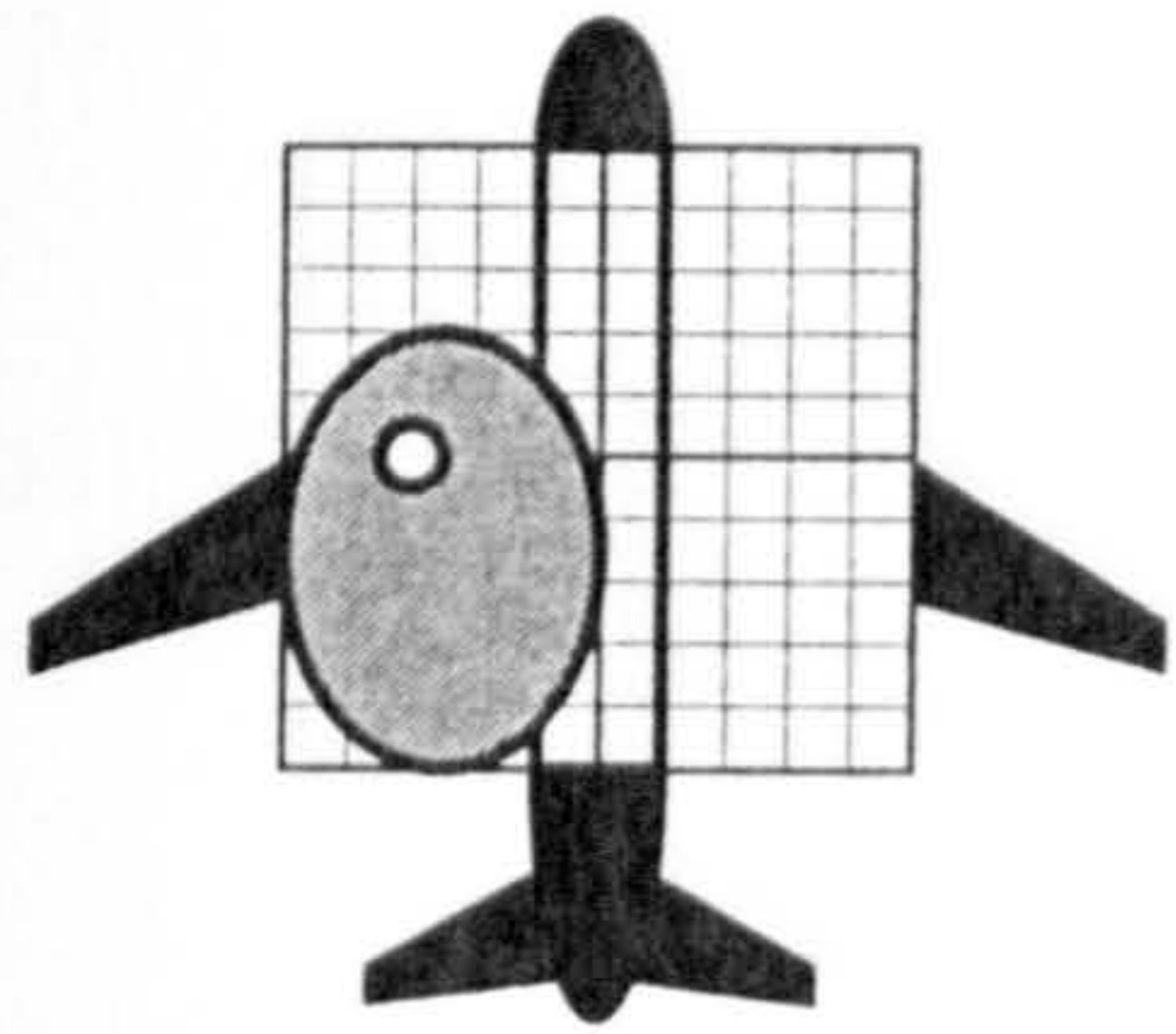
610615 (Burnthrough)	
	
Aircraft	B-707-328
Scenario	nose-gear collapse
Starting point	nose-gear bay
Initiation time	0:00
Burnthro' time	(3:00)
Cabin damage	serious
Fire fatalities	0.00

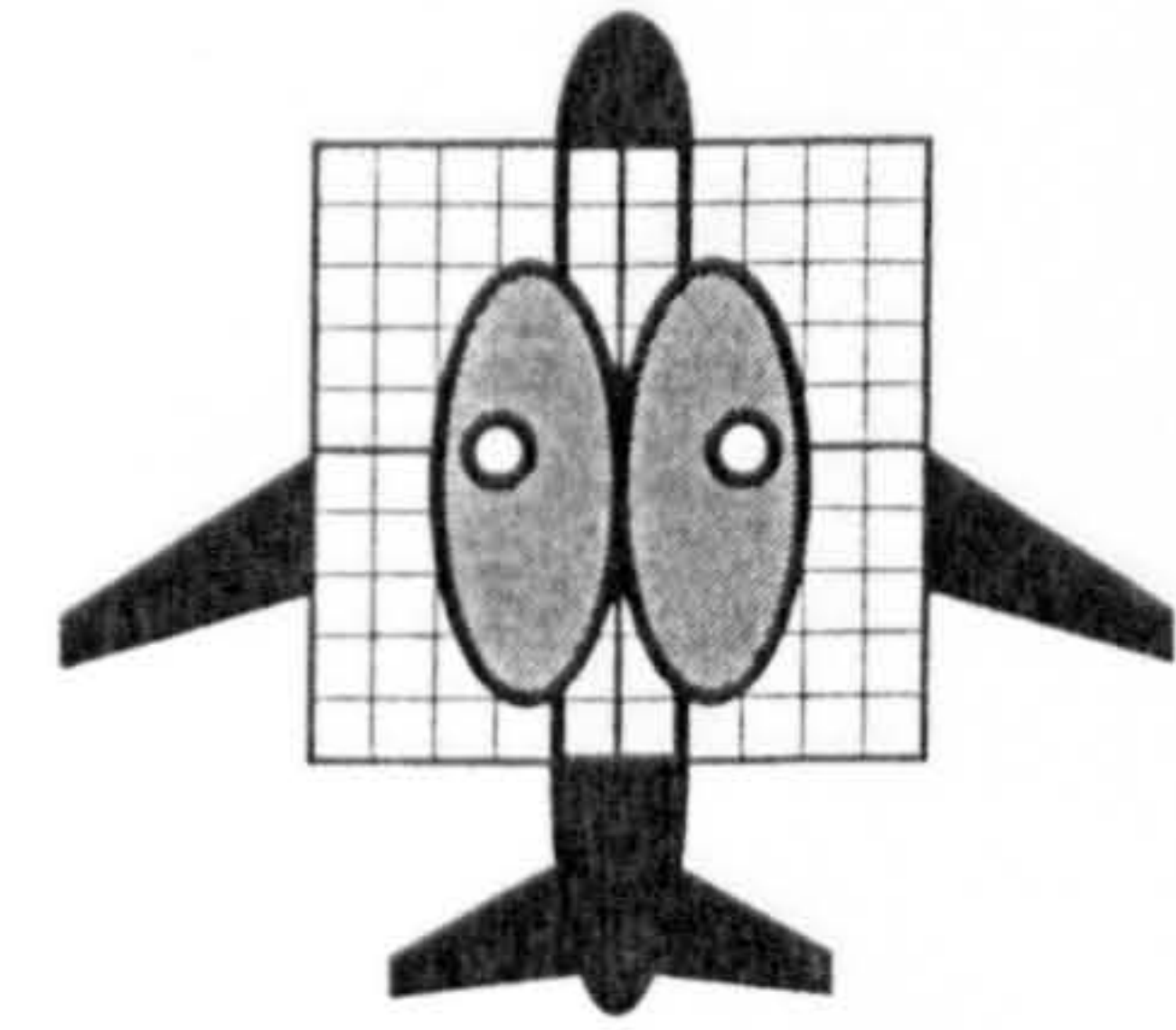
610711 (Burnthrough)	
	
Aircraft	DC-8
Scenario	left runway on landing
Starting point	left & right wings
Initiation time	0:00
Burnthro' time	(0:30)
Cabin damage	extensive on left side
Fire fatalities	0.13

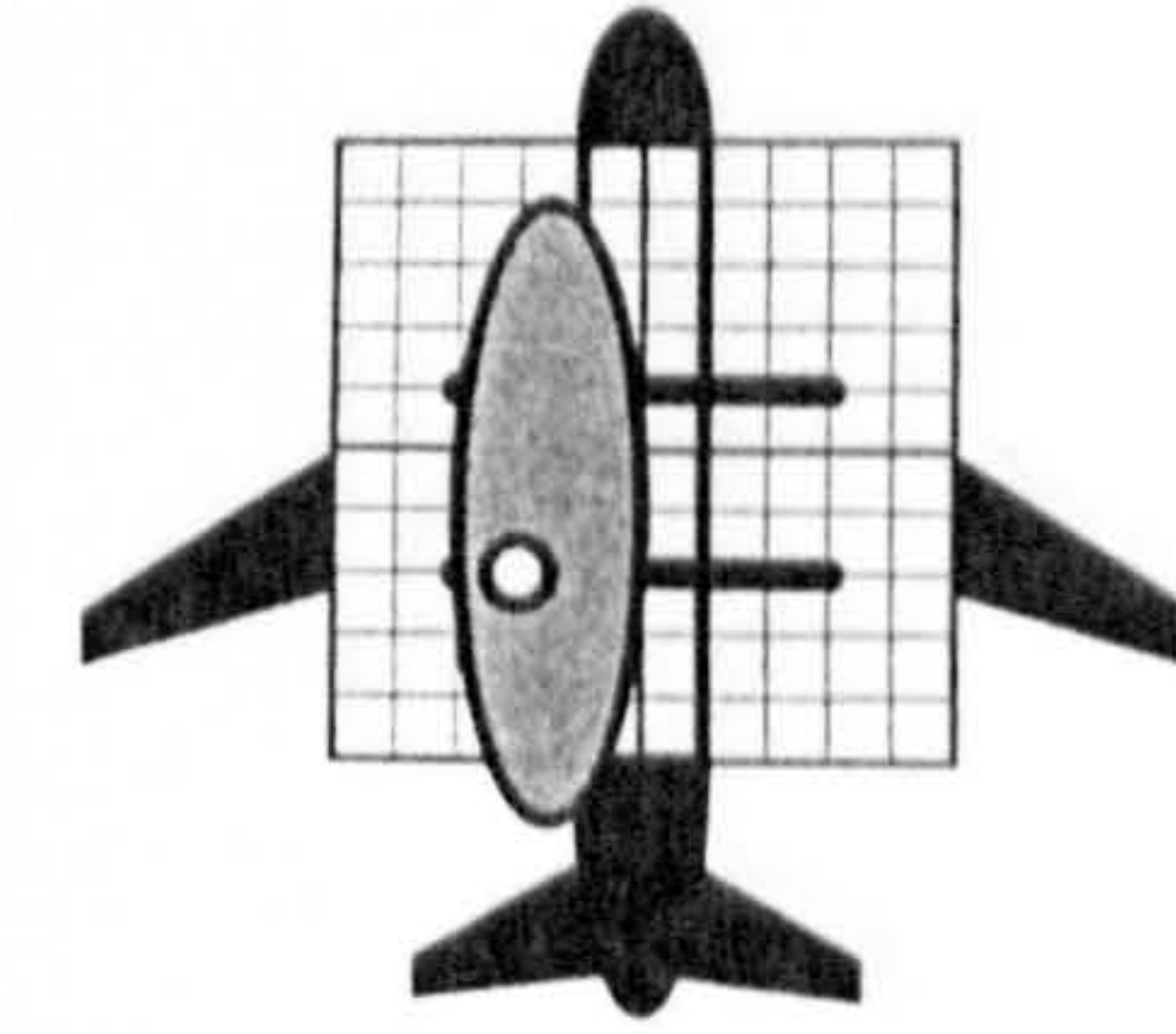
620708 (Burnthrough)	
	
Aircraft	Viscount
Scenario	forced landing in field
Starting point	engines 3 & 4
Initiation time	0:00
Burnthro' time	(2:00)
Cabin damage	destroyed
Fire fatalities	0.00

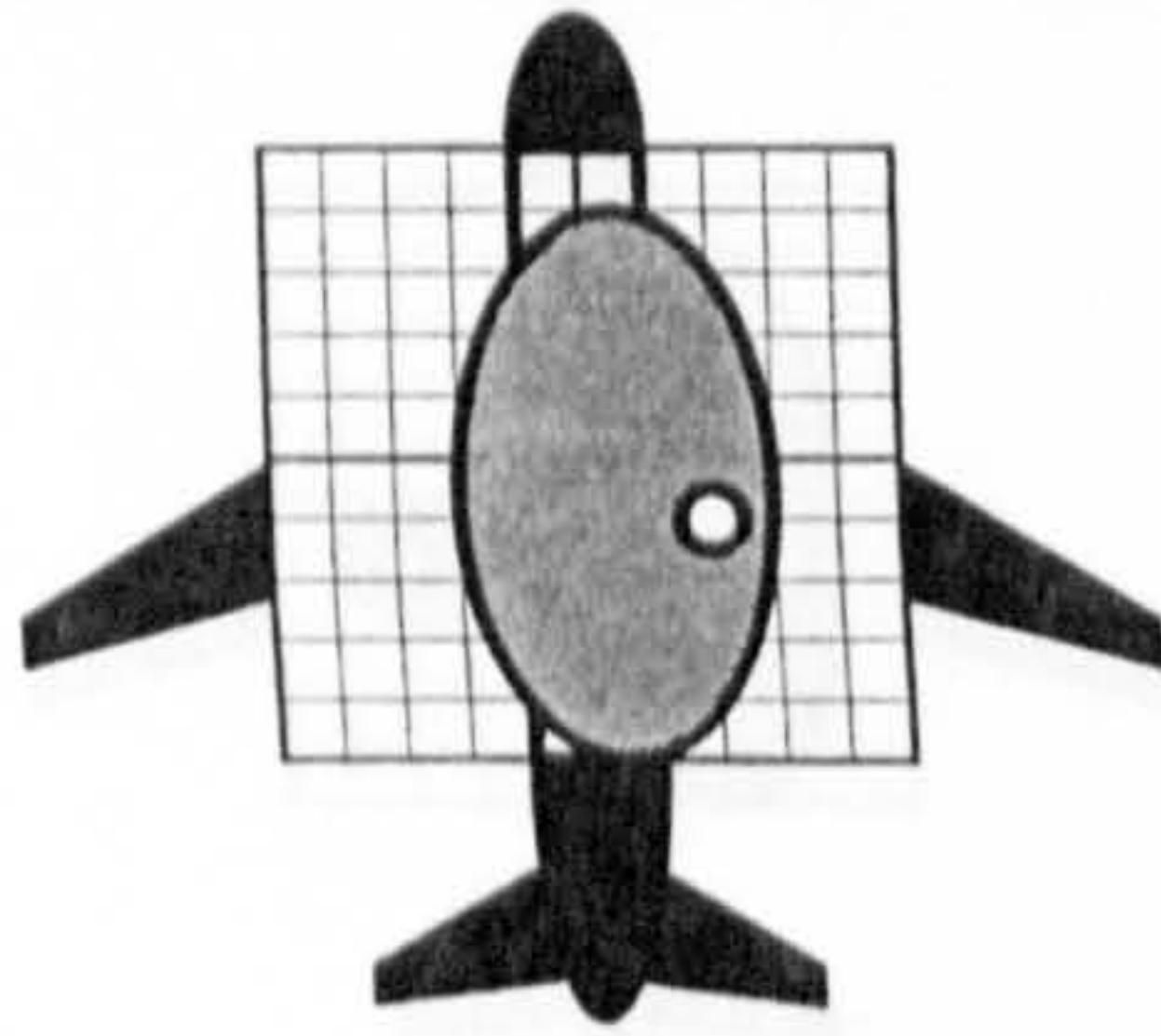
641123 (Burnthrough)	
	
Aircraft	B-707-331
Scenario	overran on takeoff
Starting point	right outer wing
Initiation time	0:00
Burnthro' time	0:30
Cabin damage	completely destroyed
Fire fatalities	0.67

651111 (Burnthrough)	
	
Aircraft	B-727
Scenario	undershot on landing
Starting point	rear cargo bay
Initiation time	0:00
Burnthro' time	0:00
Cabin damage	completely destroyed
Fire fatalities	0.47

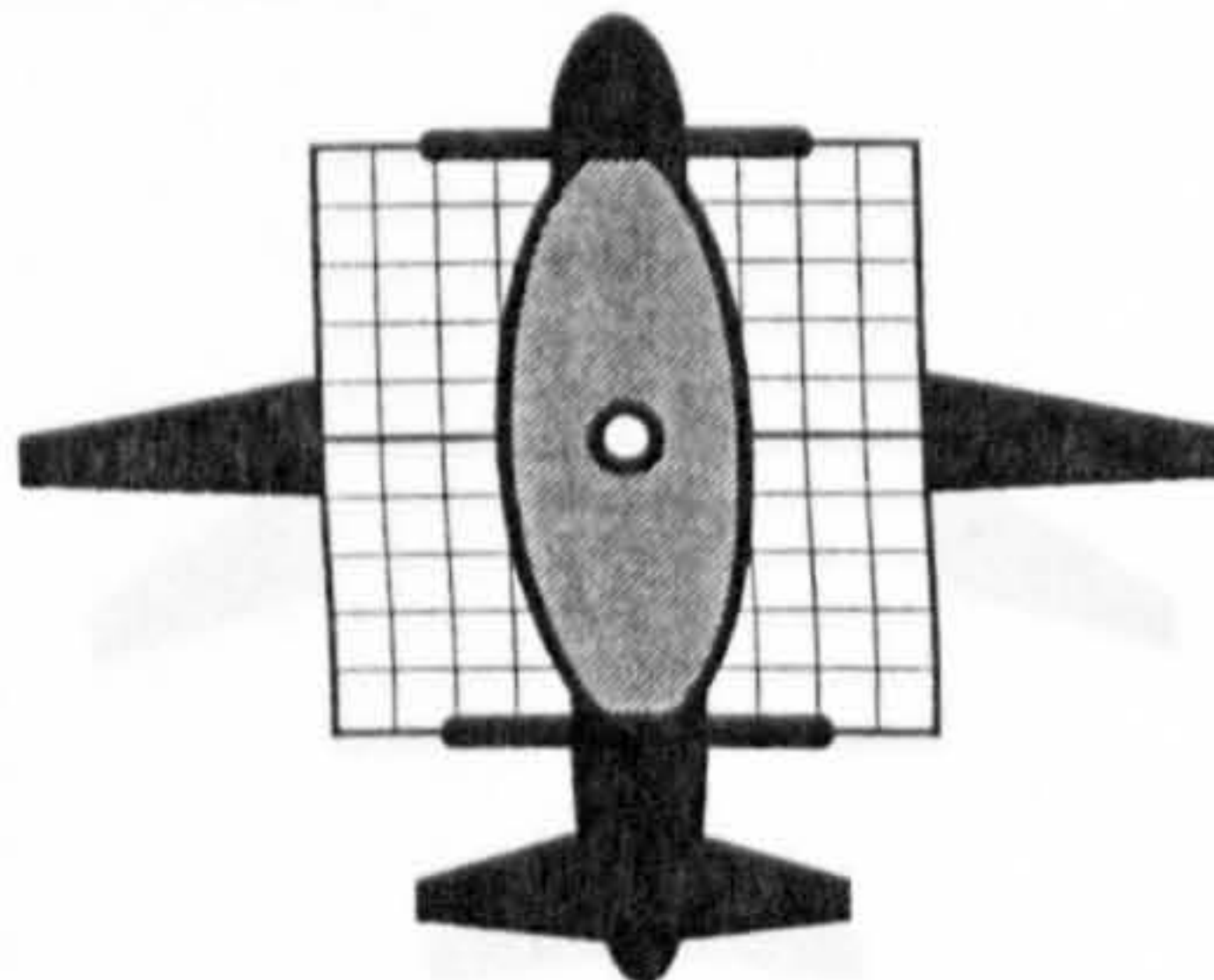
680408 (Burnthrough)	
	
Aircraft	B-707-465
Scenario	inflight engine fire
Starting point	#2 engine
Initiation time	0:00
Burnthro' time	0:10
Cabin damage	rear cabin burnt out
Fire fatalities	0.04

701127 (Burnthrough)	
	
Aircraft	DC-8-63
Scenario	overran on takeoff
Starting point	both wings
Initiation time	0:00
Burnthro' time	2:00
Cabin damage	completely destroyed
Fire fatalities	0.21

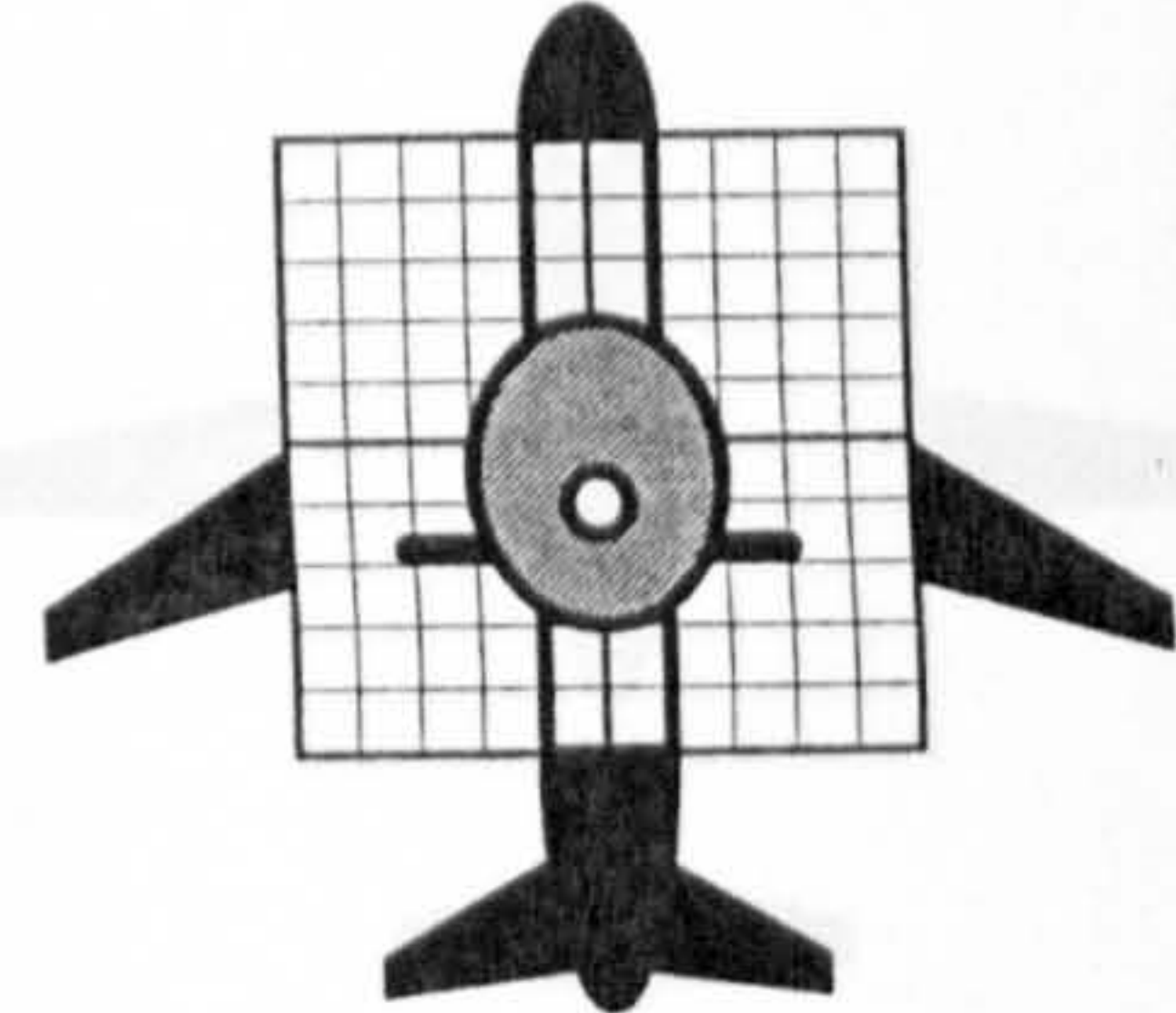
701228 (Burnthrough)	
	
Aircraft	B-727-200
Scenario	left runway on landing
Starting point	left wing area
Initiation time	0:00
Burnthro' time	1:00
Cabin damage	entirely consumed
Fire fatalities	0.04

710523 (Burnthrough)

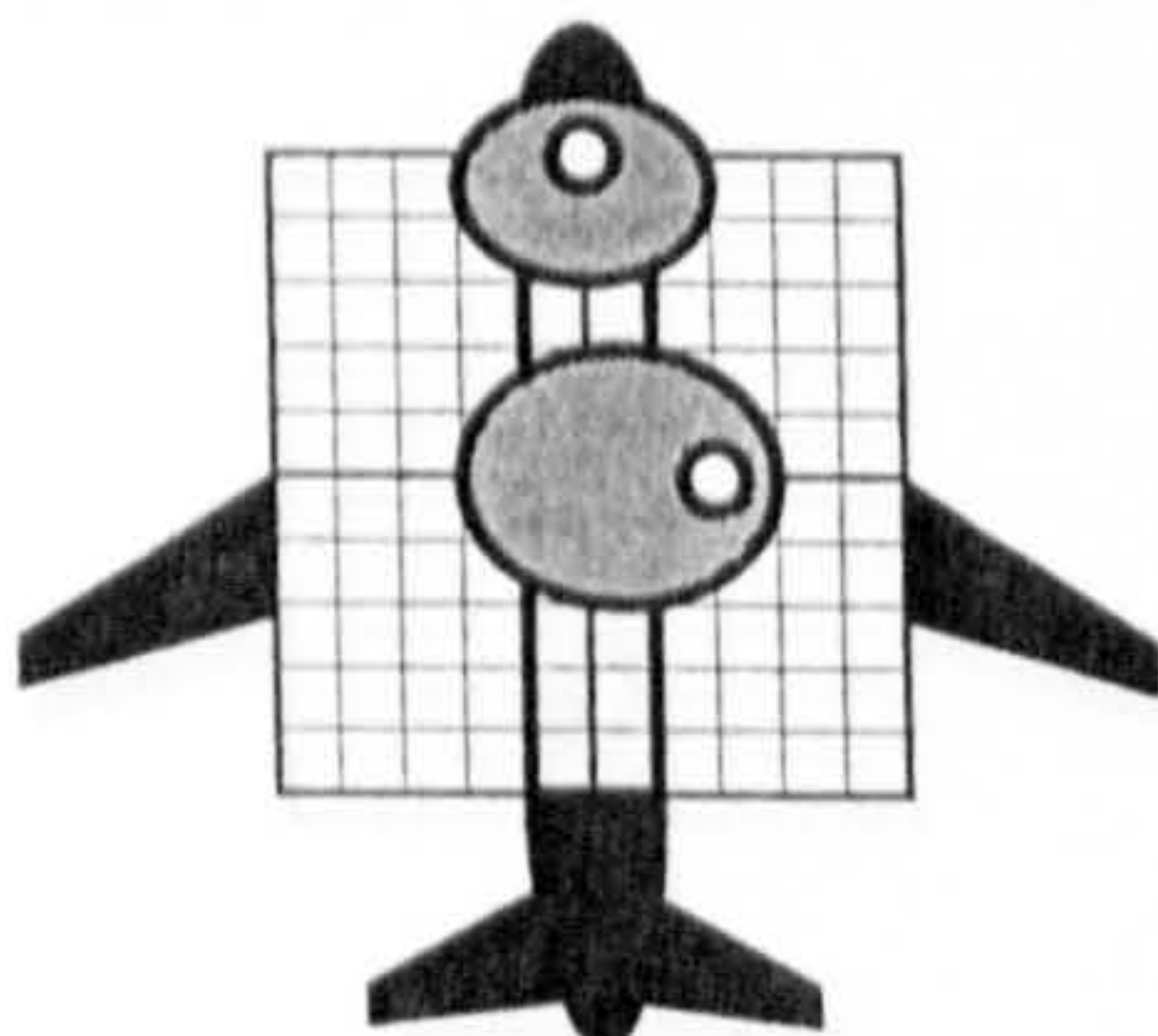
Aircraft	Tu-134A
Scenario	overturned on landing
Starting point	detached right wing
Initiation time	0:00
Burnthro' time	1:00
Cabin damage	completely destroyed
Fire fatalities	0.94

710607 (Burnthrough)

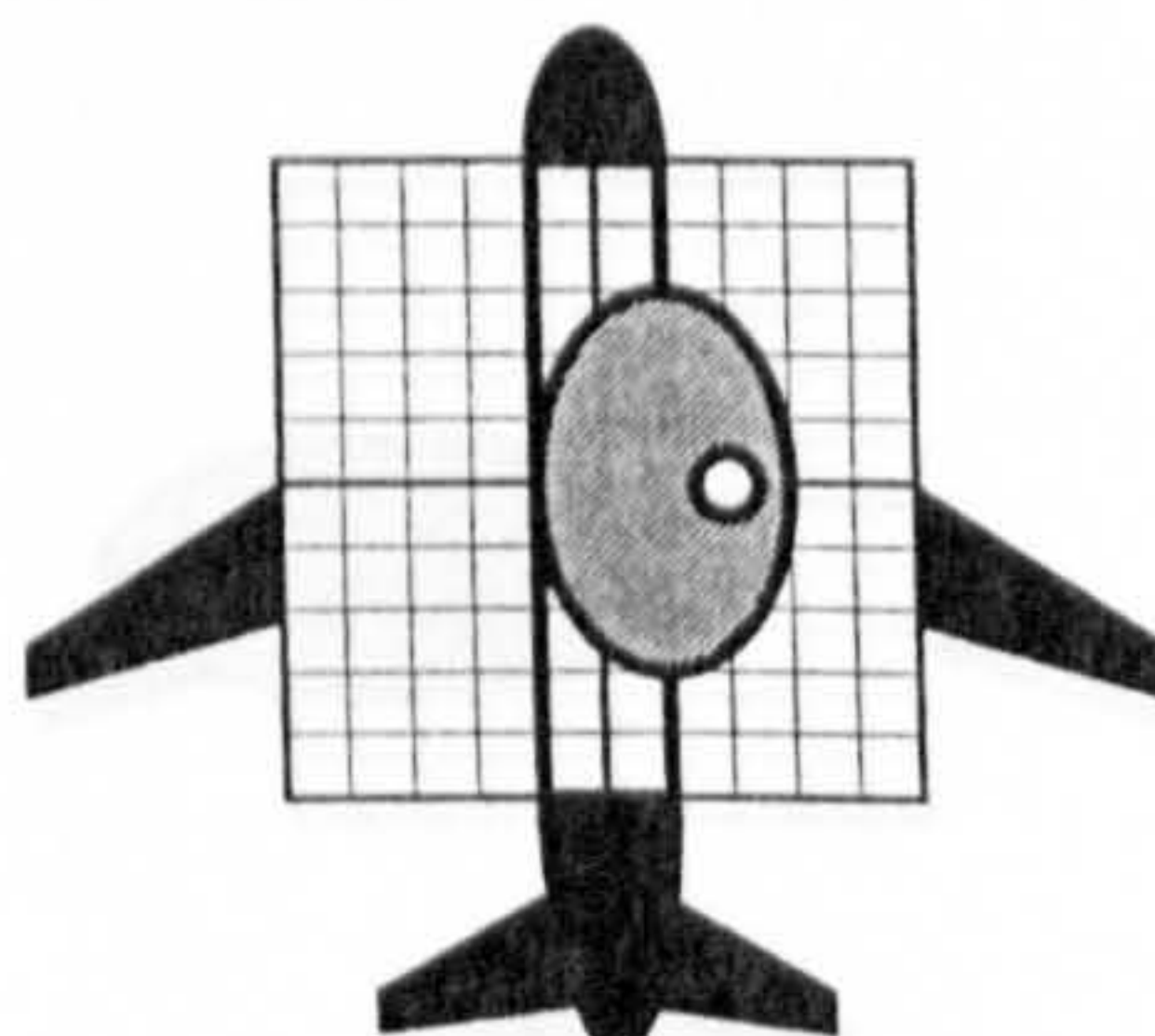
Aircraft	CV-580
Scenario	crashed on approach
Starting point	entire fuselage (?)
Initiation time	0:00
Burnthro' time	0:00
Cabin damage	completely destroyed
Fire fatalities	0.81

720518 (Burnthrough)

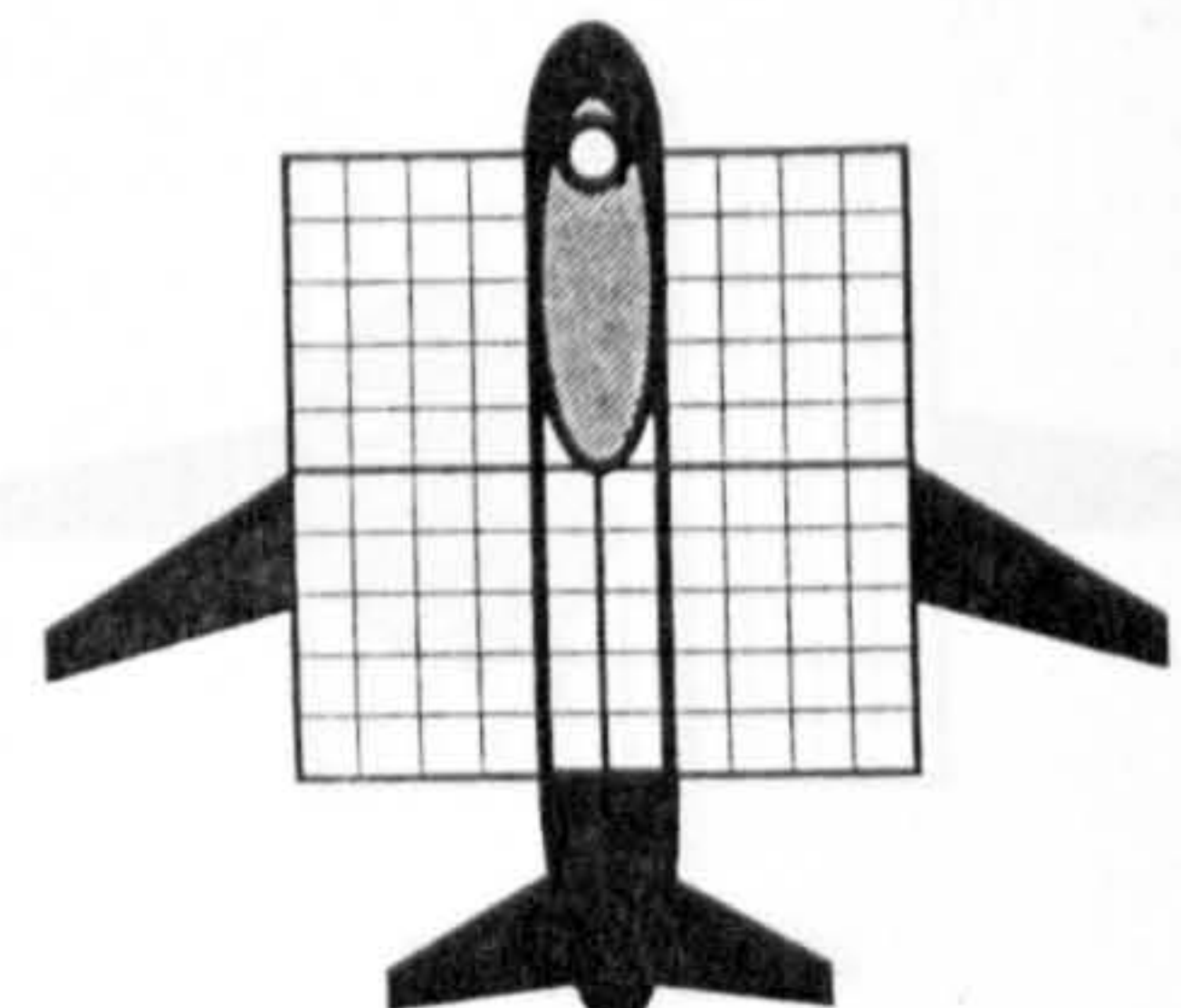
Aircraft	DC-9-31
Scenario	heavy landing
Starting point	fuselage break
Initiation time	0:00
Burnthro' time	(1:00)
Cabin damage	destroyed
Fire fatalities	0.0

721208 (Burnthrough)

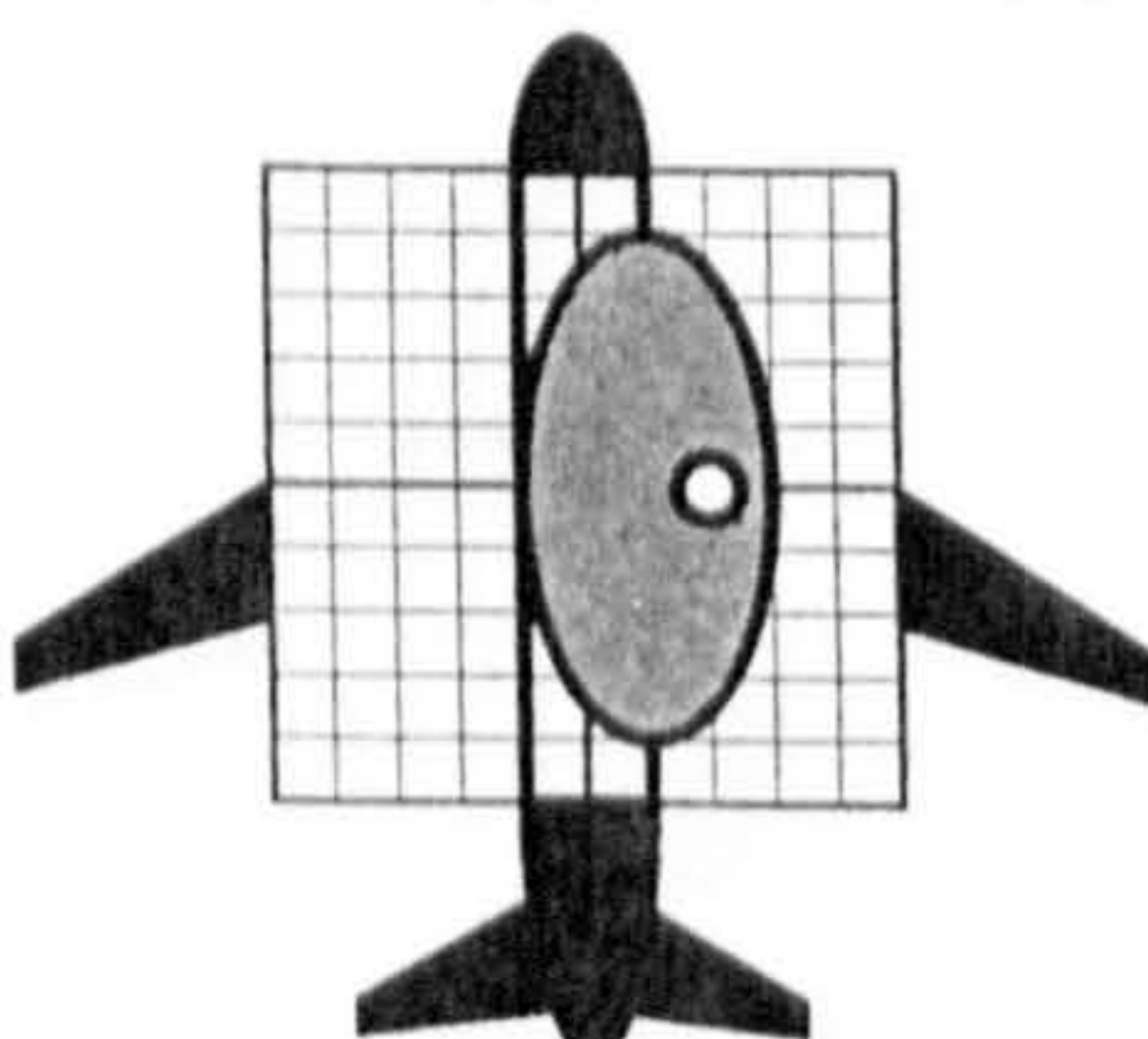
Aircraft	B-737-222
Scenario	stalled on approach
Starting point	left wing & nose
Initiation time	0:00
Burnthro' time	(0:30)
Cabin damage	completely destroyed
Fire fatalities	0.00

731220 (Burnthrough)

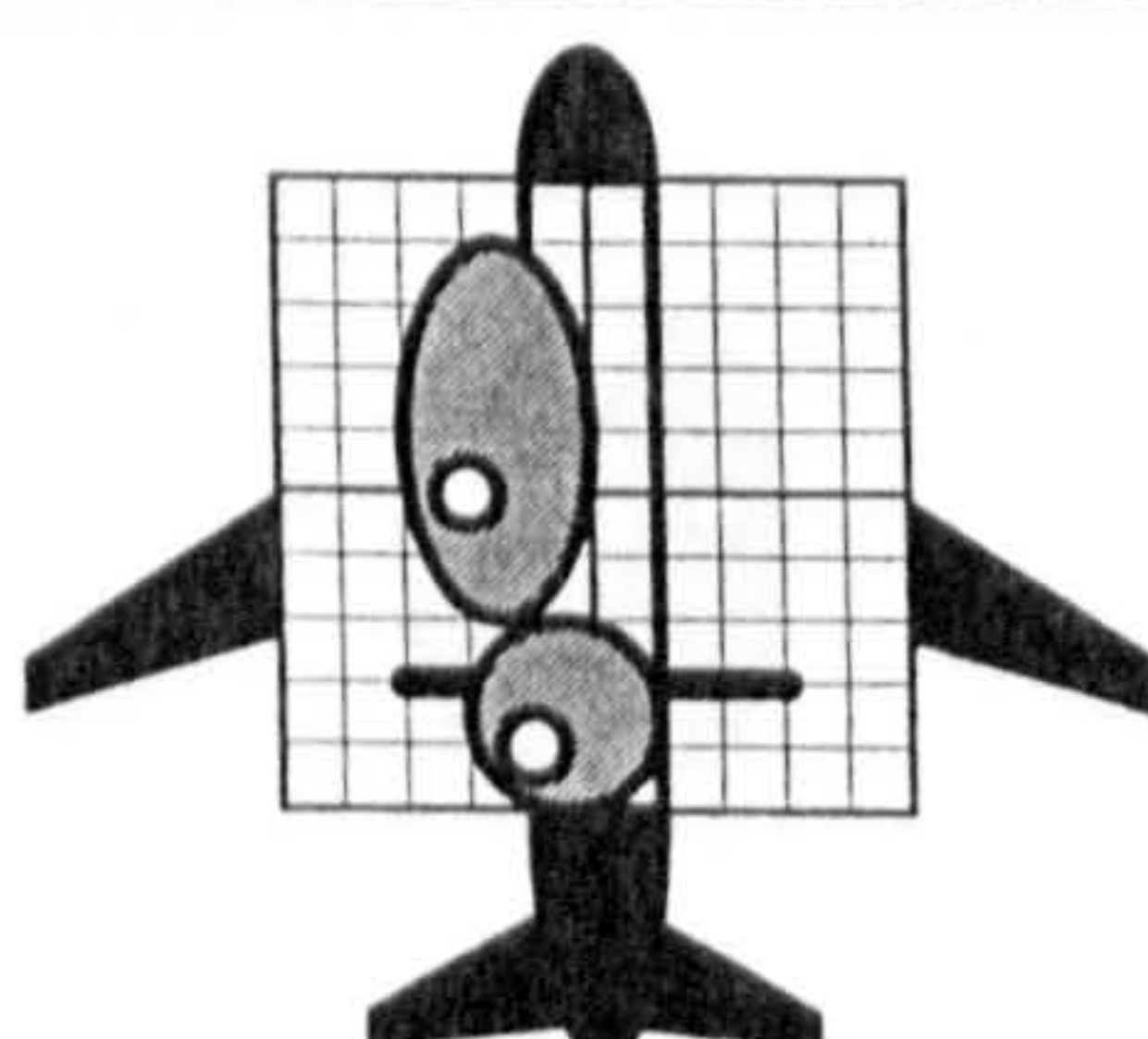
Aircraft	B-707
Scenario	undershot on landing
Starting point	left wing
Initiation time	0:00
Burnthro' time	(2:00)
Cabin damage	destroyed
Fire fatalities	0.00

740116 (Burnthrough)

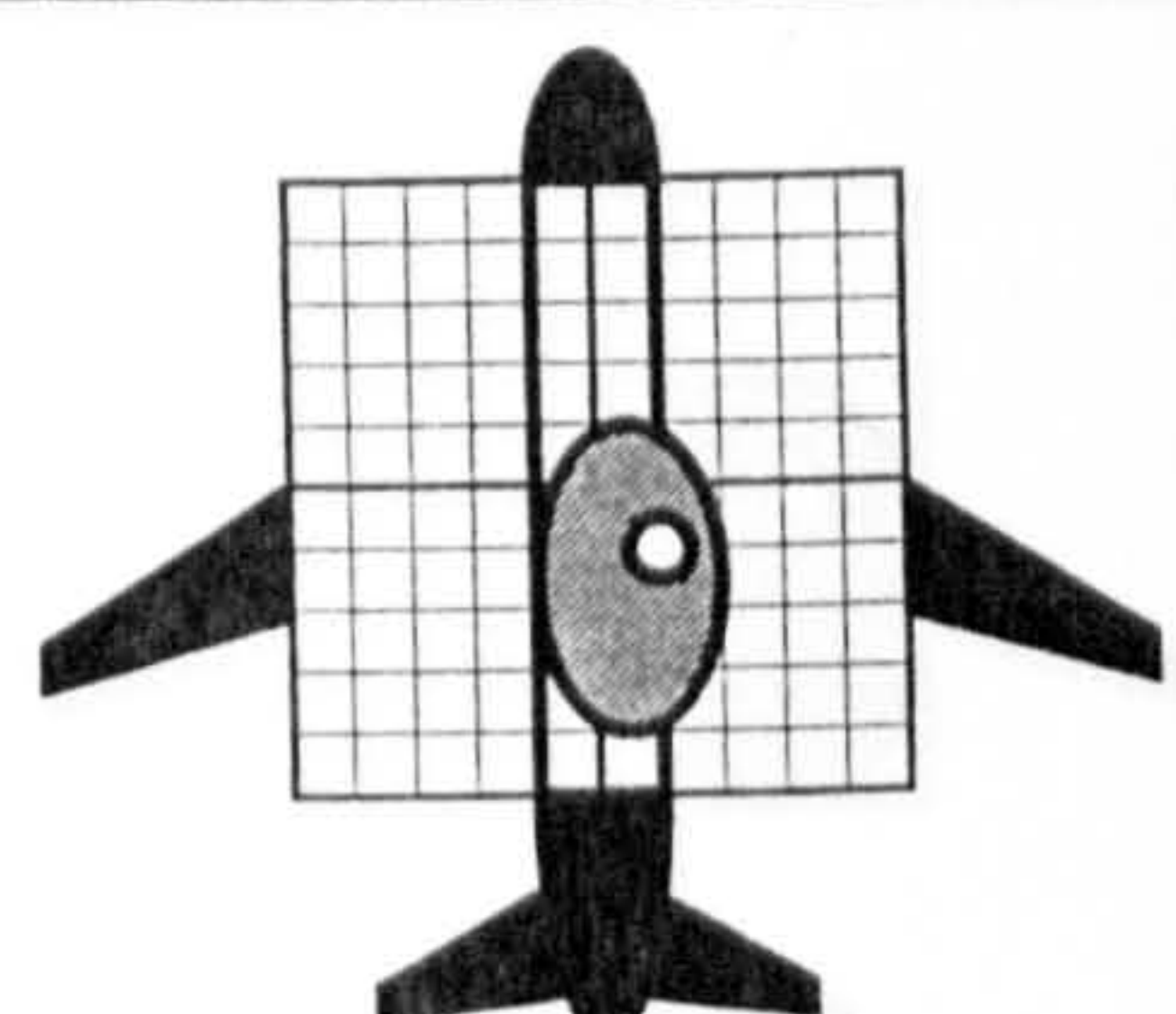
Aircraft	B-707-131B
Scenario	nose-gear collapse
Starting point	below cockpit
Initiation time	0:00
Burnthro' time	5:00
Cabin damage	destroyed
Fire fatalities	0.00

740130 (Burnthrough)

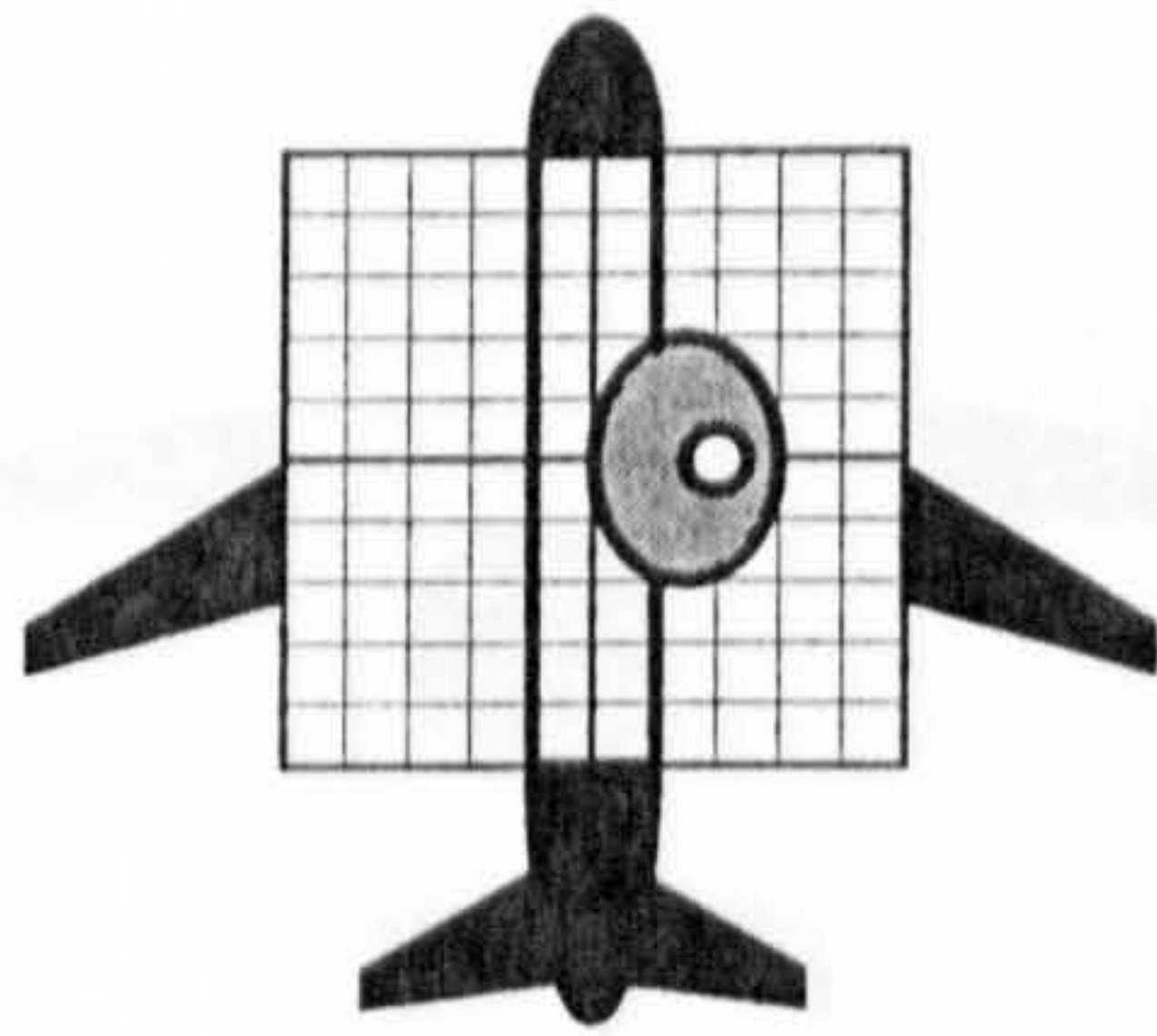
Aircraft	B-707-121
Scenario	undershot into trees
Starting point	rhs of fuselage
Initiation time	0:00
Burnthro' time	(0:30)
Cabin damage	completely destroyed
Fire fatalities	0.95

741120 (Burnthrough)

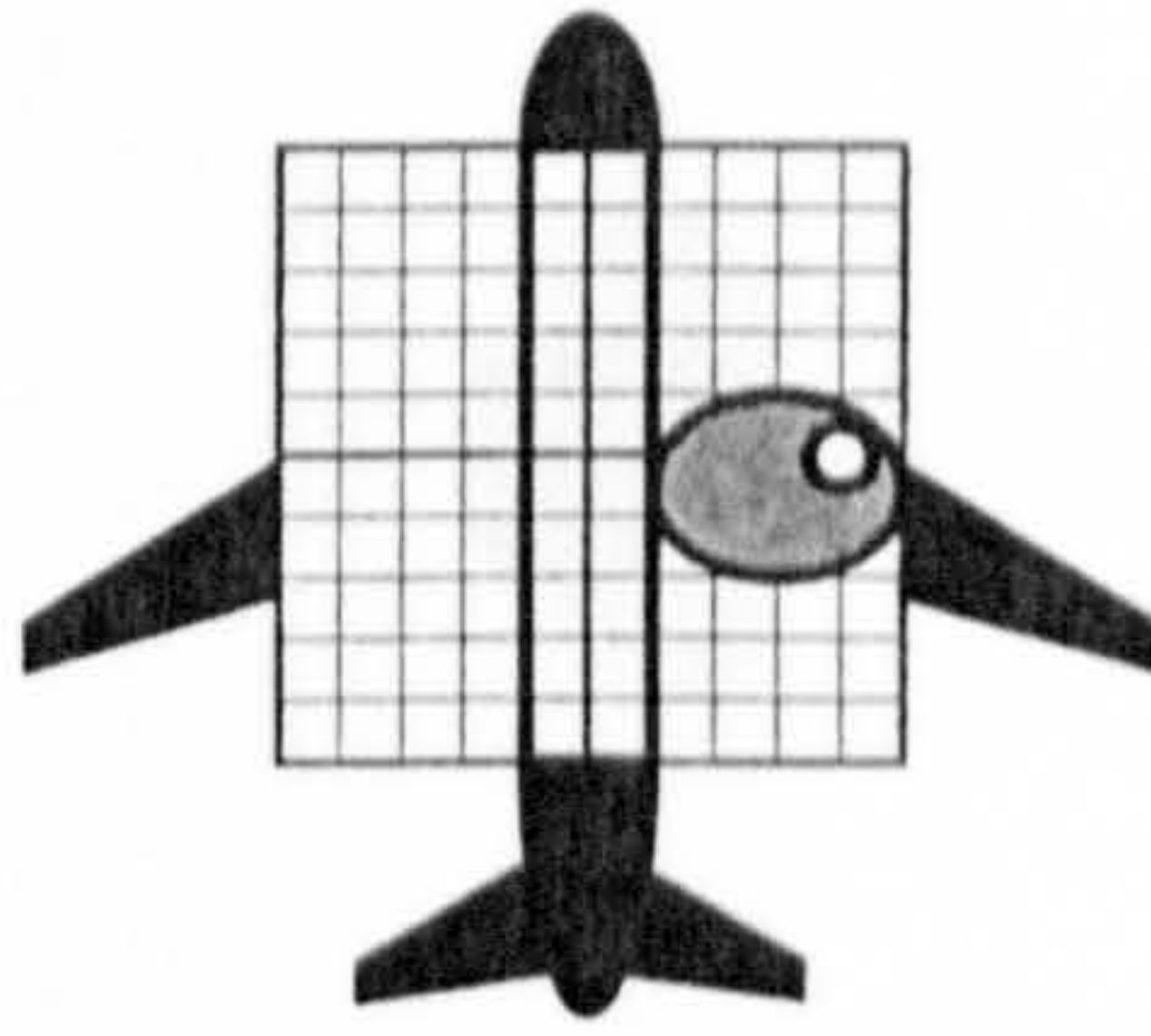
Aircraft	B-747
Scenario	stalled on takeoff
Starting point	left wing & tail section
Initiation time	0:0
Burnthro' time	(1:00)
Cabin damage	destroyed
Fire fatalities	0.10

751112 (Burnthrough)

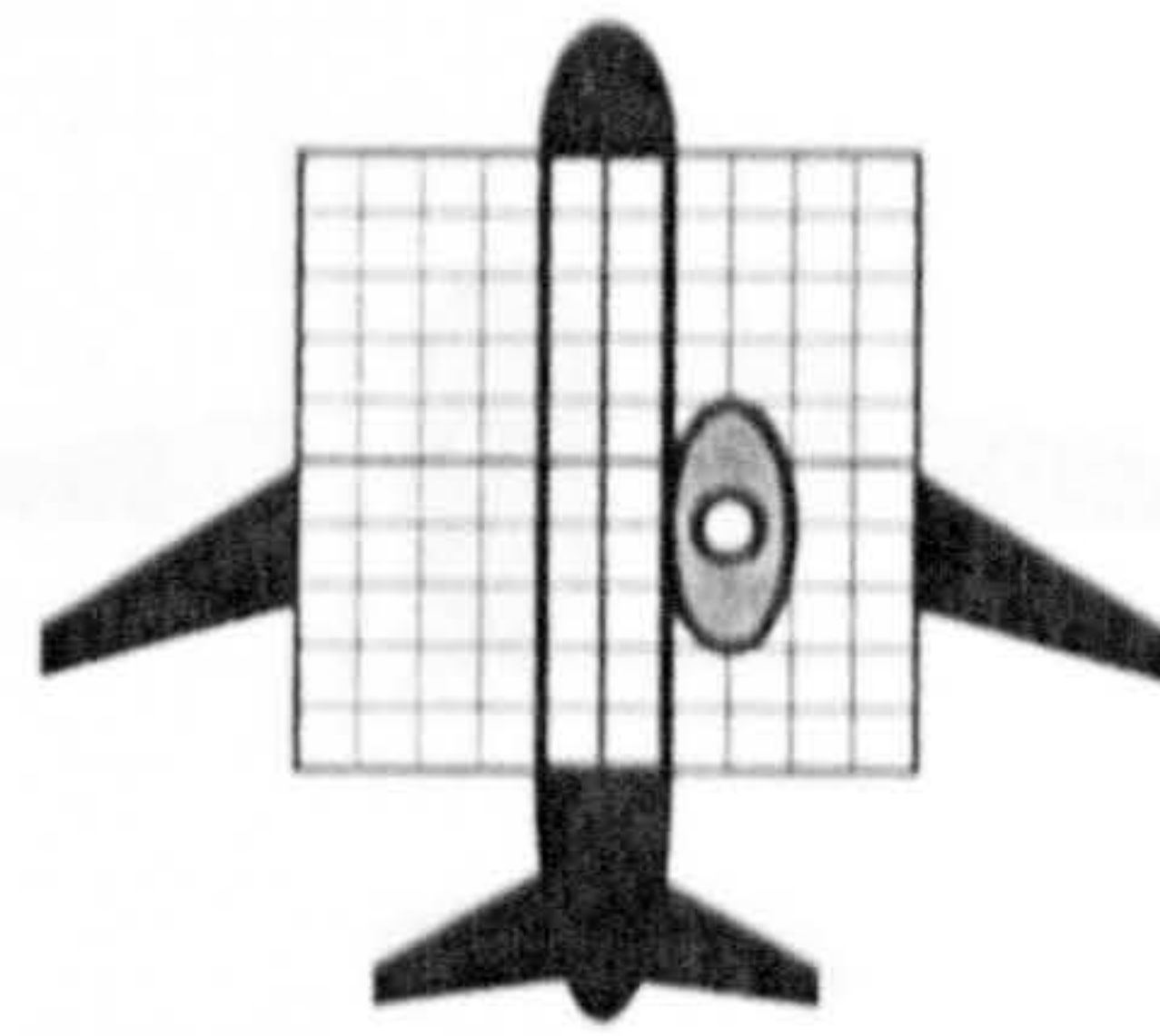
Aircraft	DC-10-10
Scenario	aborted takeoff
Starting point	right wing
Initiation time	0:00
Burnthro' time	1:00
Cabin damage	destroyed
Fire fatalities	0.0

761116 (Burnthrough)

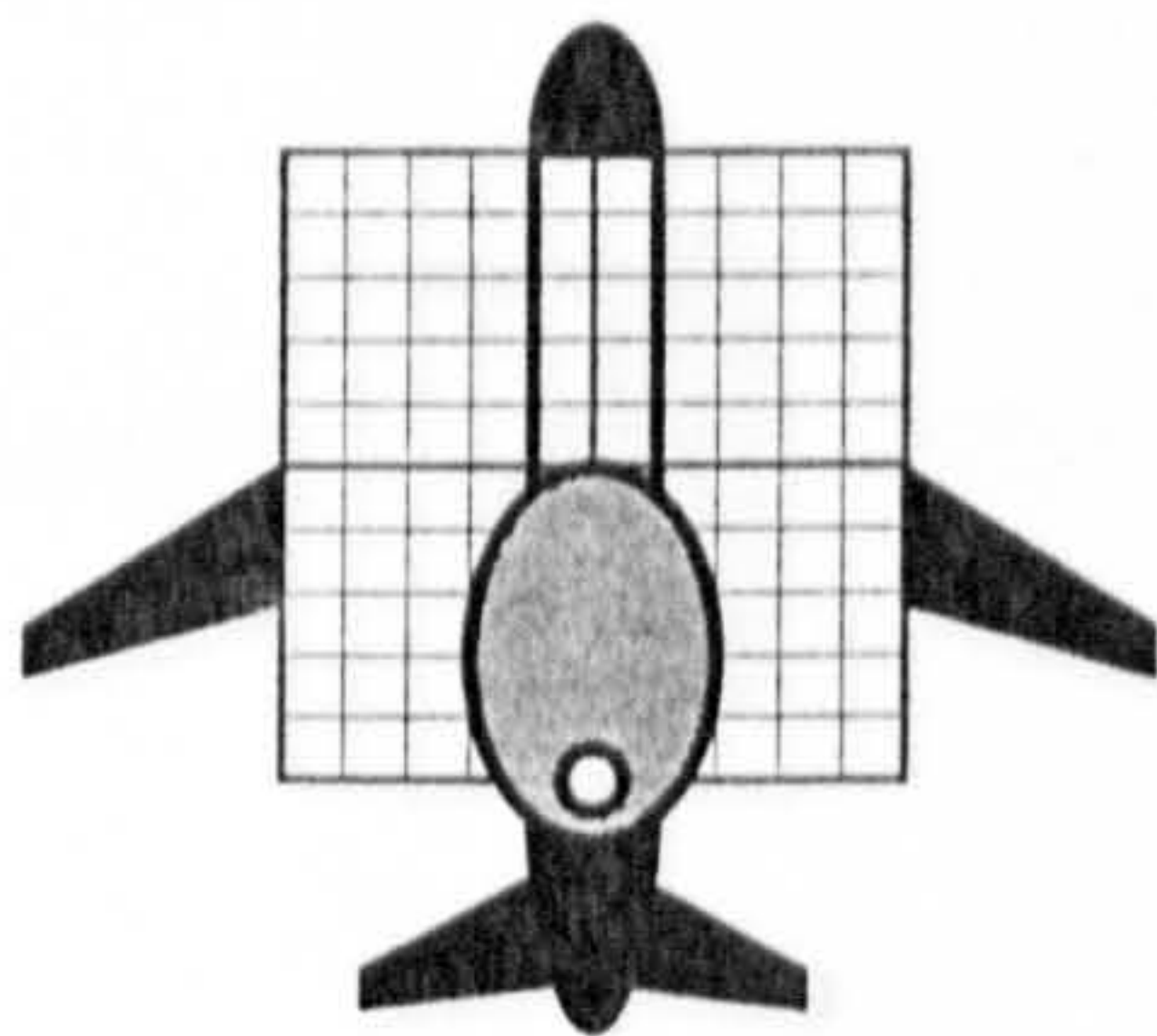
Aircraft	DC-9-14
Scenario	rejected takeoff
Starting point	left wing
Initiation time	(0:00)
Burnthro' time	(2:00)
Cabin damage	severely damaged
Fire fatalities	0.00

770302 (Burnthrough)

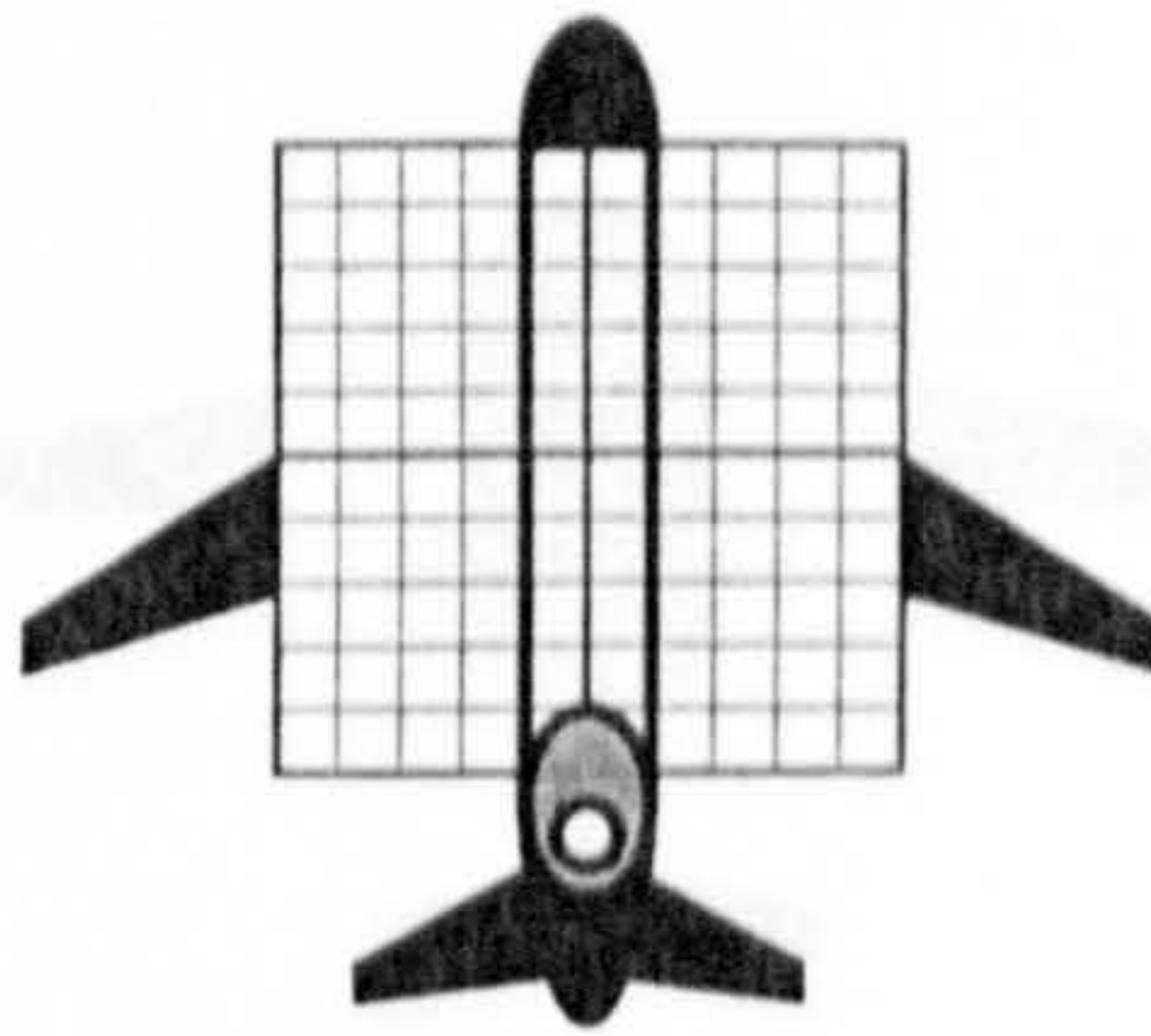
Aircraft	B-707-320
Scenario	hard landing in storm
Starting point	mid-right wing
Initiation time	0:00
Burnthro' time	(3:00)
Cabin damage	minor?
Fire fatalities	0.00

780301 (Burnthrough)

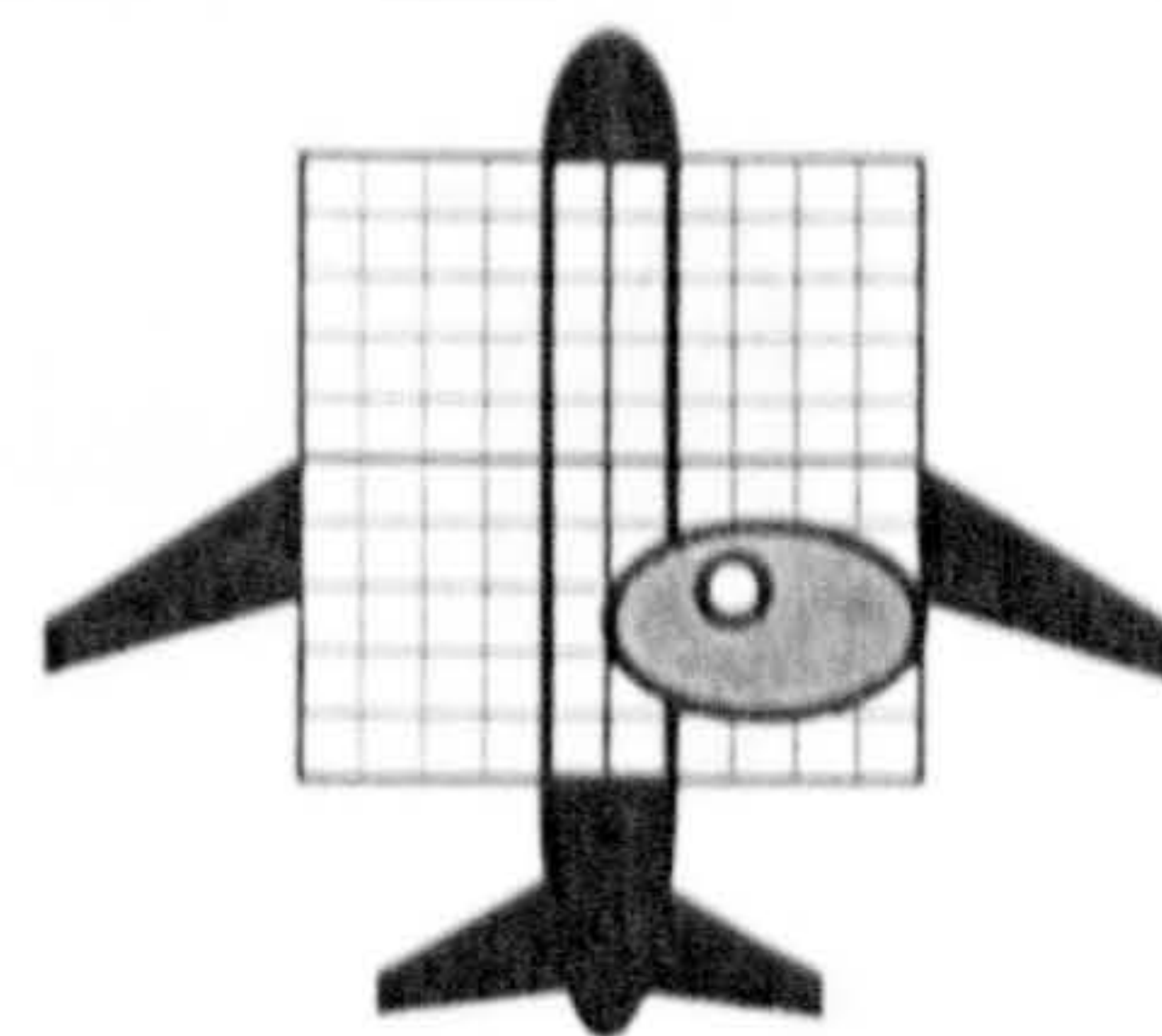
Aircraft	DC-10-10
Scenario	tyre failure on takeoff
Starting point	left wing root
Initiation time	0:00
Burnthro' time	4:00
Cabin damage	smoke damage only
Fire fatalities	0.01

781217 (Burnthrough)

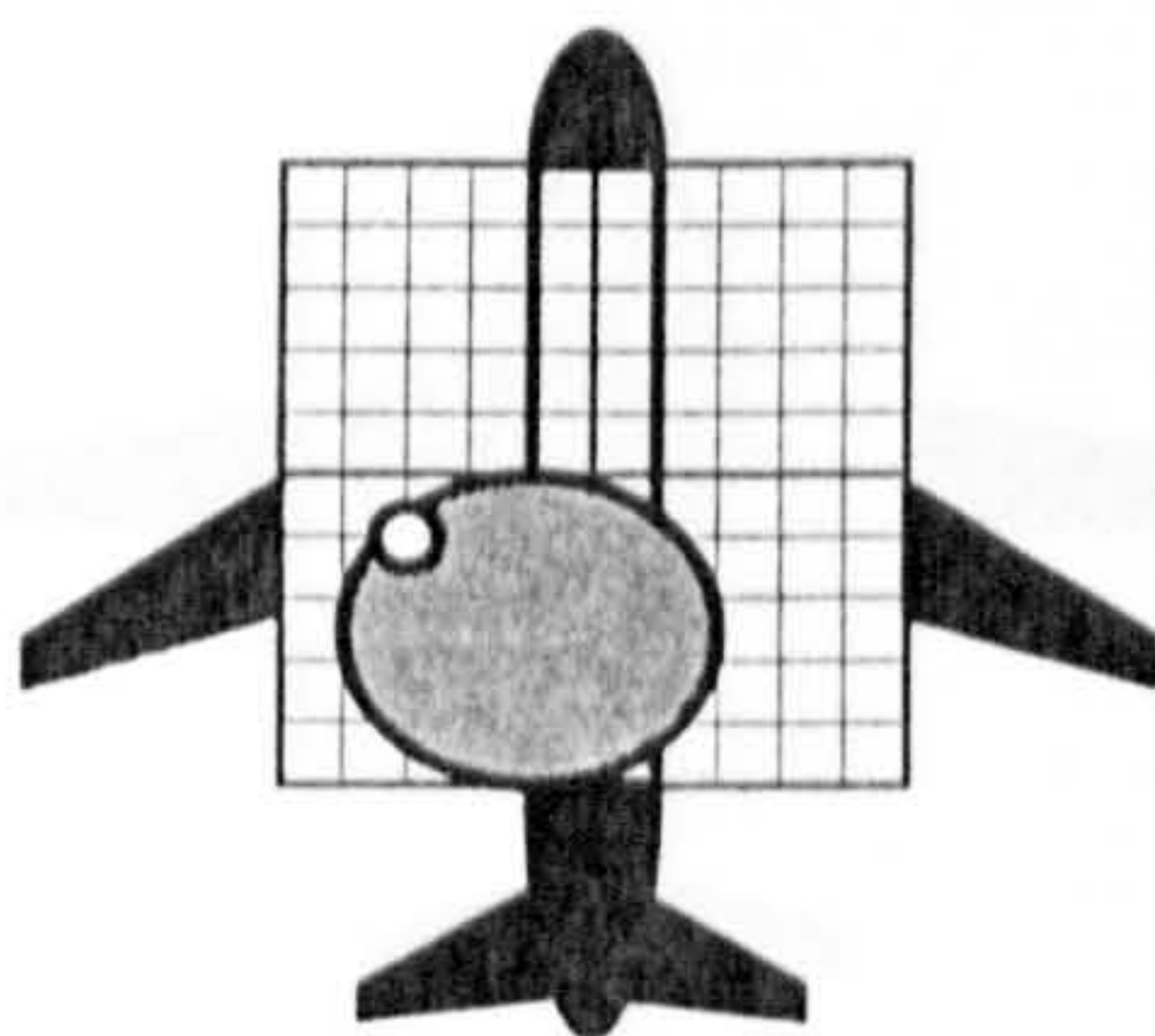
Aircraft	B-737-200
Scenario	failed to takeoff
Starting point	under rear fuselage
Initiation time	0:00
Burnthro' time	1:00
Cabin damage	destroyed
Fire fatalities	0.01

790826 (Burnthrough)

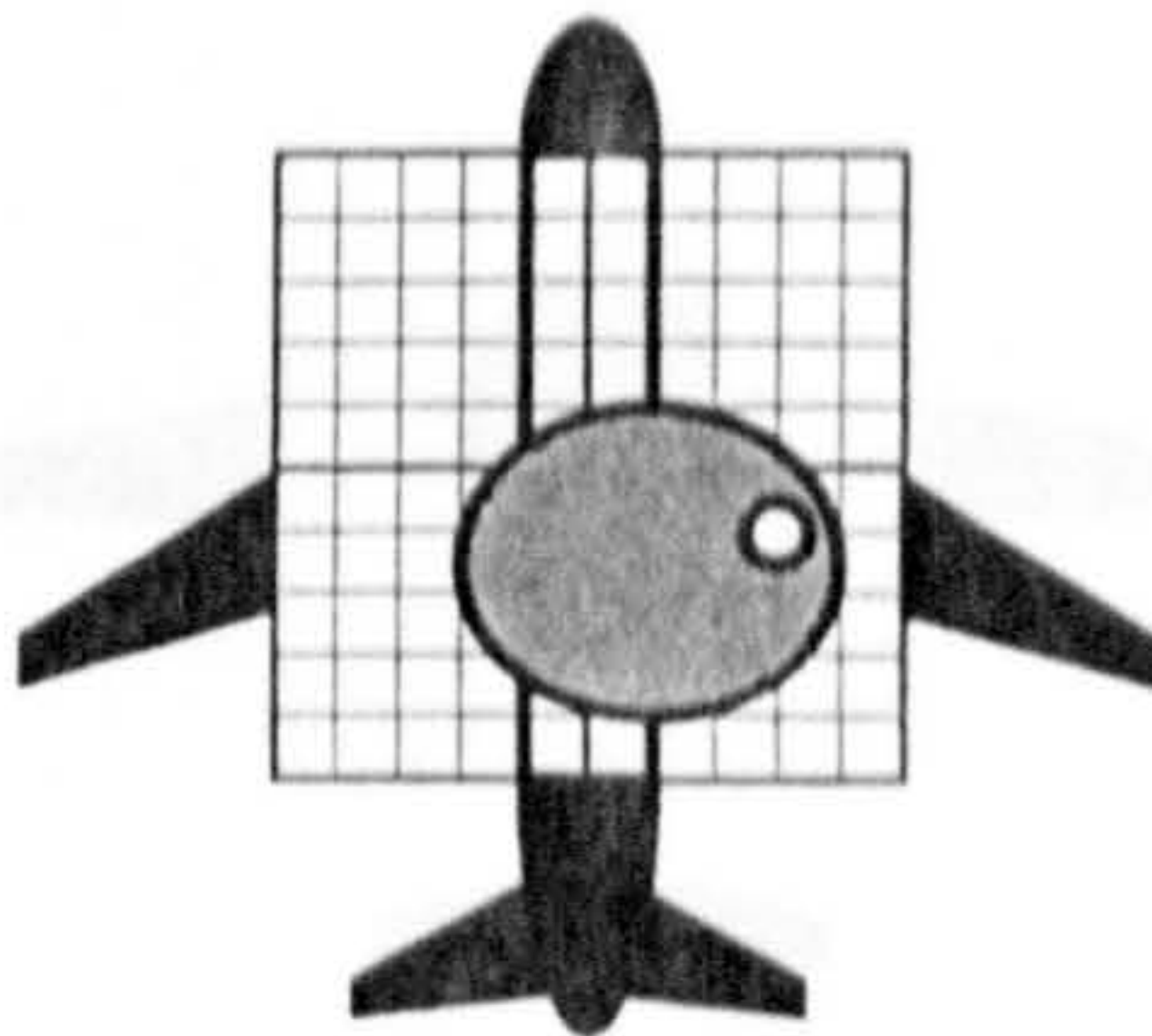
Aircraft	F-28-4000
Scenario	in-flight fire
Starting point	fuel line near engine
Initiation time	-8:00
Burnthro' time	(-5:00)
Cabin damage	modest?
Fire fatalities	0.00

820913 (Burnthrough)

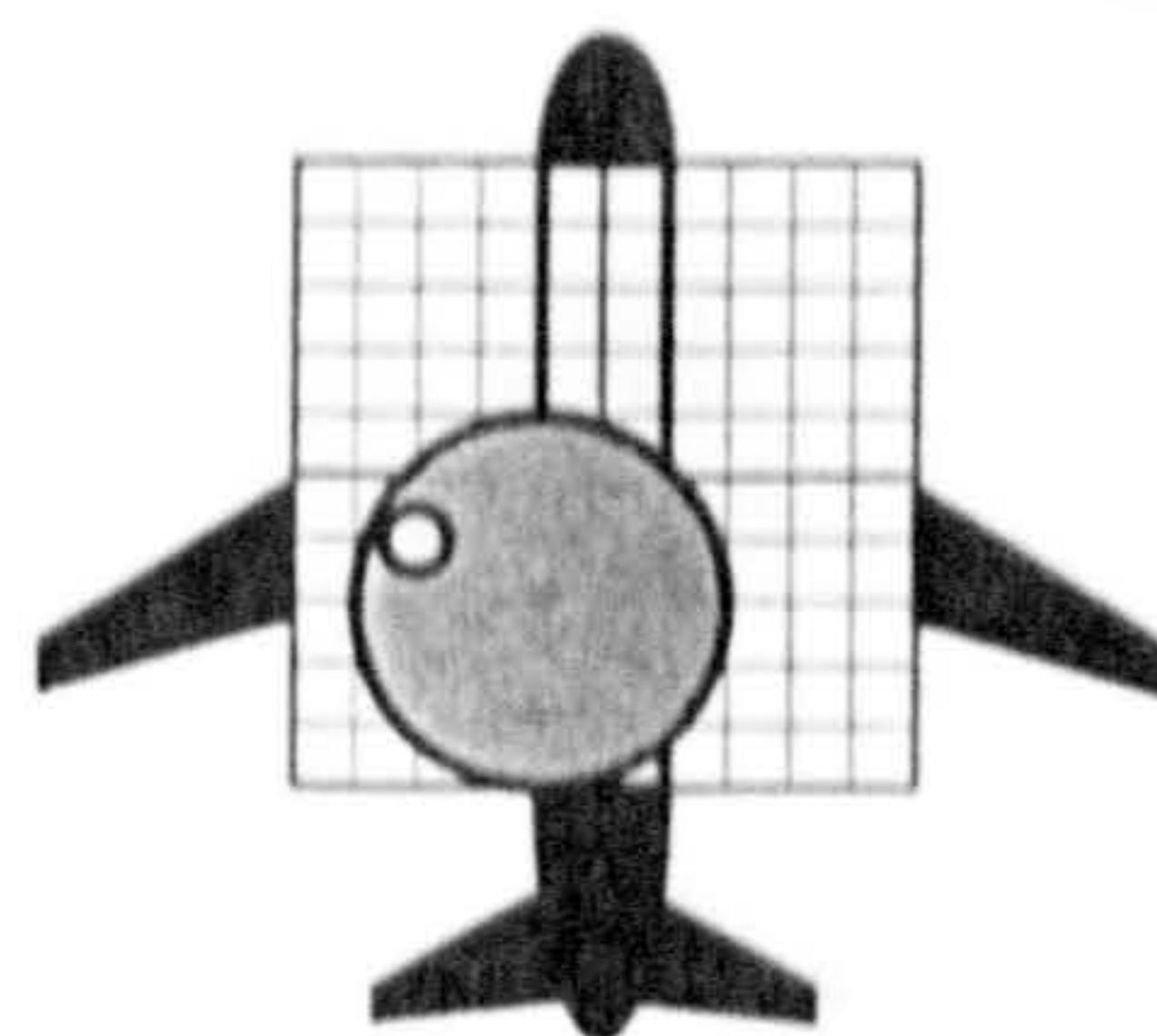
Aircraft	DC-10
Scenario	aborted takeoff
Starting point	detached right wing
Initiation time	0:00
Burnthro' time	(0:30)
Cabin damage	destroyed
Fire fatalities	0.13

840322 (Burnthrough)

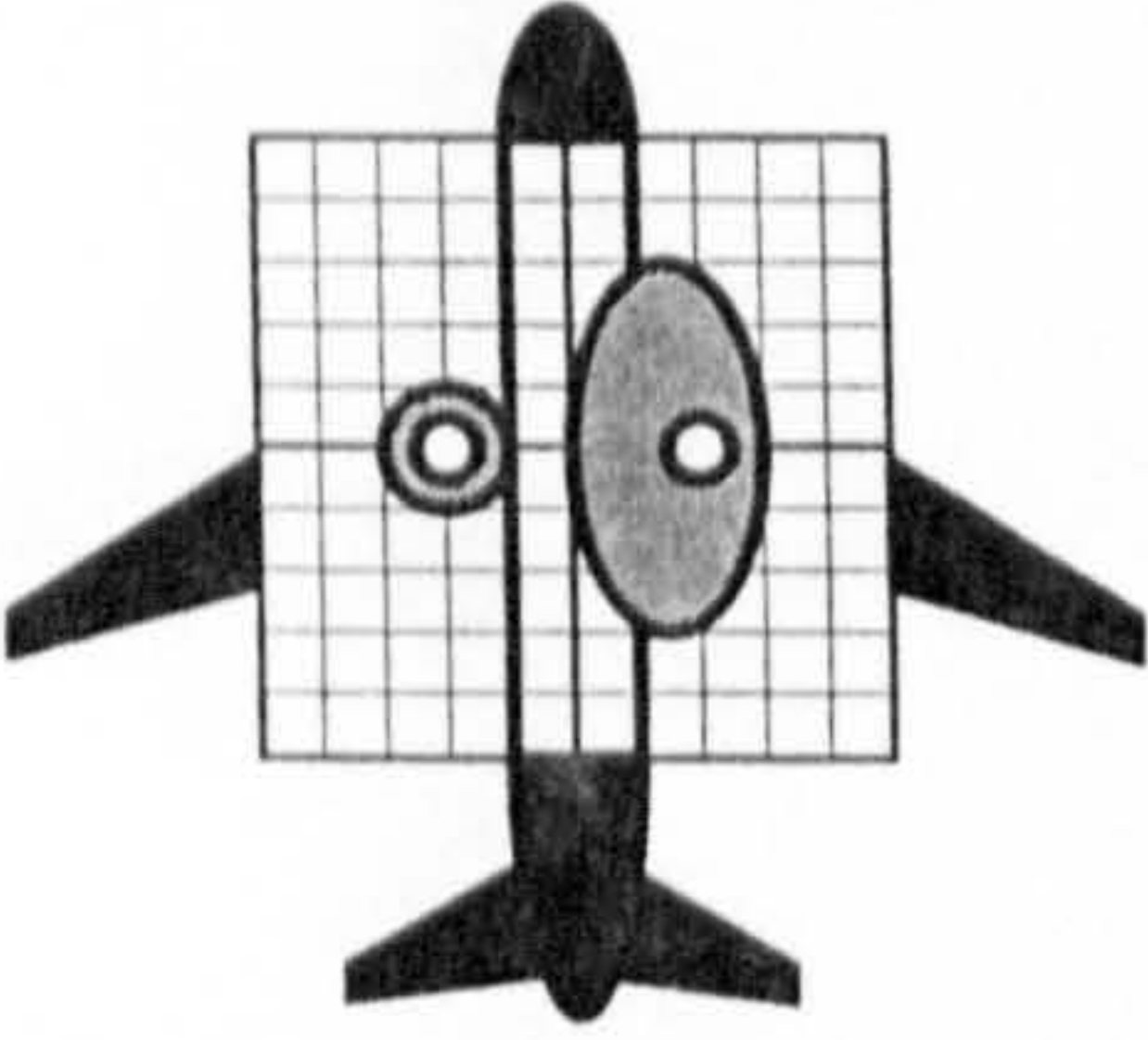
Aircraft	B-737-200
Scenario	takeoff engine failure
Starting point	left wing/engine
Initiation time	0:00
Burnthro' time	0:10
Cabin damage	destroyed
Fire fatalities	0.00

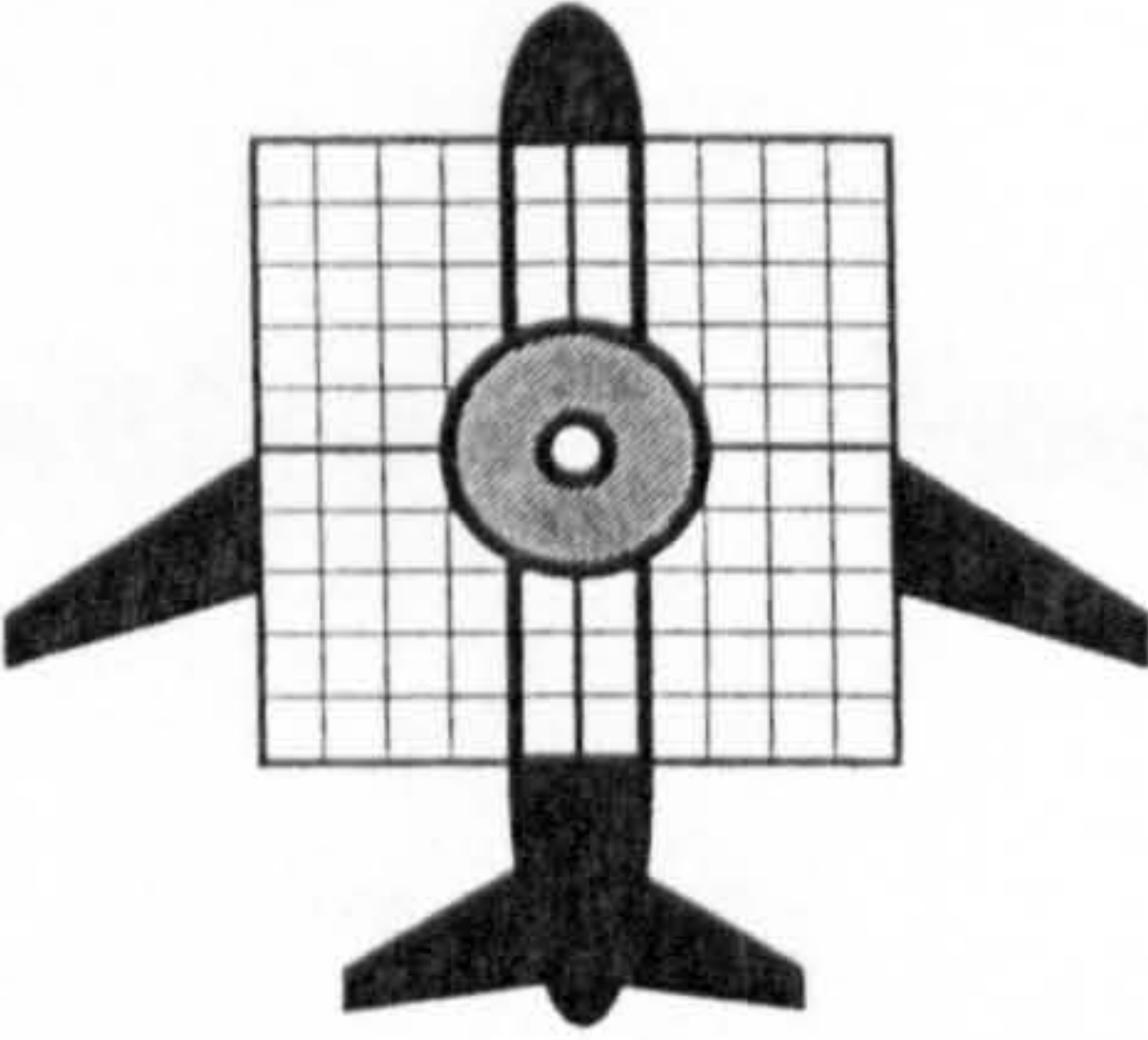
840830 (Burnthrough)

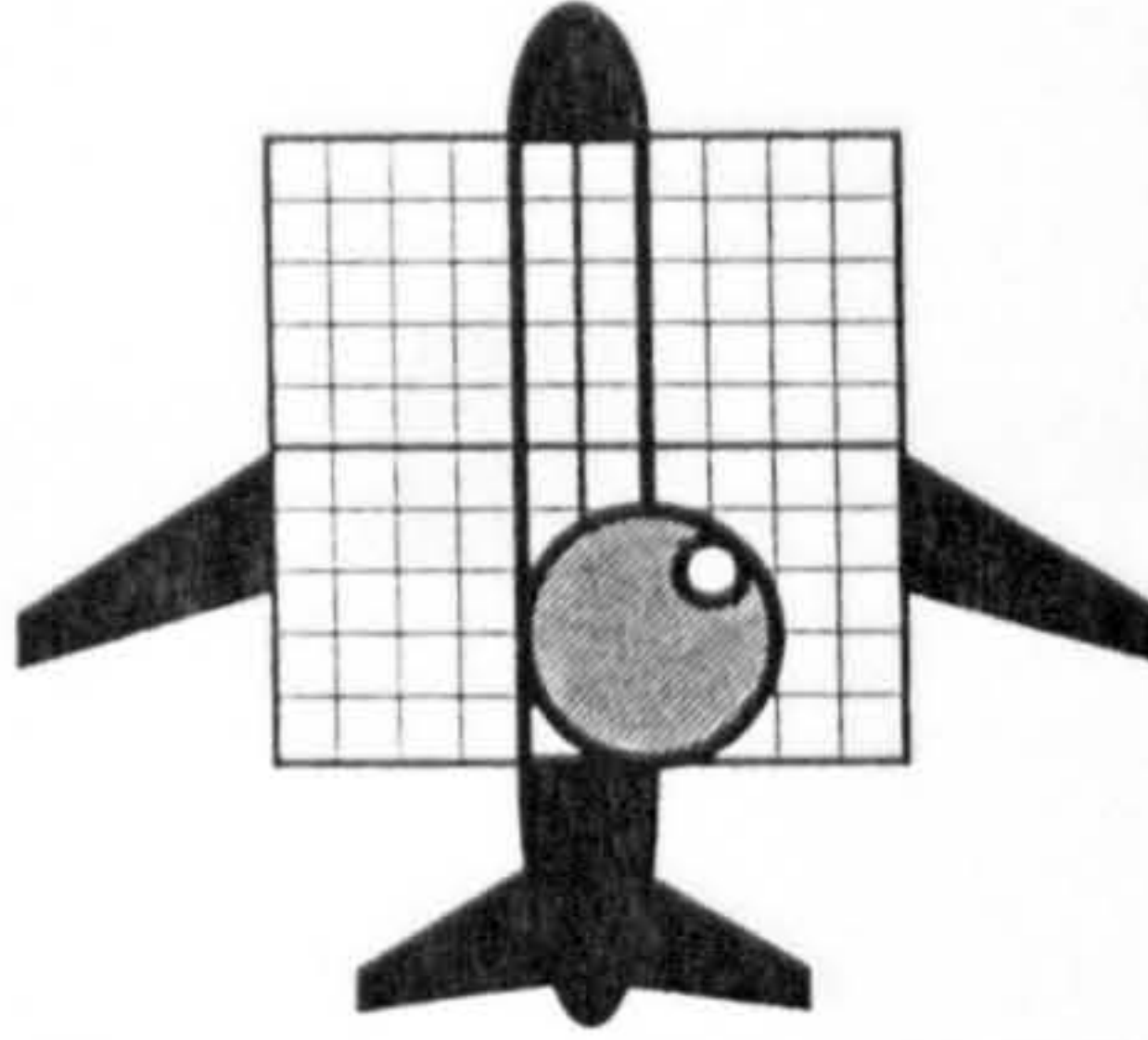
Aircraft	B-737-200
Scenario	taxiing engine failure
Starting point	right wing tanks
Initiation time	0:00
Burnthro' time	0:30
Cabin damage	destroyed
Fire fatalities	0.02

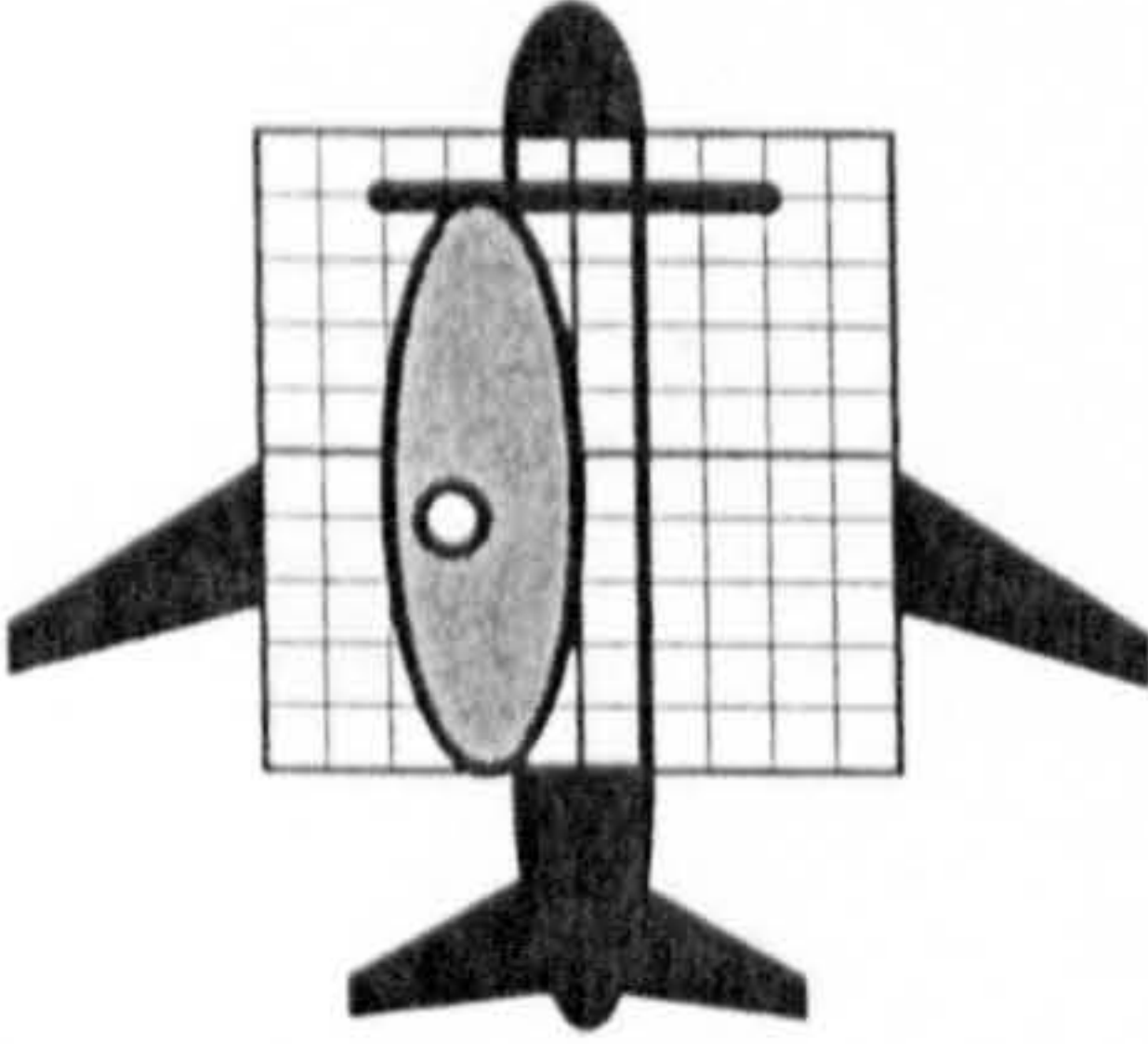
850822 (Burnthrough)

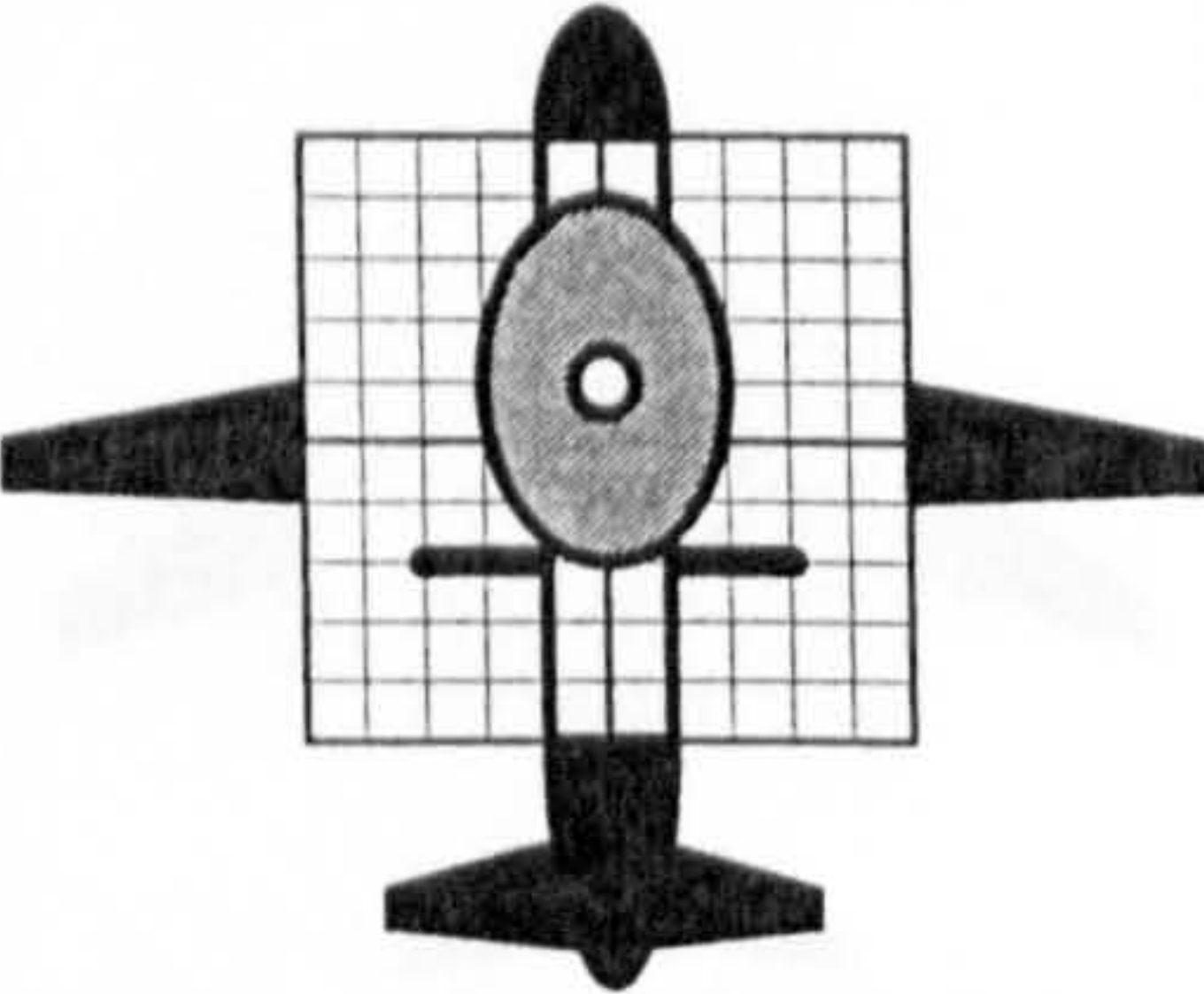
Aircraft	B-737-200
Scenario	takeoff engine failure
Starting point	left wing/engine
Initiation time	0:00
Burnthro' time	1:00
Cabin damage	destroyed
Fire fatalities	0.40

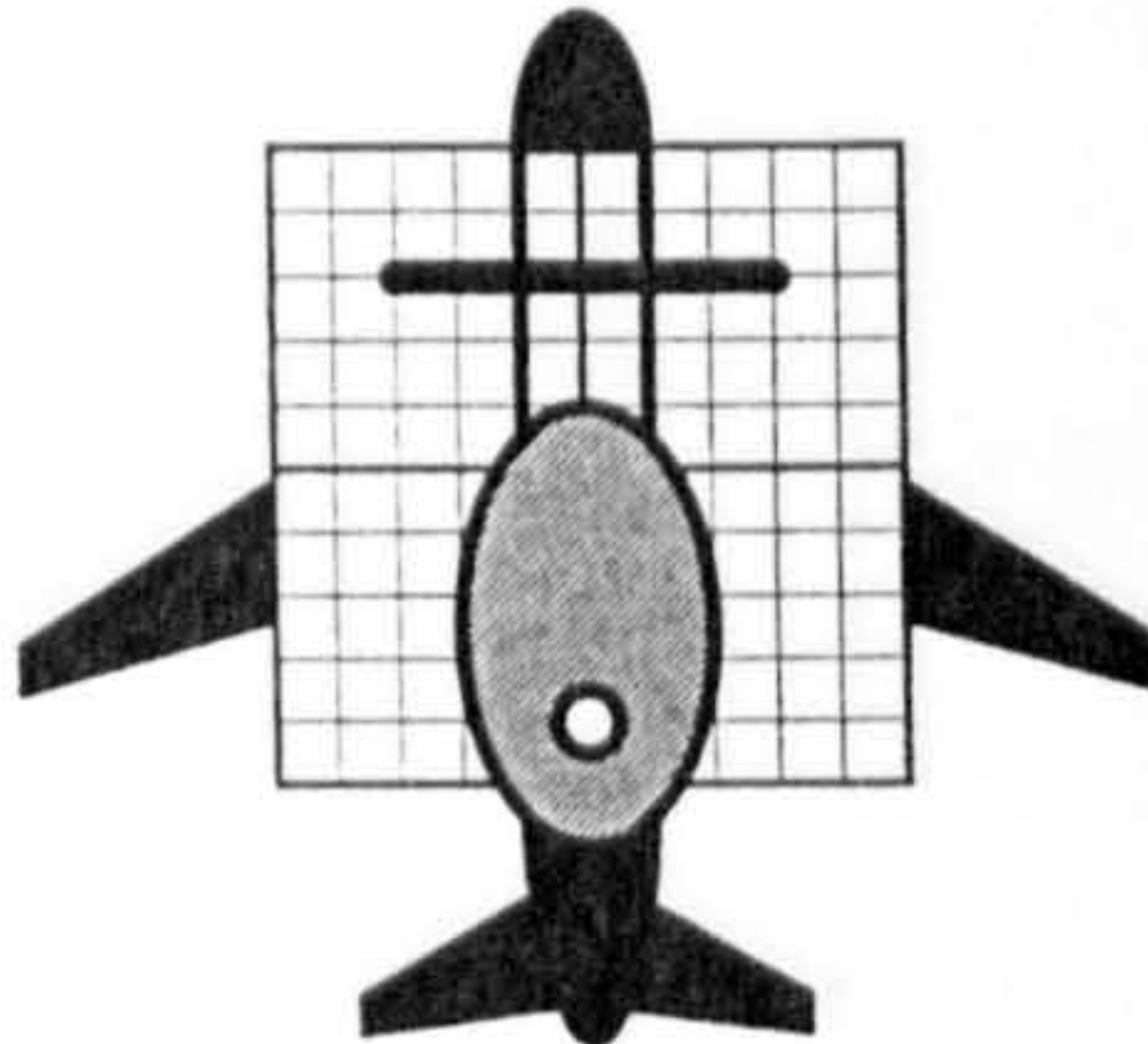
880626 (Burnthrough)	
	
Aircraft	A-320
Scenario	attempted go-around
Starting point	left & right wings
Initiation time	0:00
Burnthro' time	0:10
Cabin damage	completely destroyed
Fire fatalities	0.02

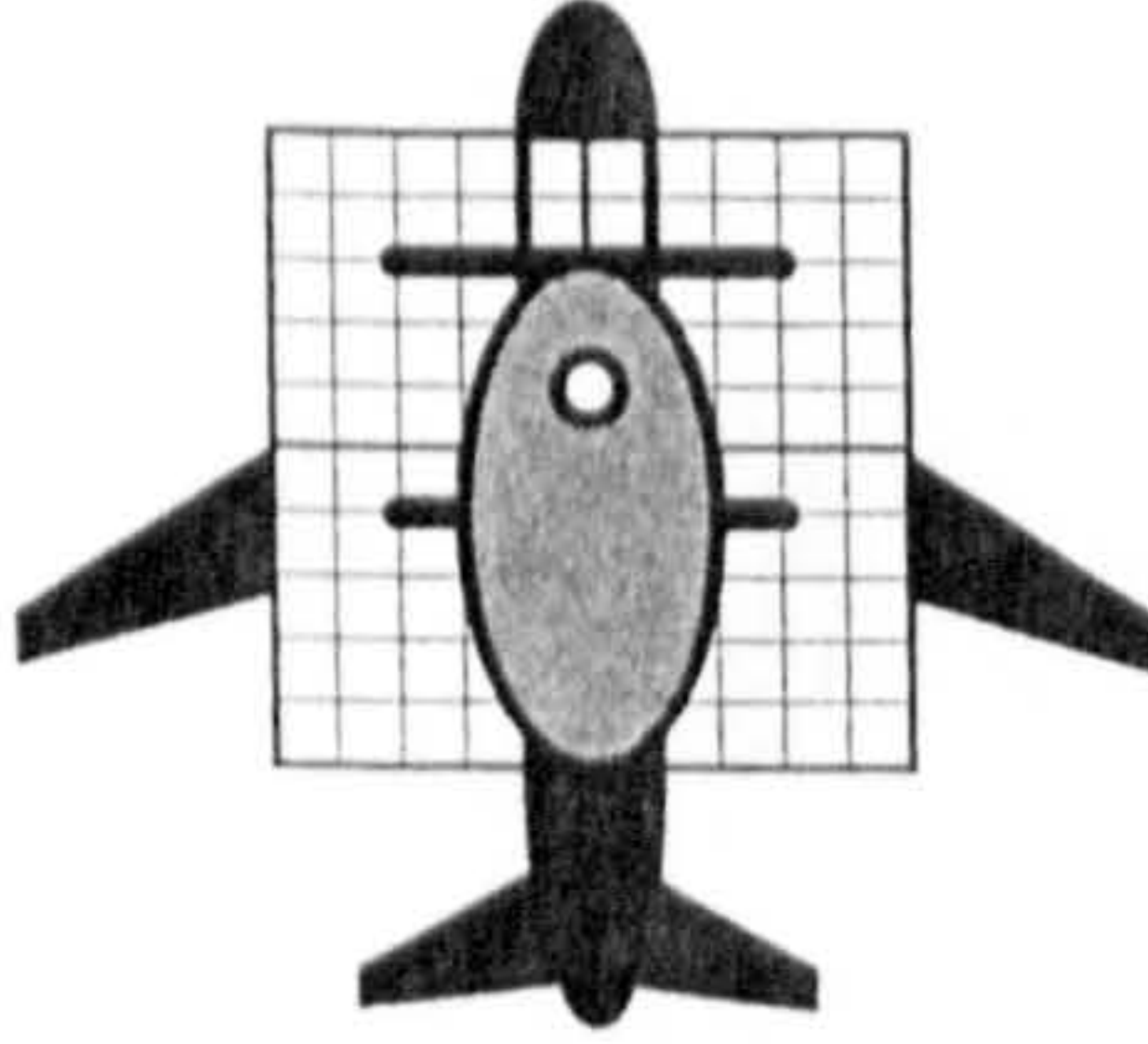
900511 (Burnthrough)	
	
Aircraft	B-737-300
Scenario	ground explosion
Starting point	centre fuel tank
Initiation time	0:00
Burnthro' time	0:00
Cabin damage	destroyed
Fire fatalities	0.06

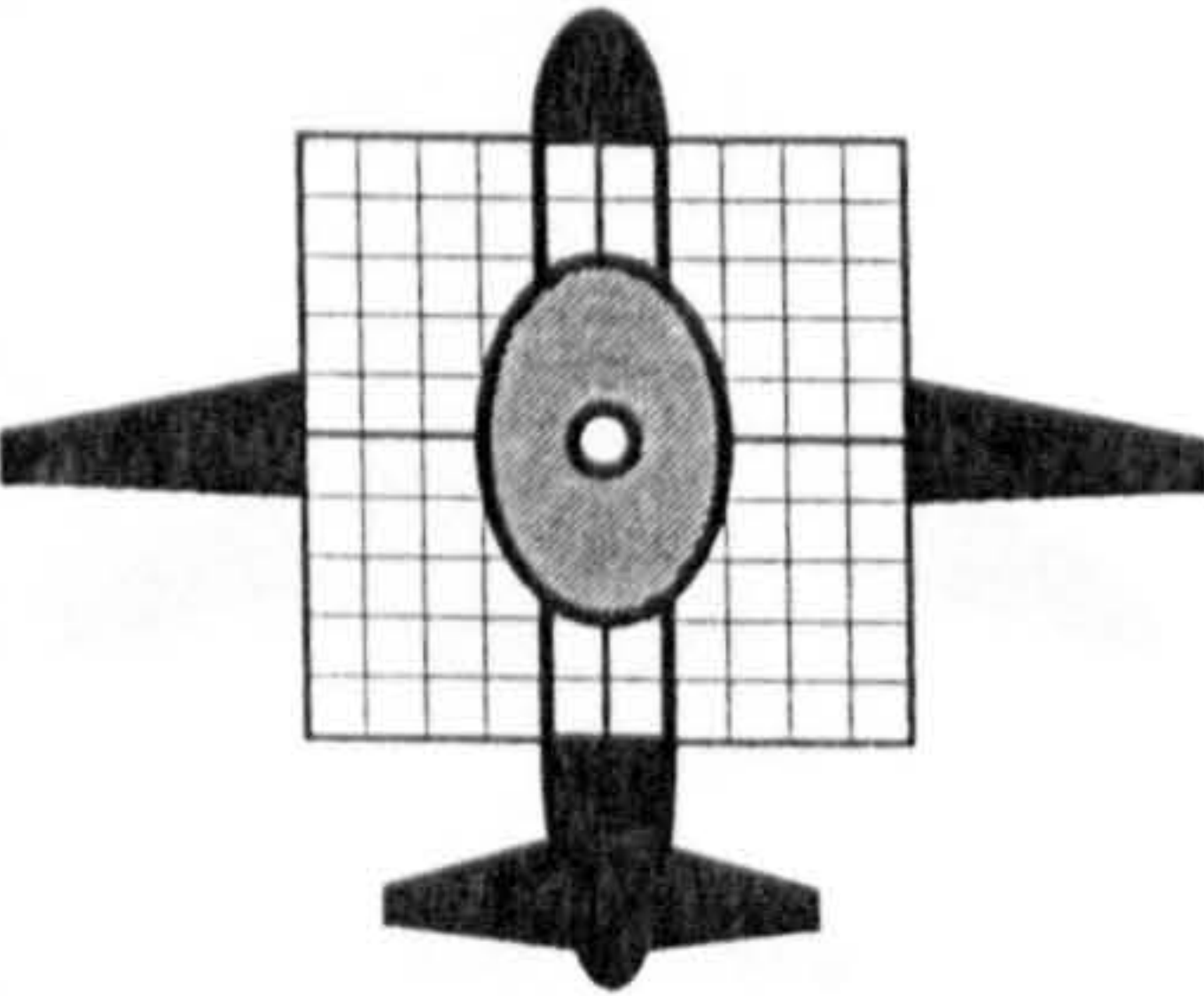
920730 (Burnthrough)	
	
Aircraft	L-1011
Scenario	aborted takeoff
Starting point	right rear fuselage
Initiation time	0:00
Burnthro' time	0:00
Cabin damage	extensive
Fire fatalities	0.00

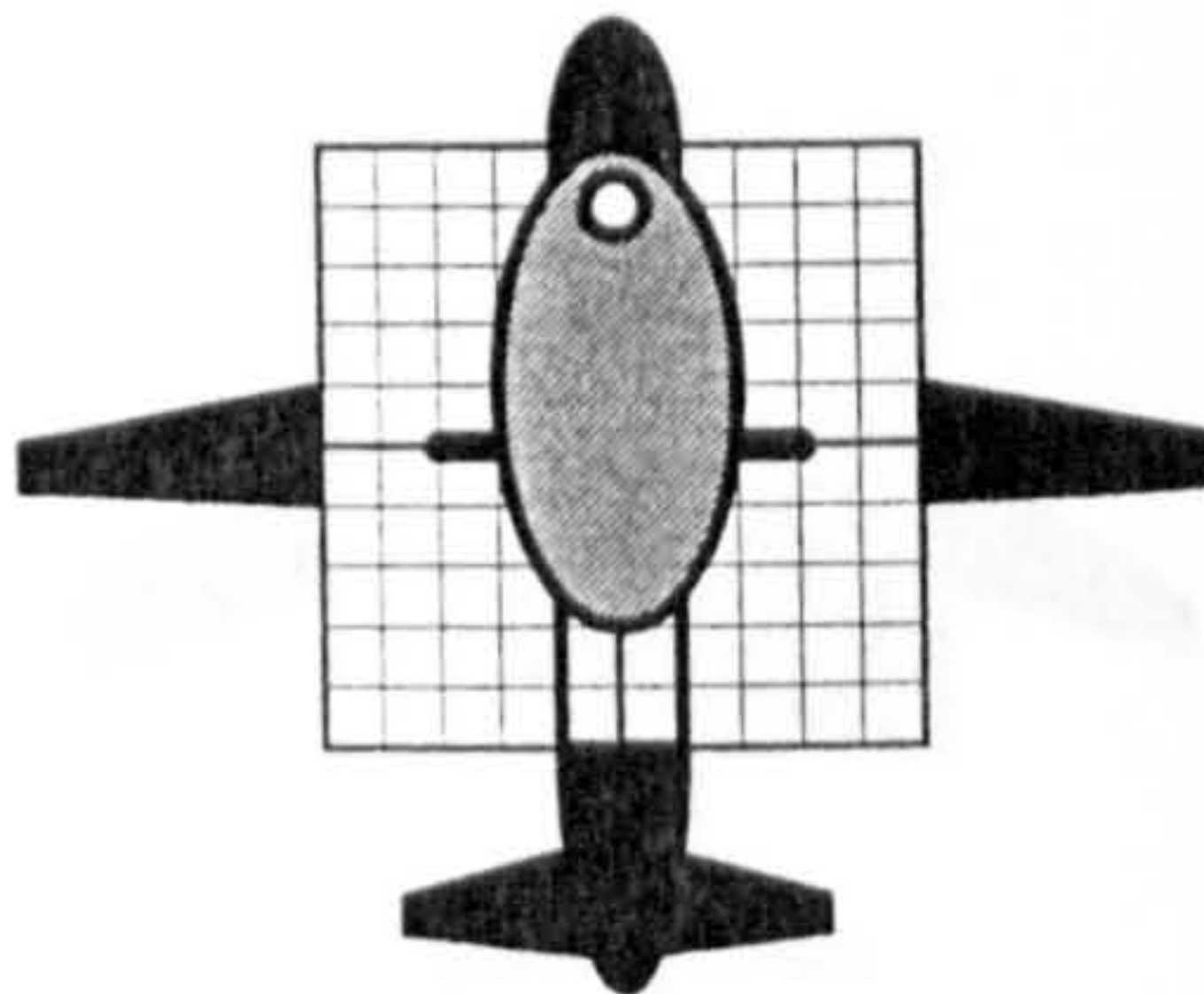
620603 (Impact)	
	
Aircraft	B-707-328
Scenario	abandoned takeoff
Starting point	left inner wing
Initiation time	0:00
Burnthro' time	(0:30)
Cabin damage	completely destroyed
Fire fatalities	0.89

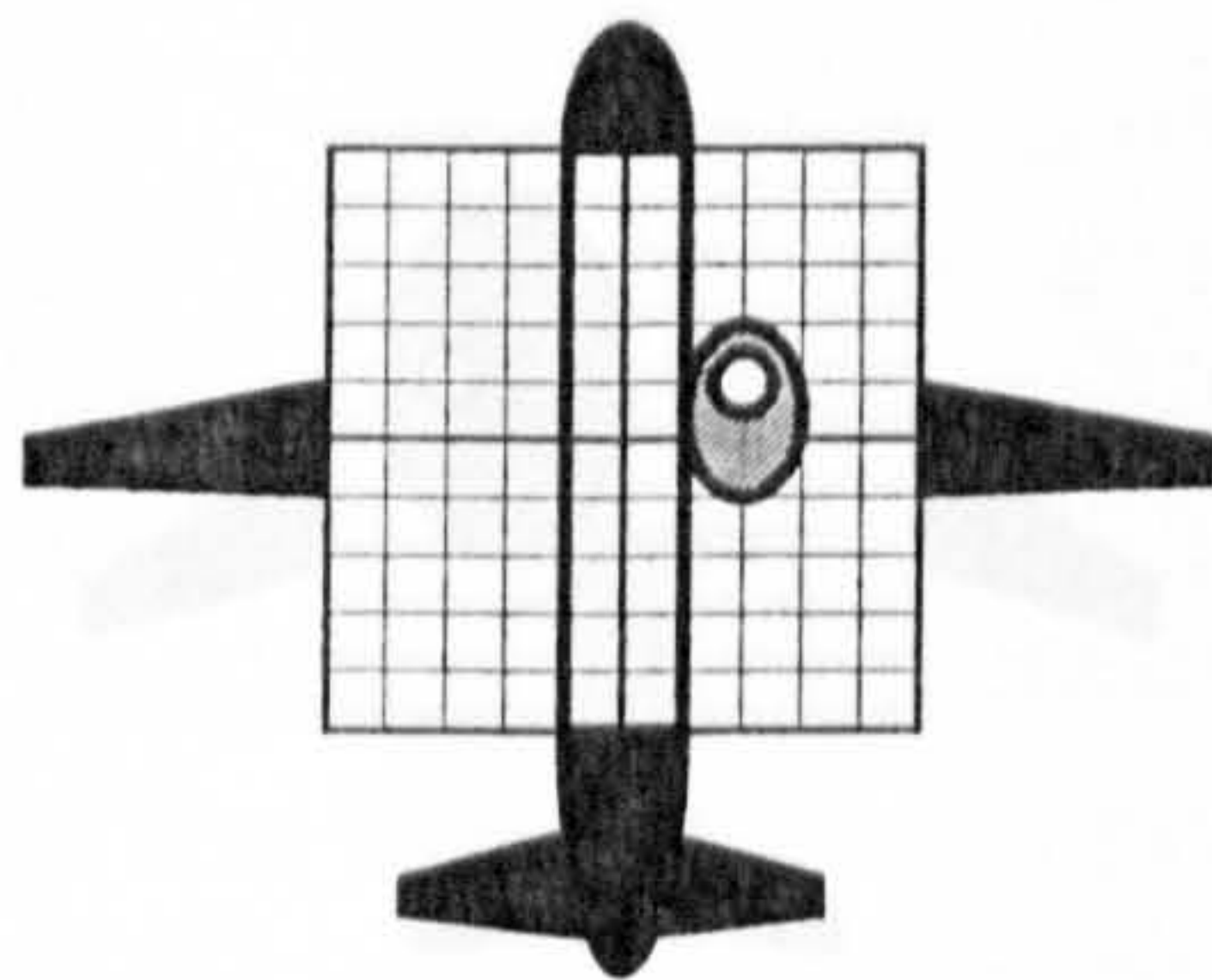
620722 (Impact)	
	
Aircraft	Britannia 314
Scenario	attempted go-around
Starting point	front section (?)
Initiation time	0:00
Burnthro' time	(0:30)
Cabin damage	destroyed
Fire fatalities	0.35

651108 (Impact)	
	
Aircraft	B-727-23
Scenario	crashed on approach
Starting point	rear of cabin
Initiation time	0:00
Burnthro' time	0:10
Cabin damage	completely destroyed
Fire fatalities	0.23

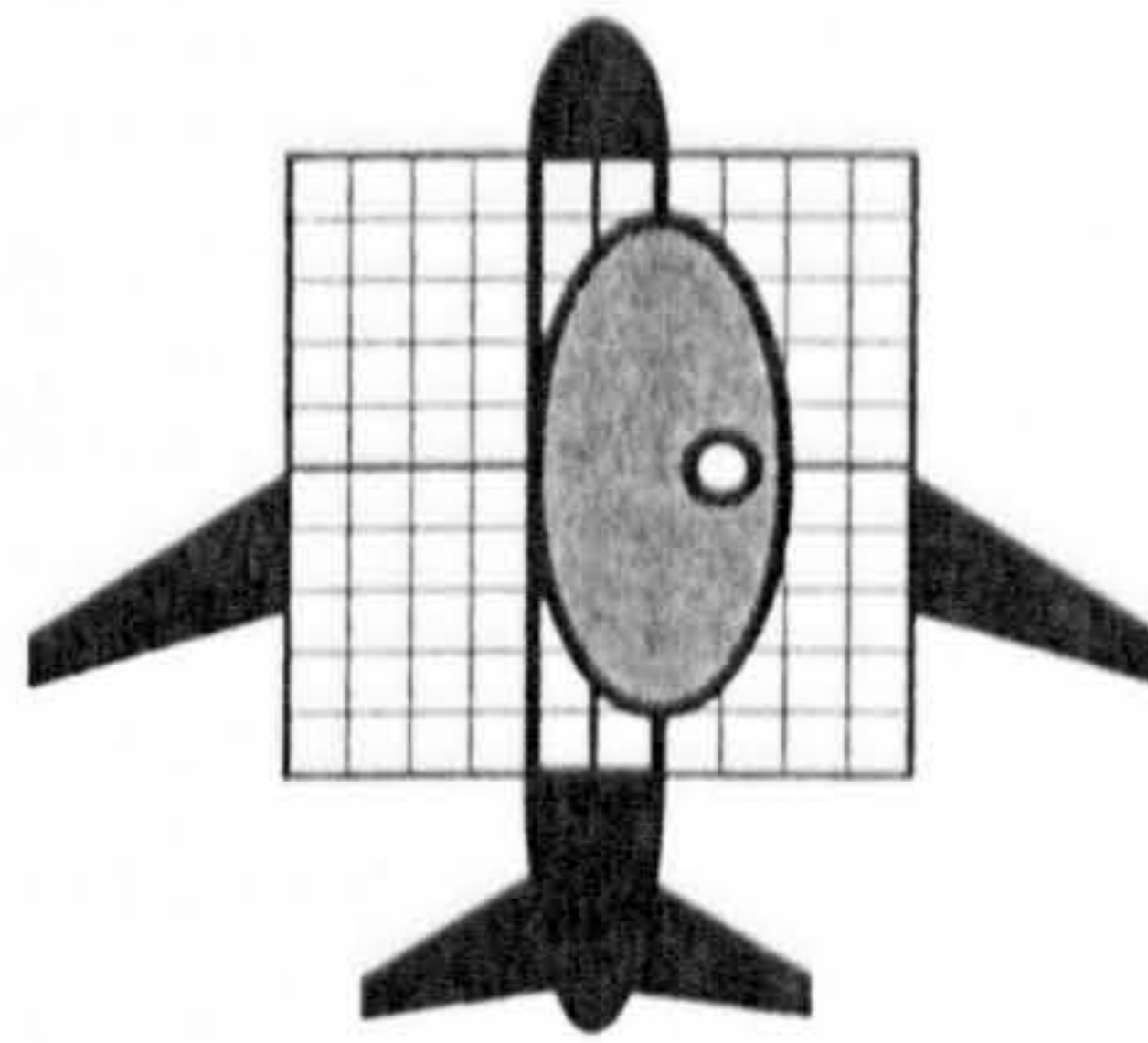
660304 (Impact)	
	
Aircraft	DC-8-33
Scenario	undershot
Starting point	inner fuel tanks
Initiation time	0:00
Burnthro' time	0:00
Cabin damage	destroyed
Fire fatalities	0.11

660422 (Impact)	
	
Aircraft	L-188C
Scenario	crashed on approach
Starting point	scattered
Initiation time	0:00
Burnthro' time	0:00
Cabin damage	destroyed
Fire fatalities	0.12

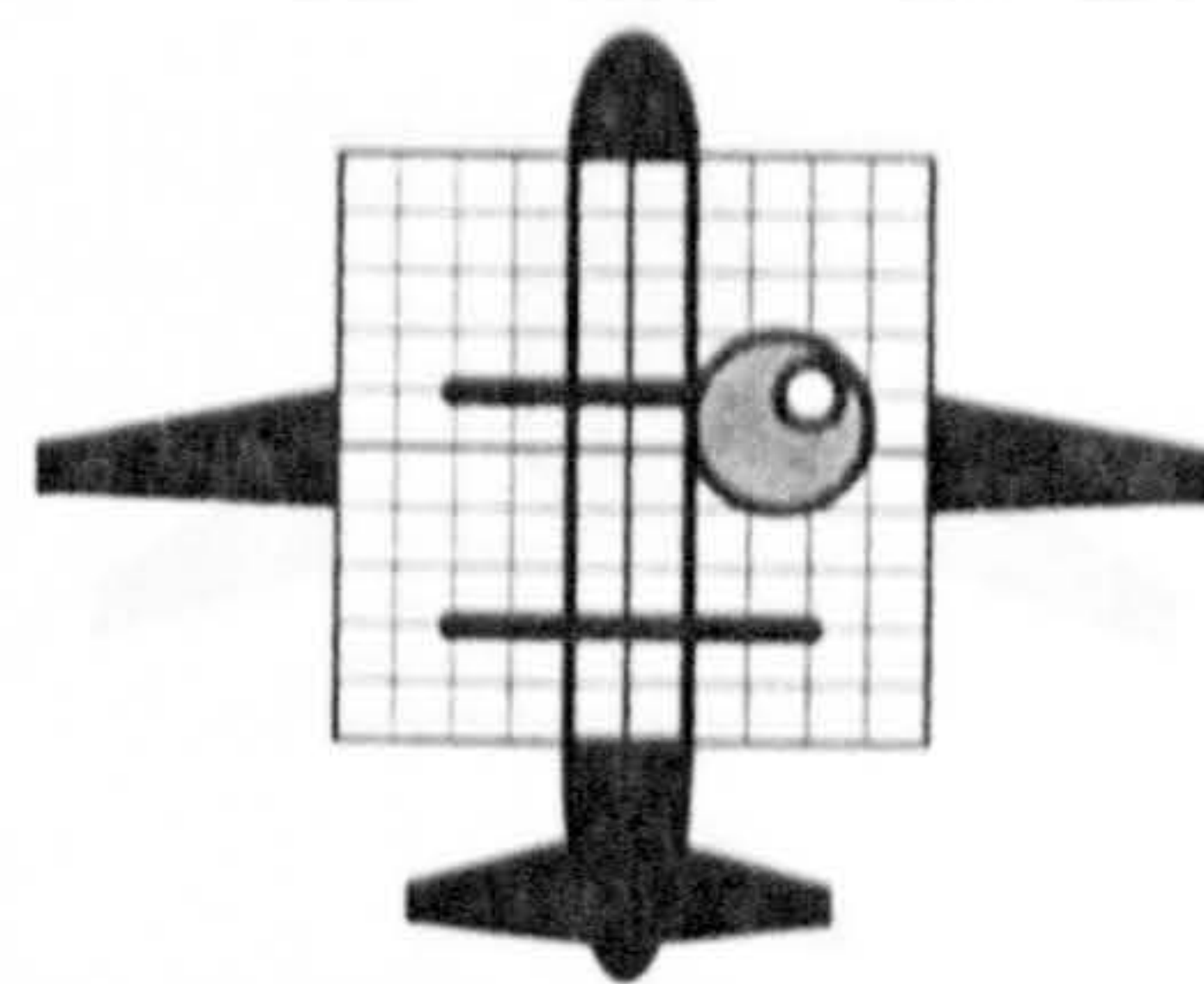
660901 (Impact)	
	
Aircraft	Britannia 102
Scenario	undershot
Starting point	nose
Initiation time	0:00
Burnthro' time	0:00
Cabin damage	destroyed
Fire fatalities	0.19

681224 (Impact)

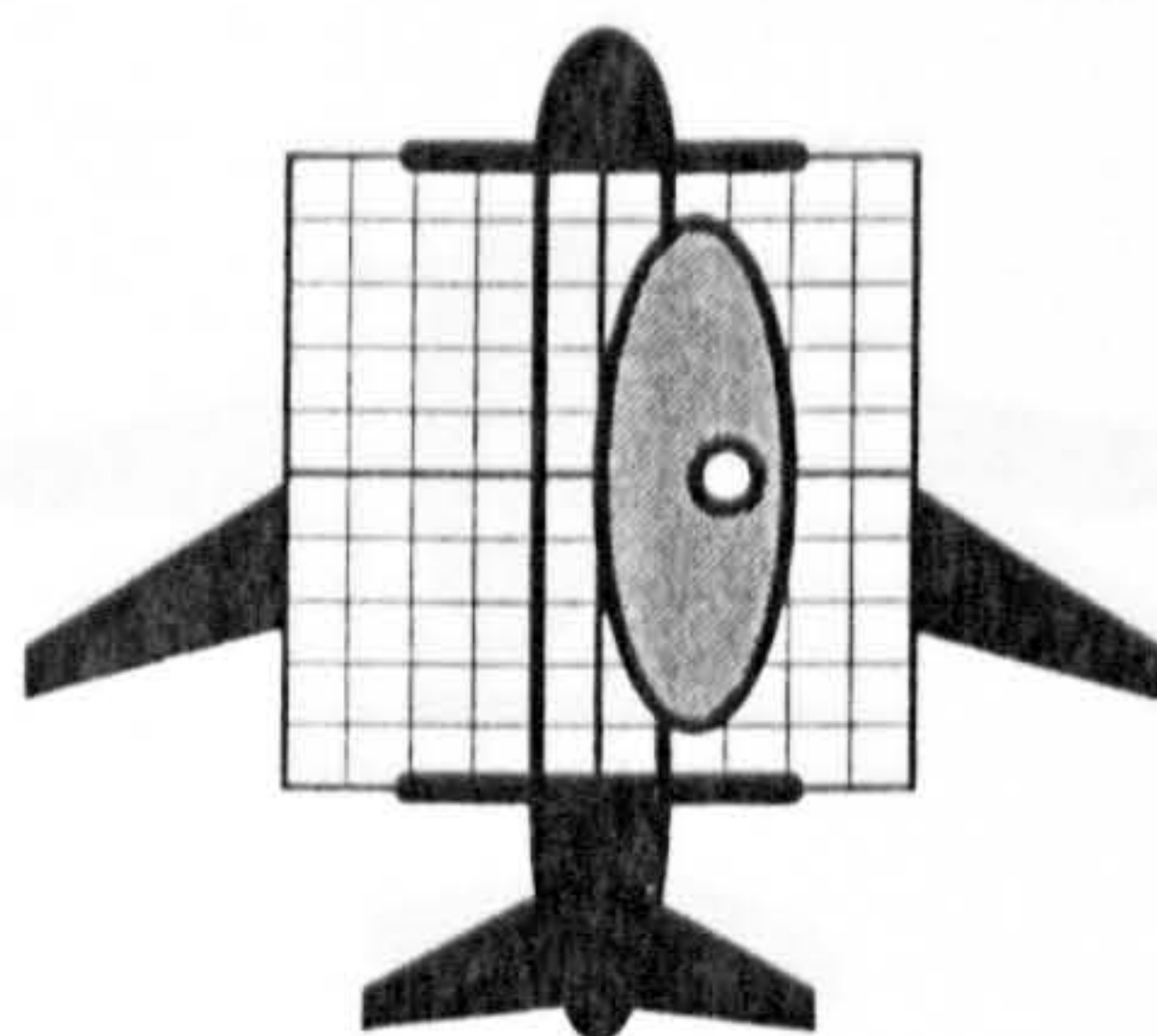
Aircraft	CV-580
Scenario	crashed on approach
Starting point	right side of fuselage
Initiation time	0:00
Burnthro' time	0:00
Cabin damage	none
Fire fatalities	0.00

730219 (Impact)

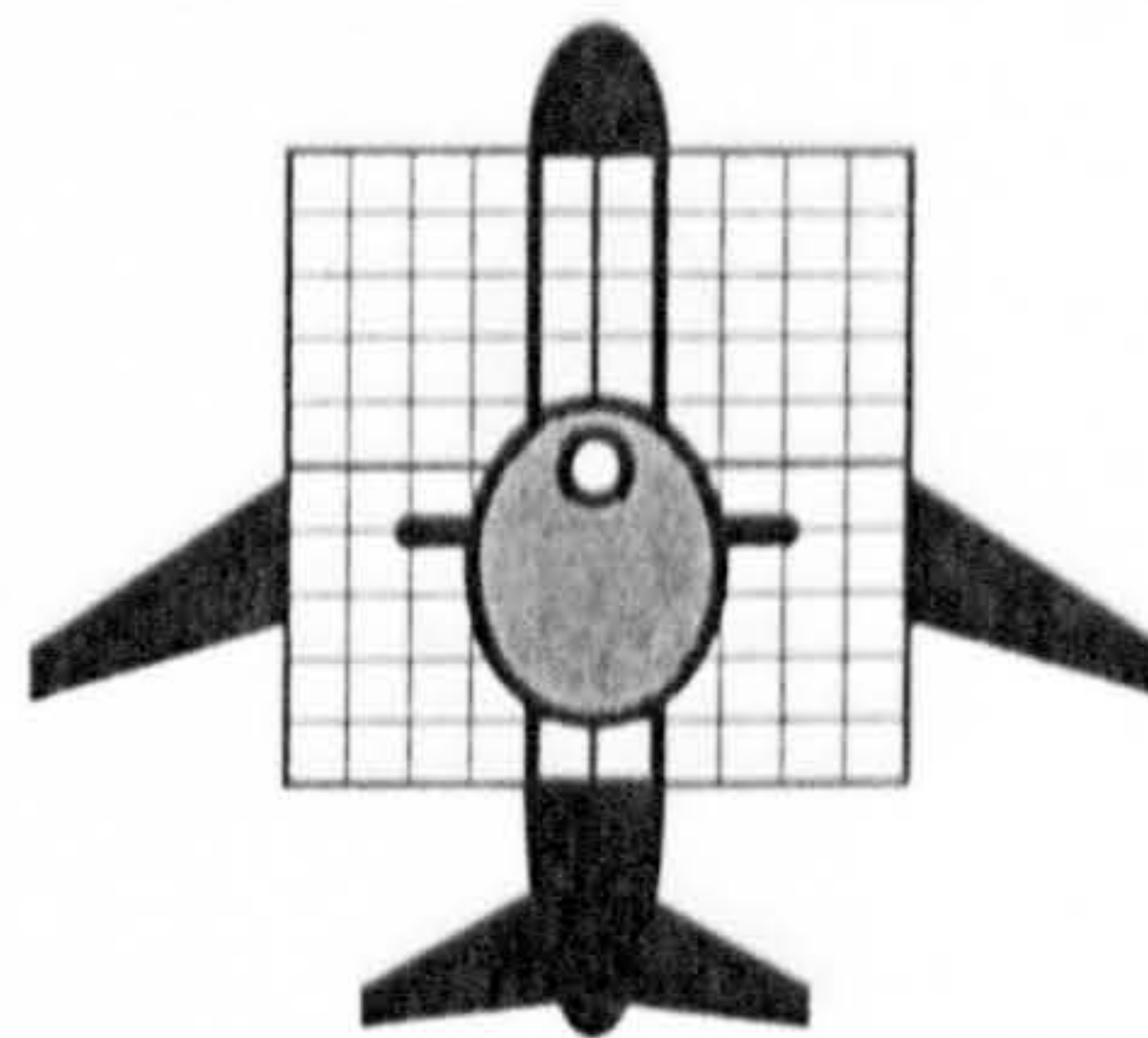
Aircraft	Tu-154
Scenario	crashed on approach
Starting point	right side of fuselage
Initiation time	0:00
Burnthro' time	(0:30)
Cabin damage	completely destroyed
Fire fatalities	0.51

730410 (Impact)

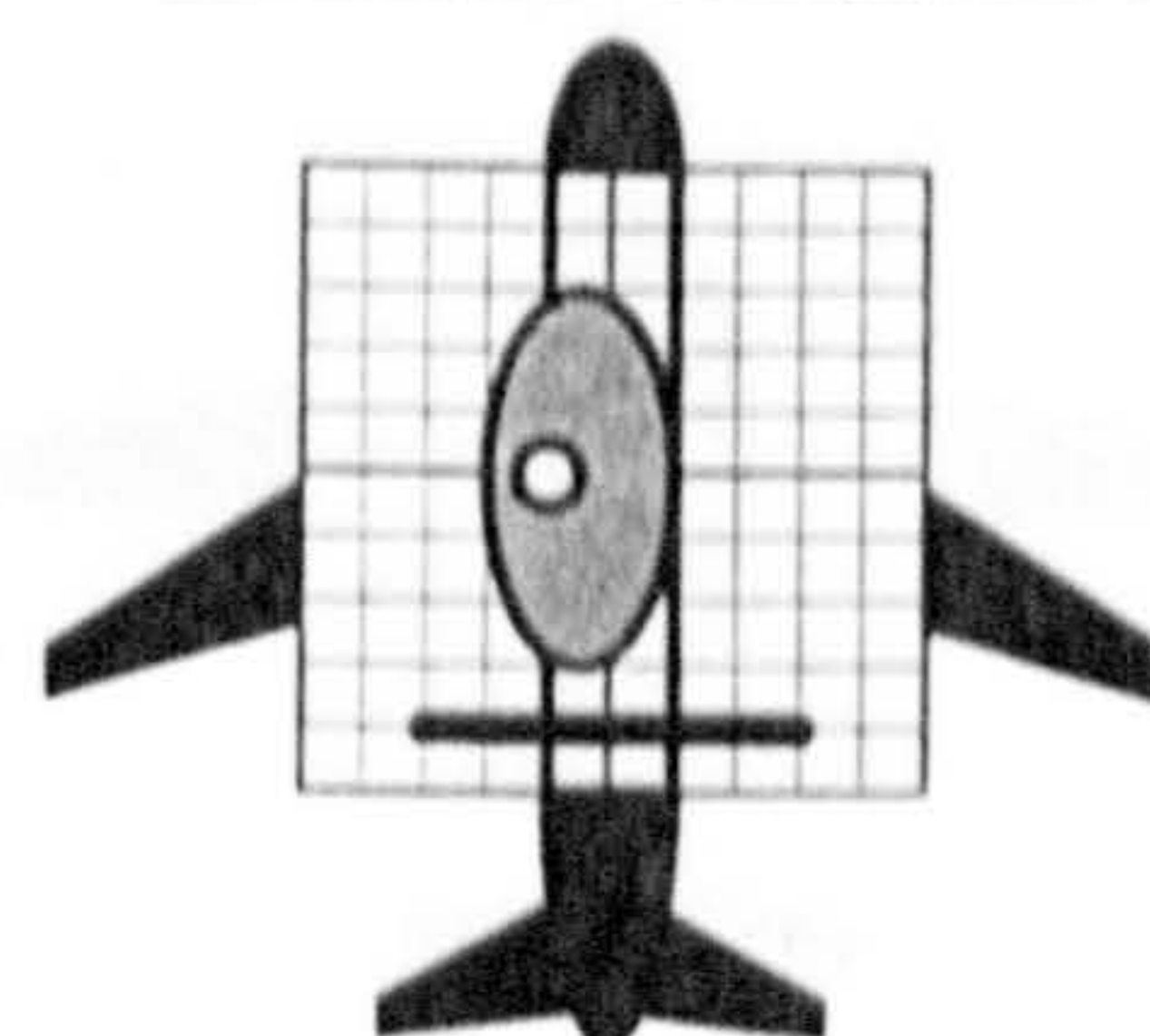
Aircraft	Vanguard
Scenario	crashed on approach
Starting point	right wing
Initiation time	0:00
Burnthro' time	0:00
Cabin damage	none
Fire fatalities	0.03

740126 (Impact)

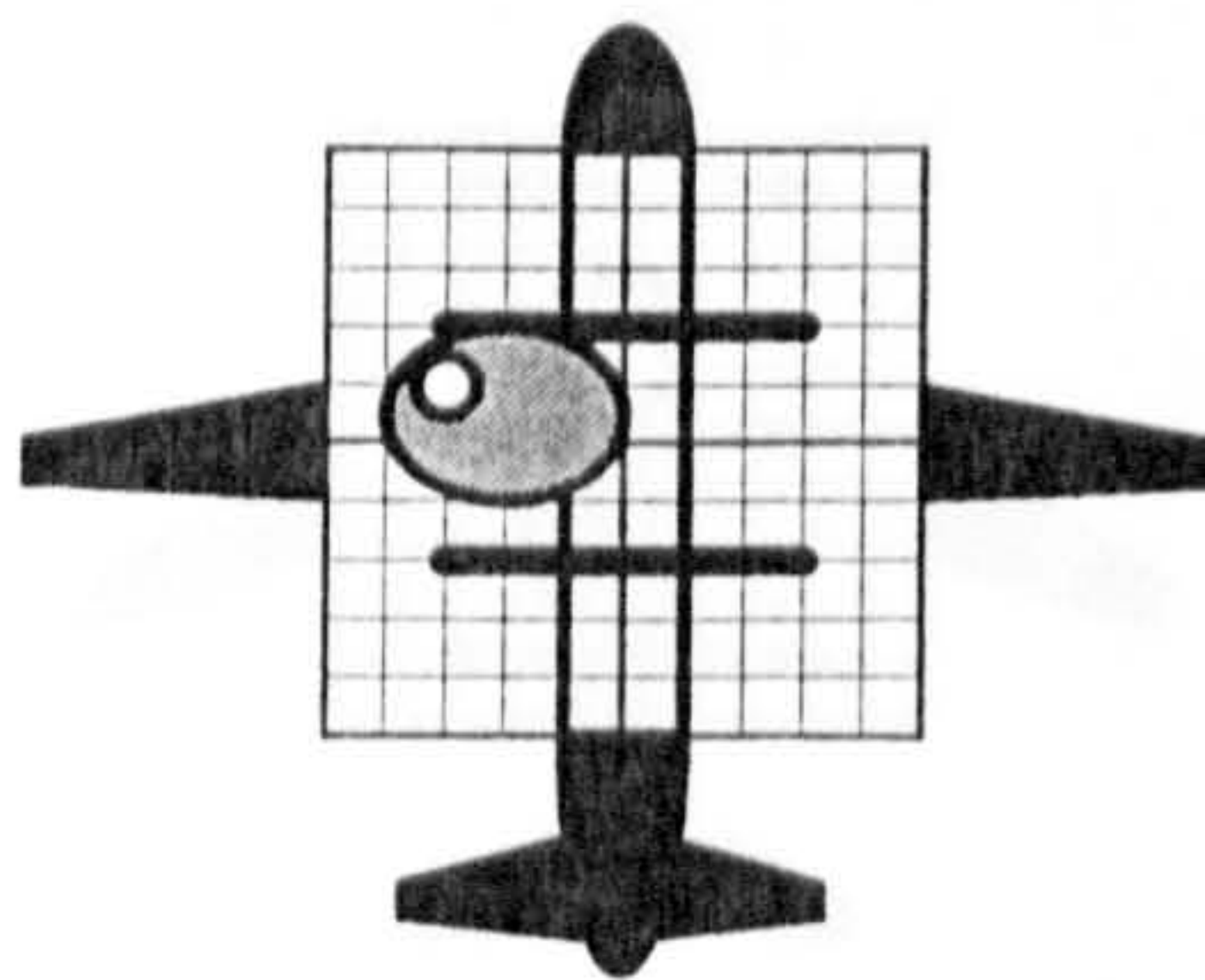
Aircraft	F-28-1000
Scenario	stalled after takeoff
Starting point	left wing
Initiation time	0:00
Burnthro' time	(0:30)
Cabin damage	completely destroyed
Fire fatalities	0.68

740911 (Impact)

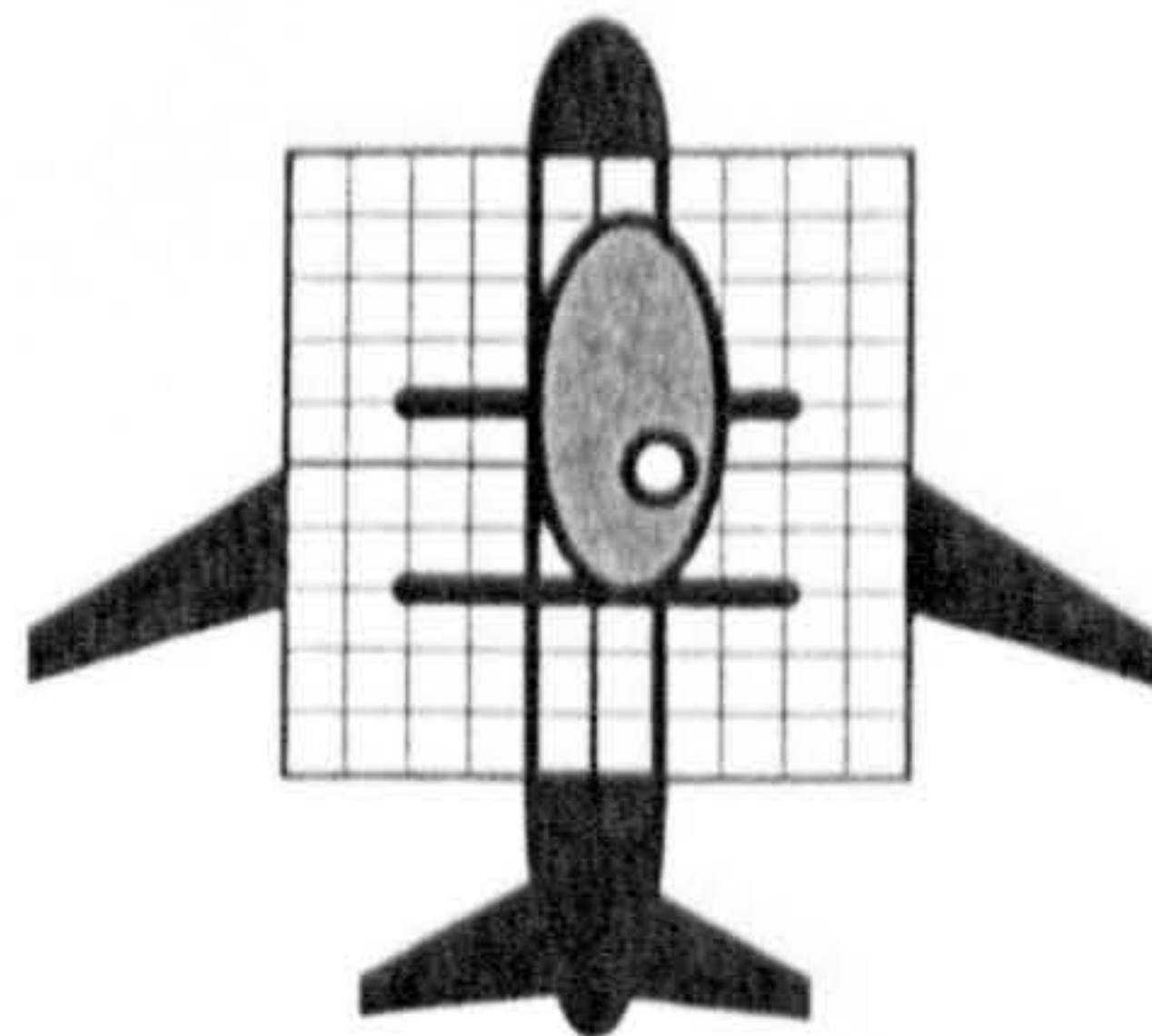
Aircraft	DC-9-31
Scenario	crashed on approach
Starting point	wing tanks
Initiation time	0:00
Burnthro' time	0:00
Cabin damage	destroyed
Fire fatalities	0.49

750624 (Impact)

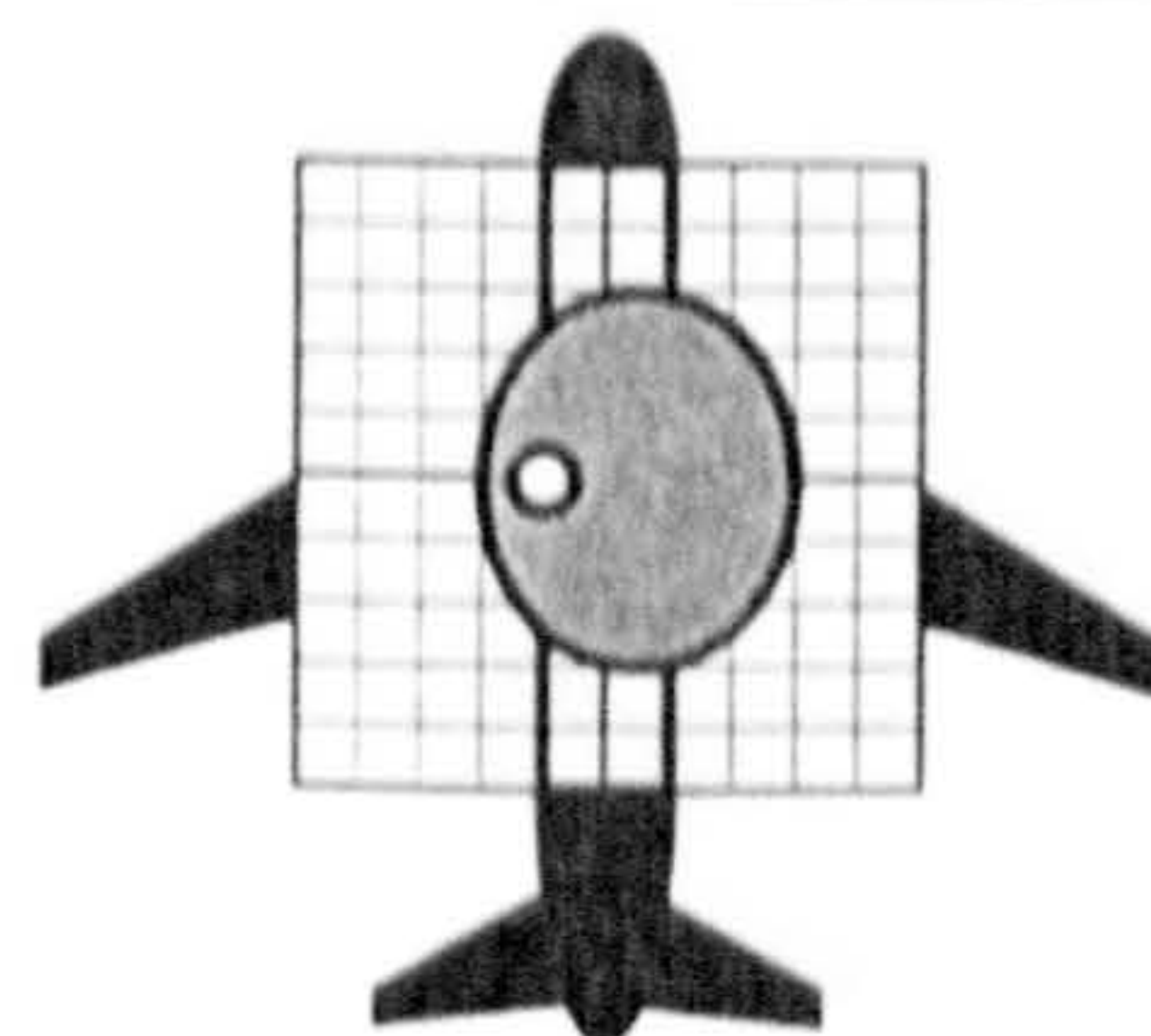
Aircraft	B-727-225
Scenario	crashed on approach
Starting point	left wing
Initiation time	0:00
Burnthro' time	0:00
Cabin damage	destroyed
Fire fatalities	0.10

750830 (Impact)

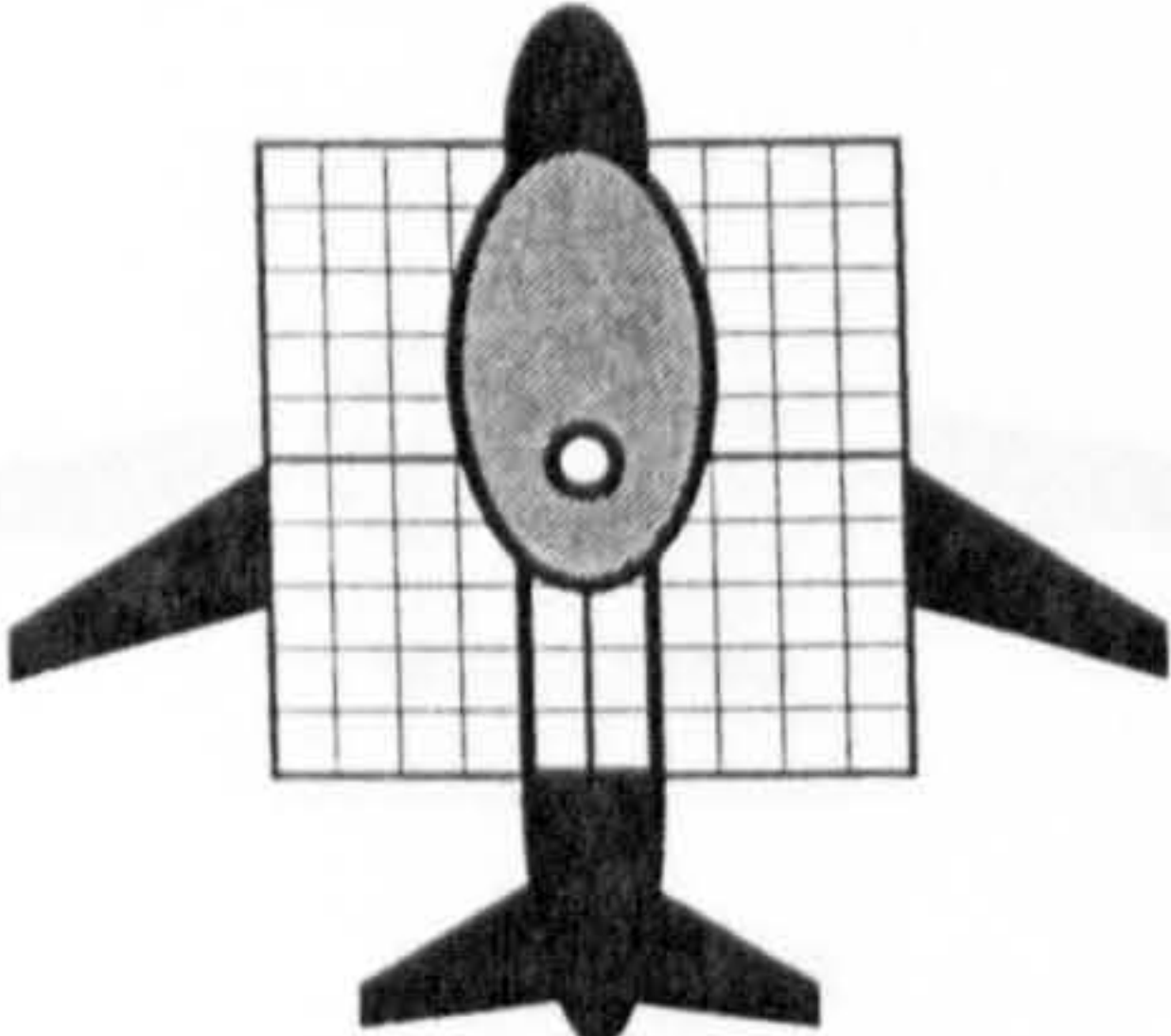
Aircraft	F-27B
Scenario	crashed on approach
Starting point	left engine
Initiation time	0:00
Burnthro' time	(5:00)
Cabin damage	extensive
Fire fatalities	0.00

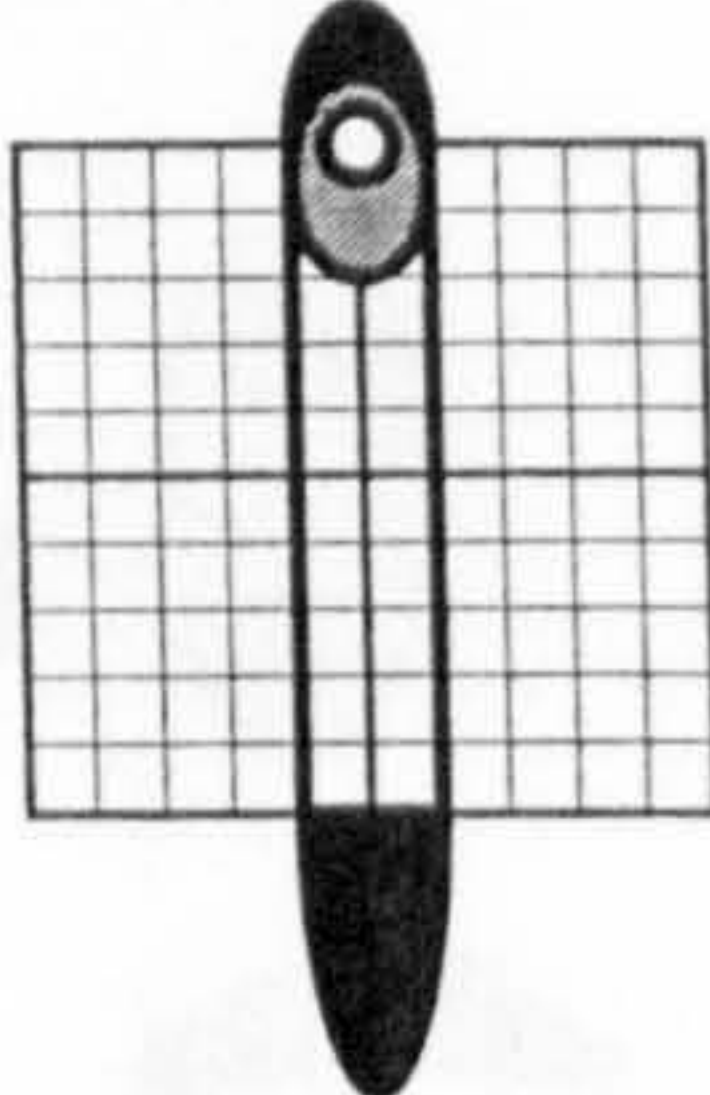
760427 (Impact)

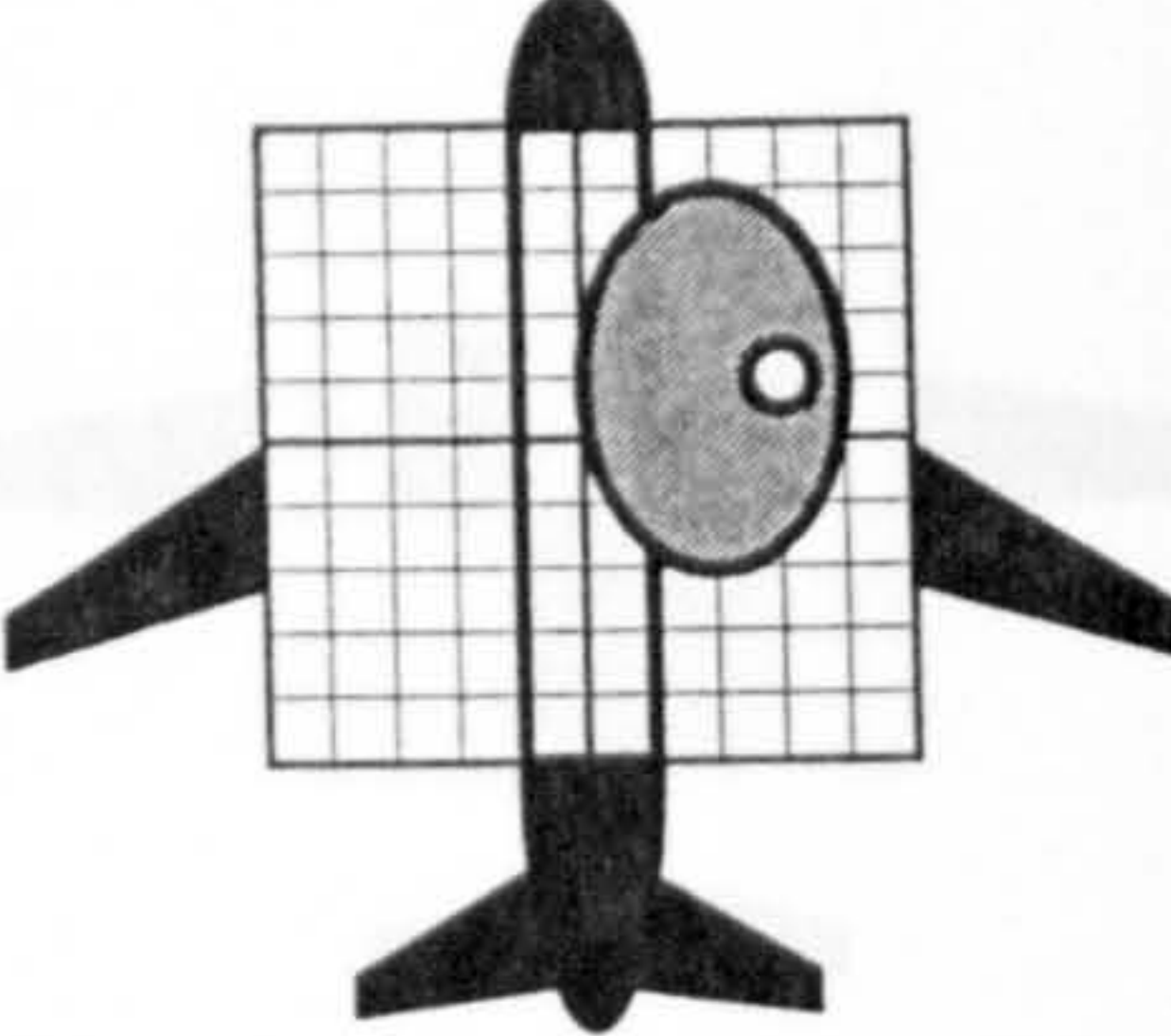
Aircraft	B-727-35
Scenario	overran on landing
Starting point	right wing
Initiation time	0:00
Burnthro' time	0:00
Cabin damage	destroyed
Fire fatalities	0.25

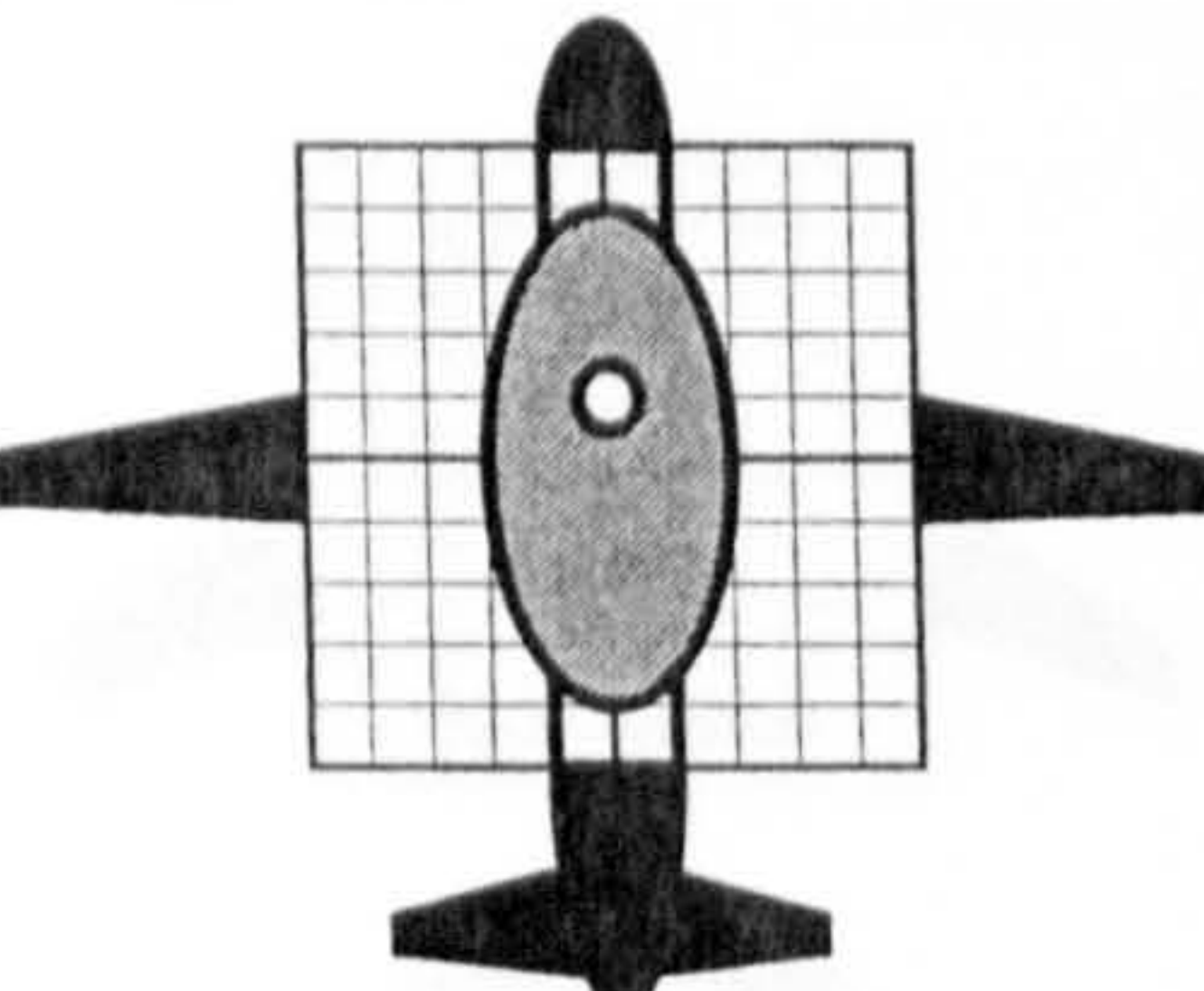
770327B (Impact)

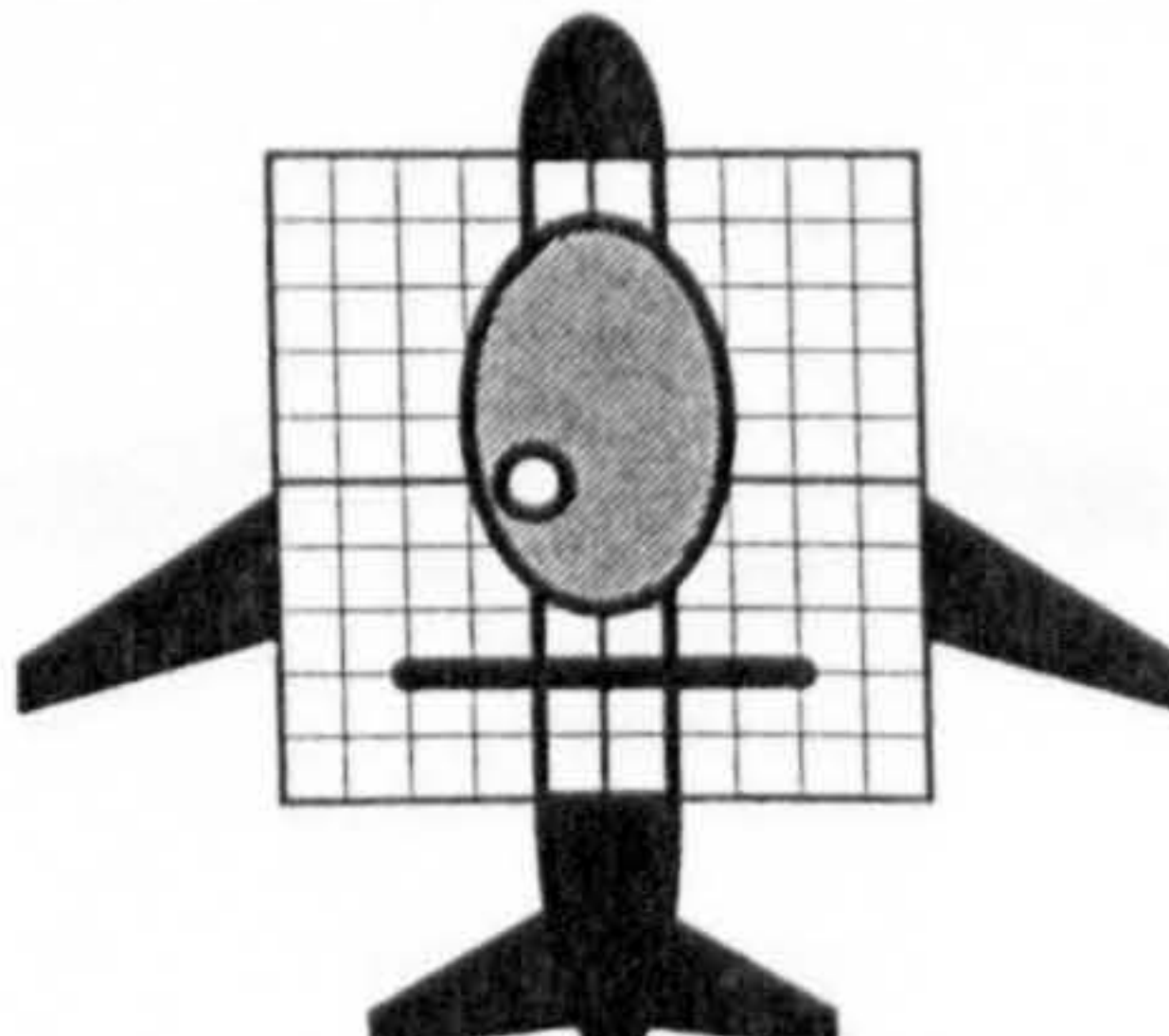
Aircraft	B-747-121
Scenario	ground collision
Starting point	under left wing
Initiation time	0:00
Burnthro' time	(0:30)
Cabin damage	destroyed
Fire fatalities	0.48

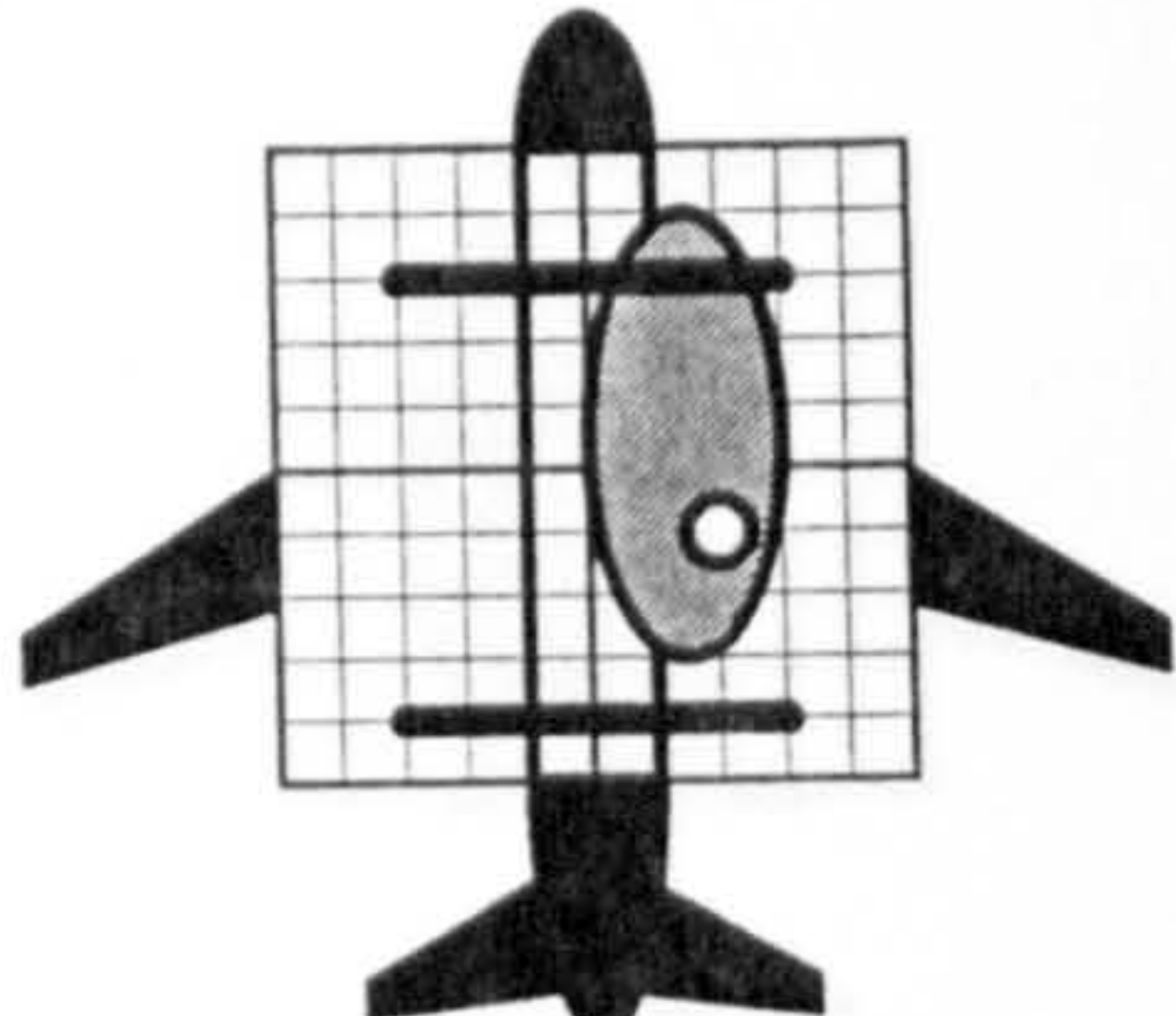
790313 (Impact)	
	
Aircraft Scenario	B-727-200 missed approach
Starting point	rear centre fuselage
Initiation time	0:00
Burnthro' time	(0:30)
Cabin damage	destroyed
Fire fatalities	0.31

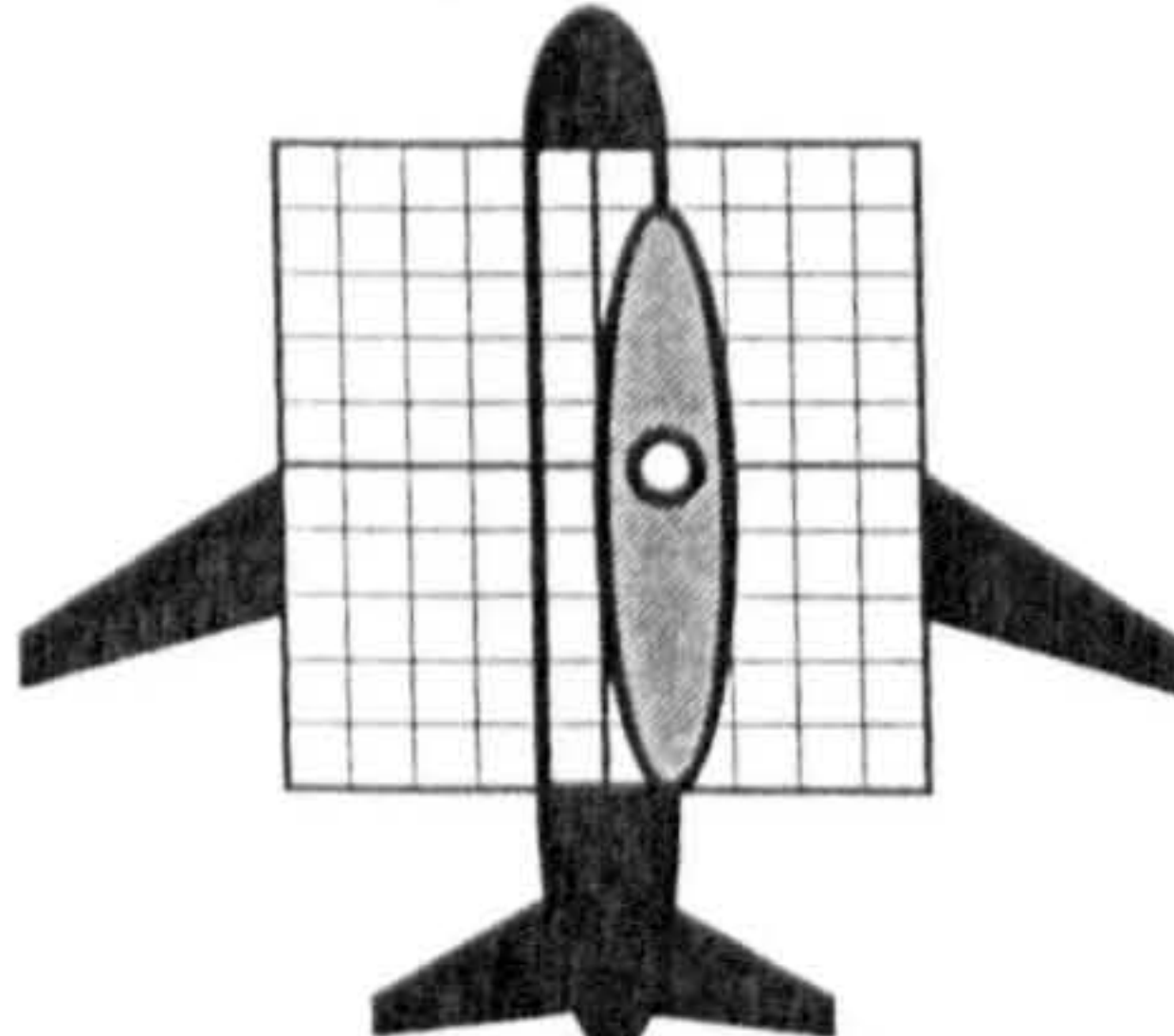
790329 (Impact)	
	
Aircraft Scenario	
Starting point	
Initiation time	0:00
Burnthro' time	?
Cabin damage	
Fire fatalities	0.00

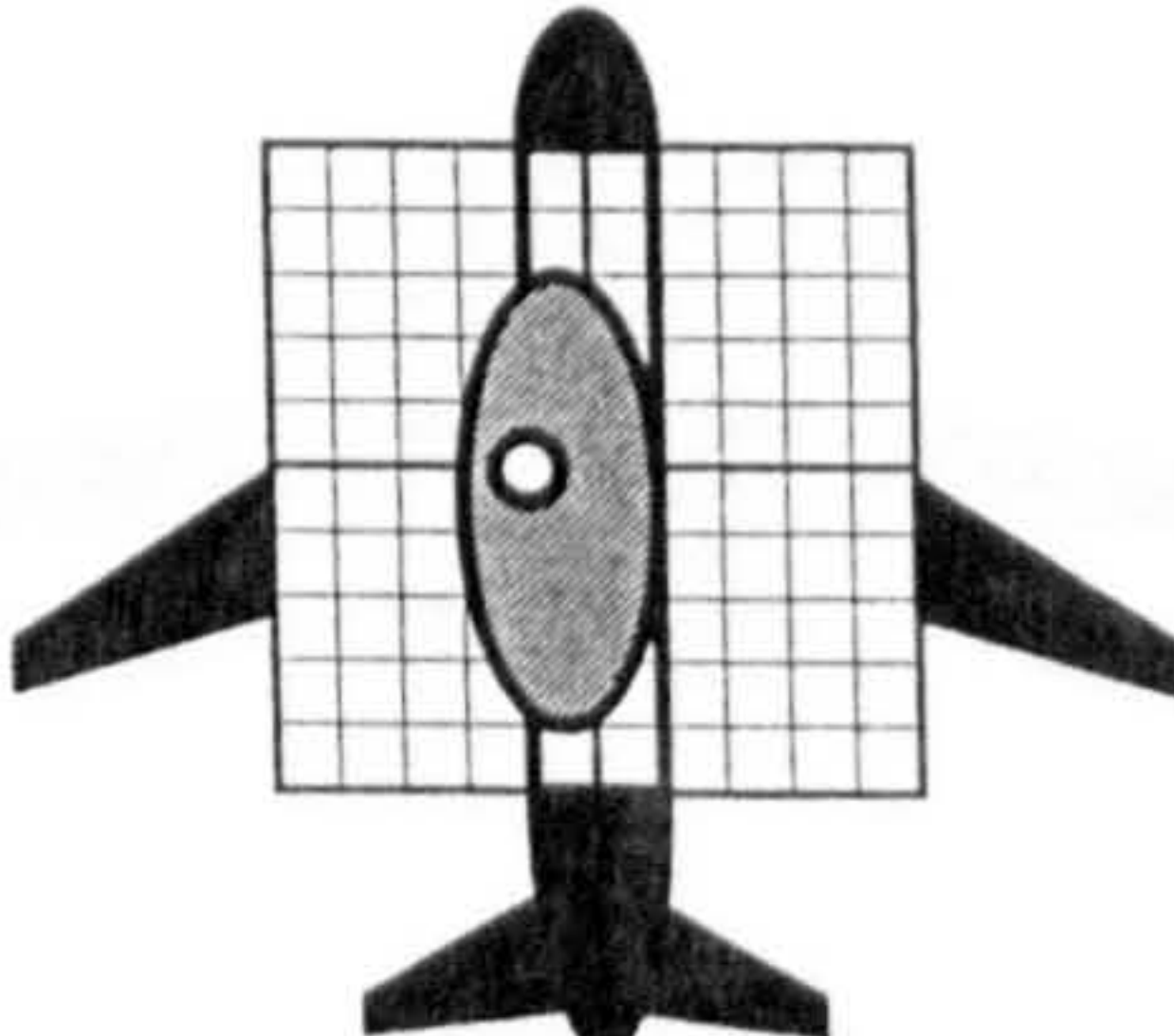
801119 (Impact)	
	
Aircraft Scenario	F-27 engine detached
Starting point	right engine
Initiation time	0:00
Burnthro' time	0:00
Cabin damage	extensive
Fire fatalities	0.13

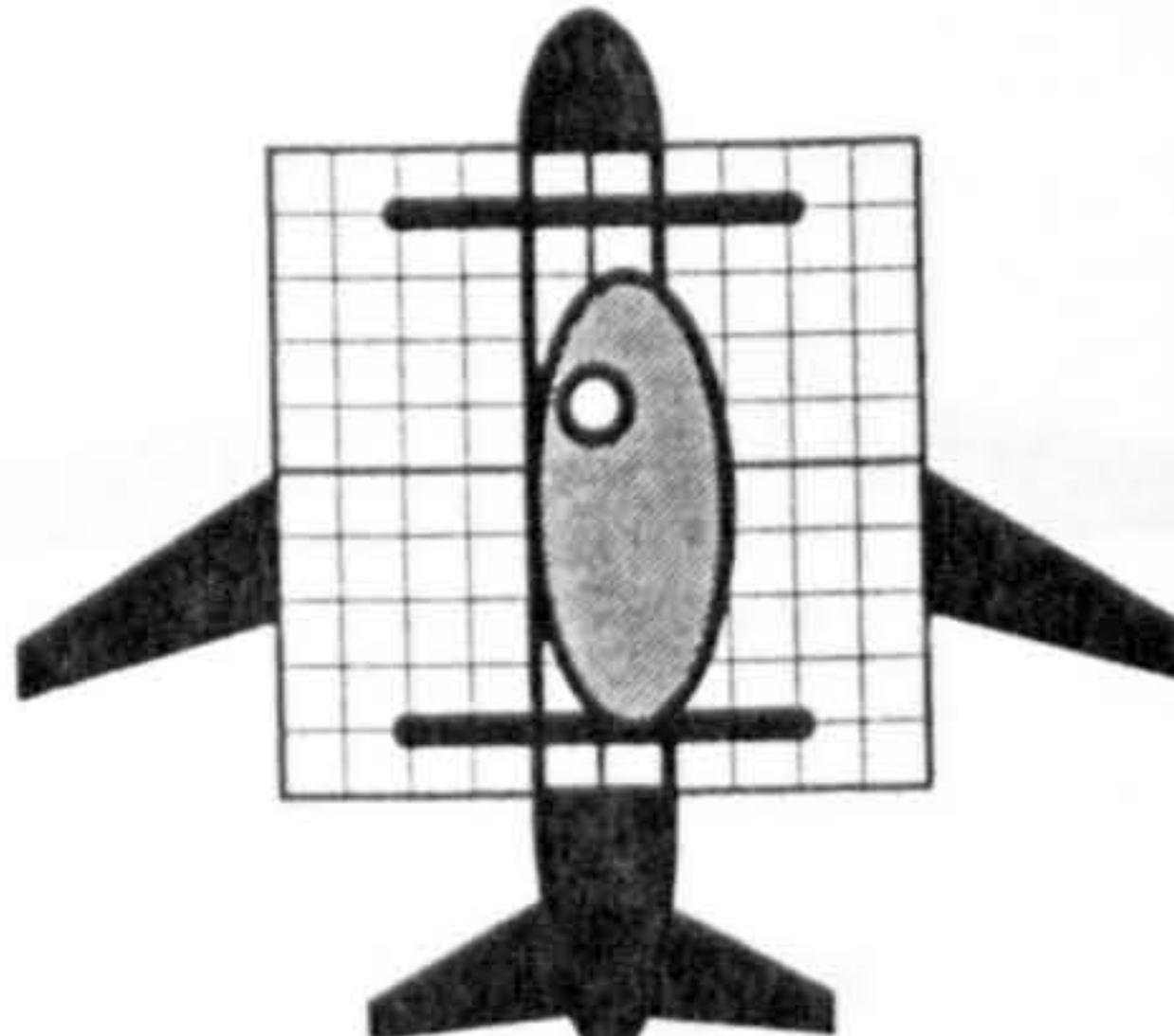
850121 (Impact)	
	
Aircraft Scenario	L-188C crashed after takeoff
Starting point	wing tanks
Initiation time	0:00
Burnthro' time	(0:10)
Cabin damage	destroyed
Fire fatalities	0.54

850802 (Impact)	
	
Aircraft Scenario	L-1011-385 crashed on approach
Starting point	left wing root
Initiation time	0:00
Burnthro' time	0:00
Cabin damage	extensive
Fire fatalities	0.12

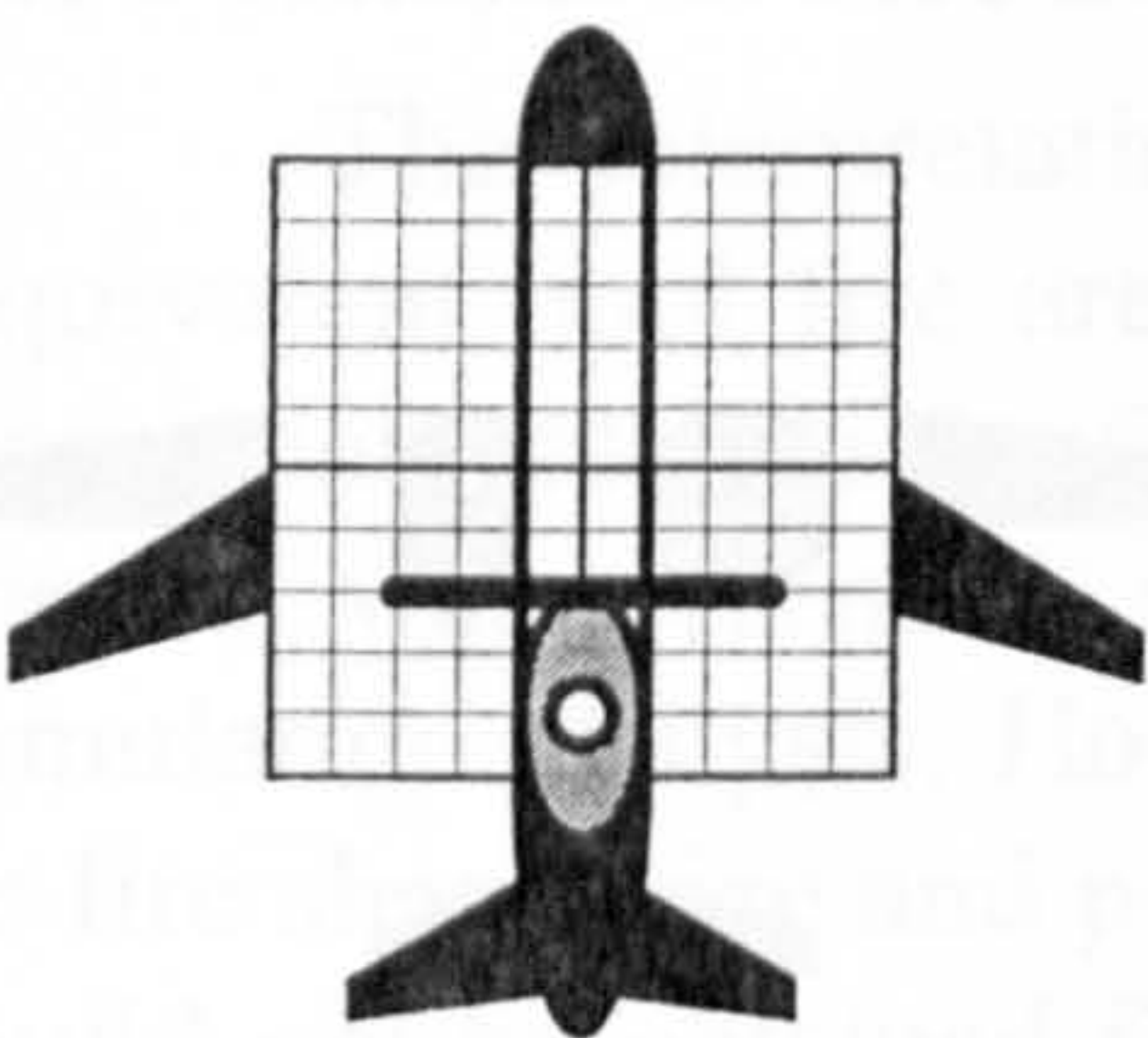
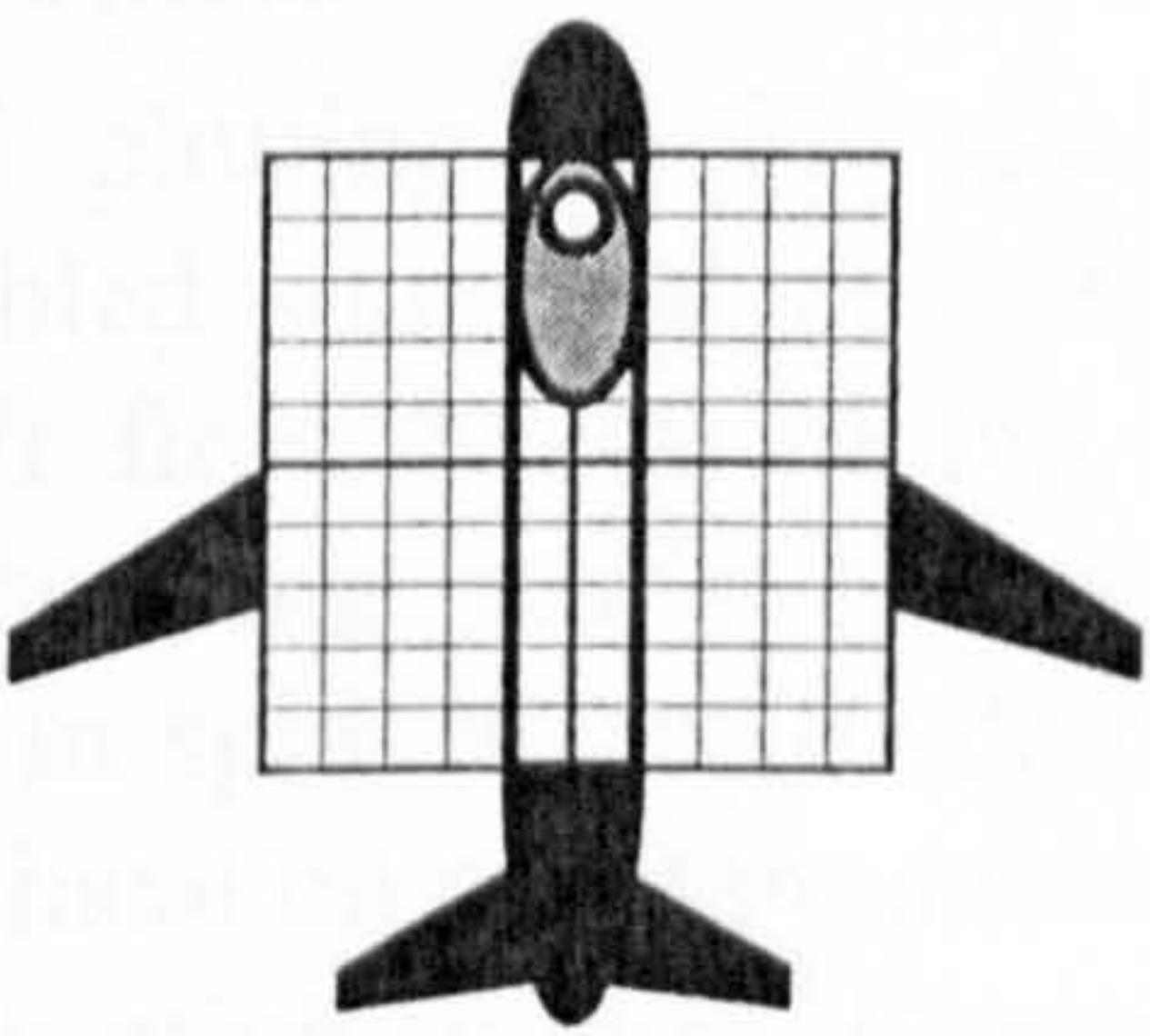
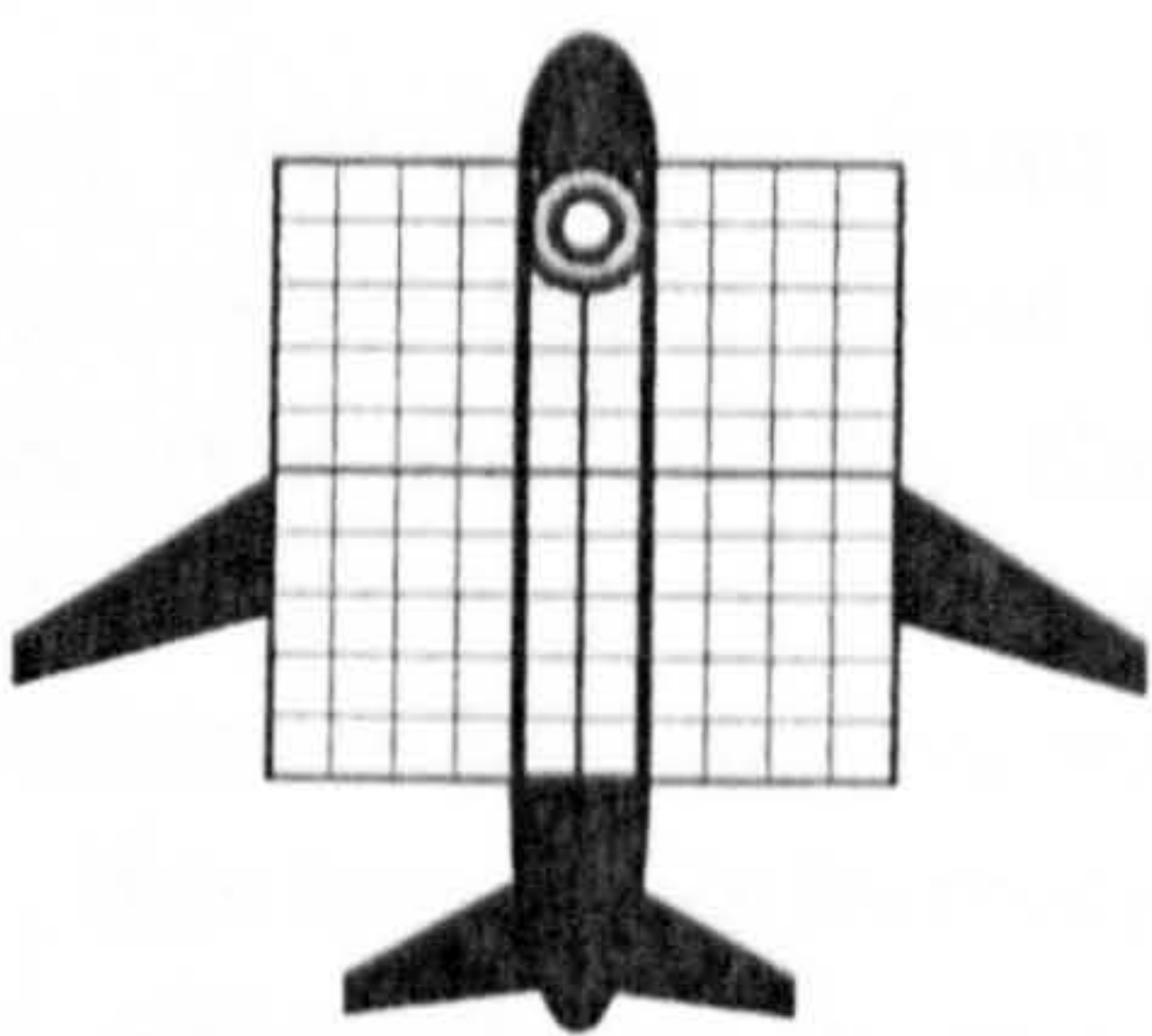
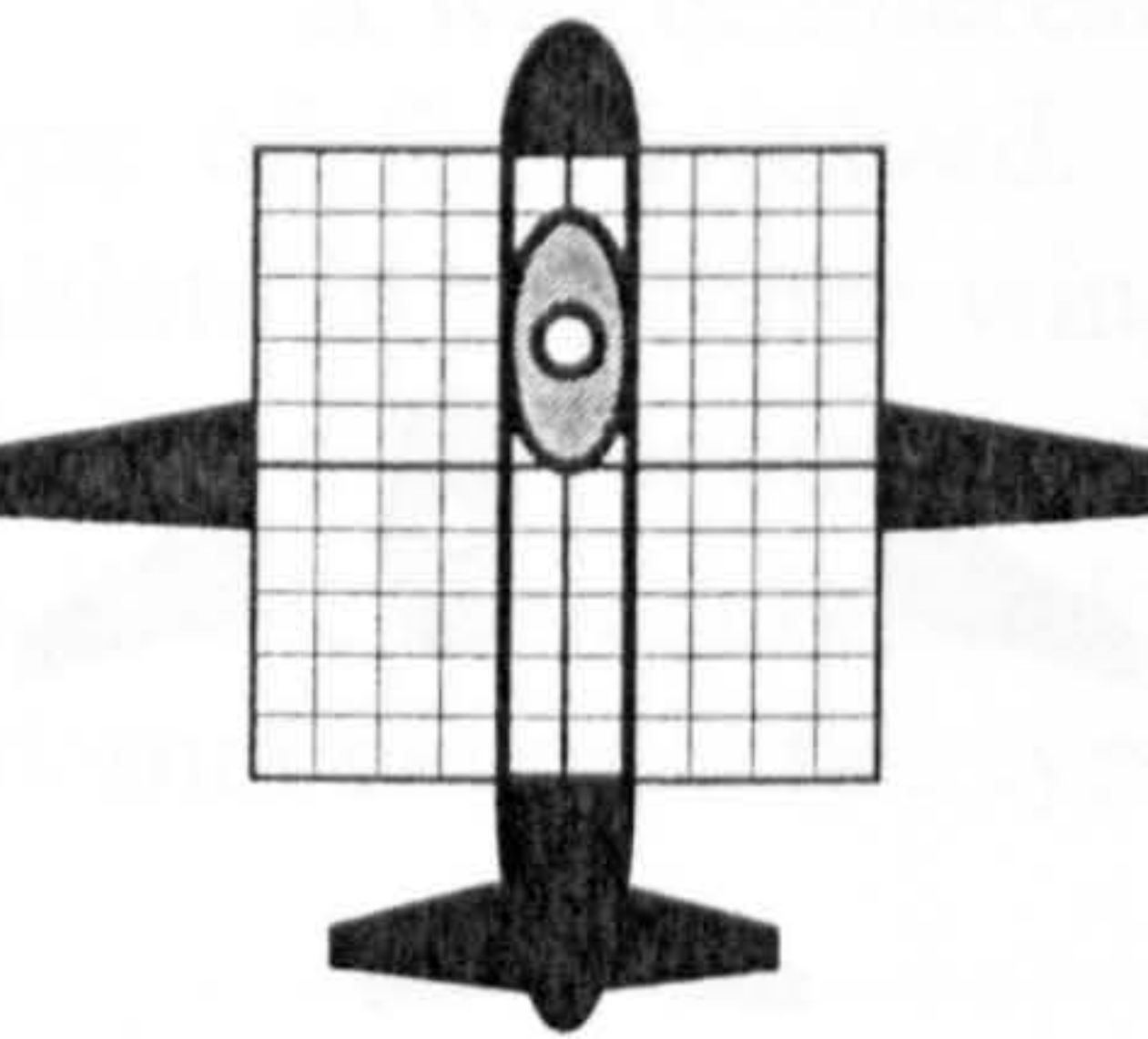
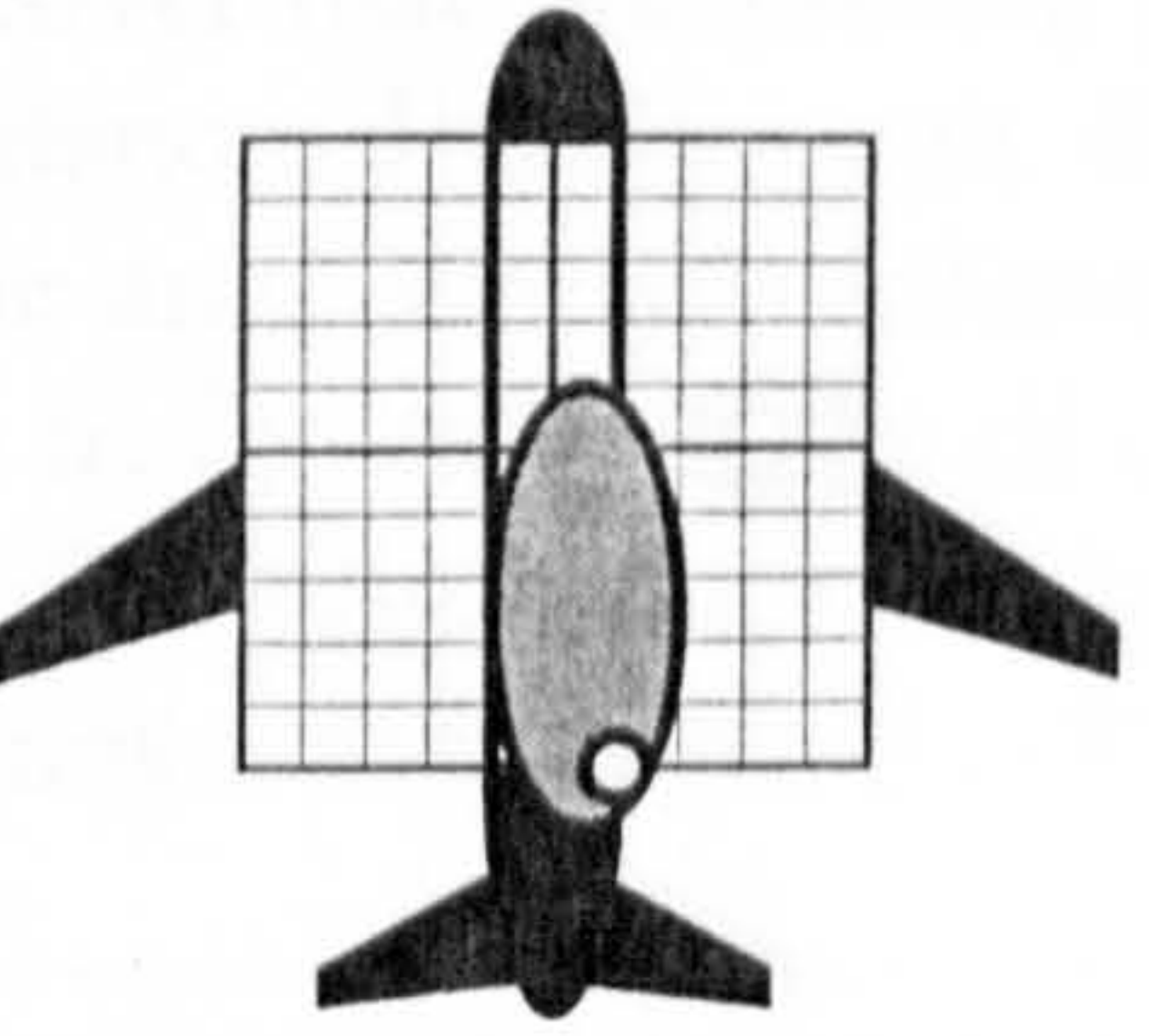
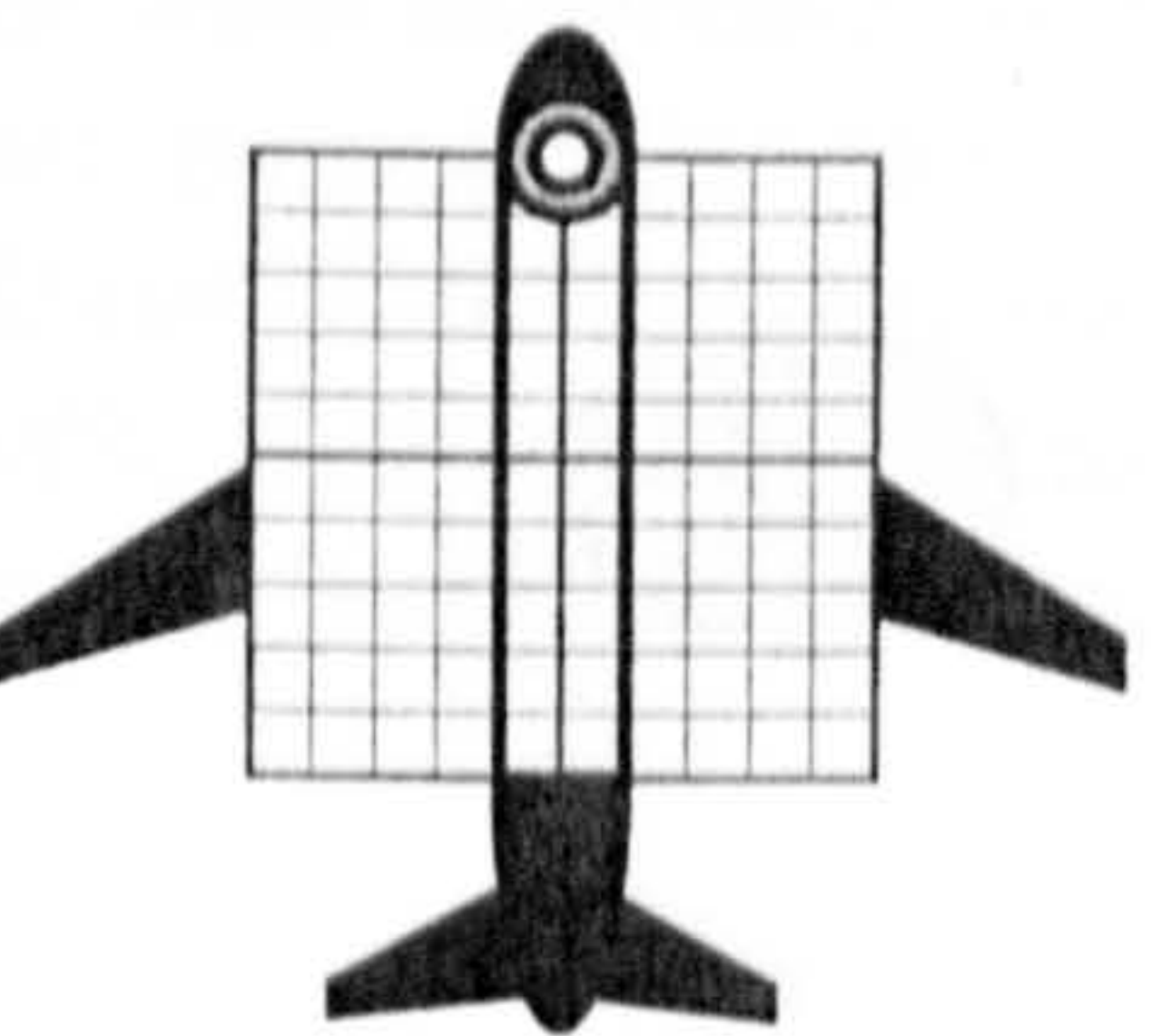
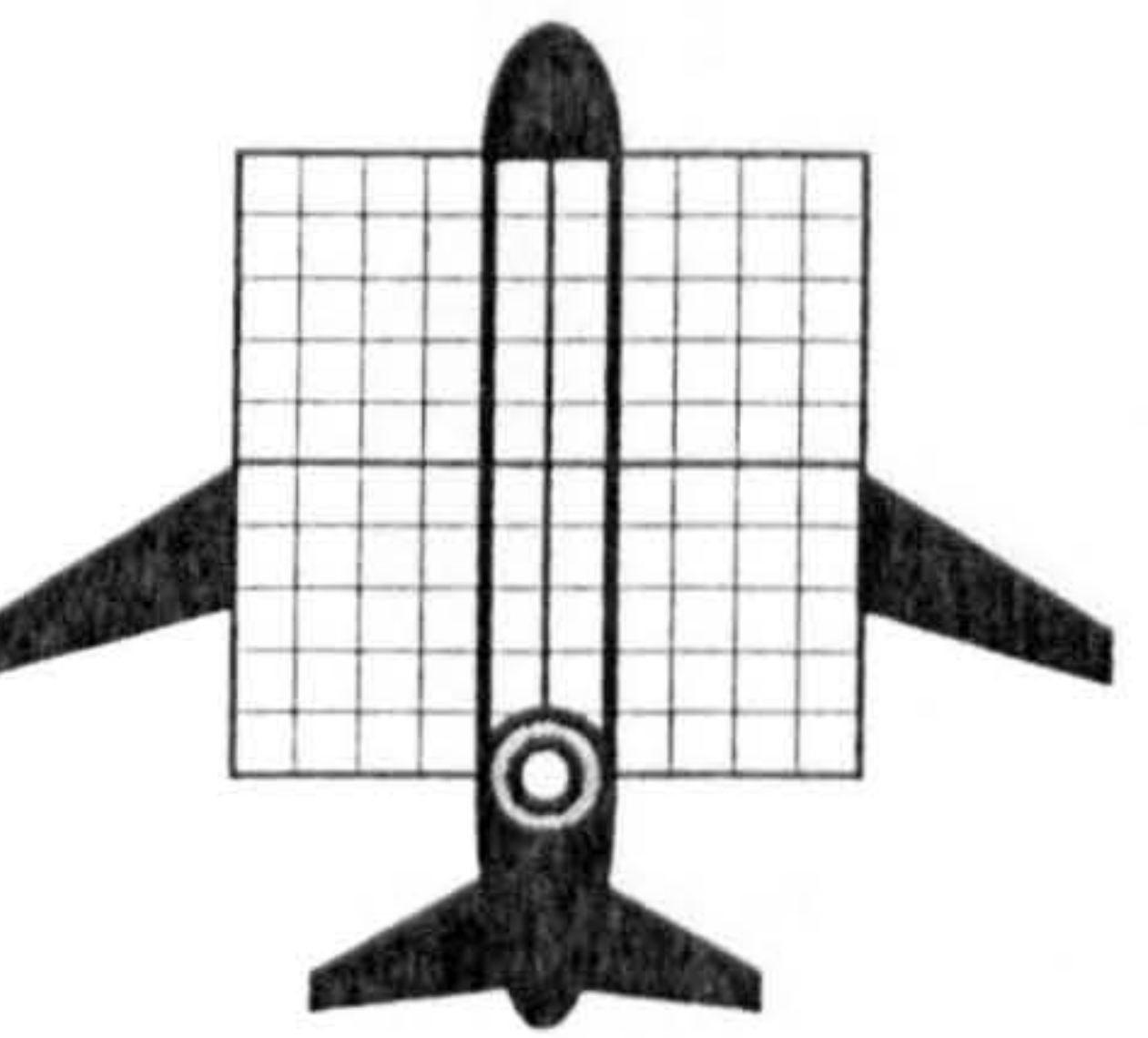
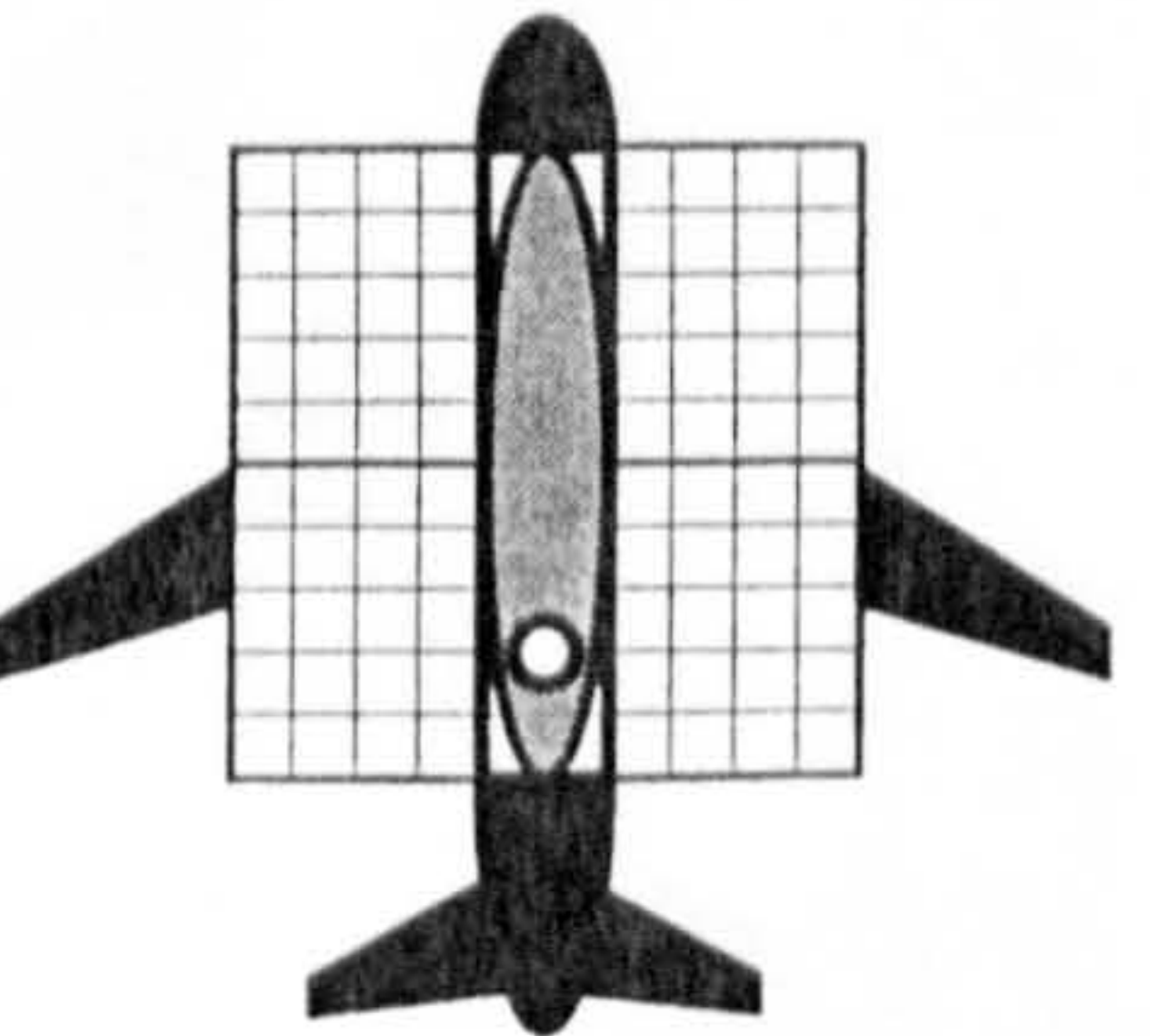
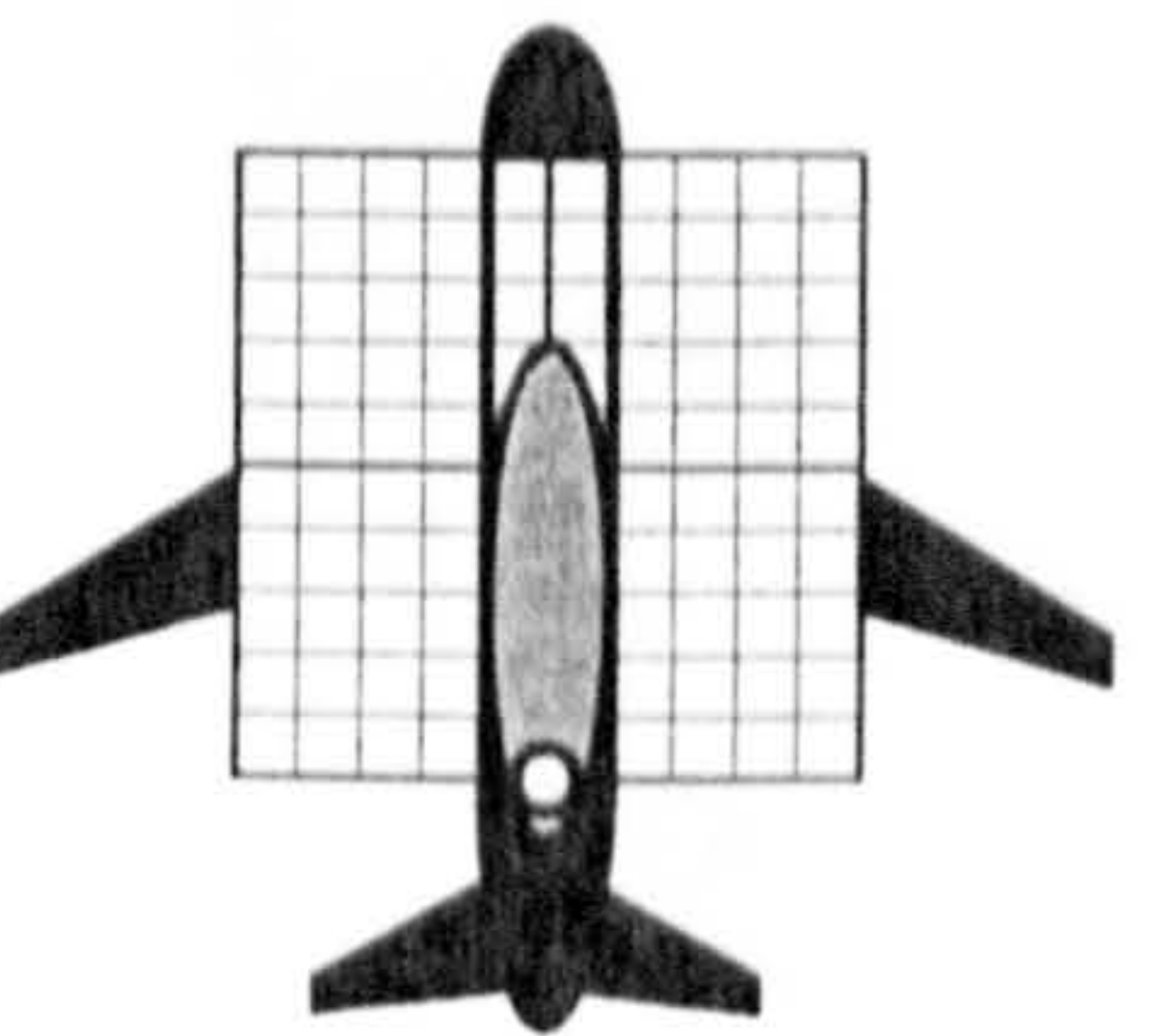
890719 (Impact)	
	
Aircraft Scenario	DC-10-10 forced landing
Starting point	separated right wing
Initiation time	0:00
Burnthro' time	0:00
Cabin damage	extensive
Fire fatalities	0.12

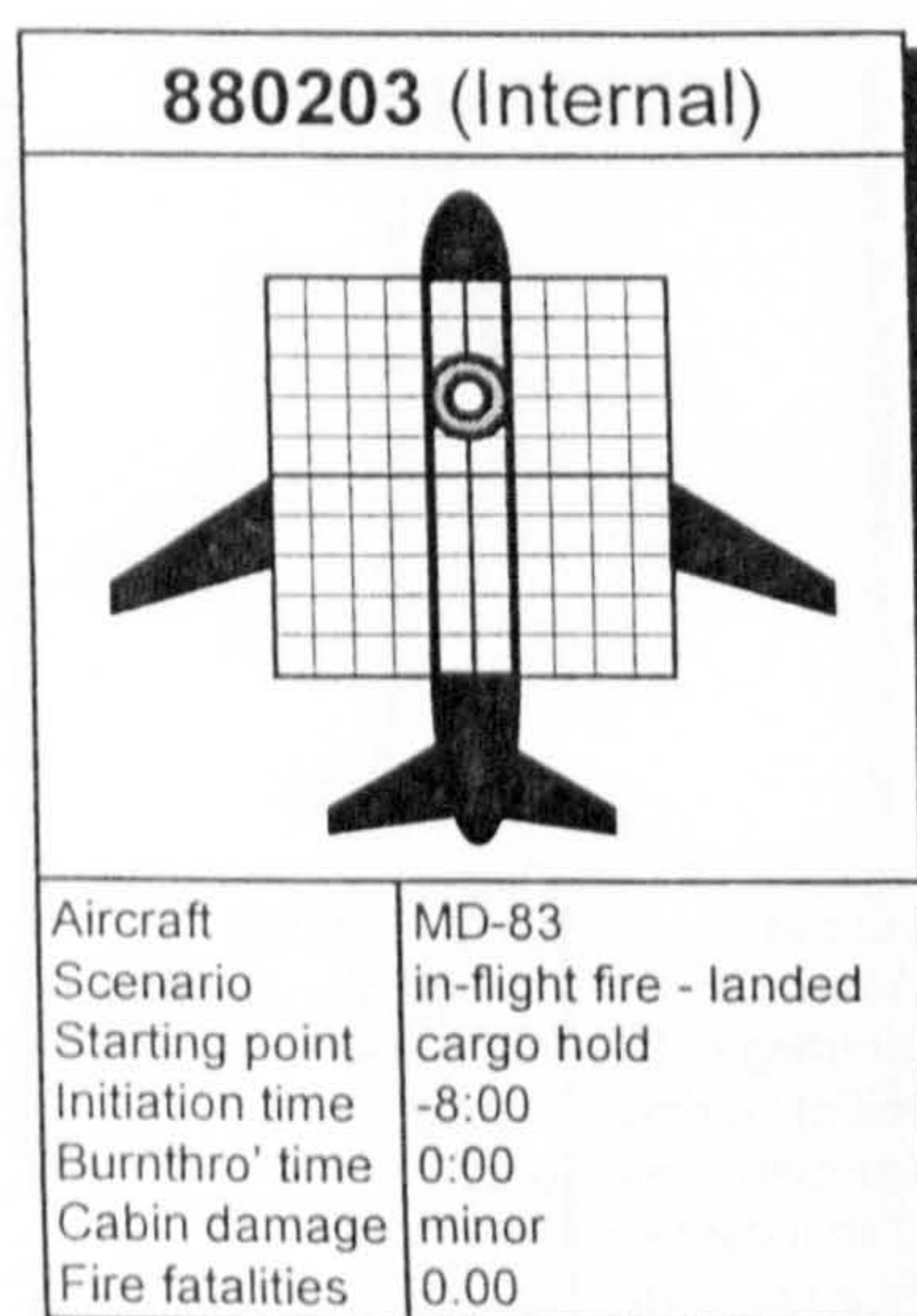
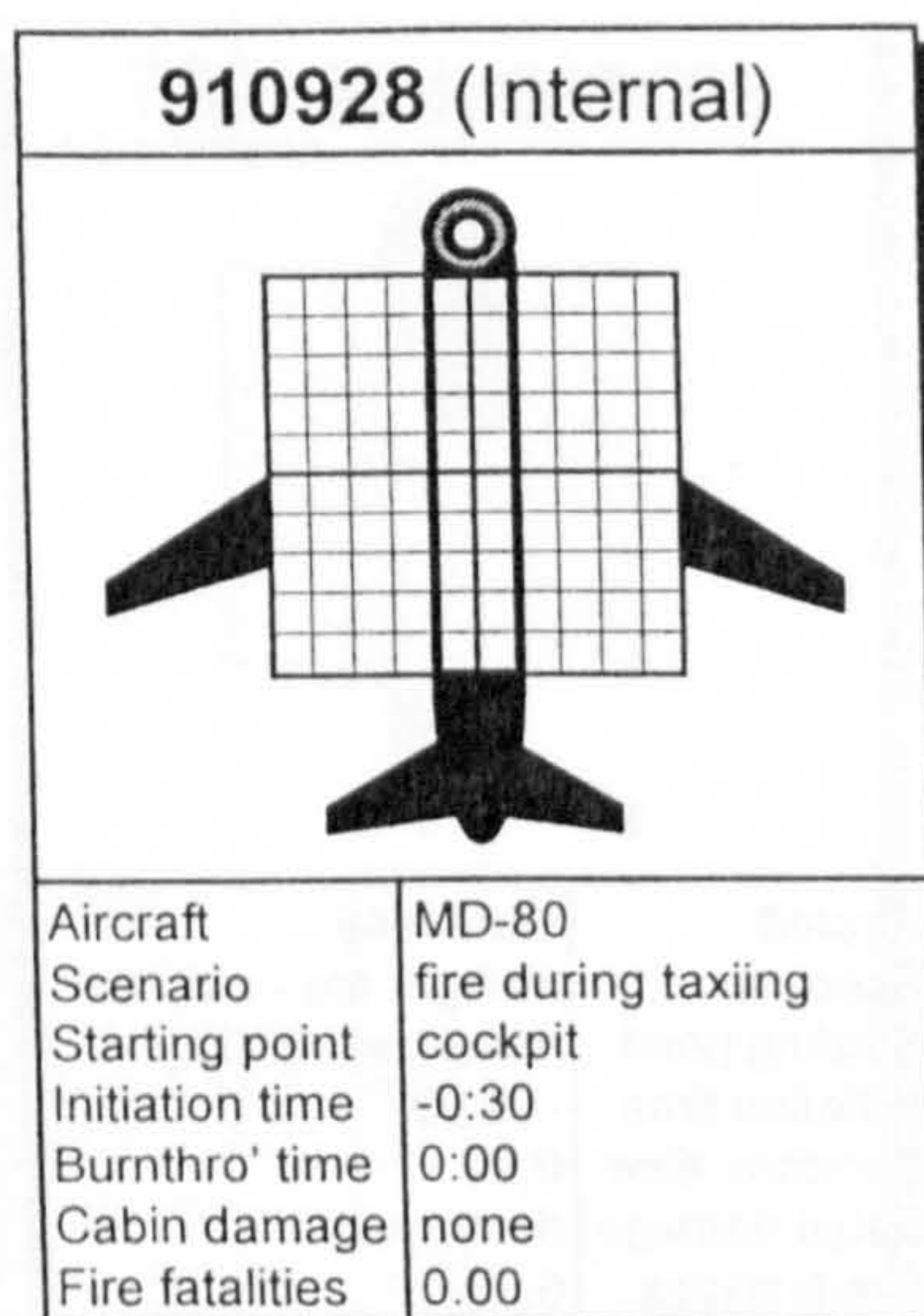
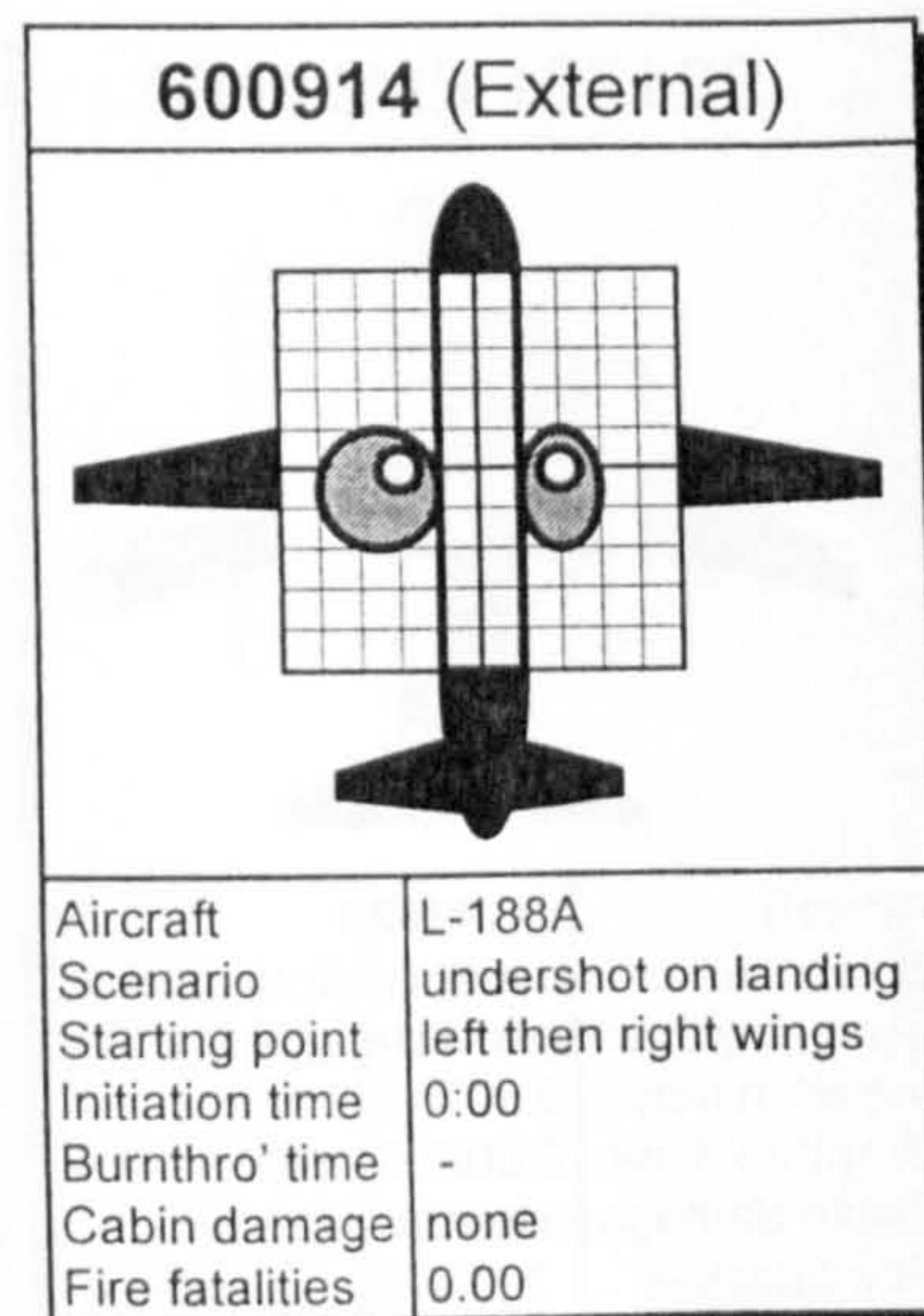
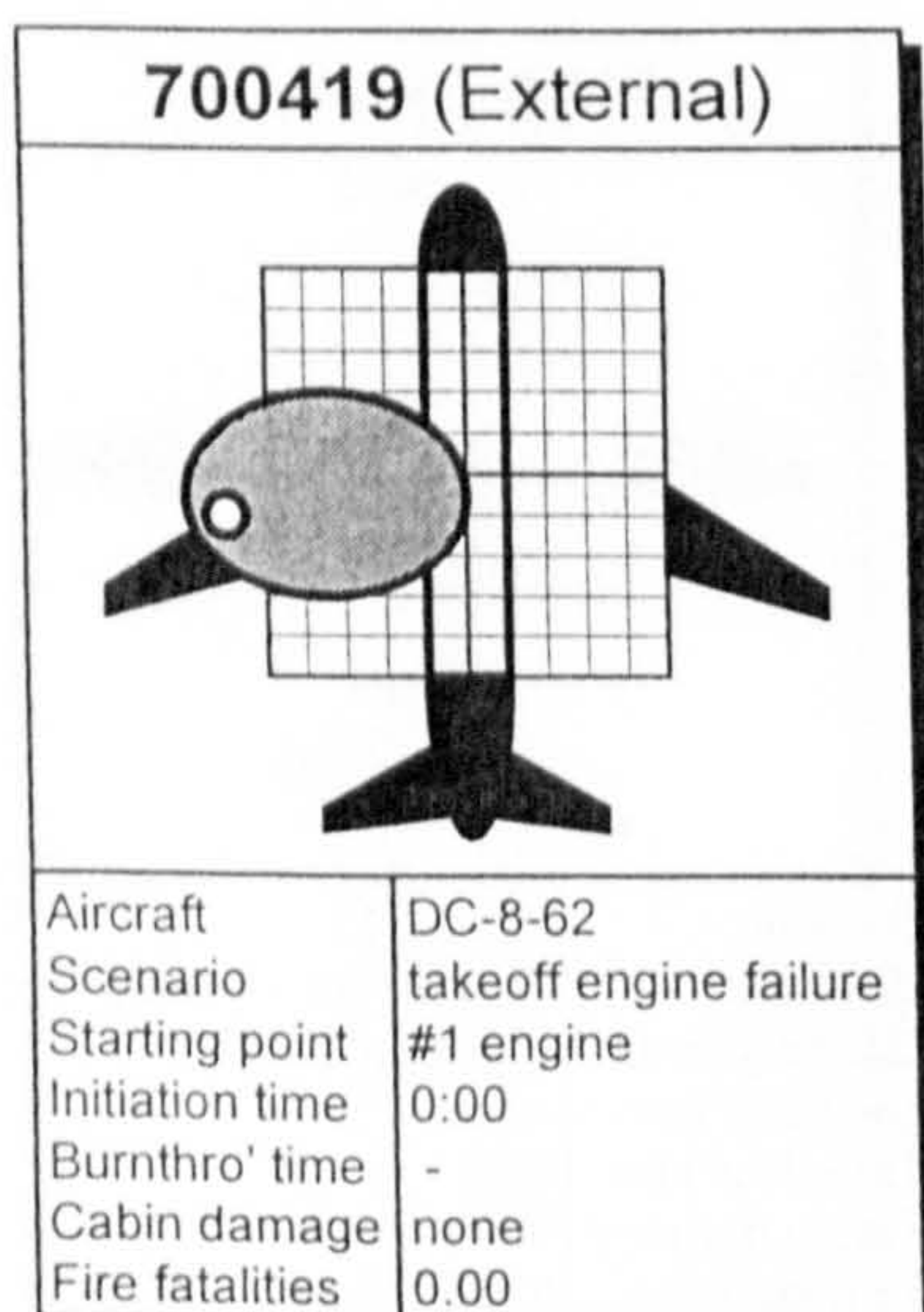
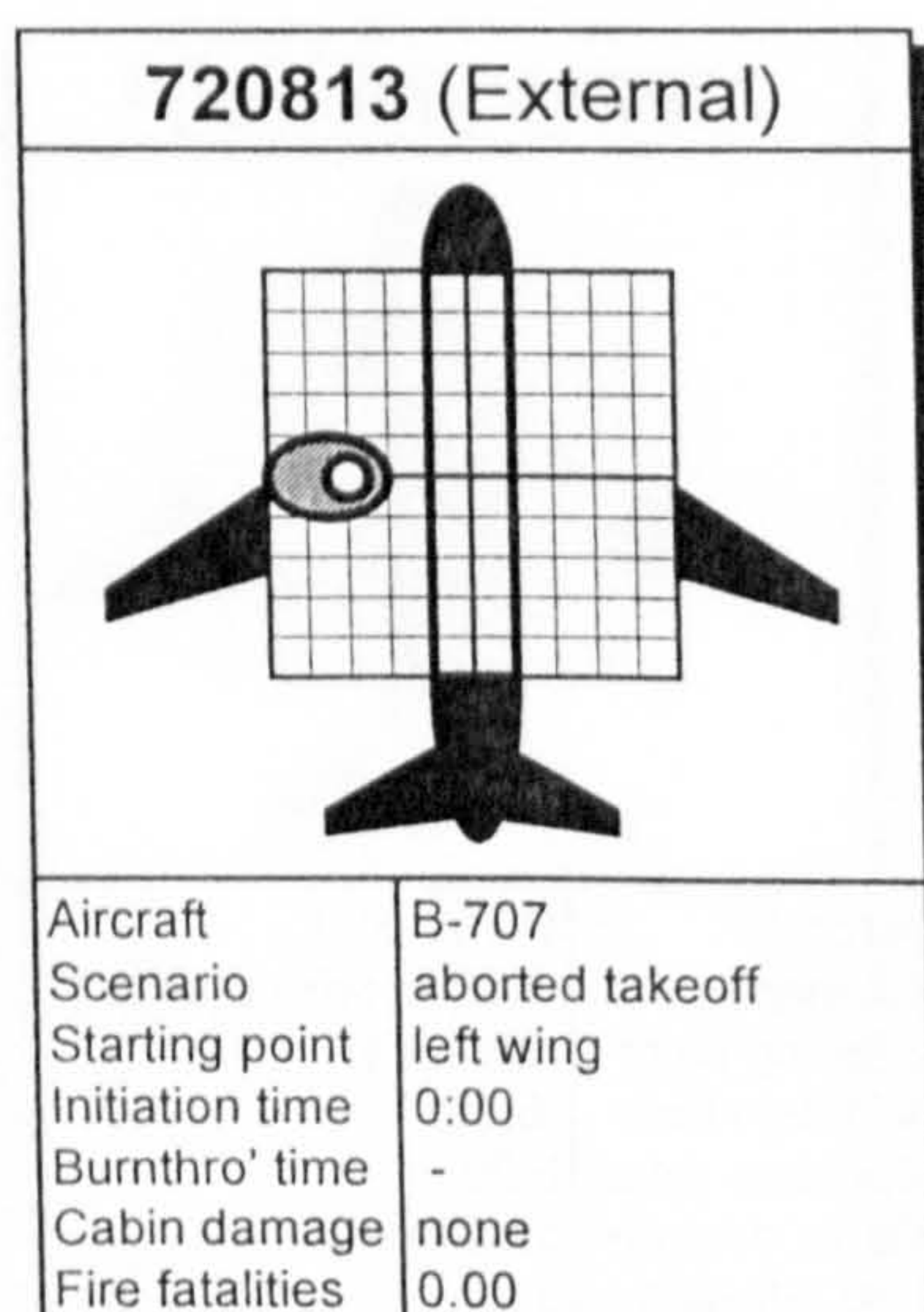
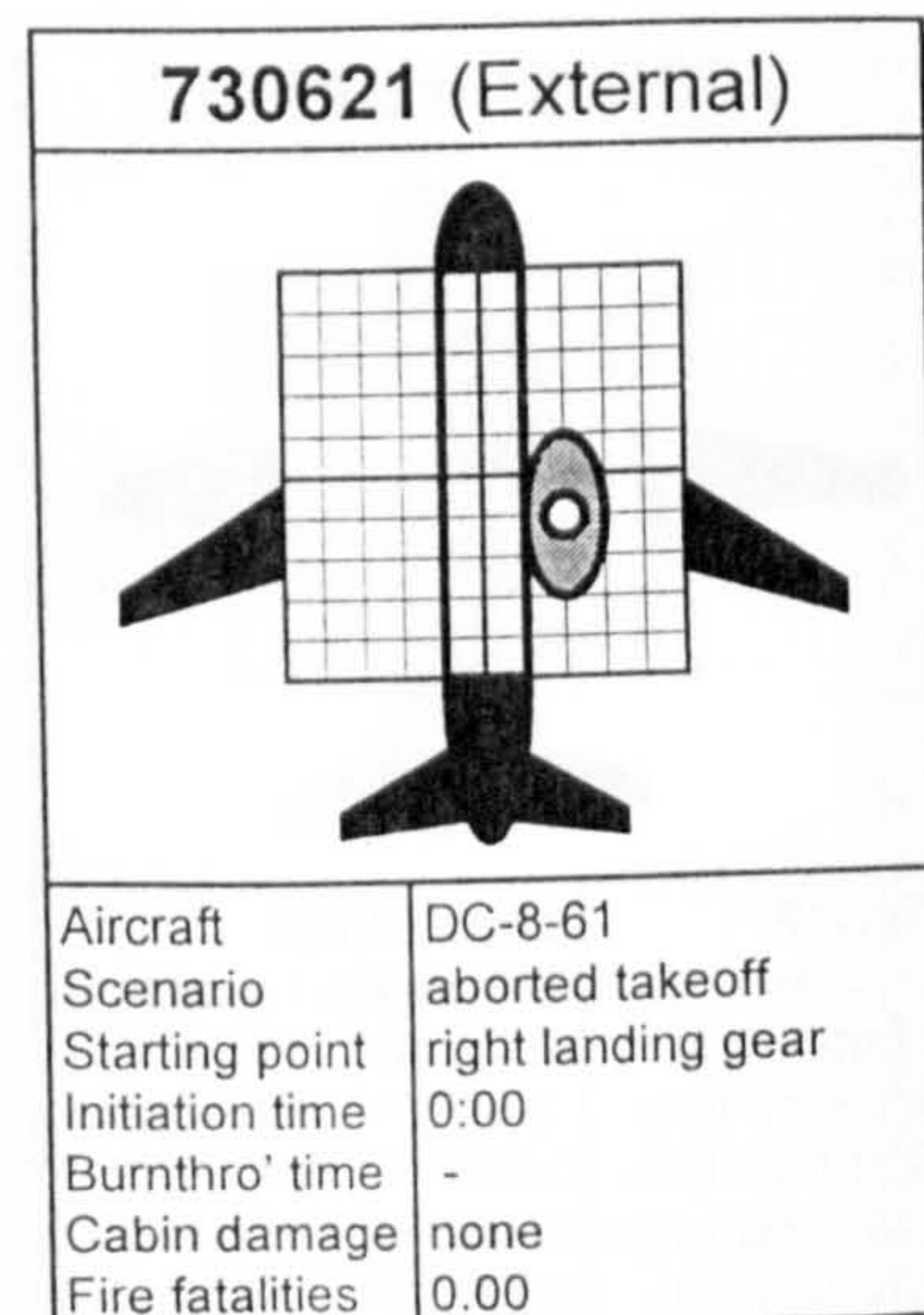
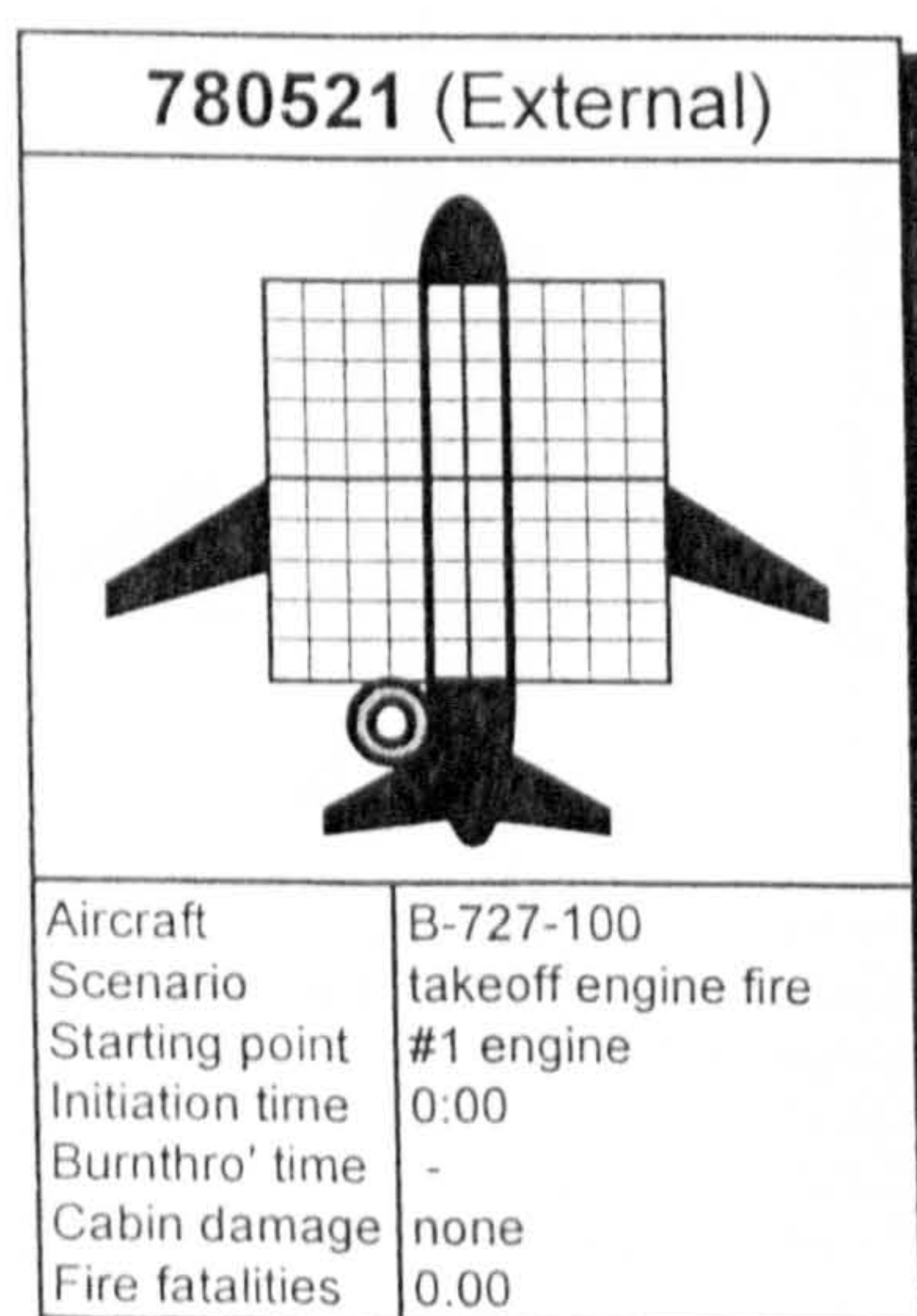
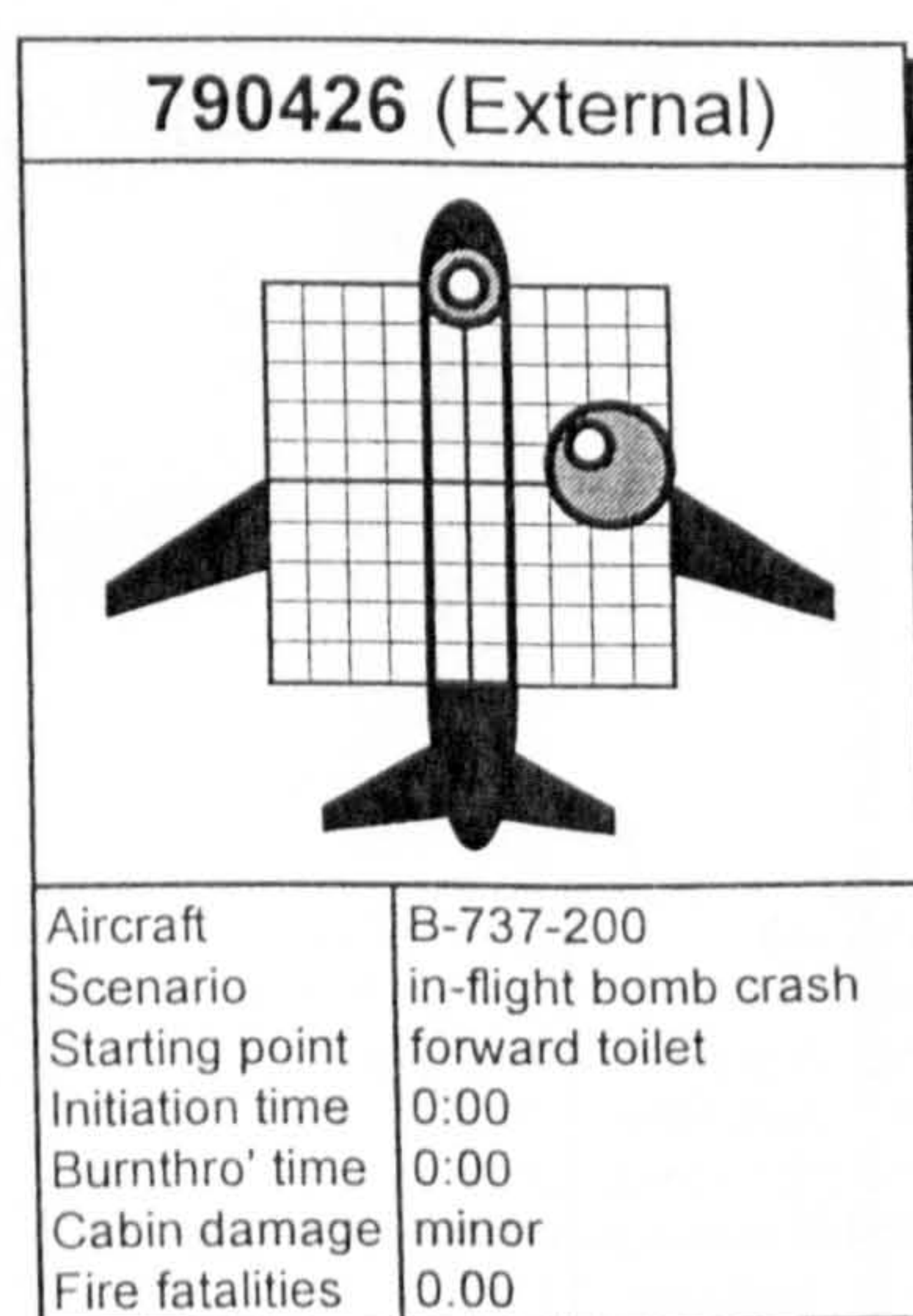
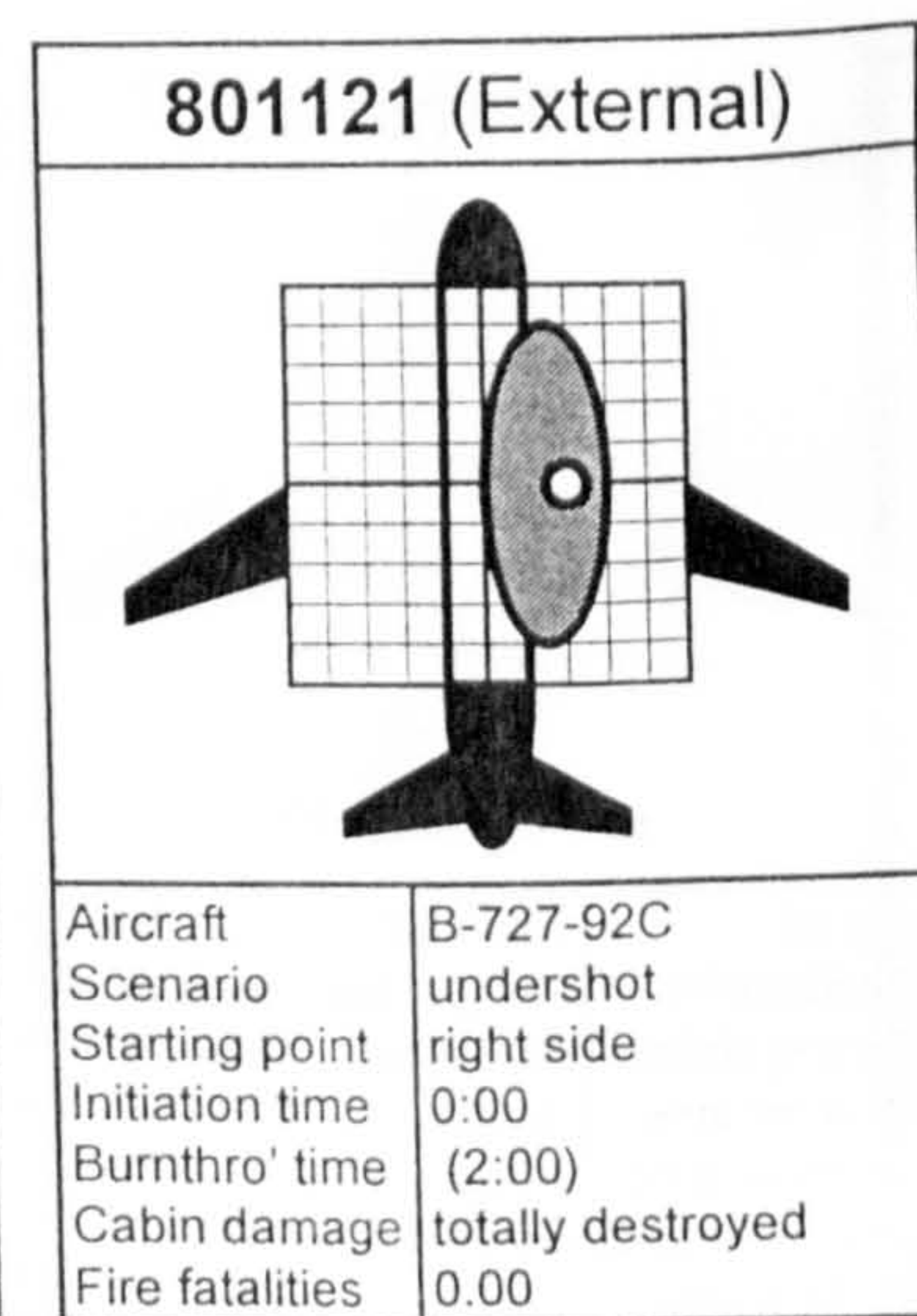
901203 (Impact)	
	
Aircraft Scenario	DC-9-14 takeoff collision
Starting point	rhs of fuselage
Initiation time	0:00
Burnthro' time	0:00
Cabin damage	completely destroyed
Fire fatalities	0.13

910201 (Impact)	
	
Aircraft Scenario	B-737-300 landing collision
Starting point	left inboard wing
Initiation time	0:00
Burnthro' time	0:00
Cabin damage	completely destroyed
Fire fatalities	0.24

920120 (Impact)	
	
Aircraft Scenario	A-320 crashed on approach
Starting point	centre of aircraft
Initiation time	0:00
Burnthro' time	0:00
Cabin damage	destroyed
Fire fatalities	?

Appendix F: Fire Scenario Analysis

<div>921221 (Impact)</div> <div></div> <div><div>Aircraft</div><div>Scenario</div><div>Starting point</div><div>Initiation time</div><div>Burnthro' time</div><div>Cabin damage</div><div>Fire fatalities</div><div>DC-10-30</div><div>overturned on landing</div><div>rear fuselage</div><div>0:00</div><div>0:00</div><div>extensive</div><div>?</div></div>	<div>690726 (Internal)</div> <div></div> <div><div>Aircraft</div><div>Scenario</div><div>Starting point</div><div>Initiation time</div><div>Burnthro' time</div><div>Cabin damage</div><div>Fire fatalities</div><div>Caravelle</div><div>in-flight fire - crashed</div><div>electrical eqt. bay</div><div>-18:00</div><div>0:00</div><div>destroyed</div><div>0.03</div></div>	<div>690817 (Internal)</div> <div></div> <div><div>Aircraft</div><div>Scenario</div><div>Starting point</div><div>Initiation time</div><div>Burnthro' time</div><div>Cabin damage</div><div>Fire fatalities</div><div>BAC 1-11-320</div><div>in-flight fire - landed</div><div>radio lead</div><div>-10:00</div><div>0:00</div><div>extensive</div><div>0.00</div></div>
<div>700506 (Internal)</div> <div></div> <div><div>Aircraft</div><div>Scenario</div><div>Starting point</div><div>Initiation time</div><div>Burnthro' time</div><div>Cabin damage</div><div>Fire fatalities</div><div>Viscount 700</div><div>in-flight fire - landed</div><div>cargo bay</div><div>-2:00</div><div>0:00</div><div>destroyed</div><div>0.17</div></div>	<div>730711 (Internal)</div> <div></div> <div><div>Aircraft</div><div>Scenario</div><div>Starting point</div><div>Initiation time</div><div>Burnthro' time</div><div>Cabin damage</div><div>Fire fatalities</div><div>B-707-320</div><div>in-flight fire - crashed</div><div>rear toilet</div><div>-6:00</div><div>0:00</div><div>destroyed</div><div>0.00</div></div>	<div>741105 (Internal)</div> <div></div> <div><div>Aircraft</div><div>Scenario</div><div>Starting point</div><div>Initiation time</div><div>Burnthro' time</div><div>Cabin damage</div><div>Fire fatalities</div><div>DC-9-31</div><div>in-flight fire - landed</div><div>electrical bay</div><div>-9:00</div><div>0:00</div><div>modest</div><div>0.00</div></div>
<div>781001 (Internal)</div> <div></div> <div><div>Aircraft</div><div>Scenario</div><div>Starting point</div><div>Initiation time</div><div>Burnthro' time</div><div>Cabin damage</div><div>Fire fatalities</div><div>DC-9-40</div><div>in-flight fire - landed</div><div>rear toilet</div><div>-8:00</div><div>0:00</div><div>minor</div><div>0.00</div></div>	<div>800819 (Internal)</div> <div></div> <div><div>Aircraft</div><div>Scenario</div><div>Starting point</div><div>Initiation time</div><div>Burnthro' time</div><div>Cabin damage</div><div>Fire fatalities</div><div>L-1011-200</div><div>in-flight fire - landed</div><div>C4 cargo bay</div><div>-19:00</div><div>0:00</div><div>totally destroyed</div><div>1.00</div></div>	<div>830602 (Internal)</div> <div></div> <div><div>Aircraft</div><div>Scenario</div><div>Starting point</div><div>Initiation time</div><div>Burnthro' time</div><div>Cabin damage</div><div>Fire fatalities</div><div>DC-9-30</div><div>in-flight fire - landed</div><div>rear toilet</div><div>-18:00</div><div>0:00</div><div>destroyed</div><div>0.50</div></div>



Appendix F: Fire Scenario Analysis

F.1 Positions of Fire Starting Points

The interpretation and plotting of 72 past accident fires in the form of equivalent pool fire areas enabled some valuable discoveries to be made about the basic characteristics of aircraft fires. Much of the data that was derived by these means was essential for generating realistic fire scenarios for use within the simulation analysis. However, in spite of the fundamental influence parameters such as fire shape, size and position have on accident survivability, this type of information could not be obtained from any other sources. Consequently, although the work was undertaken at a comparatively simple level, much of the information provided in this appendix is almost certainly unique.

The first analysis to be performed with the fire spread diagrams was to determine whereabouts, in relation to an aircraft's passenger cabin, fires were likely to initiate. Estimated fire starting points were plotted on a square grid, with units based upon the cabin length of the aircraft type involved. These were then coded into probability distributions for determining fire positions in the accident simulations.

It was of interest to discover that fire starting positions were dependent on the type of fire involved. For instance, Burnthrough fires were particularly likely to initiate in the inner wing/engine area, whereas Internal and External fires were more likely to be encountered nearer to the extremities of an aircraft. Thus, it was decided to break the analysis down by fire type. The raw data for burn-through, impact and internal/external fire types are shown in Figures F.1-3:

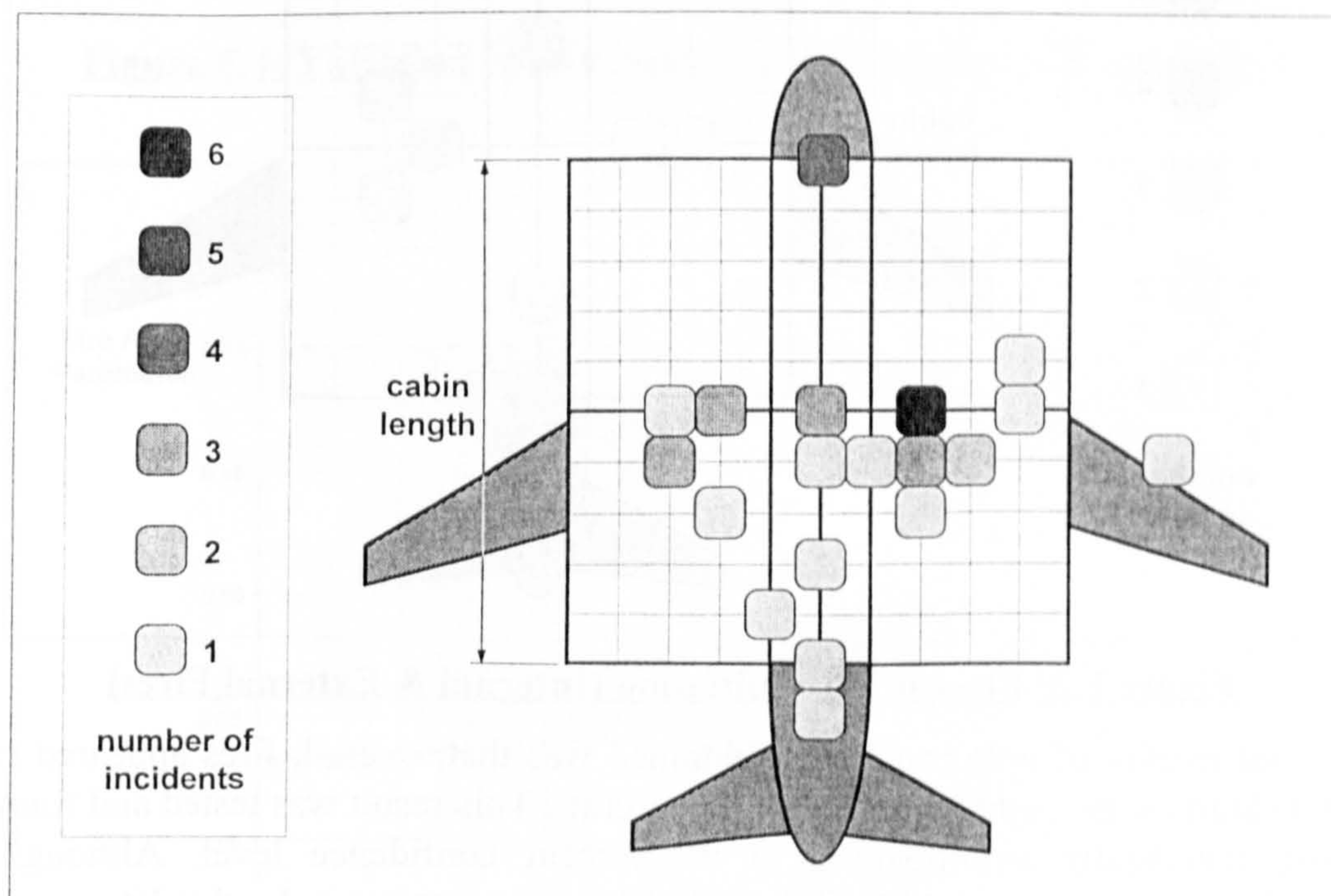


Figure F.1: Place of Fire Initiation (Burnthrough Fires)

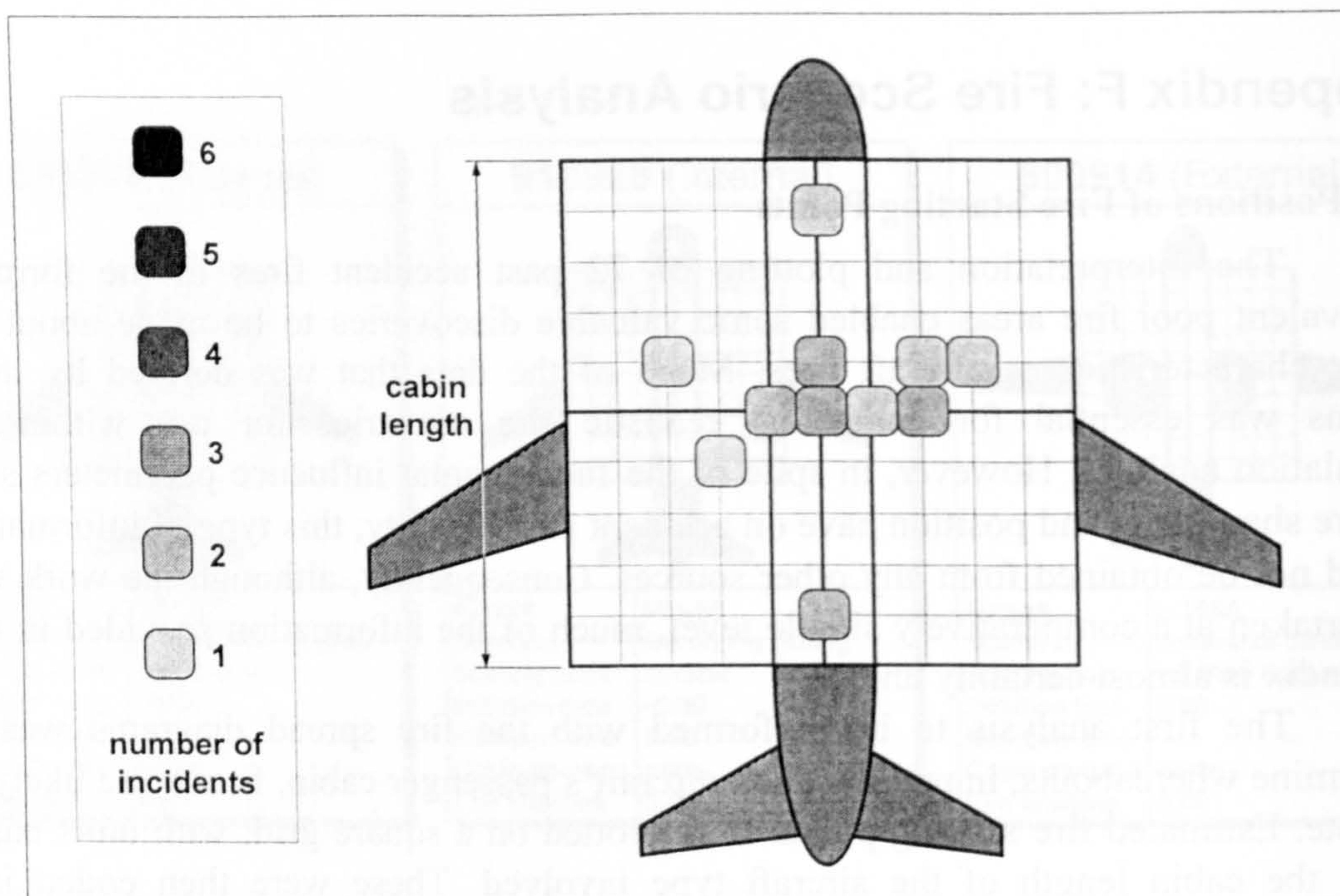


Figure F.2: Place of Fire Initiation (Impact Fires)

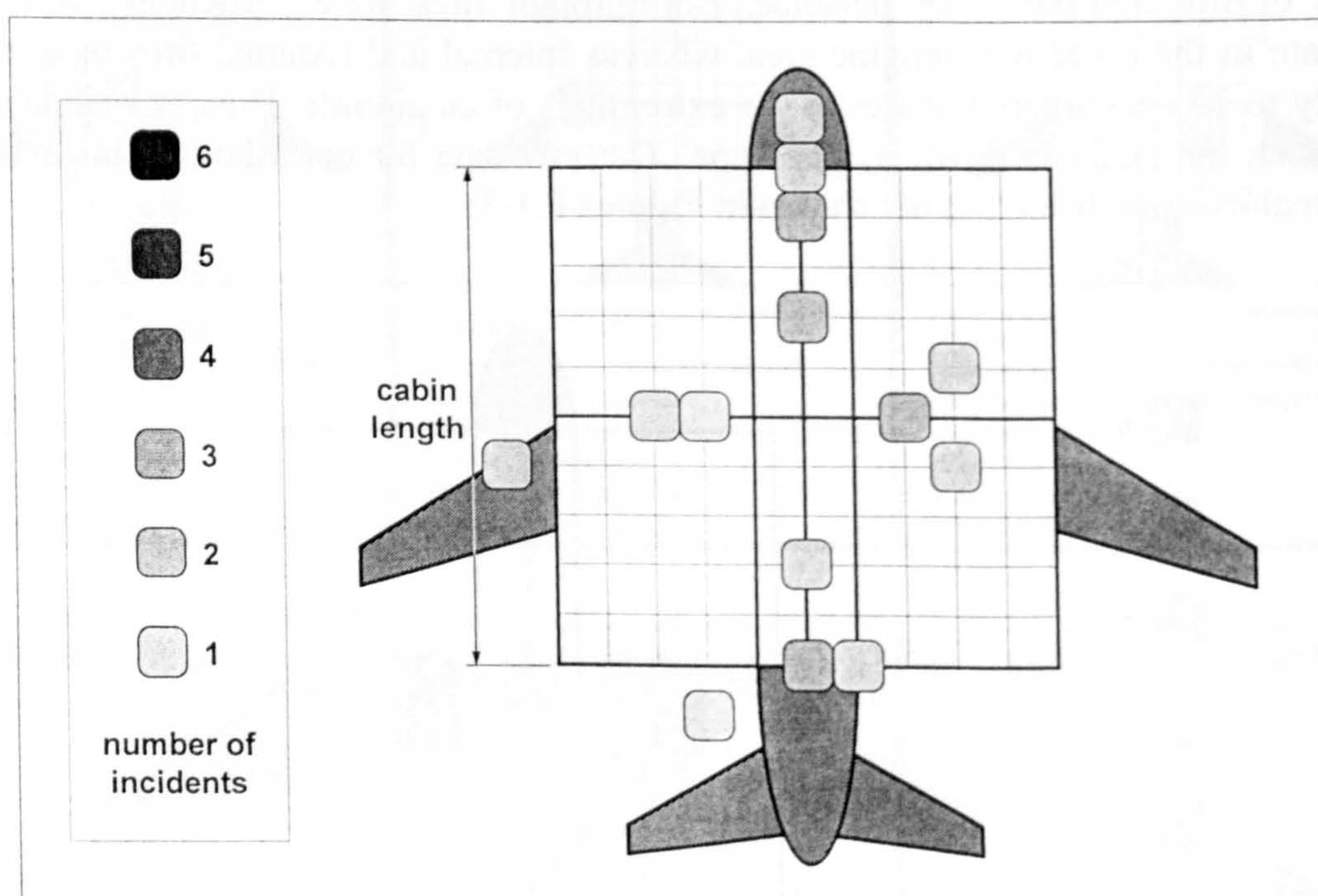


Figure F.3: Place of Fire Initiation (Internal & External Fires)

One point worthy of note in the data obtained was that, overall, fires appeared more likely to start on the right hand side of the aircraft. This result was tested and found to be just statistically significant at a 95 percent confidence level. Although no convincing explanation could be offered for this apparent anomaly, the data was used as recorded, with no corrections being applied to make the distributions symmetrical about the aircraft centreline.

F.2 Variation in Fire Areas

The areas of accident fires were non-dimensionalised to take account of variations in aircraft size. The resulting area parameter is defined as follows:-

$$\text{Fire Area Parameter} = \frac{\text{Maximum area of equivalent pool fire}}{(\text{aircraft cabin length})^2}$$

(F.1)

Distributions in fire size for various types of fire are given in Figures F-4-6.

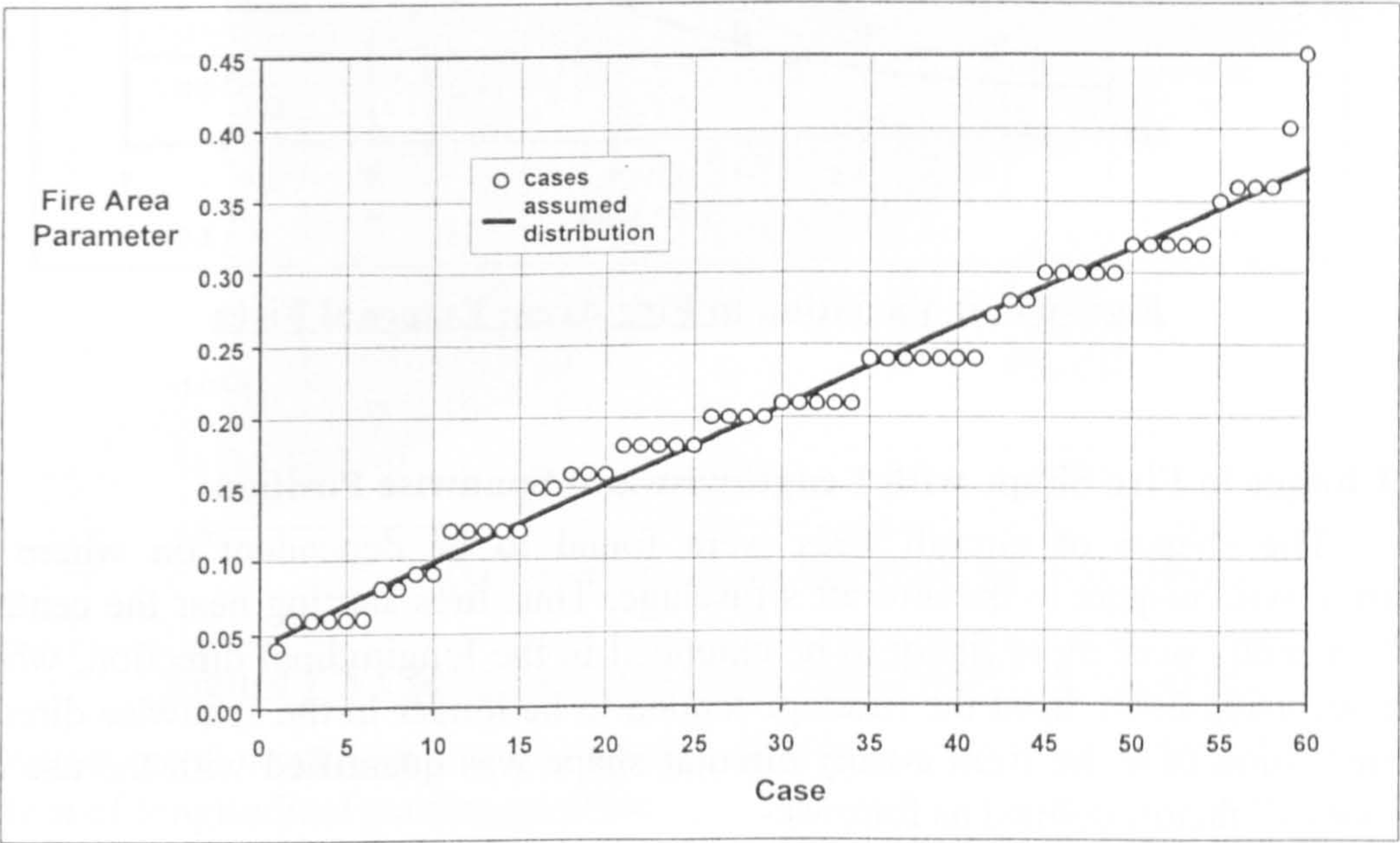


Figure F.4: Variation in Fire Area: Burnthrough and Impact Fires

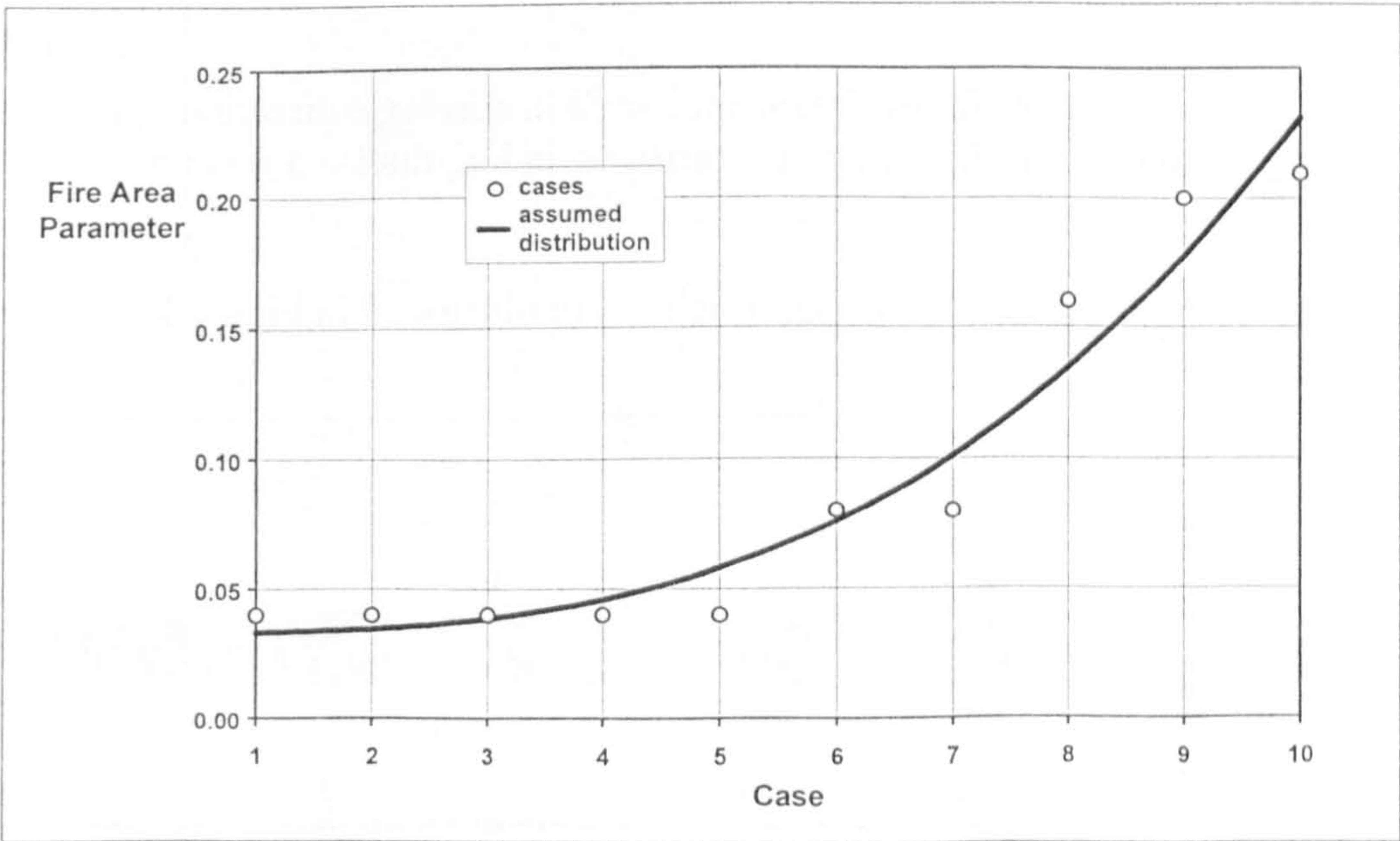


Figure F.5: Variation in Fire Area: Internal Fires

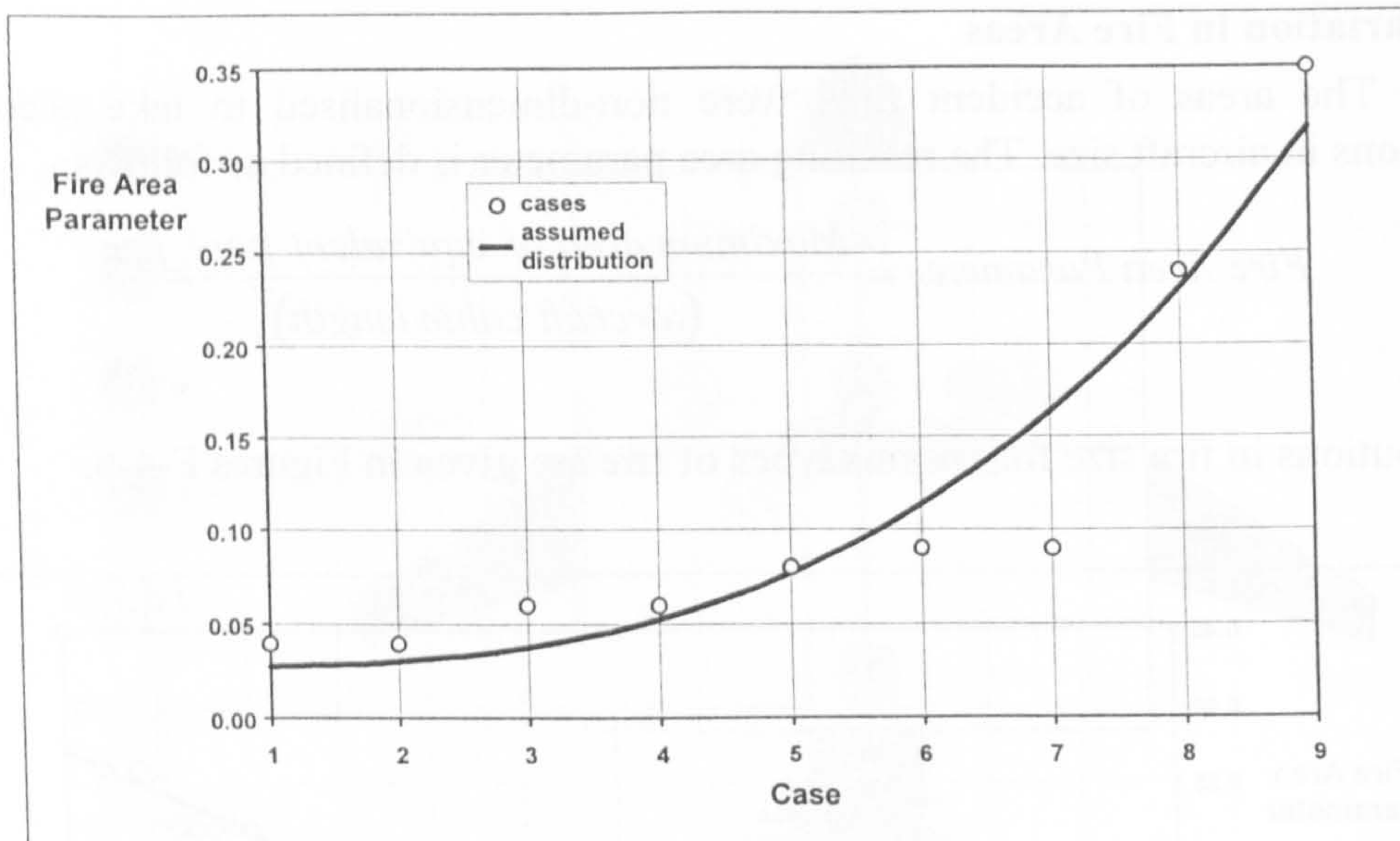


Figure F.6: Variation in Fire Area: External Fires

F.3 Change in Fire Shape with Lengthwise and Spanwise Position

The shapes of aircraft fires were found to be dependent on where they occurred with respect to the aircraft's fuselage. Thus fires starting near the centreline of the aircraft were more likely to be extended in the longitudinal direction, whereas fires occurring away from the fuselage tended to be longer in the spanwise direction. The deviation of a fire from a truly circular shape was quantified with the use of an "ellipticity" factor, defined as follows:-

$$\text{Ellipticity Shape factor} = \frac{x_{\max} - y_{\max}}{\frac{1}{2}(x_{\max} + y_{\max})} \quad (\text{F.2})$$

where:

$x_{\max}$ = maximum size of fire, as measured in spanwise direction

$y_{\max}$ = maximum size of fire, as measured in lengthwise direction

The proportions of various pool fire ellipticities are illustrated in Figure F.7:

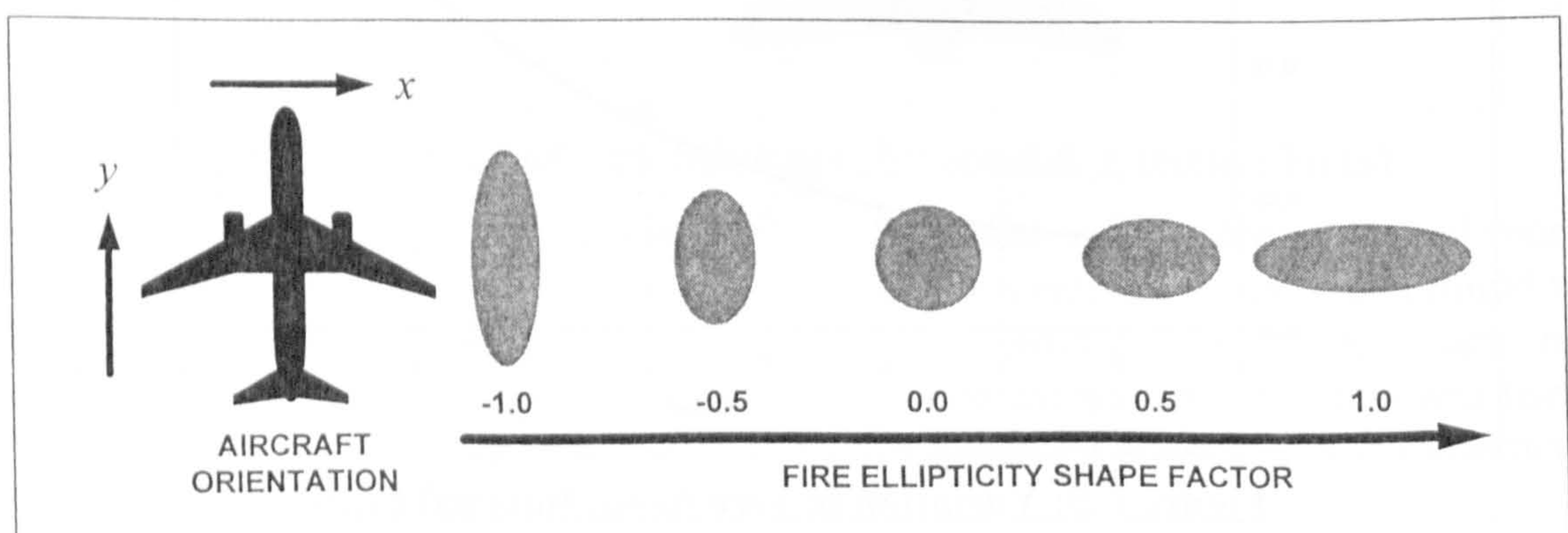


Figure F.7 Variation in Shape of Equivalent Pool Fires

Fire shapes were found to be dependent on the spanwise position at which the fire started; the closer a fire was to the aircraft's centreline, the more likely it was to be elongated in a longitudinal direction. This probability distribution used to represent this relationship is shown in figure F.8:-

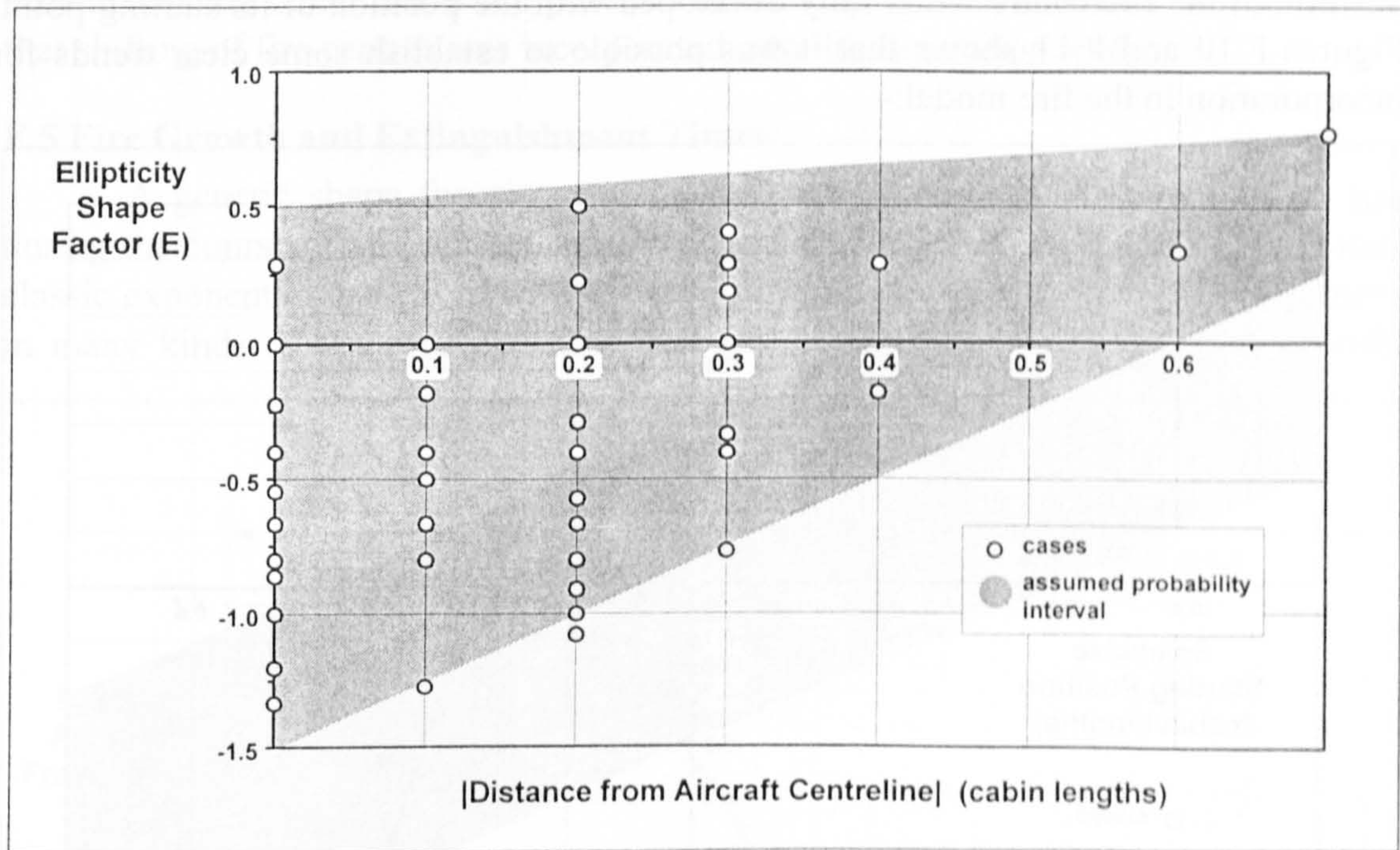


Figure F.8 Change in Fire Shape with Spanwise Position

In contrast, no clear pattern was discovered when examining changes in fire shape as a function of longitudinal starting position:-

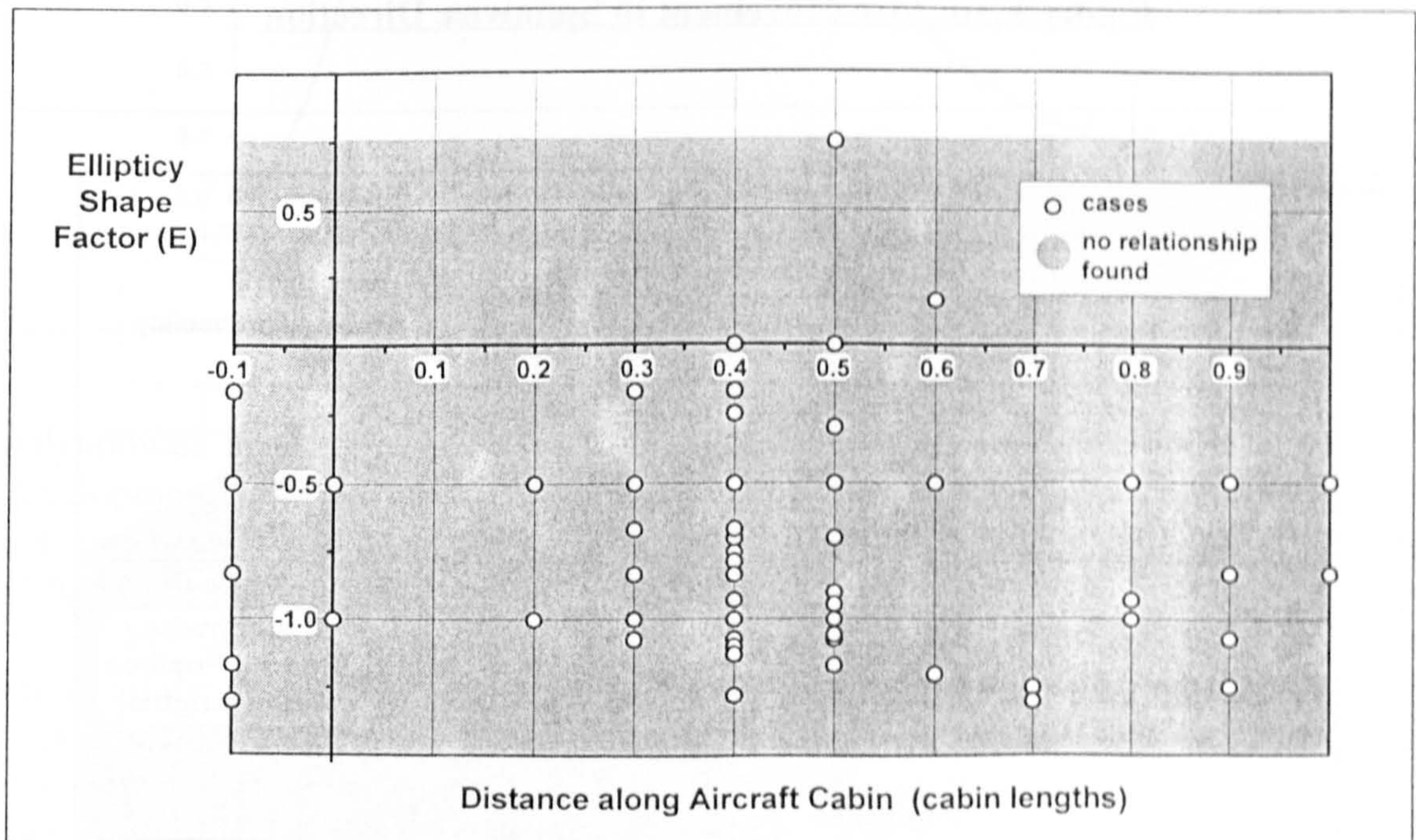


Figure F.9: Change in Fire Shape with Lengthwise Position

As a result, fire shapes were defined as a probabilistic function of spanwise starting position only.

F.4 Movement of Fire Centre

The fire growth plots clearly showed that the position of a fire can often shift as it grows in size. An attempt was made to quantify this effect by comparing the position of the fire centre when fully developed with the position of its starting point. Figures F.10 and F.11 shows that it was possible to establish some clear trends for incorporation in the fire model:-

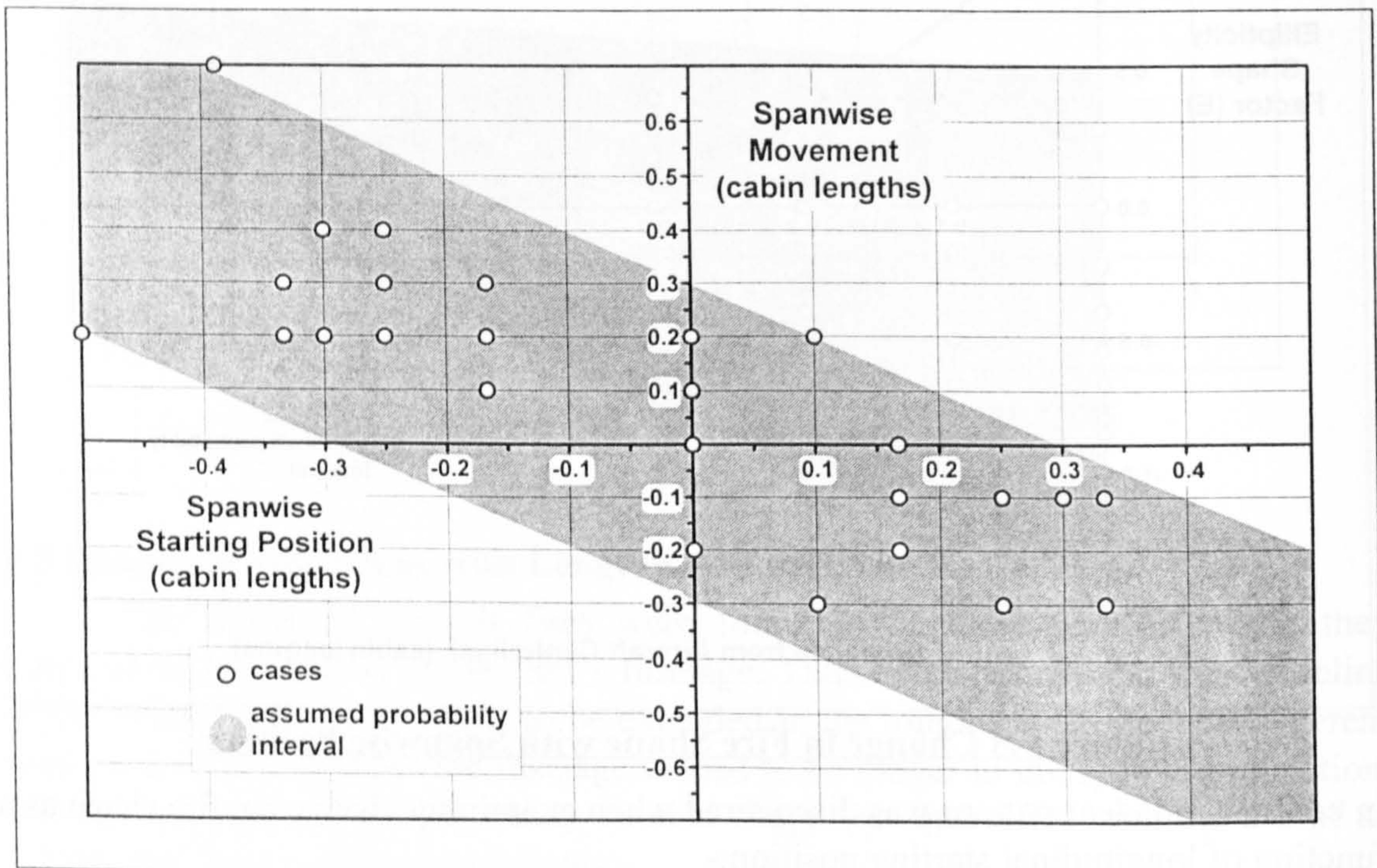


Figure F.10: Fire Movement in Spanwise Direction

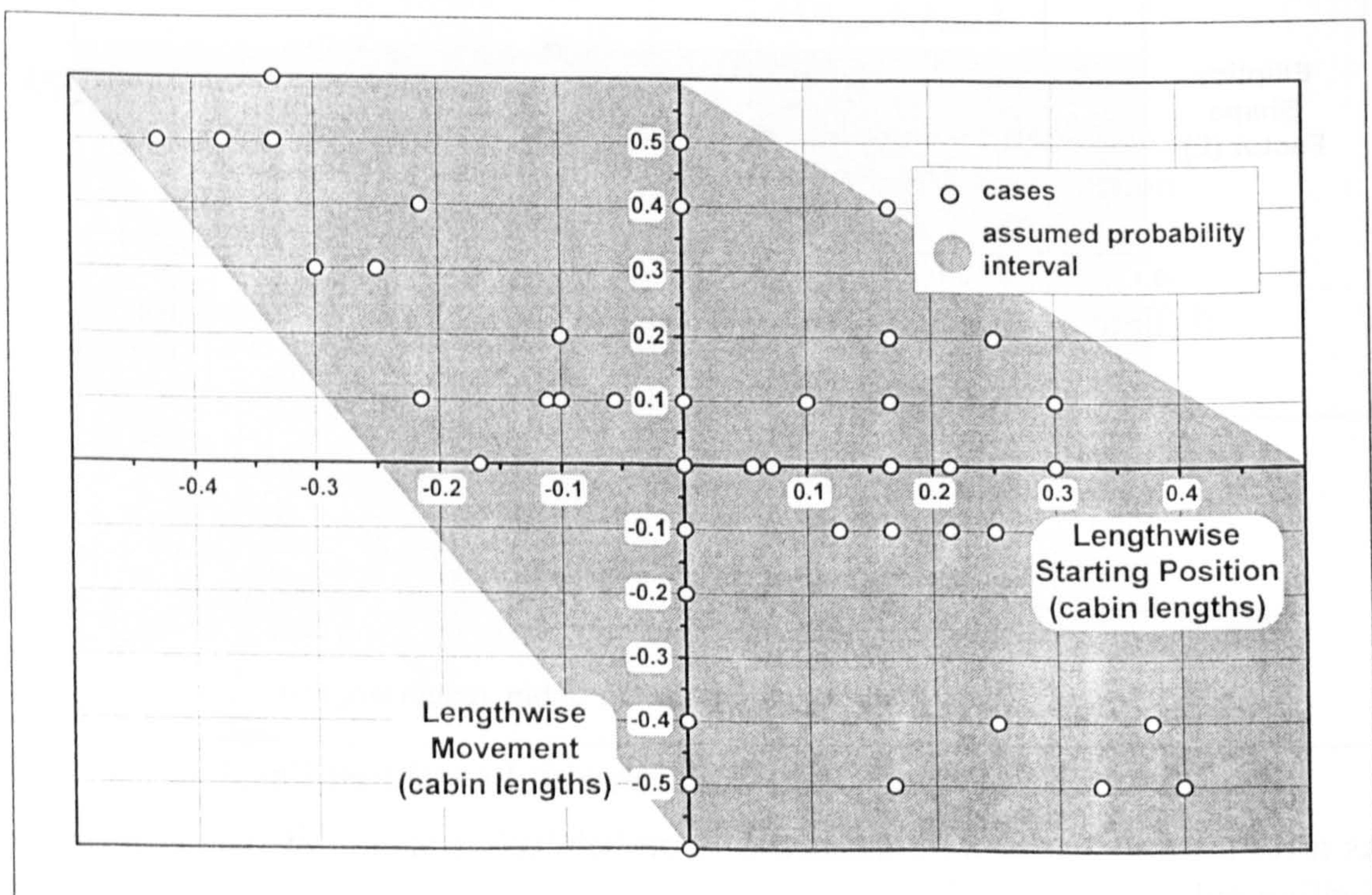


Figure F.11: Fire Movement in Lengthwise Direction

Note that, in both cases, fires starting away from the centre of an aircraft will tend to move towards the central wing area as they grow in size. The trend is particularly apparent in the spanwise direction, which implies that engine or wing fuel tank fires will usually spread towards an aircraft's fuselage. Obviously, this tendency accentuates the threat that a fire poses to aircraft occupants, and so it was imperative that shifting of fire centres was incorporated into the simulation analysis.

F.5 Fire Growth and Extinguishment Times

A generic shape function was used to model change of fire size with time during the course of an accident simulation. As shown in Figure F.7, this curve has a classic exponential growth, peak and decay distribution, typical of those encountered in many kinds of resource depletion processes. The coefficients of the three cubic

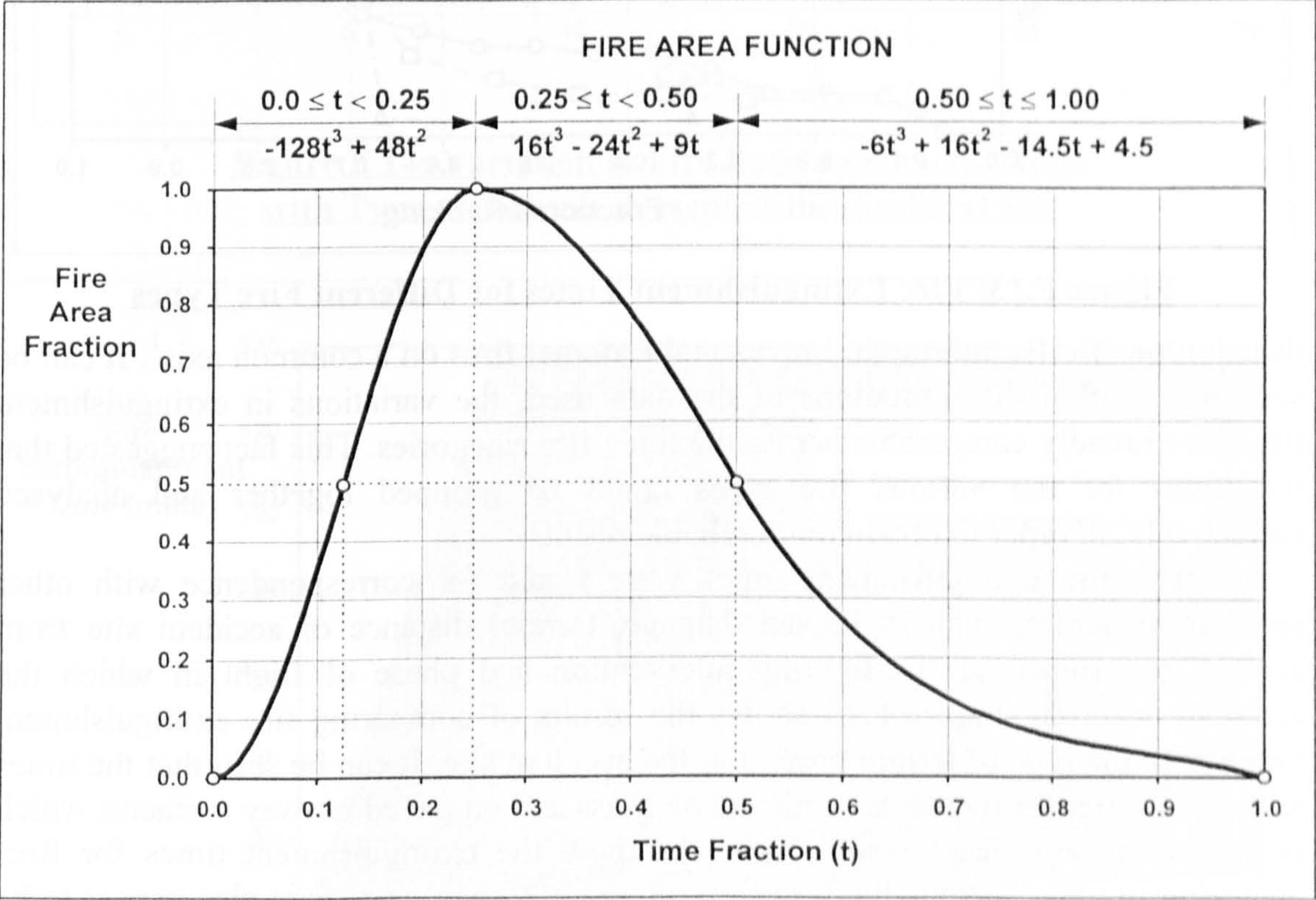


Figure 7.12: Parametric Fire Growth Function

polynomials used to define the curve can be modified to change the shape of fire development. It should be noted that the values shown have been chosen for convenience, providing points at (0.0, 0.0), (0.125, 0.5), (0.25, 1.0), (0.5, 1.0) and (1.0, 0.0) respectively.

For the parametric growth curve to be of any use, it needed to be scaled to represent the properties of a real fire. Two items of information were required for this; maximum fire area and the total time required for fire extinguishment. The former was obtained from the fire spread diagrams, as recounted in section F.2, leaving the task of establishing fire extinguishment times remaining.

The first test undertaken was to compare the extinguishment times required by different types of fire. Figure F.13 shows the results of scaling extinguishment time

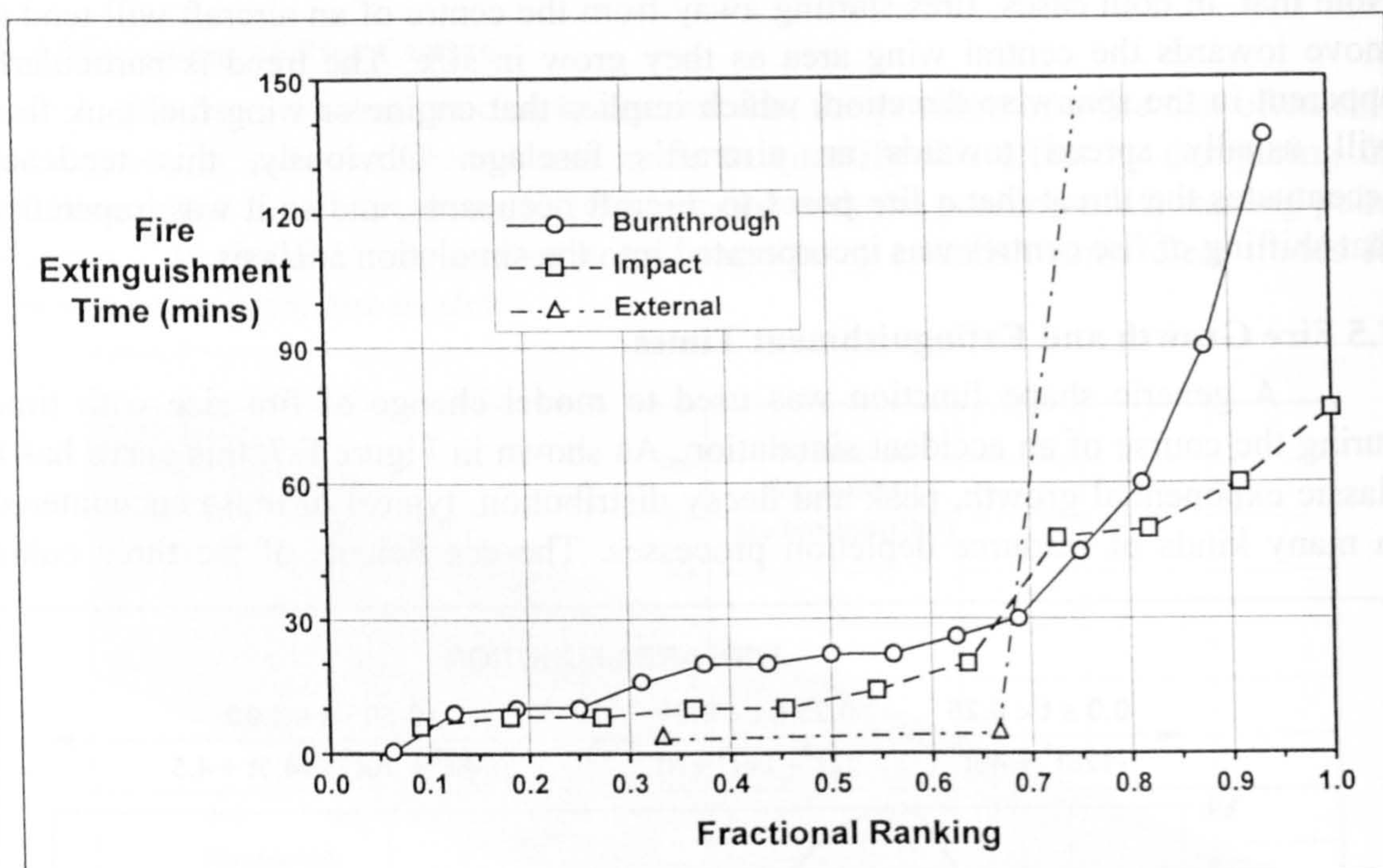


Figure F.13: Fire Extinguishment Times for Different Fire Types

distributions for Burnthrough, Impact and External fires on a common axis¹. It can be seen that, within the limitations of the data used, the variations in extinguishment times are broadly comparable across the three fire categories. This fact suggested that the times for the various fire types could be grouped together and analysed collectively, in order to obtain more reliable results.

The fire extinguishment times were tested for correspondence with other scenario variables, such as impact damage, terrain, distance of accident site from airport, occurrence of fire-fighting intervention and phase of flight in which the accident occurred. Figure F.14 shows the results of comparing fire extinguishment times with the type of terrain present at the accident site. It can be seen that the times are very similar for incidents occurring on grass and on paved runway surfaces; which is perhaps a significant result. Note also how the extinguishment times for fires occurring in other surroundings, such as a car park, ravine or street also appear to be consistent with the airport fires. Thus, it was concluded that the type of terrain present at the site tended not play a significant role in determining fire extinguishment times in aircraft accidents.

Of all the variables to be tested, the time required for fire extinguishment correlated best with the size of fire present. Rather obviously, in general, bigger fires usually take longer to put out. Significantly, however, large variations can occur in individual cases, as shown by the wide scatter of the points in Figure F.15. When data is examined more closely, some patterns begin to emerge. Firstly, note how most of the points are clustered in the bottom quarter of the plot. It is possible to group the fires into two loose categories; it was decided to label these *high-persistence* fires and *low-persistence* fires respectively. The former comprised only 26 percent of the cases

¹ Fires in each category have been ordered (shortest extinction time first) and then numbered 1, 2, 3, etc. The case number is divided by the total number of cases in present the category, to arrive at a (non-dimensional) "fractional ranking" for each fire.

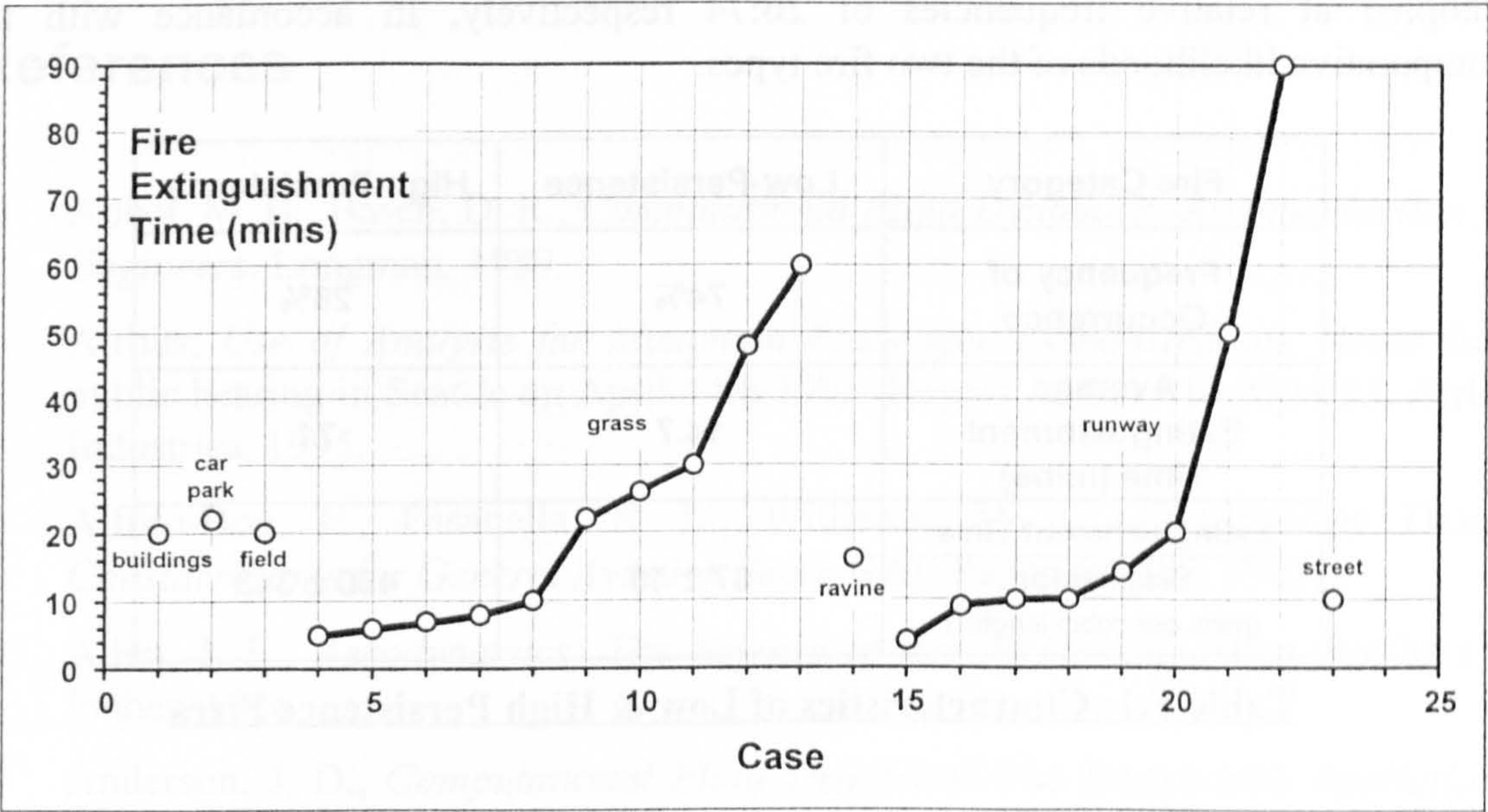


Figure F.14: Variation in Fire Extinguishment Times with Type of Terrain Present at the Accident Site

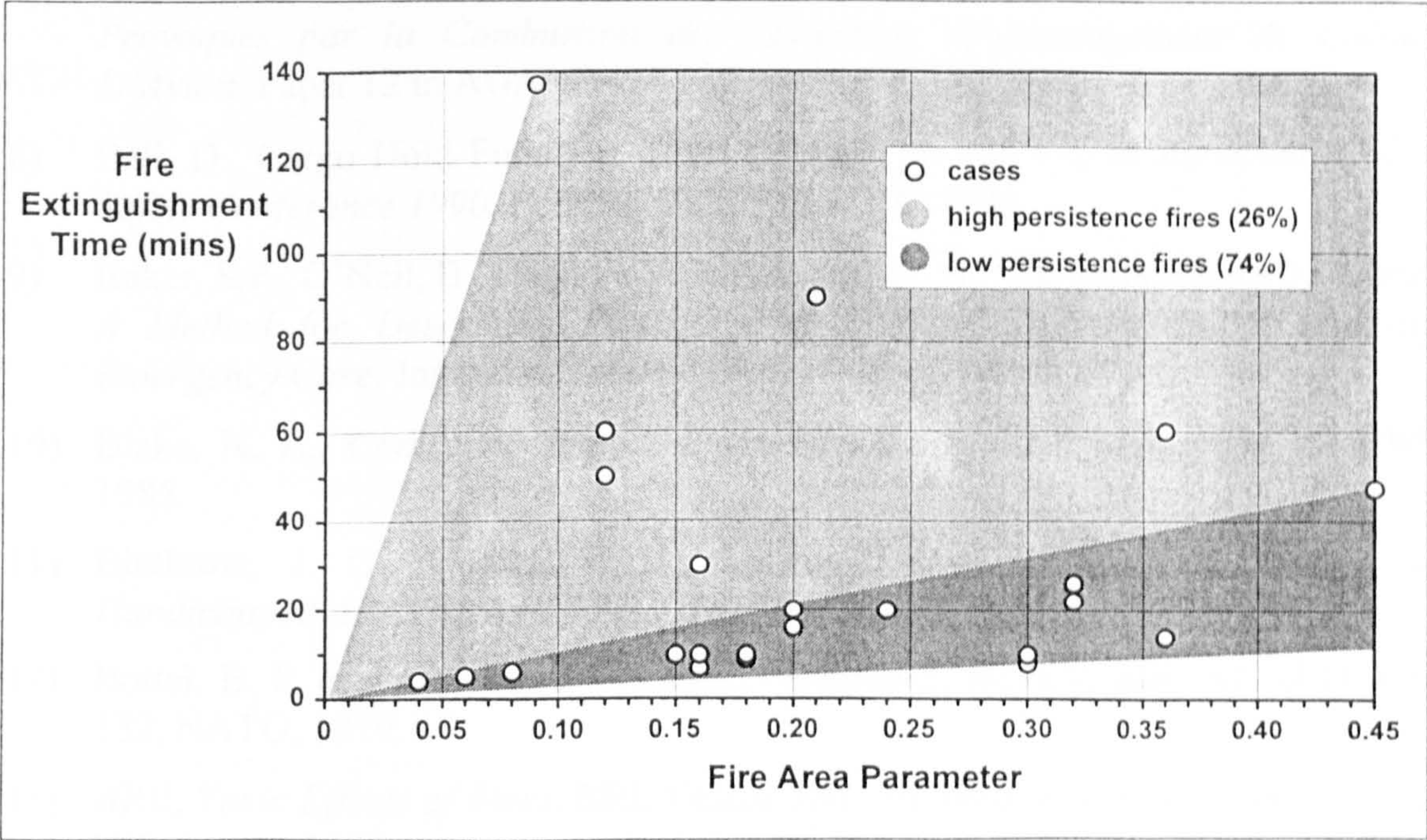


Figure F.15: Dependency of Extinguishment Time on Fire Area

studied and tended to involve fires that were either not fought effectively, inaccessible or occurred a large distance from populated areas. In both categories, the times required for fire extinction appear to be approximately proportional to maximum fire sizes, albeit with a large degree of scatter present. The relevant details are listed in Table F.1. Note that the fire area parameters have been non-dimensionalised by the square of the aircraft’s cabin length.

Fire times were generated for the simulation analysis, by taking the previously established value for maximum fire area and picking a suitable extinction time at random from the high or low persistence scatter envelopes. The two envelopes were

sampled at relative frequencies of 26:74 respectively, in accordance with the comparative likelihoods of the two fire types.

Fire Category	Low-Persistence	High-Persistence
Frequency of Occurrence	74%	26%
Average Extinguishment Time (mins)	14.7	71
<u>Extinguishment Time</u> Size Factor (mins per cabin length ²)	67 ± 40	450 ± 343

Table F.1: Characteristics of Low & High Persistence Fires

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