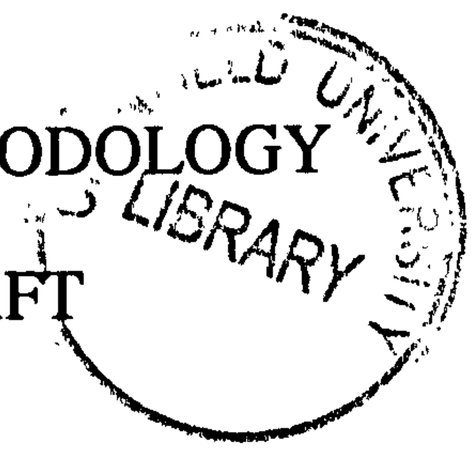
CRANFIELD UNIVERSITY

S KNIFE

# PROPULSION SYSTEM SAFETY ANALYSIS METHODOLOGY FOR COMMERCIAL TRANSPORT AIRCRAFT

VOLUME I




COLLEGE OF AERONAUTICS

PhD THESIS

# CRANFIELD UNIVERSITY

COLLEGE OF AERONAUTICS

CRANFIELD UNIVERSITY
LIBRARY

Ph.D. THESIS

Academic Year 1997

S KNIFE

# Propulsion System Safety Analysis Methodology For Commercial Transport Aircraft

Supervisor: J P Fielding

September 1997

# ABSTRACT

Airworthiness certification of commercial transport aircraft requires a safety analysis of the propulsion system to establish that the probability of a failure jeopardising the safety of the aeroplane is acceptably low. The needs and desired features of such a propulsion system safety analysis are discussed, and current techniques and assumptions employed in such analyses are evaluated. It is concluded that current assumptions and techniques are not well suited to predicting behaviour of the propulsion system in service. The propulsion accident history of the high bypass ratio commercial transport fleet is reviewed and an alternate approach to propulsion system safety analysis is developed, based on this accident history. Features of the alternate approach include quantified prediction of propulsion related crew error, engine-level reliability growth modelling to realistically predict engine failure rates, and quantified credit for design features which mitigate the effects of propulsion system failures. The alternate approach is validated by applying it to two existing propulsion systems. It is found to produce forecasts in good agreement with service experience. Use of the alternate approach to propulsion system safety analysis during design and development will enable accurate prediction of the expected propulsion related accident rate and identification of opportunities to reduce the accident rate by incorporating mitigating features into the propulsion system/ aeroplane design.

*To my husband, who made it possible*

ACKNOWLEDGEMENTS

My thanks are due to my supervisor, Dr. Fielding, whose encouragement and advice were invaluable, and to the staff of Cranfield library, whose tireless assistance enabled me to conduct a literature search from one hundred miles away. The Service Engineering Group and the Reliability Group of Rolls-Royce provided valuable initial technical support.

The Flight Safety group of General Electric provided constant financial and moral support, without which I could not have completed this work.

I would also like to thank all of the engine designers of Rolls-Royce, General Electric and Pratt & Whitney whose time and patience have helped me to understand engine operation, and to state that this study is not intended in any way to decry their capabilities - commercial jet engines reflect excellent design in their performance, reliability and safety records - but to recognise the inevitable shortfall between the design intent and the reality, and to assist in the reduction of that shortfall for future engines and installations.

# CONTENTS

## VOLUME I


| | Page |
|---|---|
| **1.0 INTRODUCTION** | 1 |
| 1.1 General Background | 1 |
| 1.2 Regulatory Requirements | 3 |
| 1.3 Previous Work | 5 |
| 1.4 Objectives and Methodology Of Present Work | 10 |
| 1.5 Layout Of Thesis | 11 |
| **2.0 A CURRENT SAFETY ANALYSIS APPROACH** | 13 |
| 2.1 Introduction | 13 |
| 2.2 Criteria For Model Selection | 13 |
| 2.3 Ground Rules | 14 |
| 2.4 Techniques | 15 |
| 2.5 Components And Systems Addressed | 16 |
| 2.6 Types Of Failure Effects Addressed | 18 |
| 2.7 Baseline Study Results | 19 |
| 2.8 RB211-22B Service Experience | 19 |
| 2.9 RB211-22B Accident And Serious Incident Review | 29 |
| 2.10 Conclusions Regarding Current Approach | 29 |
| **3.0 BASIC ASSUMPTIONS AND DEFINITIONS FOR THE SAFETY ANALYSIS** | 31 |
| 3.1 Definitions | 31 |
| 3.2 Intent of Analysis | 31 |
| 3.3 Scope of Analysis | 33 |
| **4.0 GENERAL REVIEW OF ACCIDENTS/ SERIOUS INCIDENTS** | 35 |
| 4.1 Statistical Review | 35 |
| 4.2 Discussion of Individual Failure Effects | 44 |
| 4.3 Conclusions of Accident Review | 54 |

| | Page |
|---|---|
| **5.0 REVIEW OF TECHNIQUES** | 57 |
| 5.1 Desired Features | 57 |
| 5.2 PHA/FHA | 57 |
| 5.3 Fault Tree Analysis | 58 |
| 5.4 Reliability Block Diagrams | 60 |
| 5.5 Failure Mode and Effect Analysis | 60 |
| 5.6 Simulation | 61 |
| 5.7 Failure Mode and Effect Summary | 61 |
| 5.8 Common Cause Failure Analysis Methods | 62 |
| 5.9 Alternative Analysis Techniques | 63 |
| **6.0 ALTERNATE APPROACHES TO PROPULSION SYSTEM SAFETY ANALYSIS** | 65 |
| 6.1 Areas To Be Investigated | 65 |
| 6.2 Prioritising the Effects To Be Considered By Safety Analysis | 65 |
| 6.3 Failure Progressions / Opportunities For Accident Prevention | 67 |
| 6.4 Crew Error Modelling | 70 |
| 6.5 A Novel Approach to Predicting Failure Rates | 77 |
| 6.6 Summary Of Recommendations For Improved Approach | 84 |
| **7.0 VALIDATION OF RECOMMENDED ANALYSIS IMPROVEMENTS** | 89 |
| 7.1 Introduction | 89 |
| 7.2 Validation Engine ($X_{der}$) Description | 90 |
| 7.3 Aircraft ($X_{der}$) Installation Details | 90 |
| 7.4 Prediction Of General Reliability of Propulsion System ($X_{der}$) | 91 |
| 7.5 Prediction Of Specific Engine Level Failure Modes And Accident Rate Forecast for ($X_{der}$) | 95 |
| 7.6 Validation Propulsion System Service Experience | 101 |
| 7.7 Secondary Validation | 103 |
| 7.8 Discussion Of Validation | 105 |
| 7.9 Summary | 106 |

| | Page |
|---|---|
| **8.0 DISCUSSION** | **107** |
| 8.1 Goals | 107 |
| 8.2 Traditional Approaches To Safety Analysis | 108 |
| 8.3 Alternate Approach To Safety Analysis | 120 |
| 8.4. Potential for Improvements to Alternate Approach | 124 |
| 8.5 The Role Of The Alternate Approach | 125 |
| **9.0 CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK** | **127** |
| 9.1 Conclusions | 127 |
| 9.2 Recommendations for further work | 128 |
| **10.0 REFERENCES** | **131** |

# APPENDICES


| | | Page |
|---|---|---|
| APPENDIX A | LITERATURE REVIEW | 145 |
| APPENDIX B | AIRWORTHINESS REGULATIONS | 163 |
| APPENDIX C | REVIEW OF ACCIDENTS AND INCIDENTS | 175 |
| APPENDIX D | EVENT SEQUENCE ANALYSIS SHEETS | 201 |
| APPENDIX E | CREW ERROR STUDY | 207 |
| APPENDIX F | PREDICTION OF FAILURE RATES | 217 |

VOLUME II

| | | |
|---|---|---|
| APPENDIX G | RB211-22B SAFETY ANALYSIS (RR PROPRIETARY) | II: 1 |
| APPENDIX H | EFFECT OF THRUST GROWTH ON RELIABILITY AND SAFETY (RR PROPRIETARY) | II: 187 |

## FIGURES


| | Page |
|---|---|
| 2.1 Module Contribution To Predicted RB211 IFSD Rate | 22 |
| 2.2 Module Contribution To Predicted RB211 Uncontained Rate | 23 |
| 2.3 Module Contribution To Predicted RB211Fire Incidence | 24 |
| 2.4 Module Contribution To Predicted Component Departure | 25 |
| 2.5 Module Contribution To Predicted RB211 Cabin Smoke Rate | 26 |
| 2.6 Module Contribution To Predicted RB211 Case Rupture Rate | 27 |
| 4.1 Propulsion Related Accident Rate By Model | 37 |
| 4.2 Propulsion Related Accident Rate Trend | 39 |
| 4.3 Propulsion Related Accident Rates By Most Frequent Causes | 40 |
| 7.1 Significant SDR Rates | 92 |
| 7.2 Significant SDR Rates; Recent Propulsion System | 93 |

NOTATION

| | |
|---|---|
| AAIB | Aircraft Accident Investigation Board |
| ACJ | Joint Advisory Circular |
| ACOC | Air Cooled Oil Cooler |
| AGL | Above Ground Level |
| AIA | Aerospace Industries Association |
| APU | Auxiliary Power Unit |
| ASRS | Aviation Safety Reporting System |
| BCAR | British Civil Airworthiness Regulations |
| CAA | Civil Aviation Authority |
| CAAM | Continued Airworthiness Assessment Methodology |
| CDP | Compressor Discharge Pressure |
| CIS | Communist Independent States |
| DFDR | Digital Flight Data Recorder |
| EEC | Electronic Engine Control |
| EGT | Exhaust Gas Temperature |
| EMI | Electromagnetic Interference |
| ETOPS | Extended Twin Operations |
| FAA | Federal Aviation Authority |
| FADEC | Full Authority Digital Electronic Control |
| FAR | Federal Aviation Regulation |
| FHA | Functional Hazard Assessment |
| FMEA | Failure Mode and Effect Analysis |
| FMES | Failure Mode and Effect Summary |
| FOD | Foreign Object Damage |
| FTA | Fault Tree Analysis |
| IFSD | In-Flight Shut Down of an engine |
| IP | Intermediate Pressure |
| IPC | Intermediate Pressure Compressor |
| HCF | High Cycle Fatigue |
| HIRF | High Intensity Radiation Field |
| HP | High Pressure |

| | |
|---|---|
| HPC | HP Compressor |
| HPT | HP Turbine |
| IEEE | Institute of Electrical and Electronic Engineers |
| IEPR | Integrated Engine Pressure Ratio |
| IGV | Inlet Guide Vane |
| IMechE | Institute of Mechanical Engineers (UK) |
| IP | Intermediate Pressure |
| IPT | Intermediate Pressure Turbine |
| JAR | Joint Aviation Regulation |
| LP | Low Pressure |
| LPT | Low Pressure Turbine |
| MTBF | Mean Time Between Failures |
| N1 | Rotational Speed of LP rotor |
| NASA | North American Space Agency |
| NGV | Nozzle Guide Vane |
| NTIS | National Technical Information Service (US) |
| NTSB | National Transportation Safety Board |
| OGV | Outlet Guide Vane |
| P1 | Inlet Pressure |
| PE | Engine Core Exit Pressure |
| PF | Fan Exit Pressure |
| PHA | Preliminary Hazard Analysis |
| RTO | Rejected Takeoff |
| SAE | Society Of Automotive Engineers (US) |
| SDR | Service Difficulty Report |
| TGT | Turbine Gas Temperature |
| T/O | Takeoff |
| TOGA | Takeoff/ Go Around |
| UER | Unscheduled Engine Removal |
| V1 | Decision speed for an aeroplane takeoff |

# 1.0 INTRODUCTION

## 1.1 General Background

The introduction of the jet engine as a means of propulsion for the world's commercial transport aircraft has enabled unprecedented growth in air travel. Initial concern over the safety implications of the use of the jet engine led to the manufacturers producing design safety analyses, both to satisfy the regulatory authorities of the airworthiness of jet engines, and to seek out any potential design flaws before entry into service. Operational experience of jet engines has been generally good, resulting in a lower propulsion-related accident rate than for aircraft with piston engines, as remarked by Taylor (1), yet the challenge remains of demonstrating the safety of each new jet engine model before certification, and of continuing to improve the safety of the engine design.

The intent of the safety analysis is manifold; satisfying the regulatory authorities is of paramount importance, since the engine might not otherwise obtain certification for use in service, yet it is also necessary to assess the safety of the new design in comparison to that of engines already in service. Potential weaknesses in the design may be discovered and addressed by appropriate safety analysis, avoiding troublesome and costly design changes in the future, and facilitating a trouble-free entry into service when the engine/airframe package is delivered to the customer airline. The safety analysis will minimise the risk to the travelling public both by preventing engine failures from occurring and by reducing the severity of the effects of such failures, improving overall airplane safety. Moreover, a thorough safety analysis provides a strong defence against product liability litigation at some future time, by helping defend against a charge of negligence by the engine manufacturer.

Notwithstanding the benefits cited above, conducting a safety analysis of a jet propulsion system design before entry into service is accompanied by considerable difficulties. Selection of the most appropriate analysis technique is not straightforward (2) since each has specific strengths and weaknesses, and since engine development programmes are so compressed that using a wide variety of techniques to address the same issues is unlikely to produce results until long after the engine enters service. The specific airworthiness regulations to be addressed differ according to the country of manufacture, and the certification basis of the engine or the propulsion system, as does the interpretation of regulations with almost identical wording. The issues addressed by the analysis depend entirely upon whether it is conducted from an engine or airframe perspective, and there is considerable potential for some hazards to be neglected by both parties.

Quantification of failure rates for use in the safety analysis presents a formidable difficulty; since the length of time spent during engine development on testing components or entire engines (one or two thousand hours) is generally much shorter than the component lives (tens of thousands of hours), it is virtually impossible to obtain a statistically significant failure distribution for most engine components before they go into service. Failure distributions are not readily available from components already in service on previous engines, since as soon as an engine component experiences a safety-related failure, considerable effort is expended on preventing the same failure recurring, either by component inspection, operational limitations or component redesign. Any safety analysis quantification must therefore be executed with extremely sparse data.

Finally, since certification is vital to the programme, there is considerable pressure to document the analysis in the same way that permitted certification of the last model. Any design changes resulting from the analysis are likely to be acknowledged informally rather than recorded in the documents presented for certification; a natural reluctance to point out past errors, together with concern that regulatory authorities may misinterpret a discussion of design evolution, combine to render the formal analysis documentation a simplified, condensed demonstration of compliance with the regulations, rather than a full record of trade-offs and outstanding concerns.

The considerations raised above have led to some concern that the existing approach to propulsion system safety analysis may not correctly predict the behaviour of jet engines in the field. Although no systematic audit of analysis predictions versus actual experience has been carried out upon a high bypass ratio turbofan, there have been instances of discrepancies, both in the failure rates predicted and the kinds of events addressed. This study is intended to establish where current analysis techniques are lacking and to identify an improved approach. Specific opportunities for improvement were initially identified as:

Basic assumptions used in the analysis.
General utility of the analysis to the design community
- Timely
- Credible to design community
- Cost effective
- Clear identification of potential for design improvement

Formal analysis techniques (inductive versus deductive).
Integrated analysis of the propulsion system, including human interfaces, rather than a bare engine.
Types of events addressed by safety analysis.
Quantification of failure rates.
Effect of small changes in design or in loading (derivative versus new design).

## 1.2 Regulatory Requirements

As explained above, a primary requirement of the safety analysis is that it should enable demonstration of compliance with airworthiness regulations. These regulations, together with their supporting advisory material, provide only limited guidance regarding the appropriate means of conducting a safety analysis for an aircraft engine or propulsion system. This material is largely based upon historical precedent and negotiation between the airworthiness authorities and the industry; considerable discretion is allowed the manufacturer in the means by which compliance is demonstrated, and it is then up to the appropriate authority to evaluate the demonstration on a case-by-case basis. No effort is made in the regulations to compare analytical techniques and their merits and deficiencies, nor to enumerate the details of the analysis. Excerpts from the regulations are provided in Appendix B, for easy reference.

FAR 33.75 (3), addressing engine certification only, states that the analysis should show that any probable failure will not cause the engine to catch fire, burst, overload the engine mounts or lose the capability of being shut down.

The corresponding European Regulation, JAR E 510 (4) requires a failure analysis of the engine to be carried out "to assess the likely consequence of all failures that could reasonably be expected to occur ... a summary shall be made of those failures ... which could result in Major Effects or Hazardous effects". The associated advisory material (ACJ E 510) specifies hazardous effects as significant non-contained high energy debris, or toxic bleed air being supplied to the cabin, or significant thrust in the opposite direction to that intended by the pilot, or complete inability to shut the engine down.

FAR 25 (5) (which deals with large transport category aircraft, often powered by high bypass ratio jet engines) gives guidance on safety analysis from the airline perspective. The regulations specifically addressing engine failures (25.901 and 25.903) direct the installation designer to ensure that "no single failure or malfunction or probable combination of failures will jeopardise the safe operation of the airplane" and that "design precautions must be taken to minimise the hazards to the airplane in the event of an engine rotor failure or of a fire originating within the engine which burns through the engine case".

FAR 25.1309 requires a safety analysis for systems and equipment, and gives some guidance in the advisory material regarding acceptable probabilities of hazardous and catastrophic failures, but considerable debate exists over the applicability of this regulation to propulsion systems[1]. The FAA has historically allowed major parts of propulsion systems to be

---

[1] A new rule and Advisory Circular is currently being developed to clarify the situation.

certified by showing compliance with 25.901 and 25.903 instead, by design review and statement of compliance.
The corresponding European regulations, appearing in JAR 25, (6) are less ambiguous, in that the propulsion system is explicitly required to comply with JAR 25.1309, as well as being installed so as to minimise the risk of damage (JAR 25.903) resulting from uncontained rotor burst. Although the associated advisory material does not specify the analysis technique to be used, nor means of quantification, it does suggest that the effects of potential crew error or maintenance error be included in the analysis.

The following points may be noted from this brief review of the regulatory requirements:
Both FAR 33 and JAR E address the engine in isolation, rather than the 'propulsion function' for the aircraft. As such, the analysis is directed toward those engine malfunctions which could actively prove Hazardous, such as those which direct high energy debris toward the airplane, rather than those resulting in the engine passively failing to perform an expected duty. Indeed, the advisory material for JAR E explicitly states that a failure with no result other than the complete loss of power and associated engine services from a single engine should be regarded as having a Minor effect; no suggestion is made that the engine manufacturer consider the effects of multiple engine failures. Conversely, ACJ No 5 to JAR 25.1309 explicitly requires consideration of "all possible combinations of engine and electrical power source failures ... except those that are shown to be Extremely Improbable." Engine failures such as fire and uncontained disk failure are presupposed, rather than shown to have acceptably low probabilities.[2]

The specification of undesired events in FAR 33 immediately promotes a deductive approach to analysis (one in which individual failure modes are inferred from a given result), whereas the JAR E 510 requirement to address all failures promotes a more exhaustive, inductive approach in which all failure modes are enumerated before conclusions are drawn regarding outcomes (as suggested by the wording of FAR 25.901 and both FAR and JAR 25.1309, although in practice only a small subset of possible engine failures are used to demonstrate compliance with these regulations).

Definition of the severity of a given effect is not consistent between the engine regulations and the airframe regulations. Events such as release of

---

[2]Both FARs and JARs currently incorporate an anomaly in safety analysis requirements, in that the safety analysis for engine certification is required to show that the engine will not catch fire or burst, whereas the analysis for powerplant (airframe) certification is required to show that, assuming an engine fire or engine burst occurs, the airplane will be safe. Although this approach leads to the most stringent safety requirements, it presents difficulties in consistency of quantified analysis.

high energy debris are defined or implied as Hazardous by JAR E and FAR 33, yet ACJ No.1 to JAR 25.1309 describes a Hazardous effect as being one involving:
" i) a large reduction in safety margins
ii) physical distress or a workload such that the flight crew cannot be relied upon to perform their tasks accurately or completely
iii) Serious injury to or death of a relatively small proportion of the occupants."
The vast majority of uncontained engine failures or fires do not result in any of the above effects, and might reasonably be considered to have only Major effects from the airframe perspective.

Such inconsistencies between regulatory requirements complicate the task of producing a powerplant safety analysis suitable for demonstrating compliance with all of the appropriate airworthiness regulations.

## 1.3 Previous Work

Very little work has been published on the safety analysis of jet engines, in part because of the sensitivity of the issue from the legal and regulatory standpoint. Much of the work published on safety analysis of other systems such as nuclear powerplants, chemical process plant and electricity grid systems is not directly applicable to jet engines with their severe constraints upon weight and space, as well as upon reliability and safety. The widespread use of redundancy and of protective systems, as used in the plant mentioned above, would incur prohibitive weight and performance penalties in the fiercely competitive world of jet propulsion; much effort is therefore expended in applying sophisticated design techniques to the components of architecturally simple systems, rather than in designing system architecture to accommodate the known failure characteristics of simple components. The material published on system safety is primarily written from the military perspective, concentrating on programme deliverables required by the military community and the form each task should take, rather than the substance of the task. A notable exception is Terry's (7) overview of system safety, which provides many philosophical insights into key issues confronting the system safety engineer, although guidance on execution of analyses is minimal.

No studies are available comparing the predicted and actual safety statistics for jet aircraft engines, or otherwise validating the current safety analysis techniques[3].

---

[3]The sensitivity of the issues involved has led to the safety analyses being considered company limited data, which is available to the regulatory authorities as part of the certification process, but is not released for general publication. Similarly, the details of safety-related failures are not generally released, except as a Service Bulletin to the

A considerable body of work exists in the field of reliability forecasting, some of which could potentially be applied to the safety analysis of jet engines. A significant part of this study will be devoted to establishing the applicability of such forecasting techniques to the safety analysis of jet engines (see below and Chapter 5). Many of the forecasting techniques are based upon components with well-defined failure distributions, where hundreds or thousands of components have been tested to failure under well-delineated loads in equally well-defined environments. This is not the case for a jet engine, since cost and short development programmes only permit one or two examples of the more critical components to be tested to failure during an engine development programme; the majority of the programme consisting of tests without component failures. Once the engine enters service, a safety-related failure is quickly followed by corrective action throughout the fleet; leaving little opportunity to obtain experimental failure distributions for any safety-related component failure mode. One of the challenges addressed by this study is the selection of those predictive techniques which will best allow quantification of failure rates, given the paucity of data outlined above. The problem has been summarised in general terms by Gottfried and Weiss (8).

### 1.3.1 Guidance on safety analysis

Guidance on the best approach to aircraft engine safety analysis is generally limited to that guidance appearing in the airworthiness regulations (and equivalent military standards, which leave even more freedom for interpretation (9)).

ARP926A (10), a completely general analysis procedure, recommends that analysis be limited to that which is strictly necessary:

> Specify quantitative results only to the extent essential
> Restrict the equipment item levels....
> Limit the failure effects to those necessary.
> Do not call for an analysis of all probable failure modes ...
> Do not impose a specific analytic format ....

It suggests that a combination of a hardware approach and a functional approach at any analysis level may be the optimum.

Lloyd & Tye (11) recommend in a discussion of the safety analysis of aircraft systems in general that a Preliminary Hazard Analysis (PHA) be executed to review the extent and relevance of previous experience with allegedly similar systems. This should be followed by FMEAs upon

---

airlines recommending corrective action, as an Airworthiness Directive from the FAA (or Mandatory Modification by another authority), or in the worst instances, as part of a formal accident investigation by the NTSB, AAIB or equivalent government body. Such limitations upon the availability of the relevant information effectively preclude such a study without the sanction and assistance of an engine manufacturer or regulatory body.

components, Fault Trees addressing undesired events identified in the PHA, and sensitivity analyses to establish the system effect of variations in component failure rates. Common mode failure analysis, zonal analysis and uncontained failure analysis are also recommended to address causally linked simultaneous component failures. It will be shown below (Chapter 5) that not all of these techniques are appropriate to the analysis of propulsion systems.

Conversely, Kytasty (12) recommends the use of fault tree analysis rather than the historically used FMEA for evaluating the reliability of space vehicle propulsion systems, on the grounds that a fault tree directs attention to fundamental system incompatibilities, rather than individual instances of such incompatibility that might be uncovered by FMEA. "The level at which FMEA is performed places the attention and hence controls or barriers to failure modes close to the failure mode itself. The result is an often overwhelming attempt to solve individual problems. ..... A top down analysis with reliability allocation and predictions using Fault Tree models provides a different approach by organising system hardware according to function and failure mode. .... A strategy therefore exists for emplacing failure barriers at the most beneficial nodes in the system." A similar point is made by Martin (13) advocating a functional rather than a component-based approach to reliability analysis of a system. The advantages of this approach for an architecturally complex system are clear, in that the system effect of an individual component failure is emphasised, but the relevance to propulsion system analysis will be pursued in more detail below.

The Electric Power Research Institute has published a procedure (Strong and Eagle, (14)) for conducting reliability forecasts upon selected industrial gas turbine components, based upon the use of failure rates from existing installations, modified by environmental factors, together with polling expert opinion where no failure rates are available. They have also studied the applicability of fault tree analysis for industrial gas turbine reliability, (Kelly, Erdman and Gilbert, (15)) and concluded that the technique appeared useful, provided that appropriate failure rate data could be located.

### 1.3.2 Validation of safety and reliability predictions

None of the recommendations in the above references[4] include work strictly validating the approach advocated, by comparing the results of a forecast with measured system reliability subsequently experienced in service (as in the investigations of Snaith (16) and Taylor (17)). An AIA/FAA committee has recently published a comprehensive study of

---

[4]Many of these references address reliability studies rather than safety analysis, and their recommendations are therefore of only limited applicability to the subject at hand.

recent safety-significant propulsion system events occurring in service, (18), but this has not been related to previous predictions. The results of the fault tree analysis of Kelly, Erdman and Gilbert, (15) were presented to individuals experienced in the system, who confirmed that they 'seemed reasonable', but since those same individuals originated the failure rates and system descriptions forming the basis for the fault tree, it would have been remarkable had they been surprised by the results. No studies have been published comparing the results of existing safety analyses with service experience for high bypass-ratio jet engines, and until such a comparison is made, it is impossible to assess the total capability of current techniques.

### 1.3.3 Reliability forecasting techniques

Although much reliability forecasting relies upon testing large component populations to failure, as outlined above, the following approaches offered more promise and will be discussed in some detail below.

Reliability growth modelling, as pioneered by Duane (19), was initially devised to predict reliability at entry into service by monitoring failures during the development programme. Much of the subsequent discussion of reliability growth modelling has focused on the mathematical model which most accurately represents the reliability growth curve during development testing (Lawlor, 20, Mead, 21, Taneja and Safie, 22). Since the length of time devoted to development testing in an aircraft engine programme is relatively short, and since the intended MTBF between safety-related failures is relatively long, reliability growth as measured over a single development programme is unlikely to provide useful information. (A similar objection was raised by Carter (23), on the grounds that very few failure modes can be experienced during initial prototype testing, and considerable scatter can therefore be anticipated in the measured failure rate). However, a slightly different approach to the technique permits the use of failure data from parent designs as well as improved derivative designs in the forecasting of failure rates. The validity of this philosophy is recognised by Lloyd & Tye (11), although the details of its implementation vary from one worker to the next (Lloyd, (24)). Carter objects that "no growth model could possibly span the process both before and after a major design change"; this viewpoint will be discussed later together with the concept of the continuity of design philosophy from one engine model to the next.

Another approach meriting consideration is that of Mechanical Reliability, as introduced by Bompas-Smith (25), (26) and Kececioglu (27), which attempts to forecast component failure rates by assessing the interaction of a component strength distribution with the spectrum of loads experienced by components. Forecasting safety-related component failures by directing

attention to the low-strength tail of the strength distribution should be possible, provided that the relevant distributions are sufficiently well-defined, a difficulty acknowledged by Carter (23), one of the primary advocates of this approach. Martin (28) advocates the use of a complex equipment model following an exponential reliability law for aircraft engines, as opposed to the strength-load interference model or the load-chain model. Alternatively, use of threshold techniques (Smith, 29), rather than the more conventional normal, log normal, or Weibull distributions, may prove helpful in predicting failure rates for high-integrity components.

A third approach, frequently employed in the US, is the use of generic component failure rate data, adjusted to take account of environmental severity by the use of theoretical or empirical relationships, or by using Bayesian statistics to factor in expert opinion (15). The use of such generic data to predict specific component failures leads to considerable problems when superficially similar components operating in similar environments exhibit very different failure rates (as recognised by Carter (23)).

A fourth approach, which also offers considerable promise in sharpening the focus of FMEAs, is the use of precursor data in assessing the past safety performance of systems (Bier, 30) (Venton, 31). By looking at the incidence of failures which have the potential to lead to a Hazardous effect, but need not have actually done so, failure rates can then be based on a larger number of events, and can therefore be used with more assurance. Alternatively, presentation of each propulsion-related accident as a chain of events (as proposed by the Boeing Safety Department (32), and used by Welsh and Lundberg (33), similar to the loss-cause failure analysis presented by Ball (34)) can permit multiple contributing factors to be identified for each accident, and maximise the opportunities for accident prevention.

A fifth approach recommended by some authors who have identified problems with the use of generic failure rates is the "Physics of Failure" approach in which the expected failure rate is based upon environmental stresses, temperatures, vibration etc. in a deterministic manner. Fortunately, the majority of propulsion system components have already been subjected to this type of analysis during the design process, and a "safe life" established for those considered critical to the safety of the propulsion system (the safe life is generally set considerably lower than the calculated fatigue life, using minimum material properties and a severe operating environment). This rigorous design process is partly responsible for the high component reliabilities experienced in service, and if it were completely valid, no component would produce a safety-related failure. In some cases, the design was done without full knowledge of the operational environment of the component (this would be typical of a failure of a pipe

or connector or seal; components which are not analysed in the same depth as "Critical" components). In other cases, the material or manufacture or maintenance of the component is not as intended by the designer (this would be more typical of a turbine disk failure). Prediction of these discrepancies between the design intent and the reality of the component is not possible, given the current state of the art. The "Physics of Failure" approach is therefore concluded to be of limited utility in this context.

A more detailed review of the literature published in the field can be found in Appendix A.

## 1.4 Objectives and Methodology of Present Work

The goal of this study is to identify and remedy shortfalls in the safety analysis of high bypass-ratio jet engines powering large transport category aircraft, and to improve the usefulness and cost-effectiveness of such analysis where possible.

The approach taken was initially to establish a baseline, using existing safety analysis techniques in use by the engine manufacturers to forecast the behaviour of an existing engine. Much of the original analysis work used for certification of that engine was made available by the manufacturer, providing the structure for an equitable evaluation of existing techniques and approaches. The analysis predictions were then compared with actual service experience for that engine, as recorded by the Service Engineering Department of the engine manufacturer.

The baseline thus established provided a departure point for considering potential improvements to the safety analysis procedure, prompted by identifiable discrepancies between forecast and experience, enquiries from the engine manufacturer, or service incidents involving the engines of other manufacturers. Both quantitative and qualitative discrepancies were addressed; in that rates of safety related events could be derived for the baseline engine, and compared with predicted probabilities, and predicted failure sequences could be compared with those actually occurring in service. Since different engine families tend to experience different failure patterns, consideration of accidents and incidents pertaining to other manufacturer's engines was adjudged worthwhile. The engines considered in this study were the RB211, Tay, V2500, PW2000, PW4000, JT9D, CF6, CFM56 and ALF502 models, from entry into service of each model until December 1994. The results of the study should therefore be generally applicable to high bypass-ratio turbofans powering commercial transport aircraft in the western world. Military aircraft engines, including commercial models used for military transport aircraft, experience a very different operating and maintenance environment from those in the

commercial fleet, and were therefore excluded from the study. Data from engines designed and operated in CIS countries was also excluded, for similar reasons, and because of the difficulty in obtaining the relevant records.

The proposed changes in approach were documented, and then validated by applying the new approach to a second engine and comparing the resulting prediction with service experience[5].

## 1.5 Layout of thesis

In order to preserve the confidentiality of proprietary data supplied by the engine manufacturer, the thesis has been divided into two volumes, volume II containing the proprietary material comprising appendices G and H. This material is not publicly available. The thesis is generally laid out as follows:

Chapter 1 contains introductory material and the background leading to the execution of this study, together with summaries of the relevant airworthiness regulations and of the more important references published in relevant fields. A review of the literature and a discussion of the literature search strategy is given in Appendix A. Appendix B contains verbatim extracts from the relevant airworthiness regulations, for ease of reference.

Chapter 2 establishes the baseline of current propulsion system safety analysis, outlining basic assumptions used, analysis techniques, methods of quantifying failure rates. The behaviour of the RB211-22B is predicted, using these existing techniques, and using the original safety analysis produced for engine certification (details of this analysis are given in Volume II, Appendix G.) The latter portion of chapter 2 summarises the safety related service experience of the RB211-22B.

Chapter 3 presents definitions and basic assumptions underlying the safety analysis process. Chapter 4 discusses the service experience of safety related accidents and incidents throughout the commercial high bypass-ratio fleet; Appendix C gives details of the fleet service accident experience. Chapter 5 reviews the safety analysis techniques generally in use in the aerospace industry, with particular reference to their suitability for use in propulsion system safety analysis. Chapter 6 develops alternate means of assessing propulsion system safety, based on the service experience presented in chapter 4, and focusing on areas where standard techniques

---

[5]The service experience of the second engine had been deliberately excluded from the study up to this point, to avoid the inadvertent use of pre-knowledge when validating the new analysis.

(as presented in Chapter 5) are not well suited to the analysis. An alternate approach to the safety analysis is derived.

Chapter 7 applies the alternate analysis procedure to two other unrelated propulsion systems, and compares predicted failures and failure rates with those actually experienced in service.

Chapter 8 discusses the results of the research in detail.

Chapter 9 summarises the work, and includes suggestions for further work such as other applications.

Chapter 10 presents references.

# 2.0 A CURRENT SAFETY ANALYSIS APPROACH

## 2.1 Introduction

The intent of the baseline safety assessment was to establish, for a suitable engine model, the success of the current approach to safety analysis in predicting service experience. "Current approach" in this context is intended to comprise:

Ground rules of the assessment as performed for the baseline engine model

Safety analysis techniques used for the baseline model or in widespread use for other engine models

Engine components or systems addressed by the baseline engine assessment or usually addressed by assessments for more recent engine models

Types of Hazardous or Catastrophic failure effects specified by the regulations (see Appendix B) or normally addressed in current engine safety analyses.

Each of these aspects is discussed in more detail below.

## 2.2 Criteria for model selection

The following factors were considered crucial to selection of an appropriate engine model for the baseline assessment, and for validation of the 'improved' analysis procedure:

The initial assessment should be done for an engine with many millions of hours of service experience, including a substantial number of individual engines with high time. This would afford the opportunity for the fleet to experience a full spectrum of failures, including the wear-out of long-life parts. One of the first-generation high-bypass engines, designed in the late 1960's, would meet this criterion admirably. It was also considered advantageous to have access to the original safety analysis submitted for engine certification, to ensure that the baseline assessment (as an expanded version of the certification analysis) gave an equitable and realistic view of current analysis techniques.[6] The cooperation of Rolls-

---

[6]It is recognised that some advances may have been made in safety analyses since the late 1960's, when the first generation high-bypass ratio turbofans were designed and certified, and that it could be argued that using one of these analyses does not represent the current 'state-of-the-art'. In fact, the caliber of the safety analyses produced for certification

Royce led to the selection of the RB211-22 as the engine to be used for the baseline assessment.

The engine model used to validate the improved safety analysis technique should also have significant service experience, permitting a meaningful comparison between the predicted and actual failure rates. It was considered important that the selected engine allow scope for the use of techniques assessing derivative designs with respect to their parent models, such as would be afforded by a recent model of RB211. However, it is generally recognised that different engine families may experience different kinds of failures, and so assessing a safety analysis technique by applying it to the RB211 family alone might not produce results which are generally applicable. Given these constraints, it was decided to use another manufacturer's propulsion system for validation. Considerations of commercial sensitivity preclude specific identification of this propulsion system.

## 2.3 Ground rules

The following ground rules were used for the original RB211-22 failure analyses, and are still generally in use today:

Only mechanical failures of individual components are considered.

Multiple failures are only addressed insofar as they resulted directly from the original component failure under consideration.

The component under consideration is to the design standard, and the design standard has been shown to be satisfactory by development test or by analysis.

The engine is being operated according to the operating instructions and is within its design flight envelope.

Faulty maintenance and mishandling of the engine is not considered.

Failure rates are quantified by reference to previous service experience (e.g. Spey, Tyne and Conway engines, by a simple average of incidents divided by fleet hours) or to development testing. It is

---

varies considerably from one programme to the next, and there is little evidence to suggest a steady advance in either techniques or realism. A common approach is to use the previous programme's analysis as a template, and to deliver an edited version of the previous engine's safety analysis. It is entirely possible that more critical thought and technical effort went into the original, first-generation analysis than into some of the subsequent documents.

acknowledged that this may result in higher predicted failure rates than would be expected for a mature engine. More recent RR failure analyses also permit estimation of the probability range for a failure, based on engineering judgement.

The initial analysis performed for certification of the RB211 involved many significant omissions. The original analysis was largely confined to the turbomachinery of the engine, omitting the oil system, fuel system, flight deck instrumentation and other ancillary systems. The original analysis defined neither the functionality of each assembly or component, nor the criticality of the failure effects involved. A considerable degree of background knowledge and understanding was assumed on the behalf of the reader. The original analysis has therefore been expanded and clarified, and those systems not addressed (but provided by the engine manufacturer) have been analysed.

Where analyses have been performed specifically for this baseline study, consistency with these ground rules has been maintained as far as is feasible, and consistency with the approach of the original failure analysis has also been maintained as far as possible. Since the intent of this baseline assessment was to establish the strengths and weaknesses of the techniques in use, rather than to produce the most accurate possible safety assessment of the RB211-22, any information on failure modes which has been acquired since the RB211 went into service has not been introduced into the analysis; every attempt has been made to produce analyses using the same knowledge-base as was available at the time of RB211-22 certification.

## 2.4 Techniques

Safety analysis of commercial jet engines is currently executed by Failure Modes and Effects Analysis or by Fault Tree Analysis. Written enumeration of design precautions may also be used to provide explanatory material substantiating an analysis, or to explain why an analysis conducted for a previous engine model remains valid for the model under consideration.

Individual engine manufacturers have generally used the technique most appropriate to demonstration of compliance with the regulation they are attempting to satisfy.[7] Although the combined use of FMEAs and fault

---

[7]European manufacturers have demonstrated compliance with the JARs by preparing FMEAS or similar analyses, and US manufacturers have demonstrated compliance with the FARs by preparing fault trees or by verbal documentation addressing specific Hazardous events.

trees would significantly improve the resulting analysis[8], the limited resources available for safety analysis do not generally permit this apparent duplication of effort. The original RB211 analysis took the form of a FMEA, supported by individual reports addressing specific technical issues, and the baseline safety assessment therefore followed suit, using a format intended to direct attention to the failure progression and final effect on the engine, and to explicitly state both the estimated probability and severity of the effect[9].

## 2.5 Components and systems addressed

The RB211 powerplant components and systems may be divided into three categories; those which were actually addressed by the original analyses performed by Rolls-Royce (indicated by a report name or number in the list below), those which were not actually analysed at the time, but which one might expect to be analysed according to current practice (in which case analyses have been performed as part of this study, as indicated by the wording "Analysed for study" in the list below), and those which are not normally addressed by the engine or powerplant safety analysis (indicated by the wording "Not analysed" below). This last group is largely made up of systems and components which may be supplied either by engine or airframe manufacturer, depending on contractual negotiation, and not considered to be part of the "basic engine".
A list of the major systems and assemblies of the RB211-22B as installed in the L1011 aircraft is given below, indicating how each assembly or system was addressed.

---

[8]The insight into individual component failure modes and failure propagations gained by the FMEA can be used to enhance the technical content of the fault tree; while the fault tree permits multiple failures (particularly dormant or common mode failures) to be addressed much more easily than does the FMEA.

[9]In the interests of brevity, material appearing in the original Rolls-Royce analyses relating to minor failures, to the necessity for Unscheduled Removals and to the MSG-3 process has been omitted from the baseline safety assessment.

| Component/system | Reference |
|---|---|
| LP fan module | RB211-22B FMEA<br>RB211-22 Failure Analysis |
| IP compressor module | RB211-22B FMEA<br>RB211-22 Failure Analysis |
| LP fan casing module | RB211-22B FMEA<br>RB211-22 Failure Analysis |
| IP casing module | RB211-22B FMEA<br>RB211-22 Failure Analysis |
| HP compressor, combustor and HP turbine | RB211-22B FMEA<br>RB211-22 Failure Analysis |
| LP/IP turbine module | RB211-22B FMEA<br>RB211-22 Failure Analysis |
| Engine mounts | RB211-22B FMEA<br>RB211-22 Failure Analysis |
| External gearbox | RB211-22 Failure Analysis |
| Turbine sealing air system/<br>Internal cooling air system | RB211-22B report (TDR 5730)<br>(TDR 5977) |
| Throttle control system | RB211-22B report (ORR60020) |
| Engine oil system | Analysed for study |
| Engine fuel system | |
| Engine control | RB211-22B report (TDR7537) |
| Fuel supply | Analysed for study |
| Electrical Generator | Not analysed (airframe supply) |
| Starting/ignition system | Analysed for study |
| Bearing load control system | RB211-22B axial location report |
| Aircraft bleed air system | Analysed for study |

| | |
|---|---|
| Engine instrumentation | |
| TGT control/indication system | RB211-22B report (ADR 60027) |
| EPR system | RB211-22B FMEA (ORR60031) |
| Rotor speed | RB211 FMEA |
| Oil parameters | Analysed for study |
| Fuel parameters | Analysed for study |
| Vibration | Analysed for study |
| Ice protection | Analysed for study |
| Fire protection | Not analysed (airframe supply) |
| Thrust reverser | Not analysed (airframe supply) |
| Hydraulic system | Not analysed (airframe supply) |
| Inlet and cowlings | Not analysed |

## 2.6 Types Of Failure Effects Addressed

The following failure effects are specified by the airworthiness regulations as being Hazardous:

- Uncontained engine failure
- Engine Fire
- Engine Mount overload
- Inability to shut down the engine
- Uncommanded reverse thrust
- Toxic cabin bleed air

No single failure mode was identified in the analysis which could produce an inability to shut down the engine.
The thrust reverser was not included in this study, being supplied by the airframe manufacturer.
In addition to the failure types enumerated above, the original analysis also predicted explosive casing ruptures; this was considered appropriate for consideration in the safety analysis. In-flight shutdowns were also considered, as offering a good indication of the success of predicting numerical failure rates, although it is conceded that their role in engine and aircraft risk is yet to be established.

## 2.7 Baseline study results

Appendix G presents the RB211-22B baseline safety analysis, prepared from the failure analyses and technical analyses originally produced by Rolls-Royce and from analyses produced by the author for this study. Table 2.1 summarises the results of the baseline analysis, showing predicted rates of Hazardous failures by engine module together with predicted IFSD rates. Figures 2.1 to 2.6 present the same material graphically, together with the rates actually experienced in service, where appropriate. Since a very large number of possible Hazardous failures is involved, no attempt has been made to list them outside Appendix G, but the chief contributors to the predicted rates are noted.

## 2.8 RB211-22B Service Experience

The following sources of information were used to review the RB211-22B service experience:

- Rolls-Royce database of In-Flight Shutdowns and Rejected Take-offs for the first five years of RB211-22B service, 1973 to 1977, (Company Proprietary data supplied by RR for the purpose of this research).

- FAA rotor burst studies for US operators (35 - 44)

- FAA Service Difficulty Report system (45)

- CAA Significant Event report system (46)

### 2.8.1 IFSD Rates

The IFSD rate[10] of the RB211-22B was 990/million engine hours in the first year of entry into service, gradually reducing to 160/million engine hours in the fifth year after 3 million fleet hours as the design reached maturity. An estimate was made of the proportion of that rate attributable to each module or system; although the level of detail in the database did not permit isolation of the component precipitating the failure sequence (each event was annotated with the major symptom annunciating the problem to the flight crew, together with the assemblies which were found damaged), it was nevertheless possible to perform a first-order estimate of the IFSD rate attributable to a module or system, by allocating a fraction of every IFSD to each system mentioned as being failed. It was recognised that this approach would overestimate the rate for those modules or

---

[10]Failure rates are calculated annually unless otherwise stated.

systems prone to damage originating elsewhere in the engine, but this bias could be taken into account when examining the results.
This approach showed the IP compressor and the oil system to be the major contributors to the IFSD rate, accounting for approximately 40% of IFSDs between them. The HP compressor, HP turbine, fuel system and engine instrumentation also made very significant contributions to the rate; the combustor, which had been predicted to produce over half of all IFSDs, made a relatively minor contribution. The proportion of IFSDs attributable to each system or assembly, for the baseline assessment and for service experience, is shown in Figure 2.1.

TABLE 2.1 RB211-22 SAFETY ANALYSIS SUMMARY: FORECAST FAILURE RATES (PER MILLION ENGINE OPERATING HOURS)

| MODULE | IFSD | UNCON TAINED | FIRE | SEPARA TION | CABIN SMOKE | EXPL'SIVE CASING RUPTURE |
|---|---|---|---|---|---|---|
| FAN | 1114 | 2.2 | .005 | 0 | 0 | .04 |
| IP COMPRESSOR | 1790 | 39 | 20 | .002 | 32.5 | .008 |
| HP COMPRESSOR | 1333 | 40 | 211 | 0 | 0 | 0 |
| COMBUSTOR | 8016 | 1.9 | 392 | 0 | 0 | .12 |
| HP TURBINE | 86 | 0.3 | .2 | 0 | 0 | 0 |
| IP/LP TURBINE | 615 | 21 | 44 | .01 | 0 | .05 |
| MOUNTS | 0 | 0 | 0 | .2 | 0 | 0 |
| OIL SYSTEM | 406 | 0 | 25 | 0 | 0 | 0 |
| FUEL SYSTEM | 300 | 0 | 9.2 | 0 | 0 | 0 |
| STARTING SYSTEM | 1.5 | 0 | 0.1 | 0 | 0 | 0 |
| INSTRUMENTA TION | 116 | 0 | | 0 | 0 | 0 |
| ICE PROTECTION | 1.3 | 0 | 0 | 0 | 0 | 0 |
| BLEED DUCTS | .04 | 0 | 0 | 0 | 0 | 0 |
| **TOTAL** | **13777** | **104** | **701** | **0.2** | **32.5** | **0.22** |
| **MEASURED MATURE FAILURE RATE (@ 3 E 6 HOURS)** | **160** | **0.1** | **1.5** | **0.3** | **3** | **-** |

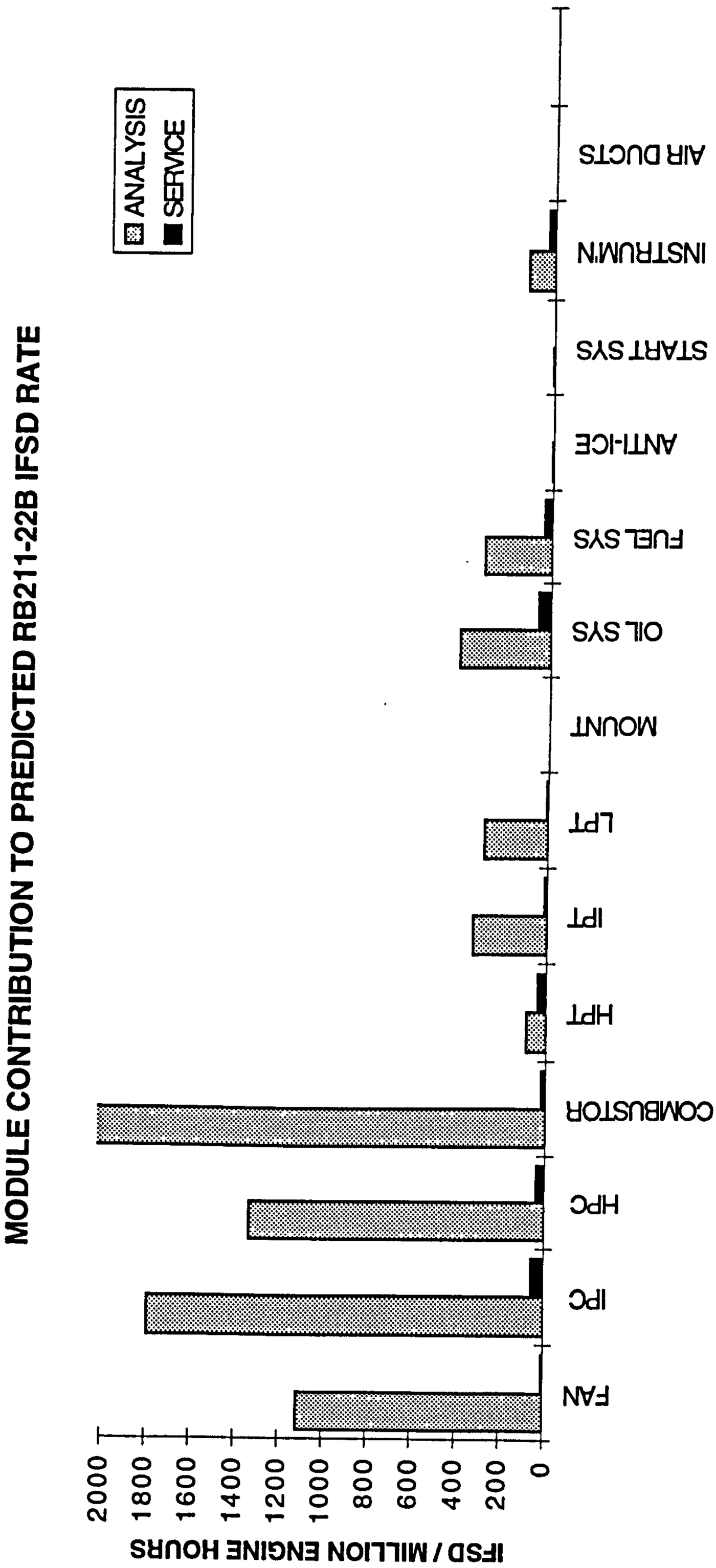

ANALYSIS
SERVICE
MODULE CONTRIBUTION TO PREDICTED RB211-22B IFSD RATE
AIR DUCTS
INSTRUMTN
START SYS
ANTI-ICE
FUEL SYS
OIL SYS
MOUNT
LPT
IPT
HPT
COMBUSTOR
HPC
IPC
FAN
2000
1800
1600
1400
1200
1000
800
600
400
200
0
IFSD / MILLION ENGINE HOURS

FIGURE 2.1

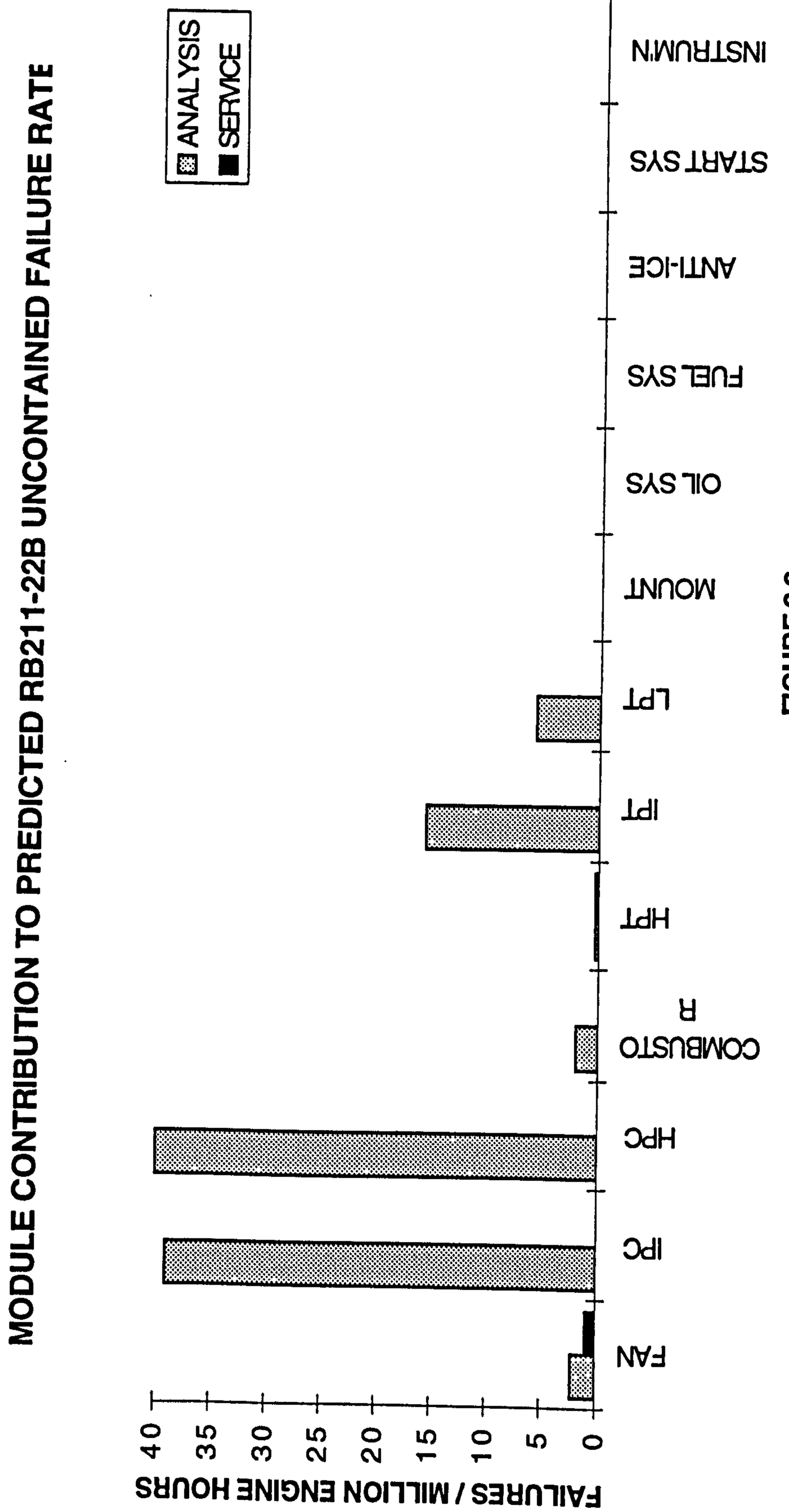

MODULE CONTRIBUTION TO PREDICTED RB211-22B UNCONTAINED FAILURE RATE
ANALYSIS
SERVICE
FAILURES / MILLION ENGINE HOURS
0
5
10
15
20
25
30
35
40
FAN
IPC
HPC
COMBUSTOR
HPT
IPT
LPT
MOUNT
OIL SYS
FUEL SYS
ANTI-ICE
INSTRUMTN
START SYS
AIR DUCTS

FIGURE 2.2

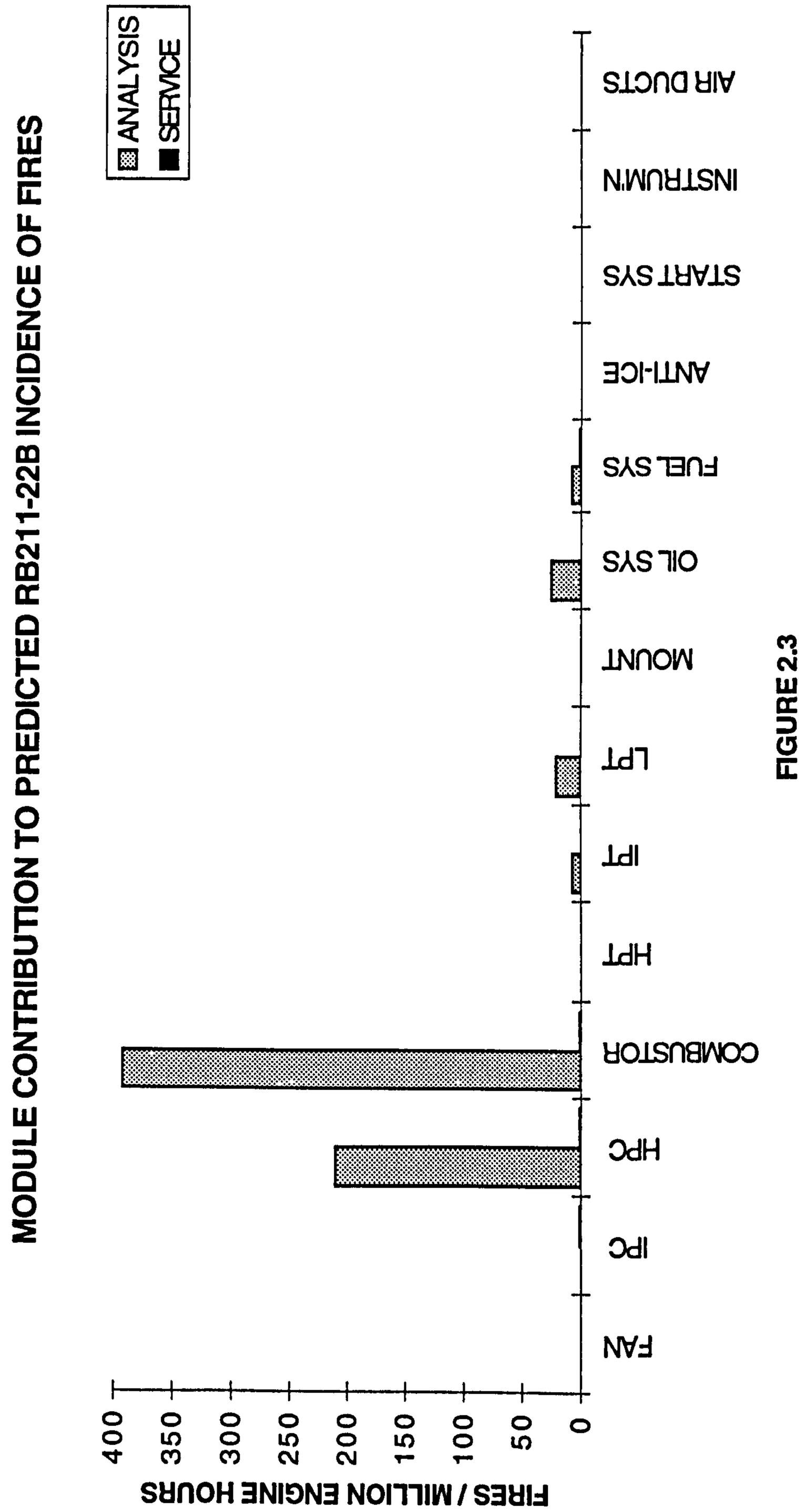

MODULE CONTRIBUTION TO PREDICTED RB211-22B INCIDENCE OF FIRES
ANALYSIS
SERVICE
FIRES / MILLION ENGINE HOURS
400
350
300
250
200
150
100
50
0
FAN
IPC
HPC
COMBUSTOR
HPT
IPT
LPT
MOUNT
OIL SYS
FUEL SYS
ANTI-ICE
START SYS
INSTRUMTN
AIR DUCTS

FIGURE 2.3

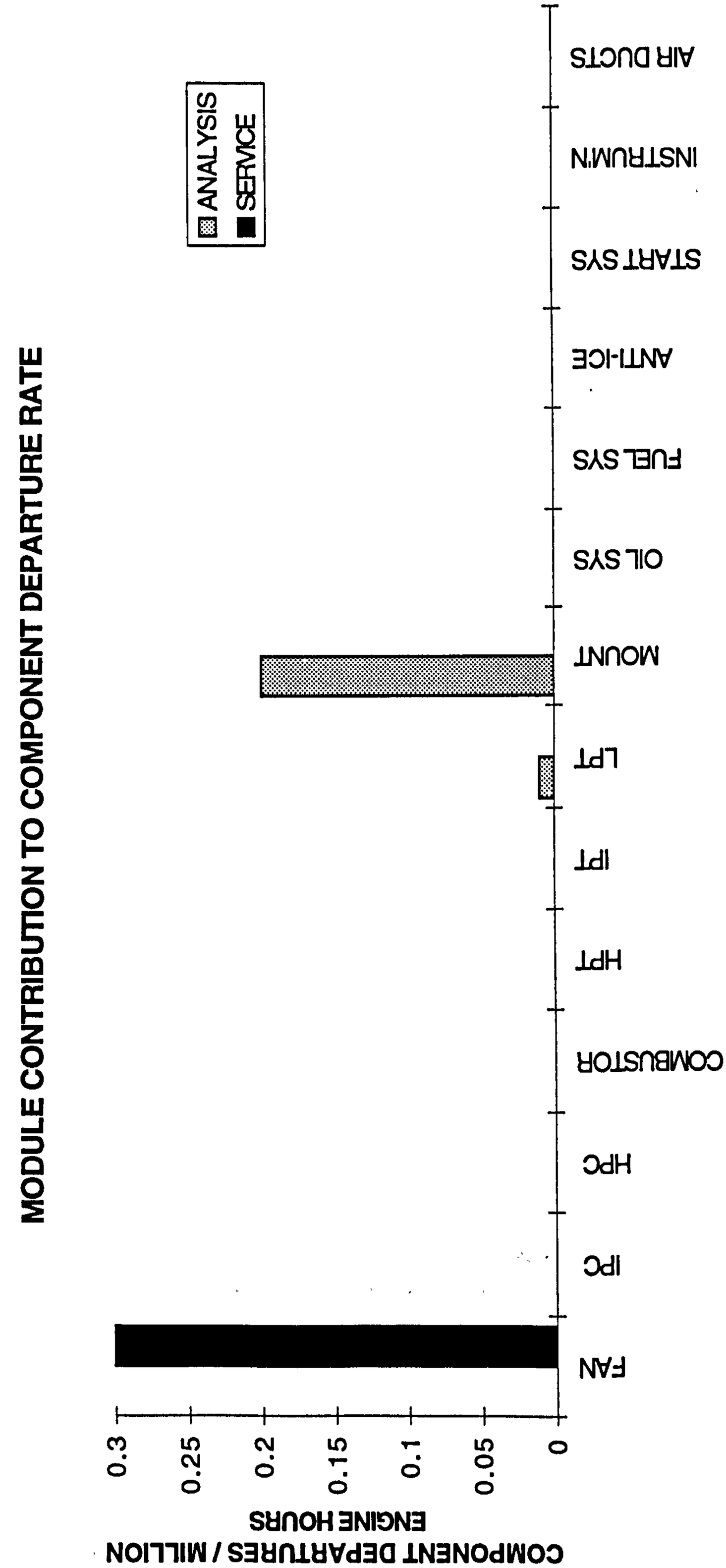

ANALYSIS
SERVICE
MODULE CONTRIBUTION TO COMPONENT DEPARTURE RATE
COMPONENT DEPARTURES / MILLION ENGINE HOURS
0.3
0.25
0.2
0.15
0.1
0.05
0
FAN
IPC
HPC
COMBUSTOR
HPT
IPT
LPT
MOUNT
OIL SYS
FUEL SYS
ANTI-ICE
START SYS
INSTRUMTN
AIR DUCTS

FIGURE 2.4

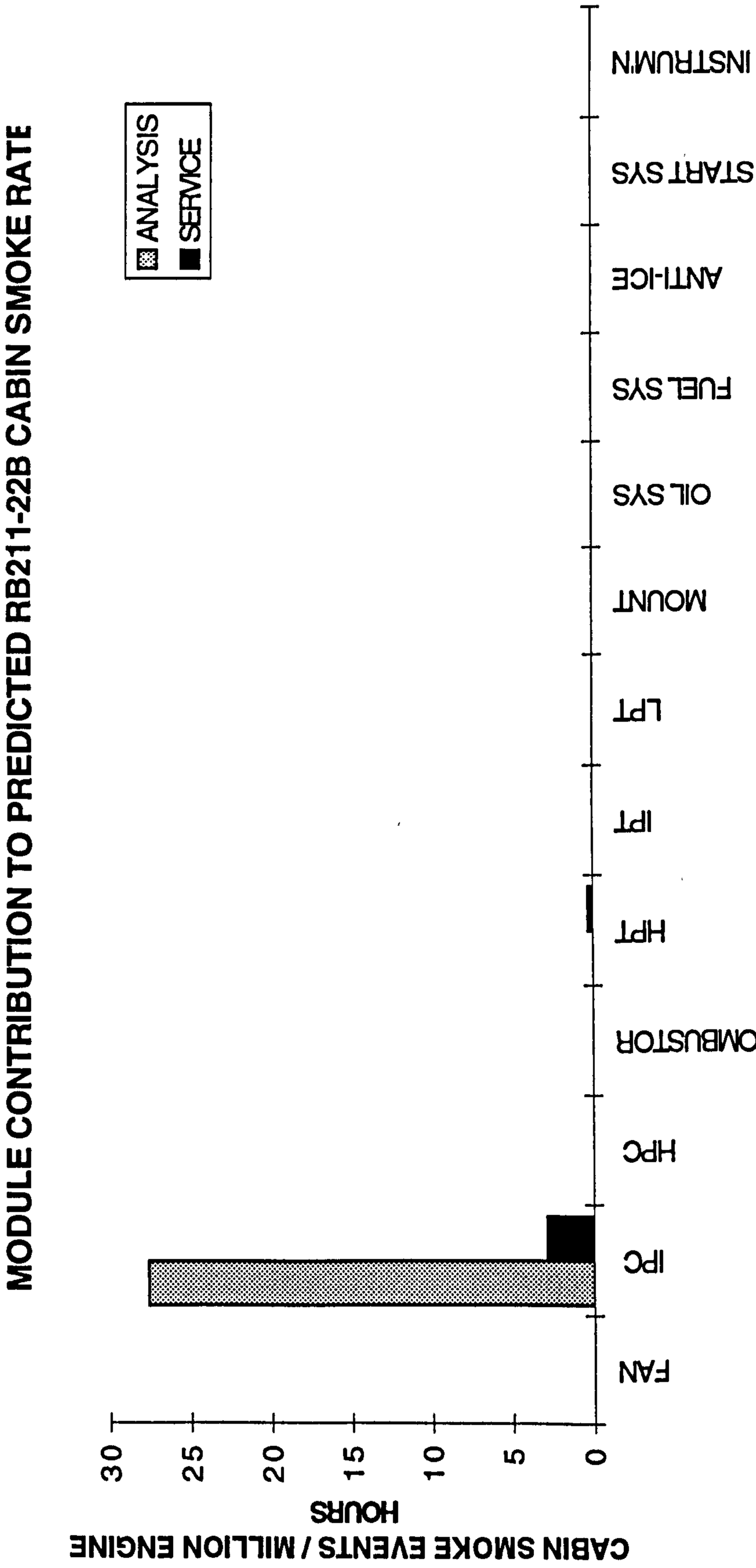

MODULE CONTRIBUTION TO PREDICTED RB211-22B CABIN SMOKE RATE
ANALYSIS
SERVICE
CABIN SMOKE EVENTS / MILLION ENGINE HOURS
0
5
10
15
20
25
30
FAN
IPC
HPC
COMBUSTOR
HPT
IPT
LPT
MOUNT
OIL SYS
FUEL SYS
ANTI-ICE
START SYS
INSTRUMTN

FIGURE 2.5

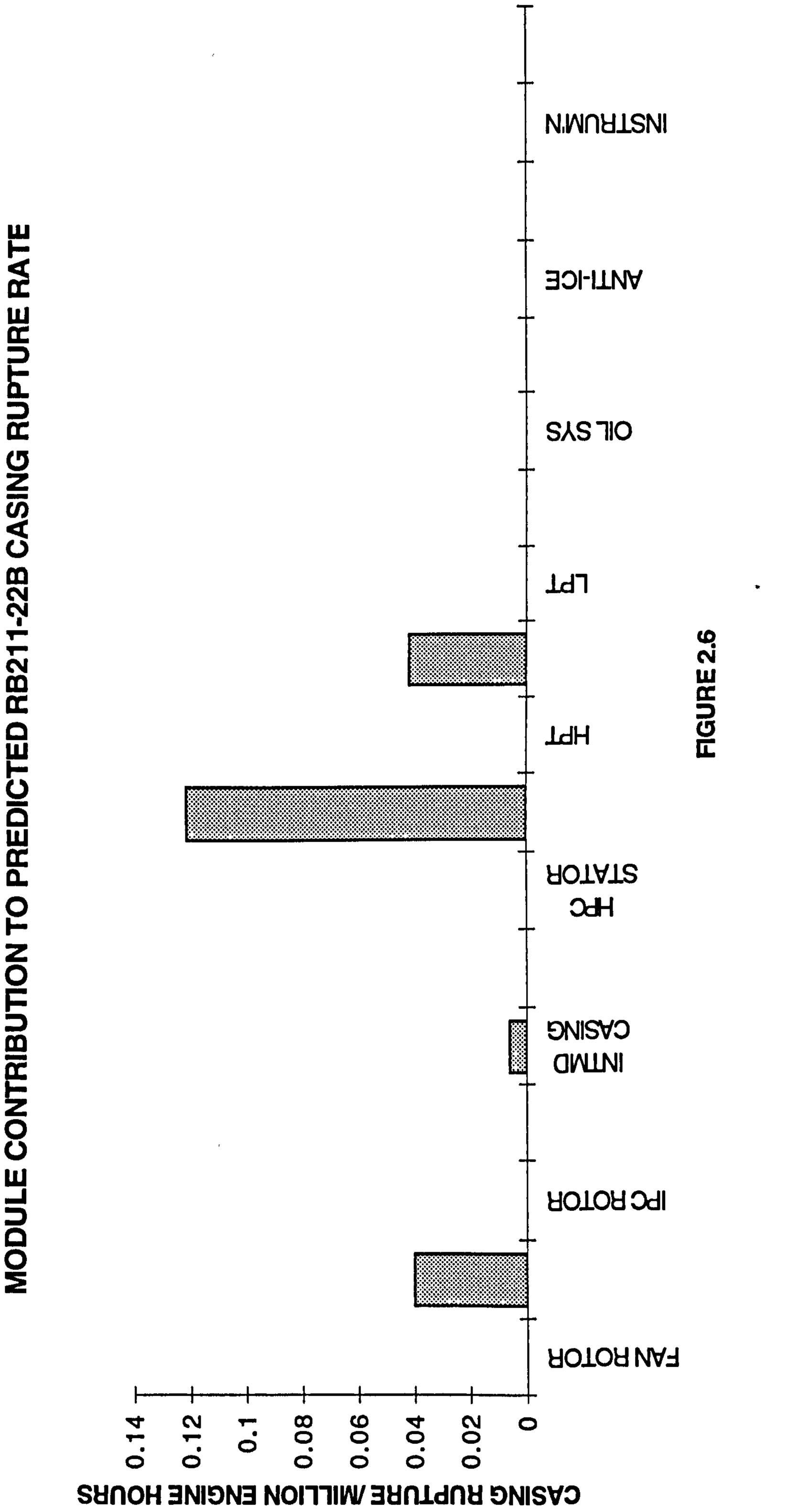

CASING RUPTURE /MILLION ENGINE HOURS
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
FAN ROTOR
IPC ROTOR
HPC STATOR
INTMD CASING
HPT
LPT
OIL SYS
ANTI-ICE
INSTRUMTN
MODULE CONTRIBUTION TO PREDICTED RB211-22B CASING RUPTURE RATE

FIGURE 2.6

### 2.8.2 Uncontained failure rates

Only four events could positively be identified as resulting in uncontained failures in the first five years of service, giving an uncontained failure rate of 1.2/million engine hours initially. The mature uncontained engine failure rate was 0.1/million engine hours over the time period 1981 to 1989 (US operators only, 35 - 44). The rate predicted by the baseline assessment was approximately 100 to 1000 times higher than that experienced in service.
The fan assembly and the HPT disc produced the uncontained failures in the first five years, exhibiting a much higher uncontained failure rate than predicted for the fan and a similar rate to that predicted for the HP turbine; the baseline assessment had predicted the majority of uncontained failures to originate in the IP and HP compressors.

### 2.8.3 Fires

The first five years of RB211 service included 29 events where there was a fire warning. However, the majority of these were due to faults in the fire detection system or to borescope plugs coming loose from engine casings (maintenance error is suspected) permitting hot air to leak out into the space between engine casing and nacelle. Only one instance was found of a fuel leak resulting in a nacelle fire; the other four events accompanied major flowpath damage. The incidence of fires (including tailpipe fires) was therefore calculated as 1.5 /million engine hours, and the baseline safety assessment prediction was approximately 400 times too high. The baseline assessment predicted that two-thirds of the fires would be caused by failures in the combustion module; in fact, only two of the five events mentioned combustor damage.
This low rate was verified by a review of the fires recorded by the FAA and CAA from 1986 to 1990, which also gave a rate of 1.5/million hours (three of the nine events being caused by failures in the combustion module).

### 2.8.4 Separation of major components

There was one recorded incident involving separation of major components from the airframe in the first five years of RB211 service. A failure of the LP shaft allowed the fan to proceed forward and depart the engine. This failure rate of 0.3/million hours was close to that predicted, although the module and failure mechanism were not those forecast.

### 2.8.5 Smoke in cabin bleed air

There were not enough incidents involving smoke in cabin bleed air to perform a meaningful trend analysis, but when averaged over the 5 year interval for which RR data was available, the failure rate was 3 /million engine hours. Almost all of these events were attributable to the IP compressor/intermediate casing, as predicted by the baseline assessment, although the actual rates predicted were too high by a factor of 10.

### 2.8.6 Explosive casing rupture

There were no instances of explosive casing rupture in the first five years of RB211 service experience ; the failure rate was therefore less than 0.3/million hours. Based on the first five years, it is possible that the baseline assessment predicted rate of 0.2/million hours was representative (although it is the author's understanding that no RB211 has ever experienced this failure mode in service).

## 2.9 Accident and serious incident review

The RB211-22B was involved in three propulsion-related accidents during the first five years of service, each involving an uncontained failure. In each case there were no injuries or fatalities, although there was substantial aircraft damage. Chapter 4 gives details of these accidents.

## 2.10 Conclusions regarding current approach

The current safety analysis approach, as used to forecast the behaviour of the RB211-22B, is demonstrated to produce unrepresentative results. Many predicted failure rates were too high by orders of magnitude, and the analysis was unsuccessful in identifying which components or assemblies pose the greatest risk of failure. The use of this analysis to draw conclusions about the safety of the engine, or to make technical decisions on component design, would be very misleading.

THIS PAGE INTENTIONALLY BLANK

# 3.0 BASIC ASSUMPTIONS AND DEFINITIONS FOR THE SAFETY ANALYSIS

## 3.1 Definitions

Accident — Event resulting in fatalities, serious injuries or in substantial damage to the airplane

Failure — Engine response other than that commanded by the flight crew, or component not performing the intended function

Hazard ratio — Measure of the likelihood of a given type of failure resulting in an accident, calculated by dividing the number of instances of the initiating failure by the number of resulting accidents (or the respective rates).

Propulsion-related event — An accident or incident in which the behaviour of the propulsion system was a major factor in leading to the event occurrence. This includes propulsion system malfunction sufficient to cause an incident of itself, benign propulsion system malfunction to which the crew responded inappropriately, and incorrect commands/ expectations of the crew which lead to an accident with normally operating propulsion systems.

Severity factor. — Factor relating the likelihood of a given failure to the flight phase. For instance, if the cowling departure rate is 5 times as high during climb as it is when averaged over the whole flight, the severity factor would be 5 for climb.

## 3.2 Intent of Analysis

There has been considerable variation in interpretation of the intent of performing a safety analysis. Some have considered it to be a design tool for comparing one design with another, without regard to the absolute values of predicted failure rates. Others have considered it to be a means of ensuring that a design meets an absolute standard of safety, such as 1E-9/hour for any individual cause of an accident. The analysis has then been performed on an 'ideal' system with standard material properties, with components manufactured to drawing and assuming correct assembly, inspection, maintenance and operation. This approach is consistent with that of other certification activities, and may be considered the 'design capability' of the system (Smith, (54)). A third approach, which has not been generally used so far, is to attempt a realistic prediction of the accident rate which will be experienced in a 'real-world' operational environment.

A realistic assessment offers an opportunity to tailor the design to reduce the accident rate, while limiting the resources devoted to prevention of purely theoretical risks. It is recommended that such a realistic approach be used using the incidence of manufacturing defects, maintenance-induced damage, unsuccessful maintenance, improper procedures by the flight crew and so forth that has actually been observed in a similar environment.

Since the intent of the analysis is to predict actual accident rates, average failure rates should be used throughout the analysis, unless there is some good technical reason to do otherwise. Component or assembly failure rates should be calculated at mean values and an average engine installation should be assessed for an average flight. Using worst-case assumptions throughout (minimum properties for materials, with 90% confidence failure rates, on an extreme day at a corner of the flight envelope, dispatching under the MMEL) will not give a realistic forecast for accident rates throughout the fleet. An exception may be made where appropriate: for instance, if the likelihood of a failure and the severity of the effect are both strongly dependent on flight phase, average values would be inappropriate.

Analyses have historically been based on "mature" failure rates, after some indeterminate but lengthy interval after introduction into service. This is reasonable for predicting accident rates over the life of the fleet, but consideration should be given to the rates at introduction into service.

Individual component failure rates may be derived from published data if no better information is available, although the published failure rates on a given component may vary by orders of magnitude for mechanical components (Appendix A). Alternatively, if the environment and duty of the component is known in sufficient detail, a failure rate can be derived from a 'Physics of Reliability' approach (55). It is recommended that service experience with a similar application and environment be used to derive component failure rates where necessary (see below). It is also recommended that aggregate failure rates for groups of components (e.g. assemblies or modules) be used wherever possible , since this will eliminate some of the variation in failure rates occasioned by details of the component manufacture or environment not known at the time of conducting the analysis. Chapter 6 discusses the prediction of failure rates in more detail.

## 3.3 Scope Of Analysis

Previous analyses have been confined to the engine, EBU and flight deck engine instrumentation. Other systems which are not specifically devoted to propulsion have made significant contributions to the propulsion-related accident rate whilst interfacing with the propulsion system. It is therefore recommended that the propulsion system safety analysis give consideration to the autothrottle system, the fuel delivery system and the flight crew, so far as they enable propulsion system operation.

THIS PAGE INTENTIONALLY BLANK

# 4.0 GENERAL REVIEW OF ACCIDENTS/ SERIOUS INCIDENTS

## 4.1 Statistical Review

It was considered essential to this research to understand how propulsion failures have led to accidents in the past, and the likelihood of a given failure resulting in an accident, with due regard to the circumstances of the event. The history of the high bypass commercial transport fleet was reviewed, and 82 accidents were identified as being propulsion-related. A summary of each accident is given in Appendix C.

Similar studies of propulsion-related accidents have been presented by the CAAM committee (18) and Sallee (47). The former was a simple tabulation of events, sanitised to de-identify airframes and engines. Sallee explored the relative safety of two, three and four engines aircraft in the context of comparing the incremental risk associated with ETOPS (all-engine power loss for unrelated causes) to existing propulsion system risks. Table 4.1 summarises the major similarities and differences between this study and references 18 and 47.

| STUDY | KNIFE | CAAM (18) | SALLEE (47) |
|---|---|---|---|
| SCOPE | High bypass ratio fleet 1970 - 1994 | Turbofan and turboprop fleet 1982 - 1991 | Transport category jet fleet 1959 - 1989 |
| # ACCIDENTS | 82 | 66 category 3 or 4 events in high bypass fleet | 22 high bypass accidents |
| ACCIDENT TREND | Downward with time | Silent | Silent |
| AIRFRAME EFFECTS | Recent designs have lower rates. 3 or 4 engine have higher rates than twins | Silent | Rate proportional to number of engines |
| FLIGHT PHASE EFFECTS | Assessed for each accident cause | Silent | Assessed for accidents as a whole |
| CAUSAL FACTORS | Uncontained 26%<br>Propulsion failure + crew error 18%<br>Thrust control 10%<br>Fire 11%<br>Engine separation 9% | For level 3+4 events. High bypass fleet;<br>Uncontained 20%<br>Propulsion failure + crew error 11%<br>Common cause 38%<br>Reverser 9% | Uncontained 27%<br>Propulsion failure + crew error 41%<br>Crew error 18%<br>Other 9% |
| HAZARD RATIOS | Calculated for most causes | Similar parameter calculated for some causes | Calculated for some causes |
| DISCUSSION OF RESULTS | Extensive | None | Very extensive |

Table 4.1 Comparison With Previous Studies Of Propulsion-Related Accidents

Note: Level 3 and 4 events are defined in detail in (18). They include both accidents and events which are considered to have hazarded the airplane.

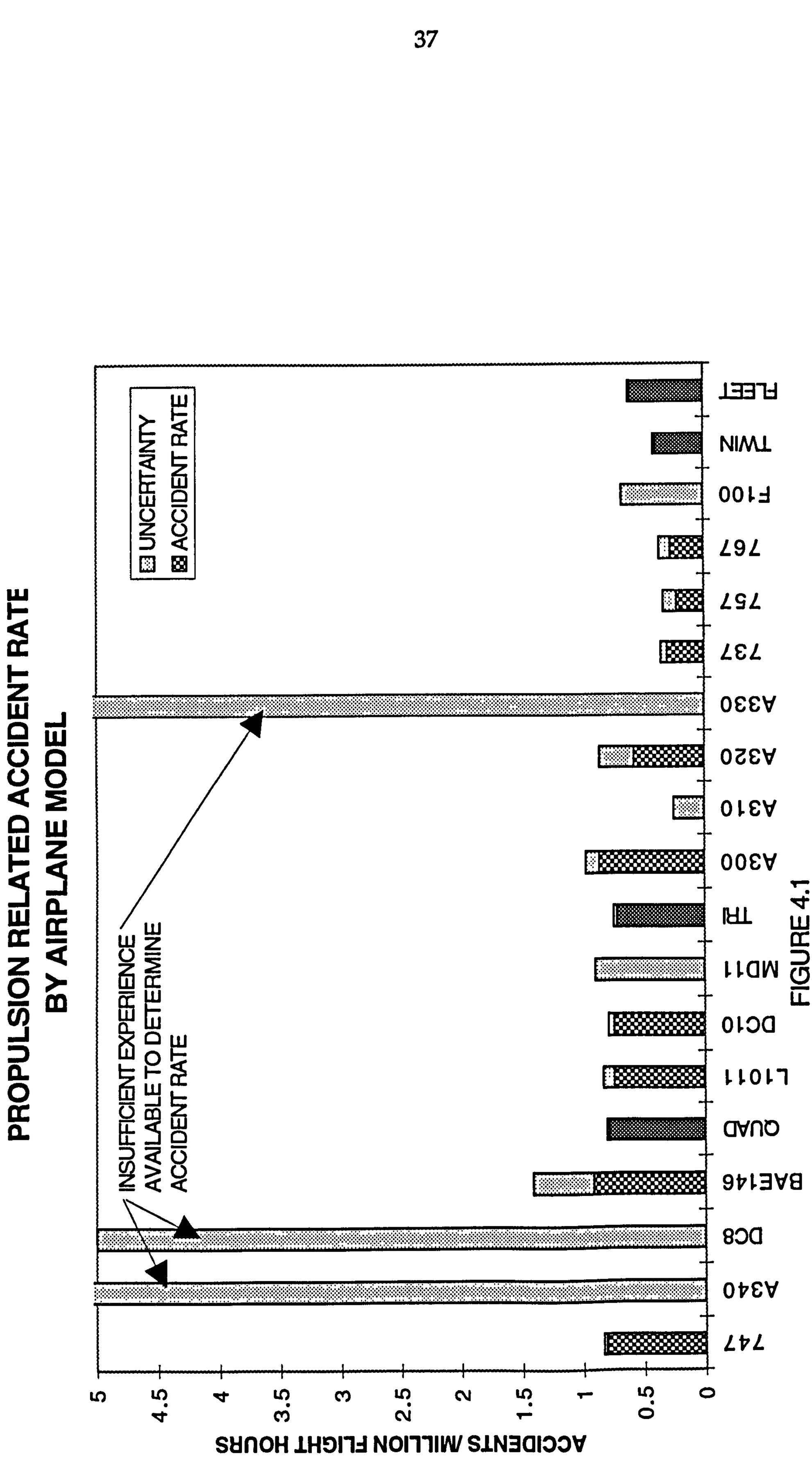

PROPULSION RELATED ACCIDENT RATE
BY AIRPLANE MODEL
UNCERTAINTY
ACCIDENT RATE
INSUFFICIENT EXPERIENCE AVAILABLE TO DETERMINE ACCIDENT RATE
FLEET
TWIN
F100
767
757
737
A330
A320
A310
A300
ΤΡ
MD11
DC10
L1011
QUAD
BAE146
DC8
A340
747
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
ACCIDENTS /MILLION FLIGHT HOURS

FIGURE 4.1

Figure 4.1 shows the distribution of accidents by airframe. It can be seen that the airplanes with more engines have a higher propulsion-related accident rate, although the increase is not directly proportional to the number of engines, as has been implied in the past (Sallee, 47); three-engined airplanes appear to have a disproportionately higher rate of propulsion related accidents .... the rate is virtually the same as for four-engined aircraft[11]. Since the number of accidents is limited, random variation plays a significant effect in some categories of accidents; the likely magnitude of this effect is indicated by quoting an error equivalent to having one more accident in the category of interest.

The overall propulsion related accident rate is 6.0 E-7/airplane hour[12].

The modernity of the aircraft design appears to have a significant influence upon the propulsion-related accident rate. If the BAe146 is excluded (as the first high bypass commercial transport produced by that manufacturer), designs from the 1980s generally have lower propulsion-related accident rates than those from the 1970s. [13] This cannot be attributed to the older airplanes wearing out and having more accidents, because the older models actually had worse accident rates on entry into service than they do currently; it seems likely that improved analytical and manufacturing techniques and consideration of lessons learned in the past are responsible for the newer aircraft models experiencing a lower propulsion-related accident rate.
The effects of contributing factors to accidents will be considered below.

It can be seen from Figure 4.2 that there has been a steady reduction in the propulsion related accident rate in the high bypass fleet from the early 1970s to the current date. This is in contrast to the constant accident rate observed throughout the 1980s for all accidents (propulsion and otherwise) in the commercial jet fleet (Boeing Statistical Summary (48). This steady improvement may be partially ascribed to the prompt introduction of improvements and fixes for problems after the engines have gone into service. Trending the accident rate for older aircraft types alone (DC10, L1011, 747 except 747-400, and A300) confirms this hypothesis. Figure 4.3 shows that the downward trend holds for each of the chief causes of propulsion-related accidents as well as for the overall statistics.

---

11 This is not the case in the low bypass fleet, according to Sallee's studies.

12 Accident rates have been measured on a flight hour basis and also on a flight basis; there is no general consensus on a preferred convention. Calculation per flight hour was more convenient in this study.

13 Definition of new types is approximately in accordance with the usage of Boeing's Commercial Accident Summary; early wide bodies are the 747, DC10, L1011 and A300; the remainder of the high bypass ratio fleet are considered new types.

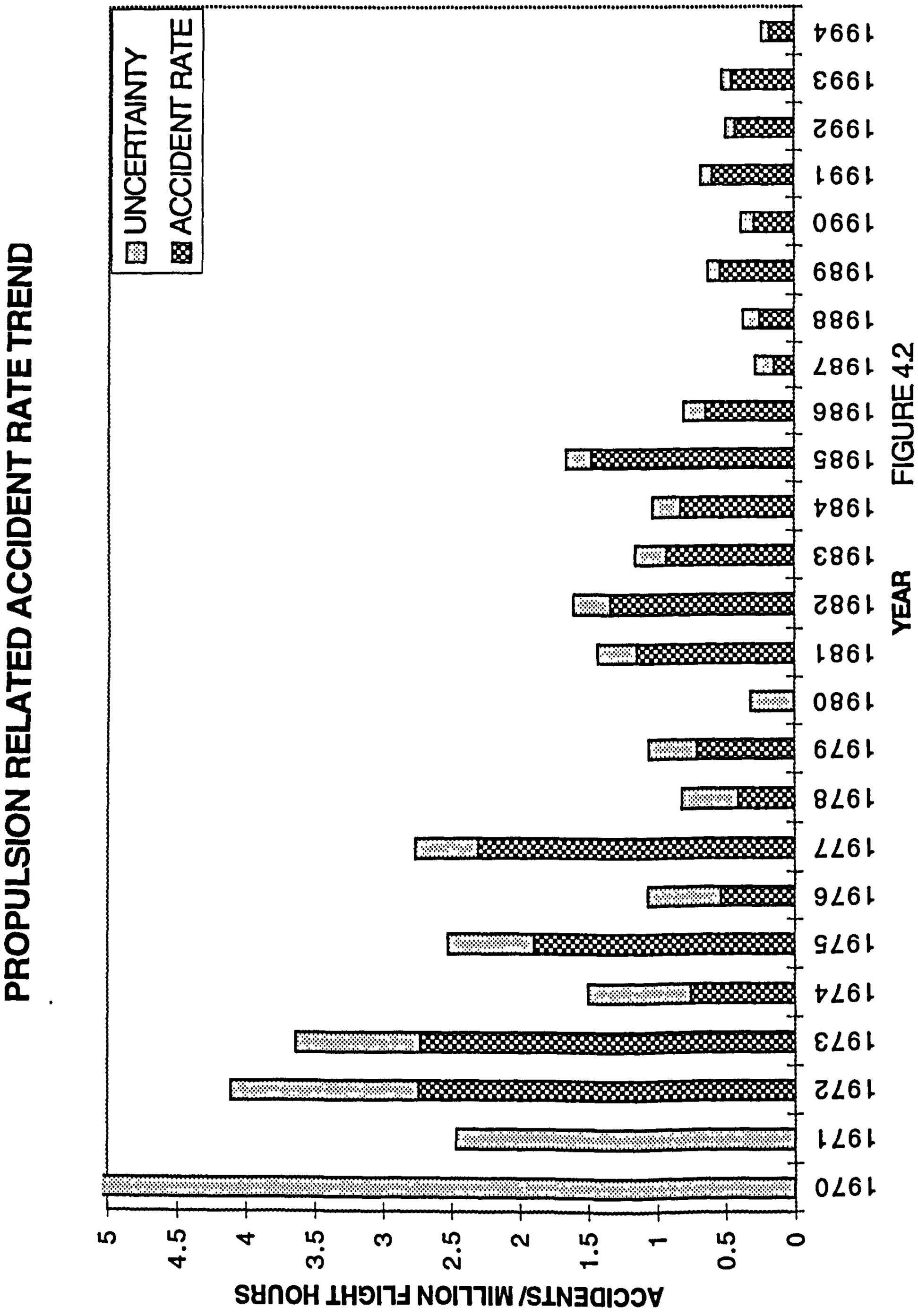

PROPULSION RELATED ACCIDENT RATE TREND
UNCERTAINTY
ACCIDENT RATE
1994
1993
1992
1991
1990
1989
1988
1987
1986
1985
1984
1983
1982
1981
1980
1979
1978
1977
1976
1975
1974
1973
1972
1971
1970
YEAR
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
ACCIDENTS/ MILLION FLIGHT HOURS

FIGURE 4.2

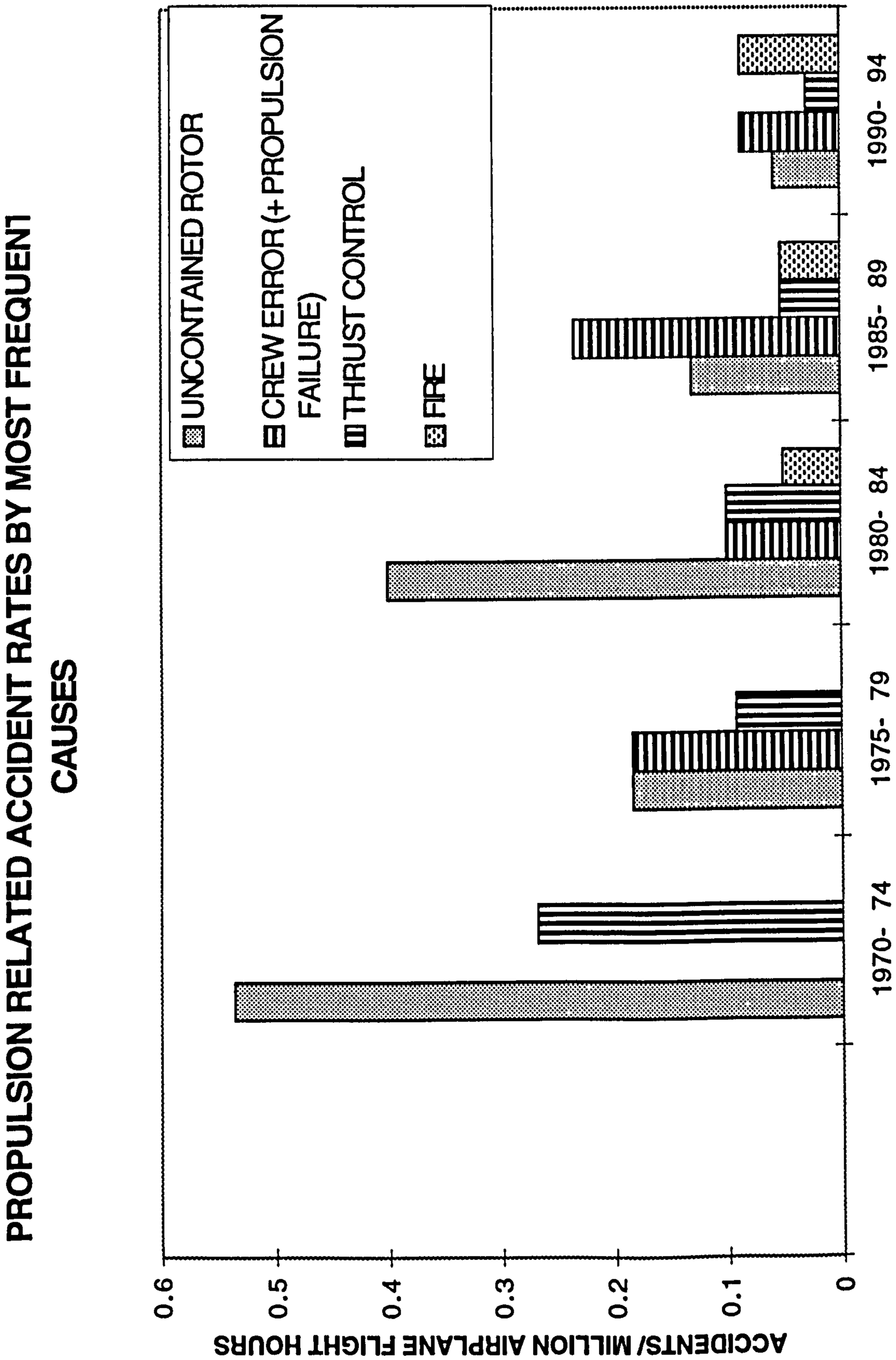

PROPULSION RELATED ACCIDENT RATES BY MOST FREQUENT CAUSES
UNCONTAINED ROTOR
CREW ERROR (+ PROPULSION FAILURE)
THRUST CONTROL
FIRE
1970- 74
1975- 79
1980- 84
1985- 89
1990- 94
5 YEAR TIME PERIOD
ACCIDENTS/ MILLION AIRPLANE FLIGHT HOURS
0.6
0.5
0.4
0.3
0.2
0.1
0

FIGURE 4.3

It has been recognised that most accidents result from a series of failures and/or circumstances, some of which may have occurred in the past and may have led to incidents rather than accidents. It is often difficult to evaluate the gravity of an incident before an accident of a similar nature occurs (Carnino et al., (49)). The study of accident precursors may provide a useful tool in the probabilistic assessment of safety in cases where the accidents themselves are rare events (as in propulsion-related aircraft accidents).

A database of 870 serious incidents was also compiled, based largely upon the records of the FAA, CAA and NTSB. The incident rates generated from this database are undoubtedly lower than reality since the database does not include many events occurring outside North America and Europe. In the interest of brevity, this database is not included in the appendices.

The accidents were categorised by causal factors as follows:
Each event was assigned a primary causal factor. These factors should be considered the proximate cause of the event, in the opinion of the author, rather than the root cause; in many cases the behaviour of the propulsion system was a minor contributing factor, but that aspect of the event has nevertheless been cited as the primary causal factor from the propulsion system perspective. In the same way, the interpretation of "propulsion related accident" has been expanded from previous studies (Sallee, 47) to include those where the propulsion system behaved normally but the expectation of the flight crew was not met.
Example: In ACC55, after a low speed, low altitude fly-by during an airshow, the flight crew increased engine power to clear trees. The engines did not spool up before the airplane hit the trees. There is no suggestion of engine malfunction in this instance, but the crew evidently expected a faster response than they received from the engines. The "reason" for the accident was determined by the French courts to be crew error.

Causal factors have been assigned according to the following convention [14](generally consistent with the CAAM study (18)):

Crew error Improper command given to fully operational engines by flight crew

Propulsion system + crew error Benign failure of an engine or instrumentation which would not itself lead to an accident if the

---

[14]In cases where several of the above causal factors were involved, the initiating factor is the one assigned. Example; uncontained failure causes undercowl fire and rejected takeoff above V1, assigned to "Uncontained" group.

appropriate AFM procedure were followed, but which provided the opportunity for the crew to respond incorrectly. Example: Rejected takeoff above V1.

Uncontained failure Release of debris at high speed through the engine casing or nacelle

Case rupture Sudden rupture of high pressure casing releasing core air.

Fire Ignition of flammable material within the nacelle, or within the engine oil system. Flowpath fires for which casings were not designed (HP compressor titanium fires, but not tailpipe fires resulting from hot starts etc.) are included.

Engine separation Inflight separation of an engine or major engine module.

Cowl separation Inflight separation of nacelle components such as cowls, tailcones, spinners etc.

Reverser Event resulting from thrust reverser malfunction

Multi-engine Event in which multiple engines cannot deliver sufficient thrust (or other required power) for safe flight and landing

Tailpipe fire Fire confined to the turbine flowpath resulting from leaked/mis-scheduled fuel.

Thrust control Event resulting from thrust so different from that intended by the pilot that aircraft control is jeopardised (although technically possible). Some accidents resulted from this type of event which could not be otherwise categorised.

The distribution of accidents (tabulated in Appendix C) by causal factor was as follows:

| CAUSE | # ACCIDENTS | % OF ACCIDENTS |
|---|---|---|
| Uncontained | 21 | 26 |
| Propulsion + crew | 15 | 18 |
| Fire | 9 | 11 |
| Thrust control | 8 | 10 |
| Engine Separation | 7 | 9 |
| Cowl separation | 5 | 6 |
| Multi-engine | 5 | 6 |
| Crew | 4 | 5 |
| Case rupture | 3 | 4 |
| Tailpipe fire | 2 | 2 |
| Reverser | 2 | 2 |
| Other | 1 | 1 |

Although casing burnthrough, inability to shut down and toxic cabin bleed air are defined as Hazardous by regulatory material, they have never resulted in an accident in the high-bypass commercial transport fleet.

## 4.2 Discussion of Individual Failure Effects

### 4.2.1 Uncontained Engine Burst

Current turbofans are designed with the intention that the disk or drum forming the structural attachment for compressor or turbine blades should never fail. In the event of a disk failure, the engine casings and nacelle are likely to be holed by the departing disk fragments, and there is a significant risk that high-energy fragments impacting the airframe may cause unacceptable system or structural damage. The high energy fragments may include released blade fragments exiting the hole in the engine casing made by the disk or disk piece. Blade failures may also result in debris fragments impacting the airframe, although the energy and number of such fragments tends to be somewhat less than in the case of a disk failure and the resulting hazard to the airplane is much less.

Aircraft accident history includes many accidents directly attributable to uncontained engine burst, and both the FARs and JARs include the requirement to consider uncontained engine failure during safety analysis. Advisory material is currently being produced to improve the ground rules for such safety analysis.

Not every uncontained failure results in an accident, even where debris produces similar airplane damage; the event progressions from uncontained engine failure to accident are presented in appendix E to focus attention on specific opportunities for accident prevention.

Usage of the term 'uncontained failure" is not universally consistent, in that the regulations pertaining to engine certification limit it to incidents in which a fragment of rotating machinery has made a hole in the engine casing, and exited through that hole. No consideration is given to the containment capability of the surrounding cowlings, and therefore a fragment emerging through a hole in the casing and falling to rest in the cowling is considered an uncontained failure by this definition, although its energy is relatively low. On the other hand, high-energy pieces of fan-blade tip released forward of the plane of the fan, to burst through the inner and outer walls of the inlet, are not considered uncontained failures because they have not penetrated an engine casing. Another school of thought places the boundary for containment at the outer envelope of the nacelle, leading to a reversal in classification for the two instances cited above. For the purposes of this study, the two usages have been combined, to include all failures in which a rotor fragment exits an engine casing or the outer envelope of the nacelle.

The majority of uncontained failures were found to occur in takeoff, which involves the highest rotor speeds and high turbomachinery

stresses. Approximately 6% of the uncontained failures resulted in accidents, generally involving significant damage to wing and fuselage skin by uncontained debris. A detailed statistical study of these events is found in Appendix C.

### 4.2.2 Single-Engine Failure Likely To Be Accompanied By Pilot Error

Since all transport category aircraft are capable of safe flight and landing with one engine shut down, and since crew training includes engine shutdown and subsequent flight, it is not initially obvious that 'single engine failure accompanied by crew error' should be designated as a safety-related event. Advisory material for airworthiness regulations has even specifically stated that a failure with no effect other than engine shutdown should be considered Minor, yet reference to the accident record and to the conclusions of CAAM shows that failure of an engine is a significant factor in precipitating pilot error, and that such a sequence of events is a major contributor to propulsion-related accidents. (This issue was recently recognised by the FAA who requested the formation of an industry working group under the auspices of the AIA, to address crew error associated with propulsion failure.) Before beginning an analysis to establish whether a given design will be subject to this type of failure, it is essential to establish which kinds of engine failure are most liable to result in hazardous pilot error. Detailed analysis of this error type is presented in Chapter 6.

The majority of these accidents took place in takeoff or landing.

### 4.2.3 Engine Fire

The danger of an uncontrolled engine fire is intuitively obvious, since many engines are located directly beneath a wing full of aviation fuel. Engine fire is one of the top five contributors to propulsion-related accidents; study of aircraft accident history produces many instances in which engine fire was at least a contributing factor to an accident, and airworthiness regulations explicitly require the possibility of engine fire to be addressed

It is extremely difficult to predict with certainty whether a given engine failure will inevitably produce a fire or not; much depends upon the flammable fluid involved, its temperature and degree of atomisation, the air pressure and velocity in the vicinity of the flammable fluid, as well as the nature of the ignition source involved. Many engine failures have led to IFSDs alone, which might have produced significant fires, had the failure occurred on a warmer day or at a different engine power setting. A deterministic approach to engine fire is therefore impracticable given the

current state of the art. Similarly, the existence of an engine fire does not necessarily result in an airplane accident; hazard ratios (i.e. the conditional probability of an accident resulting from a given failure condition) are presented in table 4.2.

The majority of engine fires and of resulting accidents were found to occur in climb, when undercowl temperatures are highest. Only 5% of engine fires resulted in accidents, and over half the accidents were not direct results of fire damage, but involved flight crew or passenger response to the fire, such as hard landings or injuries incurred during emergency evacuations. A detailed statistical analysis of engine fire events appears in C.

### 4.2.4 Thrust Control Difficulties

Although no previous studies in the field have specifically identified this as an accident cause, review of the record showed eight accidents where the thrust produced by the engine was so dramatically different from that intended by the pilot that there was great difficulty in maintaining directional control. The majority of these cases were associated with functionality of thrust reverser systems; unavailability of reversers or high forward thrust on one side with full reverse on the other creates a significant turning moment on the airplane, sufficient to cause runway departure in several instances. Detailed discussion is presented in Appendix C.

### 4.2.5 Engine mount failure or component departure

Failure of the mount of an operating engine, unless complete redundancy is provided in the mounting attachments, is likely to produce some degree of misalignment in the engine thrust vector. The resulting pivoting about the remaining attachment points is likely to lead to their sequential failure, until the engine completely breaks away from the airplane structure (except for buried installations such as centre tail engines, which may remain in place). Separation of the engine from the airframe implies the following potential risks:

The engine may hit the airframe as it departs, along some trajectory determined by its initial angular momentum, aerodynamic drag and gravity.

The airframe may suffer some consequential damage as comparatively flexible fluid lines, power cables and wiring harnesses are torn away by the engine.

Persons or property on the ground may be injured as the debris falls to earth.

The above risks from impact damage also apply to smaller components departing the engine, such as nacelle cowlings, tailcones and even small access panels.

Airworthiness regulations require the analysis to address the possibility of excessive loads being generated by the engine and failing the engine mounts; mount failure by other mechanisms such as fatigue is not specifically addressed, although in practice, stress analyses do address other causes of mount failure besides overload. The departure of "low-energy" components from the nacelle is not currently covered by airworthiness regulations.

Although no fatal accidents have yet occurred attributable to loss of an engine cowl or similar component in flight, the potential for such an outcome is clear. Many cowls and other nacelle components have been lost in flight so far, either as a result of some major engine failure, or a failure of the cowl itself, or maintenance error in latching the cowls; it seems likely that one will eventually do sufficient damage to the airplane to result in a hull loss (combined with other adverse factors). The extent of the potential hazard depends as much upon the airplane design as upon the component involved; for example it might be speculated that a composite control surface would be more vulnerable to splintering and in flight flutter following impact damage than one constructed of sheet metal.

Engine separations have primarily occurred during climb or landing, at which time pre-existing damage to an engine mount system was subjected to high loads. All engine separations have resulted in accidents. Detailed discussion of engine or cowl separations appears in appendix C.

### 4.2.6 Multiple Engine IFSD

The in-flight shutdown of multiple engines may lead to complete loss of thrust (for a twin) or partial loss of thrust, thrust asymmetry, and significant reduction in electric power, hydraulic power and bleed air available to the airplane. It should be recognised that since all commercial transport aircraft are certified to be capable of safe flight and landing with one engine shut down, loss of airplane capability is not simply a matter of the proportion of engines still operating. Four engined aircraft may not be controllable with two engines failed, if they are on the same side, and three engined aircraft may not be capable of sustained flight with only one engine running.

It should also be recognised that complete loss of engine power does not automatically entail loss of the aircraft, provided that a suitable landing site is close at hand, the pilot is sufficiently skilled and circumstances are otherwise favourable. Indeed, the loss of airplane services such as

hydraulic power may have a more immediately adverse effect than loss of airplane thrust; diligent attention to airplane system architecture is required to protect the airplane from such adverse consequences.
Notwithstanding the potential consequences of multiple engine in-flight shutdown, the airworthiness regulations do not specifically address this hazard. Some individual causes of multiple engine IFSD are addressed by specific regulations, although compliance with the regulation should generally be considered as reducing, rather than eliminating the potential for an IFSD. The following causes of multiple engine IFSD have been identified so far; new causes manifest themselves periodically:

Engine instability
Maintenance error/ Flight Crew Error
Birdstrike
Inclement weather (rain, hail)
Volcanic ash ingestion
Flowpath icing
Fuel icing
Fuel contamination/ exhaustion
Common mode component failures (e.g. fuel-nozzle coking)
Independent failures

Regulatory attention has recently been directed toward the in-flight restart capability of the engines, so that in the event of a multiple IFSD which leaves the engine undamaged, there is some confidence in the engine capability to start before the airplane reaches the ground. This would have no effect upon the accident record, however, since the limited number of accidents resulting from multiple-engine IFSDs have been in circumstances where the engines were damaged, or external factors prevented restart.
The relatively small number of accidents involving multiple engine failures have been equally distributed throughout the flight envelope.

### 4.2.7 Propulsion Related Crew Error

There were 4 accidents resulting from crew error in the high bypass ratio fleet between 1970 and the end of 1994. One of these occurred in cruise, the other three were in landing. It is not possible to discover the incidence of crew errors which do not result in accidents, although 6 such were identified in Appendix C, all of which occurred in climb. It may be hypothesised that takeoff and landing are the phases of flight in which there is least time to evaluate a situation carefully and rationally, and in which there is the greatest potential for automatic (but inappropriate) action sequences to be triggered. It may be argued that there is minimal time to re-evaluate the situation and compensate for inappropriate action during takeoff and landing, and that crew fatigue may specifically reduce

alertness during landing. These considerations are addressed further in Chapter 6.

### 4.2.8 Casing rupture

Although there is currently no explicit regulatory requirement to address engine casing rupture in powerplant safety analysis, it might reasonably be considered a safety-related failure, being accompanied by the release of high-pressure, high-temperature core air, and possibly by casing debris being propelled at high speed toward the airframe. Several accidents (below) have resulted from this type of failure occurring during the take-off roll when core air pressures are at their highest; this type of event does not, however, make a major contribution to the high bypass fleet accident record.

The majority of case ruptures occurred during takeoff, coincident with peak core air pressures. Approximately 30% of such case ruptures resulted in accidents.

### 4.2.9 Uncommanded in-flight reverse thrust

In-flight deployment of a thrust reverser immediately increases the airplane drag. The results of such in-flight deployment may include the following:

Thrust asymmetry, if the reverser of only one engine deploys.
Sudden decrease in airplane speed.
Disturbance of airflow over the adjacent wing (for wing mounted engines).
Very high loads upon reverser and nacelle structure, for high speed deployment.

The severity of the above effects will depend upon the initial flight condition, the reverser design and the engine installation in the airframe, among other factors. Deployment at low airspeed may permit aircraft control and recovery to normal flight (provided sufficient altitude margin exists), whereas deployment at high speed may produce irrecoverable loss of control. Deployment of a target reverser, typically used to reverse the core airflow of a low bypass-ratio jet engine, will produce lesser effects than deployment of a cascade-type fan reverser of a high bypass-ratio turbofan. Engines located far from the airplane centreline will produce a greater turning moment and effective thrust asymmetry than tail mounted engines.

Airworthiness regulations have, until recently, required that engine thrust be limited to flight idle during in-flight reverse, and that either the airplane should be capable of safe flight and landing with the reverser deployed, or that the reverser should be able to be stowed in flight. The

regulations are in the process of revision, to more fully account for the potential consequences of high speed fan reverser deployment.

There was only 1 accident resulting from in-flight reverser deployment in the high bypass ratio fleet between 1970 and the end of 1994. It occurred in climb. This accident followed a history of reverser deployment in flight without adverse effects on controllability; in fact the FARs required demonstration of airplane controllability with a reverser deployed in flight. There have been at least eight incidents of reverser deployment in flight in the past, and an analysis before the occurrence of ACC62 would not have predicted a catastrophic effect. The reasons the previous fleet history no longer applied are as follows:

Some of the previous incidents involved deployment of the turbine reverser, which has a relatively small net thrust effect.

Flight testing of reverser deployment was done at relatively low airspeeds, to minimise the resulting damage to the airframe. This was a valid approach, to the extent that a likely cause of inadvertent reverser deployments in flight was considered to be error by a flight crew accustomed to aircraft for which reverser deployment was an acceptable means of reducing airspeed before landing. Four of the eight reverser deployment incidents identified were in descent or landing.

The location of the reverser with respect to the wing has a greater effect on the outcome than had previously been thought. Recent aircraft designs have the powerplant closer to the wing than do earlier designs (forced, in part, by increasing engine diameters to accommodate higher bypass ratio fans). This enables a high-speed in-flight reverser deployment to induce stall near the wing root, in addition to the drag imposed by a deployed reverser.

One other accident was attributable to the reverser design, although no malfunction was involved. The reverser design did not permit deployment during landing until multiple weight-on wheels signals were received; when the airplane landed fast and in a non-level attitude, there was a significant delay before reverser deployment, which may have contributed to the airplane runway departure. The system logic contributing to the accident was explicitly intended to prevent in-flight deployment.

### 4.2.10 EMI Affecting Controls Or Instruments Of Multiple Engines

Considerable concern has been expressed recently over the potential for EMI (electromagnetic interference) affecting aircraft systems, including electronic engine controls. The move towards electronic control systems, affording much greater flexibility and diagnostic capability than hydromechanical controls, while potentially reducing system weight and

avoiding some of the reliability problems associated with mechanical control cables, has introduced the potential for high-intensity electro-magnetic sources such as lightning and military radar installations to induce spurious signals in the aircraft wiring.

The actual threat posed by EMI to engine systems and instrumentation is not well-defined. Anomalous airplane behaviour has been attributed to man-made EMI in the past, but such attribution is supposition only, since no measurements of high EMI intensities were made at the time (nor is it reasonable to expect commercial aircraft to carry the appropriate recording equipment, to address an environment that may not be encountered during the life of an individual aircraft.) Lightning activity has been associated with failure of some cockpit instruments. Arbitrary levels of EMI have been designated for use in aircraft electronics design, and the design response has generally been to shield and screen the relevant components from interference, rather than attempting to predict the response of equipment subjected to random interference signals.

It is conceivable that EMI might affect the electronic engine controls or instruments in some way that was hazardously misleading to the flight crew. It is probable that all engines would be so affected, since they would be of identical design and subject to the same environment, although variations in the exact state of the individual EECs (Electronic Engine Controls) would permit differing responses. However, a more likely response to EMI affecting the engines would be some incorrect scheduling of fuel, or incorrect instrument reading, which would be immediately apparent to the flight crew. Since it is difficult to envisage them taking any useful corrective action under the circumstances, it is fortunate that the high-intensity EMI event would be likely to be of short duration (a few seconds).

Lightning strike and HIRF have not resulted in any accidents to the high bypass ratio commercial transport fleet, other than ignition of fuel by lightning. Lightning has the potential to disrupt the airflow into an engine and cause a stall, but the effect is generally local and multiple widely separated engines are not affected. HIRF has not yet resulted in a significant number of propulsion related incidents in the commercial transport fleet. Lightning damage has generally been limited to small areas of mechanical damage to engine nacelles.

### 4.2.11 Failure Of Airplane Services From Multiple Engines

Besides supplying thrust, the engines also supply electrical power, hydraulic power and bleed air for anti-icing, cabin pressurisation and as a further power source, as mentioned above. Although these services are as essential to the airplane as thrust, little consideration is generally given to engine failures, other than multiple shutdown, depriving the relevant

system of engine-derived power. This is in part because system architecture provides for considerable redundancy - a twin airplane might have three hydraulic systems, pressurised not only by engine-driven gearbox pumps, but by air driven pumps using engine or APU bleed-air, as well as electrically driven pumps. Common-cause multiple engine shutdown therefore forms an obvious weak point in the system, since it would reduce hydraulic, electrical and pneumatic capability simultaneously.
Nevertheless, consideration should be given to all common mode failures affecting multiple airplane services, whether they result in engine IFSD/thrust loss or otherwise. Although no accidents have resulted from such failures in the past, review by the propulsion safety analyst may avoid future occurrences.

### 4.2.12 Inability To Shut Down Engine

Loss of control of the engine, so that it cannot be shut down at will by the flight crew, contains the potential for a number of adverse consequences to the aircraft. Directional control could be adversely affected; the flight crew would be deprived of the primary means of preventing other hazardous engine effects such as the spread of fire or eventual uncontained failure, and the psychological effect on the flight crew would be most disconcerting. It must be freely acknowledged that the accident record for commercial jet transports (non-Soviet) includes no instances of an accident resulting from inability to shut down an engine; this may be attributable in part to the success of airplane and engine manufacturers in complying with the airworthiness regulations requiring the engine to retain the capability of being shutdown, and in part to the relative rarity of circumstances where shutting down an engine, as opposed to throttling back to idle, is crucial to flight safety.

### 4.2.13 Toxic Fumes In Cabin Bleed Air

Jet engines extract bleed air for cabin pressurisation from the HP compressor, upstream of the normal area of combustion. It is possible for engine oil leaks to enter the compressor airflow, and for the oil to begin combustion in the compressor as the local air pressure and temperature increase. The main toxic products of such combustion are carbon monoxide and acrolein. Acrolein is an irritant to the eyes and nose, and signals the presence of contaminants in the bleed air long before the carbon monoxide could have a deleterious effect upon the health of passengers and crew. The normal response is to shut off the bleed from the engine responsible, provided it can be identified. The remaining engine(s) are capable of providing sufficient bleed air for the cabin. No accidents have resulted from toxic bleed air from a turbofan.

### 4.2.14 Casing Burnthrough

Casing burnthrough can allow a jet of extremely high pressure, high temperature air to be directed against firewall boundaries, structure and systems. This highly erosive jet can burn or abrade through most barrier materials of reasonable thickness within seconds; fortunately, it dissipates by jet mixing with a bypass stream or with ambient air before it can cause other than local damage. Provided that flight-critical systems are kept away from the engine core and that the engine can be isolated from fuel sources even if firewalls are holed locally, this type of event is unlikely to result in an accident (and has not, in fact, done so in the high bypass ratio fleet.)

## 4.3 Conclusions of Accident Review

The following failures are historically most likely to result in accidents and should be the primary focus of the safety analysis.

Uncontained engine failures account for 26% of propulsion related accidents in the high bypass ratio fleet.
Propulsion failure accompanied by crew error contributes 18% of propulsion related accidents in the high bypass ratio fleet.
Thrust control problems contribute 10% of propulsion related accidents in the high bypass ratio fleet.
Engine fire contributes 11% of propulsion related accidents.

The airworthiness regulations pertaining to safety analysis direct specific attention to three of the above; uncontained failure being cited as Hazardous by FAR 33.75, JAR-E 570 and FAR/JAR 25.903, fire being cited by FAR 33.75, and thrust in the opposite direction to the pilot's intention being cited by JAR-E 570 (this does not address the full spectrum of thrust control related accident causes). Since propulsion failure accompanied by crew error is not addressed, and thrust control is only partially addressed in safety analyses intended to show compliance with airworthiness regulations, it seems likely that the analyses are only partially effective in predicting or controlling propulsion system safety. The scope of future analyses should be expanded to address the major contributors among the accident causes cited above.

It is noteworthy that the likelihood of an accident resulting from an incident (the hazard ratio) can be strongly influenced by the details of the powerplant installation ( an example would be the chance of a cowl separation causing substantial damage to the aircraft). Although the hazard ratios shown in Table 4.2 are useful as average (and conservative) estimates, it is recommended that future analysts verify their applicability by comparing them with the most recent and applicable service experience available.

| EVENT | HAZARD RATIO | NOTE |
|---|---|---|
| Uncontained engine failure | 0.06 | Lower for outboard engines |
| Propulsion failure + crew error | 0.004 | Higher for twins |
| Thrust control | Indeterminate | |
| Fire | 0.05 - 0.025 | |
| Engine separation (engine running) | 1 | |
| Cowl separation | 0.05 | Higher for tri-jets |
| Multiple engine failure | 0.07 | |
| Case rupture | 0.3 | Engine-model dependent |
| Crew error | Indeterminate | Engine-model dependent |
| Tailpipe fire | 0.09 | Engine-model dependent |
| Reverser | Indeterminate | Airplane configuration dependent |

Table 4.2 Estimated Generic Hazard Ratios

THIS PAGE INTENTIONALLY BLANK

# 5.0 Review of Techniques

## 5.1 Desired Features

A number of formal safety analysis techniques[15] are available for the use of the analyst. The following characteristics are considered desirable for any technique to be used for Propulsion System Safety Analysis:

- Identify safety concerns

- Focusing resources selectively on safety-related failures

- Credible quantitative forecasts of accident /serious incident rates

- Generate new information or understanding of weaknesses in a design

- Results repeatable or verifiable by an outside observer

- Use available data (no dedicated tests required)

- Produce results early enough to change the design

## 5.2 Preliminary Hazard Analysis (PHA)/ Functional Hazard Assessment (FHA)

A PHA is simply a catalogue of the potential hazards existing in a system, such as high temperature components, compressed gases, flammable materials and so forth. An FHA is a high-level review of all of the functions performed by a subsystem and the effect of function loss upon the system as a whole. It may consider loss of a function, improper activation of a function (too fast, too slow, too much, not enough) or unwanted activation of a function. It is generally used to establish overall safety objectives for each functional failure condition. It is not useful in verifying that these objectives have been met.

Both a PHA and FHA are useful where the analyst is dealing with an unfamiliar system for which there is no service experience. The FHA is of particular use in establishing the extent to which subsystems are interdependent, where a large number of subsystems are being designed by semi-independent groups.

---

[15]Almost any of these techniques can be made to work on any system, if sufficient effort is involved. However, some techniques are more suited than others to particular problems, as discussed below.

The FHA is not well suited to addressing active threats (fire, Foreign Object Damage, uncontained high energy debris from an engine etc.) as opposed to passive loss of a function. It is difficult to reach agreement on the system level effect where non-deterministic failure conditions are being considered (for instance, airplane control margins are significantly reduced so that an unskilled pilot in bad weather might have difficulty in controlling the aircraft). It does not produce quantitative forecasts.

High bypass ratio turbofan installations have acquired hundreds of millions of hours operational experience, involving a large number of failure effects, which renders both PHA and FHA unnecessary provided that system architectures remain similar to those used in the past. Formal analysis is likely to produce little or no new understanding, compared with a simple list of propulsion related accidents which have already been experienced.

## 5.3 Fault Tree Analysis (FTA)

Fault tree analysis is a diagrammatic means of establishing all possible sequences of failures and combinations of failures which could result in a given undesired event or failure effect. The event of concern is selected and carefully defined, and the analyst then considers all failures and conditions which are both sufficient and necessary for the "top event" to occur. The process may be repeated for each failure until a sufficient level of detail is reached for the purpose of the analysis. The logic path so produced resembles an inverted tree, when presented as a diagram, with a single event at the top and many branches leading up to it. If failure rates are available for individual failure modes, they may be used to calculate the probability of the "top event" using Boolean algebra. Alternatively, the fault tree may be left unquantified if overall failure rates are not needed or if all component failure rates are similar (as for some electronic systems), in which case it may be valuable to derive minimum cut sets (a list of the fewest component failures required to produce system failure or the top level failure effect under investigation).

Apparently large and complex trees may in fact be dominated by a few crucial failure rates; if there is significant uncertainty regarding the numerical values to be used for these failure rates, then the outcome of the tree (the probability of the top event) may be called into question. Sensitivity analysis may be used to identify such crucial failure rates, so that further efforts may be made to reduce their uncertainty. For very reliable components, it may not be possible to reduce the uncertainty on the failure rate, in which case the sensitivity analysis is unproductive.

Fault trees are well suited to the analysis of architecturally complex systems incorporating considerable redundancy, especially where

individual component failure modes are simple and well-established. The other major advantage of the fault tree technique is that it limits analysis to those failures which are of concern, rather than requiring consideration of every possible failure. An example of the benefit of this approach would be in considering externally inflicted damage on a wire harness. Evaluation of the results of all possible combinations of wires shorting to each other and shorting to ground would be a very laborious task for more than a few wires, but by considering the fault trees for all undesired events, it may be easily determined which wires in the harness could contribute to the "top events". Damage to the remaining wires can be disregarded.

Architecturally simple systems derive little benefit from fault tree analysis. A fault tree for a series system contains the same information as a simple list of component (or subsystem) failures, presented in a diagrammatic form. It is notable that in the whole history of the high bypass fleet, no propulsion-related accident has been attributed to a combination of independent failures in multiple systems (Chapter 4, above). It is therefore questionable whether analyses need cover independent inter-system failure combinations. It is also difficult to address technically complex failure modes within a fault tree, especially a quantified fault tree. For instance, if a medium sized bird is ingested by an engine, the resulting damage can vary considerably, even if all known external factors remain the same (same aircraft speed, engine speed, bird species, engine design and construction etc.). Attempting to construct a fault tree including turbofan damage from birdstrike would therefore include some empirically based inhibit gates to account for the fact that damage is sometimes significant and sometimes minimal, depending on random variables such as the bird attitude at impact and the number of fan blades struck by the bird.

Fault tree analysis is useful for propulsion sub-systems where there is some redundancy, such as controls systems and thrust reverser systems. Much of propulsion system architecture is series systems, and although FTA may be used to provide visibility of failure propagation to a top event, it is unlikely to provide new insight into system operation. If fault tree analysis is used, it is essential that the failure rates used in propulsion system FTAs be verified and their applicability to the specific environment in question be confirmed. It is also essential to verify that contributing failures in the fault tree are truly independent, and that no common cause or cascading failures will bypass apparent redundancy in the design.

## 5.4 Reliability Block Diagrams

A reliability block diagram presents the functional relationships between components of a system, with a separate diagram for each function. It enables the analyst to see which component failures would affect functionality, and to calculate system failure probabilities. Since mechanical systems do not make great use of redundancy, reliability block diagrams may become merely a component list drawn in series for mechanical systems (23).

## 5.5 Failure Mode and Effects Analysis (FMEA)

A Failure Modes and Effects Analysis considers each component in a sub-system in turn, and assesses the failure modes of that component, the effect upon the system of each mode, and (sometimes) the probability of each failure mode and the means which would be used to detect and/or preclude failure. The results are presented as a table.

An FMEA is the most comprehensive (and most labour-intensive) means available of addressing subsystem failures. It is well suited to subsystems with simple architecture, and preferably with simple failure modes (valve fails open, closed, part-closed).

FMEAs address single failures. Systems incorporating significant redundancy (such as many electronic systems) are not easily analysed by FMEA, since most component failures will be concluded to have a system-level effect of "Loss of redundancy". If there is no means of detecting the failure, the system may continue to operate in a degraded state until sufficient failures have accumulated to cause a system-level malfunction - one not predicted by the FMEA. Systems with complex failure progressions are not easily addressed within the limited space of a FMEA (cf. the bird ingestion example above). It may be difficult to translate the results of a subsystem FMEA to the system level, since the FMEA is often conducted from the component viewpoint rather than the functional viewpoint, and generally a system-level analysis requires information on how subsystem functions change in the event of failure, and not on the fate of subsystem components.

Although a FMEA complies exactly with the wording of the Joint Airworthiness regulations relating to engine safety analysis, it is not the most effective means of conducting a propulsion system safety analysis. It is an excellent way to assess a completely new and unprecedented mechanical system, to find the effect of each potential component failure. Current turbofan designs have accrued sufficient service experience that a FMEA on the entire propulsion system is unlikely to produce new

information, if the design bears any relation to those that have gone before.[16]

## 5.6 Simulation

Computer simulation (such as Monte Carlo assessment or Markov analysis) can be used to assess the effects of individual component failures or degradations on very complex subsystems, by modelling the subsystem behaviour over time with random component failures introduced to simulate service experience. If a large number of trial runs are made, the results can be combined to give a probabilistic model of system behaviour, even if the system is too complex to be modelled analytically. The effects of different inspection and repair intervals may easily be studied, as may the probability of being in any given degraded state after a given time interval.

Although computer simulation allows systems to be modelled which could not otherwise be assessed, it is at the cost of losing visibility of the analytical process. It is difficult to justify or explain the results of such simulation if they are other than as generally expected. Similarly, it may be difficult to identify the components or design features having the most influence upon the outcome.

Markov analysis is widely used for modelling the behaviour of Electronic Engine Controls and assessing which degraded states should be permitted under Time-Limited Dispatch. Where component failures become immediately obvious, as in many mechanical systems, there is little to be gained from computer simulation safety analysis.

## 5.7 Failure Mode and Effects Summary (FMES)

A FMES presents sub-system functional failure conditions in a tabular form, relating them to the system level effect. It provides a succinct, easily comprehended system-level summary of the information found in FMEAs, omitting those failures which have no system-level effect. The FMES may be based on individual FMEAs, or it may be possible to prepare the FMES directly.

The FMES has some of the weak points of the FMEA. It deals with individual functional failures. Combinations of functional failures cannot

---

[16]This statement is not intended to imply that every possible failure (and airplane level effect) which could take place has already done so; new failures will occur in the future. However, all of the failures which could obviously occur, the failures which an analyst could be expected to foresee, have either occurred in service or are sufficiently unlikely (because they have *not* yet occurred) that the credibility of the analysis would be questioned if they were included.

be readily addressed by this format. It is difficult to reach agreement on the system level effect where non-deterministic failure conditions are being considered (safety margins are reduced).
The FMES is a good means of communicating propulsion system functionality to the airframe-level analysis (especially if each table is accompanied by a narrative explaining assumptions, approximations and the origins of failure rates). It provides little additional insight into the operation of the propulsion system itself, or the safety of the installation

## 5.8 Common Cause Failure Analysis Methods

Zonal Safety Analysis entails reviewing the systems and components within and immediately adjacent to a given spatial region. A local source of damage may be hypothesised (high pressure air leak, fire, birdstrike etc.) and the system-level effects of such damage can then be evaluated. If the results are considered unacceptable, subsystems may be re-routed or means to reduce local damage may be introduced. The use of zonal analysis presupposes that subsystem relocation is possible. It is generally the case for propulsion systems that subsystem location cannot be changed or that the alternate location is very close to the original one, or subject to similar threats as the original one.
There are individual cases involving very localised threats where zonal analysis has been used (formally or informally) to relocate systems to a more sheltered region (for instance, in reducing the risk of cross-engine debris for wing-mounted engines, or for reducing the risk of fuel leaks and fire in the event of an engine nacelle scraping the ground in a runway departure). These have not, however, identified common-cause failures which may be avoided by system relocation[17]. Zonal safety analysis should be used as an adjunct to fault tree analysis, to confirm that system redundancy is not violated by local threats.

Particular Risks Analysis entails the review of a specific cause of common-cause failure and assessment of the system-wide effects of that risk (e.g. volcanic ash ingestion). The effectiveness of this approach depends upon firstly, identifying all the particular risks which should be considered, and secondly, validating the assumptions previously made regarding the severity of that risk. Service experience is likely to prove invaluable in both of these steps. In practice, many particular risks have regulatory requirements associated with them for propulsion system certification. These do not provide complete protection against that risk, but set a minimum standard which has been shown to be generally acceptable and achievable. This minimum standard is reviewed at intervals, and may be made more stringent for new models as a result of undesired service

---

[17]The engine itself, and its safe shutdown, form a much more likely common cause for multiple subsystem losses of function in the propulsion system.

experience with existing models. Complete protection against particular risks is not generally within the state of the art (for instance, it is not currently feasible for every engine to ingest a 20 pound goose and to continue to develop enough power for safe flight and landing). The analyst should spend time hypothesising particular risks which are not yet covered by regulatory material, to establish whether their risk may be mitigated before they can produce their first accident.

## 5.9 Alternative Analysis Techniques

When dealing with extremely rare events, particularly in the absence of generally agreed and validated failure rates, the utility of highly structured analysis techniques proceeding from first principles becomes questionable. Such techniques are useful in identifying accident sequences which could reasonably be expected to occur. They are less successful in those cases where unlikely combinations of circumstances, including (but not limited to) human error, result in one-of-a-kind accidents. For instance, a FMEA (or fault tree) might predict failure of a fan blade. It would not be likely to predict that the pilot would shut down the wrong engine, contrary to the evidence of flight deck instruments. Prediction that the damaged engine vibration would coincidentally abate, so deceiving the crew into believing they had taken correct action, and that the damaged engine would then fail to produce power within minutes from landing (but at too low an altitude to allow recovery of the shut down engine) would strain the bounds of credibility; yet this is precisely the sequence of events producing ACC53. There are many examples of accidents resulting from apparently non-threatening malfunctions which occur from time to time, usually without affecting safety, including accident numbers 1, 7, 22, 32, 39, 41, 44, 45, 46, 52, 54, 57, 60, 61, 65, 68, 70, 74, 75, 76. This major contribution is not addressed by regulatory or advisory material, nor do current analyses address it.

Alternate analysis techniques may focus upon actual service experience to indicate areas of high risk, rather than attempting to proceed from first principles and to be fully comprehensive. Accident precursor analysis, for example, identifies failure combinations which are necessary (but not sufficient) for an accident, and monitors how frequently these occur in service. Accident rates may be derived from this data with reasonable confidence.[18]

Two completely new approaches were derived during this research, both of which are focused upon gaining a better understanding of service data so that predictions could be made. Details of the two new techniques, referred to as Event Sequence Modelling and of Crew Error Modelling are presented below.

---

[18]This approach is clearly most suitable for redundant systems or those with multiple levels of warnings and safeguards.

The conclusion must be drawn that emphasis on a structured analysis reviewing combinations of failures is less useful than a dual approach of firstly concentrating on high reliability in all systems and the prevention of individual failures which could in themselves, or in conjunction with inappropriate crew response, result in an accident, and secondly, assessing the vulnerability of the airplane to an accident in the event of the failure occurring.

# 6.0 ALTERNATE APPROACHES TO PROPULSION SYSTEM SAFETY ANALYSIS

## 6.1 Areas to be Investigated

Three specific areas of safety analysis were initially identified as offering significant opportunities for improvement:

a) Current airworthiness regulations either require all possible failure modes to be addressed (JARs) or certain specific failure modes which were envisaged as being particularly hazardous at the advent of commercial jet transportation. A review of the accident record to establish which propulsion system related failures present the greatest risk to the airframe would enable the safety analysis to focus on major contributing factors.

b) It has been acknowledged that the majority of accidents are caused by a combination of circumstances rather than a single event. Current safety analysis techniques generally focus upon hardware failures (although both fault trees and FMEAs are capable of documenting external circumstances). A detailed review of accident sequences, identifying critical weaknesses which enable the accident sequence to propagate in several instances (or which led to the outcome of the accident being more severe), offered an opportunity to add depth to existing analysis techniques and to identify multiple opportunities in each case to improve safety.

c) The baseline study demonstrated a significant shortfall in the prediction of quantitative failure rates. A means of predicting failure rates at entry into service was sought, both at the component level and at the overall propulsion system level.

## 6.2 Prioritising The Effects To Be Considered By Safety Analysis

Definition of the types of events which should be considered by a safety analysis presents considerable grounds for discussion. It could be argued that any engine failure, no matter how minor, has the potential to reduce airframe safety by some increment, as has any aspect of the propulsion system design which might lead to inappropriate flight crew or maintenance crew action. Such a broad definition of "Safety-related Failure" would render the task of both safety analyst and designer impossible, and would lead to concealment of key flight-safety issues by a morass of minor problems which make a negligible contribution to propulsion system risk. Consideration of the in-flight shutdown of an engine (IFSD) would include many failures with no effect upon safety (instrumentation failures leading to a precautionary shutdown) whilst

neglecting other events producing considerable cause for concern (multiple engine malfunction, high speed rejected take-off).

However, it is clear that performance of a safety analysis to address only the hazards identified by airworthiness regulations such as FAR 33.75 affords too limited a perspective upon the safety of the system of engines, airframe and flight crew. Recent debate by international committees of experts from the industry and the regulatory authorities has disclosed that the "Classical" issues of uncontained engine failure and engine fire may pose no greater threat to airplane safety than events such as failure of a single engine accompanied by crew error (18). A detailed review of propulsion-related accidents and their causes was presented in Chapter 4 illustrating this point.

Review of the accident record strongly suggests that the safety analysis should focus upon those failure types which have contributed to a large proportion of propulsion-related accidents in the past, namely; uncontained failures, propulsion system failure accompanied by crew error, engine or component separation, thrust control and fire. These five failure types account for 73% of all propulsion related accidents in the high-bypass ratio fleet.

## 6.3 Failure Progressions And Opportunities For Accident Prevention

The majority of complex systems incorporate a series of defences-in-depth (technical, procedural or organisational) intended to prevent a mistake or a malfunction, of itself, resulting in a system failure or in an accident (Maurino et al, 56). In the event of an accident, every one of these defences has been bypassed or negated. Each accident is considered to offer multiple opportunities for prevention, in the robustness of the hardware design, in system architecture or in emergency procedures. It was hypothesised that a series of detailed reviews of the sequence of events leading up to the accidents might identify significant weak points in these defences, either as recurrent patterns of cause and effect, or conversely as sequences with similar originating events but very different outcomes.

The utility of this novel approach was tested on the accidents resulting from uncontained engine failures; although future work could clearly address other accident categories. Since this research is primarily focused on safety assessment of the propulsion system of the airplane, and the intent of this study is to assess the connection between a hardware failure and loss of safe flight, organisational issues were not addressed in the assessment of failure progressions (it is acknowledged that organisational issues may provide valuable opportunities for safety improvement, but they lie outside the scope of this research). The initial engine hardware failure was generally taken as given and the study directed towards means of preventing the initial failure from propagating into an accident, or of reducing the accident severity. It should be noted that the failure of rotor disks, rather than smaller rotating parts, was the primary cause of these accidents.

Event sequence sheets were developed for each accident reviewed (the author is not aware of this specific technique having been used before). The sequence of events was tabulated, including all events which were considered material to the progression of the accident chain, together with ways in which the chain could have been interrupted at each point. Examples of event sequence sheets are presented in Appendix D. The event sequence sheets were prepared with specific reference to those events which made the accident dangerous, and to considering means which would mitigate the hazard

The results of the event sequence analysis are as follows: 16 accidents were analysed, and 31 separate means of reducing the likelihood of an accident in the event of an uncontained failure were identified. The majority of these each applied only to a single accident, and would not, therefore, significantly impact the overall accident risk if implemented. Seven of the means of mitigating the risk applied to more than one accident, and are discussed in more detail below.

An improved debris trajectory model for uncontained failures, as in the recently issued AC20-128 and the associated User's Manual, would enable system separation and local shielding or armour for critical systems in the plane of the engine turbine disks. This would have significantly reduced the system damage and concomitantly maintained margins of safety for seven of the 16 accidents, including two fatal accidents (ACC 4, 23, 24, 29, 56, 66, 84).

Improved wingskin impact-toughness, at least for the lower surface of the wing might reduce local damage and resultant repair cost for eight of the sixteen accidents. Major increases in wingskin thickness might have avoided fuel leaks from the wing tanks in four out of five accidents involving tank penetration. However, the weight penalties associated with this approach would be very significant, since disk fragment energy levels are so high.

A credible means of monitoring engine vibration in real-time, together with the use of crew procedures to reduce power and monitor other parameters in the event of high vibration, could have prevented three of the sixteen accidents (ACC 23, 24, 29).

Assessment of wing designs for residual lift with a section of leading edge destroyed could have improved safety margins for two of the sixteen accidents (ACC 2, 4).

Enhanced simulator training for flight crews of engine failure at V1 could have reduced the likelihood of two of the accidents[19]. These accidents resulted from an incorrect flight crew decision to reject the takeoff above V1, occasioned by an uncontained engine failure which was, in itself, benign (ACC 8, 33).

Improved simulator training for flight crews in the accommodation of an uncontained engine failure with concomitant secondary damage (multiple systems failures, asymmetric thrust) and physically distressing symptoms (loud noise, smoke, vibration) could have enabled flight crews to follow correct emergency procedures in two of the sixteen accidents, considerably improving safety margins (ACC 4, 29).

---

[19]The NTSB recommendations for one accident include a clear indication of V1. All transport aircraft include provision for reference markers or "bugs" to be set before takeoff, indicating V1, V2 and Vr. These may be set manually or automatically according to the flight deck design. It is the task of one of the flight crew to monitor airspeed and to call "V1", "Vr", "V2" for all takeoffs. It is not clear how crew awareness of V1 can be improved within the flightdeck. Distance-remaining markers on the runway might be of assistance in enabling better judgment of the consequences of a high-speed rejected takeoff.

It is estimated that use of the above means of mitigation would result in a 25% reduction in the overall accident rate attributable to uncontained engine failures. Of the three accidents which resulted in fatalities or a hull loss, two involved significant systems damage caused by uncontained debris, and the risk could therefore have been mitigated by appropriate systems design. The remaining accident was a hull loss because fuel leaked from shrapnel holes in the wing tanks and ignited. Means to prevent fuel leaks from the tanks could possibly have avoided this event, although the associated weight penalty is likely to limit the practicability of this approach.

The limited success of this "defences in depth" approach may be attributed to the fact that the majority of the accidents were so classified because of the cost of repairing the shrapnel punctures in the airplane resulting directly from the uncontained event, rather than from reduced safety margins, loss of life or injury. These offered little opportunity for prevention, but the safety margins for the passengers and crew could have been enhanced substantially by use of the above means of mitigation. Accident causes such as fire, involving a series of safeguards which have been bypassed or negated, might be more productively assessed by this means of analysis.

Detailed review of event progressions for the uncontained accidents resolved an anomaly which had been uncovered in Chapter 4. It has been claimed that the airplane risk of an accident resulting from an uncontained failure is proportional to the number of engines. The accident review of Chapter 4 showed that this is not the case; the accident rates for four-engined aircraft are slightly lower than for three engined or twin aircraft. The event progressions highlight the fact that most of the accidents resulting from uncontained failures were classified as such because the airframe incurred substantial damage involving local penetrations of wing, stabiliser or fuselage skin, together with engine and local pylon damage. In some cases, there was multiple system damage where systems clustered together in the wing root or in the tail. It became apparent that the outboard engines of a four-engined airplane have a greatly reduced chance of hitting the fuselage, the tail, or another engine. It might therefore be expected that an outboard engine would have a smaller chance of causing an accident in the event of an uncontained failure. Review of the accident and incident records confirmed this hypothesis; although uncontained incidents for the 747 were equally distributed between inboard and outboard engines, eight of the nine accidents resulting from uncontained failure on the 747 involved inboard engines.

## 6.4 Crew Error Modelling

### 6.4.1 Current State Of The Art

The review of the historical accident record for high bypass ratio engines powering transport aircraft, undertaken in Chapter 4, shows that crew error or propulsion system failure resulting in crew error is one of the major contributors to the propulsion related accident rate. It accounts for over 20% of propulsion-related accidents, corresponding to an accident rate of 4E-8/engine hour or 1.14E-7/flight hour fleet wide. Currently there is no propulsion-related crew error model generally available to assess the likelihood of crew error for one propulsion system compared to another, or to improve propulsion system design and operation by reducing the potential for crew error. There has been a recent increase in interest in the role of crew error within the industry, but no structured analysis of service experience has been published.

Recent work on the nature of human error (57) has pointed out the fallacy of assuming crew error to be due to the culpability of specific individuals; it is not reasonable to require perfection in flight crew performance, nor is it productive to urge them to be careful .... the desire to avoid participating in an accident is a powerful incentive for them to exercise as much skill and care as they are capable of doing on a day-in, day-out basis. A safety analysis should, therefore, assume that crew error will occur, based upon the most frequent types of error encountered in service and upon modifications in design or procedures intended to reduce the likelihood of error.

### 6.4.2 Crew Error Study

A study was initiated as part of this research project, to review those propulsion-related accidents in which crew error had played a major part; some additional accidents from the low bypass/turboprop fleet and some serious incidents were also included, to gain as much information about crew performance as possible. The intent of the analysis was to establish what kinds of crew error were most significant contributors to the propulsion-related accident record and what propulsion system features would be of material assistance in preventing crew error .

Discussion of the study is limited to those aspects which are relevant to the safety analysis of propulsion systems. More general results are recorded in Appendix E, together with an example of a detailed worksheet. Several distinct causal groups emerged from the study. These may be treated as 'normal' crew errors - that is, they are not isolated instances but form credible indicators of a potential for future errors, although the majority of

crews will not make these particular errors on the majority of occasions. A more comprehensive study would probably identify more causal groups. Each of these groups offers a significant opportunity for examining factors in design and procedures which may predispose crews to error.

### 6.4.3 Results Of Study

The most significant contributors to the propulsion related crew error accident rate were[20]:

1) Rejected takeoff after V1; 6 events, five of which were accidents (ACC 13, 22, 47, 52, 76, ASRS95408). Each of these involved a compressor stall or loud noise above V1, accompanied in some instances by tactile vibration on the flight deck (in one case the vibration was so severe that the crew were unable to read flight deck instruments). Studies of crew error (58) indicate that unfamiliar engine noise and vibration is likely to result in rejected takeoffs after V1, despite training and published procedures to the contrary. Crew simulator training frequently does not fully represent such events: the crew apparently experience doubts over the aircraft airworthiness when exposed to physically disturbing and novel symptoms and to multiple parameter changes indicating engine failure.

2) Asymmetric thrust which was not appropriately compensated for by the flight crew; 13 events, five of which were accidents (ACC 22, 39, 83, TPROP1, TPROP2, ASRS79941, 228930, 187833, 69231, 210629, 172754, 289651, 192977). The majority of the incidents occurred early in the takeoff roll, as one engine spooled up to takeoff power more slowly than the other(s) during a rolling takeoff manoeuvre. There appeared to be a significant degree of confusion over the best means to compensate for asymmetric thrust; several pilots attempted to use the rudder for directional control early in the takeoff roll, at which point it has negligible authority. Conversely, at least one accident in flight was associated with a lack of awareness that the rudder must be used to adequately compensate for an engine-out situation at high airspeeds (for wing mounted propulsion systems), even though the flight crew was fully aware that one engine was producing minimal thrust.

3) Conflict between the autothrottle or autopilot thrust control commands and the intent of the flight crew; 5 events of which three were accidents (in two accidents, the pilot attempted to land while

---

[20]Some events included more than one scenario, such as high speed rejected takeoff followed by asymmetric thrust and loss of directional control).

the autothrottle attempted a go-around). (ACC34, 83, 86, ASRS262211, 194115)

4) Propulsion system failure and crew distraction leading to a procedural violation (altitude deviation or loss of separation between aircraft); 7 events, none of which were accidents (ASRS 252461, 208817, 209170, 152464, 98530, 123465, INC751).

5) Inadvertent engine shutdown in flight; 4 events, none of which were accidents (INC317, 397, 808, ASRS235107).

### 6.4.4 Crew Error In New Designs

The historical propulsion-related accident rate for aircraft powered by high bypass ratio engines is 5.9E-7/flight hour, of which 1.14E-7/flight hour is judged to result directly from crew error in operating propulsion systems or from crew error in coping with the results of inherently non-catastrophic propulsion system malfunction. The propulsion system safety analysis should take account of this historical rate, but credit should be allowed for design features, changes in procedures or other compensating factors which would reduce the propensity for the crew error identified in the study. At the same time, the new features should be assessed critically to ascertain whether they may introduce the potential for new crew errors. [21]

The results strongly suggest that rejected takeoff above V1, crew response to asymmetric thrust, and conflicts between automatic thrust control systems and the intent of the pilot are key areas in the field of propulsion system safety and crew error. Examples of features which might reasonably be expected to reduce the crew error related propulsion accident rate, and the appropriate credit for each, are given below. These are not the only features which could reduce the accident rate.

**Means to indicate engine failure (engine fail light/ message)**

An engine failure indication would be unlikely to reduce the accident rate from rejected takeoffs above V1, since the go/no go decision appears to be heavily influenced by tactile and audible symptoms rather than by engine instrumentation. There were three events where an engine fail indication might have assisted the crew. In one case the flight crew said they did not know which engine had failed. In another, they said they thought both engines had failed. In one instance, they believed a wheel had failed when

---

[21]For example, one early accident resulted from deployment of thrust reversers in flight by the flight crew. Later airplane models included features in the reverser control logic to inhibit in flight deployment. A more recent accident resulted in part from delayed deployment of reversers and a runway overrun, because of the said inhibiting features.

the engine was experiencing high vibration but had not failed. However, it is questionable that an engine fail indication would have led them to follow their training and published procedures in the face of misplaced concern over the airplane's ability to fly.

Means to indicate engine failure might possibly be of assistance in preventing events associated with asymmetric thrust. Three of the accidents involving asymmetric thrust had an engine at idle, and in each case the flight crew believed the engine to have failed or to be in the process of failure. Following published procedures, observing and understanding all of the engine indications in each case would have shown this belief to be incorrect. It is possible, but not likely, that the absence of an "engine fail" indication would have led them to behave differently. Of the 8 incidents involving asymmetric thrust, five resulted from slow spool-up from idle. Two resulted from high forward power on one engine and reverse on another. One resulted from a misperception that a high landing speed would be advantageous if the crew needed to execute a go-around with an engine out. Since no engine failures were involved, an engine fail light would not have prevented any of these incidents.

An engine failure indication would not have been effective for the five events involving autothrottle/autopilot command in conflict with the pilot's intent. An engine fail light based on engine speed or thrust alone would not have affected the outcome of the accident where the pilot shut down the wrong engine, since the "Failed" engine was still developing significant thrust.

It is concluded that an indication of engine failure might reasonably have avoided two of the high speed rejected takeoffs. Table 6.4 assigns credit to such means.

A more sophisticated system of real-time engine health monitoring might be capable of indicating that an engine was in the process of failing but would last for a few more minutes (for some failure progressions, at least). This would be of considerable value in removing some of the time pressure from the flight crew and offering the opportunity for error recovery after an incorrect decision. The opportunity for error recovery appears a significant factor in determining the outcome of an event.

**Means to indicate autothrottle/autopilot mode and specifically to announce a go-around**

The primary flight display for modern transport aircraft indicates the autothrottle mode in the top left hand corner, by such codes as SPD, THR and so forth. The meaning of the code may be altered by the flight mode, denoted by roll and pitch mode codes on the primary flight display. In some aircraft, including one of those involved in a "control mode" accident, changes in the autothrottle or flight director modes are highlighted by a green or amber box around the mode code. It has been

noted by the FAA Human Factors Team that "Mode changes can easily be missed, even when additional cues are provided...the same mode annunciation may represent a different airplane state or behaviour in different situations." (59). It appears that more specific and noticeable means to announce a go-around might have prevented the two accidents in which the pilot attempted to land while the autothrottle attempted a go-around. It is possible that annunciation of mode might have also have prevented one or both of the incidents in which autopilot function was not as intended (operating inadvertently, or vice versa). Table 6.4 assigns credit to such means.

**Improved training of engine failure during takeoff above V1**

There have been sufficient accidents resulting from high speed rejected takeoffs to make this a high priority in prevention of accidents, although generally speaking designing out errors is preferable to addressing them by procedural means. It is of particular importance that this appears to be a rule-based error, in which the flight crew are aware of the correct procedure and the significance of V1, but their perception of the risk of becoming airborne is such that they elect to reject the takeoff.[22] Flight simulators do not give a faithful representation of the full range of somewhat perturbing symptoms likely to be encountered during such an engine failure. For example, ingestion of a large bird above V1 might be accompanied by a loud bang or series of bangs as the engine stalled, vibration (indicated and tactile) from fanblade damage and resulting unbalance, and a foul smell and smoke as burned organic material entered the flight deck air supply. A typical simulator currently represents this event as a noise and spool down of engine parameters.

It is concluded that inclusion of a realistic simulation of engine stall above V1 in crew training (including noises and tactile vibration) should be credited with a substantial reduction in the accident rate as shown in Table 6.4. Further emphasis in recurrent training could increase this to the theoretical maximum of 3.4E-8, but such airline-centred issues would be outside the scope of the initial propulsion system safety analysis.

---

[22]There has been only one instance in the high bypass ratio fleet of an accident resulting from continuing the takeoff after an engine failure above V1. In the case of ACC18, the engine separation began just before rotation (a crew member indicated concern one second before rotation). It is possible that a decision to reject the takeoff at this point would have resulted in a less severe takeoff with less loss of life, but this point cannot be established definitively.

**Means to avoid all engines being shut down in flight**
Of the four inadvertent shutdown events, three involved complete loss of engine thrust, with the concomitant risk of greatly reduced hydraulic and electrical capability and the need for emergency starting procedures. It would be reasonable to require a non-routine action in order to shut down the last remaining engine in flight (although that capability should be retained). The potential reduction in the accident rate from such a feature (approximately 5E-9/flight hour) should be balanced against the loss of architectural isolation between propulsion systems which has hitherto been a key feature in preventing common mode failures, and against the increase in complexity in what is currently a simple and robust electro-mechanical system.

**Means to clearly annunciate asymmetric thrust**
A number of incidents were attributable to one engine spooling up more slowly than the other(s) from a low power setting. In some cases, the pilots clearly did not understand the reason for the airplane yaw. An indication of significant asymmetric thrust could have been of significant assistance in these cases. It is unlikely that this feature would have prevented any accidents. In each of these accidents, the crew were aware that one engine was producing low thrust, but did not take appropriate measures to minimise drag/ maintain directional control. Credit for a reduction in the accident rate is proposed in Table 6.4. A more proactive means than annunciation might be to match engine thrusts at a given throttle setting. This approach would seriously impair propulsion system isolation, leading to a major difficulty in the event of an engine failure; it is therefore not recommended at this time.

**Means to prevent high forward thrust on one engine while another is in reverse**
This feature would be likely to have prevented one accident and three incidents. Several accidents unrelated to crew error could also have been avoided by this means. However, it has the potential to reduce architectural isolation between propulsion systems, and would lead to significant aircraft control problems in the event of inadvertent thrust reverser deployment. It is therefore not recommended.

**Means to deploy reversers promptly during a soft landing**
Some current thrust reverser logic includes the requirement for multiple squat switches in the landing gear to be closed before the reversers can deploy (to avoid deployment in flight). In the event of a soft landing, possibly with some aircraft bank, the airplane may proceed for some considerable distance down the runway before reversers can deploy. This has led to one accident. While it is desirable to have multiple inhibits on deployment, it may be possible to use other means more tolerant of airplane attitude (such as any squat switch in combination with an appropriate radio-altimeter-derived altitude of less than 10 feet AGL).

Such means could be credited with an accident rate reduction of 5E-9/flight hour.

### 6.4.5 Summary of Crew Error Study

The accident rate attributable to crew error in handling propulsion systems (failed and unfailed) is 1.14E-7/airplane flight hour, averaged across the high bypass ratio fleet. Major contributors to this rate are rejected takeoffs above V1, errors in dealing with asymmetric thrust, and conflicts between the crew intent and the commands of the autothrottle/autopilot.

The following features may substantially reduce this rate:

- Engine fail light
- Autothrottle/autopilot mode indication
- Improved training of engine failure above V1

## 6.5 A Novel Approach to Predicting Failure Rates

### 6.5.1 Engine-Level Failure Rates

Realistic and consistent predictions of component failure rates are of some importance in the propulsion system safety assessment, enabling the comparison of relative risks and assisting in design evaluation. The high integrity and reliability of aircraft propulsion system components generally precludes sufficient testing to establish a failure distribution by conventional means; alternative methods of predicting failure distribution were sought. Traditional approaches to failure rate prediction (published rates with technological severity factors) do not consider the evolution of technology as a product matures (Collas, 60). Propulsion system technology has improved considerably over the last 25 years to give a 10-fold reduction in IFSD rates (1); failure rate predictions should be able to take this into account by considering reliability growth.

Traditional reliability growth models are generally used during the development phase of a project, and incorporate assumptions which are unrepresentative of products after entry into service, such as immediate incorporation of design improvement after a failure, and a homogeneous population of components in operation. However, Collas has advocated the use of the reliability growth approach throughout the product life cycle (for mainframe computers), and discusses the analysis of non-homogeneous data collected from models of different ages and vintages, including the aggregate effects of component reliability growth, improvements in manufacturing processes and evolution of the product support system. He proposes that such an aggregate reliability growth curve be modelled as a function of the number of years since entry into service, rather than of operating hours as originally conceived by Duane (19).

A database of Service Difficulty Reports leading to In Flight Shutdowns in the CF6 fleet from 1973 to 1985 was compiled and used to assess methods of failure rate prediction; this was comprised of over 1200 events, which was felt to be enough to make valid statistical comparisons. Details of the analysis can be found in Appendix F; the results are summarised below.

The annual rate of service difficulty reports (per engine hour) decreased from entry into service both for the CF6-6 and the CF6-50. The CF6-6 entered service first and had a higher failure rate. There was considerable random variation from year to year, but the decrease in the failure rate appeared approximately exponential. Both engines experienced a low, but constant rate of induced (non-design related) failures each year. The CF6-80A entered service with the mature failure rate of the CF6-50. Further

review of the high bypass ratio fleet (all engines, all manufacturers) showed that this previously unknown relationship in IFSD rates is a general one; in all cases where data was available, the derivative[23] entered service[24] with an IFSD rate within a factor of three (and usually within a factor of two) of the precursor engine at that time (see Table 6.1). This relationship is hypothesised to be the result of increasing experience and improved design within the relevant design and development organisation; it is not closely related to physical parameters such as thrust (see Appendix H for a detailed exploration of this area).

| PRECURSOR ENGINE | DERIVATIVE ENGINE | YEAR OF DERIVATIVE ENTRY INTO SERVICE | % THRUST GROWTH OF DERIVATIVE | RATIO OF IFSD RATES DERIV/ PARENT AT ENTRY INTO SERVICE |
|---|---|---|---|---|
| CF6-50 | CF6-80A | 1983 | -4% | 3 |
| CF6-80A | CF6-80C | 1986 | +15% | 1.8 |
| CFM56-3 | CFM56-5A | 1988 | +6% | 0.5 |
| CFM56-5A | CFM56-5C | 1993 | +28% | 2.2 |
| SPEY 555 | TAY | 1986 | +31% | 1.4 |
| RB211-22B | RB211-524B | 1977 | +19% | .55 |
| RB211-524 | RB211-535C | 1983 | -25% | .54 |
| RB211-535C[25] | RB211-535E4 | 1985 | +12% | .73 |
| RB211-524D4D | RB211-524G | 1990 | +10% | 2.4 |
| JT9D-7R | PW2000 | 1985 | -25% | 1.43 |
| JT9D-7R | PW4000 | 1989 | +12% | 1 |

TABLE 6.1

---

[23]The precursor/derivative relationship was not necessarily a close one; evolution of design sophistication appeared to be the governing factor rather than the number of similar parts.

[24]first full calendar year statistics, where available

[25]Data for 1986

A reliability growth equation of the form proposed by Smith Industries,

$$\lambda = A + Be^{-Ct}$$ [26]

was found to model the behaviour of engine failure rates in service (as measured by SDR reports). When the parameters A,B,C were empirically derived from the in-service data, all but 1 data point per parameter set fell within the 90% confidence bounds for this equation. Table 6.2 gives derived parameter values for this equation, using a least mean squares fit to the data.

| | A | A | B | B | C | C |
|---|---|---|---|---|---|---|
| | Mean | Range | Mean | Range | Mean | Range |
| All SDRs CF6-6 | 1.06E-5 | 0.46 - 1.65 E-5 | 1 E-4 | .65 - 1.5 E-4 | 3E-8 | 2E-8- 4 E-8 |
| All SDRs CF6-50 | 0.86E-5 | 0.71 - 1.01 E-5 | 7 E-5 | .45 - 1.0 E-4 | 5E-8 | 4E-8- 6 E-8 |
| New SDRs CF6-6 | - | - | 2.7E-5 | 1.3 - 5.4 E-5 | 8E-8 | 6E-8 -1 E-7 |
| New SDRs CF6-50 | - | - | 2 E-5 | .74 - 5.2 E-5 | 8E-8 | .55 - 1.1 E-7 |

Table 6.2

Carter has objected to the use of reliability growth to forecast the behaviour of a product subject to major design changes, on the grounds that no model could account for the results of such a change. This viewpoint is theoretically correct, yet it is evident empirically that both jet engines and mainframe computers (Collas, 60) do, indeed experience reliability growth despite major design changes. A partial explanation for this phenomenon may be found in the rigorous internal disciplines of the design establishments for products where a single system failure may result in a financial loss of tens of millions of dollars. Before a major design change is incorporated into a jet engine, it is formally audited at several stages of its evolution by the most experienced and astute technical experts in the company (61). The design may be audited for compliance with compliance with company design practices, which codify the company's experience of good and bad designs over several decades. Abusive testing locates any problems in areas not subject to analysis. The net effect of this screening

---

26 $\lambda$= incidence of SDRs per engine hour

A = random failures unrelated to specific design or manufacturing problems, e.g. maintenance error or birdstrike

t= fleet hours summed over all models

process is that most of the components have a negligible failure rate both before and after the design change. The components with an initial unacceptable failure rate have received sufficient unfavourable attention that in most cases the new design incorporates measures to substantially reduce the failure rate. The key to answering Carter's objection lies in acknowledging that for high reliability systems, the system will demonstrate reliability growth through the course of design changes if a few of the least reliable components - upon which attention is focused - improve in reliability, and no really bad mistakes are made with the other components. It is not necessary for every component to experience reliability growth.

Reliability growth trending has been established above as a valuable means of predicting aggregate failure rates at entry into service, but the utility of the approach for specific safety-related failures must also be established. The service history of uncontained[27] failures was therefore reviewed for high bypass ratio engines in the commercial transport fleet. The reliability growth behaviour observed for SDRs was also seen for uncontained failures. The second generation high bypass fleet appear to enter service with uncontained failure rates very similar to those of the mature first generation engines at that time, just as was the case for IFSDs. It follows that reliability growth techniques appear valid for predicting the rates of uncontained failures for new engine models at entry into service.

### 6.5.2 Component Failure Rates

A fundamental issue in safety analysis is that of whether to address component failures individually, or to treat all instances of a certain type of failure as a statistical aggregate. Identification of individual component failure modes affords greater technical understanding of system behaviour and shows more promise of directing the attention of the designer to areas of potential weakness, and thus improving the overall design, yet the task of quantifying the failure distribution for each component in the engine is a formidable one, much of which would produce results irrelevant to safety-related failures. Grouping failures of a given type (such as all disc failures) renders numerical prediction very much easier, yet the result may be of very limited value to the designer who wishes to reduce the incidence of such failures - there is nothing in such an aggregate result to direct him or her to the components or issues most likely to cause problems.

---

[27] Uncontained failures were selected because they are the major contributor to propulsion related accidents and therefore form an important indicator of propulsion system safety. Accurate statistics on uncontained failures were available in the SAE studies AIR 4003, AIR1537, AIR 4770 (Refs. 50, 51, 52).

An attempt was made to predict failure rates for engine submodules such as HPC blades and vanes, using a similar approach to that employed for engine-level analysis. Details of the analysis appear in appendix F. The submodules with the highest initial failure rates showed reliability growth over time and from one engine model to the next. Those which had relatively low initial failure rates were less predictable in their behaviour.

Although the high reliability of individual components results in statistically sparse data, making the reliability growth techniques above impracticable at the component level, there may still be a need to forecast failure rates at the component level. The following approach is therefore proposed:
Consider an engine with a known failure rate, comprised of N components. Some number (M) of these will never have caused an inflight shutdown in the history of the fleet (X hours). Making the classic assumption of a failure tomorrow for each of the M components would be unrealistic, resulting in M unprecedented failures all occurring at once. It would be more reasonable to assume one failure tomorrow, and to divide it out equally among the M components. Each of the M components has an assigned failure rate of 1/MX.
For the remaining N-M components (these have each actually experienced a failure at some time), a reasonable approach is to take the forecast failure rates for each submodule and divide it amongst the submodule components not already addressed. The division may be done equally among components, or if the results are sufficiently critical to the outcome of the analysis as a whole, the allocation may be weighted in proportion to past failure rates.

### 6.5.3 Effect Of Flight Phase On Failure Rates

Failure rates are generally averaged over the flight without regard to the effect of flight phase upon the likelihood of a given failure. If the outcome of a failure depends strongly upon the external circumstances such as the flight phase, consideration should be given to factoring the failure rate so that it is more truly representative of the phase of interest. The effect of flight phase can be very significant, as demonstrated in Table 6.3; the severity factors presented may be used to convert an average failure rate to a flight-phase dependent rate for the types of failures shown. It should be recognised that the factors calculated in table 6.3 are based on an average fleet and flight profile. Individual engine models and specific failure modes would each have a separate set of factors which would better represent the engine behaviour. The factors presented are nevertheless more representative than a simple average over the flight.

The physical and technical reasons for the variation of failure rate by flight phase are discussed further in appendix F.

| PHASE | % time exposure (48) | % IFSDs (47) | IFSD factor | % uncontained failures (35 - 44) | Uncontained factor | % fires | Fire factor | % component separation | Separation factor | % all-engine power loss | Power loss factor | % case rupture | Rupture factor |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| T/O | 1 | 4 | 4 | 43 | 43 | 12 | 12 | 23 | 23 | 8 | 8 | 77 | 77 |
| Climb | 14 | 31 | 2 | 30 | 2 | 42 | 3 | 34 | 2.5 | 22 | 1.6 | 0 | 0 |
| Cruise | 60 | 37 | 0.6 | 21 | 0.4 | 20 | .3 | 7 | .1 | 32 | .5 | 15 | .25 |
| Descent | 10 | 19 | 2 | 3 | 0.3 | 1 | .1 | 0 | 0 | 6 | .6 | 0 | 0 |
| Approach /Landing | 15 | 9 | 0.6 | 4 | 0.3 | 6 | .4 | 15 | 1 | 5 | .3 | 0 | 0 |

Table 6.3 Severity Factors

### 6.5.4 Summary of Failure Rate Prediction

Engines exhibit reliability growth after entry into service, not only during the formal development cycle. This reliability growth continues from one engine model to the next, so that a derivative engine enters service with inherent "maturity". This effect appears to hold true for all three of the major engine manufacturers for which data was available.

The IFSD rate of an engine may be predicted at entry into service by applying reliability growth techniques to previous engines produced by the same manufacturer. The prediction is likely to be within a factor of two of the measured value.

For any given submodule, reliability growth from parent to derivative engine cannot be universally assumed at entry into service. The "Worst" submodule of the parent engine will exhibit significant reliability growth, both within the model and in the transition from parent to derivative. It is likely that at least one submodule of the derivative will have much worse reliability than it did for the parent, but this will still be higher reliability than that of the parent's worst submodule.

Component reliabilities are so high that insufficient failure data can be accrued to apply reliability growth techniques generally with confidence in the results. Estimates of failure rates for individual components can be made by allocating out the submodule rate. Special consideration is required for the subset of components which have not failed in the fleet experience.

Failure modes more directly related to safety are infrequent and therefore difficult to trend. Reliability growth techniques may provide a useful estimate of rates at the engine level as shown for uncontained failures; dividing rates between submodules or components is unlikely to prove dependable.

## 6.6 Summary Of Recommendations For Alternate Approach

1. The safety analysis should attempt to predict failure rates and accident rates which will actually be experienced in service, since this approach offers the greatest opportunity to actually reduce accident rates.

2. The scope of future analyses should be expanded to address all of the following major contributors to the accident rate:

Uncontained engine failures (26% of propulsion related accidents ).
Propulsion-related crew error (23% of propulsion related accidents ).
Thrust control problems including autothrottle failures and asymmetric thrust (10% of propulsion related accidents ).
Engine fire ( 11% of propulsion related accidents).

The safety analysis should give consideration to the autothrottle system, the fuel delivery system and the flight crew, so far as they enable propulsion system operation.

3. Failure effects which have not yet resulted in accidents in service need not be addressed, unless novel aspects of the design make such effects much more likely. The requirements of the certification regulations may be met in these cases by a statement of previous service experience and similarity of the proposed system to those previously certified. The historical record shows that single initiating failures in conjunction with adverse circumstances are much more significant than combinations of independent failures. The analysis should be structured accordingly.

4. The historical accident rate for non-contained rotor bursts should be used. Credit may be taken for the state-of-the-art of engine design (e.g. first generation vs. second generation high bypass ratio engines) and for specific airplane installation measures to reduce risk (up to 25% reduction in this accident rate).

5. A baseline accident rate attributable to crew error in handling propulsion systems (failed and unfailed ) is 1.14E-7/airplane flight hour. Credit should be taken for specific airplane installation measures to reduce risk.

6. Engine fire should be addressed by a review of service experience to identify means of risk mitigation other than those already in place.

7. Engine separation while the engine is running, in flight, may be addressed elsewhere, by analysis of the engine trajectory and resulting damage, and by AC 25.571-1A (62) on engine mount damage tolerance .

8. The historical accident rate associated with thrust control should be used. Evaluation of the thrust reverser reliability may significantly alter this rate.

9. Table 6.4 presents some specific means of mitigating the risk for some accident causes, together with the relevant accidents and proposed "credit". This is not a complete list of mitigating features.

10. Details of the propulsion system design should be reviewed qualitatively, to establish that it affords a similar level of safety to previous designs and that the use of historical failure rates is valid.

11. Service experience with a similar application and environment [28]should be used to derive component failure rates .
Aggregate failure rates for groups of components (e.g. assemblies or modules) should be used wherever possible. Analysis in great depth should be avoided, since it will not predict those components with abnormally high failure rates due to design problems, while giving a false impression of precision.

12. Average failure rates should be used throughout the analysis, except that severity factors may be used to account for variation of failure rate with flight phase. Mean component or assembly failure rates should be calculated.

13. Reliability growth from one engine model to the next should be used to forecast IFSD rates at entry into service. The prediction is likely to be within a factor of two of the measured value.

14. Reliability growth techniques should be used to estimate infrequent, safety-related failure effects at the engine level only; dividing rates between submodules or components is not recommended.
Relatively frequent failures (IFSDs) may be forecast at the submodule level at entry into service, to a limited extent. Submodules making a major contribution to the parent engine failure rate will exhibit significant reliability growth. Submodules making minimal contributions to the parent failure rate may have worse reliability than for the parent.
Estimates of failure rates for individual components can be made if absolutely necessary by allocating out the submodule rate. Special consideration is required for the subset of components which have not failed in the fleet experience.

---

[28] This should include the incidence of manufacturing defects, maintenance-induced damage, unsuccessful maintenance, improper procedures by the flight crew and so forth that has actually been observed in a similar environment.

| Mitigating feature | Relevant accidents | Associated accident rate (per 100 million airplane hours) | Estimated Effectiveness | Credit Assigned (per 100 million airplane hours) |
|---|---|---|---|---|
| Credible engine vibration monitoring | 23, 29, 52, 53 | 2.9 | 50% | 1.5 |
| Enhanced simulator training - multiple systems failures | 4, 23, 29, 53, 64 | 3.7 | 20% | .7 |
| Enhanced simulator training - engine failure @ V1 | 8, 9, 13, 17, 33, 47, 51, 52, 54, 61, 76 | 8.0 | 50% | 4.0 |
| Local armour/ separation for critical systems | 4, 23, 24, 29, 56, 66 | 4.4 | 40% | 1.8 |
| Engine fail light (sub-idle) | 30, 33, 39 | 2.2 | 40% | 0.9 |
| Engine fail light (about to fail) | 21, 27, 30, 33, 39, 51, 53 | 5.1 | 60% | 3.1 |
| Go-around alert | 83, 86 | 1.4 | 80% | 1.1 |
| Prevention of inadvertent all-engine IFSD | - | | | |
| Thrust asymmetry annunciation | 1, 17, 22, 32, 39, 40, 45, 57, 74, 83 | 7.3 | 40% | 2.9 |
| Prompt reverser deployment | 82 | 0.7 | 80% | 0.5 |
| | | | | |
| Maximum Credit possible | | | | 15.6 |

Table 6.4 Estimated Credit for Features Mitigating the Risk of Propulsion Related Accidents

15. Since the approach outlined above attempts to predict and mitigate accident causes in a conscientious and realistic manner, it is likely that it will result in less exposure to product liability litigation. The approach permits identification of potential problems in a timely manner, enabling them to be resolved before airplane certification.

16. The principles of the above approach, although generated using data from high bypass ratio commercial transport aircraft, are generally applicable to other aircraft propulsion systems. (Consideration of causes of actual accidents, limiting the depth of analysis to that essential to generate valid numbers, consideration of crew error and manufacturing defects, and so forth). The details would require modification for other types of propulsion system; for example, quantification of failure rates would be subject to considerable uncertainty if the propulsion system incorporated unique and novel design changes without prior service experience.

THIS PAGE INTENTIONALLY BLANK

# 7.0 VALIDATION OF RECOMMENDED ANALYSIS IMPROVEMENTS

## 7.1 Introduction

The recommendations made in Chapter 6 were primarily based on the service experience of the high bypass ratio fleet, observed throughout the 1970s and 1980s. However, it was considered essential that the validity of these recommendations be tested by applying them to an engine/airframe combination which had made a minimal contribution to the original data, to establish whether the recommendations were generally valid or only applied to the special case of the propulsion system database used to generate them in the first place. In view of the commercial sensitivity of such a prediction in today's intensely competitive marketplace, the engine and airplane have been de-identified.

The validation propulsion system (system $X_{der,}$ as in derivative) was selected as such for the following reasons:

- This installation went into service recently enough that it did not appear in the data used for the analyses of chapter 6.

- Service data was readily available for its parent engine models.

- Propulsion system $X_{der}$ has an electronic engine control and engine parameters are displayed in a "glass cockpit" style flight deck. This will be typical of many future engine/airframe combinations; it is therefore essential that any recommendations regarding safety analysis approaches should be valid for such installations, in which control signals are transmitted by databuses rather than mechanical throttle cables and the capability exists for specific flight deck text messages relating to an engine conditions, rather than a warning light or gage.

## 7.2 Validation Engine ($X_{der}$) Description

The validation engine (engine $X_{der}$) is a two-spool high bypass ratio turbofan rated in the 60 to 70,000 lb. takeoff thrust range. It entered service in the early 1990s, and is a close derivative of an engine (engine $X_{parent}$ as in parent) which entered service in the mid 1980s.

Significant changes from engine $X_{parent}$ to engine $X_{der}$ are as follows:

- Increased fan diameter, number of fanblades reduced slightly.

- Booster pressure ratio increased by 12%.

- High temperature alloys used for the 14th stage of the HP compressor and the HP turbine. HPT rotor strengthened and cooling flows improved.

- LP turbine redesigned to improve efficiency and cooling flows.

- Second generation Electronic Engine Control .

- Fuel system staging valve to improve low power operability.

## 7.3 Aircraft ($X_{der}$) Installation Details

The engine is conventionally installed in an under-wing configuration on a twin-engined medium/long range wide-body transport aircraft. The aircraft features many automated systems intended to improve overall safety and reliability such as:

- Fly-by-wire

- Electronic flight deck

- Redundant fuel system monitoring computers controlling fuel transfer and balance

- Autothrottle

-Flight Management Computers

The architecture of these systems is conventional as regards the power plant and thrust control functions, and is closely based on that of previous aircraft produced by this manufacturer. In particular, engine to engine isolation is maintained between control systems.

## 7.4 Prediction Of General Reliability of Propulsion System $X_{der}$

### 7.4.1 Prediction at Entry into Service

It was proposed in Chapter 6 that the reliability of an engine at entry into service could be predicted by reference to the reliability at that time of a previously certified, related engine model. The annual rates of significant Service Difficulty Reports (here defined as IFSDs and RTOs) were tracked for engine $X_{parent}$, (same engine family as engine $X_{der}$). Figure 7.1 shows the results (data only).

Figure 7.2 shows the same results with an equation of the form proposed by Smith Industries fitted to the data, using a least mean squares technique. It is concluded from Figure 7.2 that the significant SDR rate for propulsion system $X_{parent}$ is 12/million hours, and lies between 8 and 15 per million engine hours with 90% confidence. Based on the empirical relationships developed in Chapter 6, propulsion system $X_{der}$ is predicted to enter service with a significant SDR rate between 6 and 20/million hours. The accuracy of this prediction will be evaluated below (section 7.6).

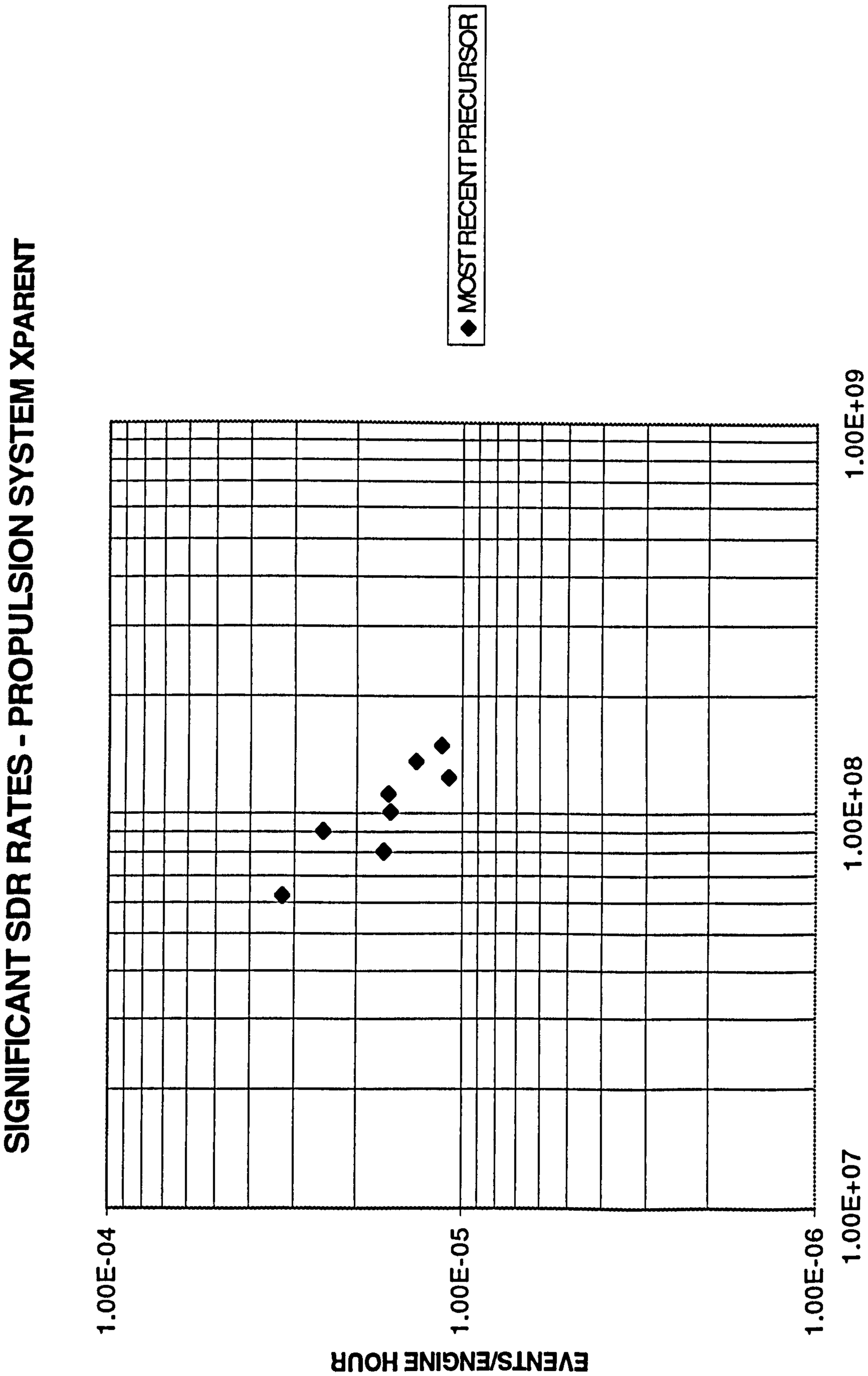

SIGNIFICANT SDR RATES - PROPULSION SYSTEM XPARENT
◆ MOST RECENT PRECURSOR
EVENTS/ENGINE HOUR
1.00E-04
1.00E-05
1.00E-06
1.00E+09
1.00E+08
1.00E+07
TOTAL FLEET HOURS

FIGURE 7.1

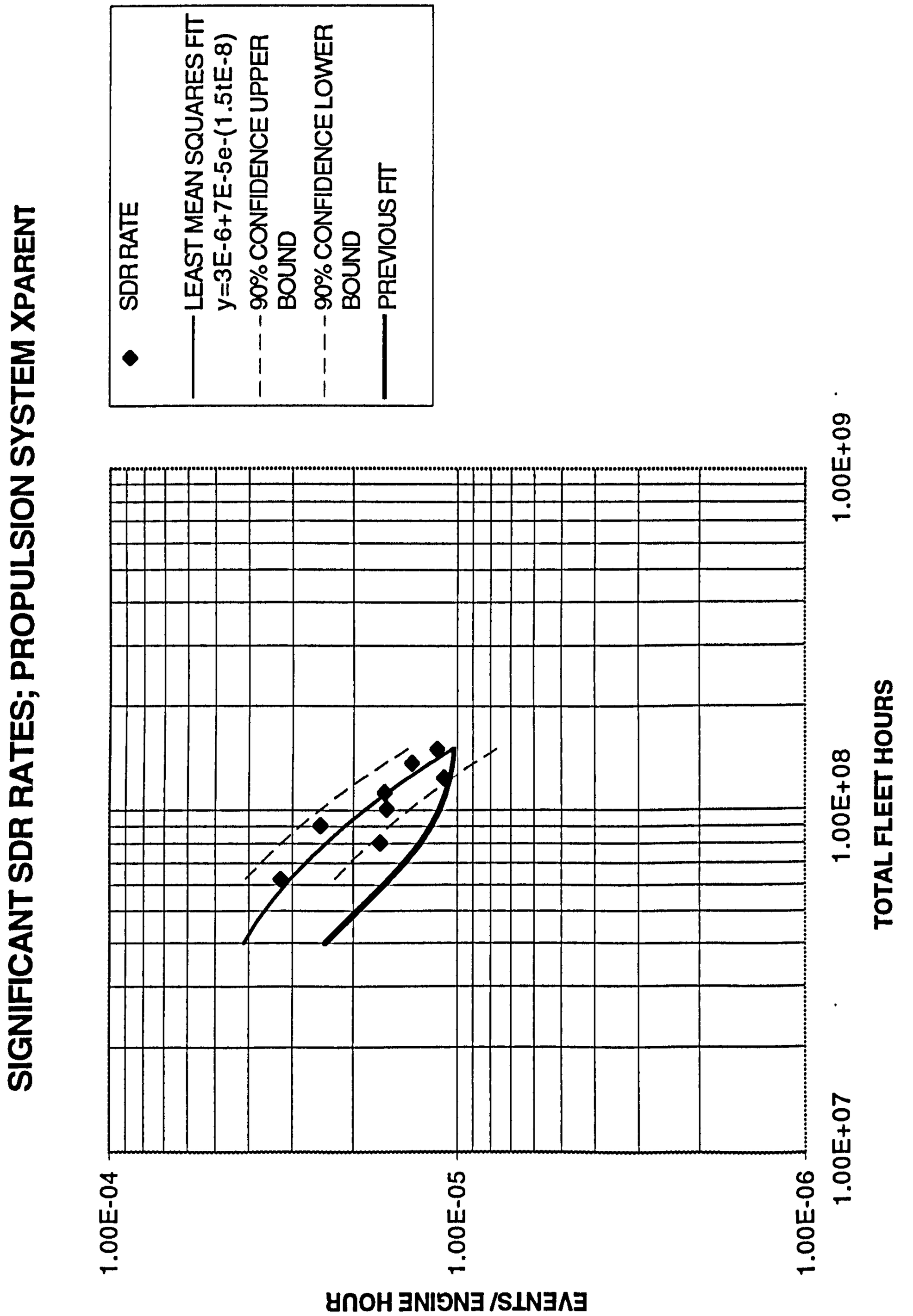

SIGNIFICANT SDR RATES; PROPULSION SYSTEM XPARENT
SDR RATE
LEAST MEAN SQUARES FIT
y=3E-6+7E-5e-(1.5tE-8)
90% CONFIDENCE UPPER BOUND
90% CONFIDENCE LOWER BOUND
PREVIOUS FIT
1.00E-04
1.00E-05
1.00E-06
EVENTS/ ENGINE HOUR
1.00E+08
1.00E+09
TOTAL FLEET HOURS
1.00E+07

FIGURE 72

### 7.4.2 Long Term Prediction

It was noted in Chapter 6 that an engine family reliability growth characteristic was well represented during the first fifteen years of operational experience by the Smith Industries equation:

$$\lambda = A + Be^{-Ct}$$

Values of A, B and C for the first 40 million engine operating hours were empirically established in Chapter 6 using least mean squares (or arithmetic average in the case of A) as:

A=8 to 10 E-6 /hour
B=1E-4 /hour
C=3 to 5E-8

In order to establish whether these constants would continue to predict engine family behaviour indefinitely, the Smith equation with the empirically derived constants was tested against the behaviour of engine $X_{parent}$ in the 1990s, by which time the fleet experience was approaching 150 million hours. It was immediately evident, on calculating the failure rates for $X_{parent}$, that A (corresponding to the rate of random failures induced by external events such as bird ingestion, maintenance errors etc.) was significantly lower than the value observed for the propulsion systems modelled in Chapter 6. An average value of A was calculated at 3E-6 /hr for $X_{parent}$ . This reduction is a reflection of technical advances being incorporated into the propulsion systems to make them more resistant to such induced failures, as had been speculated in Appendix F.
For large values of t, the value of B is not critical. The previously derived value was therefore retained.
It was also noted that the previously derived value of C (approximately 4E-8) was no longer valid as t grew large (over 100 million hours). A new value of C was therefore derived empirically from the measured failure rates for $X_{parent}$, using a least mean squares approach, and found to be 1.5 E-8. The new equation describing reliability growth of the preceding engine model is

$$\lambda = 3E\text{-}6 + 1E\text{-}4\ e^{-1.5E\text{-}8t}$$

The extent to which the new equation models the data (with upper and lower 90% confidence bounds) is shown in Figure 7.2. The prediction of the equation using the Chapter 6 constants is also shown, for comparison (it predicted service experience within a factor of 2, which is reasonably good agreement for a ten year forecast). It may be concluded from this experience that as t continues to increase, the current constants will describe the propulsion system reliability growth somewhat less accurately, and new values of constants A, C may need to be derived. The current constants (A= 3E-6, C= 1.5E-8) should remain useful for the next 100 million engine hours.

## SIGNIFICANT SDR RATES; PROPULSION SYSTEM XPARENT

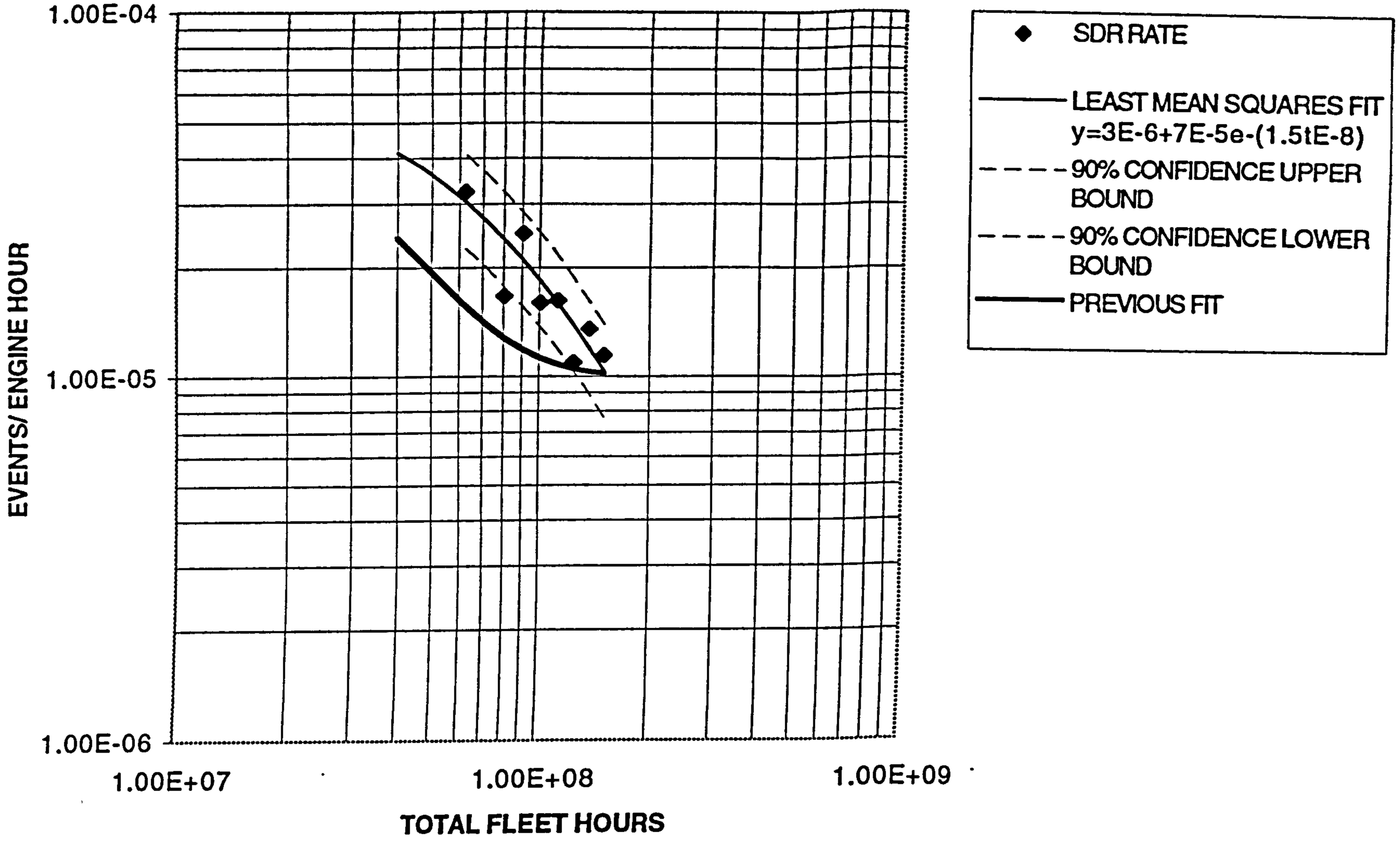



*FIGURE 7.2*

## 7.5 Prediction Of Specific Engine-Level Failure Modes and Resulting Accident Rate Forecast for Propulsion System $X_{der}$

This forecast is based on the data available up to the year before entry into service, at which point the safety analysis would be expected to be complete.

### 7.5.1 Uncontained engine failures ($X_{der}$)

Engine $X_{der}$ is a second (or possibly third) generation high bypass ratio turbofan. The incidence of uncontained engine failures for this type of engine, based on the industry -wide SAE study (52) may be estimated as 1.6E-7/engine hour (for the time period 1985 -1989). The rate of non-contained events for this engine at entry into service may therefore be estimated as close to 2E-7/ engine hour; equivalent to 4E-7/ airplane flight hour.

The hazard ratio derived in Chapter 6 indicates that 6% of uncontained events result in accidents[29]. The airplane was designed and went into production before the intensive industry study (AC 20-128 under ARAC) of means to mitigate the hazard of non-contained debris, and does not incorporate the specific mitigating factors enumerated in 3.5; the above hazard ratio is therefore likely to be reasonably representative.
Based on the above assumptions, the accident rate resulting from non-contained failures for the validation propulsion system might be predicted to be in the range of 2.4E-8 /airplane flight hour, compared with a historical average of 1.6E-7/ airplane flight hour (equivalent to a "credit" of 1.36E-7/airplane flight hour).

---

.[29] This is an overall hazard ratio, based on non-containment of both small parts like blades and large, high energy parts such as disks. It could be argued that more specific hazard ratios, relating to disks and to blades separately, would give a more precise prediction (accidents have only resulted from disk failures so far in the high bypass fleet). However, there is insufficient data (to the time of certification) to reasonably predict the rate of uncontained disk failures for this engine, and therefore generic hazard ratios and failure rates are used here.

### 7.5.2 Propulsion Related Crew Error ($X_{der}$)

The baseline rate, derived above in 6.4, for crew error in handling propulsion systems is 1.14E-7/airplane flight hour. The high reliability of second generation turbofans will result in fewer unanticipated engine failures likely to produce crew error. It may be argued that against this must be offset the limited experience of flight crews in dealing with such eventualities; yet even in the early days of jet transport, engine reliabilities were such that a pilot might only encounter a jet engine failure once or twice in his life - flight crews have never been accustomed to engine failures on large commercial jet aircraft.
Credit may be taken for reliability of the propulsion system as follows: the high bypass fleet historical average failure rate (IFSDs plus high speed RTOs) is estimated as 90 per million hours. The equivalent rate for this propulsion system has been estimated above as 12/million hours. This would apparently reduce the incidence of propulsion related crew error accidents by 87%. Even if it is assumed that the crew is twice as likely to react incorrectly to a propulsion failure, an overall credit of 40% (4.5E-8) should be attributed to increased reliability.

Specific features of the airplane flight deck which may alter this rate include the following:

Engine failure indication

ENG FAIL message with single chime and master caution light. Enabled during all phases of flight, when an engine core speed drops below idle. There is also a separate ENG SHUTDOWN message to announce that the crew has shut down an engine (same chime, master caution light).
There is also an ENG STALL message with single chime and master caution light, which is inhibited during the critical phases of flight (takeoff roll from 80kts to 1500 ft, approach from 800 ft to 80 kts).

In the event of an engine failure resulting in a high speed rejected takeoff and accident, a review of DFDR data/accident reports indicates that the flight crew responds very quickly to a loud bang or vibration. The response time (to retard the throttles and reject the takeoff) was typically 1 to 3 seconds, so the actual decision by the crew may be considered "immediate". The core of a high bypass engine may take from 5 to 7 seconds to spool down below idle from an initial takeoff power setting after an engine failure; in the case of a bird ingestion which only impacts the fan[30], the core may not spool down at all. It follows that an engine failure indication based on the core spooling down sub-idle is likely to appear too late to assist the flight crew in their decision, and will have no

---

[30] 30% of propulsion-related accidents resulting from high speed rejected takeoffs are caused by birdstrike.

effect on the incidence of high speed rejected takeoffs. An engine failure indication would have to appear within substantially less than a second of the bang or vibration in order to contribute to the flight crew's decision.

The record shows some accidents occurring during other flight phases as a result of the crew being uncertain of the engine status (ACC30, ACC39, ACC53). The appearance or non-appearance of an engine failure indication would have been of some assistance in these cases, and sufficient time was available for methodical evaluation of the situation. In two of these accidents, the "core sub-idle" implementation of an engine failure indication would have been technically effective, in the third, the "ENG STALL" message would have been effective. Assuming a 50% effectiveness for crew recognition of this information, these messages are credited with a reduction of 1.1E-8/airplane hour.

Autopilot/autothrottle mode annunciation/go around

The thrust limit mode (e.g. TOGA) selected by the thrust lever is displayed in blue at the upper right corner of the primary engine parameter display. In some circumstances (alpha floor protection) go-around thrust may be commanded regardless of throttle position, in this case messages "A FLOOR" and "TOGA LK" are displayed, surrounded by an amber flashing box.

Pending review by human factors specialists, a visual indication is not considered sufficiently compelling to completely prevent the type of confusion observed in ACC83 and ACC86.

Asymmetric thrust

The airplane has no direct indication of different thrust being produced by left and right hand engines.

If the airplane is in autothrust mode, LVR ASYM amber caution message will be displayed if one of the two thrust levers is set at takeoff or max. continuous power while the other is set in the climb/cruise/idle range.

Both N1 commanded by the FADEC and actual N1 are displayed on the primary engine parameter display for each engine. The discrepancy between the two is highlighted if autothrust is active.

If the engine FADECs select different thrusts for takeoff, a message ENG TO THRUST DISAGREE is displayed, with a single chime and master caution light.

Three accidents involving asymmetric thrust did not involve reverse thrust (ACC39, ACC57, ACC74). One involved a crew aware of asymmetric thrust, who did not provide the requisite input to the flight controls to maintain the flight path. None of the flight deck annunciations incorporated in this airplane would prevent such an event. One involved slight thrust asymmetry in the takeoff roll; the ENG TO THRUST

DISAGREE might possibly have been effective in preventing this event. One involved an engine which did not spool up when the throttles were advanced; the resulting thrust asymmetry went unnoticed by the flightcrew. None of the caution or advisory messages provided here would appear effective in preventing this event. It may be concluded that the incidence of asymmetric thrust-related accidents for this propulsion system is likely to be unchanged from the baseline, historical figure.

Prompt reverser deployment ($X_{der}$)

The validation airplane thrust reverser logic requires an indication of main gear compression to enable reverser deployment on command; signals indicating each shock absorber (left and right main landing gear) is not compressed disable the reversers until the airplane was level and on the ground. No credit should therefore be given for "means to enable prompt reverser deployment".

It is concluded that the rate of propulsion related accidents associated with propulsion failure followed by crew error may be forecast as the baseline rate (1.14E-7/ airplane flight hour) minus credit of 4.5 E-8 for increased propulsion system reliability and of 1.1E-8 for engine failure messages - that is, a rate of 5.8E-8/airplane flight hour.

### 7.5.3 Thrust Control Difficulty ($X_{der}$)

The majority of accidents resulting from asymmetric thrust involved reverse thrust on one side of the aircraft and forward thrust on the other, producing a turning couple. The thrust reversers are controlled independently for the two engines of this airplane. Redundant sensors in the reverser translating cowls indicate to the FADEC when the reverser is in the process of deploying. The FADEC will not command the engine to produce thrust greater than idle during the reverse cycle until the reverser is almost deployed. It is therefore extremely unlikely that a thrust reverser malfunction could result in unwanted high forward thrust on one engine when the flight crew had commanded reverse thrust. Credit should be given to this logic of 1.5E-8/airplane hour.

It is also likely that increases in overall reliability of propulsion subsystems will actually improve this rate compared to the baseline, but insufficient details on thrust control architecture are available to determine the magnitude of this effect. It is therefore proposed that a baseline rate of 5E-8/airplane flight hour be used for thrust control accidents (average historical rate both for the total twin fleet and for the specific airplane manufacturer's twin fleet), as opposed to the overall baseline of 6.1E-8/airplane hour. Applying the above credit results in a reduced accident rate of 3.5E-8/airplane hour for thrust control difficulty.

### 7.5.4 Engine Fire ($X_{der}$)

The baseline accident rate for propulsion system fire is 6E-8/ airplane flight hour. Insufficient detail was available in the public domain to establish the detailed circumstances of four of the eight accidents contributing to this historical accident rate.
Two of the remaining four accidents were caused by the response to the fire rather than by fire damage itself; a similar response could have resulted from a false fire warning (and has, in fact, done so).
One accident resulted from a fire in the strut area. This contains the main fuel inlet line, electrical cabling supplying power from the engine to the airplane, and hot air ducts. It has no dedicated fire detection or fire extinguishing, either on the airplane involved in the accident or on the validation airplane.
One fire was associated with an uncontained engine failure, the relative damage caused by the fire and by the ejected debris is not known.

Of the four accidents where some details were available regarding the origin of the fire, no fundamental design changes can be identified which would prevent recurrence of these events for the validation propulsion system. It is therefore proposed that the baseline rate accident rate for propulsion system fire be used for the validation propulsion system.

### 7.5.6 Overall Propulsion Related Accident Rate Forecast for Propulsion System $X_{der}$

The historical overall propulsion related accident rate for high bypass ratio turbofans is 5.9E-7/airplane flight hour. Credit reducing that rate may be attributed as follows:

| Mitigation | Reduction from baseline (per airplane flight hour) |
|---|---|
| Low uncontained failure rate | 1.36E-7 |
| Eng fail messages | 1.1E-8 |
| Engine reliability (fewer crew errors) | 4.5E-8 |
| Thrust control logic in reverse | 1.5E-8 |
| Total credits | 2.07E-7 |

The overall propulsion-related accident rate forecast for propulsion system $X_{der}$ is therefore approximately 3.8E-7/ airplane flight hour; a 35% reduction below the historical average for the high bypass commercial transport fleet.

## 7.6 Validation Propulsion System $X_{der}$ Service Experience

Propulsion system $X_{der}$ has acquired over 100,000 engine hours (50,000 airplane hours) in service to date. It has experienced:

- No RTOs
- No IFSDs
- No uncontained engine failures
- No Fires
- No events involving thrust control difficulty
- No propulsion related accidents of any kind.

Although a much longer period of service experience would be required to verify all of the rates predicted in 7.5 (of the order of 50 million hours) the service experience so far does enable upper bounds to be placed on the actual rates for comparison with those predicted.

### 7.6.1 General Reliability - Service Experience of $X_{der}$

If the assumption is made that an IFSD or RTO occurs tomorrow on propulsion system $X_{der}$, an estimate of the significant SDR rate may be made as 1E-5/engine hour. Since no such event has in fact occurred, the use of confidence levels in connection with this estimate is not felt to be justifiable.[31] The measured rate of 1E-5/engine hour or less is completely consistent, so far, with the predicted range of 6E-6 to 2E-5/engine hour made in 7.4.

It is theoretically possible that the measured rate could be very much lower than 1E-5, such as 1E-6/engine hour. The most reliable propulsion systems in service today have basic engine IFSD rates of 3E-6/hour; it is therefore considered very unlikely that the significant SDR rate for the validation propulsion system (including basic engine IFSDs, non-engine IFSDs, and rejected takeoffs) would be lower than 3E-6/engine hour.

It is concluded that the measured SDR rate for the validation propulsion system lies somewhere between 10E-6 and 3E-6/ engine hour, and that the predicted value agrees with the measured value within an "average" factor of two.

---

[31] If an event had indeed occurred, the rate could be estimated to 90% confidence as being between 6E-6 and 14E-6/engine hour, using the standard deviation of the SDR rates for the precursor engine to calculate confidence bounds.

### 7.6.2 Specific Engine-Level Failure Modes and Resulting Accident Rate - Service Experience of $X_{der}$

The service experience accrued so far (50,000 airplane flight hours) is not sufficient to thoroughly validate the predicted rates for accidents and safety significant failures (in the range of 4E-7 to 1E-8). However, an upper bound may be placed on an estimate of the measured rate for total propulsion related accidents and for uncontained failures, by assuming one such event occurred tomorrow.

If such an assumption is made[32], the "measured "rate of propulsion related accidents would be 2E-5/aircraft hour compared to a prediction of 3.8 E-7/aircraft hour. The prediction therefore agrees with the measured rate within a factor of 53. As more time in service is accumulated, a closer estimate may be made of the measured rate and it is anticipated that agreement between measurement and prediction will become very much closer.

If an equivalent assumption to the above is made, the measured rate of uncontained failures would be 1E-5/engine hour, compared with a prediction of 2E-7/engine hour. The prediction therefore agrees with the measured rate within a factor of no more than 50 (it is anticipated that agreement will be seen to be much closer).

---

[32] This is an extremely pessimistic assumption in the opinion of the author. However, it enables an estimate of the worst possible case discrepancy between forecast and measured rates.

## 7.7 Secondary Validation (Propulsion System Y)

It was felt that the very limited service experience of propulsion system $X_{der}$ detracted significantly from the above validation, although it was sufficient to demonstrate the validity of the reliability growth concept as applied to general reliability. A second, supplementary validation was therefore conducted on propulsion system Y. An outline of this validation is given below.

### 7.7.1 Description of propulsion system Y

Propulsion system Y is based on a second generation high bypass ratio turbofan, powering a twin-engine narrow-body commercial transport. The propulsion system entered service in the mid 1980s, and has accrued approximately 10 million engine hours of service experience to date. It was not initially chosen for the validation because comparatively little detailed technical information was available on the engine, propulsion system and airplane as a whole.

The engine is not a close derivative of the previously certified engine, $Y_{parent}$. It is a "new centreline" engine (i.e. the modules were designed ab initio rather than scaled or otherwise modified from a previous existing engine) and is the first large commercial engine produced by this manufacturer to feature an electronic engine control, rather than a hydromechanical control.

The airplane features an electronic flight deck display, generally modelled on previous mechanical displays to maintain commonality with previous aircraft. The engines are mounted conventionally under the wings.

### 7.7.2 Prediction Of Specific Engine-Level Failure Modes and Resulting Accident Rate Forecast for Propulsion System Y

This forecast is conducted using the information which would have been available to analysts at the time of propulsion system. Baseline rates which would have been calculated in the mid-80s are used, rather than those developed in Chapter 6.

Uncontained Failures The industry report 4003 (51) was published in the early 1980s and the data it contains would therefore have been available to the analysts at the time of propulsion system certification. Reference to the published statistics for high bypass ratio turbofans in the commercial transport fleet, given in this reference, would lead to a prediction of an uncontained failure rate of approximately 6E-7/engine hour for this second generation turbofan. The corresponding accident rate

for propulsion system Y, using the hazard ratios developed in Chapter 6, would be 7.2E-8/airplane hour, compared with a baseline of 3.5E-7/airplane hour..

Propulsion Related Crew Error. The mid-80s baseline rate for this type of accident is 8.8E-7/airplane flight hour. No specific flight deck measures could be identified which would mitigate against this failure mode. However, the reliability of the previous propulsion system, $Y_{parent}$, at the time of Y entering into service, was somewhat higher than the overall fleet average (7E-5/engine hour rather than 9E-5/engine hour for a significant SDR rate) and a case could therefore be made for mitigation by general reliability improvement. A credit of 20% reduction to the baseline "Propulsion Failure plus Crew Error" accident rate is therefore used, bringing the forecast rate for this mode down to 7E-7/airplane flight hour.

Thrust Control No measures were identified for this propulsion system which would mitigate the potential for a thrust control accident.

Fire No measures were identified for this propulsion system which would mitigate the potential for a fire-related accident. The mid-80s baseline rate of 8.8E-8/airplane hour is therefore used for propulsion system fire-related accidents. N.B. This corresponds to a rate of 4E-7/engine hour for fires).

Overall accident prediction The mid-80s baseline propulsion system accident rate is 10.5E-7/airplane hour. After credit was taken for mitigating factors as described above, the forecast propulsion related accident rate for propulsion system Y is 5.9E-7/airplane hour, a 44% reduction from the industry baseline rate.

| Mitigation | Reduction from baseline (per airplane flight hour) |
|---|---|
| Low uncontained failure rate | *2.78E-7* |
| Engine reliability (fewer crew errors) | *1.8E-7* |
| Total credits | *4.6E-7* |

### 7.7.3 Service Experience Of Specific Failure Modes And Accident Rate for Propulsion System Y

Uncontained Failures. Review of the available data shows that propulsion system Y has experienced approximately eight[33] uncontained events in 10 million engine hours, corresponding to an uncontained failure rate of 8E-7/hour. This is remarkably close to the predicted rate of 6E-7/engine hour (although the prediction applied to the time of entry into service, and the measured rate is averaged over the last ten years - an approach necessitated by the limited data available). None of these uncontained events has resulted in an accident.

Fires Propulsion system Y has experienced at least two engine fires (excluding tailpipe fires) to date. This corresponds to a rate of 2E-7/engine hour, compared to a prediction of 4E-7. It is believed that some events are likely to have been omitted and the measured rate should be higher; nevertheless, agreement is remarkably close.

Overall Accident Rate There has been one propulsion related accident to date involving propulsion system Y. This corresponds to an accident rate of 2E-7/airplane flight hour. This accident rate agrees very closely (within a factor of 3) with that predicted.

## 7.8 Discussion of Validation

The validation was successful in giving close numerical agreement between predicted failure rates and those actually measured. There was insufficient service experience available to measure every failure rate which could be predicted with this approach, and the statistical sample (of one accident) was too small to enable confidence limits to be placed upon the measured accident rate. However, the agreement was excellent (within a factor of three, where measurements could be made) when compared with the results from a previous approach (Chapter 2 showed agreement within a factor of 10 to a factor of 1000 between prediction and experience).

The validation did not give any insight into system architecture, other than in those specific areas where previous architectural decisions had led indirectly to accidents. It would be entirely possible for a poorly designed system architecture to result in an accident for a completely new cause; this analysis would not be able to predict such an event. Similarly, poor design of a single component could result in an accident under the right circumstances, and it would not be predicted by this type of analysis.

---

[33] Tally based on review of Service Difficulty Reports and Airworthiness Directives. It is very likely that some events have been omitted, but it is believed that the number is of the correct order of magnitude.

## 7.9 Summary of Validation

The following significant features should be noted from the validation presented above:

Reliability growth can be used with assurance to forecast propulsion system failure rates at entry into service, for engine-level reliability as well as for safety specific failure modes such as non-containment.

Propulsion system accident rates can be forecast with assurance, using historical data with credit given for mitigating design factors.

The above approaches apply to new (but similar) engines using existing technology, as well as to close derivatives of existing engines.

The proposed technique produces clear, concise results. It can be applied to a proposed propulsion system and produce results within a very short time span, using information readily available once the propulsion system and airplane flight deck design is defined.

The proposed technique relies heavily on continuity of design philosophy within the propulsion and airframe communities. It could not easily be applied to a truly novel installation with unique system architecture (e.g. a single-engine hypersonic transport powered by a ram-jet).

For propulsion systems powering large commercial transports, in today's design tradition, it offers an opportunity to produce very accurate forecasts with a minimum of resources, and to focus very clearly on prioritisation and appropriate technical design of safety features (mitigating design features).

# 8.0 DISCUSSION

## 8.1 Goals

### 8.1.1 Goals of research

The intent of this research was to establish the major shortfalls in the current approach to safety analysis of high bypass ratio turbofans powering the commercial transport fleet, and to develop an alternate safety analysis approach to address these shortfalls. Significant areas of interest identified at the beginning of the research program were:

- Realism of neglecting human error as a material factor in propulsion system safety (assumption that all parts are produced and assembled to drawing, maintained in accordance with maintenance manuals and the airplane operated in accordance with crew training and published procedures).
- Effect of small design changes upon safety.

### 8.1.2 Goals of safety analysis

The intent of the safety analyses performed in the past has been to demonstrate that the safety of the propulsion system design meets an acceptable standard, and therefore to enable certification of the engine or propulsion system by the airworthiness authorities. This goal presents the following difficulties:

It is not easy to establish whether the analysis is realistic or otherwise. The airworthiness authority may accept it at face value, or may request substantiation of every aspect of the analysis, to the point of checking arithmetical details. Either approach has disadvantages.

The "acceptable standard" was developed based upon the information available in the late 1970s, which may be considered as largely outdated (ref. BCAR paper No. 484 (146)). It should be noted that this acceptable standard is too stringent for any current or past propulsion system to achieve in service.

This approach does not adequately account for the operating environment of the propulsion system.

The results of the analysis clearly conflict with service experience, since the analysis addresses only the "design capability" of the system. This places the analyst in the somewhat awkward situation of justifying that a significant number of observed failure progressions were not caused by the design as such and therefore need not be considered.

It is therefore proposed that the goal be modified to assessment of propulsion system safety by forecasting propulsion-related accident rates likely to be encountered in service, specifically in relation to existing propulsion systems. It is proposed that certification should subsequently be sought on the basis of equivalent safety to existing propulsion systems. Highly desirable features of the alternate safety analysis might include:

Identification of specific safety concerns and areas requiring design changes.
Focusing resources on the failure sequences most critical to safety.
Using data readily available early in the design, so that any necessary changes to design can be made at minimum cost.
Producing new information or understanding of design weaknesses.
Incorporating realistic, defensible assumptions.
Addressing an integrated propulsion system, from basic engine to flight deck.
Reproducible, easily understood results.
Credibility within the design community.

## 8.2 Traditional approaches to safety analysis

### 8.2.1 Overview

The two approaches which have been traditionally used for propulsion system safety analysis are Failure Modes and Effect Analysis (a bottom-up, deductive approach) and Fault Tree Analysis (a top-down, inductive approach). The two techniques are frequently portrayed as one being the inverse of the other: this is indeed the case for the logic required to develop the failure sequence, but there is one significant assumption common to both approaches - the assumption that component level failure rates will be available for quantification. The FMEA assigns failure rates to each component or subsystem failure mode; those resulting in a given effect can then be summed up to give an overall event rate. The FTA graphically depicts all component failures resulting in a given effect; Boolean logic is then used to sum individual component (or subsystem) failure rates to produce an overall event rate. It will be shown below that this assumption contains significant flaws when considering extremely reliable series systems comprised of many components unique to the system under consideration.

The true converse of the FMEA would resemble a fault tree diagram in which the probability of the top event was known a priori. This probability could then be subdivided amongst the contributing event paths (in a similar manner to a reliability allocation process), and the fault tree developed downward to the extent required to identify design features or other controllable factors having a significant effect on the overall probability. Both the traditional Fault Tree and the approach developed in Chapter 6 combine elements of synthesis and analysis. The key philosophical difference between the two is that the fault tree explores the details of hardware failures, taking conditioning events as given. The alternate approach effectively assumes groups of hardware failures at historical rates and explores the potential for reduction of the failure criticality by inhibit gates.

The dichotomy between approaching the issue by synthesis (FMEA) and analysis having been noted, the other major issue to be confronted in the propulsion system safety analysis is the analytical intent, which will determine the ground rules by which the analysis is to be conducted. If the intent is to develop a formal mathematical model of the propulsion system failure process, which is internally consistent and complete, and can then be compared with the results of previous similar mathematical models, then the ground rules used previously should be applied, i.e.:

- Mechanical failures of individual components and cascading failure sequences may be considered.

- Failures are assumed to be independent unless demonstrated otherwise.

- All components are produced and assembled according to the design.

- The propulsion system is operated and maintained in accordance with manufacturers' published instructions.

- The aircraft is flown only within the certified flight envelope by pilots following published procedures.

The above ground rules will provide a reasonable assessment of the design capability of the system (Smith, 54), provided reasonable component failure rates can be obtained. It must be recognised that the concept is a somewhat artificial one, in that the distinction between a maintenance error and a design fault is frequently arbitrary. Many designs are conducive to maintenance error (Norman, 144), to the point where extraordinary skill or care may be required to avoid perpetrating an error. In such circumstances,

taking full credit for the reliability of the hardware whilst neglecting the poor maintainability of the design would appear a significant distortion of reality.

If, however, the analysis is intended to produce realistic forecasts of accident rates and so to enable reduction of the measured accident rates, as described above, completely different ground rules are appropriate. Much of the mathematically correct formalism and completeness of the traditional approach may be neglected as making third or fourth order contributions to the outcome. The data and resources required for the analysis may therefore be greatly reduced or applied to the most productive aspects of the design. Appropriate ground rules for this approach might be as follows:

- Component manufacturing and assembly defects should be assumed at a rate representative of today's technology and operating environment.

- Flight crew error must be assumed at representative rates.

- Maintenance crew error must be assumed at representative rates.

- Component failures which have not resulted in accidents or serious incidents in the past need not be addressed, unless:

  Failure of a single such component would be likely to result in the loss of the aircraft
  or
  The component design or system architecture is unique and is more likely than previous designs to result in loss of the aircraft in the event of a failure.

The merits of traditional approaches to safety analysis must be acknowledged. Both the FMEA and the Fault Tree Analysis promote a careful review of the system or assembly design down to the component level. A component FMEA, conducted by the analyst and designer working together, might or might not uncover design weaknesses which could then be addressed. If the design were subject to a failure mode which had not been considered by the designer (for instance, low cycle fatigue driven by thermal stress), or if the analyst had special information regarding system interfaces, this approach might well be productive. If the failure mode had been considered, and assessed as presenting no problem (due to a misunderstanding or incomplete knowledge of the operating environment and the loads on the component) it

is unlikely[34] that this decision would be revisited by the safety analyst/designer team.
Traditional approaches have been demonstrated to be acceptable during engine and airplane certification. Both fault trees and FMEAs specifically address the requirement that 'no single failure or probable combination of failures' should produce a hazardous effect. Both provide a sufficiently detailed description of the engine and systems design to allow the certifying authority to gain reasonable confidence that the design is indeed conventional, well-understood and of a similar safety standard to previous designs. Furthermore, the results (failure rates) of the fault trees or FMEAs could theoretically be compared to those of previous propulsion systems designs to enable a quantified assessment of comparative safety standards; any departure from the traditional safety analysis approaches would prevent such a comparison.[35]

### 8.2.2 Component Failure Rate Prediction

It has been noted above that the synthesis approach to safety analysis (FMEA and traditional FTA) assumes the availability of individual component or system failure rates. There are a number of approaches to obtaining these failure rates, some of which will be enumerated below. The following points should be considered first since they apply to several of the approaches below:

a) The majority of components comprising the propulsion system are either unique to that propulsion system, or common to that system and one or two similar engine models. Items such as O-rings, nuts, bolts and clamps will have more widespread use, but most of the components are unique.

b) Almost all of the components are very reliable (many thousands of hours between failures). Many of the components never fail in service. For example; an engine will often spend 10,000 hours or more on wing before maintenance to recover lost performance margin. The overall engine life is of the order of 30,000 to 40,000 hours. This shows clearly how most engines never experience a component failure sufficient to cause an IFSD or to affect airplane safety in any way.

---

[34] In practice, if the team were to review and check every assumption or piece of information used in the design, the workload would be prohibitive and the designer would rapidly become frustrated and uncooperative.
[35] The validity of this comparison is questionable, since the overall airplane level effect rates will be strongly influenced by the thoroughness and conservatism used in any individual analysis.

c) Propulsion system development cycles are being steadily shortened to reduce development costs and gain market advantage. Only a few complete engines and flight test airplanes will be involved in the development program.

d) Component testing accurately represents those aspects of the design loading with which the test engineer and designer are familiar, and which the component was designed to withstand. Component testing is less likely to disclose the component response to unforeseen loads.

e) The expense of engine components and mechanical test stands makes it unlikely that a large number of engine components will be tested without some overriding cause for concern.

f) Points b, c and e above imply that there will be at most a few failures of the least reliable components during the development program. These are likely to be redesigned immediately to improve reliability for the propulsion systems to be delivered to airlines. It is not possible to obtain a failure distribution, or even a credible failure rate, for any of the propulsion system mechanical components or subsystems based on development testing.

8.2.2.1 Published Data

It has been noted above that the majority of components are unique to the engine model or a very few engine models. Published data will not be available for the specific component model of interest. It is also noted that there is wide variation in the published failure rates for given components, even those operated in similar environments (Appendix A). Moreover, the published data discovered in the course of the literature search generally dated from the 1960s, and was therefore obsolete.[36]

---

[36] Furthermore, even if these difficulties could be overcome, data is generally presented as a simple failure rate or MTBF. This does not afford any opportunity to establish the scatter in failure rates, a component subject to infant mortality with a very low subsequent failure rate would have a much better long-term failure rate capability than one where all components failed at similar times, although they might average out to the same MTBF.

### 8.2.2.2 Physics of Failure

This approach uses generic failure rates as a baseline and then weights failure rates by environmental severity factors expected to affect failure rates because of the fundamental physics of the failure mode[37]. For example, semiconductor failure rates might be expected to be affected by ambient temperature in accordance with the Arrhenius equation. The difficulty of obtaining initial generic failure rates has already been noted; this approach compounds the difficulty by requiring a forecast of the most significant failure mode before obtaining the failure rate (unless the failure mode is known, the appropriate environmental stress factor cannot be chosen). In fact, the study performed in Appendix H showed no clear relationship between easily obtained physical parameters and engine-level failure rates (and by implication, component level failure rates). It follows that the use of this approach would necessitate very detailed environmental data for every component. It is unlikely that the analyst, who must divide attention between multiple components and systems, would be able to obtain better environmental information than the designer, who has many months to devote attention to a single component and to the environment experienced by that component.

### 8.2.2.3 Mechanical Reliability

The approach to failure rate prediction known as Mechanical Reliability (Carter 23, Bompas-Smith 25, 26) is based on the premise that component failures reflect the overlap between the distribution of loads experienced by a component and the distribution of component strengths in the population.[38] A stochastic approach may then be taken to predicting component failure rates, provided that the distribution of component strengths and that of component loading is completely known, for all load types. Considerable emphasis is placed upon reducing the spread in either distribution as a means of reducing overlap and hence failures.

A version of this approach to component strength is currently being used for certain specific components where integrity is crucial and where material properties have historically made a significant contribution to the failure rate.

---

[37] Assuming the information regarding the failure mode can be developed, it would seem to oblige the analyst to return to the designer and obtain assurance that compensating measures had been taken to ensure that failure rates were not adversely affected by the increased environmental stress. These measures would then invalidate the previous analysis.

[38] The terms load and strength are used here in the broadest sense to include all possible modes of failure.

The resulting analysis addresses material anomalies only using data derived from material test specimens. It cannot be used to address manufacturing defects or maintenance induced damage, since

i) These components are too expensive to test thousands of items in order to derive the "low strength" tail of the distribution

ii) As soon as a manufacturing or maintenance induced defect is discovered, a program is instituted to purge the fleet of any similar items and to prevent recurrence of the problem. Such efforts have been very successful for critical rotating parts such as turbine disks. This corrective action immediately changes the form of the "strength " distribution, which becomes unknown once more.

Difficulties with this approach include the following: The technical effort in developing the detailed load spectra required for every component of a turbofan would be prohibitive. The unavailability of extreme values of loads and strengths has been previously acknowledged by proponents of this technique (Freudenthal 143, Carter 23). Moreover, the utility of deriving every component failure rate by such means in order to develop a system failure rate is extremely questionable, as noted by Carter. His exposition may be summarised in the following points:

1) For mechanical systems, the majority of component failures occur to a few of the components - the 'weak links of the chain'. Pareto data is available to support this statement, both generally (Carter) and for high bypass turbofans (Appendix F). Deriving failure rates for every component would be largely wasted effort.

2) For those components which make significant contributions to the system failure rate, failures may not necessarily be independent, since the same increase in loading may drive failures in different components. This lack of independence invalidates the traditional approach of Fault Tree Analysis/ summing FMEA failure rates to derive system reliability.

### 8.2.2.4 Precursor Data

The use of accident precursor data is based upon the concept that several failures are required before an accident can result. The database of failure rates measured in service can then be used to make realistic forecasts of accident rates. This technique has proved valuable in the nuclear industry, which uses system redundancy and functional redundancy to preclude a serious accident, but is not so easily applied to a series mechanical system.

A similar concept was used by the CAAM committee in the initial development of hazard ratios, which has been incorporated into the alternate approach proposed in this work.

### 8.2.2.5 Reliability Growth

It has been acknowledged that service experience provides the best estimates of failure rates (Martin, Strutt and Kinkead, 87). The work of Chapter 7 and Appendix F shows that the use of a Reliability Growth approach can predict the behaviour of failure rates in service at the overall propulsion system level, and that the failure rate of a propulsion system model at entry into service is closely related to the failure rates of preceding models. This effect may be considered as a reasonable consequence of conservatism and the use of precedent in propulsion system designs, driven by the high cost of development programs and by a desire to facilitate engine and airframe airworthiness certification. . The use of a reliability growth model of the form proposed by Smith Industries permits forecasting of the reliabilities of future engine models with reasonable assurance, up to ten years into the future, providing there is significant service experience with previous engines.

This approach has been shown to be less successful when applied to components or groups of components. Although component groups with high failure rates do experience reliability growth, the same may not be true for all component groups; the failure rate for a group of components may actually increase from one model to the next.[39] The effectiveness of reliability growth modelling as applied to individual components across engine programs is not proven.

---

[39] This pattern may be perceived as a rational use of limited resources to make design improvements where they will most benefit the customer, or as a sporadic, reactive approach to system reliability, depending on the perspective of the observer.

### 8.2.2.6 A Note on Confidence Limits

Many workers in the reliability field have made a practice of specifying high confidence limits (90% or 95% confidence) when quantifying failure rates. This practice is perceived as offering the following benefits:

- Use of high confidence limits will compensate for incomplete reporting on the number of failures which have actually occurred.

- If an additional failure occurs in the near future, any remedial action based on current data will still probably be appropriate if high confidence limits were initially used, all that will be required is a statement of a lower confidence limit.

- The result is perceived as being conservative and therefore 'safer' than a less conservative approach.

- The likelihood and repercussions of the analysis being demonstrated to be incorrect by subsequent field experience is reduced.

The validity of these benefits becomes questionable under closer scrutiny. Recently published work differentiates clearly between statistical variation (to be addressed by confidence limits) and uncertainty (to be addressed by other means). Incomplete reporting - where the extent of the incompleteness is unknown - falls under the heading of uncertainty, and should not be addressed by mandating high confidence limits. Such an approach is likely to produce a misleading impression in the mind of an observer, by a confusion between statistical confidence and credibility.

Moreover, the concept of confidence limits is based on the assumption of a normal distribution of failure rates. When the events being considered are very rare and no physical basis for assuming a normal distribution exists, this assumption is questionable.

A further consideration applies to the practice of specifying high confidence limits. Unless this is done consistently through all calculations and trade studies, it is likely that the results of any decisions made based on failure rates will be biased by the use of the high confidence limits. Since these decisions generally involve weighing benefits against penalties (even safety benefits against safety penalties - more frequent inspection of a part may increase the risk of induced failure in it and surrounding components), overall safety may actually be decreased by this bias.

#### 8.2.2.7 Component Failure Rate Conclusions

It has been shown above that the unique designs of propulsion system components, their reliability and the limited time available for the development cycle place considerable obstacles in the way of producing component failure rates. If an aggregate propulsion system failure rate is considered instead, the problem is greatly simplified. The aggregate rate is so much higher than the individual rates that it becomes measurable within a few years of entry into service (although not within the development program) and the statistical variation of the rate from year to year becomes relatively small (of the magnitude of the rate itself, or less). It is then possible to discern trends over time for the rate, establish relationships between one propulsion system rate and another, and produce forecasts with some degree of assurance.

### 8.2.3 FMEA

The use of an FMEA to predict propulsion system safety was evaluated at the beginning of the study (Chapter 2). It should be recognised that the FMEA is generally acknowledged as a very comprehensive technique, and that since the RB211-22B was the first high bypass ratio engine designed by Rolls-Royce, a comprehensive approach covering all possible failure effects could have significant advantages. Notable difficulties experienced with the technique were:

- Labour expended. This approach addresses every component, regardless of whether it could or could not affect propulsion system safety.

- Volume of output. The large volume of material generated by a propulsion system FMEA makes it difficult to extract the data needed for a safety assessment, since the entire document may need to be reviewed to cover a single failure effect. Kytasty et al have noted that the FMEA approach leads to attention being divided amongst an overwhelming number of individual problem areas, lack of perspective on relative importance of problems and neglect of the potential for creating simple solutions by architectural change.

- Unrealistic failure rates. The failure rates for individual components and failure modes were almost impossible to estimate realistically, even using experienced engineering judgement from the designers most closely involved and service experience from a previous engine model. The reliability of some components is so high that it is outside

normal everyday experience. Although designers may be familiar with the technical capabilities of a component, it may be very difficult to make an apparently rash estimate of a component failure rate of 1E-8 or 1E-9/hour, although many components actually realise these failure rates. There is, therefore, an inherent conservatism associated with engineering judgement, made up of a reluctance to promulgate what appears a wildly optimistic number, a sense that conservatism equates to greater safety, and the general inexperience of most experts in estimating very low failure rates. It has also been noted that the opinions of experts vary widely, so that no overall compensating factor can be made for this conservatism (Mosleh, Bier and Apostolakis, 145). The use of service data from a previous engine model for component failure rates is limited by the difficulties noted in 8.2.2.

- Questionable arithmetic processes. As noted by Carter, summing component failure rates to produce a system failure rate assumes independence of failures from one component to the next. Moreover, even if the failures are truly independent, arithmetic summing of the rates may magnify the inaccuracies of assumptions made in generating the failure rates. For example, in the case of a system with a large number of components, none of which have yet failed in service, the failure rate for each component might reasonably be estimated by making a Weibayes-type assumption that a failure occurs in the immediate future. However, if such an assumption is made for every system component, the system failure rate resulting from such a series of assumptions becomes completely unrealistic.

- Most likely result. The format of the FMEA lends itself to a simple, short series of steps in a failure progression. As the number of steps in the progression increases, or as alternative results in the failure progression are identified and the event path followed, the presentation of the analysis becomes more tortuous and the reader becomes inclined to question the plausibility of the successive assumptions made regarding the failure propagation. In the majority of cases of a specific failure, the reader would be right to do so - a bearing failure may be detected during maintenance activity and magnetic chip detector inspection on 99% of occasions. However, review of historical propulsion system accidents shows they can and do involve unlikely coincidences and apparently far-fetched failure progressions. It is difficult for the analyst to present these in a credible manner using an FMEA.

### 8.2.4 Fault Tree Analysis

The selection of the FMEA as the conventional technique to be tested in Chapter 2 was based on the original use of the FMEA in RB211 certification. It might be argued that selection of Fault Tree Analysis might have produced a better result; the advantages and disadvantages of such an approach can be evaluated here without actual execution of such an analysis.

A Fault Tree Analysis (FTA) applied to the RB211-22B would have greatly reduced the number of component failures considered, relative to the original FMEA. The results would have been more easily understood by the reader (provided that he or she was familiar with the FTA pictorial conventions) since overall rates of undesired events would be specifically presented in a specified location and since it would be relatively easy to track down the components making major contributions to the undesired event.[40] However, since the component failure rates used in the fault tree would be the same as those used in the FMEA, which have been demonstrated in Chapter 2 to include major inaccuracies, the overall failure rate derived by the fault tree would be no better than that extracted from the FMEA, and the highest risk components would have been incorrectly identified.

The fault tree would have allowed assessment of the system architecture. This is a significant advantage for the electronic control systems of today's engines, but is of little advantage in the case of a hydromechanically controlled engine such as the RB211-22B.

Fault tree analysis would have explicitly assumed independence of failure rates, which may not necessarily be the case (Carter) although in the author's opinion, such an assumption is a good approximation at the engine level.

The Fault Tree has a significant disadvantage when compared with an FMEA for assessment of a completely novel type of engine; it is necessary to specify at the outset which airplane level effects are considered hazardous /catastrophic and should be addressed by the Fault Tree(s). This information is currently available from a review of the accident record, but in the late 1960s, when high bypass turbofans were initially being designed, the severity

---

[40] There would be significant advantages to some means of identifying these major contributors diagrammatically. For a series mechanical system, where the component failure rates are generally summed to produce the overall event rate, this could be done relatively easily by depicting the branch (or branches) of the fault tree making the greatest contribution in bold typeface.

of various failure effects (compared to low bypass turbofans) could only be a matter of conjecture.

## 8.3 Alternate approach to safety analysis

### 8.3.1 Features of alternate approach

The alternate approach to safety analysis developed in Chapter 6 may be summarised as follows:

-An airplane level analysis of the propulsion system, rather than a component level analysis.

-Analysis is focused on types of accidents which have made major contributions to past accident rates. It is proposed for the high bypass turbofan-powered commercial transport fleet that the analysis should primarily address

-Uncontained high energy debris
-Propulsion related crew error
-Thrust control difficulty
-Fire

-Hypothetical accident sequences, or those which have only resulted in a single accident for which specific corrective action has been implemented, need not generally be considered unless unconventional architectures or features greatly increase the potential for an accident from a single failure.

-Historical engine-level failure rates and accident rates are used, calculated by a simple average or by reliability growth trending where sufficient data exists. Historically representative types and rates of crew error are fundamental to the analysis. Consideration of the effect of flight phase on failure rate is crucial in those cases where the airframe level criticality of the failure is determined by flight phase.

-There is no requirement to repeat the analysis after small design changes or thrust rating changes (unless airplane level mitigating features are introduced or invalidated). The component design details are transparent to the analyst; it has been shown that continuity of design practices and expertise compensates for major component design changes and introduction of new technologies such as electronic engine controls.

- Mitigating design features are identified which would have prevented or reduced the severities of past accidents. Partial credit is then ascribed to each of these features, provided that close scrutiny confirms the feature would be likely to be effective in the specific application and implementation proposed. The partial credit is applied to the appropriate element of the accident rate.

- Detailed review of the details of past accidents is both expected and necessary to the evaluation of mitigating design features and the credit to be given for them. Techniques such as Event Sequence Analysis may be required to uncover installation-specific aspects of failure criticality for past accidents (as in the discovery of the very low hazard ratio for uncontained failure of the outboard wing-mounted engines of four-engined aircraft, discussed in Chapter 6).

### 8.3.2 Strengths of the proposed approach

The approach outlined above has a number of significant advantages compared to the conventional safety analysis approaches, as follows:

The most significant advantage of this approach to safety analysis, compared with previous conventional techniques, is the fidelity of quantitative results to actual service experience. Accident rates and engine level failure rates predicted by this means are extremely close to those occurring in service, as demonstrated in Chapter 7. This reflects the extensive historical database of accidents used as a baseline for the analysis, together with the general level of competence in the design and manufacture of propulsion systems among a limited number of European/US manufacturers of commercial transport aircraft and their engines. The close agreement between prediction and actual experience demonstrated in Chapter 7 may assist the credibility of this approach in the design community, although there is likely to be some difficulty in gaining acceptance of the approach as discussed below.

Since the analysis requires comparatively little time and effort once the initial research into the historical accident record is complete, it can be executed at the design-study phase of a program when it is most likely that the actual design will be influenced by analysis results. Proposed mitigating features can be associated with quantifiable accident rate reductions rather than the somewhat nebulous claim that safety in general will be improved.

The analysis specifically focuses on those aspects of the design which have the potential to mitigate the effects of a propulsion system failure, based on the

historical record. The majority of propulsion related accidents do not result from combinations of failures, but from individual failures in conjunction with extraneous enabling circumstances. The proposed technique specifically directs attention to mitigation of the circumstances.

The results are concise and require no special knowledge (e.g. Boolean logic, fault tree pictorial conventions) to be understood.
The airplane-level view of engine failure effects, as justified by the statistical analysis of Chapter 6 and validated by Chapter 7, takes no account of changes in the detailed engine component design. This eliminates the requirement to repeat the analysis after design changes producing new engine variants, provided that the new design is performed in the same manner as previous designs.[41]

The results of the analysis are reasonably reproducible, being based on the historical accident record. There could be some dispute over the exact rate to be used; since the definition of an accident is not precisely the same in different countries, some events might be excluded under one definition but admitted under another. Events which were classified as accidents because of injuries incurred in emergency evacuations would have been excluded by some experts in the aircraft safety field. Moreover, some individual judgement is required in deciding the extent of the partial credit to be allowed for mitigating design features; one analyst might consider that a feature would avoid 20% of a given type of accident where another might assign a 50% credit. However, this variability of judgement is likely to be within a factor of five or ten, whereas estimation of failure rates without a baseline may vary by up to two or three factors of ten (as in Chapter 2).

Review of the advantages cited above shows that the technique meets many of the criteria originally specified as desirable in a safety analysis methodology. The disadvantages of the proposed approach are considered in detail below.

---

[41] In this context, "the same approach" need not imply the same analytical tools; it is the structured design process by a group which has acquired an appropriate level of technical sophistication, of defining design requirements, validating these requirements, complying with published internal Design Practices which incorporate the cumulative knowledge of that design function, review by peers and technical experts at critical phases of the design, testing and validation of the hardware, and so forth.

### 8.3.3 Limitations of the proposed approach

The major limitation of this airplane-level approach is the lack of guidance it gives to the component or system designer in evaluating the relative safety benefits and penalties of design options and in identifying problems with system architecture or deficiencies in detail design[42]. The proposed approach is of no assistance in reducing component failure rates. The insensitivity of the approach to design decisions may also reduce its credibility with the design community, or at worst, lead them to believe that their design choices do not affect safety. Nothing could be further from the truth; the proposed approach depends upon the design community maintaining the diligence and foresight with which they have approached previous propulsion system designs, and any reduction in such diligence will invalidate this historically based approach. Communication of this point will be essential to successful implementation of this technique.

The lack of detail and generic nature of the approach may be interpreted as resulting in a superficial analysis incorporating insufficient mathematical rigour. It is difficult to prove that such a concept as 'continuity of design community technical sophistication' will always result in reliability growth between very dissimilar engine models; although the concept may be relatively easy to accept for close derivatives. The approach is completely empirical, and will appear unsatisfactory to those who do not consider the historical evidence sufficient to predict future behaviour.

In the event of a completely new approach to design (such as the greatly increased validation activity associated with early ETOPS), the approach would be difficult to apply. It is not possible to forecast the quantitative effect on failure rates of such a paradigm shift; nor is feasible to use the historically derived accident and failure rates in the event of a new manufacturer entering the propulsion field, or an existing manufacturer producing a propulsion system based on principles not previously used in commercial transport (e.g. a ram-jet).

---

[42] Conventional techniques are generally assumed to be helpful in this respect, yet this assumption is open to question. In practice, only the most naive errors or those occasioned by misinterpretation of system interfaces are likely to be discovered by FMEA or FTA; the safety analyst cannot devote as much time and attention to the design as the original designer because the analyst must address many systems and assemblies. Much of the designers activity must (and should) be accepted in good faith by the analyst.

## 8.4 Potential for improvements to alternate approach

The proposed approach is based primarily upon the service history of the high bypass ratio commercial transport fleet. In some accident records there was little or no detailed information available; this severely curtailed the ability to propose and assess mitigating design features. More detailed information would enable the construction of event sequence sheets and improved understanding of event causal factors. Close liaison with engine and airframe manufacturers might reveal such accident details. It is likely that such a study would enable mitigating features to be identified for accidents resulting from propulsion system fires, for example.

The mitigating design features proposed in this study are concepts rather than detailed design proposals. Each concept should be reviewed by a wide audience, including line pilots, airworthiness authorities, engine manufacturers and the many groups within the airframe design community to establish its practicality, desirability and possible associated penalties before a firm decision could be made that it should be implemented in future aircraft. A necessary part of such a review would be some form of validation to demonstrate that each proposed feature would actually deliver the intended safety benefit; the validation means might include the following:

- Expert review by line pilots.
- Review of propulsion-related accidents since 1994[43] (and therefore not in the database used to derive the mitigating design features) to assess the likely effectiveness of the proposed concepts.
- In some cases, simulator modelling of proposed flight deck indications may enable such a validation.

## 8.5 The Role Of The Alternate Approach

The multiple roles of a propulsion system safety analysis were pointed out earlier in this work and may be briefly recapitulated at this point:

- To gain airworthiness certification

- To assess the safety of the design compared with previous designs

---

[43] The extended interval between the occurrence of an accident and the publication of accident findings, together with the infrequent occurrence of propulsion-related accidents, makes such a review impracticable before publication of this study.

- To improve the propulsion system safety by identifying safety concerns and enabling appropriate design changes

- To facilitate engineering trade studies where safety is a significant factor by provision of credible quantitative risk analysis/failure rate forecasting.

The traditional methods of propulsion system safety analysis have been historically successful in gaining engine/ propulsion system certification. Much credence is placed by the airworthiness authorities in the structured, comprehensive approach of an FMEA or FTA; it is felt that since every component or failure condition has been addressed, the analysis has been thorough and nothing is likely to have been inadvertently omitted. There is much to be said for this viewpoint if the system is completely unfamiliar or if no service experience is available.

Some members of the airworthiness authorities believe that the reason for the excellent propulsion system accident experience record relating to multiple independent failures is the structured analyses which have been conducted to comply with certification requirements. This may be the case[44] when considering systems with significant architectural flexibility; fuel systems and electronic control systems are notable examples. Moreover, there is a general concern among regulatory authorities that as propulsion systems become more highly integrated with aircraft systems, visibility of system interactions under failure conditions will be lost unless a structured analysis is completed.

Lastly, it has already been mentioned that traditional analyses, showing compliance with a standard of Catastrophic failure conditions being Extremely Improbable (1E-9/hour or flight) have the advantage of facilitating comparison from one certification program to another, since they are assumed to be conducted with similar ground rules.

Given the above advantages ascribed to traditional methods, it is not likely that the traditional methods could be immediately discarded across the board for propulsion system certification; nor should they ever be discarded for some systems (those with architectural flexibility). It is proposed that the enhanced approach be used in conjunction with more traditional approaches. The relative emphasis placed on each may change through the years as the alternate approach becomes more generally accepted.

---

[44] It is the author's personal experience that the certification safety analyses are generally conducted so late in the development program that their outcome is actually very unlikely to affect the design.

Specific implementation proposals are as follows:

- The enhanced approach should be considered by airframe manufacturers as a means of forecasting propulsion related accident rates and of selecting mitigating design features for reduction of those accident rates.

- Specific aspects of the research, which deal with the quantitative forecasting of engine-level failure rates and their variation with flight phase, should be used by the engine manufacturers as soon as possible.

- The detailed assessment of engine component and assembly design should be addressed as before, by detailed design reviews, incorporation of lessons learned, and hazard analyses for the airworthiness authorities comparing design safeguards and margins to those of previous engines. Supporting FTAs and FMEAs may be significantly curtailed in comparison to previous analyses.

- Where systems architecture is dissimilar to that of previous systems, a full-up FTA may be necessary.

- For series mechanical systems, hazard analysis sheets (demonstrating the similarity of the design to those in service) in conjunction with the enhanced approach developed in this study, should be sufficient to demonstrate compliance with the safety requirements of the airworthiness authorities.

# 9.0 CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

## 9.1 Conclusions

a) The propulsion system safety analysis plays multiple roles; it may assist propulsion system design, assess propulsion system safety and also support engine and airplane certification.

b) Current methods of propulsion system safety analysis are only partly successful in these roles. A baseline safety assessment of the RB211-22B showed that a FMEA approach did not forecast failure rates comparable to those experienced in service nor correctly identify high risk components or modules; hence the analysis would have been misleading rather than useful during propulsion system design and the assessment of propulsion system safety.

c) It is proposed that failure effects to be addressed by the propulsion system safety analysis should be selected and prioritised according to historical accident rates. The failure effects considered during the analysis of high bypass ratio turbofans used in commercial transport airplanes should include the following:

Uncontained rotor failure
Propulsion failure accompanied by crew error
Thrust control difficulties
Fire.

d) Traditional structured analytical approaches to propulsion system safety analysis rely upon the availability of component failure rates. Such failure rates are not generally available at entry into service since reliability is too high to obtain failure rates during development testing, since propulsion systems incorporate many unique components and published failure rates for off-the-shelf components are very misrepresentative, and since an approach to using service experience to develop failure rates at the component level is yet to be developed. The unavailability of these failure rates limits the effectiveness of traditional structured analysis techniques.

e) Historical accident records suggest that independent combinations of failures do not make a significant contribution to the propulsion system accident rate. The record shows that single failures accompanied by adverse circumstances are a more significant contributor.

f) It is therefore recommended that quantitative safety analysis of propulsion systems be focused on airplane level effects rather than on component failures. Forecasts of accident rates based on historical levels, with credit allowed for mitigating design features, have been demonstrated to give good agreement with service experience, both for a derivative engine and a new centre-line engine incorporated in new aircraft.

g) It is suggested that the alternate approach of forecasting airplane-level effects using historical propulsion system accident data is generally applicable to all conventional commercial transport high bypass ratio propulsion systems where the designer/ manufacturer has previous experience in commercial transport propulsion systems powered by large turbofans. It is further suggested that the consistency of propulsion system failure rates at entry into service is attributable to the continuity of design expertise within engine and airplane manufacturers, so that new designs are partially mature at entry into service. Nevertheless, a qualitative review of each new design should be conducted to establish that the new design is sufficiently similar in design philosophy and technology that historical engine-level failure rates are applicable.

h) Engine level failure rates can be forecast with some assurance at entry into service using reliability growth modelling, based on data from previous engine models, or on a simple average where data is insufficient to support trending.

i) Small design changes such as thrust increases or component design changes for a derivative engine, have no apparent effect on engine level failure rates overall, (apart from those changes introduced to address a known reliability problem). It follows that a new propulsion system safety analysis need not be executed after each such a design change.

## 9.2 Recommendations for Further Work

A) If this approach is successful in identifying mitigating design features and incorporating them into new propulsion systems, the propulsion-related accident rate will be significantly reduced for new aircraft. As newer types become predominant in the world fleet, dilution effects will reduce the overall propulsion-related accident rate; some mitigating design features might even be retrofitted into older airplanes, as is being done with the "Engine Fail" indication, accelerating this improvement in the accident rate. It follows that eventually this study, based on accidents over the first twenty-five years of high-bypass turbofans, will no longer be applicable since the

original predominating accident causes will have been greatly reduced. A new study will therefore be required in fifteen or twenty years time to address the new major contributors to the propulsion related accident record.

B) The approach used in this study i.e. constructing the safety analysis around the historical accident record, may be used to address other systems on commercial transport aircraft, and other aircraft fleets besides the high-bypass turbofan commercial transport fleet. The approach may be applied in any fleet where detailed accident records are available, there have been sufficient accidents to draw meaningful conclusions regarding the vital few causes of failure, and the design and construction of the fleet is conducted by a few manufacturers with a well disciplined design process. Specific examples of applicability would include:

- helicopters
- commuter airplanes
- commercial transport fleet
  (mechanical systems excluding propulsion)

C) The lack of success of reliability growth modelling at the component level in this study may be attributed in part to the sparsity of SDR data and the concomitant difficulty in isolating trends from random variation. The ability to predict component reliabilities would be of great commercial interest in spares forecasting at entry into service; it is possible that examination of component failure rates rather than IFSD rates would enable the construction of component level reliability growth models. Such a model would be of limited value in safety analysis, however, since failure rates of critical parts (those which are primarily concerned in safety analyses) do not follow classical reliability growth patterns[45].

D) The enhanced safety analysis process developed in this study does not assist a component designer in making safety-related trade studies. It is crucial that some effective means of assisting the designer be developed; one possible approach would be to identify areas where the design process has been only partly successful, so that a component experiences early failures in service. Examination of multiple such areas might reveal some common features, implying weaknesses in aspects of the design and validation process which

---

[45] Premature failure of a critical part is generally handled by a very aggressive field program, and by an internal audit to establish where the design process was lacking. As a result, these failures are generally single events, so that most critical part designs do not have a measurable failure rate in any meaningful sense.

could be identified and corrected. The safety analyst could be tasked with monitoring these aspects for new designs until an improved design process was implemented and validated. This approach would necessarily be internal to the engine or airframe manufacturer's organisation.

E) The alternate approach does not readily lend itself to the safety analysis of completely novel propulsion systems based on new technologies or technologies without significant experience in the commercial transport aircraft environment. It is possible that a similar approach could be applied by analysing the propulsion system at the sub-system level rather than the airframe level, for those sub-systems with previous experience upon which the analysis could be based. A sensitivity analysis would be appropriate where the previous experience used was in a different environment.

## 10.0 REFERENCES


1. Taylor RW, 'Twin-Engine Transports, A Look at the Future', pp 22-23, The Boeing Company, 1990

2. Knife SM, 'Application of failure analysis techniques to powerplant airworthiness", AEROTECH '94, Birmingham, England, 1994

3. Federal Airworthiness Regulations, Part 33, Change 29

4. Joint Airworthiness Regulations, Part E, Change 8

5. Federal Airworthiness Regulations, Part 25, Change 29

6. Joint Airworthiness Regulations, Part 25, Change 14

7. Terry GJ 'Engineering System Safety' Mechanical Engineering Publications Ltd London 1991

8. Gottfried and Weiss 'Reliability Prediction With Inadequate Data' Annals of 6th Reliability and Maintainability Conference, Cocoa Beach, Florida, 1967

9. MIL-STD 882B 'System Safety Program Requirements', March 1984

10. ARP 926A 'Fault/Failure Analysis Procedure', SAE

11. Lloyd E and Tye "Systematic Safety" Civil Aviation Authority UK 1982

12. Kytasty A , Shemanski and Ford, "Reliability of propulsion system interfaces" AIAA 89-2625, 1989

13. Martin P "A Systematic approach to interactive failures" Symposium "Mechanical Reliability", IPC Science+Technology Press 1980

14. Strong and Eagle "Development and validation of reliability forecast techniques"Westinghouse Electric Corporation NTIS 8100, May 1981

15. Kelly Erdman and Gilbert "FTA analysis for reliability prediction of gas turbine type powerplants" EPRI AF-811 Volume 1 June 1978

16. Snaith ER "Can reliability predictions be validated?" Second National Reliability Conference, Birmingham, March 1979

17. Taylor A "Comparison of actual and predicted hazard rates" Second National Reliability Conference, Birmingham, March 1979

18. AIA PC 342 "Initial report on propulsion system and APU related aircraft safety hazards" Committee on Continued Airworthiness Assessment Methodology, May 1993

19. Duane JT "Learning curve approach to Reliability Monitoring" General Electric, IEEE Transactions on Aerospace, Vol. 2 No. 2 April 1964

20. Lawlor EF 'Analysis of reliability growth and an improved model derived from first principles' Presentation to TTCP W6 Reliability Working Group. Colorado Springs, USA August 1977

21. Mead PH 'Maximum likelihood estimation of the SIL reliability growth model' Presentation to TTCP W6 Reliability Working Group, September 1979

22. Taneja VS and Safie, 'An overview of reliability growth models and their potential use for NASA applications' NASA Technical Paper 3309, December 1992

23. Carter ADS, "Mechanical Reliability" 2nd ed., Macmillan 1986

24. Lloyd DK "Forecasting reliability growth" 9th Advances in Reliability Technology Symposium, 1986

25. Bompas-Smith JH "The Determination of distributions that describe the Failure of Mechanical Components" Rolls-Royce, Annals of Assurance Sciences 1969

26. Bompas-Smith JH "Mechanical Survival: the use of reliability data" McGraw-Hill London 1973

27. Kecegliogl u D, Smith and Felsted "Distributions of cycles-to-failure in simple fatigue and the associated reliabilities" Annals of Assurance Sciences 1969

28. Martin, P 'Aspects of Mechanical System Reliability' 10th Advances in Reliability Technology Symposium, Bradford, National Centre of Systems Reliability, Elsevier Applied Science 1988

29. Smith RL "Extreme value statistics and reliability applications" Reliability '85, National Centre of Systems Reliability, 1985

30. Bier V "Statistical methods for the use of accident precursor data in estimating the frequency of rare events" Reliability Engineering and System Safety vol. 41 (1993) pp 267-280

31. Venton A 'Pursuing reliability in mechanical design' Symposium "Mechanical Reliability" ed Moss TR, IPC Science andTechnology press Guildford 1980

32. Airplane Safety Engineering 'Accident Prevention Strategies' Boeing Commercial Airplane Group, October 1993

33. Welsh and Lundberg 'Methods used to assess the safety and reliability of a nuclear reactor control rod system' 2nd National Reliability Conference, Birmingham England, National Centre of Systems Reliability, 1979

34. Ball RE 'The fundamentals of aircraft combat survivability analysis and design' Ed. JS Przmieniecki, AIAA Education Series

35. Chapdelaine et al. "Statistics on gas turbine rotor failures that occurred in US commercial aviation during 1989" DOT/FAA/CT-92/5, NASA STAR tech report issue 21, June 1992

36. Delucia et al. "Statistics on gas turbine rotor failures that occurred in US commercial aviation during 1986" DOT/FAA/CT-89/30, NASA STAR tech report issue 14, January 1990

37. Delucia et al. "Statistics on gas turbine rotor failures that occurred in US commercial aviation during 1979" AD A130463 NASA STAR tech report issue 18, October 1982

38. Delucia et al. "Statistics on gas turbine rotor failures that occurred in US commercial aviation during 1988" DOT/FAA/CT-91/28 NASA STAR tech report Issue 23, March 1992

39. Delucia et al. "Statistics on gas turbine rotor failures that occurred in US commercial aviation during 1985" , DOT/FAA/CT-89/7 NASA STAR tech report issue 23, July 1989

40. Delucia et al. "Statistics on gas turbine rotor failures that occurred in US commercial aviation during 1984" DOT/FAA/CT-89/6, NASA STAR tech report issue 23, June 1989

41. Delucia et al. "Statistics on gas turbine rotor failures that occurred in US commercial aviation during 1982" DOT/FAA/CT-88/23 NASA STAR tech report issue 2, July 1988

42. Delucia et al. "Statistics on gas turbine rotor failures that occurred in US commercial aviation during 1987" DOT/FAA/CT-90/19, NASA STAR tech report issue 10, January 1991

43. Delucia et al. "Statistics on gas turbine rotor failures that occurred in US commercial aviation during 1983" AD-A207592 NASA STAR tech report issue 21, March 1989

44. Delucia et al. "Statistics on gas turbine rotor failures that occurred in US commercial aviation during 1977-78" AD-A113767 NASA STAR tech report issue 18, September 1981

45 FAA Service Difficulty Reports, January 1986 to December 1993

46. CAA, Reported high bypass-ratio jet engine malfunctions, 1984 to May 1994

47. G P Sallee 1990 "An Overview of Propulsion System Risks", D6-55456 Rev A, The Boeing Company 1990

48. Boeing Company "Statistical Summary of Commercial Jet Aircraft Accidents" 1993

49. Carnino Nicolet and Wanner, "Man and Risks"

50. AIR 1537 "Report on Aircraft Engine Containment" SAE October 1977

51. AIR 4003 "Report on Aircraft Engine Containment", SAE, September 1987

52. AIR 4770 "Report on Aircraft Engine Containment",SAE, Final Draft 1994

53. Jay And Todd, Effect Of Steady Flight Loads On JT9D-7 Performance Deterioration, NASA CR 135407 1978).)

54. Smith D J 'Reliability and Maintainability in perspective' 2nd edition, Macmillan 1985

55. CALCE Electronic Packaging Research Center "Perspective on Physics-of-failure approach to Reliability" (Presentation) University of Maryland 1993 - 1994

56. Maurino, Reason, Johnston and Lee, "Beyond Aviation Human Factors", Avebury Press

57. Reason, "Human Error", Cambridge University Press, 1990

58. R Chamberlin, "Rejected Takeoffs, Causes, Problems and Consequnces", NASA Flight Safety Digest January 1993

59. FAA Human Factors Team "The Interfaces between Flightcrews and Modern Flight Deck Systems" , Federal Aviation Administration, June 1996

60. Collas, "Dynamic Reliability Prediction", Proceedings Annual Reliability and Maintainability Symposium, IEEE, 1991

61. Alford, "How Design Criteria and Design Reviews have Used Past Experience to Avoid Repeating Mistakes", SAE

62. Advisory Circular 25.571-1A, "Damage Tolerance and Fatigue Evaluation of Structure" 3/5/86

63. Clemens P, 'A Compendium of Hazard Identification and Evaluation Techniques for System Safety Application', Sverdrup Technology Safety Office, 1981

64. Roland and Moriarty "System Safety Engineering and Management" 2nd ed., Wiley 1990

65. Brown D 'Systems Analysis and Design for Safety' Prentice-Hall 1976

66. van Baal JB, "Hardware/Software FMEA applied to aircraft safety" Proceedings of Annual Reliability and Maintainability Symposium New York 1985

67. Collins and Leathley, "Psychological predispositions to errors in safety, reliability and failure analysis" Safety and Reliability Vol.14 No 3, 1995, Safety and Reliability Society

68. Shooman ML 'Probabilistic Reliability; an engineering approach' Brooklyn Polytechnic Series 1968

69. 'Reliability, Stress and Failure Rate Data' MIL-HDBK 217, Government Printing Office, Washington DC 1962

70. 'Reliability, Stress and Failure Rate Data' MIL-HDBK 217A, Government Printing Office, Washington DC 1965

71. Feduccia and Klion "How accurate are reliability predictions?", Annual Symposium on Reliability, Boston, January 1968

72. Shurman 'Development of in-flight steady-state failure rates' Proceedings, Annual Reliability and Maintainability Symposium IEEE, 1979

73. Andre P 'Human factors in reliability failure rate prediction' 2nd National Reliability Conference 1979

74. 'RB211-524G/H Reliability Status Report 31 May 1994' Rolls-Royce Product Data Centre, 1994

75. NTSB recorded accidents/incidents attributed to engine malfunction, 1994

76. World Airline Accident Summary, CAA CAP479 to December 1993

77. Guided Weapon System Reliability Prediction Manual MOD report DX/99/013-100 Marconi-Elliott Avionic systems Ltd, November 1974

78. Def STAN 00-41 (Part 3) MOD 'Practices and Procedures for Reliability and Maintainability: Reliability Prediction" 7 December 1983

79. Kapur KC and Lamberson "Reliability in engineering design" John Wiley New York 1977

80. Dhillon and Singh "Engineering Reliability: new techniques and applications" Wiley 1981

81. Lloyd DK and Lipow M 'Reliability ; management, methods and mathematics' Published by authors, 1977

82. Beasely M "Reliability for engineers" Macmillan 1991

83. Aven T "Reliability and risk analysis" Elsevier Applied Science Barking, Essex, 1992

84. Blockley D 'Engineering Safety' McGraw-Hill 1992

85. Green A and Bourne 'Reliability Technology'Wiley and Sons New York 1972

86. Lemon and Manning 'Literature survey on Structural Reliability' IEEE Transactions on Reliability October 1974

87. Martin P, Strutt and Kinkead 'A review of mechanical reliabilty modelling in relation to failure mechanisms' 7th Advances in Reliability Technology Symposium, 1982

88. Ghare P 'Quality and Safety factors in reliability' IEEE Annals of Reliability and Maintenance 1970 pp 637-641

89. Kececioglu D and Haugen 'A unified look at design safety factors, safety margins and measures of reliability' Annals of Reliability and Maintenance Conference IEEE 1968

90. Harrison and Shepherd 'Lifing philosophies for aero engine fracture critical parts' Aero engine Reliability Integrity and Safety Conference, RAeS/IMechE October 1991

91. Metz and Zimmerman "Development of simulated mission endurance test acceleration factors" AIAA, SAE and ASME 19th joint propulsion conference, Seattle, 1983

92. Osias, Meyer and Hill, "Complex mission history effects on LCF of disks" from Fatigue Life Technology, Ed. Cruse and Gallagher, 22nd Annual International Gas Turbine Conference, Philadelphia, ASME March 1977

93. Forrester and Thevonov 'Designing for expected fatigue life' Annals of Reliability and Maintenance IEEE 1968

94. Pickard AC 'Design and life assessment of aeroengine components' Aero engine Reliability Integrity and Safety Conference, RAeS/IMechE October 1991

95. Jeal R 'Should safe life be replaced by damage tolerance?' AGARD Conference Proceedings 393, Damage Tolerance Concepts for Critical Engine Components, 1985

96. Adamson J "Development of a probabilistic rotor design techniques Pratt & Whitney AIAA 90/2176, 1990

97. Hunsley C 'The Development Of Mechanical Failure Mode Models For Use In Design' Reliability '85, Vol. 2 National Centre of Systems Reliability, 1985

98. Moore N and Ebbeler D 'Failure risk assessment by analysis and testing' AIAA 92-3515 1992

99. Kao JHK, 'A summary of some new techniques on failure analysis' Proceedings 6th National Symposium on Reliability IEEE 1960

100. Abernethy et al 'Weibull Analysis Handbook' AFWAL-TR-83-2079 November 1983

101. Gumbel EJ 'Statistical Theory of Extreme Values and some Practical Applications' US Department of Commerce Applied Mathematics Series 1951

102. Perera 'Reliability growth models and application to a processor' Ed. P Comer Elsevier Applied Science, 11th Advances in Reliability Technology Symposium, Liverpool, National Centre of Systems Reliability, 1990

103. Jackson RG, "Reliability and maintainability, a look at the RR RB211" NASA IAA SAE 851829 Aerospace Technology conference and Exposition, Long Beach October 1985

104 Boiles and Hadel "Reliability Growth measured by AFM66-1 data" Proceedings of Annual Reliability and Maintainability Symposium New York 1981

105. Haasl et al 'Fault Tree Handbook' U.S. Nuclear Regulatory Commission NUREG-0492 January 1981

106. Bendell and Ansell 'Practical aspects of Fault Tree Analysis and the use of Markov Reliability models' Proceedings of Reliability '85, Vol. 2 National Centre of Systems Reliability *Date?*

107. Martin P 'Consequential failures in Mechanical Systems' 6th Advances in Reliability Technology Symposium, Bradford, National Centre of Systems Reliability, 1980

108. Ansell and Wells 'Dependency modelling' Ed. P Comer Elsevier Applied Science, 11th Advances in Reliability Technology Symposium, Liverpool, National Centre of Systems Reliability, 1990

109. Horsley J, 'Testing for integrity' Aero-engine Reliability, Integrity and Safety Conference, RAes/IMechE October 1991

110. Thurston D "Design for safety" McGraw-Hill 1980

111. Dhillon BS, ' Mechanical Reliability; theory, models and application' AIAA Education Series 1988

112. Hunns DM and Daniels, 'The method of paired comparisons' 6th Advances in Reliability Technology Symposium, Bradford, National Centre of Systems Reliability, 1980

113. Pinkel et al, "Factors that affect operational reliability of turbojet engines" NASA TR R54, 1960

114. Tseitlin and Fedochenko "Safety factor evaluation in multicomponent loading...." Strength of materials May 1980

115. Mahorter, Fowler and Salvino "Statistical analysis of spin pit failure data to predict inservice B1 lives of gas turbine disks." NASA STAR Conference Paper Issue 16, 60th meeting of Structures and Materials Panel, San Antonio April 1985

116. Drexler and Statecny ARTI Z-47 1986 "A contribution to airworthiness certification of gas turbine disks" NASA IAA 1986

117. Voysey RG "Flutter failure of turbine blades" Aeronautical Research Council 1945

118. Yaker "Investigations of mechanisms of blade failure in forged hastelloy...." NACA RM E51D16, 1951

119. Bagnall "Aspects of turbine blade design for integrity" Aero engine Reliability Integrity and Safety Conference, RAeS/IMechE October 1991

120. Singh BR and Thomas FH, "A method for predicting turbine blade lives using unfailed specimens and analytical techniques" Mechanical Reliability, ed T. Moss , IPC Science and Technology Press, Guildford 1980

121. Goodall D 'The ignition of inflammable fluids by hot surfaces' ASTM (New Orleans) January 1966

122. Johnson, Roth and Moussa 'Hot surface ignition tests of aircraft fluids' AFWAL-TR-88-2101 Air Force Wright Aeronautical Laboratories, November 1988

123. Clodfelter and Anderson 'Hot surface ignition in aircraft engine compartments' Air Force Wright Aeronautical Laboratories June 1988

124. Strasser, Walters and Kuchta 'Ignition of aircraft fluids by hot surfaces under dynamic conditions' AFAPL-TR-71-86 Bureau of Mines PMSRC Report No. 4162, November 1971

125. Kuchta and Cato 'Review of ignition and flammability properties of lubricants' AFAPL-TR-67-126, Bureau of Mines , January 1968

126. Love, Hatchett and Peat "Fuel related problems in engine fuel systems" SAE Aeronautic and Space Engineering and Manufacturing meeting, Los Angeles October 1966

127. Devine K "Inclement weather induced aircraft engine power loss" AIAA 90-2169 AIAA 26th joint propulsion conference Orlando FL July 1990

128. Frings "A study of bird ingestions into large high bypass ratio turbine aircraft engines" DOT/FAA/CT-84/13 FAA Technical Center September 1984

129. Martino, Skinn and Wilson "Study of bird ingestions into small inlet area aircraft turbine engines (May 1987 - April 1989)" DOT/FAA/CT-90/13 FAA Technical Center, December 1990

130. Clifford D 'Aircraft mishap experience from atmospheric electricity hazards', AGARD LS110 'Atmospheric electricity - aircraft interaction' June 1980

131. Plumer JA 'Lightning effects on aircraft: a cockpit perspective', AGARD LS110 'Atmospheric electricity - aircraft interaction' June 1980

132. Dubro G 'Atmospheric electrcity interactions with aircraft', AGARD LS110 'Atmospheric electricity - aircraft interaction' June 1980

133. Lloyd and Tye "Is it safe? The safety assessment of Aircraft Systems" Aircraft Engineering May 1981

134. Sprogis H, "Continuing the ETOPS debate, a philosophy of safety overview" SAE 902021 Aerospace Technology Conference Long Beach October 1990

135. Reason and Mycielska "Absent-minded? the psychology of mental lapses and everyday errors" Prentice-Hall Inc 1982

136. Reason "Comprehensive Error Management In Aircraft Engineering" University of Manchester.

137. Green R et al "Human factors for pilots" Avebury Technical Press 1991

138. Williams JC "A human factors database to influence safety and reliability" Safety and Reliability Symposium '88 Manchester, 1988

139. Fitts and Posner "Human Performance" Prentice-Hall International Inc, 1973

140. Sumwalt and Watson, 'ASRS Incident Data Reveals Details Of Flight Crew Performance During Aircraft Malfunctions', Batelle, Flight Safety Digest October 1995

141. Davies AE 'Principles and Practice of Aircraft Powerplant Maintenance' Trans. I. Mar. E. Vol 84 1972

142."A tri-service maintainer's view" Reliability and Maintainability Symposium, Air Force Logistics Command, Philadelphia January 1987

143. Freudenthal AM et al, "Structural Safety, Reliability and Risk Assessment", Reliability Approach in Structural Engineering, Maruzen Co. Ltd, Tokyo, 1975

144. Norman D. 'The psychology of everyday things' Basic Books, 1988, New York

145 Mosleh A, Bier V, and Apostolakis G, "A Critique Of Current Practice For The Use Of Expert Opinions In Probabilistic Risk Assessment", Reliability And System Safety 20, Elsevier Applied Science 1988

146 BCAR Paper No. 484 'Proposed Method for Assessment of Airworthiness Systems' Draft 4, Issue 2, July 1970

# APPENDICES

THIS PAGE INTENTIONALLY BLANK

# APPENDIX A

THIS PAGE INTENTIONALLY BLANK

# APPENDIX A: DETAILED LITERATURE REVIEW

## A i Introduction to literature review

Since comparatively little has been published relating directly to the safety analysis of high bypass-ratio gas turbines, the literature search extended over a considerable range of related subjects, in the hope that aspects of related work would prove pertinent to the topic of research. The search goals are first summarised, and the search methodology outlined, before a more detailed discussion of the literature pertaining to each goal in turn.

The literature search was intended to:

Ascertain the material already published on the safety analysis of high-bypass ratio jet engines, including guidance on the best means of conducting such an analysis.

Review safety analysis techniques in general, in order to establish their relevance to jet engines.

Establish sources of failure rate data for jet engines and their constituent components, to be used in quantification of safety analyses.

Locate service data on high bypass-ratio jet engines, showing frequency of safety related events and accidents, and giving technical details of failure sequences of such events and accidents.

Research reliability modeling approaches and techniques, in order to establish whether they could usefully be applied in new ways to safety analysis.

Assure reasonable familiarity with the technical design pertaining to each type of safety-related event or issue, in order to assess the best means of addressing it in the safety analysis. Examples would include lifing of critical parts, fire precautions, thrust reverser system design, and the relationship between design and the propensity to maintenance error.

In addition to the above specific goals, the search was intended to promote general familiarity with the field of jet engine reliability, and to establish the originality and utility of this research topic.

## A ii Literature search strategy

Both on-line and manual search strategies were pursued, taking particular care to establish citation paths on both sides of the Atlantic, since it soon became apparent that a philosophical conflict existed between European reliability practitioners and those in the US. A relevance tree was constructed to facilitate identification of search paths (Figure A1), together with a diagram of sources and interrogation strategies employed (Figure A2).

Initial sources of references included:

- Cranfield Library catalogue, searched by keywords, by names of relevant manufacturers and by relevant sponsoring bodies, as follows:
  (RELIABILITY or SAFETY or FAILURE or ACCIDENT or AIRWORTHINESS) and (AIRCRAFT ENGINE or POWERPLANT or TURBOFAN or AEROENGINE or GAS TURBINE or PROPULSION SYSTEM)
  Rolls-Royce, General Electric, Pratt & Whitney, Allison, Garrett, SNECMA, Turbomeca, MTU, Fiat, Hispano-Suiza, Boeing, Airbus, British Aerospace.
  Flight Safety Foundation, IMechE.

- Proceedings of Advances in Reliability Technology Symposia for years 1980, 1982, 1984, 1986, 1988, 1990

- Proceedings of 1979 National Reliability Conference, and of Reliability '85, Reliability '87, Reliability '89 and Reliability '91

- Proceedings of Safety and Reliability Society Symposia, 1981 to 1993

- FAA Service Difficulty Reports for the RB211, Tay, V2500, CF6, CFM56, PW2000 and PW4000 engines, from 1986 to 1993.

- CAA database report of Engine-related Failures, Malfunctions and Defects, for the ALF 502, CFM56, RB211, PW2000, PW4000, JT9D, V2500 and Tay engines, from 1984 to 1993

- NTSB database report of engine-related accidents and incidents, 1983 to 1993.

- Texts available in Cranfield Library, together with their bibliographies and references

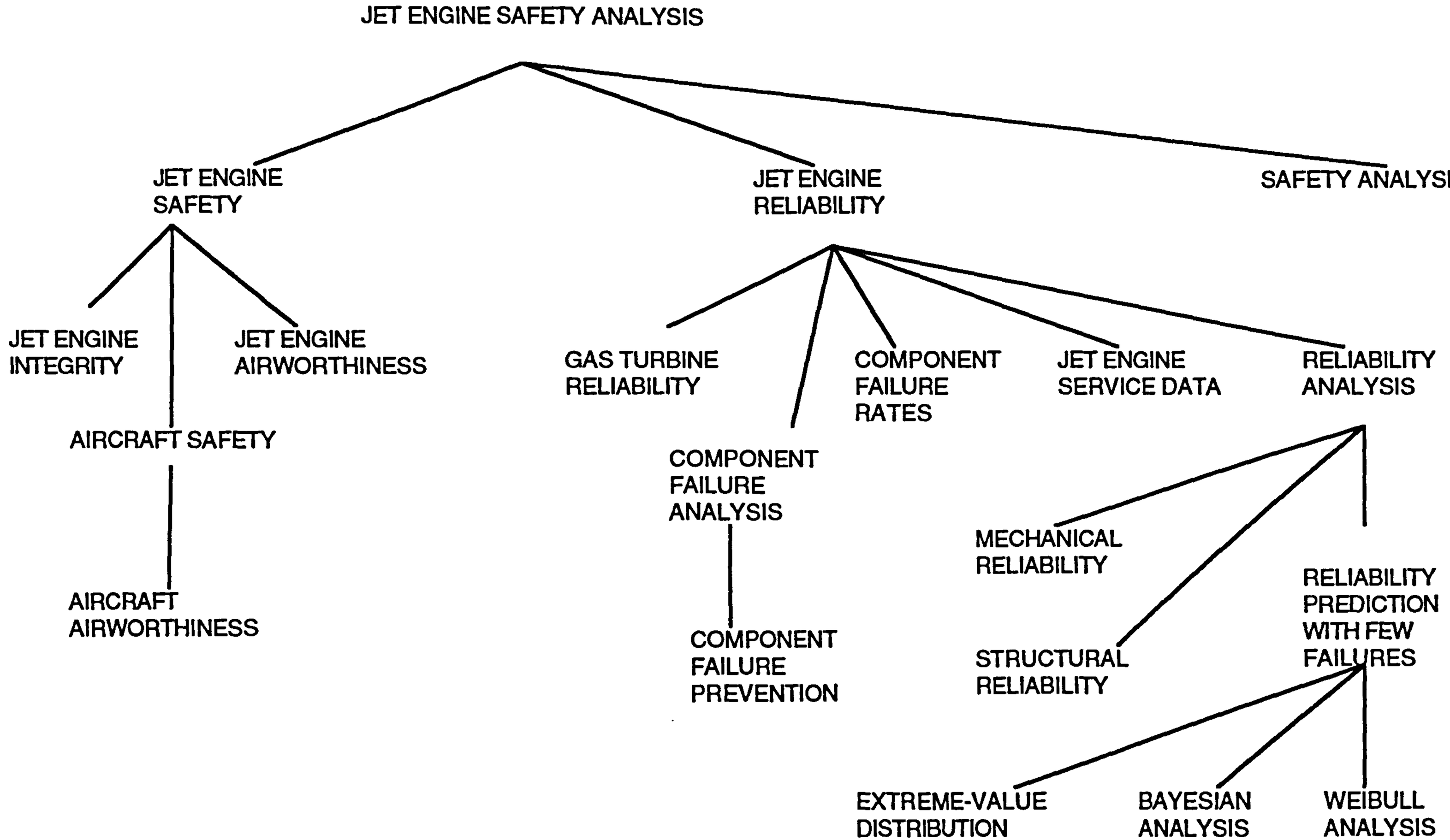
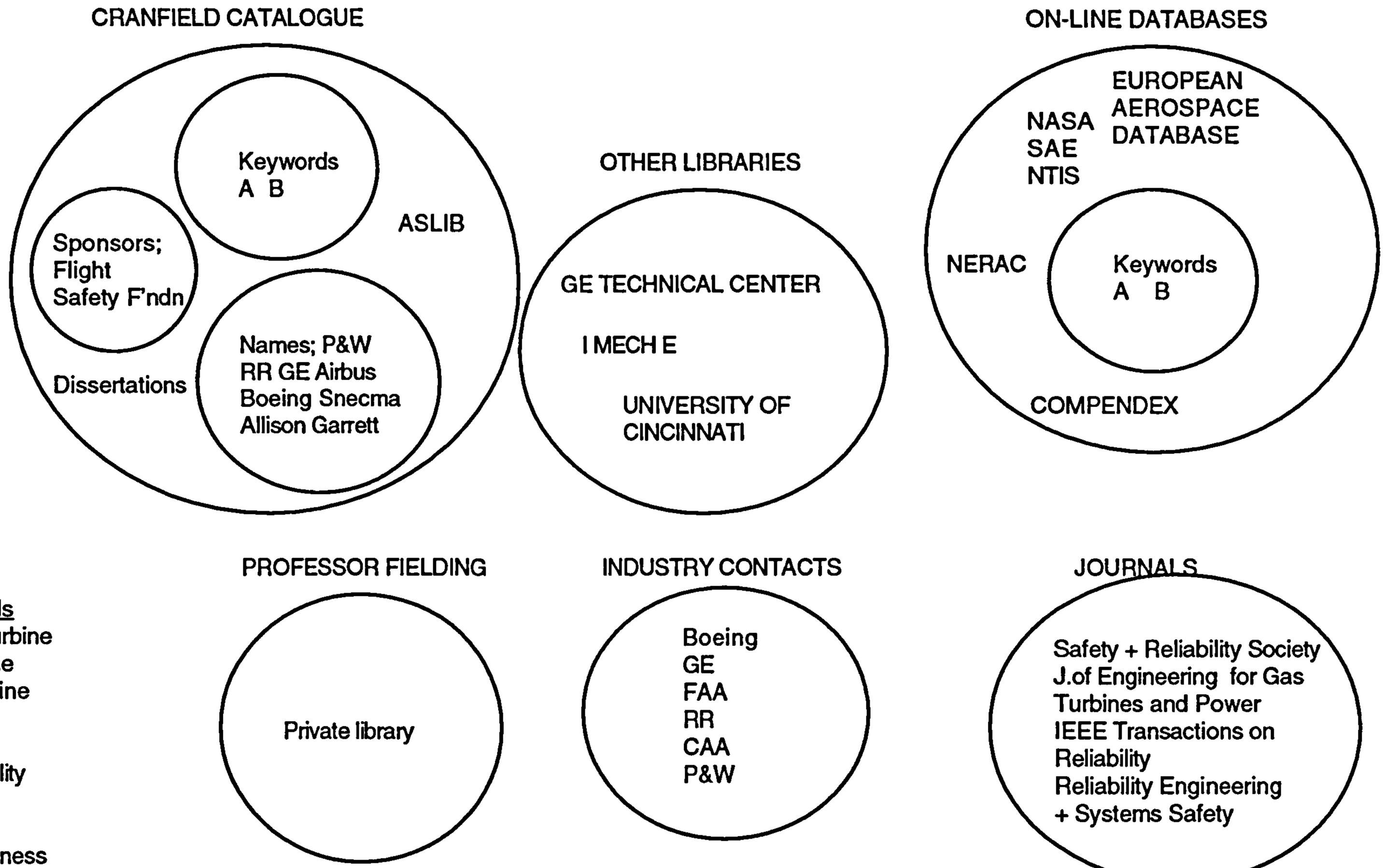



FIGURE A-1

RELEVANCE TREE




Keywords
A- gas turbine
jet engine
aeroengine
turbofan

B- reliability
failure
safety
airworthiness

FIGURE A-2 LITERATURE SEARCH STRUCTURE

- On-line search of NASA, European Aerospace Database, Society of Automotive Engineers, Compendex and NTIS databases from 1980 to 1994 using keywords (GAS TURBINE or JET ENGINE or AEROENGINE or TURBOFAN) and (RELIABILITY or FAILURE or AIRWORTHINESS or SAFETY)

- On-line search of IMechE database, using keywords AIRCRAFT ENGINE, SAFETY, RELIABILITY.

- Review of recent articles and their references in professional journals, viz.:
  Reliability Engineering and Systems Safety , volumes 41 to 44
  Journal of Engineering for Gas Turbines and Power, 1984 to 1994
  IEEE Transactions on Reliability, 1992 to 1994

- Solicitation of advice from personal contacts in engine and airframe industry.

Each source thus located formed a new departure point, citing further references, or being cited itself by more recent works. In fields where the volume of published literature appeared too great for an exhaustive survey, only those references with multiple citations or with titles of particular interest were pursued.

A iii Review of literature

a) Safety analysis techniques

A compendium of safety analysis techniques in general use is provided by Clemens (63), outlining advantages and disadvantages of each. Many of these techniques are primarily intended to assure the safety of an individual maintaining or otherwise interacting with a system or plant at close quarters, rather than assurance of design safety, and are therefore less appropriate to the assessment of jet engine safety (a fundamental ground rule being that an operating jet engine is, by its nature, hazardous to approach). A detailed discussion of the applicability of different assessment techniques is given in Chapter 5.

The background and major philosophical issues of system safety are discussed by Terry (7); whilst affording valuable insights into key conceptual problems of safety analysis, this does not, and is not intended to give specific recommendations on the best way to conduct an analysis. Guidance on the discipline of system safety in general can be found in Roland and Moriarty (64); this guidance is generally framed within the context of compliance with requirements and contract items of military

programmes, or of the superposition of a 'safety system' upon an existing design (Brown (65)), and emphasizes correct documentation rather than appropriate selection of analysis techniques or validation of failure rates used. Much of the material is irrelevant to the analysis of commercial products in general and civil jet engines in particular, but techniques such as Fault Tree Analysis and Failure Mode and Effect Analysis are described in rather more detail than is given by Clemens (63). Van Baal (66), addressing commercial airplane design, recommends a Hazard Analysis be performed to identify those airplane functions for which loss of an individual function could lead to a hazard to airplane or crew. FMEAs may then be performed upon the hardware and software supporting such functions. This approach gives no consideration to failures which could be actively hazardous, or to multiple failures. Collins and Leathley (67) point out that the analysis itself may be subject to errors and bias.

b) Sources of failure rate data

Generic failure rates have been published for a wide variety of components used in jet engines, among other applications. Use of such generic rates is currently under considerable scrutiny, even for the electronic components for which the approach is best suited. Shooman (68) points out that failure rates nominally from the same source (MIL-HDBK-217 (69), and MIL-HDBK-217A, (70) may vary by a factor of ten for the same component. Feduccia and Klion (71) have expressed concern over the link between stress-analysis reliability predictions, based upon MIL-HDBK-217, and electronic component failure rates experienced in the field; their comparison of predicted and observed failure rates indicated that predictions were generally pessimistic. Shurman (72) shows predicted subsystem failure rates, based on MIL-HDBK-217, being up to 62 times those measured, for military aircraft applications. Recent work conducted by the University of Maryland (55) suggests that the use of published failure rates should be completely avoided, even for electronic components, and an approach based upon the physics of failure should be employed instead.

Smith (54) emphasizes the importance of properly accounting for different environments when using published generic rates, and of only making comparisons between reliability predictions which use data from the same source. Given the limited information available to the analyst, correctly accounting for different environments for a large number of components is likely to require an impracticable level of resources. Every effort should therefore be made to obtain failure rates seen in service on similar components, and the published data should be considered as a benchmark with which to compare these empirical results, rather than taken at face value. The work of Andre (73) illustrates some of the difficulties in such an exercise, where he assesses the scatter in failure rates due to the outlook

of the individual reliability engineer when using generic failure rates and severity factors.

Table A1 gives some specific examples of the differences between published failure rates and those currently experienced in service by the RB211-524 G/H (74). Reference to historical trends for jet engine reliability (1) confirm that overall failure rates as indicated by in-flight shutdown rates, have improved by an order of magnitude over the past twenty years; it is therefore no surprise to note a difference between published and current failure rates for individual components. Conversely, reference to the service records of many other engine models with apparently similar operating environments (such as the RB211-22B) would reveal a much higher failure rate than that of the RB211-524G/H. It is difficult to see how use of environmental severity factors would properly account for this effect, which may be attributed in part to reliability growth.

TABLE A1. COMPARISON BETWEEN PUBLISHED AND MEASURED COMPONENT FAILURE RATES

| COMPONENT | PUBLISHED FAILURE RATE (per million hours) | SOURCE | RB211 FAILURE RATE (RECENT) f6 |
|---|---|---|---|
| Ball Bearings (heavy | 12<br>1.3 - 5.1<br>14.4 | 77 [1]<br>111<br>78 | 0.08 |
| Accelerometer | 88<br>72 | 77<br>78 | |
| Hydraulic pump | 50<br>80<br>573 | 77<br>78<br>111 | 100 [2] |
| Shaft | 0.55 | 77 | 0.08 |
| Solenoid valve | 12<br>25<br>29 | 77<br>78<br>111 | |
| Engine driven pump | 18.5<br>36 | 111<br>78 | .08 |
| Check valve | 30<br>4 to 7 | 111<br>78 | |
| Mounting bracket | 0.6 | 78 | |
| Fuel filter | 33 | 78 | |
| Heat exchanger | 3.2 | 78 | |
| Shut-off valve (hydraulic) | 18 | 78 | |

1 Operating equipment in airborne exposed environment.
2 767 service experience

c) Service data

Undoubtedly the most comprehensive records of engine failures in service are those kept by the engine manufacturers; since in the event of a failure their field representatives are immediately approached by the airline for technical advice and possible redress, and since the field representatives have a direct link (paper or electronic) back to the parent company. These records are proprietary and not generally available for consultation without special permission of the company involved; this permission has been granted by Rolls-Royce and the relevant material is located in Volume II.

Otherwise, subsets of engine failures falling into well-defined categories may be reported to the appropriate regulatory authorities by the manufacturer, such as a Service Difficulty Report (45) reported to the FAA, or a Failure or Malfunction (46) reported to the CAA. It should be emphasized that this system is not comprehensive or consistent, depending in part upon the airline involved, the country in which the event took place and the interpretation of the individual responsible for filing the report. Some service incidents are called to the attention of other bodies such as the NTSB (75) which maintain independent databases.

Statistical summaries of particular types of failure are published at intervals by various bodies within the industry (18), (50 - 52) and (35 - 44); although these are limited in scope, they often provide comprehensive coverage of all instances of a particular type of failure. The completeness of reporting of the above references is assessed in Appendix C; it is sufficient to remark at this point that available reports in the public domain do not permit failure rates to be produced for all failure types and engine models of interest, and that quantitative comparisons of predicted and actual failure rates are therefore limited to a few engine models.

Aircraft accidents form a better-documented (47) and more accessible source of information than do safety-related engine failures, being recorded in the World Airline Accident Summary (76) in sufficient detail to isolate those accidents in which a high bypass-ratio engine was a significant factor. Fortunately for the industry, there are too few propulsion-related accidents to generate statistically significant failure rates for individual engine models, but records of accidents nevertheless form an extremely valuable resource for reviewing sequences of events leading to accidents (the necessary technical detail being obtained from individual accident reports).

d) Reliability modeling

Many textbooks have been published giving general overviews of reliability modeling techniques, which form the foundation of much of the safety analysis produced today. The approach varies from the practical (Smith, (54)) to the theoretical (Kapur and Lamberson, (79)) and is considerably affected by the background of the author (electronics versus process plant versus mechanical engineering). The following were found to be particularly useful in the context of this study; Dhillon and Singh (80) (which also includes comprehensive reference lists) and Lloyd and Lipow (81). Alternative approaches are to be found in Beasely (82), Aven (83), Blockley (84), Green and Bourne (85) and Shooman (68). Previously published literature surveys include those of Lemon and Manning (86) and Martin, Strutt and Kinkead (87), and Taneja and Safie (22).

Reliability modeling, as it pertains to safety analysis, may be considered as falling into several distinct areas:

> Forecasting failure distributions of individual components, either analytically or statistically.
>
> Synthesis of system failure rates given individual component failure rates, to assess design reliability.
>
> Verification of design reliability predictions by test.
>
> Estimation of the likely achieved reliability, given the design reliability (in other words, accounting for manufacturing errors, operational difficulties and maintenance problems).

1. Analytical forecasting of failure distributions requires a thorough understanding of both the strength distribution of the component and the distribution of stresses to which it is exposed. The stress-strength interference technique, originally developed in the 1960s (Ghare, 88, and Kececioglu, 89) is discussed at some length by Carter (23); a brief summary being provided by Chapter 6 of Dhillon and Singh (80). Specific examples of its use in relation to aircraft engine components can be found in the works of Bompas-Smith (25), (26). It is not rigorously used in critical component life prediction for gas turbines due to the complexity of the models required (Harrison and Shepherd (90)), but aspects of the technique such as the statistical assessment of mission mix to generate the load distribution (Metz and Zimmerman (91), Osias, Meyer and Hill (92)) and the use of statistical strength distributions in conjunction with nominal design loads (Forrester and Thevonov (93), Pickard (94), Jeal (95), Adamson (96), Harrison and Shepherd (90)) are widespread. Hunsley (97) claims that this deterministic approach is more promising than the use of generic failure rates with severity. Martin (28) proposes the use of a complex

equipment model for such equipment as aircraft engines, in the context of explaining observed failure distributions rather than actual forecasting of reliability.

Purely statistical forecasting of failure distributions generally requires hundreds or thousands of component tests and failures (Moore and Ebbeler (98)) before a distribution can be modelled with confidence. The high reliability of current commercial jet engines confines the analyst's interest to the short-life 'tail' of the distribution in many instances (the majority of components are retired from service without failing); techniques dealing with the modeling of distributions given a few failures at one of the extremes include Weibull analysis (Kao (99), Abernethy (100)), Extreme-value theory (Gumbel (101)), and threshold techniques (Smith (29)). However, the majority of the modeling techniques discussed require half a dozen failures of a single component or design before the distribution can be characterised; in practice, demonstrably hazardous failures are not permitted to recur several times in commercial aircraft engines without corrective action being instituted, throughout the fleet and in forthcoming designs. Gottfried and Weiss (8) summarizes the problem of making reliability predictions with only minimal data available.

The challenge of forecasting the failure distribution of a component subjected to design changes in response to each failure may be partly met by Reliability Growth modeling. The basic concept of the technique is described by Duane (19) and model refinements are outlined in Lawlor (20) Mead (21) and Taneja (22), and models compared by Perera (102), who found that both Duane and Weibull-based models gave good agreement with observed trends for an electronic processor. Application of the technique to successive engine models is implied in Jackson (103) and Lloyd and Tye (11); Boiles and Hadel (104) has noted that the apparent 'step-change' in reliability from parent design to derivative may be accounted for, in part, by instantaneous incorporation into the derivative of all of the improvements gradually being introduced into the parent fleet.

2. Once individual component failure rates have been established, system failure rates may be synthesized from component failure rates by fault tree analysis, as described by Haasl (105) and discussed by Bendell and Ansell (106) (or by Markov modeling for state-dependent systems). Such synthesis generally assumes independent component failures; Martin (107) discusses the appropriate mathematical treatment for mutually exclusive failures (such as alternative failure modes of a single component) and of the frequently encountered consequential failures (such as are identified in an FMEA). Ansell and Walls (108) discusses the issue of dependency of failure modes in greater detail, and warns of the tendency to model a statistically apparent dependency without investigating the actual causal

equipment model for such equipment as aircraft engines, in the context of explaining observed failure distributions rather than actual forecasting of reliability.

Purely statistical forecasting of failure distributions generally requires hundreds or thousands of component tests and failures (Moore and Ebbeler (98)) before a distribution can be modelled with confidence. The high reliability of current commercial jet engines confines the analyst's interest to the short-life 'tail' of the distribution in many instances (the majority of components are retired from service without failing); techniques dealing with the modeling of distributions given a few failures at one of the extremes include Weibull analysis (Kao (99), Abernethy (100)), Extreme-value theory (Gumbel (101)), and threshold techniques (Smith (29)). However, the majority of the modeling techniques discussed require half a dozen failures of a single component or design before the distribution can be characterised; in practice, demonstrably hazardous failures are not permitted to recur several times in commercial aircraft engines without corrective action being instituted, throughout the fleet and in forthcoming designs. Gottfried and Weiss (8) summarizes the problem of making reliability predictions with only minimal data available.

The challenge of forecasting the failure distribution of a component subjected to design changes in response to each failure may be partly met by Reliability Growth modeling. The basic concept of the technique is described by Duane (19) and model refinements are outlined in Lawlor (20) Mead (21) and Taneja (22), and models compared by Perera (102), who found that both Duane and Weibull-based models gave good agreement with observed trends for an electronic processor. Application of the technique to successive engine models is implied in Jackson (103) and Lloyd and Tye (11); Boiles and Hadel (104) has noted that the apparent 'step-change' in reliability from parent design to derivative may be accounted for, in part, by instantaneous incorporation into the derivative of all of the improvements gradually being introduced into the parent fleet.

2. Once individual component failure rates have been established, system failure rates may be synthesized from component failure rates by fault tree analysis, as described by Haasl (105) and discussed by Bendell and Ansell (106) (or by Markov modeling for state-dependent systems). Such synthesis generally assumes independent component failures; Martin (107) discusses the appropriate mathematical treatment for mutually exclusive failures (such as alternative failure modes of a single component) and of the frequently encountered consequential failures (such as are identified in an FMEA). Ansell and Walls (108) discusses the issue of dependency of failure modes in greater detail, and warns of the tendency to model a statistically apparent dependency without investigating the actual causal

relationship. The issue of dependent failures is explicitly applied to turbine blade-sets of an aircraft engine by Martin, Strutt and Kinkead (87). Architecturally simple systems may be modelled by FMEA alone, using the chain rule to develop the system failure rate from individual component failure rates; disadvantages of this approach are raised by Kytasty et al (12).

3. The majority of reliability predictions regarding high bypass ratio jet engines cannot be confirmed during engine development testing; since the predicted MTBFs are so high that no failures are expected during development running, and reliability can therefore only be truly measured in service. However, engine and component testing can give some measure of the robustness of the whole system, compared to previously established benchmarks, and of such parameters as component fatigue life, as described by Horsley (109).

4. Most of the references cited above address what Smith (54) has termed the "design reliability", resulting from 'the inherent reliability of the chosen components, their quantity, method of interconnection and from the configuration of the equipment.....it is never achieved in practice.' This bears a strong relationship to the basic engine failure rate quoted by manufacturers; failures attributable to exterior influences such as Foreign Object Damage, maintenance errors, flight crew error or aircraft systems are added to this to produce the total failure rate, which determines the safety of the propulsion system as a whole. Thurston (110) points out the importance of considering the pilot, aircraft and engines as a whole, rather than assessing design in isolation. Dhillon (111) provides a brief overview of human errors in mechanical systems, and Hunns and Daniels (112) discusses the quantification of human factors in reliability assessment, offering the method of paired comparisons as a means of extracting probabilities from the unquantified experience of an expert group.

e) Component failure mechanisms and failure propagation

Some consideration of the failure mechanisms prevalent in jet engines is appropriate to a study of reliability and safety analysis techniques, as is a basic technical understanding of potential safety-related failure effects.

1. Component failure

Pinkel et al (113) presents an overview of failure mechanisms important to jet engine operation; although advances in technology have altered the relative importance of the failure modes cited, the basic principles remain unchanged. The predominant mechanisms of jet-engine component failure are still fatigue (high and low-cycle), creep, wear, corrosion, overtemperature, and mechanical overload attributable to such events as foreign object damage. Interaction between different damage mechanisms and loading orientations is the subject of considerable debate; various alternatives have been proposed to simple summation using Miner's law (for example, Tseitlin and Fedorchenko (114), propose superimposing multi-component loading by accounting for dynamic cycle asymmetry, resulting in the use of somewhat lower safety factors.)

The low cycle fatigue (LCF) lifing of critical parts such as compressor and turbine discs was discussed above in some detail, in the latter portion of subsection (d), although it is worth noting that concerns have been expressed by Mahorter, Fowler and Salvino (115) over the use of statistical materials data in such life prediction; they have documented significant discrepancies between disc lives so predicted and those actually measured during a programme of spin-pit testing (measured lives were found to be considerably lower). Occasionally alternative approaches to life prediction are suggested such as that of Drexler and Statecny (116) who hypothesize that any disc crack will be accompanied by a large number of slightly smaller cracks which nucleated shortly after the first one (assuming a homogeneous disc), thus greatly increasing the likelihood of successful crack detection. The main stream of disc lifing philosophy, however, is as described by Harrison and Shepherd (90).

High cycle fatigue is of considerable importance to the reliability of flexible components subject to severe vibration, such as blades and tubes. Voysey (117) initially predicted that the introduction of high pressure ratios would be likely to result in compressor stall and consequent high-cycle fatigue blade failure, by analogy with wing flutter (a prediction born out by subsequent experience). Considerable efforts are made to detune the component natural frequency from engine running speeds (and harmonics), but cracking from some other cause may alter component stiffness to permit eventual HCF failure as documented by Yaker (118), who conducted laboratory testing of turbine blades, simulating service running, and determined that initial failures originated from stress-rupture cracking, followed by high-cycle fatigue.

Creep presents a major problem in the life of turbine blades, as described by Bagnall (119), even though recent blade designs incorporate sophisticated internal and surface film-cooling. Creep life prediction may be augmented by inspection of unfailed components to establish the remaining life, as described by Singh and Thomas (120).

2. Fire safety

Propulsion system fires generally originate from the coexistence of leaked flammable fluid (neglecting titanium and magnesium fires for the moment), an ignition source (electrical or thermal) and an appropriate air supply. Conflicting work has been published on the temperature of the ignition source required to ignite leaked fluids; Goodall (121) has published experimental data supporting considerably higher surface temperatures required for the ignition of kerosene in engine compartments than have been reported by others (Johnson et al (122), Clodfelter and Anderson (123) and earlier work by Kuchta et al (124, 125)). The discrepancy may be attributable to experimental technique, such as the degree of fluid atomisation, surface geometry differences, or to the use of airflows representative of those in an engine nacelle. The wide variation in measured spontaneous ignition temperatures, together with the effect of air pressure and local ventilation flows renders the confident prediction of powerplant fire or fire safety difficult; minimising the likelihood of flammable fluid leakage would appear to be the best means of defence against fire.

3. Common mode failures

The majority of common-mode failures affecting multiple engines are imposed by the external environment; notably by the fuel or air supplied to the engine, by foreign object ingestion, or by human error (discussed below). Independent, but near-simultaneous failures by the same failure mechanism on multiple engines form the exception rather than the rule. However, the potential for multiple-engine system malfunction under unusual operating conditions continues to present a real and significant threat.

Early problems associated with contaminated fuel have been documented by Love, Hatchett and Peat (126). More rigorous fuel specifications have addressed some of these issues, but the potential for gross contamination by ice, dirt or bacteriological activity still remains.

The role of excessive rain and hail in causing multiple engine flameout is outlined briefly by Devine (127). The potential for multiple engine birdstrike has long been recognised throughout the industry; many such incidents are recorded in recent birdstrike studies (128, 129).

There is almost no published material documenting any effects of man-made electromagnetic interference (EMI) upon aircraft engines. Lightning activity in close proximity to the aircraft has been recorded as causing failure of engine instrumentation (Clifford (130)) such as rpm and exhaust gas temperature gauges. Lightning strike has also produced engine stalls,

flameouts and rollbacks on small, fuselage mounted engines; instances of multiple engines being affected have been noted by Plumer (131). These events are ascribed to ingestion of the hot air column produced by the lightning (and therefore unlikely to affect larger, high bypass-ratio engines); there are no published instances of induced electromagnetic effects leading to engine malfunction, although the potential for such a common mode failure remains a cause for concern (Dubro, (132)).

Since aircraft services (pneumatic bleed, electrical power and hydraulic power) are supplied by more than one engine, and designed to operate satisfactorily with one engine shut down, the architecture of each system has considerable redundancy. Consequently, little consideration has been given in the past to the loss of multiple systems, other than as a result of uncontained engine failure (addressed by system separation, as described by Lloyd and Tye (133)), or of multiple engine shutdown (in which case the emphasis has been on loss of thrust, systems consideration being secondary, as typified by Sprogis, (134)).

4. Crew error

The contribution of flight crew error to propulsion-related aircraft accidents, either in isolation or in conjunction with an engine failure, has been discussed by Reason and Mycielska (135), who propose attentional capture as the main mechanism inducing the crew to misinterpret information presented on the flightdeck. Reason (136) has proposed a comprehensive error management approach to reducing the contribution of flight crew (and other) errors to aircraft accidents. Green et al (137) also emphasize the role of stress in narrowing the focus of flight-crew attention so that important information is excluded from the decision-making process. The deleterious effect of time pressure upon the accuracy of a decision is also cited, implying that engine failures occurring during times of peak workload are more likely to result in crew errors. Chamberlin (58) discusses the contribution of flight crew error in high speed rejected takeoff. Williams (138) presents a series of factors reducing the reliability of decisions, together with a numerical range by which the reliability may be affected, including shortage of time and channel capacity overload in the decision-maker.

Reason and Mycielska present the execution of a highly organised (but inappropriate) sequence of actions as a weakness of expertise, in diametrical opposition to lack of familiarity with a task (implying that further training is not the best means of addressing this issue). This position is the logical consequence of the statement made by Fitz and Posner (139) "During the final phase of skill learning, component processes become increasingly autonomous, less directly subject to cognitive control and less subject to interference from other ongoing activities" and provides considerable insight into some instances of crew error.

Quantitative evaluation of the propensity for crew error is hindered by the rarity of such events resulting in accidents; it may be assisted by consultation with flightcrew using the method of paired comparisons (Hunns and Daniels (112)) to give an order-of-magnitude numerical estimate.

Sumwalt and Watson (140) point out that the seriousness of the initial malfunction is unrelated to the seriousness of the outcome after the crew has responded inappropriately.

Maintenance error is a significant source of engine failures, both those hazardous in themselves and those affecting multiple engines. Davies (141) and others have pointed out the close link between reliability and maintainability; the reliable component does not require routine maintenance action, and therefore is less prone to maintenance-induced failures. Dhillon (111) cites human error rates for selected maintenance tasks, although their general applicability is open to question, since many error rates are installation-specific, as emphasized in the US Air Force/ Army/ Navy presentations of (142).

# APPENDIX B

THIS PAGE INTENTIONALLY BLANK

# APPENDIX B REGULATORY REQUIREMENTS

## CODE OF FEDERAL REGULATIONS, PART 33.

### 33.75 SAFETY ANALYSIS

It must be shown by analysis that any probable malfunction or any probable single or multiple failure, or any probable improper operation of the engine will not cause the engine to -
(a) Catch fire
(b) Burst (release hazardous fragments through the engine case)
(c) Generate loads greater than those ultimate loads specified in 33.23(a)
(d) Lose the capability of being shut down.

### 33.23 ENGINE MOUNTING ATTACHMENTS AND STRUCTURE

(a) The maximum allowable limit and ultimate loads for engine mounting attachments and related engine structure must be specified.

See also ADVISORY CIRCULAR 33-2B; 6/30/93

*CODE OF FEDERAL REGULATIONS.*
PART 25 Subpart E - Powerplant

25.901 Installation
(c) For each powerplant and auxiliary power unit installation, it must be established that no single failure or probable combination of failures will jeopardize the safe operation of the airplane except that the failure of structural elements need not be considered if the probability of such failure is extremely remote.

25.903 Engines
(b) *Engine isolation.* The powerplants must be arranged and isolated from each other to allow operation, in at least one configuration, so that the failure or malfunction of any engine, or of any system that can affect the engine, will not -

(1) Prevent the continued safe operation of the remaining engines or

(2) Require immediate action by any crew member for continued safe operation

(d) *Turbine engine installations.* For turbine engine installations -
(1) Design precautions must be taken to minimize the hazards to the airplane in the event of an engine rotor failure or of a fire originating within the engine which burns through the engine case.
(2) The powerplant systems associated with engine control devices, systems, and instrumentation, must be designed to give reasonable assurance that those engine operating limitations that adversely affect turbine rotor structural integrity will not be exceeded in service.

Subpart F - Equipment
25.1309 Equipment, systems and installations

(a) The equipment, systems and installations whose functioning is required by this subchapter, must be designed to ensure that they perform their intended functions under any foreseeable operating condition.

(b) The airplane systems and associated components, considered separately and in relation to other systems, must be designed so that -

(1) the occurrence of any failure condition which would prevent the continued safe flight and landing of the airplane is extremely improbable, and-

(2) The occurrence of any other failure condition which would reduce the capability of the crew to cope with adverse operating conditions is improbable.

(c) Warning information must be provided to alert the crew to unsafe system operating conditions, and to enable them to take appropriate corrective action. Systems, controls and associated monitoring and warning means must be designed to minimize crew errors which would create additional hazards.

(d) Compliance with the requirements of paragraph (b) of this section must be shown by analysis, and where necessary, by appropriate ground, flight or simulator tests. The analysis must consider -

(1) Possible modes of failure, including malfunctions and damage from external sources.

(2) the probability of multiple failures and undetected failures.

(3) The resulting effects on the airplane and occupants, considering the stage of flight and operating conditions.

(4) The crew warning cues, corrective action required, and the capability of detecting faults.

(e) Each installation whose functioning is required by this subchapter, and that requires a power supply, is an 'essential load' on the power supply. The power sources and the system must be able to supply the following power loads in probable operating combinations and for probable durations:

(1) Loads connected to the system with the system functioning normally.

(2) Essential loads, after failure of any one prime mover, power converter or energy storage device.

(3) Essential loads after failure of -

(i) Any one engine on two-engine airplanes

(ii) Any two engines on three-or-more engine airplanes

(4) Essential loads for which an alternate source of power is required by this chapter, after any failure or malfunction in any one power supply system, distribution system, or other utilization system.

(f) In determining compliance with paragraphs (e)(2) and (3) of this section, the power loads may be assumed to be reduced under a monitoring procedure consistent with safety in the kinds of operation authorized. Loads not required in controlled flight need not be considered for the two-engine-inoperative condition on airplanes with three or four engines.

(g) In showing compliance with paragraphs (a) and (b) of this section with regard to the electrical system and equipment design and installation, critical environmental conditions must be considered. For electrical generation, distribution, and utilization equipment required by or used in complying with this chapter, except equipment covered by Technical Standard Orders containing environmental test procedures, the ability to provide continuous safe service under foreseeable environmental conditions may be shown by environmental tests, design analysis, or reference to previous comparable service experience on other aircraft.

See also ADVISORY CIRCULAR 25.1309-1A; 6/21/88

JOINT AIRWORTHINESS REGULATIONS PART E
SUB-SECTION D - TURBINE ENGINES; DESIGN AND CONSTRUCTION

JAR-E 510 FAILURE ANALYSIS
(See ACJ E 510)

(a) A failure analysis of the engine including the control system for a typical installation shall be carried out in order to assess the likely consequence of all failures that can reasonably be expected to occur. From this, a summary shall be made of those failures (including those multiple failures referred to in (c) and (d)), which could result in Major Effects or Hazardous Effects, together with an estimate of the probability of occurrence of those Effects. Where significant doubt exists on the Effects of failures and likely combinations of failures the Authority may require any assumptions to be verified by test (e.g. the effects of extreme unbalance arising from a large blade failure; the effects of a bearing failure; the effects of shaft failure).

(b) It is recognised that the probability of prime failures of certain single elements (e.g. rotor discs) cannot be sensibly estimated in numerical terms. Where the failure of such items is likely to result in Hazardous Effects, reliance must be placed on their meeting the prescribed integrity requirements and where this is so, it shall be stated in the failure analysis. (See also JAR-E 515)

(c) Where reliance is placed on safety devices, instrumentation, early warning devices, maintenance checks etc. to prevent a failure progressing to Hazardous Effects, the possibility of a 'safety system' failure in combination with a basic engine failure shall be covered. Where items of a 'safety system' are outside the control of the engine constructor, the assumptions of the failure analysis in respect of the reliability of these parts shall be clearly stated and supplied to the aircraft constructor.

(d) Consequential secondary failures shall be taken fully into account.

(e) Where the acceptability of the failure analysis is dependent on one or more of the following, these shall be identified in the analysis and appropriately substantiated.

(1) Maintenance actions, including the verification of serviceability of items the failure of which could be dormant, being carried out at stated periods. These periods must be published in the appropriate manual. Additionally, where errors in maintenance of the engine control system could lead to Hazardous Effects, (e.g. particularly in respect of reverse thrust), the appropriate vital points shall be identified for inclusion in the engine maintenance manual.

(2) Justification for the inclusion; in the Master Minimum Equipment list of any Engine-associated item permitted to be carried in an unserviceable state for specific periods.
(3) Verification of satisfactory functioning of safety or other devices, etc., at preflight or other stated periods, the details of which must be published in the appropriate manual.
(4) The provision of specific instrumentation not otherwise required.

(f) In certain cases the failure analysis will depend on assumed installed conditions. Such assumptions shall be stated in the analysis.

Amendment E/91/1

JAR-E 515 CRITICAL PARTS INTEGRITY
(See ACJ E 515 and AMJ E 515)
The Engine Critical Parts shall be identified and their integrity shall be established by the following disciplines:
(a) An engineering plan, the execution of which demonstrates that the combination of loads, material properties, environmental factors and conditions are sufficiently well-known or predictable by analysis, or test experience to allow the parts to be withdrawn from service at a life before hazardous failure can occur.
(b) A manufacturing and inspection plan, which defines the method of manufacture
(1) For producing all parts with the attributes assumed by the engineering plan of (a)
(2) To enable the relevant manufacturing history to be traceable.
(3) To ensure that manufacturing changes will be controlled to prevent the assumed attributes being degraded.
(c) The manufacturer shall demonstrate that adequate procedures are adopted to ensure the necessary control of the engineering and manufacturing functions associated with the production of Critical Parts. These procedures shall specify the objectives and responsibilities of the organisation necessary to control and implement the overall Product Assurance Policies.
(d) The manufacturing processes, maintenance in service and overhaul of Critical Parts must be such as to ensure that they have characteristics essentially similar to those on which the certification of the design was based, and must be associated with specified acceptance standards and Non-Destructive Inspection.

Amendment E/91/1

JOINT AIRWORTHINESS REGULATIONS PART 25

SUBPART E - POWERPLANT
GENERAL
JAR 25.901 Installation
(a) For the purpose of this JAR-25 the aeroplane powerplant installation includes each component that -
(1) Is necessary for propulsion
(2) Affects the control of the major propulsive units or
(3) Affects the safety of the major propulsive units between normal inspection intervals or overhauls.
(b) For each powerplant
(1) The installation must comply with -
(i) The installation instructions provided under JAR-E Section 4 paragraph 7 and
(ii) The applicable provisions of this subpart (see also AMJ 20X-1)
(2) The components of the installation must be constructed, arranged and installed so as to ensure their continued safe operation between normal inspections or overhauls. (See ACJ 25.901(b)(2))
(3) The installation must be accessible for necessary inspections and maintenance
(4) The major components of the installation must be electrically bonded to the other parts of the aeroplane (See ACJ 25.901(b)(4))
(c) The powerplant installation must comply with JAR25.1309.
(d) Not required.
(e) The satisfactory functioning of the power unit must be demonstrated by ground and flight tests over the range of operating conditions for which certification is required and must include tests under hot climatic conditions, unless equivalent evidence can be produced. (See ACJ 25.901(e)).

JAR 25.903 Engines

(a) *Engine type certification*
(1) Each engine must have a type certificate (See ACJ 25.903(a))
(2) Any engine not certificated to JAR-E must be shown to comply with JAR-E 790 and JAR-E 800 or be shown to have a foreign object ingestion service history in similar installation locations which has not resulted in any unsafe condition.

(b) *Engine isolation.* The powerplants must be arranged and isolated from each other to allow operation, in at least one configuration, so that the failure or malfunction of any engine, or of any system that can affect the engine, will not -
(1) Prevent the continued safe operation of the remaining engines, or

(2) Require immediate action by any crew member for continued safe operation.

(c) *Control of engine rotation.* There must be a means for stopping the rotation of any engine individually in flight, except that, for turbine engine installations, the means for stopping the rotation of any engine need be provided only where continued rotation could jeopardise the safety of the aeroplane.

(1) In particular, where no means is provided to prevent continued rotation, the safety of the aeroplane must be shown in the event of failure of the engine oil supply (See JAR-E 710 and ACJ E 710)

(2) Each component of the stopping system on the engine side of the firewall that might be exposed to fire must be at least fire resistant.

(3) If hydraulic propeller feathering systems are used for this purpose, the feathering lines must be at least fire-resistant under the operating conditions that may be expected to exist during feathering.

(d) *Turbine engine installations.* For turbine engine installations -

(1) Design precautions must be taken to minimise the hazards to the aeroplane in the event of an engine rotor failure or of a fire originating within the engine which burns through the engine case. (See ACJ No 1 and ACJ No 2 to JAR 25.903(d)(1).

(2) The powerplant systems associated with engine control devices, systems, and instrumentation, must be designed to give reasonable assurance that those engine operating limitations that adversely affect turbine rotor structural integrity will not be exceeded in service.

(e) *Restart capability*

(1) Means to restart any engine in flight must be provided.

(2) An altitude and airspeed envelope must be established for in-flight engine restarting, and each engine must have a restart capability within that envelope. (See ACJ 25.903(e)(2)).

(3) For turbine engine powered aeroplanes, if the minimum windmilling speed of the engines, following the in-flight shutdown of all engines, is insufficient to provide the necessary electrical power for engine ignition, a power-source independent of the engine-driven electrical power generating system must be provided to permit in-flight engine ignition for restarting.

See also ACJs to JAR 25.903(d)(1)

SUBPART F - EQUIPMENT
GENERAL

JAR 25.1309 Equipment, systems and installations

(a) The equipment, systems and installations whose functioning is required by the JAR and national operating regulations must be designed to ensure that they perform their intended functions under any foreseeable operating conditions. (See AMJ 25.1309 and ACJ No 2 to JAR 25.1309) However, systems used for non-essential services need only comply so far as is necessary to ensure that the installations are neither a source of danger in themselves nor liable to prejudice the proper functioning of any essential service.

(b) The aeroplane systems and associated components, considered separately and in relation to other systems, must be designed so that (see AMJ 25.1309 and ACJ No 3 to JAR 25.1309 and AMJ 25.1309(b)) -

(1) The occurrence of any failure condition which would prevent the continued safe flight and landing of the aeroplane is extremely improbable; and

(2) The occurrence of any other failure condition which would reduce the capability of the aeroplane or the ability of the crew to cope with adverse operating conditions is improbable.

(c) Warning information must be provided to alert the crew to unsafe system operating conditions, and to enable them to take appropriate corrective action. Systems, controls, and associated monitoring and warning means must be designed to minimise crew errors which could create additional hazards. See AMJ 25.1309 and ACJ Nos. 4 and 8 to JAR 25.1309.

(d) Compliance with the requirements of subparagraph (b) of this paragraph must be shown by analysis, and where necessary, by appropriate ground, flight or simulator tests. The analysis must consider (see AMJ 25.1309) -

(1) Possible modes of failure, including malfunctions and damage from external sources

(2) The probability of multiple failures and undetected failures

(3) The resulting effects on the aeroplane and occupants, considering the stage of flight and operating conditions, and

(4) The crew warning cues, corrective action required, and the capability of detecting faults.

(e) Each installation whose functioning is required for certification and that requires a power supply is an 'essential load' on the power supply. The power sources and the system must be able to supply the following

power loads in probable operating combinations and for probable durations (see ACJ No 6 to JAR 25.1309)

(1) Loads connected to the system with the system functioning normally.

(2) Essential loads, after failure of any one prime mover, power converter, or energy storage device.

(3) Essential loads after failure of -

(i) Any one engine on two-engined aeroplanes, and

(ii) Any two engines on three or more engined aeroplanes.

After the failure of any two engines on a three-engined aeroplane, those services essential to airworthiness must continue to function and perform adequately within the limits of operation implied by the emergency conditions. (see ACJ No 7 to JAR 25.1309).

(4) Essential loads for which an alternate source of power is required by any applicable JAR or national operating regulations after any failure or malfunction in any one power supply system, distribution system, or other utilisation system.

(f) In determining compliance with subparagraphs (e)(2) and (3) of this paragraph, the power loads may be assumed to be reduced under a monitoring procedure consistent with safety in the kinds of operation authorised. Loads not required in controlled flight need not be considered for the two-engine inoperative condition on aeroplanes with three or more engines.

(g) In showing compliance with sub-paragraphs (a) and (b) of this paragraph with regard to system and equipment design and installation, critical environmental conditions including vibration and acceleration loads, handling by personnel and where appropriate fluid and pressure effects, must be considered. For power generation, distribution, and utilisation equipment required by or used for certification, the ability to provide continuous safe service under foreseeable environmental conditions may be shown by environmental tests, design analysis or reference to previous comparable service experience on other aeroplanes.

See also ACJs to JAR 25.1309.

THIS PAGE INTENTIONALLY BLANK

# APPENDIX C

THIS PAGE INTENTIONALLY BLANK

# APPENDIX C: SERVICE EXPERIENCE BASE

## C i Substantiation of Data

The attempt to relate propulsion system safety analysis to previous service experience required the compilation of a service experience database, including all propulsion-related accidents in the high bypass commercial transport fleet up to the end of 1993. A database of safety-related incidents was also compiled. It must be recognised, however, that any attempt to generate failure rates relies upon the accuracy and completeness of the reporting of such failures from the field. No single database can be relied upon to include every relevant powerplant failure, but it was anticipated that amalgamation of failure events from several databases would both allow assessment of the completeness of reporting, and also allow production of failure rates representative within a few percent, and at least as accurate as any currently published within the industry.

Events were selected and assigned primary causal factors as described in 3.2. Data was extracted from the following sources:

a) NTSB
b) FAA Service Difficulty Reports for US airlines, January 1986 - December 1994, engine failures.
c) CAA, Reports of Failures, Malfunctions and Defects reported for high-bypass engines, January 1984 - December 1994
d) FAA Service Difficulty Reports for US airlines, 1978 -1979 and 1981 - 1989, Engine Rotor Failures

The accident record from the above sources was cross-checked against the annual airline safety report issued by "Flight International" and against the World Airline Accident Summary published by the CAA. It is felt that the accident database presented in table C.1 is relatively complete. Some events may have been included which might not be considered accidents by some groups: this results from the inconsistent usage of the term "substantial damage" from one airworthiness authority to another.

The safety-related incident record, omitted in the interest of brevity, is known to be incomplete. Cross-checking between the above sources showed that there was minimal redundancy, in that only one event was reported by more than one of the databases (RB211-535 multiple engine flameout on , reported by FAA, CAA and NTSB). This initially caused some concern, since it implied the potential existence of large numbers of safety related events external to both Britain and the US, unreported by sources a), b) and c). It was

also discovered during the course of the research that although US engine manufacturers report all in-flight shutdowns, rejected takeoffs and safety-related events to the FAA, only a small fraction of this material is then published in the FAA SDR database for public reference. The reason for this anomaly is unclear, but the implication is that the SDR database cannot be used to generate reliable rates. Hazard ratios and failure rates generated using incident data should therefore be treated with considerable scepticism unless they can be confirmed by an alternate source such as data published by independent industry committees, which have access to larger data samples.

## Cii Detailed World Fleet Accident and Incident Experience

The following material describes statistical details of the data assembled in table C.1.

### Uncontained debris

There were 21 accidents resulting from uncontained failures in the high bypass ratio fleet between 1970 and the end of 1994. The majority of these accidents were the direct result of airplane system damage or structural damage, although there were three or four accidents involving high speed rejected takeoffs, which might arguably have affected the outcome. Uncontained failures were the single greatest contributor to propulsion-related accidents. The risk of an uncontained failure-type accident appeared to be confined mostly to the older aircraft models; the 747, L1011, DC10 and A300. It had been proposed by Taylor (1) that the rate of uncontained-failure accidents would be proportional to the number of engines. This is not the case; the uncontained failure rates (accidents and total events, per airplane flight hour) for the models cited above are as follows[46]:

| | 747 | DC10 | L1011 | A300 |
|---|---|---|---|---|
| Accident rate | 21.9E-7 $\pm$.2 | 2.3E-7 $\pm$.4 | 2.7E-7 $\pm$.9 | 2.1E-7 $\pm$1.1 |
| Uncontained failure rate | 1.5E-6 | 1.2E-6 | 1.2E-6 | 1E-6 |

[46]It is acknowledged that this distribution of accidents does not agree with that of table 6.1-17 of AIR4770 (52), which showed twins having a lower "uncontained accident" rate per aircraft departure, by a factor of 4, than 3 or 4 engine aircraft. AIR 4770 dealt with a 5 year timespan, involving only 8 uncontained-event accidents, and is therefore considered more likely to be affected by random variation. It also calculated rates based on departures, not hours, which would make long-haul operations typical of 3 and 4 engined aircraft appear worse for the same number of accidents.

There is no clear difference between the three airplane configurations as regards the likelihood of having an uncontained failure which results in an accident.

8 of these uncontained failure accidents occurred during takeoff, 8 in climb, 3 in cruise and 2 during landing (reverse thrust). The distribution of uncontained failures by flight phase and that of resulting accidents are similar (within the scatter imposed by one additional uncontained accident) for all flight phases but cruise, where the risk of an accident resulting given an uncontained failure is somewhat reduced (see below). It would be reasonable to expect a slightly reduced risk in cruise, given the additional time for the flight crew to make optimal decisions in dealing with the engine failure and any consequent damage before landing the airplane.

| | Incidence of uncontained failures | Incidence of accidents caused by uncontained failures ±5% |
|---|---|---|
| T/O | 43% | 38% |
| Climb | 30% | 38% |
| Cruise | 21% | 14% |
| Landing | 4% | 9% |

The magnitude of the hazard ratio may be estimated as follows: the high bypass ratio fleet accrued 400 million engine hours by the end of 1994. This gives an uncontained-failure accident rate of 5.2E-8/engine flight hour. The SAE studies (50, 51, 52) on uncontained failures quote the high-bypass-ratio uncontained failure rates as 8.5E-7/hour; the hazard ratio may therefore be estimated as 0.06, that is, that in the event of an uncontained failure, six times out of a hundred an accident will be the result.
As a comparison, the uncontained incidents and accidents in the author's database would lead to an uncontained failure rate of 3.3E-7/hour, implying that the database used for this study has no more than 38% of the incidents which actually occurred (the reporting of uncontained failures can be expected to be significantly better than that of less dramatic failures, the truth is probably less than 38% for other failure modes).

Propulsion failure plus crew error

There were 15 accidents resulting from propulsion system malfunction + crew error in the high bypass ratio fleet between 1970 and the end of 1994. 10 of these occurred in takeoff, two in climb, one in cruise and two in landing. It may be assumed that every inflight shutdown or high speed (100kts+) rejected takeoff affords an opportunity for crew error resulting in an accident. The total number of IFSDs in the high bypass fleet is estimated as 35,000±15%, the number of rejected takeoffs above 100 kts has been estimated as of the order of 500 (ref. personal communication with GP Sallee, Boeing). An estimated hazard ratio would be 4E-4, in close agreement with the mean value of 3.7E-4 cited by Sallee (47).

| | Incidence of engine failures | Incidence of accidents caused by propulsion system + crew error ±7% |
|---|---|---|
| T/O | 5% | 66% |
| Climb | 31% | 13% |
| Cruise | 36% | 7% |
| Descent | 19% | 0% |
| Landing | 9% | 13% |

The majority of these accidents resulted from an engine malfunction late in the takeoff roll, and an incorrect decision to reject the takeoff with insufficient runway available. There have been a large number of rejected takeoffs and continued takeoffs with an engine malfunction recorded (203 RTOs and 130 continued takeoffs). It is noteworthy that in the high bypass fleet, a decision to continue the takeoff given an engine malfunction has almost always resulted in a safe landing[47]. Given the limited number of occasions upon which a performance-limited takeoff occurs[48], the practice of some operators of using a lesser value of V1 than recommended for the airplane and ambient conditions (and thus reducing the chance of an unsuccessful RTO) is endorsed by service history.

---

[47]One exception is the engine separation at rotation, ACC18, which resulted in the loss of the aircraft and all crew and passengers.

[48]V1, the speed at which an irrevocable decision is made to continue or to reject the takeoff, is based upon airplane weight, local conditions such as altitude, ambient temperature, runway length and slope, wind and airplane configuration such as bleed selection and engine thrust derate.

The remaining accidents in this category have involved injuries incurred during unwarranted emergency evacuations[49] [50], failure to stabilise the airplane flight path whilst troubleshooting an engine problem, and shutting down the wrong engine. Reference to reports submitted under the ASRS system shows a number of further incidents in which an engine problem has led to procedural errors such as altitude deviations, incursions into forbidden airspace and loss of separation between aircraft. It is a cause for considerable concern that each one of these 15 accidents was initiated by a propulsion system problem which should have been handled easily by the aircraft and crew. It will not be technically possible to eliminate all propulsion system failures with the capability of precipitating crew error; vigorous efforts must therefore be made to understand the source of the error and to address it, either by design or procedure.

It was hypothesized that those aircraft with a flight engineer (three rather than two-person crews) might be less susceptible to propulsion system failure followed by crew error; flight crew reports in ASRS contain comments that two people are not enough to handle an engine problem in busy airspace. The accident rates for this cause do not support this contention (.12/million hours for 2-person, .10/million hours for 3-person aircraft).

It was conversely hypothesized that the number of engines might affect the propensity to crew error after propulsion system failure. Other things being equal, more failures would be anticipated with more engines, and the need to keep track of additional information might exacerbate any tendency to misinterpret instrument readings.. The relative accident rates by twin, tri and quad (propulsion system failure and crew error) are .13, .06 and .12/ million flight hours. The relatively good performance of three-engined aircraft in this respect invites further investigation; it has been attributed by some to the existence of a dedicated engine failure indication in the cockpit, which may reduce confusion under some circumstances (this concept is discussed further in Chapters 6 and 7). It might also be speculated that it is easier to maintain directional control of a three engined aircraft in the event of an engine failure.

---

[49]Gross has shown an average of 0.6 serious injuries per emergency evacuation of commercial transports. There has, however, been a downward trend in the 1990s.
[50]The majority of studies have excluded evacuation injuries from consideration.

Fire

There were 9 accidents resulting from propulsion system fire in the high bypass ratio fleet between 1970 and the end of 1994. One of these was at takeoff power, four were in climb and two occurred while the airplane was static/taxiing on the ground. There were 141 engine fire incidents identified which did not result in accidents.

| | Incidence of engine fires | Incidence of accidents caused by fire±13% |
|---|---|---|
| T/O | 12% | 11% |
| Climb | 42% | 44% |
| Cruise | 20% | |
| Descent | 1% | |
| Landing | 6% | |
| Other[51] | 20% | 33% |

It had been anticipated that the majority of fires would occur in takeoff, where temperatures and ambient pressures are highest. It was anticipated that very few fires would occur in cruise, since the undercowl pressures are generally insufficient to sustain combustion at high altitudes. However, there have been a large number of oil system fires within the bearing chambers and/or gearbox, which are pressurised enabling combustion throughout the flight envelope. Given the role of the oil system fires, the length of time spent at cruise accounts for the high percentage of fires occurring there.

The contribution of the oil system fires is particularly interesting because the airworthiness regulations contain many prescriptive rules on fire precautions, requiring fire detection and extinguishing in engine nacelles, to ensure that undercowl fires will always be detected and extinguished. These prescriptive rules are effective for fires resulting from flammable liquid leaking and igniting on hot engine casings, but they are not effective against a fire originating in a gearbox, and burning its way out into the undercowl region. Even if the fire detectors have been routed to respond to such a local fire, there is generally no means of shutting off the supply of flammable fluid feeding the fire (engine oil) nor is discharging fire extinguishant likely to be effective, since the extinguishing agent will not enter the pressurised gearbox where the fire originates. The volume of engine oil available to the fire is too

[51]These fires occurred while the airplane was static.

small for the fire to hazard the airplane, but in one instance, the fire did sufficient damage to the cowl door latches that the cowling separated and damaged the airplane.
Those fires resulting in accidents have not necessarily been so severe in themselves that they caused substantial damage to the airplane. In some cases, the fire was the occasion for a heavy landing and substantial damage, or for an emergency evacuation in which passengers were injured. It may be argued that there is some contribution from human error in these cases. The hazard ratio for engine fires is estimated at .06. If only those fires which inherently caused substantial damage/ severe injuries are included, the hazard ratio becomes .025 (four accidents).

There were 2 accidents resulting from tailpipe fires in the high bypass ratio fleet between 1970 and the end of 1994. Both of these involved L1011 aircraft. 27 incidents were identified which did not result in accidents. More than half of these incidents also involved the L1011 airplane. It appears likely that the RB211, particularly as installed in the L1011, is especially subject to tailpipe fires.

| | Incidence of tailpipe fires | Incidence of accidents caused by tailpipe fires ±33% |
|---|---|---|
| T/O | 7% | |
| Climb | 3% | |
| Landing | 7% | |
| Static | 79% | 100% |

Both these accidents were injuries incurred in emergency evacuations, evacuations which should never have taken place, since a tailpipe fire does not in any way threaten the passengers. The hazard ratio has been calculated as 0.07, but it is likely that the incidence of tailpipe fires is greatly under-reported and that the hazard ratio is therefore smaller.

Engine separation

There were 7 accidents resulting from engine separation in the high bypass ratio fleet between 1970 and the end of 1994. One occurred in takeoff, three in early climb and three in landing. No incidents were found in which engine separation did not lead to an accident. This may be because the failure sequence as an engine tears away from a wing is likely to produce substantial

damage of itself; there is also a risk of the separated engine hitting the airplane or of a major fire resulting from the fuel leak at the wing/pylon interface after separation.
None of the accidents resulted from the failure progression specifically cited in FAR 33.75; in which the engine generates extreme loads beyond the design capability of the mount system. The accidents resulted from existing damage in the mount system as a result of maintenance abuse or of a design flaw, which propagated to the point of mount failure during normal or severe transient loads. The designed-in redundancy of the mount system did not prevent failure because inspections did not detect the mount damage before the accident. As a result of these accidents, visual reference points have been added to the nacelles of 747 engines, to enable easy detection of partial mount failure during pre-flight checks.

| | Incidence of accidents caused by engine separation±14% |
|---|---|
| T/O | 14% |
| Climb | 43% |
| Landing | 43% |

Of the three engine separations occurring in landing, one resulted from the vertical loads during touchdown (although reference to the DFDR showed that it was in no sense a hard landing, with vertical speeds of 10 ft/s or less), one occurred during reverse thrust and one occurred after cancellation of reverse thrust in the landing roll.
It is notable that four of the seven accidents involved 747 freight airplanes. Two of these were attributed to fatigue failure of the mid-spar fuse pins attaching the engine strut to the wing, possibly induced by corrosion. One of the engine separations resulted from overload during severe mountain-wave turbulence, imposing multi-axis loads of over 2g upon a strut weakened by an existing fatigue crack in the forward firewall web. The remaining freighter accident resulted from failure of the strut forward bulkhead, as a result of fatigue cracking originating from damage caused by collision with a baggage cart (this was the accident in touchdown referenced above). The relatively high airplane weights associated with a freight operation can only have exacerbated any weakness in the engine mount system and pylon, leading to failure earlier than would be the case for more lightly loaded passenger-carrying aircraft of the same design. (The other two engine separation accidents involved maintenance-induced damage). It is also notable that all of these separations have been for wing-mounted engines. This might be

expected from the limited fleet exposure of high bypass ratio tail mounted engines, and does not necessarily imply design superiority.

There were 5 accidents resulting from major component separation in the high bypass ratio fleet between 1970 and the end of 1994. All of the accidents were due to cowl separation in climb and the subsequent impact of the cowl on the airplane wing or tail. There were 39 instances of component separation identified which did not lead to an accident, ranging from cowls to fan spinners and exhaust cones. Smaller components have the capability to penetrate fuel tanks or depressurise the fuselage if they hit the airplane with the right orientation, but the risk is considerably less than for a large item such as a cowl.

| | Incidence of separations | Incidence of accidents caused by component separation±20% |
|---|---|---|
| T/O | 23% | |
| Climb | 34% | 100% |
| Cruise | 7% | |
| Landing | 15% | |

Cowl separation does not necessarily result in an accident, of the 39 component separation incidents in the author's incident database, 20 were cowl separations. These occurred primarily during takeoff and climb, as aerodynamic loads upon the cowls became significant. The overall hazard ratio is .11, but if only cowl separations are considered and smaller components assumed to be de facto non-hazardous, then the hazard ratio for cowls is .2, averaged over the fleet. However, the validity of such a fleet average must be called into question when it is realised that all of the accidents resulting from cowl separation were experienced by tri-jets. The path taken by a detached cowling has been considered unpredictable, as the aerodynamic loads on the detached cowl vary with its orientation as it tumbles in the airstream. However, the general path of the cowling appears from this study to be strongly affected by the model of airplane involved, to the extent that it is somewhat predictable. It appears that if a wing engine loses its cowl on a DC10, it is very likely (3 events out of 4) to impact the tail engine or tail control surfaces under the effect of aerodynamic forces. The same may be true for other tri-jets such as the L1011; this was the case for the single L1011 cowl loss event on record. This is not the case for other aircraft; the 747 experienced a substantial number of cowl separations (17 events, for a variety of causes), none of which produced

accidents and only one of which resulted in an impact to the tail. (The aerodynamic loads upon the Boeing 747 inboard engines are known to be in the outboard direction (53)). There is not sufficient data to draw firm conclusions regarding the likely trajectory of cowlings for twin engine aircraft; only three Airbus twins have had cowl separations, one of which impacted the tail but did not result in substantial damage.

Multiple engine failure

There were 5 accidents involving multiple engine failures in the high bypass ratio fleet between 1970 and the end of 1994. It should be noted that four of the five would affect all engines equally (fuel exhaustion, volcanic ash, maintenance procedural error) no matter whether a twin or a four-engined airplane were involved. One accident was due to multiple-engine birdstrikes on a 747. It should also be noted that all of these multiple engine failures involved either some degree of permanent damage to one or more of the engines involved or some other circumstance definitively precluding the engines from being restarted. The capability of an undamaged engine to restart in flight was not a factor in any of these accidents.

| | Incidence of multiple engine failures | Incidence of accidents caused by multiple engine failure ±20% |
|---|---|---|
| T/O | 8% | 20% |
| Climb | 22% | |
| Cruise | 32% | 40% |
| Descent | 6% | |
| Landing | 5% | 40% |

It should be noted that the 62 incidents of multiple-engine failure include a number of independent engine failures occurring on the 747, with first generation high-bypass ratio engines featuring relatively high IFSD rates. No accidents have resulted from independent failures, and given the IFSD rates currently existing in the fleet (5/million engine hours), independent failures would not be expected to form a significant contribution to future accident rates.

The hazard ratio for multiple engine failure is estimated as .07.

Case rupture

There were 3 accidents resulting from engine case rupture in the high bypass ratio fleet between 1970 and the end of 1994. All of these involved CF6 engines . Two of the accidents were the result of bird or tire ingestion by the engine; the other resulted from fatigue cracking. Only one of the three involved a hull loss or serious injuries, as a result of the fuel fire which spread to the rest of the aircraft. A case could be made for crew error (high speed rejected takeoff) as being a more appropriate classification for these accidents. Ten incidents were identified which did not result in accidents, the majority of these involved the JT9D engine.

| . | Incidence of engine failures | Incidence of accidents caused by case rupture ±33% |
|---|---|---|
| T/O | 77% | 66% |
| Climb/Cruise | 15% | 33% |

The hazard ratio has been estimated as 0.3.

Thrust control

There were 8 accidents resulting from loss of thrust control in the high bypass ratio fleet between 1970 and the end of 1994, corresponding to a historical accident rate of 5.6E-8/airplane flight hour. All but one of these occurred during approach or landing. A detailed review shows that the incidence of thrust control-related accidents is much higher for first generation high bypass commercial transports; the 747, and A300 both have accident rates of about 1E-7/airplane hour from this cause. Of the second generation commercial transports, only the 737 has experienced this type of accident, presumably reflecting higher thrust reverser reliability and the greater integrity of redundant electronic throttle control signals compared to mechanical throttle cables. It may therefore be postulated that a new aircraft type would have a significantly lower incidence of these accidents than the fleet history; possibly 5E-8/airplane flight hour (reflecting the rate for the twin fleet). Aircraft with fuselage mounted engines such as the F100 might do even better than this, since less asymmetry would be involved in inadvertent thrust excursions.

## Crew Error

There were 4 accidents resulting from crew error in the high bypass ratio fleet between 1970 and the end of 1994. There was insufficient data available to develop hazard ratios for this type of event.

## Summary of Accident Experience

The major contributors to the causal factors of the historical propulsion-related accident rate are uncontained failures, propulsion failure accompanied by crew error, thrust control problems and engine fire. Multiple independent failures do not appear to contribute to this rate, nor do several other factors playing a significant part in airworthiness regulations, such as EMI, HIRF, inability to shut an engine down, toxic cabin bleed air, or casing burnthrough by a torching flame.

| ACCIDENT # | REFERENCE | PHASE | DATE | AIRPLANE | ENGINE | CAUSAL FACTORS | SUMMARY |
|---|---|---|---|---|---|---|---|
| ACC1 | NTSB-AAR-73-13 | L | 15/12/72 | 747 | | Thrust control | Birdstrike during T/O, shutdown #4 engine and returned. #3 reverser malfunctioned so reverse thrust limited, airplane slid off wet runway, substantial damage |
| ACC2 | CAA NTSB AAR-73-14 | C | 28/12/72 | L1011 | RB211-22B | Uncontained | #3 engine fan disk failure at 31K. Nose cowl, fan disk, blades and front fan casing missing. Wing leading edge, horizontal stabilizer damaged, window holed. 8" x 12" piece fancase embedded in wing. Air return |
| ACC3 | CAA | T | 30/4/73 | 747 | JT9D | Multi-engine | Bird ingestion in climbout. One engine failed, one experienced some power loss, one had external damage. Safe return. |
| ACC4 | CAA NTSB AAR-752 | CR | 3/11/73 | DC10 | CF6-6 | Uncontained | Fan blade/fancase interaction at high rpm. Blades penetrated hull, depressurization, 1 fatality. Loss of some electric and #1 and #3 hydraulic systems. |
| ACC5 | CAA | C | 8/5/73 | DC10 | CF6 | Cowling separation | #2 reverser deactivated incorrectly, no lockout bolts installed. Right transcowl separated in climb. In subsequent ferry flight, both fancowls and right inner cowl separated, holing right elevator. |
| ACC6 | NTSB AAR 74-09 | C | 8/7/74 | DC10 | CF6-6 | Cowl separation | Core cowling separation; only 1 of 3 retention bolts installed after maintenance (without nut). Holed upper wing surface, dented stabilizer, loss of a hydraulic system and electric bus, #2 engine extensively damaged. |

Table C.1 Propulsion Related Accidents

| ACCIDENT # | REFERENCE | PHASE | DATE | AIRPLANE | ENGINE | CAUSAL FACTORS | SUMMARY |
|---|---|---|---|---|---|---|---|
| ACC7 | NTSB | S | 14/6/75 | L1011 | RB211 | Tailpipe fire | Fuel ignition switch failure and internal engine fire. Passenger injury in emergency evacuation. |
| ACC8 | NTSB | T | 25/8/75 | DC10 | | Uncontained | Tire failure in takeoff, FOD to engine and fire. Substantial damage |
| ACC9 | CAA, NTSB | T | 12/11/75 | DC10 | CF6-50 | Casing rupture | Birdstrike during T/O roll and rejected T/O. #3 engine disintegrated and caught fire from ingestion of birds/tyres. Poor braking, landing gear collapsed, airplane destroyed by fire, 2 serious injuries. |
| ACC10 | CAA | T | 1/1/76 | DC10 | CF6 | Casing rupture/ multi-engine | Bird ingestion for engines 1 and 3 during climbout. #1 compressor casing flange bolts failed. Air return, Substantial damage, no injuries. |
| ACC12 | CAA | C | 2/6/77 | DC10 | | Cowl separation | #1 engine had 16th stage HPC blade failures in climb (10K). Outboard cowl separated, debris damaged wingskin and flaptrack. Air return, substantial damage |
| ACC13 | CAA | T | 19/8/77 | DC10 | CF6 | Propulsion failure + crew error | #3 engine compressor stall on t/o, from combustor failure. Substantial damage, serious injuries during evacuation. |
| ACC14 | CAA | C | 31/8/77 | 747 | JT9D | Uncontained | #2 engine uncontained failure in climb. Falling debris damaged property on ground. Substantial damage. |
| ACC15 | CAA | CR | 13/10/77 | 747 | | Other | Extensive damage to engine in flight. |

Table C.1 Propulsion Related Accidents

| ACCIDENT # | REFERENCE | PHASE | DATE | AIRPLANE | ENGINE | CAUSAL FACTORS | SUMMARY |
|---|---|---|---|---|---|---|---|
| ACC16 | CAA | CR | 23/10/77 | DC10 | CF6-6 | Crew error | Pilot inadvertently deployed #1 and #3 reversers in flight at FL290, IAS 328 knots (top of descent). #3 fan reverser partly separated from engine. Severe damage to right wing and stabilizer. |
| ACC17 | CAA | T | 29/8/78 | 747 | JT9D-7 | Thrust control | Surge from tyre ingestion; rejected t/o at 150 kts. Engines 3 and 4 would not reverse. Runway departure, substantial damage |
| ACC18 | CAA | T | 25/5/79 | DC10 | CF6 | Engine separation | Engine separation at rotation (improper maintenance had damaged pylon structure). System damage caused outboard slat retraction, aircraft stall. Aircraft destroyed, 271 fatalities. |
| ACC19 | CAA | L | 27/12/79 | 747 | JT9D | Engine separation | Forward bulkhead of pylon separated in fatigue, (old damage from baggage cart collision) rupturing fuel inlet line and fire detectors. Severe fire, substantial damage from delay in performing fire drill. |
| ACC21 | CAA | T | 3/7/81 | A300 | CF6-50 | Uncontained | HPT disk rim fracture and disk separation (unbalance) at 120 kts in T/O roll. Shrapnel damage to left wing and fuselage. Substantial damage. |
| ACC22 | CAA | T | 15/9/81 | 747-200 | JT9D-7 | Propulsion failure + crew error | Engine failure (bang, high EGT), rejected t/o at 80 kts, asymmetric thrust and runway overrun. 1 death, many injuries during evacuation in complete darkness. |

Table C.1 Propulsion Related Accidents

| ACCIDENT # | REFERENCE | PHASE | DATE | AIRPLANE | ENGINE | CAUSAL FACTORS | SUMMARY |
|---|---|---|---|---|---|---|---|
| ACC23 | CAA, NTSB-AAR-82-5 | C | 22/9/81 | L1011 | RB211-22B | Uncontained | #2 engine fan shaft failure at 10k, uncontained fan rotor. (High vibration in climbout was ignored). Hydraulic systems A,B,D lost. Engine shutdown, airplane return, landed with rudder jammed in neutral position. Substantial damage. |
| ACC24 | CAA, NTSB AAR-82-83 | T | 22/9/81 | DC10-30 | CF6-50 | Uncontained | #3 engine had LPT1 disk overspeed in T/O roll (tool left in bore wore off bolts and allowed disconnection of drive arm). Uncontained debris damaged #1, #3 hydraulic systems, #3 thrust lever cable and fire extinguishant line. Uncommanded slat retraction. |
| ACC25 | CAA | T | 17/3/82 | A300 | CF6-50 | Uncontained | #1 engine HPT1 disk failure from LCF at disk rim embossment, not detected in previous inspection. Uncontained debris punctured wing tank, fuel fire destroyed aircraft. |
| ACC26 | CAA | CR | 24/6/82 | 747 | RB211 | Multi-engine | Encountered volcanic ash at 37K, all engines flamed out. Four attempts to relight #4, successful at 13K. Relit other engines. Ash cloud base at 15K. Substantial damage. |
| ACC27 | Flight International, CAA | T | 12/9/82 | 747 | | Uncontained | Uncontained engine failure and aborted takeoff at V1, multiple tire failures. Substantial damage |
| ACC28 | CAA | T | 29/9/82 | 747 | JT9D | Uncontained | Uncontained turbine failure and aborted takeoff at 127 kts. Minor skin damage from exiting debris. |

Table C.1 Propulsion Related Accidents

| ACCIDENT # | REFERENCE | PHASE | DATE | AIRPLANE | ENGINE | CAUSAL FACTORS | SUMMARY |
|---|---|---|---|---|---|---|---|
| ACC29 | CAA | C | 27/12/82 | 747 | RB211-524 | Uncontained | AVM at rotation. Crew ignored AVM. No clear maintenance procedures. #2 engine fanshaft failure at 6.5K. Turbine separated, wing, #1 engine and pylon damage |
| ACC30 | CAA NTSB AAR-84-04 | D | 5/5/83 | L1011 | RB211 | Multi-engine | O-rings omitted from chip detectors on all engines, resulting in complete oil loss and all-engine IFSD. One engine restarted for landing. |
| ACC31 | CAA | CR | 23/7/83 | 767 | JT9D | Multi-engine | Calculation error for fuel units. Complete fuel exhaustion. Landed on disused airbase, substantial damage |
| ACC32 | CAA ICAO 1984-3 | L | 4/8/83 | 747 | JT9D | Thrust control. | Asymmetric thrust from #4 engine having power applied on exiting reverse. Improper operation of controls. Runway departure, substantial damage. |
| ACC33 | CAA, FSF Digest | T | 18/10/83 | 747 | CF6-50 | Propulsion + crew error | HPT blade retainer failure, rejected t/o above V1 and runway departure (ran off side). Substantial damage to nosegear |
| ACC34 | FAA, CAA | L | 28/2/84 | DC10 | CF6-50 | Thrust control | Auto throttle error and runway overrun. Injuries, substantial damage |
| ACC35 | CAA | C | 2/6/84 | 747 | JT9D | Fire | Fuel leak and fire at 16K, unable to extinguish in flight. Return, emergency evacuation, 1 serious injury, substantial damage. |
| ACC36 | CAA 8403611G | C | 30/10/84 | A300 | CF6-50 | Case rupture | Case rupture and air return (fire warning) |

Table C.1 Propulsion Related Accidents

| ACCIDENT # | REFERENCE | PHASE | DATE | AIRPLANE | ENGINE | CAUSAL FACTORS | SUMMARY |
|---|---|---|---|---|---|---|---|
| ACC37 | CAA 8403795D | T | 18/11/84 | 747 | JT9D | Uncontained | #3 engine HPT2 disk rim failure at airplane rotation, caused by vane creep permitting axial movement and rubbing of inner shroud. Fire. Uncontained debris damaged adjacent engine, tailplug and cowlings separated. Substantial damage. |
| ACC38 | CAA 8500150C | C | 19/1/85 | 747 | CF6-50 | Uncontained | LPT disk overheat (broken cooling tube) and uncontained failure. Airplane diverted. Holed upper and lower wingskin. Substantial damage. |
| ACC39 | CAA, NTSB AAR-86-03 | CR | 19/2/85 | 747-SP | JT9D | Propulsion failure + crew error | Engine stall at 41K, aircraft uncontrolled descent and structural damage. Captain relied on autopilot to fly plane while he troubleshot engine, without giving rudder input to offset asymmetric thrust. |
| ACC40 | CAA | L | 30/3/85 | A300 | CF6-50 | Thrust control | Asymmetric thrust (reverse one side, full forward other side) caused runway departure. Substantial damage. |
| ACC41 | CAA | C | 28/5/85 | DC10 | CF6-6 | Cowl separation | #3 Cowling separation, punctured and depressurised fuselage, damaged #2 engine and horizontal stabilizer. No injuries. Latches not adjusted and shear pins not installed per Douglas SB of 12/5/85. |
| ACC42 | CAA | L | 1/8/85 | 747 | JT9D-7J | Uncontained | #2 engine uncontained LPT failure in reverse thrust. Cowling separated. Cause; sheared anti-rotation pins allowed stators to spin, which machined away casing, casing moved aft and stators popped out. Substantial damage. |

Table C.1 Propulsion Related Accidents

| ACCIDENT # | REFERENCE | PHASE | DATE | AIRPLANE | ENGINE | CAUSAL FACTORS | SUMMARY |
|---|---|---|---|---|---|---|---|
| ACC43 | CAA, FSF digest | C | 9/8/85 | 747 | | Fire | #4 engine fire. Fuel dumped, air return. Substantial damage |
| ACC44 | CAA, FSF digest | L | 3/9/85 | DC10 | CF6-6 | Propulsion failure + crew error | Engine fire warning from failed bleed duct. Emergency landing and evacuation, serious injury |
| ACC45 | CAA | L | 2/12/85 | 747 | CF6-50 | Thrust control | Asymmetric thrust from broken throttle cable accelerating engine to t/o power. Runway departure, aircraft destroyed. |
| ACC46 | CAA | S | 15/2/86 | L1011 | RB211 | Tailpipe fire | Tailpipe fire, unauthorised emergency evacuation, passenger injuries. |
| ACC47 | CAA | T | 29/9/86 | A300 | CF6-50 | Propulsion failure + crew error | Birdstrike to #2 engine at rotation. Rejected t/o. Airplane departed runway, damaged beyond repair. |
| ACC48 | CAA | S | 12/5/86 | L1011 | RB211 | Fire | Engine fire during refuelling (dispenser ruptured and fuel sprayed on hot engine). |
| ACC49 | CAA | L | 15/11/86 | 747 | JT9D | Uncontained | LPT vane uncontained failure (anti-rotation pins) in reverse thrust. Damage to wing flaps, fuselage, adjacent engine |
| ACC50 | CAA 8700347C | CR | 27/2/87 | BAe146 | ALF502 | Uncontained | Reduction gear failure led to turbine overspeed, 4th stage turbine uncontained, blades punctured fuselage. Failed o/speed detection system. Airplane diverted, substantial damage. |
| ACC51 | CAA, FSF Digest | T | 23/7/88 | 747 | CF6-50 | Propulsion failure + crew error. | Casing rupture and rejected t/o at 160 kts. Runway departure. Substantial damage to landing gear, belly, wings from terrain impact. |

Table C.1 Propulsion Related Accidents

| ACCIDENT # | REFERENCE | PHASE | DATE | AIRPLANE | ENGINE | CAUSAL FACTORS | SUMMARY |
|---|---|---|---|---|---|---|---|
| ACC52 | CAA | T | 29/9/88 | 757 | RB211-535 | Propulsion failure + crew error. | Rejected t/o above V1. Engine noise (loose cam) misinterpreted as burst tyre. Poor communication. No crew briefing. Substantial damage. |
| ACC53 | CAA 8900005F | C | 8/1/89 | 737-400 | CFM56 | Propulsion failure + crew error. | Fan blade fatigue failure. Crew shut down wrong engine and diverted. Airplane crashed on approach. 47 fatalities. |
| ACC54 | Flight Int'l | T | 24/1/89 | A300-600 | PW4000 | Propulsion failure + crew error | Fire warning and rejected T/O. 15 passengers injured |
| ACC55 | French criminal court report | L | 26/6/89 | A320 | CFM56 | Crew error | Low power fly-by, power increase too late, hit trees. 3 fatalities |
| ACC56 | CAA 8902684E | CR | 19/7/89 | DC10 | CF6-6 | Uncontained | Fan disk fatigue failure originating at material defect. Uncontained debris ruptured all hydraulic systems. Airplane diverted, cartwheeled off runway during landing. 111 fatalities. |
| ACC57 | NTSB | T | Sep-89 | 737 | CFM56 | Propulsion failure + crew error | Minor thrust asymmetry. Crew unwittingly applied full rudder, runway departure |
| ACC58 | NTSB ANC90FA020 | C | 15/12/89 | 747-400 | CF6-80C2 | Multiple engine | All engines flamed out in volcanic ash cloud. Crew interrupted start attempts repeatedly. Engines started after 13K altitude loss. No fatalities, substantial damage by ash. |
| ACC59 | Flight International, FSF Digest | L | 7/5/90 | 747-200 | JT9D | Engine separation | Partial mount system failure in landing, uncontrolled fire damage to wing. Maintenance error |

Table C.1 Propulsion Related Accidents

| ACCIDENT # | REFERENCE | PHASE | DATE | AIRPLANE | ENGINE | CAUSAL FACTORS | SUMMARY |
|---|---|---|---|---|---|---|---|
| ACC60 | CAA 9003509G | L | 7/8/90 | 747 | JT9D | Propulsion failure + crew error | Reverse at low speed. A/C turning. Multiple engine surge as reverse thrust cancelled. Passengers evacuated, minor injuries. |
| ACC60a | Airclaims summary | | 2/10/90 | 747 | JT9D | Fire | In flight fire damaged wing surface (substantial damage) |
| ACC61 | Flight Int'l | T | 7/1/91 | 737 | CFM56 | Propulsion failure + crew error | Fire warning and rejected T/O. Runway overrun into soft ground. |
| ACC62 | CAA | C | 26/5/91 | 767 | PW4000 | Reverser | Uncommanded lefthand thrust reverser deployment at Mn .78. Uncontrolled descent, airplane broke up in air. Fatalities |
| ACC63 | CAA 9103119B | C | 30/8/91 | 767 | CF6-80C2 | Uncontained | #1 engine uncontained HPT disk failure and loss. Core cowls separated. Inboard half of #2 reverser deployed. Shrapnel, substantial damage. |
| ACC64 | CAA | C | 19/9/91 | 747 | JT9D | Fire | Strut fire in climb from chafed fuel tube. Multiple EICAS warnings, lost pressurisation. Injuries during evacuation on return. |
| ACC65 | Airclaims Accident Summary | L | Nov-91 | 737-300 | CFM56 | Thrust control | Reversers locked out (aftermath of Lauda accident). Landed on short runway, bad weather. Overrun. Substantial damage |
| ACC66 | CAA 9104168F | C | 5/11/91 | BAe146 | ALF502 | Uncontained | Bearing failure and turbine shaft failure caused 4th stage turbine disk burst. Uncontained debris damaged airplane, including shut down of another engine. Runway overrun, no fatalities. |

Table C.1 Propulsion Related Accidents

| ACCIDENT # | REFERENCE | PHASE | DATE | AIRPLANE | ENGINE | CAUSAL FACTORS | SUMMARY |
|---|---|---|---|---|---|---|---|
| ACC67 | CAA 9104772B | C | 29/12/91 | 747 | JT9D | Engine separation | Inboard engine mount failure and engine separation, impacted outboard engine. Directional control of a/c lost. Hull loss, all 5 crew killed. |
| ACC69 | CAA | C | 9/3/92 | L1011 | RB211 | Cowl separation | Transcowl departed in climb, struck tail. Substantial damage |
| ACC70 | CAA | S | 8/4/92 | 737-400 | CFM56 | Fire | Seized starter motor produced fire warning, at pushback, passenger injured in evacuation. |
| ACC71 | CAA 9203949J | C | 23/9/92 | DC10 | CF6-6 | Uncontained | Uncontained HP compressor. Flash fire, cowl separation. Debris embedded in wing and fuselage. Substantial damage, no injuries. |
| ACC72 | CAA 9204053E | C | 4/10/92 | 747 | JT9D | Engine separation | Two engines separated in flight. Pylon fire. Airplane attempted return, lost directional control and crashed into buildings. 70 inhabitants killed, with all crew. |
| ACC73 | CAA 9205408X | T | 2/11/92 | A300 | JT9D/ PW4000 | Fire | #1 engine fire warning, RTO. Reverser and fancowl destroyed, a/c gear doors, undercarriage and flap track fairings damaged. Substantial damage |
| ACC74 | CAA | A | 24/11/92 | 737-300 | CFM56 | Thrust control | HP compressor vibration on #2 engine which stayed at idle when throttles pushed. Autopilot compensated by increased thrust on good engine, thrust asymmetry and aircraft roll accentuated by pilot. Aircraft hit high ground, hull loss, 141 fatalities |

Table C.1 Propulsion Related Accidents

| ACCIDENT # | REFERENCE | PHASE | DATE | AIRPLANE | ENGINE | CAUSAL FACTORS | SUMMARY |
|---|---|---|---|---|---|---|---|
| ACC75 | CAA | C | 23/2/93 | 757 | | Propulsion failure + crew error | #2 engine stalled from 15th stage HPC failure, high EGT in climb (12K). IFSD, airplane returned and made hard landing. Substantial damage. |
| ACC76 | CAA | T | 20/3/93 | 747 | CF6-50 | Propulsion failure + crew error | #2 engine birdstrike. Rejected T/O @ 177 kts, runway overrun, substantial damage. Pilot believed both engines damaged |
| ACC77 | CAA | S | 22/3/93 | 747 | JT9D | Fire | Engine fire during taxi, damaged engine and wing. Substantial damage |
| ACC79 | CAA 9300945C, NTSB AAR9306 | C | 31/3/93 | 747 | JT9D | Engine separation | Engine separated in turbulence (fatigue crack in pylon). Serious damage to leading and trailing edge flaps. Airplane returned. No injuries. |
| ACC81 | CAA 9302784B | C | 12/8/93 | 747 | RB211 | Fire | Fuel leak at 16K from HP filter at manifold gave engine fire. Engine shutdown, fuel dumped, aircraft returned. Brake fire, no injuries. |
| ACC82 | Flight International | L | 14/9/93 | A320 | CFM56 | Reverser | High speed landing in windshear on wet runway. Reverser logic would not allow deployment for 9 seconds after light touchdown, ran off end runway. Hull loss, fatalities |
| ACC83 | Airclaims | L | 12/9/93 | 747 -400 | CF6-80C2 | Crew error | Autothrottle left active in landing. CFIT system pushed throttles on approach, manually countermanded by pilot. On reverse, lever slipped from pilot's hand, full forward thrust commanded by autothrottle. Runway overrrun, substantial damage |
| ACC84 | FAA ANC94FA036 | T | 1/3/94 | L1011 | RB211 | Uncontained | Uncontained IP6,7 compressor disk in T/O, ricochet caused #1 engine power loss, RTO. Substantial damage |

Table C.1 Propulsion Related Accidents

| ACCIDENT # | REFERENCE | PHASE | DATE | AIRPLANE | ENGINE | CAUSAL FACTORS | SUMMARY |
|---|---|---|---|---|---|---|---|
| ACC85 | NTSB SIR 94/02 | L | 1/3/94 | 747 | JT9D | Engine separation | Partial engine separation and fire in landing roll. Fuse pin retainers omitted, diagonal brace pin fell out, forward pin failed in overload. Substantial damage. |
| ACC86 | Airclaims | A | 26/4/94 | A300 | PW4000 | Crew error | Attempted landing in go-around mode, with crew fighting autopilot/autothrottle commands. Pitch-up and low airspeed, stall. Hull loss, fatalities. |

Table C.1 Propulsion Related Accidents

# APPENDIX D

THIS PAGE INTENTIONALLY BLANK

# APPENDIX D EVENT SEQUENCE ANALYSIS

## Di Introduction

The majority of accidents do not occur as the result of a single failure, but after a series of specific circumstances or failure consequences has bypassed the safeguards and defences intended to prevent the accident (Reason, 57). Identifying the specific circumstances required for the component failure to produce an accident, or the specific results of the component failure which contributed to the accident, could enable weak points in the safeguards to be pinpointed and design measures taken to reduce the likelihood of future component failures resulting in such an accident.

## Dii Results

Event sequence sheets were derived for each of the accidents resulting from uncontained failures for which sufficient data was available. Examples of event sequence sheets are presented in this appendix. Means which were specifically recommended in the accident investigation report are marked thus*, and means which have either been implemented on at least one application, or which are planned to be implemented in the near future are marked thus**. Details of the analysis of the results are given in Chapter 6.

It should be noted that a large proportion of the accidents reviewed were so classified as a result of the high cost of repairing local punctures or gouges in aircraft skin, rather than because airplane safety was jeopardised. No safeguards could intervene (or be bypassed) between the rotor fragment departing the engine and impacting the aircraft skin. The fact that skin damage alone was involved could be interpreted as a successful airplane design, in terms of avoiding critical system damage as a result of uncontained rotor failure. Those uncontained rotor failures which involved system damage or fatalities offered considerably more potential for improvement of safeguards. These results may imply that the event sequence analysis technique is most useful for those accidents or events strictly related to safety.

| EVENT SEQUENCE ANALYSIS SHEET | | ACCIDENT NUMBER: ACC24 |
|---|---|---|
| | | ACCIDENT TYPE: Substantial damage |
| | | DC10 #3 engine |
| **EVENT SEQUENCE** | | **INTERVENTION OPPORTUNITIES** |
| | | |
| Tool left inside engine during maintenance | | Maintenance procedures to positively locate all tools before releasing engine. |
| | | |
| Tool destroyed bolts securing LP turbine disc to shaft | | Credible vibration monitoring might detect a change in vibration signature |
| | | Damage tolerant means to secure disc to shaft |
| | | |
| Disk oversped and burst | | Reduce strength of blade attachment relative to disk strength |
| | | |
| Debris caused structural damage to front spar and to #1 and #3 hydraulic systems at that location | | Local armour for critical systems in debris zone** |
| Debris damaged slat cables | | |
| Shrapnel damage to aircraft skin (wing and fuselage) | | Enhanced wingskin toughness |
| | | |
| Outboard slats retracted without cable input | | Control surfaces to remain in the last commanded position if input is lost.** |
| | | |
| Rejected takeoff @ 96 kts. No injuries | | |

| EVENT SEQUENCE ANALYSIS SHEET | | ACCIDENT NUMBER: ACC8 |
|---|---|---|
| | | ACCIDENT TYPE: substantial |
| | | DC10 #1 engine |
| **EVENT SEQUENCE** | | **INTERVENTION OPPORTUNITIES** |
| | | |
| Tyre failure in takeoff roll | | |
| | | |
| Engine ingested tyre, engine fire | | Possible improvement from enhanced bird ingestion standards (8 lb bird)** |
| | | |
| Rejected takeoff at 148 kts (above V1) | | Improved crew training to continue takeoff above V1. |
| | | Clear indication of V1** |
| Runway departure | | |
| | | |
| Substantial damage, no injuries | | |

| | | |
|---|---|---|
| EVENT SEQUENCE ANALYSIS SHEET | | ACCIDENT NUMBER: ACC33 |
| | | ACCIDENT TYPE: substantial damage |
| | | 747 #2 engine |
| **EVENT SEQUENCE** | | **INTERVENTION OPPORTUNITIES** |
| | | |
| Rolling takeoff. HPT blade retainer failure on #2 engine at 56 kts (EGT, rpm began to rise) | | Prohibit rolling takeoffs at maximum weight and unfavorable conditions* |
| | | |
| Flight engineer reduced throttle | | Discuss go/no-go strategy before initiating takeoff** |
| | | |
| EGT reached 990 C @125 kts | | |
| | | |
| Flight engineer called for RTO @ 154 kts (rotation) | | Means to monitor actual airplane acceleration compared to flight manual*. |
| | | Clear indication of V1*. ** |
| Rejected takeoff above V1 | | Improved flight crew training to continue takeoff above V1. |
| | | |
| #2 engine did not develop full reverse thrust. Airplane veered left. | | Simulator training on asymmetric thrust (especially on ground, low speed) |
| | | |
| Airplane ran off side of runway @ 55 kts. Gear collapsed. | | |
| | | |
| | | * Recommended in accident report |

# APPENDIX E

THIS PAGE INTENTIONALLY BLANK

# APPENDIX E CREW ERROR STUDY

## Ei Introduction

Worksheets for all of the events are included at the end of this appendix. The worksheets were intended to establish which crew errors relating to propulsion systems are most likely, and to give insight into major factors potentiating the error, and particularly to provide insight into the potential for design modifications or changes in training or procedures which could reduce the likelihood of crew error. Difficulties pertaining to individual flight crews (Crew Resource Management, pilot fatigue) or airlines (organizational factors) were generally omitted in favour of issues relating to engine performance and instrumentation and widely implemented procedures and training, which would apply throughout the fleet.

The worksheet questions were structured around the SHEL model (Software, Hardware, Environment and Liveware) with the omission of the Liveware for the reasons given above, and around the RAIT approach cited by (Johnstone et al "Beyond Aviation Human Factors"), neglecting the organizational factors which cannot reasonably be used in the safety analysis of hardware design.

The implications of the study for propulsion system safety analysis are discussed in Chapter 6 above; this appendix presents the factual results of the study.

Thirty-nine propulsion related events involving crew error were studied, comprised of sixteen accidents and twenty-three incidents. These form only a sample of the relevant events, but it is a sufficiently large sample to identify some significant features. This sub-set of accidents and incidents should not be used directly to generate rates for the commercial transport fleet, but it can be used to estimate the proportional contribution of various factors, given existing rates. A study based on different selection criteria for the accidents might result in some change in relative importance between factors, especially if a different operational environment were considered (e.g. commuters). Some of the accidents appearing in Table C.1 as attributable in part to crew error were not used in this study because insufficient detail was available to draw conclusions regarding the causes of crew error. The data for this study was primarily drawn from NTSB and Flight Safety Forum reports prior to 1995, and from de-identified incident reports from the ASRS system (selecting on crew error and propulsion failure and on asymmetric thrust). Some significant accidents involving non-high bypass ratio engines have been included in the study, since they contained valuable data.

## Eii ERROR SCENARIO

Five distinct error scenarios emerged from the study as being involved in multiple accidents or incidents:

Five accidents and one incident resulted from a rejected takeoff above V1.

Five accidents and eight incidents resulted from asymmetric engine thrust and loss of directional control or other inappropriate compensation by the crew.

Three accidents and two incidents arose from mismanagement of the engine thrust by the autothrottle/autopilot (either from lack of congruence between the crew intention and the autothrottle logic, or an actual malfunction).

Seven incidents resulted from a propulsion system malfunction distracting the crew so that the airplane deviated from the course approved by ATC.

Four incidents resulted from unintended shut down of one or more engines in flight.

The remainder of the accidents and incidents were distributed among a number of isolated events.

## Eiii HARDWARE

Concerns have been raised over the practice of Time Limited Dispatch (permitting airplane departure for a limited number of flights with some equipment inoperative which is normally required). It has been stated that this significantly raises the accident risk for those aircraft dispatched in this condition, by reducing safety margins. None of the accidents were influenced by the unavailability of equipment due to Time Limited Dispatch. One incident (a deviation of 300 ft from the assigned altitude ) was caused by high workload from dispatching with the autothrottles, thrust rating computer and performance management system inoperative. It appears that Time Limited Dispatch does not significantly increase the risk of crew error resulting in an accident/serious incident, as far as the propulsion system is concerned.

## Eiv ENVIRONMENT

It had been suggested in another field that error would be more likely in times of high workload and reduced time for decisions, and that external factors (such as traffic and weather) might form a distraction potentiating crew error. (Bello and Colombari, TESEO model).

Traffic appeared to be a factor in only one accident (wake turbulence may have contributed to 3 of 4 engines stalling in the landing roll). Traffic was a factor in six of the incidents; three of these were simple loss of separation after a propulsion related problem, and two incidents involved an unintended action or a deviation from procedure directly initiated as a result of the presence of traffic.

Thirteen out of sixteen of the crew errors resulting in accidents occurred at low altitude (below 2000 ft above the ground, during the takeoff and climb-out or approach and landing phases). All of these resulted directly from the attempt to take off or land. It is not possible to distinguish between the effects of high workload and the reduced time for decisions and error recovery, since both of these are the case during takeoff and landing. Three of the landing accidents might have been avoided had the crew chosen to conduct a missed approach once they realized that all was not well; allowing more time to evaluate the situation. Fourteen out of twenty three of the incidents also occurred below 2000 ft. It might be postulated that the events at higher altitude resulted in benign outcomes because more time was available for recognition and recovery, but review of the event details does not support this position. The higher altitude incidents were not generally likely to have resulted in an accident if they had occurred at lower altitude (for example, six out of nine of these higher altitude incidents were traffic conflicts or minor deviations from the assigned altitude).

Adverse weather conditions were a factor in three out of the sixteen accidents (windshear delaying touchdown in two cases and a tailwind contributing to a non-stabilized approach in another). In two of these cases weather conditions were deteriorating and the crew may have been unwilling to conduct a missed approach, lest the additional delay result in diversion to another airport. The majority of accidents took place in good weather. Adverse weather was a factor in eight of twenty-six incidents (three events involved snowy runways and loss of directional control at low speed, three involved propulsion system failures initiated by thunderstorms/turbulence, one involved crosswinds in landing and one involved an air-miss in IMC.

It is concluded that altitude/flight phase (specifically the high workload associated with takeoff and landing) is by far the most significant environmental factor associated with propulsion related crew error resulting in accidents. Weather and traffic have some contribution to make, but the majority of these accidents were not influenced by weather or traffic.

## Ev SOFTWARE

One accident and one incident resulted from autothrottle malfunction; in both cases the autothrottle commanded a higher thrust than desired. This disoriented the crew in both cases so that they did not maintain the desired flightpath. In the case of the accident, the autothrottle malfunction went undetected for some time, and was not corrected after detection. Instrumentation was sufficient to show that the airspeed was too high during final approach, but it was not effectively monitored.

Control mode awareness was a major factor in three accidents and two incidents. Two of the accidents involved a correctly operating autothrottle commanding a missed approach without the knowledge of the flightcrew. The other resulted from the autopilot's attempts to compensate for asymmetric thrust while the crew were otherwise occupied - when they attempted to re-enter the loop, they were unprepared for the extreme inputs required to the control surfaces. The incidents resulted from confusion over which systems (autopilot, autothrottle) were engaged.

## Evi ERROR CLASSIFICATION

Errors were classified according to the logic proposed by Rasmussen and broadly accepted in the field of cognitive psychology, as being skill-based, rule-based or knowledge based. Briefly, a skill-based error is one in which the protagonist has all the information necessary, makes an appropriate decision, and then at an unconscious level, does something other than intended (pours tea into the sugar bowl as a trivial example). A rule-based error is one in which the protagonist has all the information necessary but makes an inappropriate decision, and executes it as intended (example; setting off to work on a Saturday morning, having forgotten the day). A knowledge based error is one in which the protagonist is faced with an unprecedented situation and must reason out the correct course of action, based on the data available. The importance of distinguishing between these error types can be appreciated when considering the frequent response to human error; a demand for more training. Skill based errors are typical of the highly trained individual doing a task which is second nature (and accompanied by infrequent conscious checks); training is unlikely to be effective here. Likewise, training cannot prepare flight crew for situations which have not been covered in training .. it might even have a reverse effect, and exacerbate the disbelief and bewilderment associated with a new situation for individuals who "know" they have been thoroughly and comprehensively trained for all situations.

The majority of the errors fell into the skill-based (22 errors) or rule-based(27 errors) categories. The number of errors exceeded the number of events, since many events involved multiple distinct errors. Lateral error

Inappropriate performance of an over-learned sequence appeared only in those incidents where engines were shut down inadvertently.

Accidents generally involved rule-based or knowledge based errors, skill-based errors generally led to incidents rather than accidents. It is possible that recovery from a skill-based error is much faster, since the crew member recognizes that an error has occurred as soon as their attention is drawn to the undesired situation, whereas in the event of a rule-based or knowledge-based error, the crew member is already attempting, however inappropriately, to recover the situation. Reluctance to revoke a decision or reconsider a strategy, once initiated, is a well-recognised phenomenon in the field of human error (Reason, 57)[1]. The implications for safety assessment/accident prevention are discussed in Chapter 6.

## Evii ERROR RECOVERY

The ability of the crew to recover from an error was considered by assessing significant situational factors. In 13 cases a single error relating to propulsion system control was immediately followed by the accident or incident (within a few seconds) so that no error recovery was possible. For the cases where error recovery may have been possible, recovery was delayed in eleven cases by imminent and essential crew activity diverting attention from the error. Accidents where recovery was possible generally resulted from a sequence of errors producing a gradually deteriorating situation.

In nine cases the error was not readily detectable by cockpit instrumentation. The autothrottle mode was not recognised in four cases and in three cases it was unclear whether an engine was flamed out, operating transiently sub-idle, or operating normally at low power.

In six cases propulsion system damage delayed recovery from the error.

In six cases the system response time was sufficiently slow that it delayed recovery from the error.

In six cases the crew were aware of the error for a significant time before taking action to address it; and this procrastination may be assumed to make error recovery more difficult.

---

[1] Previous studies have noted that recovery from skill-based errors is more likely than from rule-based or knowledge based errors. (Reason, 57).

# CREW ERROR WORKSHEET

PROPULSION RELATED ACCIDENTS/SERIOUS INCIDENTS

EVENT DATA

| | | | |
|---|---|---|---|
| REFERENCE # | *ASRS95408* | OUTCOME | *Incident* |
| SCENARIO | *High speed RTO* | LOCATION | *ORD* |
| DATE | *10/88* | OPERATOR | *Unknown* |
| AIRPLANE MODEL | *Unknown* | ENGINE MODEL | Unknown |
| DATA SOURCE | *ASRS* | | |

SUMMARY

*Compressor stall at rotation and rejected takeoff. Crew could not tell which engine had failed.*

HARDWARE

| | |
|---|---|
| TIME LIMITED DISPATCH? | *No* |
| CREW RECONFIGURING? | *No* |

PROPULSION SYSTEM EVENT

| | |
|---|---|
| ENGINE POSITION | *#3* |
| ENGINE POWER | *T/O* |
| TACTILE SYMPTOMS | *Vibration, loud stall noises* |
| INSTRUMENT SYMPTOMS | *Engine fail light (not specific engine position)* |
| # REMAINING ENGINES | *2* |

SOFTWARE

| | |
|---|---|
| AUTOPILOT | *Unknown* |
| AUTOTHROTTLE | *Unknown* |

ENVIRONMENT

(within last 5 minutes of pivotal decision/event)

| | | | |
|---|---|---|---|
| FLIGHT PHASE | *Takeoff* | ALTITUDE | *0ft* |
| TRAFFIC | *No* | WEATHER | *VMC* |
| TIME PRESSURE | *Extreme* | | |

ERROR *A*

CREW MEMBER *Captain*

TASK *Monitor first officer's takeoff*

ERROR DESCRIPTION
*Took command and rejected takeoff above V1.*

ERROR CLASSIFICATION *Rule based*

ERROR ANALYSIS
*Correct procedure is to continue the takeoff above V1. Studies have shown that loud noises of engine failure and airframe vibration are associated with a decision to reject a takeoff above V1, flightcrew are concerned for the airworthiness of the airplane in these conditions. These conditions are generally not simulated during flight training. Inability to identify the engine which had failed could only increase the concern of the flightcrew.*

ERROR RECOVERY

*No recovery possible in time*
Was instrumentation/displays correct/sufficient to show error?
*Yes, but clearer indication of which engine had failed (beyond an engine fail light applying to any) might have avoided the error.*
Did propulsion system damage hinder recovery?
*No*
Did system response time hinder recovery?
*No*
Was control mode awareness a factor?
*No*
Did imminent necessary crew activity divert attention?
*No*
Were crew reluctant to deviate from planned activities?
*No*

# APPENDIX F

THIS PAGE INTENTIONALLY BLANK

# APPENDIX F PREDICTING FAILURE RATES

## Fi Demonstration Of Reliability Growth In Service

Figures F.1 and F.2 show the annual incidence of Service Difficulty Reports (SDRs) as described above. Some form of reliability growth is evidently occurring in the field, and the CF6-50 has benefited in some respects from the experience of the earlier CF6-6 model. It is significant that the CF6-80A entered service with the same reliability (based on SDRs) as the mature CF6-50. The inflight shutdown and rejected takeoffs which were due to random events such as bird ingestion or errors during routine maintenance are shown separately; it appears that the overall failure rate trends toward the random rate after sufficient service experience (as proposed by Smith).

Figure F.3 shows the SDR rates versus the total fleet hours. Although there is considerable random variation from year to year, the CF6-6 and CF6-50 engines appear to have similar reliability growth rates between 2 million and 20 million fleet hours, the CF6-50 remaining generally more reliable by a factor of 2 to 3.

It was hypothesized that variation in product support policies (over time and between engine programs and operators) might account for some of the "random variation", in that a concerted effort to introduce a fix into the fleet would cause a discontinuity in the SDR rate. This effect was assessed by considering only new problems, thus eliminating the effects of repeat failures. Figures F.4 and F.5 show the results. The CF6-6 and CF6-50 behaviour is very similar if only new failure modes are considered. This result supports the approach of treating derivative engines as variants on an existing engine with respect to reliability growth trending.

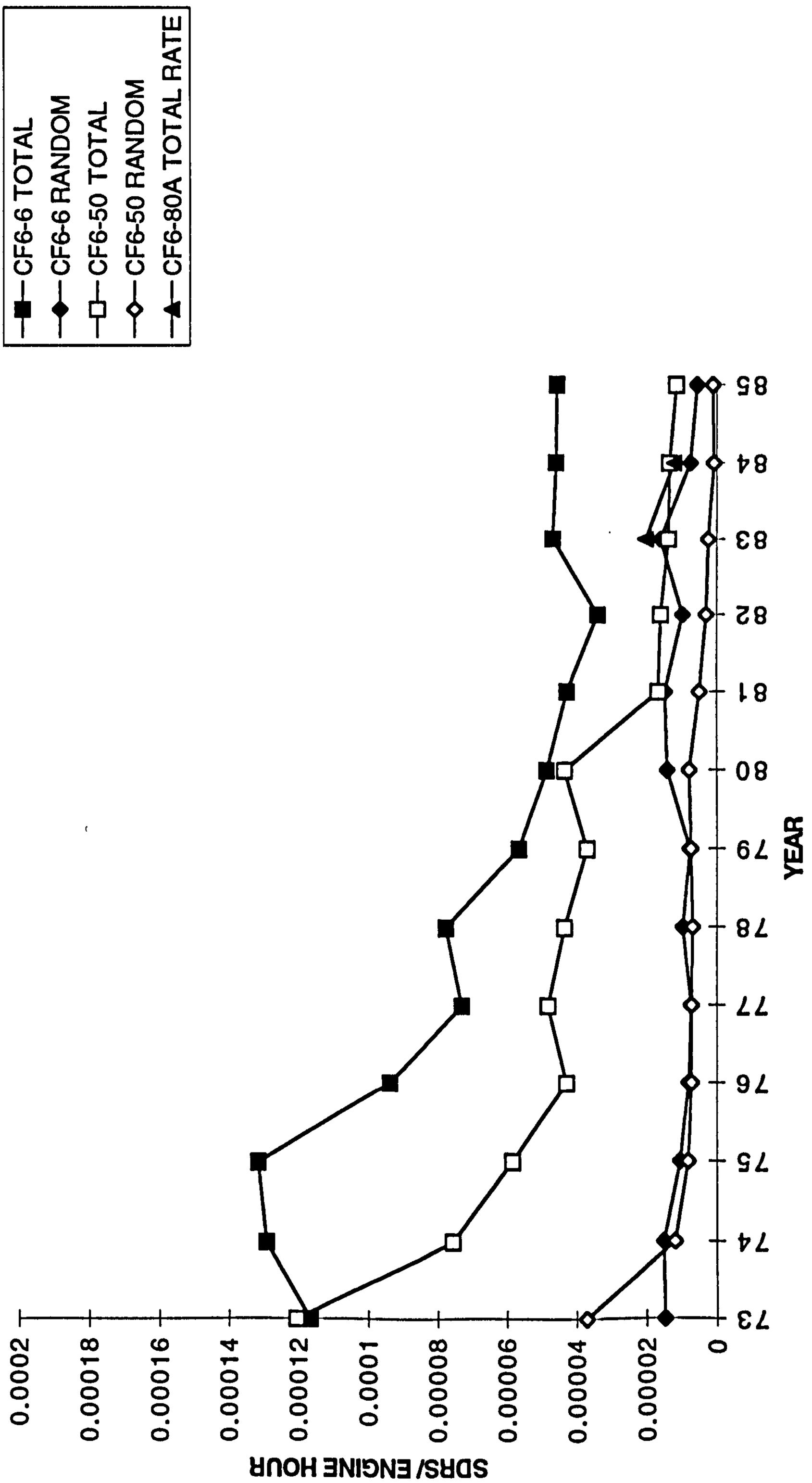

CF6-6 TOTAL
CF6-6 RANDOM
CF6-50 TOTAL
CF6-50 RANDOM
CF6-80A TOTAL RATE
CF6 FLEET ANNUAL FAILURE RATES (SDRS/
85
84
83
82
81
80
79
78
77
76
75
74
73
YEAR
0.0002
0.00018
0.00016
0.00014
0.00012
0.0001
0.00008
0.00006
0.00004
0.00002
0
SDRS/ ENGINE HOUR

Figure F.1

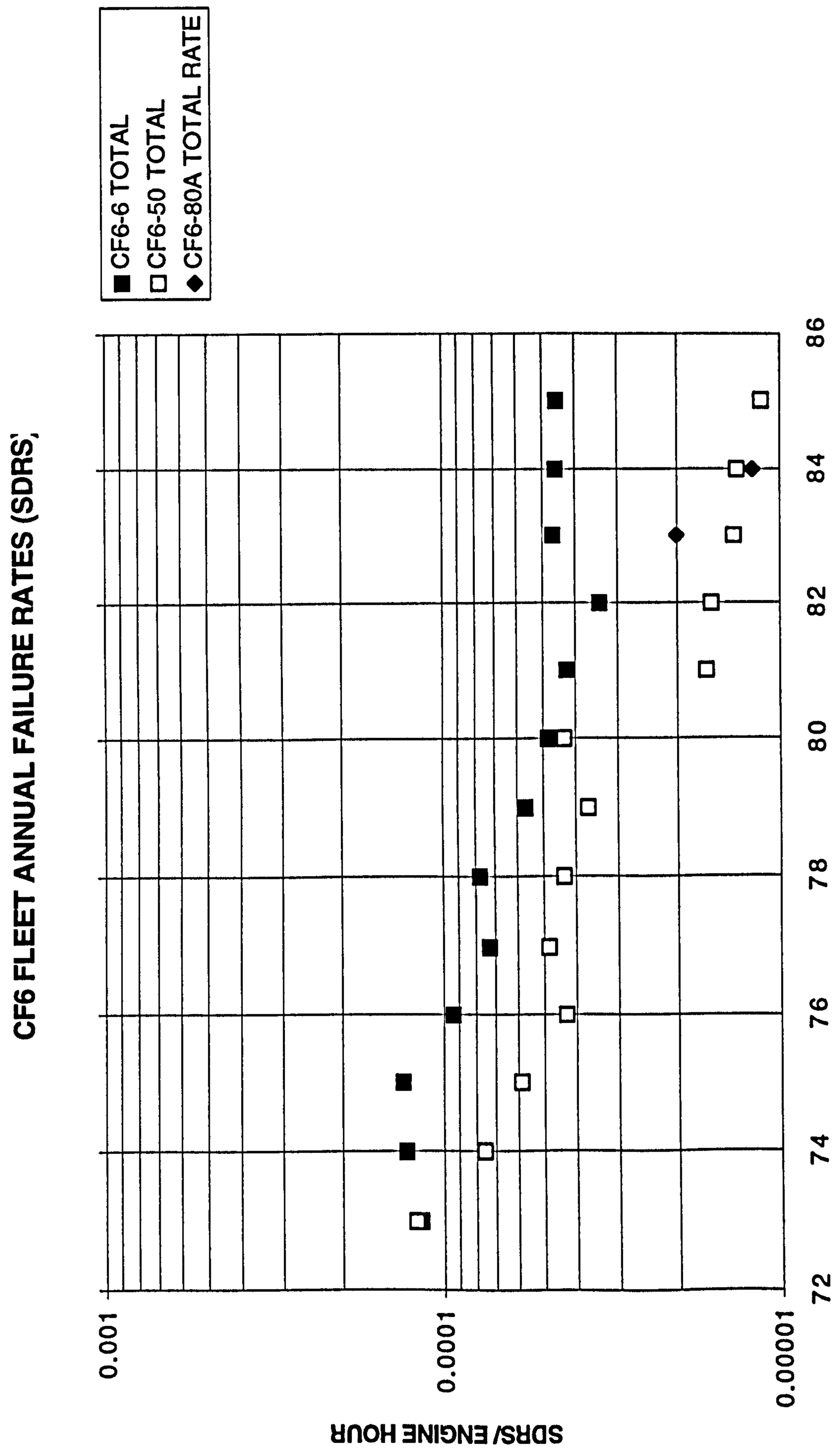

■ CF6-6 TOTAL
□ CF6-50 TOTAL
◆ CF6-80A TOTAL RATE
CF6 FLEET ANNUAL FAILURE RATES (SDRS/
0.001
0.0001
0.00001
SDRS/ ENGINE HOUR
72
74
76
78
80
82
84
86
YEAR

Figure F.2

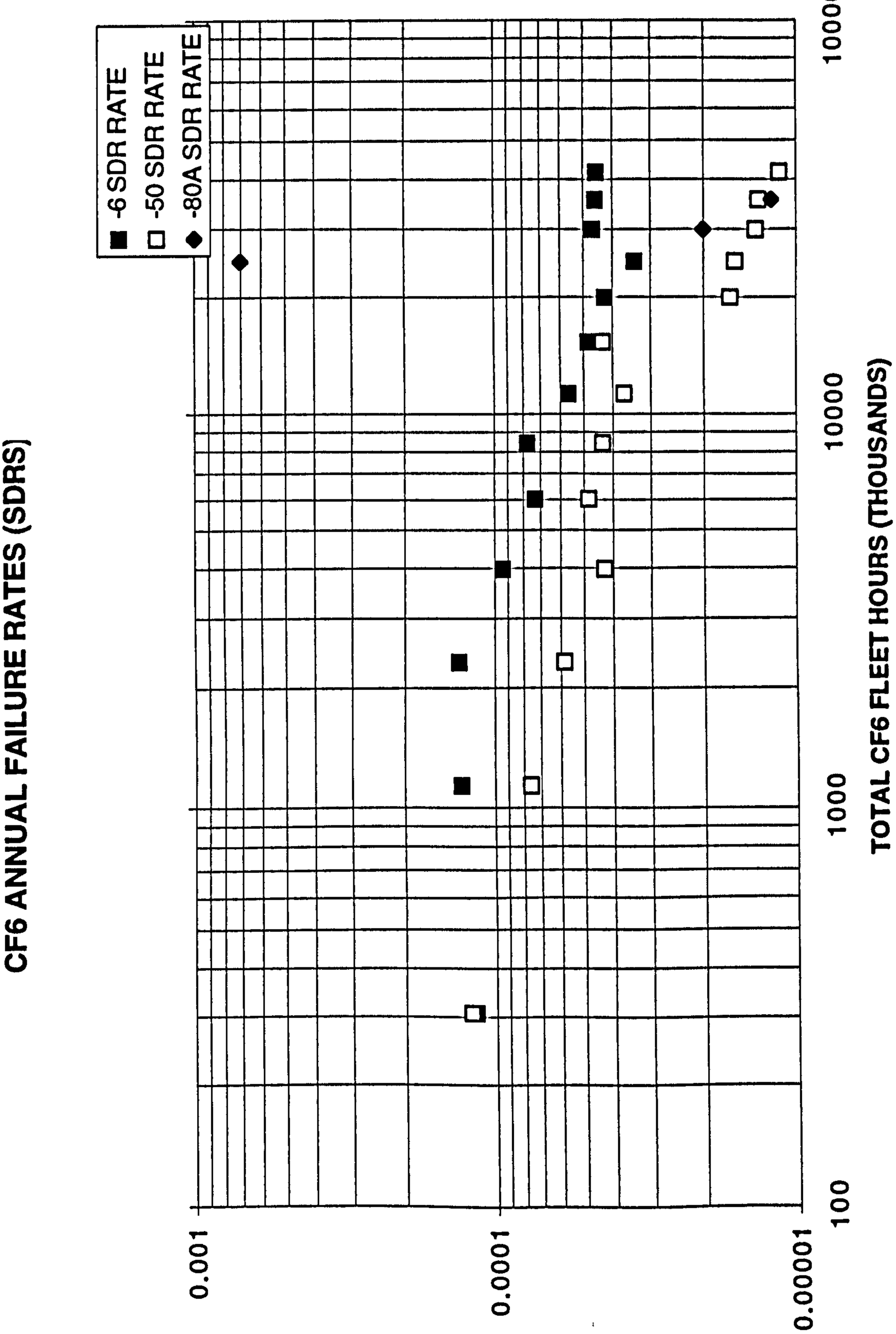

CF6 ANNUAL FAILURE RATES (SDRS)
SDRS/ENGINE HOUR
TOTAL CF6 FLEET HOURS (THOUSANDS)
-6 SDR RATE
-50 SDR RATE
-80A SDR RATE
0.001
0.0001
0.00001
1000
10000
100000

Figure F.3

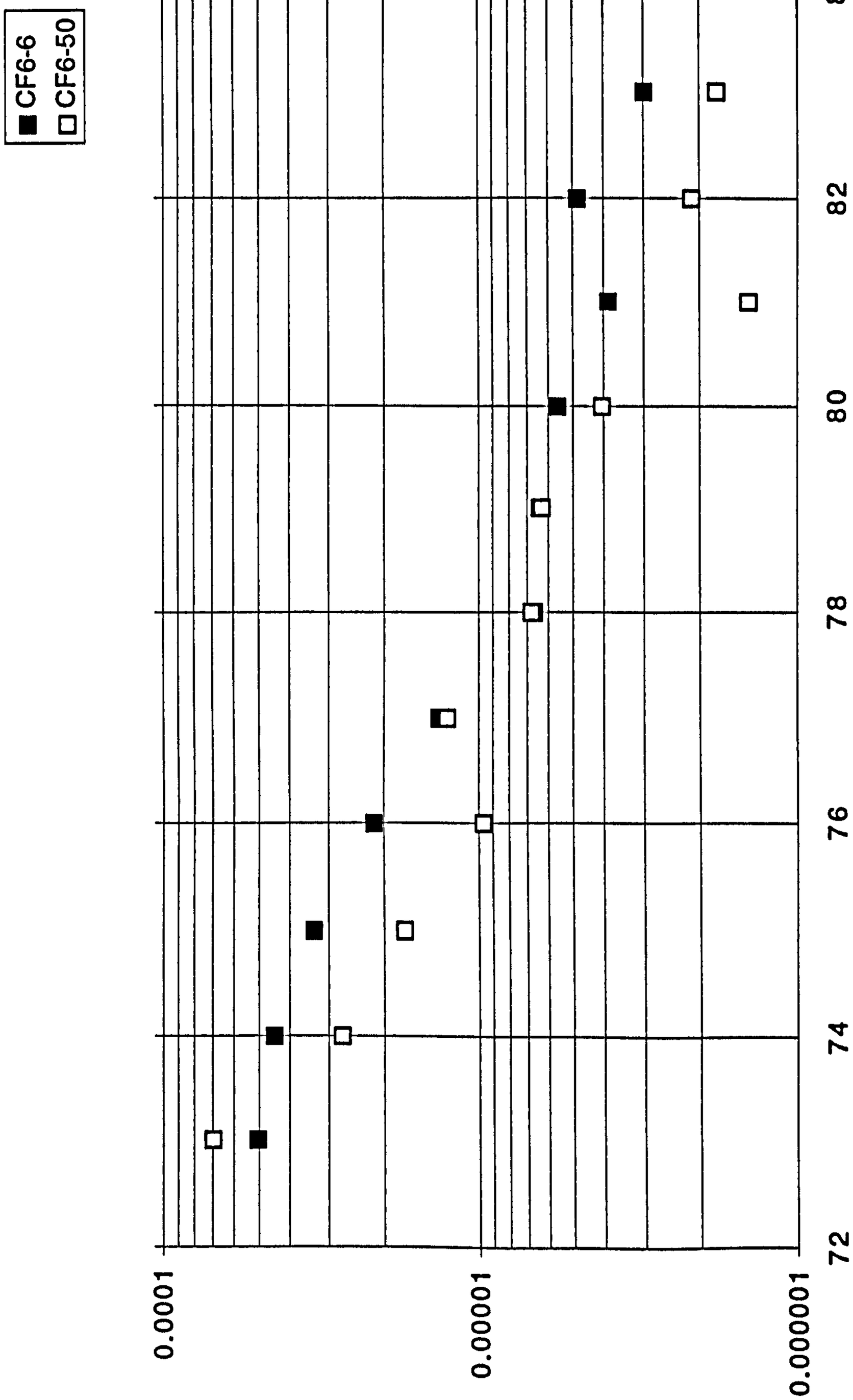

CF6-6
CF6-50
INCIDENCE OF NEW FAILURE MODES
0.0001
0.00001
0.000001
NEW FAILURE MODES/ENGINE HOUR
72
74
76
78
80
82
84
YEARS

Figure F.4

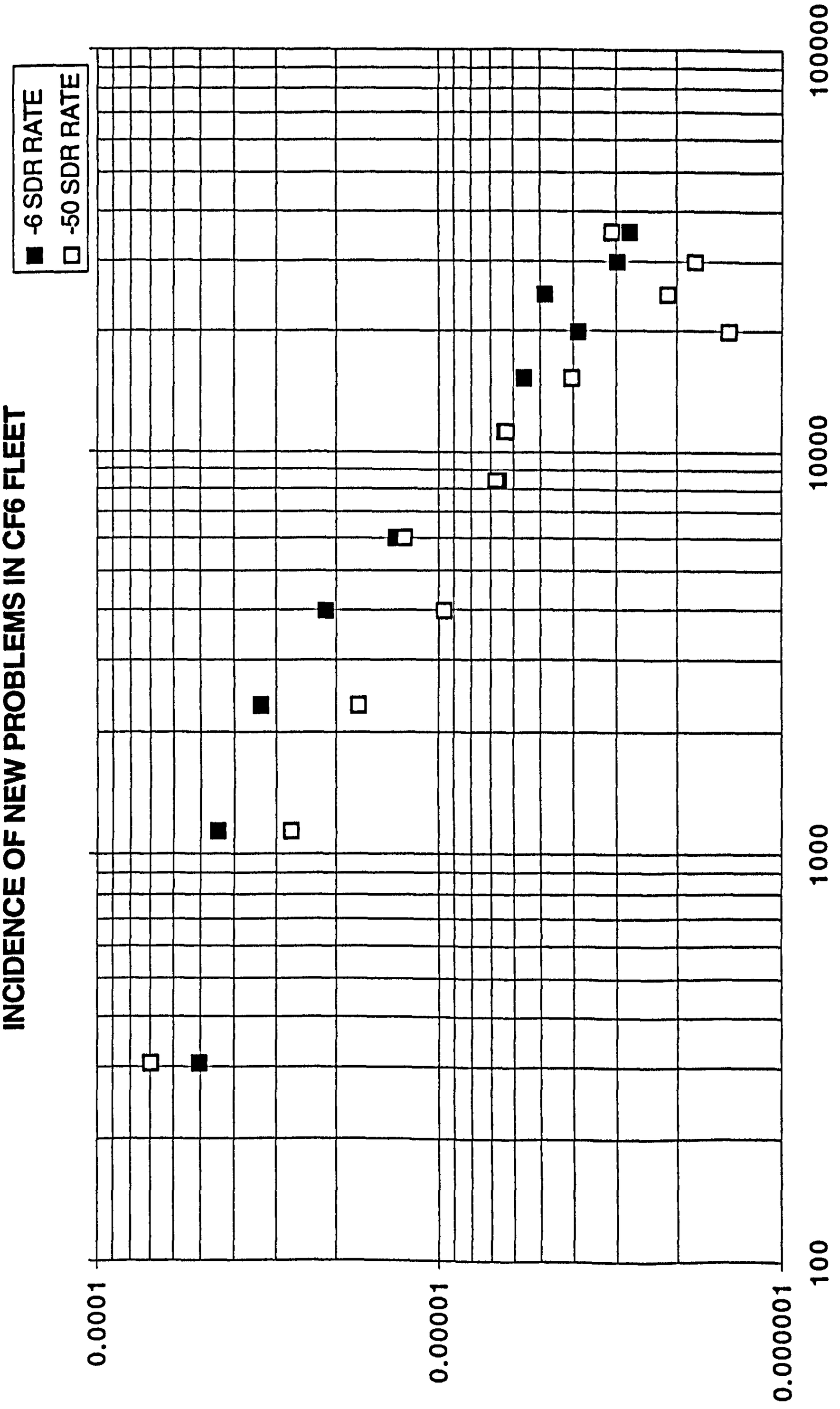

■ -6 SDR RATE
□ -50 SDR RATE
INCIDENCE OF NEW PROBLEMS IN CF6 FLEET
NEW FAILURE MODES/ ENGINE HOUR
0.0001
0.00001
0.000001
100000
10000
1000
100
CUMULATIVE CF6 FLEET HOURS

Figure F.5

## Fii Quantitative Modelling Of Reliability Growth

Development of a mathematical model at the engine level was hindered by the difficulty of accounting for the gradual dilution of the fleet by engines incorporating design fixes, by the dependence of reliability growth on both operating hours and calendar time and by the effects of varying product support policies in the prevention of failure recurrence. These indeterminate effects, together with the random variation from year to year in the data, made anything but the simplest mathematical treatment of questionable value (as previously noted (22)). An equation of the form proposed by Smith Industries (20) was consistent with the observed behaviour of the fleet:

$\lambda = A + Be^{-Ct}$

where

$\lambda$= incidence of SDRs per engine hour

A = random failures unrelated to specific design or manufacturing problems, e.g. maintenance error or birdstrike

t= fleet hours summed over all models

The following values of A,B,C were calculated using a least-mean-squares technique, and calculating the 90% confidence range (two-sided):

| | A | A | B | B | C | C |
|---|---|---|---|---|---|---|
| | Mean | Range | Mean | Range | Mean | Range |
| All SDRs CF6-6 | 1.06E-5 | 0.46 - 1.65 E-5 | 1 E-4 | .65 - 1.5 E-4 | 3E-8 | 2E-8- 4 E-8 |
| All SDRs CF6-50 | 0.86E-5 | 0.71 - 1.01 E-5 | 7 E-5 | .45 - 1.0 E-4 | 5E-8 | 4E-8- 6 E-8 |
| New SDRs CF6-6 | - | - | 2.7E-5 | 1.3 - 5.4 E-5 | 8E-8 | 6E-8 -1 E-7 |
| New SDRs CF6-50 | - | - | 2 E-5 | .74 - 5.2 E-5 | 8E-8 | .55 - 1.1 E-7 |

Table F.1

It is evident that A (the rate of random, non-design-related failures) is effectively the same number for both the CF6-6 and CF6-50. Future engine models designed to be more resistant to birdstrike or maintenance abuse might have lower values of A.

Likewise, B is the same for both the CF6-6 and CF6-50, within the statistical variation of the measured rates.

C has a different value for the CF6-6 and CF6-50, for all SDRs, but is the same if only new SDRs are considered. There is a strong case for modeling reliability growth of both engines with the same equation, given the statistical variation in the measured rates. These results are shown on Figures F.6 to F.9.

In order to confirm that the reliability growth seen for engine failures as a whole extended to safety-specific failures, uncontained failure trends were reviewed. Although comprehensive data specific to each engine is not publicly available, fleet-wide rates of uncontained failures were available for both first generation (entry into service before 1980) and second generation engines. Figure F.10 shows the results. There is a steady improvement evident in the uncontained failure rate, which may be expected to deviate from linearity as the rate becomes lower and lower (the exact form of the relationship is difficult to assess given the magnitude of random variation from year to year).

## Fii Quantitative Modelling Of Reliability Growth

Development of a mathematical model at the engine level was hindered by the difficulty of accounting for the gradual dilution of the fleet by engines incorporating design fixes, by the dependence of reliability growth on both operating hours and calendar time and by the effects of varying product support policies in the prevention of failure recurrence. These indeterminate effects, together with the random variation from year to year in the data, made anything but the simplest mathematical treatment of questionable value (as previously noted (22)). An equation of the form proposed by Smith Industries (20) was consistent with the observed behaviour of the fleet:

$\lambda = A + Be^{-Ct}$

where

$\lambda$= incidence of SDRs per engine hour
A = random failures unrelated to specific design or manufacturing problems, e.g. maintenance error or birdstrike
t= fleet hours summed over all models

The following values of A,B,C were calculated using a least-mean-squares technique, and calculating the 90% confidence range (two-sided):

| | A | A | B | B | C | C |
|---|---|---|---|---|---|---|
| | Mean | Range | Mean | Range | Mean | Range |
| All SDRs CF6-6 | 1.06E-5 | 0.46 - 1.65 E-5 | 1 E-4 | .65 - 1.5 E-4 | 3E-8 | 2E-8- 4 E-8 |
| All SDRs CF6-50 | 0.86E-5 | 0.71 - 1.01 E-5 | 7 E-5 | .45 - 1.0 E-4 | 5E-8 | 4E-8- 6 E-8 |
| New SDRs CF6-6 | - | - | 2.7E-5 | 1.3 - 5.4 E-5 | 8E-8 | 6E-8 -1 E-7 |
| New SDRs CF6-50 | - | - | 2 E-5 | .74 - 5.2 E-5 | 8E-8 | .55 - 1.1 E-7 |

Table F.1

It is evident that A (the rate of random, non-design-related failures) is effectively the same number for both the CF6-6 and CF6-50. Future engine models designed to be more resistant to birdstrike or maintenance abuse might have lower values of A.
Likewise, B is the same for both the CF6-6 and CF6-50, within the statistical variation of the measured rates.

**ALL MISSING PAGES ARE BLANK**

**IN**

**ORIGINAL**

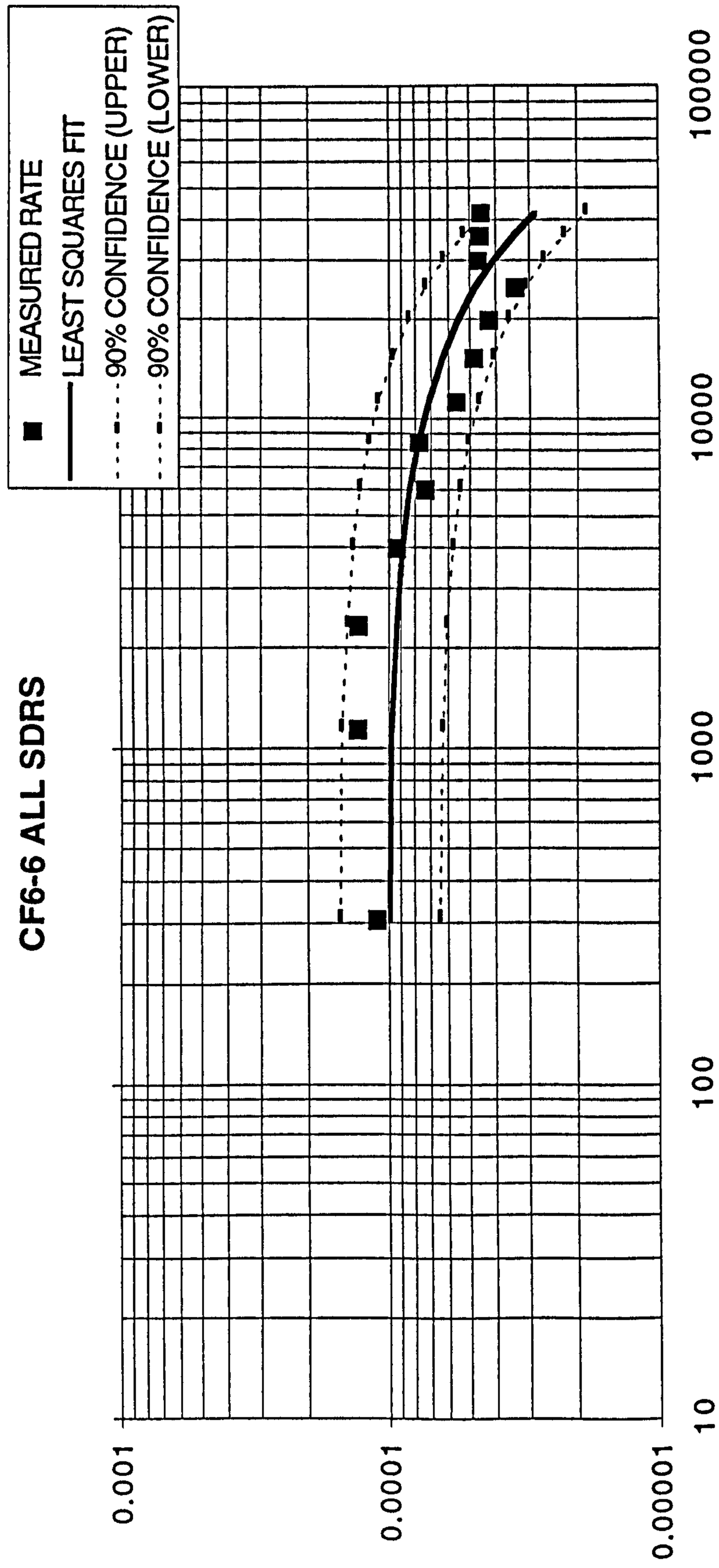

CF6-6 ALL SDRS
MEASURED RATE
LEAST SQUARES FIT
90% CONFIDENCE (UPPER)
90% CONFIDENCE (LOWER)
SDR RATE /1000 ENGINE HOURS
0.001
0.0001
0.00001
10
100
1000
10000
100000
CUMULATIVE CF6 FLEET HOURS (THOUSANDS)

Figure F.6

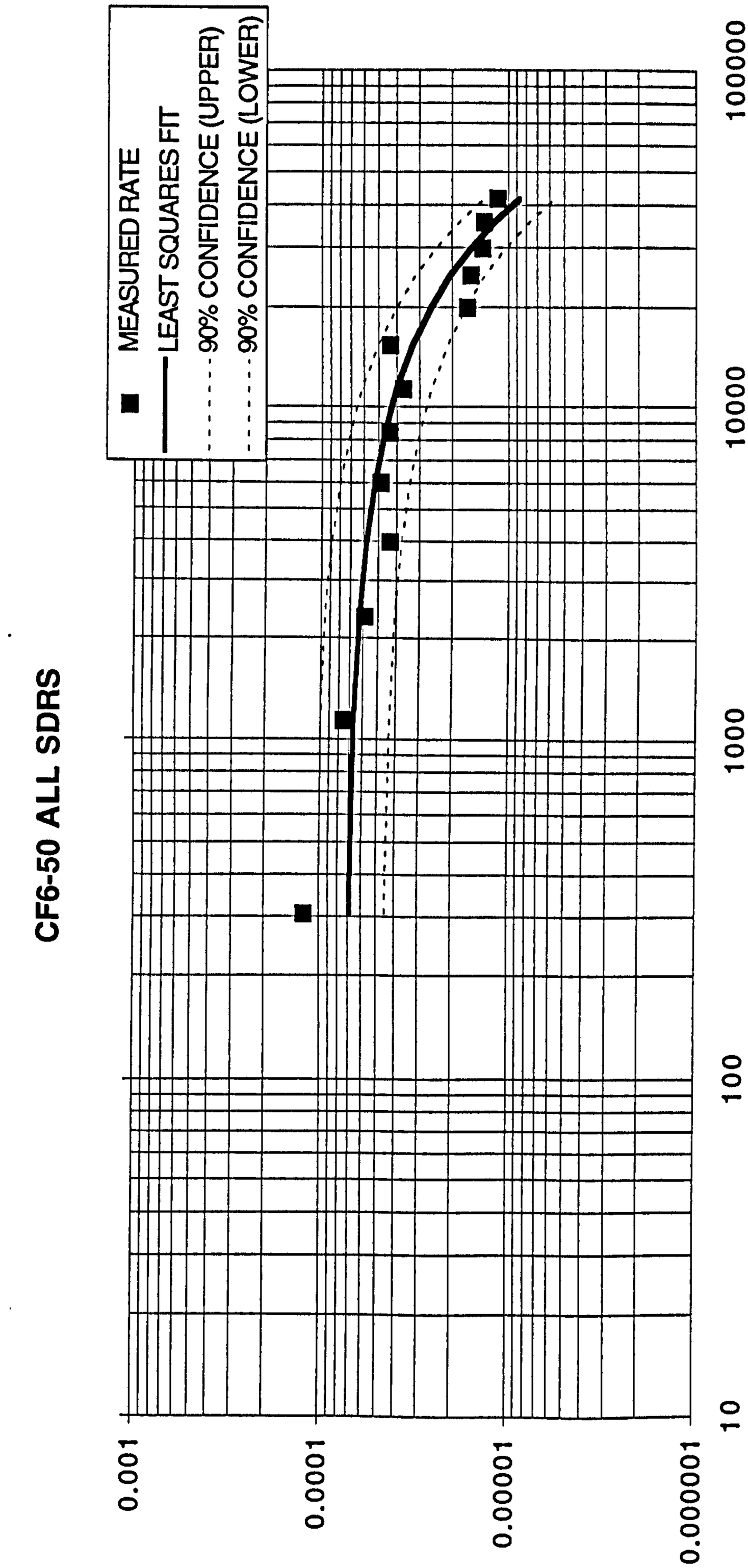

MEASURED RATE
LEAST SQUARES FIT
90% CONFIDENCE (UPPER)
90% CONFIDENCE (LOWER)
CF6-50 ALL SDRS
100000
10000
1000
100
10
0.001
0.0001
0.00001
0.000001
SDR RATE/ 1000 ENGINE HOURS
CUMULATIVE CF6 FLEET HOURS (THOUSANDS)

Figure F.7

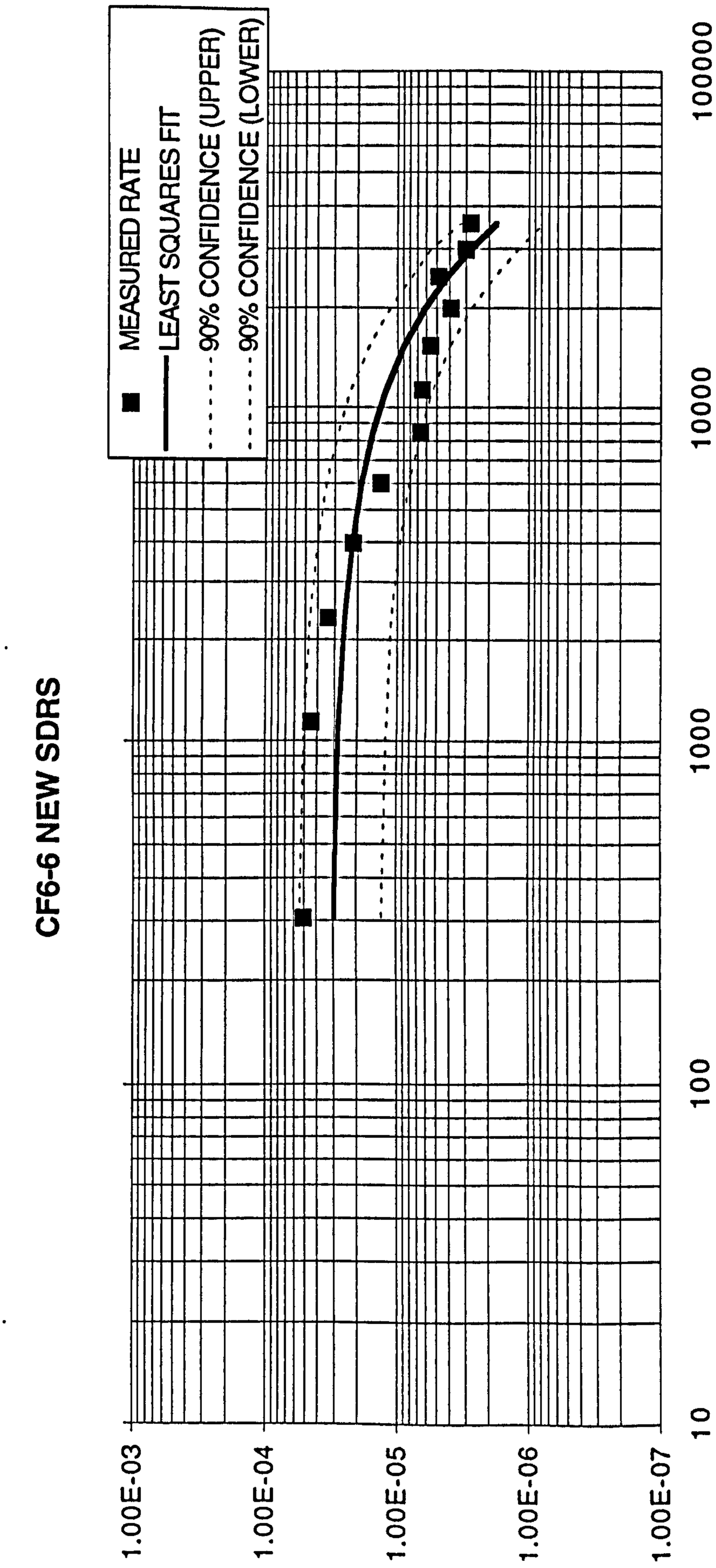

CF6-6 NEW SDRS
MEASURED RATE
LEAST SQUARES FIT
90% CONFIDENCE (UPPER)
90% CONFIDENCE (LOWER)
SDR RATE/ 1000 ENGINE HOURS
1.00E-03
1.00E-04
1.00E-05
1.00E-06
1.00E-07
CUMULATIVE CF6 FLEET HOURS (THOUSANDS)
100
1000
10000
100000
10
100
1000

Figure F.8

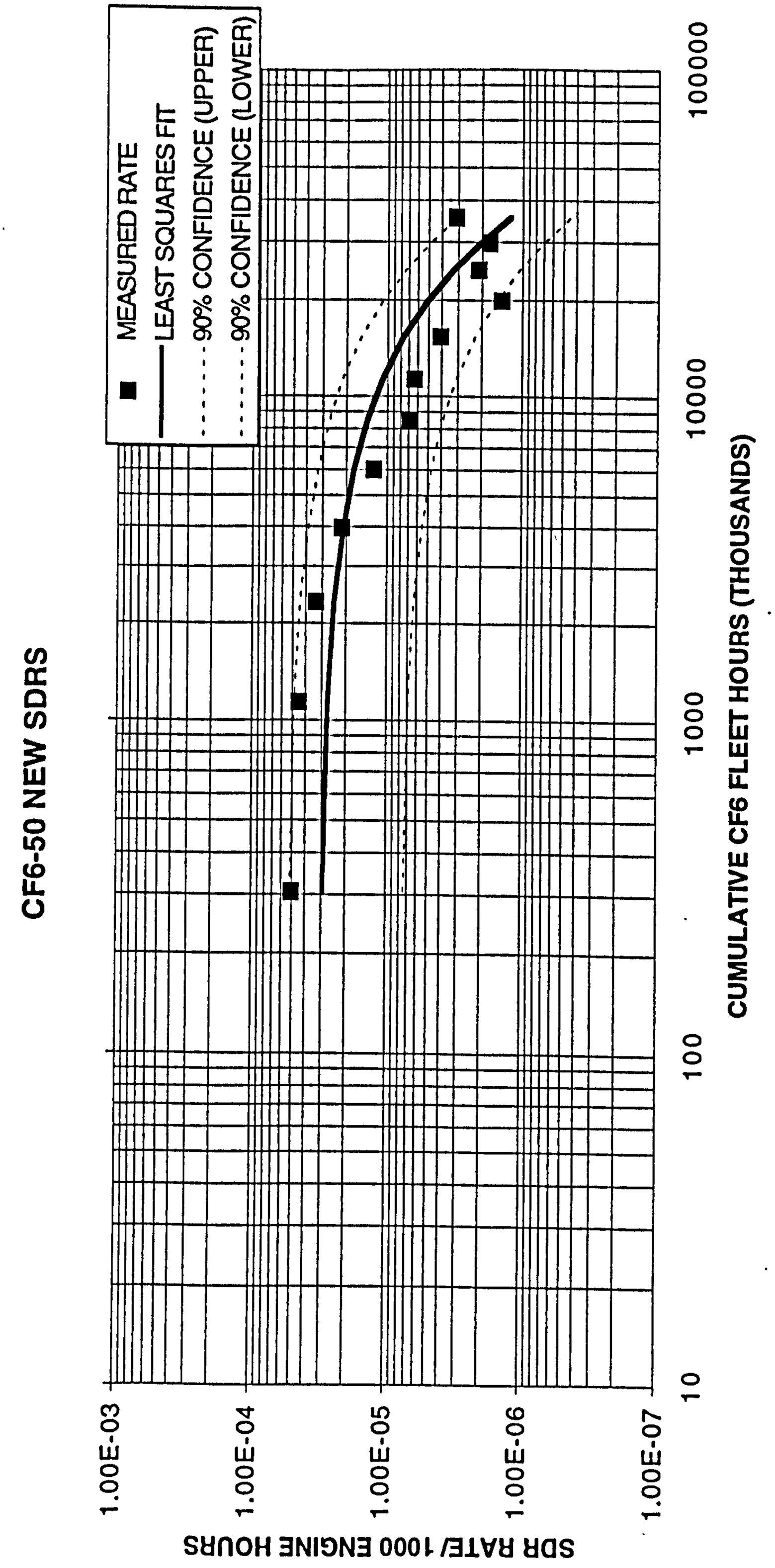

MEASURED RATE
LEAST SQUARES FIT
90% CONFIDENCE (UPPER)
90% CONFIDENCE (LOWER)
CF6-50 NEW SDRS
CUMULATIVE CF6 FLEET HOURS (THOUSANDS)
100000
10000
1000
100
10
1.00E-03
1.00E-04
1.00E-05
1.00E-06
1.00E-07
SDR RATE/ 1000 ENGINE HOURS

Figure F.9

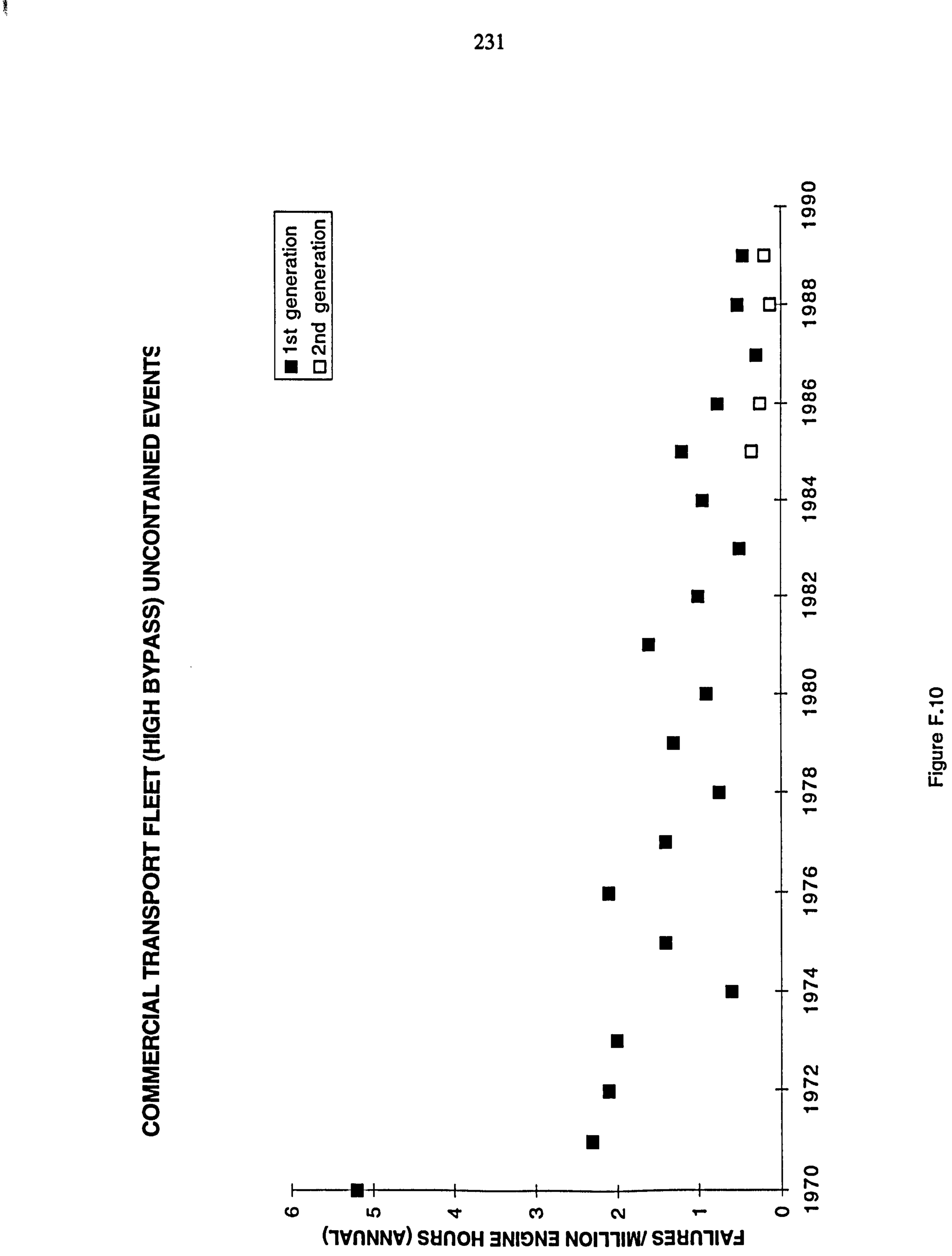

COMMERCIAL TRANSPORT FLEET (HIGH BYPASS) UNCONTAINED EVENTS
1st generation
2nd generation
1970
1972
1974
1976
1978
1980
1982
1984
1986
1988
1990
0
1
2
3
4
5
6
FAILURES /MILLION ENGINE HOURS (ANNUAL)

Figure F.10

## Fiii Detailed (Component) Failure Rate Prediction

The work described above relates to failure prediction at the engine level. The feasibility of producing more detailed predictions of failure rates was assessed by grouping the service difficulty reports into submodules of similar components (such as HP compressor blades and vanes, main bearings, or power offtake gearboxes and drives). Figures F.11 and F.12 rank the relative contributions of these submodules to the overall SDR totals. Many submodules made a minimal contribution; seven submodules were major contributors and were selected for further examination. These seven submodules each contributed 50 or more events in the time period of interest, and accounted altogether for over 75% of all events. The annual SDR rates for each of these submodules are found in figures F.13 and F.14. There is substantial variation from one year to the next, suggesting that trending of less significant contributors (or at the component level) would not be informative.

For each engine model, the single least reliable submodule (referred to below as "Worst" submodule) accounted for the majority of the overall reliability growth in the first few years after entry into service. More reliable submodules show relatively modest (or negligible) reliability growth. This result could be anticipated from a rational deployment of product support effort. Comparison of submodule reliability from one engine model to the next shows that design changes do introduce higher failure rates into some submodules, but that the overall effect is an improvement from the parent model to the derivative. Specifically, the CF6-6 HPT blade problems were fixed for the CF6-50, but the -50 HPC blades did not do as well as the -6 HPC blades (although still twice as well as the -6 HPT blades). After many years, the CF6-50 failure rates were generally lower than those of the CF6-6. The CF6-80A "worst" submodule was the bearings at entry into service, although the bearing failure rate was only half that of the CF6-50 HPC blades at the peak of their unreliability (the CF6-80A "worst" submodule was still much better than the worst submodule of its' precursor.

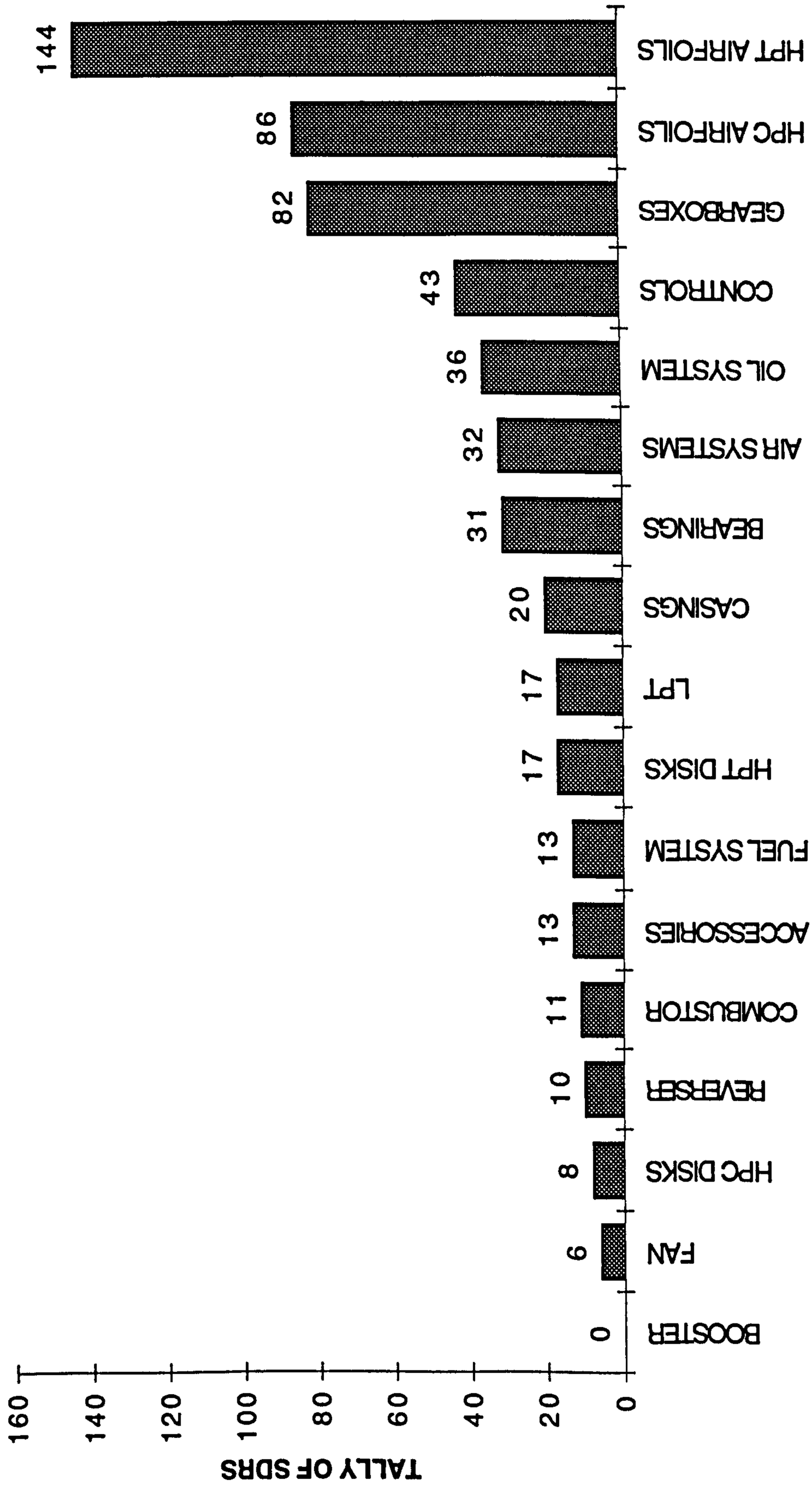

CF6-6 SUB-MODULE CONTRIBUTION TO SDRS
TALLY OF SDRS
0
20
40
60
80
100
120
140
160
BOOSTER
FAN
HPC DISKS
REVERSER
COMBUSTOR
ACCESSORIES
FUEL SYSTEM
HPT DISKS
LPT
CASINGS
BEARINGS
AIR SYSTEMS
OIL SYSTEM
CONTROLS
GEARBOXES
HPC AIRFOILS
HPT AIRFOILS
144
86
82
43
36
32
31
20
17
17
13
13
11
10
8
6
0

Figure F.11

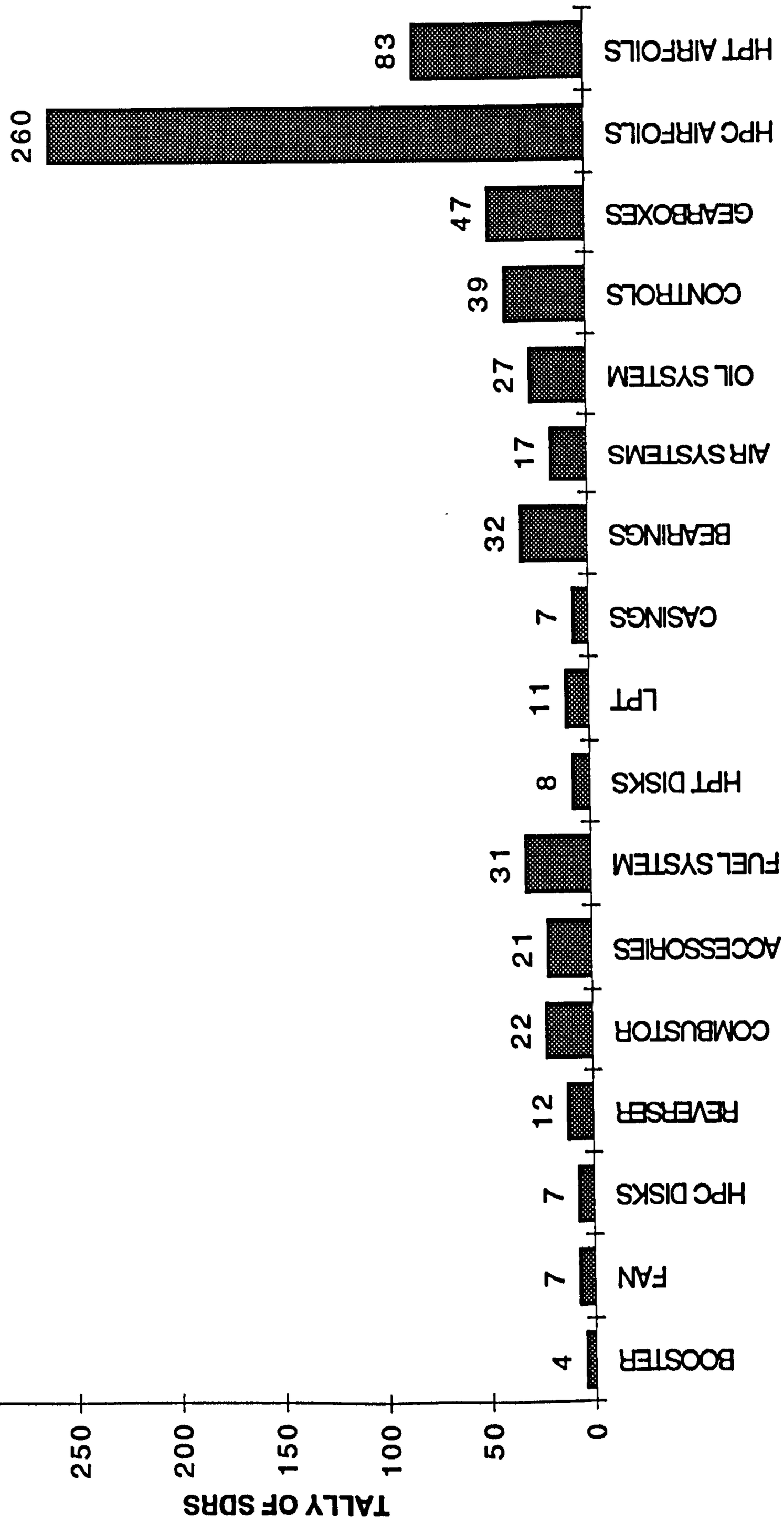

CF6-50 SUB-MODULE CONTRIBUTION TO SDRS
TALLY OF SDRS
0
50
100
150
200
250
300
BOOSTER
4
FAN
7
HPC DISKS
7
REVERSER
12
COMBUSTOR
22
ACCESSORIES
21
FUEL SYSTEM
31
HPT DISKS
8
LPT
11
AIR SYSTEMS
17
OIL SYSTEM
27
CONTROLS
39
GEARBOXES
47
BEARINGS
32
CASINGS
7
HPC AIRFOILS
260
HPT AIRFOILS
83

Figure F.12

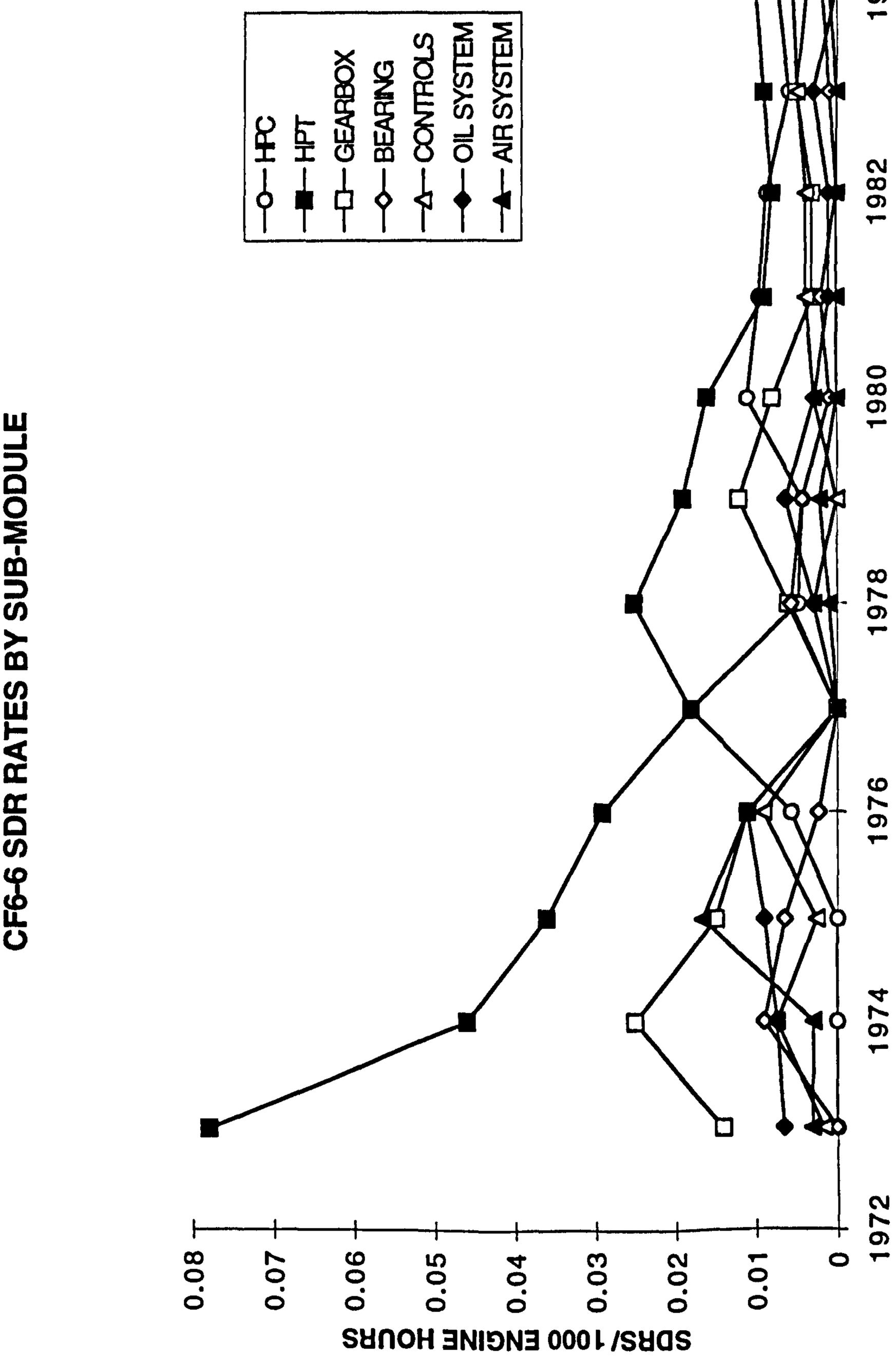

CF6-6 SDR RATES BY SUB-MODULE
HPC
HPT
GEARBOX
BEARING
CONTROLS
OIL SYSTEM
AIR SYSTEM
1972
1974
1976
1978
1980
1982
1984
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
SDRS/ 1000 ENGINE HOURS

Figure F.13

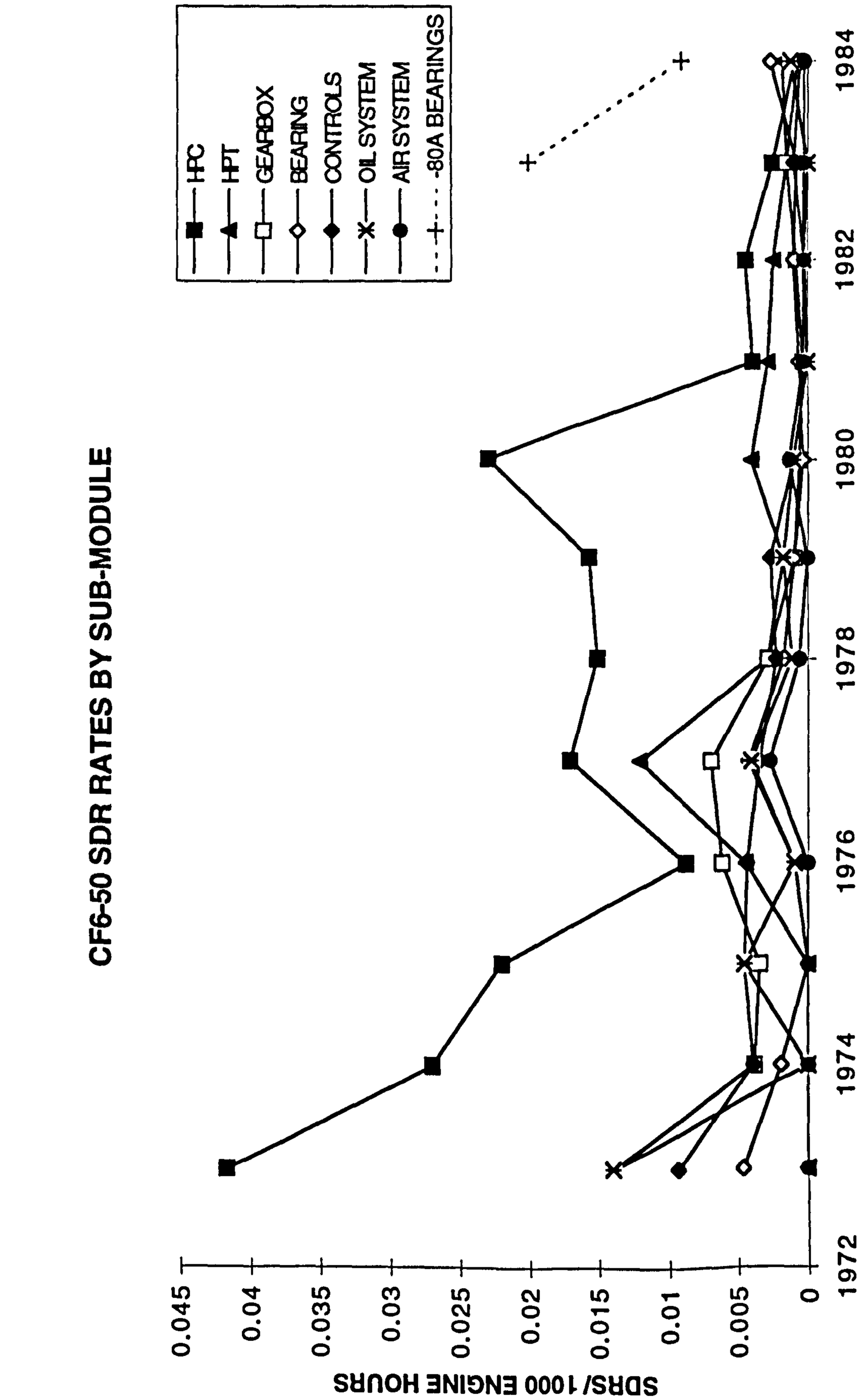

CF6-50 SDR RATES BY SUB-MODULE
HPC
HPT
GEARBOX
BEARING
CONTROLS
OIL SYSTEM
AIR SYSTEM
-80A BEARINGS
1984
1982
1980
1978
1976
1974
1972
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
SDRS/ 1000 ENGINE HOURS

Figure F.14

## Fiv Effect Of Flight Phase

Further insight can be gained into the desirability of using phase-dependent failure rates by consideration of the failure mechanisms which could potentially be associated with different phases of flight, and by review of experience to establish *their importance.*

The take-off phase entails the highest rotor speeds and gas temperatures and pressures, and imposes severe thermal transients upon core components. There is considerable exposure to foreign object damage such as bird ingestion. Flight crew workload is high, and response to a failure may be time-critical; there is therefore a higher potential for even benign failure to precipitate crew error. In the event of such error, there is minimal time for recovery.
Uncontained failures are overwhelmingly more likely during takeoff than any other phase of flight, and this is primarily due to the high rotor speeds encountered, which both precipitate a rotor failure if one is incipient, and also entail higher fragment energies than experienced in other flight phases, so that parts are more likely to penetrate the engine casings. It had been postulated that bird ingestion might also play a significant role in generating uncontained failures in takeoff, but in fact Foreign Object Damage accounted for only 4% of such events. The FAA (35 - 44) has explicitly linked the rate of rotor bursts with high power settings (take-off and climb), although review of the data shows that takeoff is very much more significant than climb.

At climb power, gas path pressures, temperatures and the hazards of low altitude (birds, time pressure in crew response) are much reduced from takeoff. Temperatures of some components (disk bores) may actually be higher than at take-off due to the lag in temperature response. High disk temperatures have resulted in uncontained failures on some occasions, although this is not a typical disk failure cause. there is significant potential for nacelle fire when power is reduced from takeoff to climb. Casing temperatures are high, and the reduction in nacelle cooling flow (associated with power reduction) around the core may be of critical importance in increasing the residence time of leaked flammable fluid sufficiently to enable spontaneous ignition.

The cruise phase of flight is relatively unlikely to precipitate failures. Components may approach steady-state temperatures and stresses; gas path temperatures and pressures are moderate, and engine performance has been exhaustively modeled at the "design point". It is instructive to compare the extended lives of industrial gas turbines, which essentially spend all of their

time at cruise, with that of aircraft turbofans. Nevertheless, there are some types of time-dependent failure prevalent at cruise, such as gearbox failures. The risk of under cowl fire resulting from a flammable fluid leak is negligible since ambient pressures will not support combustion. In the event of a serious failure, the crew may have time to plan their response and possibly to respond better than for failures in time-critical phases of flight. The exposure to Foreign Object Damage is very limited, although it must be acknowledged that ice shed by the airframe poses a serious threat to the engine, and that migratory waterfowl have been known to fly at cruise altitudes.

Descent and final approach would appear initially to place few demands upon the integrity of the engine (and this is indeed the case for rotor burst type failures). However, the relatively low operating pressure ratios and rotor speeds make many engines vulnerable to flameout if severe weather is encountered, or even if rapid throttle movements are commanded by the flight crew.

# CRANFIELD UNIVERSITY

COLLEGE OF AERONAUTICS

CRANFIELD UNIVERSITY LIBRARY

Ph.D. THESIS

Academic Year 1997

S KNIFE

# Propulsion System Safety Analysis Methodology For Commercial Transport Aircraft

vol 2

Supervisor: J P Fielding

September 1997

# CONTENTS

## VOLUME II


| | | Page |
|---|---|---|
| APPENDIX G | | |
| RB211-22B SAFETY ANALYSIS (RR PROPRIETARY) | | 1 |
| Gi | Introduction To Baseline Safety Analysis | 3 |
| Gii | Substantiation Of Failure Rates | 4 |
| FMEA | Fan Rotor | 7 |
| FMEA | Fan Stator | 17 |
| FMEA | IP Compressor Outer Case | 24 |
| FMEA | Fan OGV Assembly | 29 |
| FMEA | IP Compressor Rotor | 33 |
| FMEA | IP Compressor Stator | 43 |
| FMEA | Intermediate Casing | 65 |
| FMEA | HP Compressor Rotor | 79 |
| FMEA | HP Compressor Stator | 89 |
| FMEA | Combustor | 95 |
| FMEA | HP Turbine | 115 |
| FMEA | IP Turbine | 121 |
| FMEA | LP Turbine | 135 |
| FMEA | Turbine Bearings | 143 |
| FMEA | Engine Mounts | 151 |
| FMEA | Oil System | 157 |
| FMEA | Fuel System | 169 |
| FMEA | Starting System | 177 |
| FMEA | Engine Instrumentation | 181 |
| FMEA | Ice Protection System | 185 |
| FMEA | Air Bleed System | 187 |

| | | Page |
|---|---|---|
| APPENDIX H | | |
| EFFECT OF THRUST GROWTH ON RELIABILITY AND SAFETY (RR PROPRIETARY) | | 189 |
| Hi | Introduction | 191 |
| Hii | Engine Selection | 191 |
| Hiii | Reliability/Safety parameter | 192 |
| Hiv | Variation Of Failure Rates With Time | 192 |
| Hv | Relationship Between Failure Rates And Physical Parameters | 194 |
| Hvi | Installation Effects | 196 |
| Hvii | Design Margin | 196 |
| Hviii | Conclusions | 197 |

# FIGURES


| | | Page |
|---|---|---|
| G.1 | Fan Rotor | 5 |
| G.2 | Fan Rotor | 6 |
| G.3 | Fan Casing | 15 |
| G.4 | IP Compressor Stator | 23 |
| G.6 | IP Compressor Rotor | 31 |
| G.7 | Fixed IGVs | 41 |
| G.8 | Variable IGVs | 42 |
| G.9 | LP and IP Compressor Front Roller Bearings | 55 |
| G.10 | Intermediate Casing | 63 |
| G.11 | Location Bearings | 69 |
| G.12 | HP Compressor Rotor | 77 |
| G.13 | HP Compressor Stator | 87 |
| G.14 | Combustion Outer Casing | 93 |
| G.15 | Combustion Chamber | 103 |
| G.16 | HP Turbine Rotor And Stator | 113 |
| G.17 | IP Turbine Rotor And Stator | 119 |
| G.18 | Turbine Casings | 127 |
| G.19 | Tail Bearing Support Structure | 133 |
| G.20 | HP/IP/LP Roller Bearings | 141 |
| G.21 | Engine Mounts | 149 |
| G.22 | Oil System | 155 |
| G.23 | Fuel System | 167 |
| H.1 | Rotor Burst Rates (Spey) | 199 |
| H.2 | Annual IFSD Rates (Spey) | 200 |
| H.3 | Annual UER Rates (Spey) | 201 |
| H.4 | Mature Failure Rates vs. Year Entered Service (Spey) | 202 |
| H.5 | Annual IFSD Rates vs. Fleet Hours (Spey) | 203 |
| H.6 | Annual UER Rates vs. Fleet Hours (Spey) | 204 |
| H.7 | Mature Failure rates vs. Rated Thrust (Spey) | 205 |
| H.8 | Mature Failure Rates vs. CDP (Spey) | 206 |
| H.9 | Mature Failure Rates vs. Core Speed (Spey) | 207 |
| H.10 | Mature Failure Rates vs. TGT (Spey) | 208 |
| H.11 | Spey 505 IFSD Rates by System Group | 209 |
| H.12 | Spey 506 IFSD Rates by System Group | 210 |
| H.13 | Spey 511 IFSD Rates by System Group | 211 |
| H.14 | Spey 512 IFSD Rates by System Group | 212 |
| H.15 | Spey 555 IFSD Rates by System Group | 213 |
| H.16 | Tay IFSD Rates by Model and System Group | 214 |
| H.17 | Mature Failure rates vs. Thrust (CFM56) | 215 |
| H.18 | Mature Failure Rates vs. CDP (CFM56) | 216 |
| H.19 | Mature Failure Rates vs. EGT (CFM56) | 217 |

# APPENDIX G

# BASELINE ASSESSMENT

THIS PAGE INTENTIONALLY BLANK

# APPENDIX G: RB211 BASELINE SAFETY ANALYSIS ASSESSMENT

## Gi Introduction to baseline safety analysis.

The following analysis is intended to evaluate the safety of the RB211-22 as it would have been done in the approach to engine certification, in the late 1960s. It is largely based upon the original failure analysis performed by Rolls-Royce, except that some assemblies and systems have been added, and some additional material is presented throughout (such as item function and hazard classification). Original Rolls-Royce material appears in plain text, material added for this study is in italics. The analysis has been supplemented by additional drawings of engine details and systems, in conjunction with an icon indicating the general area of the assembly being analysed.

The hardware analysed is to the 1969 standard (no service bulletins incorporated) and where there are differences in the predictions of several Rolls-Royce reports, the 1969 version is used.

The failure rates used by Rolls-Royce were based upon service experience of previous engines such as the Spey, Tyne and Conway, and upon a limited amount of development running with the RB211. Material added during this study uses failure rates obtained from one of the following sources (in order of preference):

Rolls-Royce technical report prediction, failure analysis or $FMEA_a$.
Close analogy to a RR technical report prediction, e.g. from one oil line to another$_b$
Spey experience up to 1970$_c$
Published industry data$_d$
Best estimate based upon author's personal experience$_e$

The source of each failure rate is indicated by the corresponding subscript, supplemented in some cases by a note in the right-hand column of the analysis.

In the interest of brevity, failures with no safety effect have been omitted from the safety analysis, unless it forms the only permanent record of such failure effects (i.e., analysis performed solely for this study includes all failures).

A summary of the results of the analysis and a comparison of predicted failure rates with service experience can be found in Chapter 2.

## G ii Substantiation Of Failure Rates For Baseline Analysis

It was considered essential that the engine selected for the baseline comparison should have accrued a significant basis of experience in service; this factor, together with access to the original safety analysis, led to the selection of the RB211-22 as a test case. It must be recognised, however, that any attempt to generate failure rates relies upon the accuracy and completeness of the reporting of such failures from the field. No single database can be relied upon to include every relevant powerplant failure, but it was anticipated that amalgamation of failure events from several databases would both allow assessment of the completeness of reporting, and also allow production of failure rates representative within a few percent, and at least as accurate as any currently published within the industry.

Data was extracted from the following sources:

a) NTSB
b) FAA Service Difficulty Reports for US airlines, January 1986 - December 1993, engine failures.
c) CAA, Reports of Failures, Malfunctions and Defects reported for high-bypass engines, January 1984 - December 1993
d) FAA Service Difficulty Reports for US airlines, 1978 -1979 and 1981 - 1989, Engine Rotor Failures

It was discovered that there was minimal redundancy between sources a), b) and c), in that only one event was reported by more than one of the databases (RB211-535 multiple engine flameout on , reported by FAA, CAA and NTSB). This initially caused some concern, since it implied the potential existence of large numbers of safety related events external to both Britain and the US, unreported by sources a), b) and c). The option remained of generating failure rates based on the limited experience of a few carriers for which the comprehensiveness of data could be verified; for instance, that of the US carriers, for which reporting engine failures to the Service Difficulty Report system forms a legal requirement. The limitations of this approach are evident for the types of events where the entire commercial fleet may only experience a few occurrences.

The assistance of Rolls Royce was therefore solicited in determining in-flight shutdown service experience for the baseline assessment only. This proprietary information is confined to Volume II of this thesis.

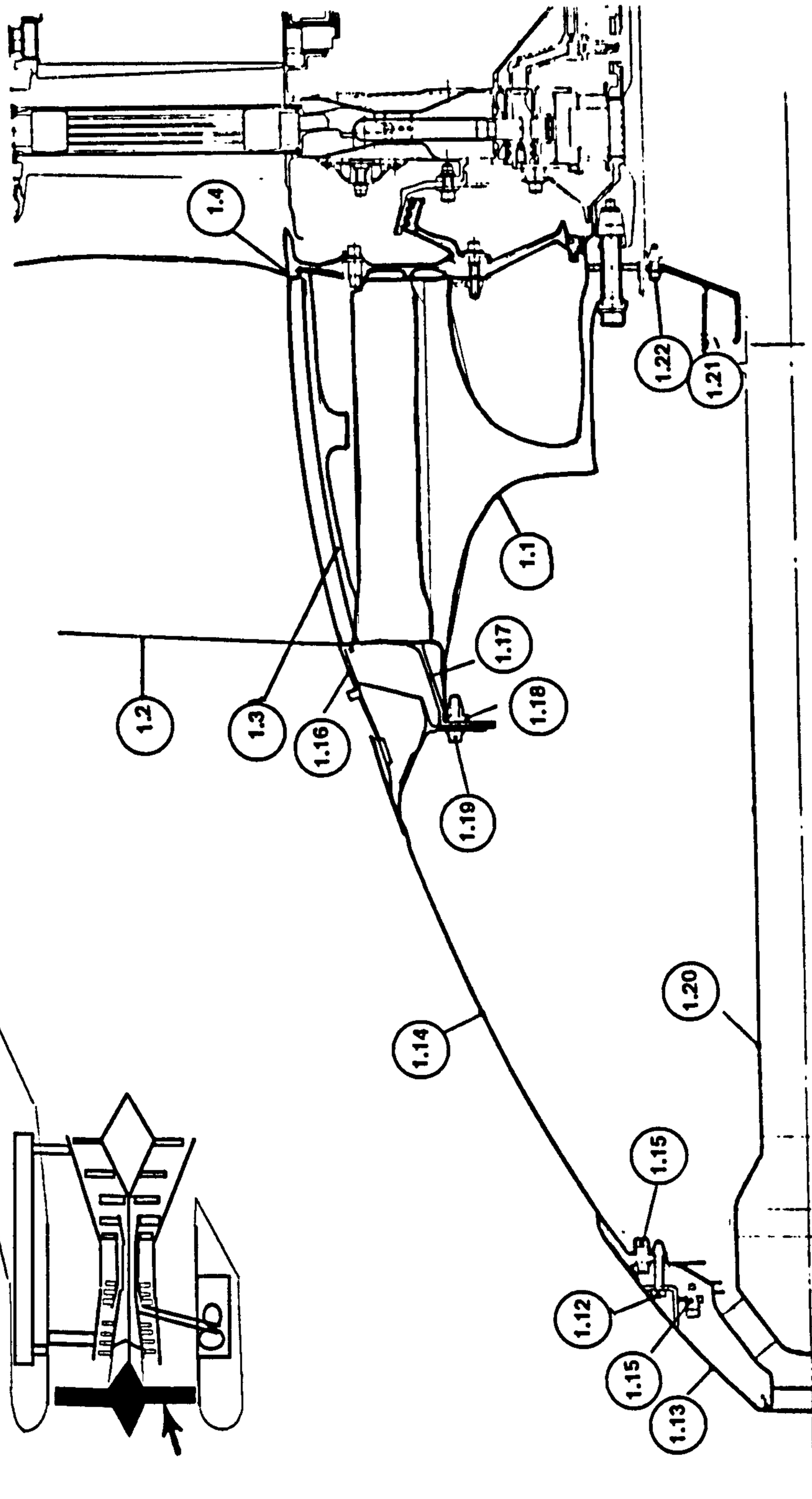



FIGURE G.1 FAN ROTOR

○ CODE Nos.

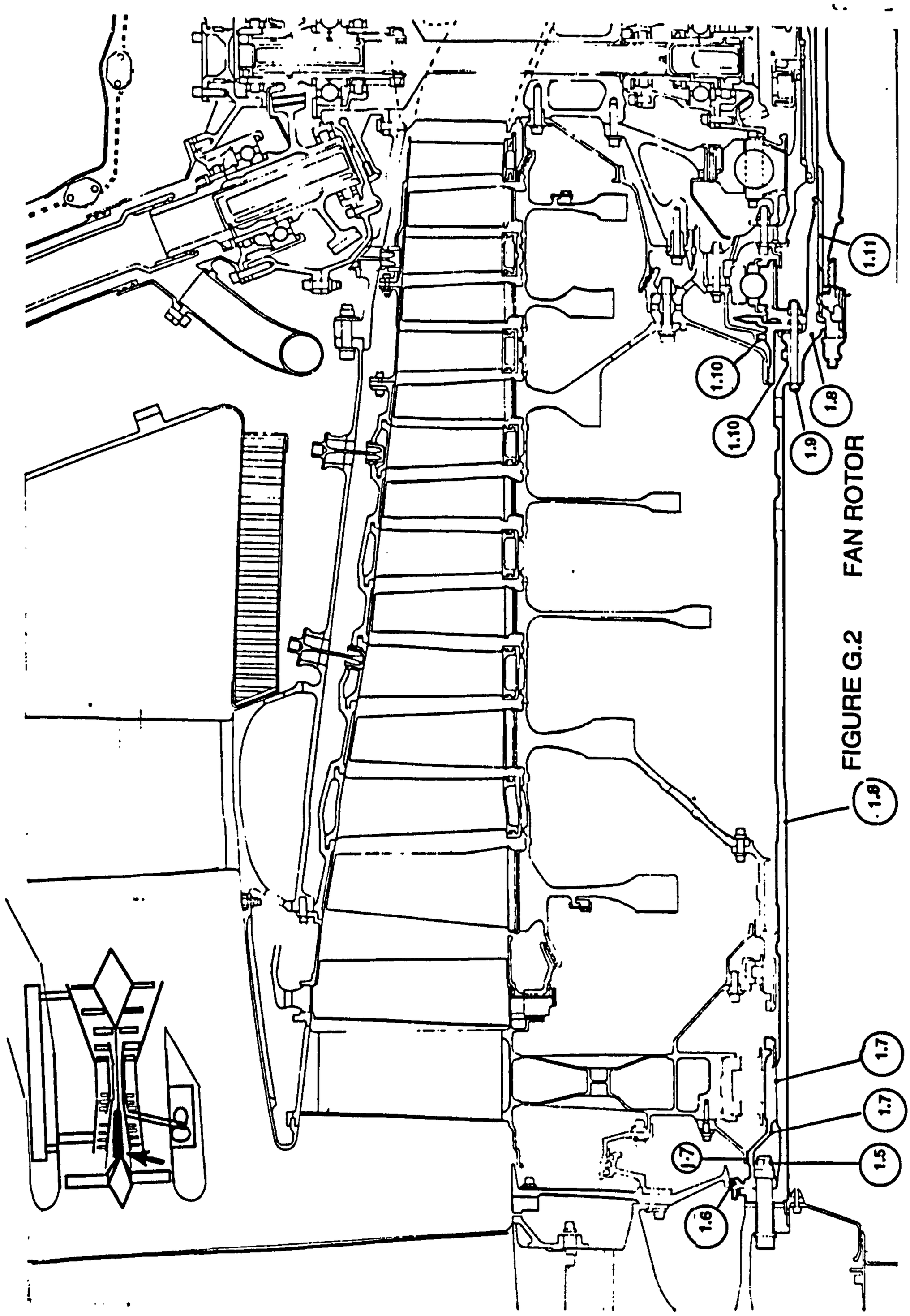



FIGURE G.2

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 1.1 Fan disc | *Radial retention of fan-blades. Transmits torque between fanblades and fan shaft.* | Fatigue (rim) | Release of two or more fanblades as disc firtree attachment neck cracks across | Damage to fan, OGVs, fan case. Severe unbalance. | IFSD Possible uncontained failure | Hazardous | .01 | SER 90074 Iss 1, SER 90074 Iss 2 |
| | | Fatigue (bore) | Release of all fanblades and pieces of disc. | Fan case penetration, LP turbine overspeed and LP turbine disc burst. | IFSD. Uncontained failure | Hazardous | .01 | SER 90074 Iss 1, SER 90074 Iss 2 |
| 1.2 Fan blade | *Compression of air at engine inlet* | Impact (foreign object) | Loss of blade aerofoil outboard of clapper | Damage to remaining blades, OGVs and fan case. Severe unbalance. | IFSD (non-basic) | Major | 1 | SER 90074 Iss 1, SER 90074 Iss 2 |
| | | | Loss of blade at root | Severe damage to fan, fan case and OGVs. High loads on bearings, support structure deformation | IFSD (non-basic) | Major | 1 | SER 90074 Iss 1, SER 90074 Iss 2 |
| | | Fatigue | Loss of blade aerofoil outboard of clapper | As above | IFSD | Major | 1 | SER 90074 Iss 1, SER 90074 Iss 2 |
| | | | Loss of blade at root | As above | IFSD | Major | 1 | SER 90074 Iss 1, SER 90074 Iss 2 |

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| *1.3 Annulus filler* | *Forms aerodynamic fan stream inner wall at blade roots* | Fatigue | *Cracking of filler allows its release into gas-stream* | *Damage to fanblades, OGVs. Unbalance* | *IFSD* | *Minor* | *10* | *SMK* |
| *1.4 Annulus filler retention ring assembly* | *Prevents aft movement of annulus fillers. Forms inner wall of gas path aft of fanblades.* | Fatigue | *Cracking and ring disintegration under centrifugal loads* | *Axial movement of annulus fillers, release into gas path. Damage to fanblades and OGVs. Unbalance.* | *IFSD* | *Major* | *10* | *SMK* |
| | *Provides outer sealing surface for ring seal (1.6). Provides labyrinth seal between bearing chamber and IP compressor inlet air.* | Bolt loosening | *For multiple bolt loosening, assembly moves relative to fan rotor. Eventual fatigue and ring break-up.* | *As above* | *IFSD* | *Minor* | *10* | *SMK* |
| | | Wear | *Increased seal leakage* | *None* | *Reduced surge margin* | *Minor* | *10* | *SMK* |



*CONTAINS RR PROPRIETARY DATA*

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 1.5 Nuts/bolts | *Attach fan disc to fan shaft* | Loosening | Fan assembly swash. | Heavy rub to air seal at rear of disc. | IFSD | *Minor* | 0.1 | MISC 61 |
| | | | Failure of a few bolts. | Possible air seal failure. | Surge | | | |
| | | Impact over-load | Multiple bolt failure | Loss of fan radial location. | IFSD | *Major* | .01 | MISC 61 |
| | | | | Bearing housing failure. | Fire | *Hazardous* | .005 | MISC 61 |
| | | | | Release of fan assembly forward. | Un-contained failure | *Hazardous* | .01 | MISC 61 |
| 1.6 Front ring seal | *Seals fan bearing chamber from fan disc rear face* | Wear | Leakage of IP air and oil mist up rear face of fan disc rim | Increased blade root temperature. Oil loss. | IFSD (non-basic) | *Minor* | 8 | MISC 61 |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 1.7 Inner race/seal assembly | *Primary oil/air seal forward of front bearing* | Wear | Seal rub | Oil leakage. | IFSD | *Minor* | 50 | MISC 61 |
| | | | | Oil contamination by seal particles | | | 35 | MISC 61 |
| | *Attaches front seal and fan bearing inner race* | Fatigue | Weld failure between seal and inner race | Bearing race spins relative to shaft. N1 signal incorrect. | IFSD | *Minor* | .01 | MISC 61 |
| | | | | Axial movement of race damages oil jet; loss of cooling. | IFSD | *Major* | .005 | MISC 61 |
| | | | | Bearing failure. | IFSD | *Major* | .02 | MISC 61 |
| 1.8 LP compressor shaft | *Transmits torque from LP turbine to fan. Transmits axial loads to location bearing* | Fatigue | Shaft failure | Forward release of fan assembly, if shaft fails forward of bearing. LP turbine overspeed and blade release. | IFSD. Un-contained failure | *Hazardous* | <.01 | MISC 61 |
| 1.9 Bolts | *Attach intershaft bearing inner race to LP compressor shaft* | Loosening | Bolt failure and release | Damage to LP shaft and IP drum from bolt impact. | IFSD | *Major* | 0.8 | MISC 61 |
| | | | Failure of all bolts | Axial movement of LP assembly | IFSD, surge, | *Major* | <.01 | MISC 61 |



*CONTAINS RR PROPRIETARY DATA*

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 1.10 Intershaft bearing chamber forward seal | *Oil/air seal for location bearing chamber* | Wear | Leakage of IP delivery air and oil mist into 4th stage of IP compressor | Oil loss | IFSD<br>Surge | *Minor* | .05 | MISC 61 |
| | | Rapid wear (from unbalance) | As above | Oil loss | IFSD<br>Surge | *Minor* | .2 | MISC 61 |
| 1.11 Compressor shaft/turbine shaft coupling | *Transmits torque between shafts* | Spline fretting | Spline cracking and progressive failure | Loss of axial location of LP turbine, turbine overspeed | IFSD<br>Uncontained failure | *Hazardous* | <.001 | MISC 61 |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 1.12 Nose cap/cone bolts | *Attach nose-cap to nose-cone* | Loosening | Failure of all bolts | Release of nose-cap Unbalance | IFSD | *Minor* | .08 | MISC 61 |
| 1.13 Nose cap | *Aerodynamic fairing at shaft end* | Impact | Break-up of nose-cap | Unbalance Distorted flow of anti-ice air over nose cone | Compressor damage IFSD | *Major* | .1 | MISC 61 |
| 1.14 Nose cone | *Aerodynamic fairing at shaft end* | Impact<br>Fatigue | Deformation<br>Pieces of cone skin detach | Unbalance. Distorted flow of anti-ice air<br>Unbalance | IFSD<br>Comp'r damage. IFSD | *Minor*<br>*Major* | 8<br>1 | MISC 61<br>MISC 61 |
| 1.15 Nose cone balance weight | *Allows radial balancing of nose-cone assembly* | Loosening | Detachment of weight | Unbalance. Fatigue crack in nose-cone skin | IFSD | *Minor* | .1 | MISC 61 |
| 1.16 Nose cone support ring | *Provides location for nose-cone. Radially retains annulus fillers between fanblades* | Fatigue | Ring cracking and break-up | Unbalance. Release of pieces of ring into gas-path. Release of annulus fillers. | IFSD Compressor damage | *Major* | .03 | MISC 61 |



*CONTAINS RR PROPRIETARY DATA*

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 1.17 Nose cone retaining ring | *Retains fanblades axially in disc* | Fatigue | Cracking of ring allows deformation. | Fan blade load transfers to support ring | IFSD | *Minor* | .1 | MISC 61 |
| 1.18 Nose cone retaining ring bolts | *Attach retaining ring to nose cone* | Loosening | Failure of bolts may release parts of nose-cone assembly | Detached parts damage fan disc or escape into gas-path | IFSD | *Major* | .1 | MISC 61 |
| 1.19 Nose cone bolts | *Attach nose cone assembly to fan disc* | Loosening | Failure of bolts may release parts of nose-cone assembly | Detached parts may damage fan disc or escape into gas-path | IFSD | *Major* | 1 | MISC 61 |
| 1.20 Anti-icing tube | *Directs IP4 compressor air to nose-cap, for nose-cone anti-icing.* | Fatigue | Crack allows leakage of anti-icing air into nose-cone. | Reduced nose-cone anti-icing. Ice shedding. | Ice ingestion IFSD | *Minor* | 10 | MISC 61 |
| | | | Tube deflects under centrifugal forces, buckles and collapses. | Nose cone failure<br>Reduced cooling to fan disc rim | | *Minor* | .2 | MISC 61 |
| 1.21 Anti-ice tube support cone | *Provides radial support to aft end of anti-ice tube* | Fatigue | Crack allows anti-ice air leak into nose-cone. | Reduced nose-cone anti-icing | Ice ingestion IFSD | *Minor* | 2 | |
| | | | Loss of support for anti-ice tube, tube failure. | Unbalance. Reduced cooling to fan disc rim. | | *Minor* | .04 | |

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 1.22 Anti-ice tube support cone bolts | *Attach support cone to fan shaft assembly* | Loosening | Single bolt fails | Unbalance.<br>Some leakage of anti-ice air into nose-cone.<br>Impact damage to fan disc or nose-cone.<br>Damage to compressor blading | IFSD (non-basic) | *Major* | .9<br>.4<br>.01 | MISC 61<br>MISC 61<br>MISC 61 |
| | | | Multiple bolts fail | Leakage of anti-ice air into nose-cone.<br>Impact damage to fan disc or nose-cone.<br>Anti-ice tube failure.<br>Damage to compressor blading | | *Minor*<br>*Major*<br>*Minor*<br>*Major* | .05<br>.02<br>.025<br>.01 | MISC 61<br>MISC 61<br>MISC 61<br>MISC 61 |



*CONTAINS RR PROPRIETARY DATA*

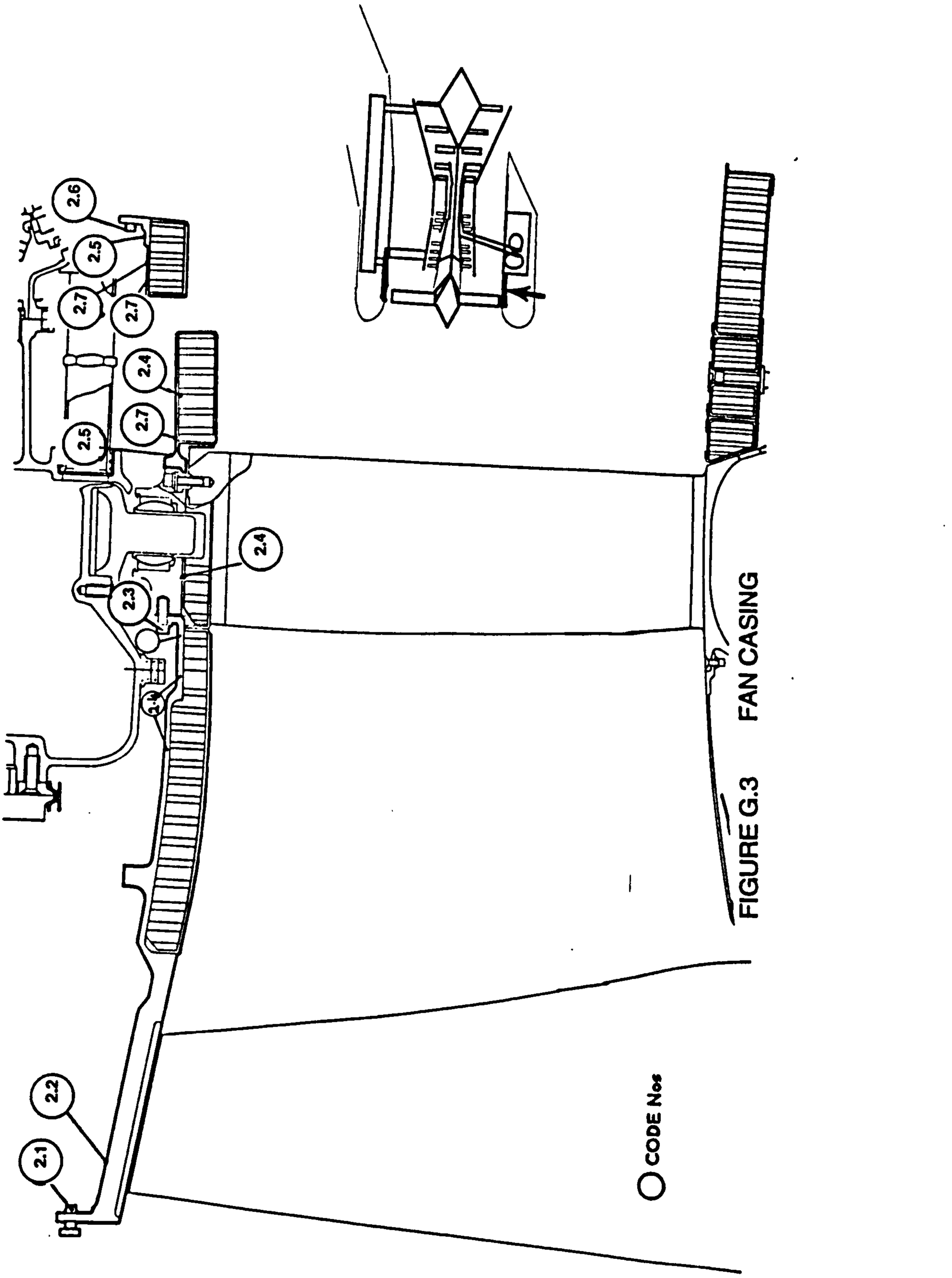



FIGURE G.3

THIS PAGE INTENTIONALLY BLANK

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 2.1 Inlet attachment flange | *Transmits loads between inlet and fan case* | Bolt loosening or fracture | Multiple adjacent bolt failure produces high loads on end-bolts, rapid successive bolt failures. | Rapid separation of joint, inlet distortion | IFSD, surge | *Major* | <.01 | MISC 61 |
| | | | | Inlet release/ ingestion. Fan blade damage and unbalance. | IFSD | *Major* | <.005 | MISC 61 |
| | | | | Fan disc failure | IFSD Uncont'd failure | *Hazardous* | <.001 | MISC 61 |
| 2.2 Fan case | *Transmits loads between airframe (via front mount) and inlet, thrust reverser, and engine rotors (via bearings, OGVs and A-frame) Supports external gearbox and accessories. Blade containment* | Fatigue cracking | Casing rupture and inlet displacement. | Inlet distortion. | IFSD, surge | *Minor* | <.01 | MISC 61 |
| | | | | Detachment or break-up and ingestion of inlet. Fan blade damage and unbalance. | IFSD | *Major* | <.005 | |
| | | | | Fan disc failure | IFSD Uncont'd failure | *Hazardous* | .001 | |
| | | | Cracking around front mount link. | Engine drops until load carried on thrust link fail-safe pin. | Vibration | *Minor* | 1 | SER 90074 Iss 1, SER 90074 Iss 2 |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 2.2 Fan case (continued) | | Fatigue | Cracking around gearbox mounts. | Gearbox drops and accessory drive disconnects. Leakage of fuel and oil from broken lines | IFSD | *Major* | .01 | SER 90074 Iss 1, SER 90074 Iss 2 |
| | | | Major cracking impairing structural load path | Casing flexure, shaft/bearing misalignment | IFSD | *Major* | | SER 90074 Iss 1, SER 90074 Iss 2 |
| | | Impact by released fan-blade | Casing penetrated locally | Load path through casing maintained | IFSD Uncontained failure | *Hazardous* | <.01 | SER 90074 Iss 1, SER 90074 Iss 2 |
| 2.3 Fan case rear flange | *Transmits loads from OGV outer support ring* | Bolt loosening or fracture | Multiple adjacent bolt failure produces high loads on end-bolts, rapid successive bolt failures. | Loss of fan case radial location, fan blade tip rubs. Fan blade damage, unbalance. | IFSD | *Minor* | .01 | MISC 61 |
| | | | | Fan disc failure | IFSD Uncontained failure | *Hazardous* | <.01 | MISC 61 |



*CONTAINS RR PROPRIETARY DATA*

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 2.4 Noise attenuation liners | *Attenuates fan-generated noise* | Separation | Detached liners proceed aft under aerodynamic loads | Impact damage to OGVs, OGV distortion under load. | IFSD | *Minor* | 1 | MISC 61 |
| | | | | Impact damage to fanblades, unbalance. | IFSD, surge | *Minor* | 1 | MISC 61 |
| 2.5 Bypass duct | *Guides fan air to cold nozzle, producing thrust.* | Fatigue | Major cracking produces casing rupture | Thrust reverser loses location and becomes displaced. | Surge. IFSD. Thrust misalignment | *Minor* | <.02 | MISC 61 |
| | | | | Disconnection of gearbox drive. | Loss of fuel supply, IFSD | *Major* | <.004 | |
| | | | | Casing flexure, fan blade tip rubs, fan blade damage. Unbalance. | IFSD | *Major* | <.02 | |
| | | | | Fan disc failure | Uncont'd failure, IFSD | *Hazardous* | <.0001 | |

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 2.6 Bypass duct aft flange | *Attaches thrust reverser to bypass duct* | Bolt loosening or fracture | Multiple adjacent bolt failure produces high loads on end-bolts, rapid successive bolt failures. | Loss of location of thrust reverser and LP final nozzle. | IFSD | *Major* | <.01 | MISC 61 |
| | | | | Bypass duct distortion. Overloading of OGVs | | *Major* | <.01 | MISC 61 |
| | | | | Fan blade tip rubs, unbalance. | IFSD | *Minor* | <.005 | MISC 61 |



*CONTAINS RR PROPRIETARY DATA*

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 2.7 U-assembly | Transmits loads from bypass duct to intermediate casing | Fatigue | Major cracking from axial welded joints | Loss of location of thrust reverser and LP final nozzle. | IFSD | *Minor* | <.01 | MISC 61 |
| | | | | Bypass duct distortion. | | *Minor* | <.01 | MISC 61 |
| | | | | Casing rupture | IFSD | *Hazardous* | <.02 | MISC 61 |
| | | | | Fan blade tip rubs, unbalance. | | | | |
| | | | | Fan disc failure. | Uncontained | *Hazardous* | .00001 | MISC 61 |
| | | | | External gearbox drive loss, no fuel supply | IFSD | *Major* | .002 | MISC 61 |
| | | | Major cracking from circumferential welded joints | Effects as for cracking of axial joints above | IFSD | *Minor* | .04 | MISC 61 throughout |
| | | | | | IFSD | *Minor* | .04 | |
| | | | | | Uncont'd | *Hazardous* | .00002 | |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 2.8 Splitter | *Separates core air from bypass air* | Fatigue | Skin cracking and detachment | Damage to fan OGVs. Loss of axial location of splitter nose, fan blade damage. | IFSD | *Minor* | 30 | MISC 61 |
| | | | | Damage to IP compressor blades | IFSD, surge | *Major* | 50 | MISC 61 |
| | | | Bonded joint failure at skin/ splitter nose and skin/splitter rear support ring joints. Skin separates. | Damage to fan OGVs. Loss of axial location of splitter nose, fan blade damage. | IFSD | *Minor* | 300 | MISC 61 |
| | | | | Damage to IP compressor blades | IFSD, surge | *Major* | 500 | MISC 61 |
| | | Fret-tage | Nose spigot loses location, failure of splitter nose | Damage to IP compressor blades | IFSD, surge | *Major* | 100 | MISC 61 |
| 2.9 Radial set screws | *Retain splitter* | Loosening or fracture | Failure of multiple set screws allows splitter deflection under aerodynamic loads | Skin breakup, damage to OGVs and to IP compressor blading | IFSD, surge | *Major* | <.01 | MISC 61 |



*CONTAINS RR PROPRIETARY DATA*

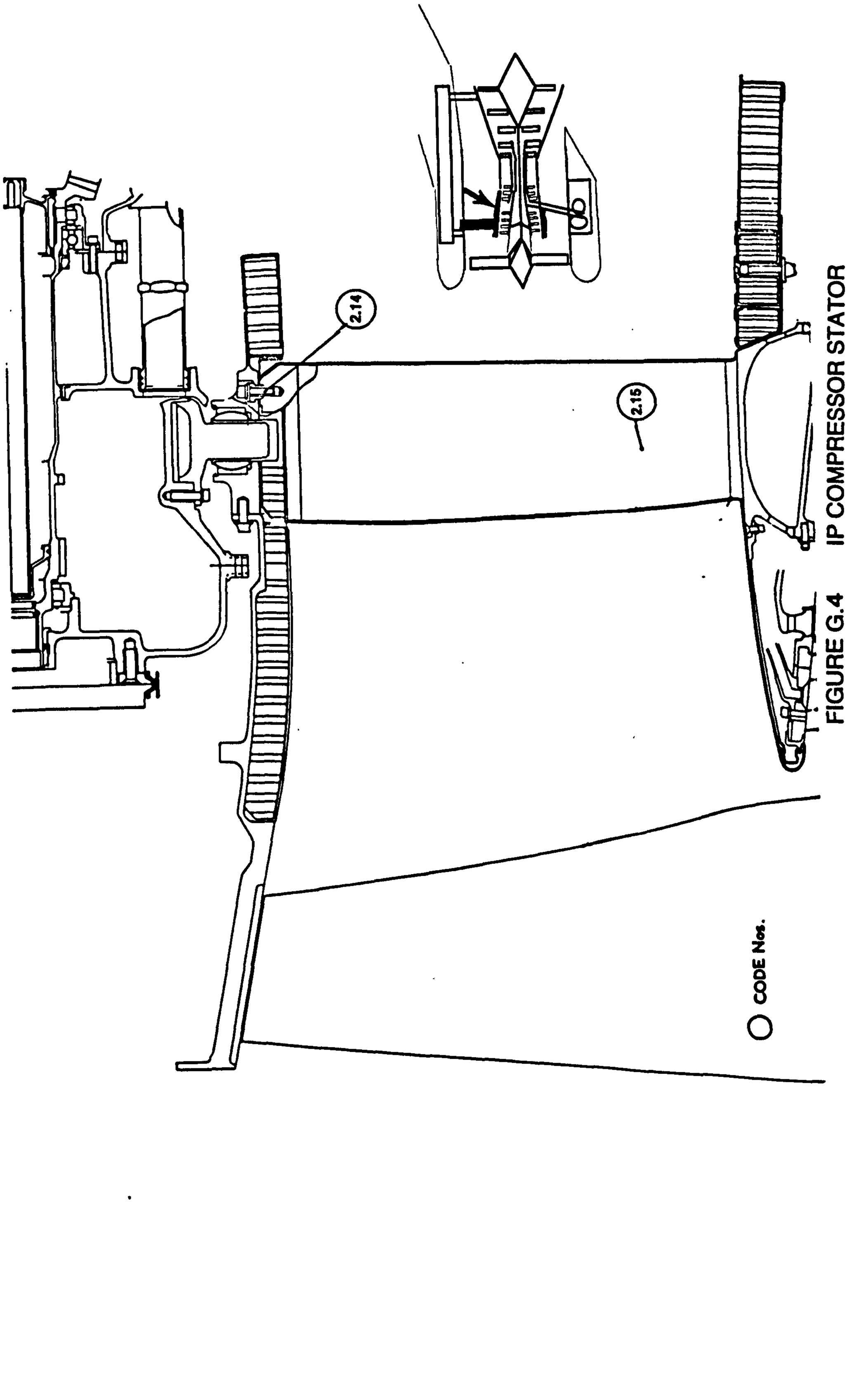



FIGURE G.4

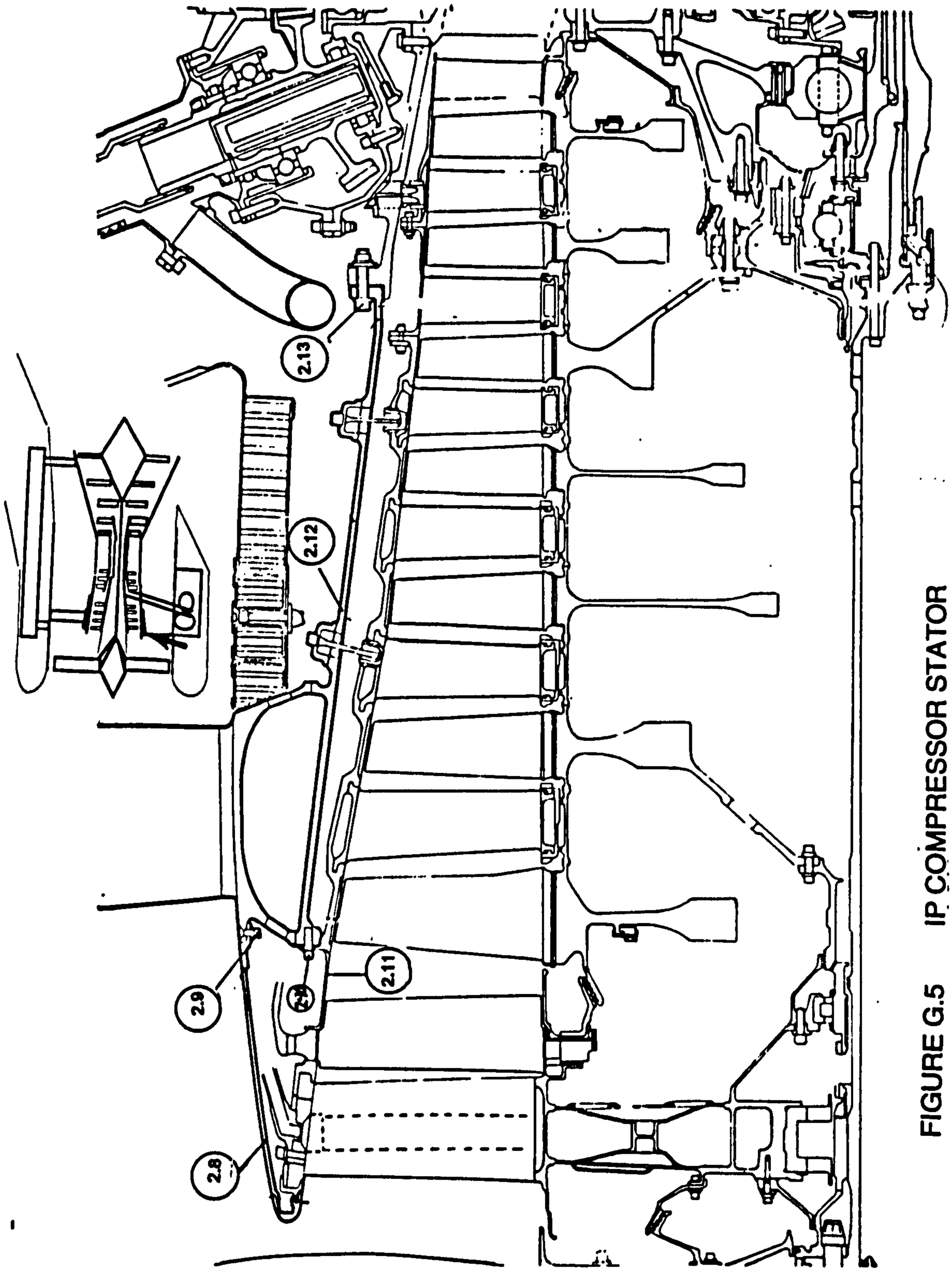



FIGURE G.5 IP COMPRESSOR STATOR

○ CODE Nos.

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 2.10 IP compressor case flange | *Mounting point for OGVs, transmitting loads from core to fan case* | Bolt loosening or fracture | Multiple adjacent bolt failure produces rapid progressive failure and joint separation | Loss of location of front bearing housing structure. LP and front of IP compressor whirl, rotor blade break-up and bearing failure | IFSD | *Major* | <.01 | MISC 61 |
| | | | | LP or IP disc failure | IFSD, uncontained failure | *Hazardous* | <.01 | MISC 61 |
| 2.11 IP IGV outer support casing | *Forms load path between IP IGVs and fan OGVs. Forms outer wall of core gas path* | Fatigue | Circumferential cracking adjacent to flange. Casing rupture | Misalignment of IP and LP shafts and bearings, rotor blade break-up and bearing failure. | IFSD | *Major* | <.016 | MISC 61 |
| | | | | LP or IP disc failure | IFSD, uncontained failure | *Hazardous* | <.01 | MISC 61 |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 2.12 IP outer casing | *Forms load path between IP IGV outer support casing (2.11) and LP OGVs Blade containment* | Fatigue | Major circumferential cracking adjacent to flange leading to casing failure. | Casing rupture and leakage of IP delivery air into zone 2. | | | | |
| | | | | Distortion of fan OGV inner support ring, fan blade tip rubs. | IFSD | *Major* | <.02 | MISC 61 |
| | | | | Engine casing flexing, shaft and bearing misalignment | IFSD | *Major* | <.02 | MISC 61 |
| | | | | Blade break-up and unbalance. | IFSD | *Major* | <.016 | MISC 61 |
| | | | | LP and IP disc failure | IFSD, uncontained failure | *Hazardous* | <.01 | |

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 2.12 continued | | Fatigue | Major cracking of axial welded joints | Casing rupture and leakage of IP air to zone 2. | | | | MISC 61 |
| | | | | Engine casing flexing, shaft and bearing swash | IFSD | *Major* | <.01 | |
| | | | | Blade break-up and unbalance. | IFSD | *Major* | <.008 | |
| | | | | LP and IP disc failure | Uncontained | *Hazardous* | <.001 | |
| | | | | Misalignment of accessory gearbox drive. Loss of fuel supply | IFSD | *Major* | <.06 | |
| | | | Major cracking of circumferential welded joints | As for cracking of axial joints above. | IFSD | *Major* | <.01 | |
| | | | | | IFSD | *Major* | <.008 | |
| | | | | | Uncont'd | *Hazardous* | <.001 | |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 2.13 IP outer casing rear flange | *Bolts to compressor intermediate casing* | Loosening or fracture | Multiple adjacent bolt failure produces rapid progressive failure and joint separation | Leakage of IP delivery air into zone 2. Loss of load path for main engine carcase, severe rotor damage. | IFSD | *Major* | <.01 | MISC 61 |
| | | Fatigue | Circumferential cracking leading to casing failure | Casing rupture and leakage of IP delivery air | IFSD | *Minor* | <.02 | MISC 61 |
| | | | | Engine casing flexing, shaft misalignment | IFSD | *Major* | <.018 | |
| | | | | Rotor unbalance. | IFSD | *Hazardous* | <.016 | |
| | | | | LP and IP disc failure | Uncontained | | <.01 | |
| | | | | Misalignment of accessory drive. | IFSD | *Major* | <.012 | |
| | | | | Loss of fuel supply | | | | |
| | | | | Explosive casing rupture | IFSD | *Major* | <.002 | |



*CONTAINS RR PROPRIETARY DATA*

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 2.14 Fan OGV outer bolts | *Transmit loads from engine core into outer support ring, to engine front mount* | Loosening or fracture | Multiple bolt failure reduces strength of OGV structure. | Flexure of front end of engine, fan blade tip rubs. | IFSD | *Minor* | <.01 | MISC 61 |
| | | | | Fan blade damage and unbalance. | IFSD | *Minor* | <.007 | |
| | | | | LP disc failure | Uncont'd failure, IFSD | *Hazardous* | <.01 | |
| 2.15 Fan OGV | *Transmits radial loads from stiff box-section inner ring of IPC outer case assembly to stiff flanged outer ring of fan casing* | Fatigue | Cracking in butt welds (multiple OGVs) | Flexure of front end of engine, fan blade tip rubs. | IFSD | *Minor* | 1 | MISC 61 |
| | | | | Fan blade damage and unbalance. | IFSD | *Minor* | .7 | |
| | | | | LP disc failure | Uncont'd | *Hazardous* | .01 | |
| | | | Cracking in aerofoil (multiple OGVs | Flexure of front end of engine, fan blade tip rubs. | IFSD | *Minor* | 5 | MISC 61 |
| | | | | Fan blade damage and unbalance. | IFSD | *Minor* | 2.5 | |
| | | | | LP disc failure | Uncont'd IFSD | *Hazardous* | .05 | |



CONTAINS RR PROPRIETARY DATA

THIS PAGE INTENTIONALLY BLANK

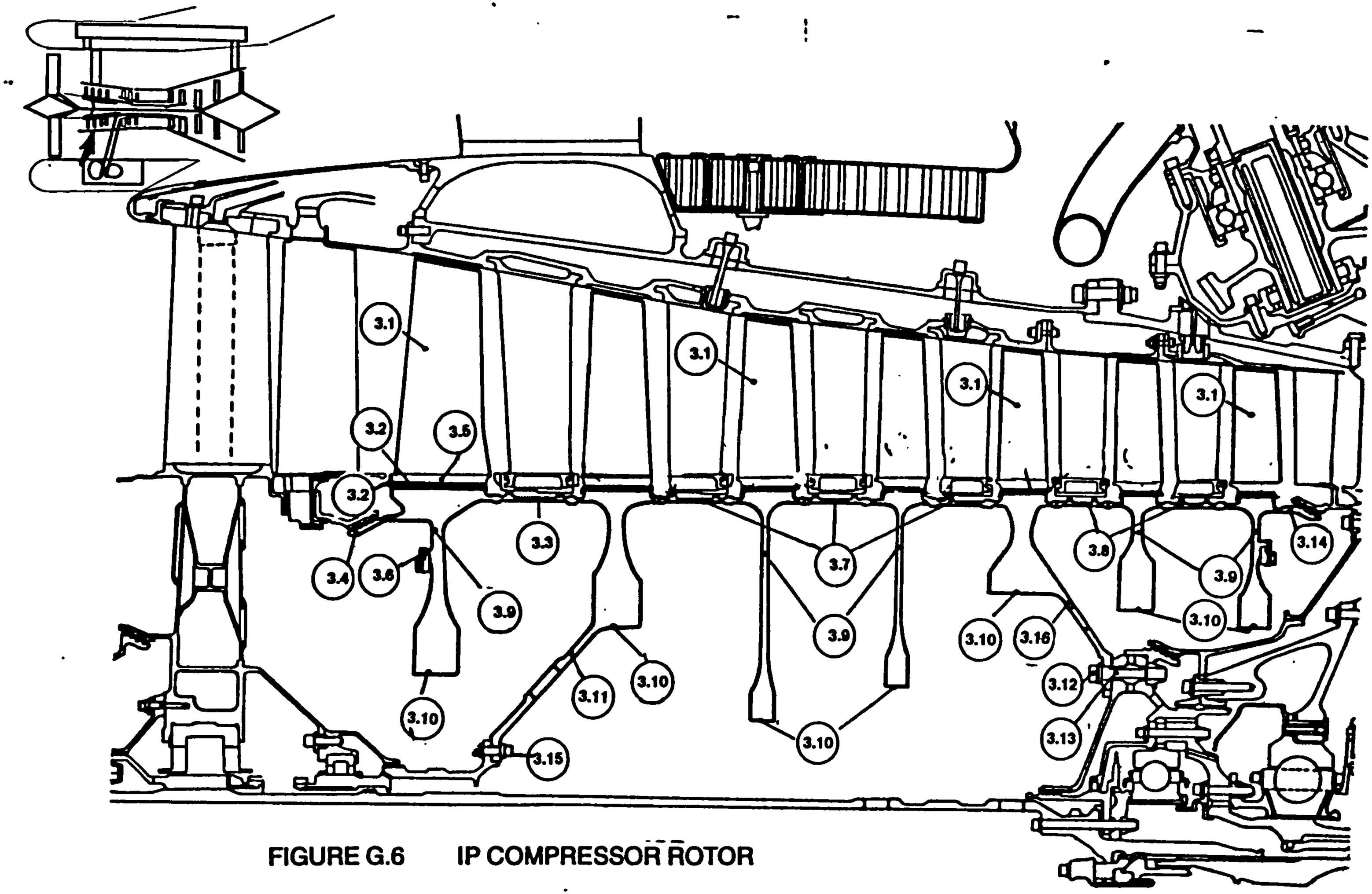



FIGURE G.6 IP COMPRESSOR ROTOR

○ CODE Nos.

THIS PAGE INTENTIONALLY BLANK

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 3.1 IP compressor blades (stages 1 to 7) | *Compress fan air* | Primary fatigue in aerofoil | Blade failure | Consequent damage to IP and HP rotors<br>Possible titanium fire | IFSD, surge.<br>Contaminated bleed air | *Major*<br>*Hazardous* | 600<br>12 | MISC 61 |
| | | Impact (FOD) | Blade failure | Consequent damage to IP and HP rotors<br>Possible titanium fire | IFSD, surge.<br>Contaminated bleed air | *Major*<br>*Hazardous* | 80<br>1.6 | MISC 61 |
| | | Fatigue excited by tip rub | Blade failure<br>Abradable liner release<br>OGV shroud ring failure | Consequent damage to IP and HP rotors<br>Possible titanium fire | IFSD, surge.<br>Contaminated bleed air | *Major*<br>*Hazardous* | 50<br>10 | MISC 61 |
| | | Fatigue in dovetail | Blade failure in dovetail | Consequent damage to IP and HP rotors<br>Possible titanium fire | IFSD, surge.<br>Contaminated bleed air | *Major*<br>*Hazardous* | 100<br>2 | MISC 61 |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 3.1 continued | | Fret-tage | Failure of blade root tang | Loss of axial location. Blades move forward and interfere with stators. Blade failure | IFSD, surge. | *Major* | 8 | MISC 61 |
| | | | | Possible titanium fire | Contaminated bleed air | *Hazardous* | .1 | |
| 3.2 Lockplates (stage 1 only) | *Prevent forward movement of blades out of disc slots* | Retaining tang distortion | Loss of blade axial location, rubbing against IGV inner support ring | Blade excitation and fatigue failure | IFSD, surge | *Major* | 50 | MISC 61 |
| | | | | Titanium fire | IFSD, contaminated bleed air | *Hazardous* | 1 | |
| 3.3 IP drum assembly 1st/2nd stage | *Transmits torque to 1st stage of compressor. Locates 1st stage axially and radially* | Fatigue | Cracking produces complete failure of drum between IP1 and IP2 discs. | Loss of 1st stage location. Rotor/stator rubbing and damage.. | IFSD | *Major* | 10 | MISC 61 |
| | | | | Unbalance may give IP/LP shaft rub and LP shaft failure. | IFSD. Uncontained failure | *Hazardous* | 1 | |



*CONTAINS RR PROPRIETARY DATA*

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 3.4 IP front rotating seal | *Seals between gaspath and compressor drum bore* | Fatigue excited by airflow or vibration | Seal rub and failure. | Damage to IP blading, oil leaks from bearing chamber. | IFSD | *Major* | 25 | MISC 61 |
| | | | | Seal crack extends into IP2 disc, disc failure | IFSD, uncontained failure | *Hazardous* | 1 | |
| 3.5 IP drum dovetails | *Transmit torque from drum to blades. Retain blades against centrifugal loads.* | Fatigue | Dovetail cracking and failure. | Release of 2 or more blades. | IFSD | *Major* | 20 | MISC 61 |
| | | | | Failure of disc rim sector. | IFSD. Possible uncontained failure | *Hazardous* | 20 | |
| | | | | Failure of complete disc rim | IFSD Uncontained failure | *Hazardous* | 1 | |
| 3.6 IP drum balance weight | *Permits drum balancing radially* | Fatigue | Release of weight | Disc damage. Unbalance | IFSD | *Major* | 1 | MISC 61 |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 3.7 IP drum spacers (stages 2 to 5) | *Transmit torque forward to front stages of compressor. Provide axial location for forward stages. Locate drum forward end radially* | Fatigue | Cracking and complete failure of an integral spacer | Unbalance. Compressor blade tip rubs. Flailing and deceleration of front end of drum. | IFSD, surge | *Major* | 10 | MISC 61 |
| | | | | LP shaft distortion. Bearing failures. | IFSD | *Major* | 7 | |
| | | | | IP turbine overspeed Titanium fire | IFSD Smoke in cabin bleed air | *Major Hazardous* | 1 .4 | |
| 3.8 IP drum spacers (stages 5 to 7) | *Transmit torque to rear compressor stages. Provide axial location for aft stages. Provide radial location for aft end of drum* | Fatigue | Cracking and complete failure of an integral spacer | Loss of location of 6th/7th stage discs. Unbalance, IPC blade damage. | IFSD | *Major* | 10 | MISC 61 |
| | | | | Deceleration of 6th/7th stage drum, IP/LP shaft rub and LP shaft failure. | IFSD, uncontained failure | *Hazardous* | 7 | |
| | | | | Titanium fire. | IFSD, smoke in bleed air | *Hazardous* | .4 | |



*CONTAINS RR PROPRIETARY DATA*

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 3.9 IP drum disc diaphragms | *Transmit radial loads between disc rim and disc bore* | Fatigue | Cracking in disc diaphragm. Local disc rim deflection | Disc disintegration. Possible casing penetration | IFSD Uncontained failure | *Major Hazardous* | 10<br>8 | MISC 61 |
| 3.10 IP drum disc bores | *Retain disc and blades against centrifugal loads* | Fatigue | Cracking in disc bore. Local disc rim deflection | Disc disintegration. Possible casing penetration | IFSD Uncontained failure | *Hazardous* | .01 | MISC 61 |
| 3.11 IP drum forward support cone | *Transmits radial loads between forward roller bearing and IP drum forward end* | Fatigue | Cracking and failure of support cone | Loss of drum radial location at forward end. Compressor blade and seal rubs<br>Bearing failure<br>Titanium fire | IFSD<br>IFSD Combustion products in bleed air | *Major*<br>*Major Hazardous* | 1<br>.8<br>.04 | MISC 61 |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 3.12 IP drum curvic coupling bolts | *Secure drum to stub-shaft. Transmit axial loads and radial loads from drum to location bearing.* | Loosening or fracture | Multiple bolt failure | Loss of drum radial location at aft end.<br>Compressor blade and seal rubs<br>Bearing failure<br>Titanium fire | IFSD<br><br><br>IFSD<br>Contaminated bleed air | *Major*<br><br>*Major*<br><br>*Hazardous* | .15<br><br>.006<br><br>.006 | MISC 61 |
| 3.13 Taper bolts | *Secure rotor drum to thrust bearing seal. Transmit torque to drum* | Loosening or fracture | Multiple bolt failure | Torque transmitted by curvic coupling bolts if all taper bolts fail.<br>Curvic bolt failure<br>Loss of drum aft radial location. Blade and seal rubs.<br>Bearing failure<br>Titanium fire | IFSD | *Major* | .035 | MISC 61 |
| 3.14 IP drum rear rotating seal | *Seals aft end of IP drum assembly preventing recirculation of IP delivery air into drum bore* | Fatigue | Crack propagation into disc. | IP7 disc failure<br>Casing penetration | IFSD<br>Uncont'd failure | *Major*<br>*Hazardous* | .7<br>.5 | MISC 61 |



*CONTAINS RR PROPRIETARY DATA*

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 3.15 IP drum front stubshaft bolts | *Transmit radial loads from front end of drum to stub shaft* | Fracture or fatigue | Multiple bolt failures | Loss of drum radial location at forward end. Compressor blade and seal rubs | IFSD | *Major* | .1 | MISC 61 |
| | | | | Bearing failure Titanium fire | IFSD Smoke in bleed air | *Major* *Hazardous* | .08 .004 | |
| 3.16 IP drum stage 5 conical extension | *Transmits torque, radial and axial loads between drum and location bearing* | Fracture or fatigue | Cracking and failure disconnect IP compressor from location bearing and turbine. | IP drum orbiting and deceleration. IP and HP blade damage. IP turbine overspeed and burst. Titanium fire. | IFSD | *Major* | 1.5 | MISC 61 |
| | | | | | Uncontained | *Hazardous* | .04 | |
| | | | | | Smoke in bleed air | *Hazardous* | .04 | |



CONTAINS RR PROPRIETARY DATA

THIS PAGE INTENTIONALLY BLANK

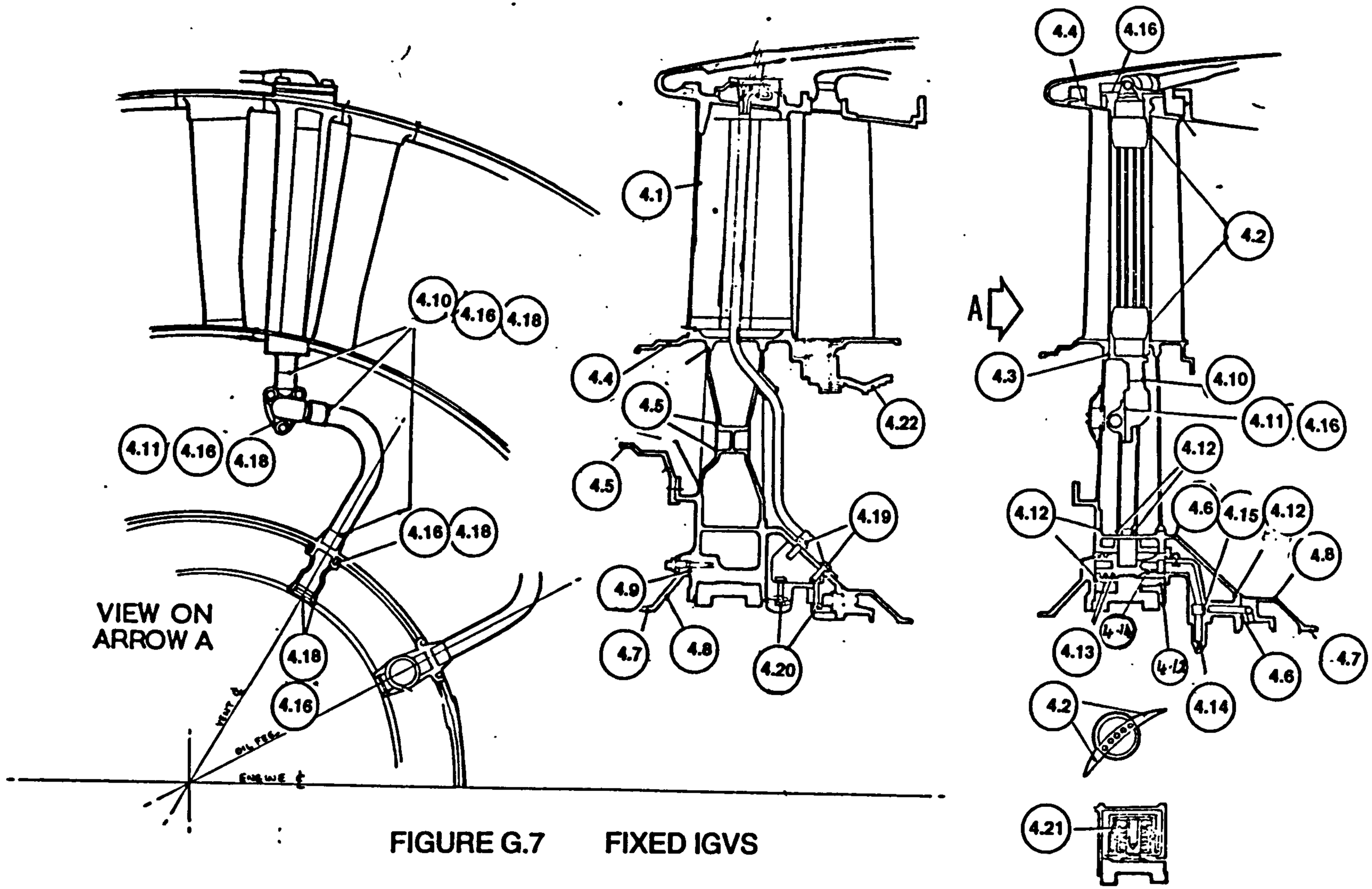



FIGURE G.7 FIXED IGVS

○ CODE Nos.

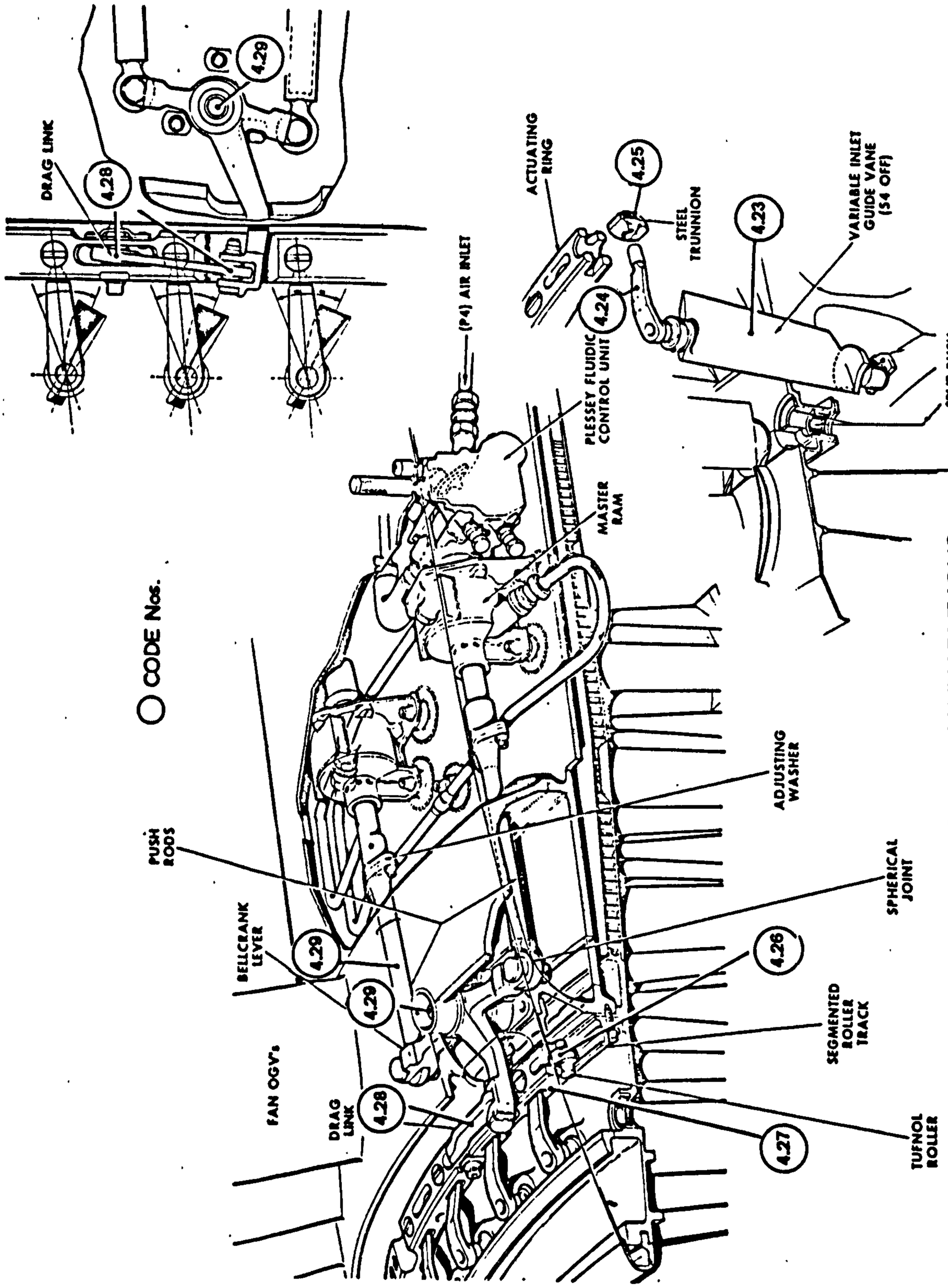



FIGURE G.8 VARIABLE IGVS

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 4.1 Compressor inlet guide vanes | *Transfer radial loads from fan and IP roller bearings to IP casing. Guide air into IP compressor.* | Fatigue in inner or outer weld | Vane cracking and loss of sections of vane. | Secondary damage to IP compressor. | IFSD | *Major* | 150 | MISC 61 |
| | | | Multiple vane cracking. Annulus filler release into IP compressor | Reduced strength of front bearing support. Heavy blade rubs. Fracture of oil pipes, oil loss. | IFSD | *Major* | 10 | |
| | | Impact (FOD) | Multiple vane failure or distortion. | | IFSD | *Major* | 10 | |
| | | | | Reduced strength of front bearing support. Heavy blade rubs. | IFSD | *Major* | 1 | |
| | | | | Fracture of oil pipes, oil loss. | IFSD | *Major* | 1 | |
| | | Support tube braze fatigue | Partial loss of vane | Secondary damage to IP and HP compressor | IFSD | *Major* | 1 | MISC 61 |
| | | Weld fatigue at vane plat-forms | Multiple vane cracking | Reduced strength of front bearing support. Heavy blade rubs | IFSD | *Minor* | .02 | MISC 61 |
| | | | | Loss of oil | | *Major* | .01 | |

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 4.2 Compressor IGVs carrying oil feed lines | *As 4.1, plus transfer oil feed across gas path* | Fatigue | Cracking in aerofoil (leading or trailing edge). | Secondary damage to IP compressor. | IFSD | *Major* | 7.5 | MISC 61 |
| | | | Partial loss of a vane. Multiple vane failure | Reduced structural strength of front bearing support. Heavy blade rubs. | IFSD | *Major* | .5 | |
| | | | | Fracture of oil pipes, loss of oil. | IFSD | *Major* | .5 | |
| | | Fatigue | Cracking of oil tube welds to end fittings | Loss of oil feed to fan and IP roller bearings. Oil leakage into IP compressor. | | | | |
| | | | | Bearing failure | IFSD | *Major* | .2 | |
| | | | | Tubes ingested into IP compressor with secondary damage | IFSD | *Major* | .2 | |
| 4.3 Compressor IGVs carrying oil vent and scavenge lines | *As 4.1, plus transfer oil vent and scavenge across gas path* | Fatigue | Cracking of oil tube welds to end fittings | Oil leakage into IP compressor. | IFSD | *Minor* *Major* | 6 | |
| | | | | Tubes ingested into IP compressor with secondary damage | IFSD | | 1.2 | |

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 4.4 Outer stiffening ring | *Supports outer ends of inlet guide vanes* | Fatigue | Cracking in vane weld to stiffening ring | Reduced stiffness in bearing support structure. Vibration, fan blade tip rubs, seal rubs, oil loss | IFSD | *Minor* | <.01 | MISC 61 |
| | | | Cracking in vane weld to outer casing | Effects as above | IFSD | *Minor* | .01 | |
| 4.5 Inner support panel assembly | *Box-section supporting inner ends of IGVs* | Fatigue | Cracking in weld of annulus or hub | Reduced stiffness in bearing support structure. Bearing misalignment, vibration. Fan blade and IP blade tip rubs, seal rubs, oil loss | IFSD | *Minor* | .01 | MISC 61 |
| | | Fatigue | Cracking of welds at panel connections | Unsupported panel sections part, allowing cracking of welds at annulus or hub (see above) | IFSD | *Minor* | .01 | MISC 61 |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 4.5 continued | | Fatigue | Front air seal carrier failure | Leakage of bearing chamber pressure air and oil leak from front bearing seal | IFSD | *Minor* | 1 | MISC 61 |
| | | Wear | Front air seal loses wear-away coating | Oil leakage from front bearing seal | IFSD | *Minor* | 7 | MISC 61 |
| | | Loosening or fracture | Cover plate nut or plate shank fails. Coverplate detachment. | Leakage of bearing chamber pressure air, oil leak. Air recirculation into IP intake. | IFSD | *Minor* | 1 | |
| 4.6 Hub assembly | *Transfers radial loads from front bearing outward* | Fatigue | Cracking of rear cone weld | Reduced stiffness of IP bearing support. IP blade rubs. | IFSD | *Minor* | .001 | MISC 61 |
| | | | | Rub between IP and LP shaft | IFSD | *Major* | .001 | |
| 4.7 and 4.8, Front and rear seals | *Form outer sealing surface for IP bearing chamber forward and rear seals* | Fatigue | Seal cracking and deflection | Oil leakage from bearing chamber | IFSD | *Minor* | .01 | MISC 61 |
| | | Wear | Loss of wear-away coating in seal bore | Oil leakage from bearing chamber | IFSD | *Minor* | 10 | |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 4.9 Bolt | *Secures LP bearing retaining plate /front oil seal to housing* | Loosening | Loss of clamping load and leakage through joint face | Oil leakage from squeeze film into IP sealing air. | IFSD | *Minor* | .2 | MISC 61 |
| 4.10 Oil feed pipe | *Transfers oil across bearing housing to bearing chamber* | Fatigue | Cracking in weld | Oil leakage into IPC air, reduced oil flow to LP /IP bearings.<br>Bearing failure | IFSD<br>IFSD | *Minor*<br>*Major* | .1<br>.05 | MISC 61 |
| 4.11 Oil feed sealing ring | *Seals feed pipe joint against oil leakage* | Vibration or rubber deterioration | Oil leakage past ring | Oil leakage into IPC air, reduced oil flow to LP and IP bearings.<br>Bearing failure | IFSD<br>IFSD | *Minor*<br>*Major* | .1<br>.05 | MISC 61 |
| 4.12 Oil transfer body | *Conducts oil from feed pipe to oil jet* | Vibration | Braze failure | Reduced support to jet body permitting vibration and jet failure. Oil loss. | IFSD | *Minor* | .01 | MISC 61 |
| 4.13 Filter sealing rings | *Seals transfer body joint against oil leakage* | Vibration or rubber aging | Oil leakage past sealing ring | Oil leakage into IP sealing air | IFSD | *Minor* | 1 | MISC 61 |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 4.14 In-line oil filter | *Prevents debris in oil line reaching bearings* | Block-age | Reduced oil flow to fan front bearing and IP roller bearing | Bearing failure | IFSD | *Major* | 1 | MISC 61 |
| 4.15 Oil jet | *Directs oil flow at bearings* | Block-age | Reduced oil flow to fan front bearing and IP roller bearing | Bearing failure | IFSD | *Major* | 1 | MISC 61 |
| | | Loosening | Leakage at spigot fitting to oil transfer body | Uncontrolled leakage of oil into bearing chamber, exceeding scavenge capacity. Oil leakage into IP sealing air. | IFSD | *Minor* | .5 | |



*CONTAINS RR PROPRIETARY DATA*

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 4.16 Oil vent pipe | *Controls bearing chamber air pressure (vent air exhausted through vent pipe)* | Fatigue | Cracking of weld at inner fitting or expansion pipe | IP sealing air leakage into vent pipe. Rise in bearing chamber pressure, oil leakage into IP sealing air | IFSD | *Minor* | .4 | MISC 61 |
| | | Vibration or degradation of sealing rubber | Leakage of expansion pipe outer end fitting | IP sealing air leakage into vent pipe. Rise in bearing chamber pressure, oil leakage into IP sealing air | IFSD | *Minor* | .4 | MISC 61 |
| | | Vibration | Braze failure of standpipe at hub (outer end) | IP sealing air leakage into bearing chamber. Rise in bearing chamber pressure, oil leakage into IP sealing air | IFSD | *Minor* | .2 | MISC 61 |
| 4.17 not used | | | | | | | | |

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 4.18 Oil scavenge pipe | *Transfers oil from bearing chamber to oil scavenge system* | Vibration | Cracking of weld at inner fitting or expansion pipe | IP sealing air leakage into scavenge pipe. Rise in bearing chamber pressure, oil leakage into IP sealing air | IFSD | *Minor* | .4 | MISC 61 |
| | | Vibration or degradation of sealing rubber | Leakage of expansion pipe outer end fitting | IP sealing air leakage into scavenge pipe. Rise in bearing chamber pressure, oil leakage into IP sealing air | IFSD | *Minor* | .4 | MISC 61 |
| | | Vibration | Braze failure of standpipe at hub (outer end) | IP sealing air leakage into bearing chamber. Rise in bearing chamber pressure, oil leakage into IP sealing air | IFSD | *Minor* | .2 | MISC 61 |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 4.19 Shaft speed probes; bolt /mounting block assembly | *Secures speed probe assembly to rear cone.* | Loosening or bolt fracture | Mounting block displacement. | Leakage of IP air into bearing chamber, oil leakage into IP air. Probes or block damage oil jets, starving bearings of oil. Bearing failure | IFSD | *Major* | .1 | MISC 61 |
| | | | Breakage of wires to speed probes. | | IFSD | *Minor* | .15 | |
| 4.20 Shaft speed probes; bolt /insert | *Secures probes to mounting block* | Loosening | Setscrews lose locking. Probes move relative to mounting block | Probes damage oil jets, starving bearings of oil. Bearing failure | IFSD | *Major* | .15 | MISC 61 |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 4.21 Support shoe spring assembly | *Maintains shaft centring at low speeds and with normal out-of-balance.* | Spring load loss | Shaft runs off-centre at low speed. | Seal rubs. Vibration. | IFSD | *Minor* | .1 | MISC 61 |
| 4.22 IP front air seal | *Seals IP rotor bore from gaspath* | Wear | Seal clearance opens up | Upset pressure balance across bearing chamber. Oil leak into IP compressor air. Cabin air contamination | IFSD Cabin smoke | *Hazardous* | 5 | MISC 61 |
| | | | | Excitation of disc rotating seal, damage to IP blading | IFSD | *Major* | .1 | MISC 61 |



*CONTAINS RR PROPRIETARY DATA*

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 4.23 Variable inlet guide vane | *Rotates to maintain swirl angle of IPC air at different engine conditions, preserving stall margin.* | Fatigue | Aerofoil cracking, loss of portion of vane. | Secondary damage to IP compressor blading | IFSD, surge | *Major* | 50 | MISC 61 |
| 4.24 Vane operating lever | *Transfers torque from trunnion and actuating ring to vane, turning vane on its axis.* | Fatigue | Lever cracking and failure | Loss of control for single vane, local airflow disturbance | Surge, IFSD | *Minor* | .01 | MISC 61 |
| 4.25 Trunnion | *Locates ring-end of vane actuating lever, converting circumf'l ring movement into angular lever movement* | Jamming | IGVs remain locked at -7.5° or +37.5°, depending on engine condition at which jamming occurred | IP compressor surge on power change, or choked flow and low engine power | Surge, IFSD | *Minor* | 10 | MISC 61 |
| 4.26 Rollers | *Support actuator ring on roller track* | Roller skidding on track | Jamming of roller in ring and in roller track. | IGVs no longer accurately controlled by pneumatic ram position | Surge, IFSD | *Minor* | <.09 | MISC 61 |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 4.27 Actuating ring | *Drives IGVs in unison, in response to pneumatic ram position.* | Fatigue | Ring cracking and failure | IGVs no longer accurately controlled by pneumatic ram position | Surge, IFSD | *Minor* | 10 | MISC 61 |
| 4.28 Driving link | *Drives rotation of ring in response to bell crank movement* | Fatigue | Link cracking and failure | IGVs no longer controlled by pneumatic ram position | Surge, IFSD | *Major* | <.01 | MISC 61 |
| 4.29 Bell crank linkage | *Translates pneumatic ram position into circumferential movement of driving link* | Bolt loosening or fracture | Loss of location of bell crank lever. | Loss of IGV control | Surge, IFSD | *Major* | <.01 | MISC 61 |
| | | Fatigue | Failure of rod from ram | Loss of IGV control | Surge, IFSD | *Major* | <.01 | MISC 61 |



*CONTAINS RR PROPRIETARY DATA*

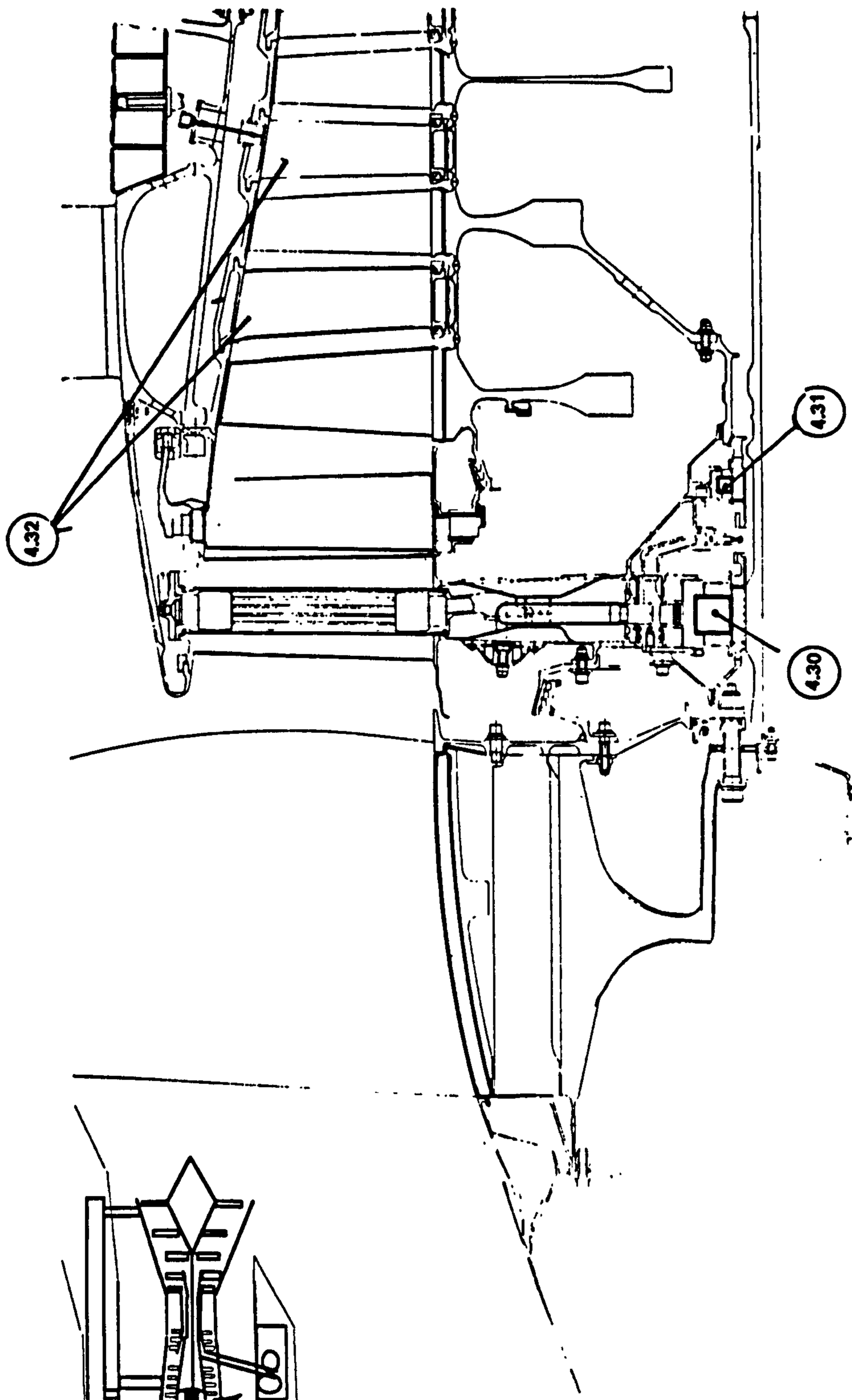



FIGURE G.9 LP AND IP COMPRESSOR FRONT ROLLER BEARINGS

○ CODE Nos.

THIS PAGE INTENTIONALLY BLANK

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 4.30 Fan front roller bearing | *Transfers radial loads from fanshaft to front bearing housing structure* | Fatigue | Break up of tracks and rollers | Air and oil seal rubs<br>Fan blade tip rubs<br>Oil loss from bearing chamber<br>Fanshaft rubs IP compressor front stub shaft<br>LP shaft failure | IFSD<br>IFSD<br>IFSD<br>IFSD<br>Uncontained failure | *Minor*<br>*Minor*<br>*Minor*<br>*Major*<br>*Hazardous* | 5<br>3.5<br>2.5<br><br><br><br><.05 | MISC 61 |
| | | Poor oil flow | Break up of tracks and rollers | Air and oil seal rubs<br>Fan blade tip rubs<br>Oil loss from bearing chamber<br>Fanshaft rubs IP compressor front stub shaft<br>LP shaft failure | IFSD<br>IFSD<br>IFSD<br>IFSD<br>Uncontained failure | *Minor*<br>*Minor*<br>*Minor*<br>*Major*<br>*Hazardous* | 20<br>14<br>4<br><br><br><br><.2 | |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 4.30 continued | | Roller skidding | Break up of tracks and rollers | Air and oil seal rubs | IFSD | *Minor* | 20 | MISC 61 |
| | | | | Fan blade tip rubs | IFSD | *Minor* | 14 | |
| | | | | Oil loss from bearing chamber | IFSD | *Minor* | 10 | |
| | | | | Fanshaft rubs IP compressor front stub shaft | IFSD | *Major* | .2 | |
| | | | | LP shaft failure | Uncontained failure | *Hazardous* | <.2 | |
| | | Fatigue | Cage or rivet failure | Air and oil seal rubs | IFSD | *Minor* | 20 | MISC 61 |
| | | | | Fan blade tip rubs | IFSD | *Minor* | 14 | |
| | | | | Oil loss from bearing chamber | IFSD | *Minor* | 10 | |
| | | | | Fanshaft rubs IP compressor front stub shaft | IFSD | *Major* | .2 | |
| | | | | LP shaft failure | Uncontained failure | *Hazardous* | <.2 | |



*CONTAINS RR PROPRIETARY DATA*

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 4.31 IP compressor front roller bearing | *Transfers radial loads from front of IP compressor rotor to front bearing housing support structure* | Fatigue | Break up of tracks or rollers | Air and oil seal rubs | IFSD | *Minor* | 5 | MISC 61 |
| | | | | IP compressor blade tip rubs | IFSD | *Minor* | 3.5 | |
| | | | | Oil loss from bearing chamber | IFSD | *Minor* | 2.5 | |
| | | | | IP compressor front stub shaft rubs fanshaft | IFSD | *Major* | .05 | |
| | | | | Fanshaft failure | Uncontained failure | *Hazardous* | .05 | |
| | | Poor oil flow | Break up of tracks or rollers | Air and oil seal rubs | IFSD | *Minor* | 20 | MISC 61 |
| | | | | IP compressor blade tip rubs | IFSD | *Minor* | 14 | |
| | | | | Oil loss from bearing chamber | IFSD | *Minor* | 4 | |
| | | | | IP compressor front stub shaft rubs fanshaft | IFSD | *Major* | 0.2 | |
| | | | | Fanshaft failure | Uncontained failure | *Hazardous* | <.02 | |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 4.31 continued | | Roller skidding | Break up of tracks and rollers | Air and oil seal rubs | IFSD | *Minor* | 20 | MISC 61 |
| | | | | IP compressor blade tip rubs | IFSD | *Minor* | 14 | |
| | | | | Oil loss from bearing chamber | IFSD | *Minor* | 10 | |
| | | | | IP compressor front stub shaft rubs fanshaft | IFSD | *Major* | .2 | |
| | | | | Fanshaft failure | Uncontained failure | *Hazardous* | <.2 | |
| | | Fatigue | Cage or rivet failure | Air and oil seal rubs | IFSD | *Minor* | 20 | MISC 61 |
| | | | | IP compressor blade tip rubs | IFSD | *Minor* | 14 | |
| | | | | Oil loss from bearing chamber | IFSD | *Minor* | 10 | |
| | | | | IP compressor front stub shaft rubs fanshaft | IFSD | *Major* | .2 | |
| | | | | Fanshaft failure | Uncontained failure | *Hazardous* | <.2 | |



*CONTAINS RR PROPRIETARY DATA*

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 4.32 Stators and OGVs | *Direct and compress core airflow* | Fatigue crack-ing | Loss of aerofoil. | Compressor rotor damage. Vibration | IFSD | *Minor* | 10 | SER 90074 Iss 1, SER 90074 Iss 2 |

CONTAINS RR PROPRIETARY DATA

THIS PAGE INTENTIONALLY BLANK

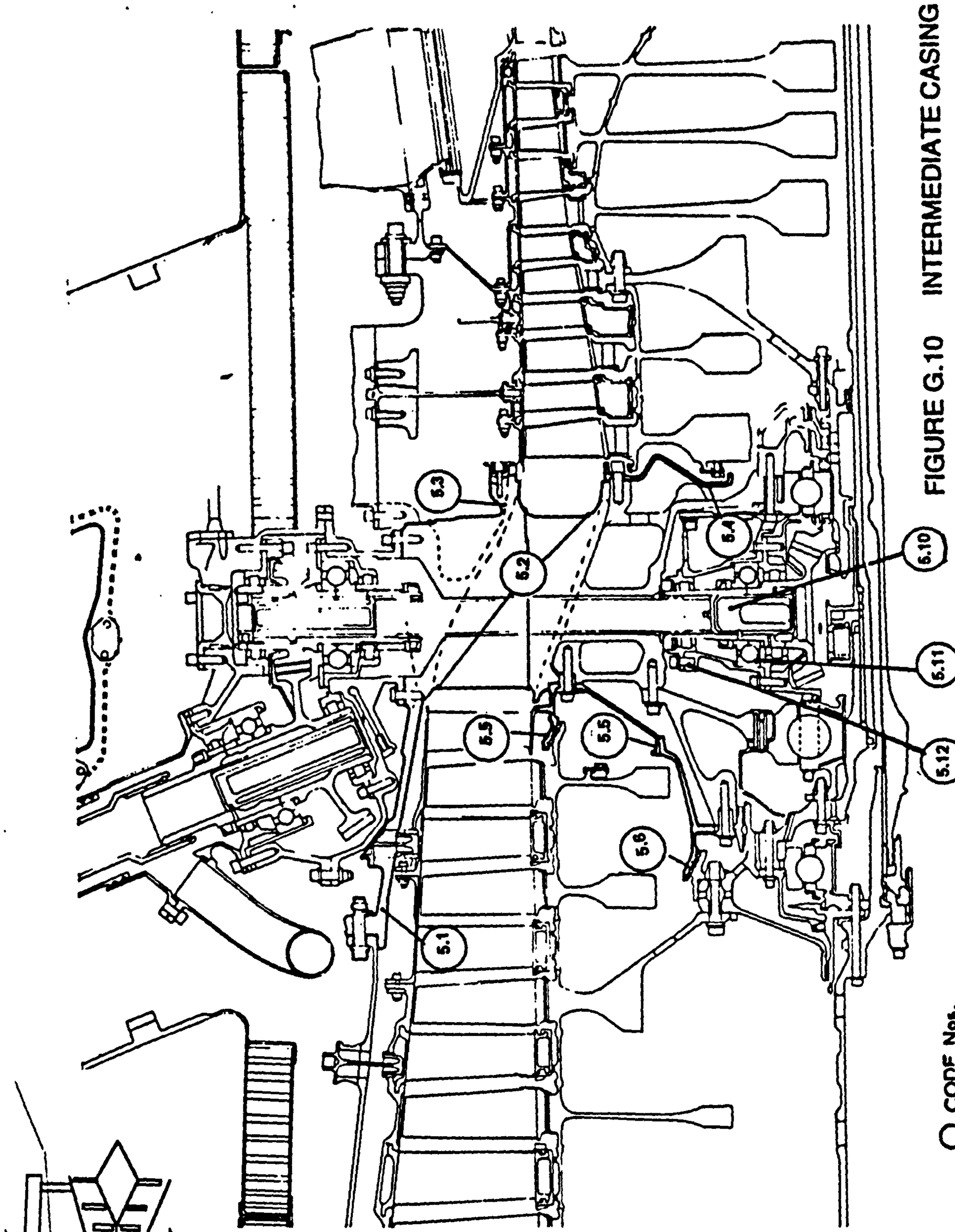



FIGURE G.10 INTERMEDIATE CASING

THIS PAGE INTENTIONALLY BLANK

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 5.1 Flange to IP compressor casing | *Transmits axial and torsional loads.* *Prevents compressor air leakage?* *Supports and locates accessory drive train* | Fatigue crack-ing circumf 'ly | Casing rupture | IP air leakage into zone 2 | IFSD | *Minor* | <.02 | MISC 61 |
| | | | Casing flexure | Misalignment of shafts and bearings, blade tip rubs. | IFSD | *Minor* | <.018 | |
| | | | | Severe blade damage. | IFSD | *Major* | <.014 | |
| | | | | Disc failure | Uncontai ned | *Hazardous* | <.002 | |
| | | | | Loss of gearbox drive | IFSD | *Major* | <.012 | |
| | | | | Explosive casing rupture | *Explosio n* | *Hazardous* | <.002 | |
| 5.2 Radial support struts | Stiffen casing by providing radial load path to internal gearbox | Fatigue | Cracking of strut | Crack propagating into oil feed drilling, resulting in oil loss | IFSD | *Minor* | 0.5 | MISC 61 |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 5.3 Flange to combustor casing | *Transmits axial and torsional loads. Prevents compressor air leakage?* | Fatigue crack-ing circumf'ly | Casing rupture | IP air leakage into zone 2 | IFSD | *Minor* | <.02 | MISC 61 |
| | | | Casing flexure | Misalignment of shafts and bearings, blade tip rubs. | IFSD | *Minor* | <.016 | |
| | | | | Loss of gearbox drive | IFSD | *Major* | .001 | |
| | | | | Explosive casing rupture | *Explosion* | *Hazardous* | .004 | |
| | | | | Loss of load path (engine thrust and aerodynamic loads) to rear mount. | *Engine separation* | *Hazardous* | .002 | |
| 5.4 IP air offtake air baffle | *Seals between IP air offtake and HP1 air* | Fatigue | Cracking and failure | Break-up of HP1 disc air seal, damage to compressor blading, increased temperature of IP cooling air, HP discs and IP shaft | IFSD | *Major* | 80 | MISC 61 |



*CONTAINS RR PROPRIETARY DATA*

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 5.5 IP7 disc stepped air seal (static) | *Seals IP7 air from drum bore* | Fatigue (bell mode) | Major cracking and failure, releasing fragments into gaspath | Compressor blade damage | IFSD | *Major* | 50 | MISC 61 |
| | | Fretting | Wear at inner diameter, leading to cracking and break-up of seal, releasing fragments into gaspath | Compressor blade damage | IFSD | *Major* | <5 | MISC 61 |
| 5.6 IP rotor inner air seal (static) | *Seals internal gearbox from IP drum bore, controlling airflow and preventing oil leakage* | Fatigue (bell mode) | Major cracking and failure, releasing fragments | Damage to compressor drum. Drop in pressure outboard of location bearing seal, oil leakage.<br>Internal oil fire | IFSD<br>Fire | *Major*<br>*Hazardous* | 25<br><.25 | MISC 61 |



CONTAINS RR PROPRIETARY DATA

THIS PAGE INTENTIONALLY BLANK

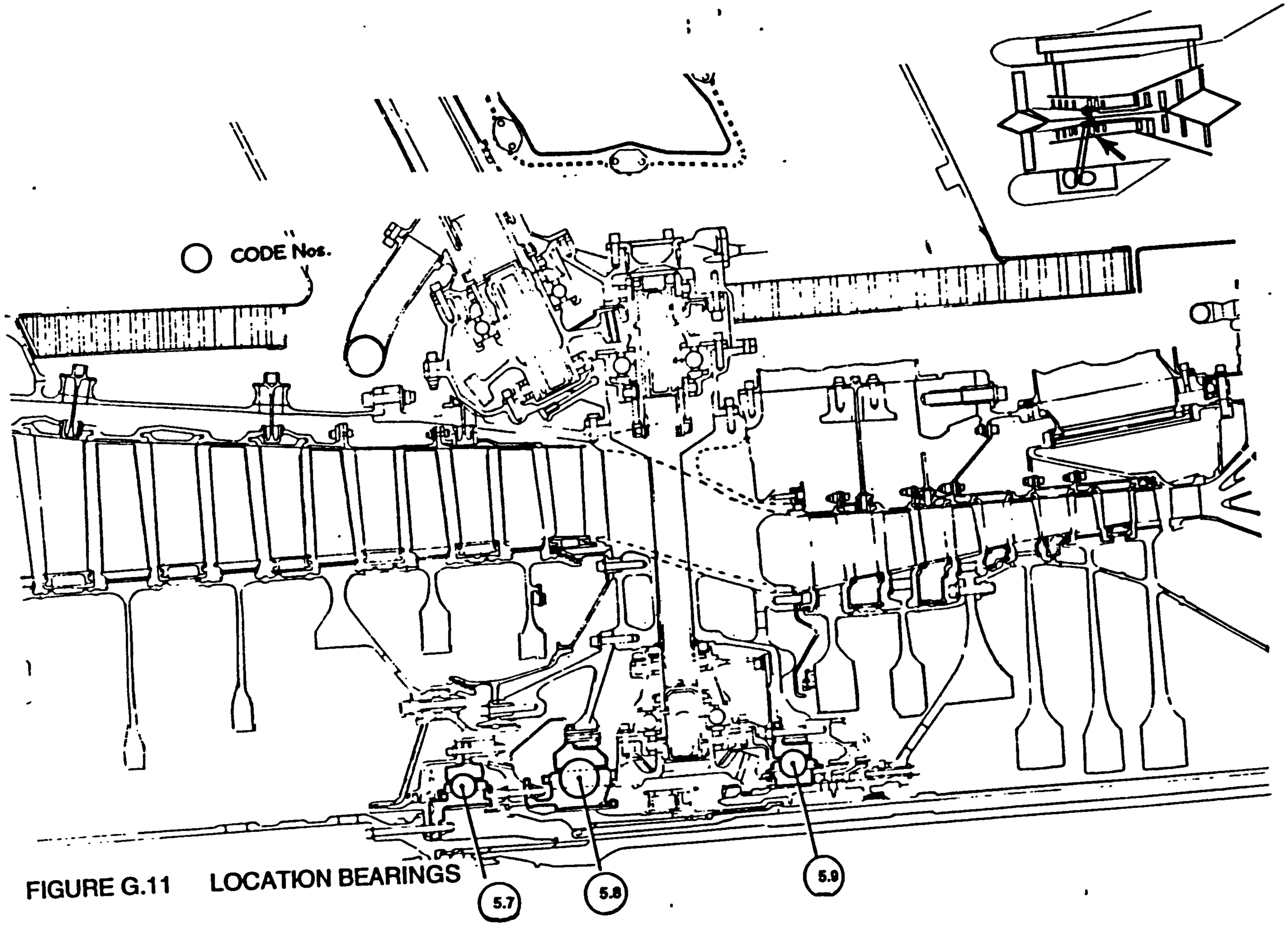



FIGURE G.11 LOCATION BEARINGS

THIS PAGE INTENTIONALLY BLANK

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 5.7 Fan location bearing | *Transmit axial loads from fan rotor to fan stator. Locate fanshaft radially at rear.* | Fatigue | Track or ball disintegration | Axial movement of fan and LP turbine, fouling static parts. | IFSD | *Major* | 10 | MISC 61 |
| | | | | Blade tip and seal rubs. Oil leaks into IP cooling air on shutdown, internal fire on restart. | Fire | *Major* | .5 | |
| | | | | LP to IP shaft rub, LP shaft overheating and failure. LP turbine overspeed and burst. Cowling disruption | Uncontained High aerodynamic loads | *Hazardous* | <.1 | |
| | | Poor oil flow | Track or ball disintegration | As above | As above | *As above* | 5<br>.25<br><.05 | As above |
| | | Skidding | Track or ball disintegration | As above | As above | *As above* | 1<br>.05<br>.01 | As above |
| | | Fracture | Cage or bolt failure | As above | As above | *As above* | 5<br>.25<br>.05 | As above |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 5.8 IP compressor location bearing | *Transmits axial loads from IP compressor rotor to IP stator. Locates compressor drum radially at rear.* | Fatigue | Track or ball disintegration | Axial movement of IP and LP rotors fouling static parts. Blade tip and seal rubs. Oil leaks into IP cooling air on shutdown, internal fire on restart. | IFSD | *Major* | 10 | MISC 61 |
| | | | | | Fire | *Major* | .5 | |
| | | | | IP to HP shaft rub, IP shaft overheating and failure. IP turbine overspeed and non-containment. Cowling disruption | Uncontained High aerodynamic loads | *Hazardous* | .1 | |
| | | Poor oil flow | Track or ball disintegration | As above | As above | As above | 5<br>.25<br>.05 | As above |
| | | Skidding | Track or ball disintegration | As above | As above | As above | 1<br>.05<br>.01 | As above |
| | | Fracture | Cage or bolt failure | As above | As above | As above | 5<br>.25<br>.05 | As above |



*CONTAINS RR PROPRIETARY DATA*

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 5.9 HP location bearing | *Transmit axial loads from HP rotor to static structure. Locate HP compressor drum radially at rear.* | Fatigue | Track or ball disintegration | Axial movement of HP rotor fouling static parts. | IFSD | *Major* | 10 | MISC 61 |
| | | | | Heavy gearbox loading, loss of fuel supply. Blade tip and seal rubs. Oil leaks into IP cooling air on shutdown, internal fire on restart. | IFSD | | | |
| | | | | | Fire | *Major* | .5 | |
| | | | | IP to HP shaft rub, IP shaft overheating and failure. IP turbine overspeed and non-containment. Cowling disruption | Uncontained | *Hazardous* | .1 | |
| | | | | | High aerodynamic loads | | | |
| | | Poor oil flow | Track or ball disintegration | As above | As above | As above | 5<br>.21<br>.05 | As above |
| | | Skidding | Track or ball disintegration | As above | As above | As above | 1<br>.05<br><.01 | As above |

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 5.9 HP location bearing (cont.) | As above | Fracture | Cage or bolt failure | As above | As above | As above | 5<br>.25<br>.05 | As above |



*CONTAINS RR PROPRIETARY DATA*

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 5.10 Shaft and drive | *Transmits torque to external gearbox, driving fuel and oil pumps and airframe accessories* | *Fatigue* | Drive failure | Loss of fuel supply to engine. Impaired electric and hydraulic power to airframe. | IFSD | *Minor* | 10 | SER 90074 Iss 1, SER 90074 Iss 2 |
| 5.11 Bearings of internal gearbox | *As above* | *Fatigue* | Bearing failure | As above. Oil fire | IFSD Fire | *Hazardous* | 10 | SER 90074 Iss 1, SER 90074 Iss 2 |
| 5.12 Seals and casing | *As above* | *Seal failure* | | Oil fire | IFSD Fire | *Hazardous* | 10 | SER 90074 Iss 1, SER 90074 Iss 2 |



CONTAINS RR PROPRIETARY DATA

THIS PAGE INTENTIONALLY BLANK

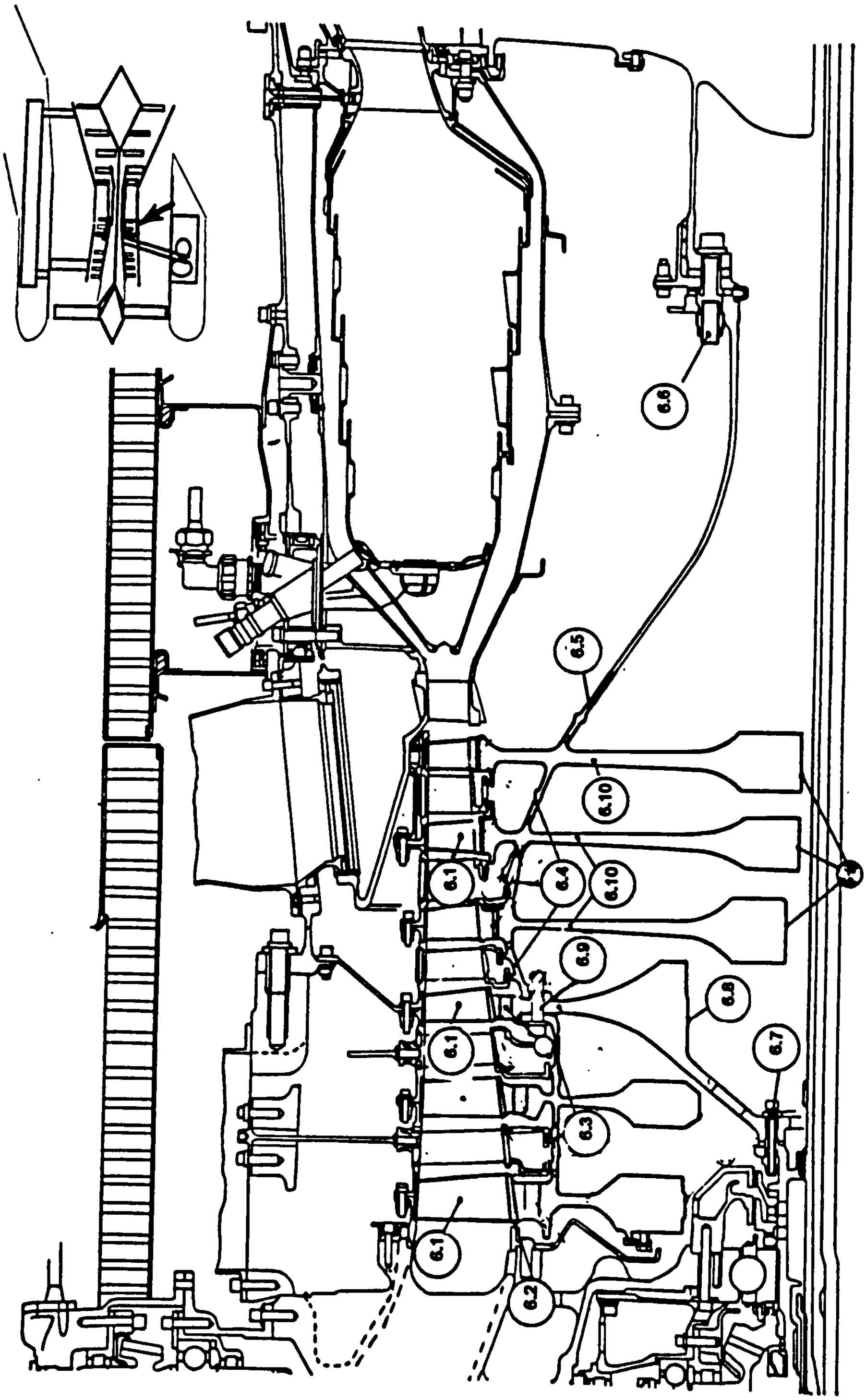



FIGURE G.12 HP COMPRESSOR ROTOR

THIS PAGE INTENTIONALLY BLANK

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 6.1 Compressor blades | *Compress core air* | Fatigue | Separation of aerofoil | HP compressor blade and casing damage.<br>Titanium fire | IFSD<br>Fire | *Major*<br>*Hazardous* | 600<br>200 | MISC 61 |
| | | Impact | As above | As above | As above | As above | 8<br>.16 | MISC 61 |
| | | Wear | Tip rubbing not accommodated by abradable liner.<br>Aerofoil separation. | HP compressor blade and casing damage.<br>Titanium fire | As above | *As above* | 5<br>1 | MISC 61 |
| | | Fatigue | Failure from dovetail | HP compressor blade and casing damage. | IFSD<br>Fire | *Major*<br>*Hazardous* | 100<br>2 | MISC 61 |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 6.2 Blade lockplates | *Prevent axial movement of blades in dovetails* | Fatigue | Lockplate failure or release | Axial movement of blades, fouling stators.<br>Titanium fire | IFSD<br>Fire | *Major*<br>*Hazardous* | 270<br>1 | MISC 61 |
| 6.3 HP drum spacer (stages 1 to 3) | *Transmits torque from HP shaft. Locates stages 1 and 2 radially.* | Fatigue | Major cracking and failure of spacer | Radial and forward movement of disc(s) to rub casing<br>Bearing failure. HP/IP shaft rub and IP shaft failure.<br>Titanium fire | IFSD<br>Uncontained<br>Fire | *Major*<br>*Hazardous*<br>*Hazardous* | 15<br>1.5<br>.3 | |



*CONTAINS RR PROPRIETARY DATA*

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 6.4 HP drum spacer (stages 3 to 6) | *Transmits torque from HP shaft. Locates stages 1 and 2 radially.* | Fatigue | Major cracking and failure of spacer | HP blading damage Flailing of drum parts and deceleration of front end of drum. Acceleration of rear end of drum and HPT | IFSD | *Major* | 15 | MISC 61 |
| | | | | HPC disc failure | Uncont'd | *Hazardous* | 4.5 | |
| | | | | HPT overspeed and disc burst | Uncont'd | *Hazardous* | 1.5 | |
| | | | | Titanium fire | Fire | *Hazardous* | .15 | |
| 6.5 Rear conical shaft extension | Locates aft end of compressor drum radially. Transmits torque to HP compressor | Fatigue | Cracking and failure of extension | HP blading damage Flailing and deceleration of drum. | IFSD | *Major* | 1 | MISC 61 |
| | | | | IP shaft rub and failure | | | .2 | |
| | | | | Acceleration and aft movement of HPT, HPT overspeed and disc burst | Uncontained | *Hazardous* | .1 | |
| | | | | Internal oil fire | Fire | *Hazardous* | .4 | |

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 6.6 HP drum curvic coupling bolts | *Secures rear shaft to HP turbine* | Fracture or fatigue | Multiple bolt failure | As above | As above | As above | .15<br>.09<br>.03<br>.06 | MISC 61 |
| 6.7 HP drum bolts | *Secure HP3 disc to front stubshaft* | Fatigue | Multiple bolt failure | Flailing of front end of HP rotor<br>Flailing and acceleration of rear end of drum and HP turbine<br>HP compressor disc failure<br>HP turbine overspeed and disc burst<br>Titanium fire | IFSD<br><br>Uncontained<br>Uncontained<br>Fire | *Major*<br><br>*Hazardous*<br>*Hazardous*<br>*Hazardous* | .1<br><br>.03.<br>.02<br>.001 | MISC 61 |



*CONTAINS RR PROPRIETARY DATA*

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 6.8 HP3 disc | *Retains HP3 blades against radial and axial loads. Transmits torque to forward drum. Locates front end of HP drum axially and radially* | Fatigue | Cracking at spacer spigot on rim, leading to spigot and bolt failure and failure of adjacent spacer. | HP blading damage. Flailing and deceleration of front end of drum. | IFSD | *Major* | 2 | MISC 61 |
| | | | | IP shaft rub and failure. | IFSD | *Major* | 1.4 | |
| | | | | HPC disc failure | Uncontained | *Hazardous* | .6 | |
| | | | | HPT overspeed and failure. | Uncont'd | *Hazardous* | .2 | |
| | | | | Titanium fire | Fire | *Hazardous* | 1.4 | |
| | | | | Internal oil fire | Fire | *Hazardous* | .02 | |
| | | | Cracking and failure from bolt hole | As above | As above | *As above* | As above | MISC 61 |
| | | | Cracking at disc rim | Disc burst | Uncont'd | *Hazardous* | 2 | MISC 61 |
| | | | | Effect propagation as for cracking at spacer spigot, above | IFSD | | | |
| | | | | | Uncont'd | *Hazardous* | .2 | |
| | | | | | Fire | *Hazardous* | 1.4 | |
| | | | | | Fire | | .02 | |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| HP3 disc continued | As above | Fatigue | Cracking in disc bore | Disc burst | Uncontained, IFSD | *Hazardous* | .01 | MISC 61 |
| | | | Cracking in conical extension | Loss of HP rotor front end location Flailing and deceleration of front end of drum. IP shaft rub and failure. | IFSD | *Major* | 1 | MISC 61 |
| | | | | HP turbine overspeed and failure. | Uncontained | *Hazardous* | .2 | |
| | | | | Internal oil fire | Fire | *Hazardous* | .7 | |
| | | | | Titanium fire | Fire | | .01 | |



*CONTAINS RR PROPRIETARY DATA*

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 6.9 Drum bolted joint | *Secures first two stages of compressor to drum assembly* | Fracture or fatigue | Multiple bolt failure and separation of forward two discs | HP blading damage Flailing and deceleration of front end of drum. Flailing and acceleration of rear end of drum and HP turbine | IFSD | *Major* | .1 | MISC 61 |
| | | | | HP compressor disc failure | Uncontained | *Hazardous* | .03 | |
| | | | | HP turbine overspeed and disc burst | Uncontained | *Hazardous* | .02 | |
| | | | | Titanium fire | Fire | *Hazardous* | .001 | |
| 6.10 HP drum | *Retains HP compressor blades against radial and axial loads. Transmits torque from turbine .* | Fatigue | Cracking at disc dovetails and blade release | HP blade and stator damage | IFSD | *Major* | 20 | MISC 61 |
| | | | | Disc rim failure (partial) | Uncontained | *Hazardous* | 20 | |
| | | | | (complete) | Uncontained | *Hazardous* | 1 | |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 6.10 HP drum continued | *As above* | Fatigue | Cracking in disc diaphragm | Disc burst | IFSD Uncontained | *Hazardous* | 7 | MISC 61 |
| | | | Cracking in disc dovetail | Disc burst | IFSD Uncontained | *Hazardous* | .01 | MISC 61 |



*CONTAINS RR PROPRIETARY DATA*

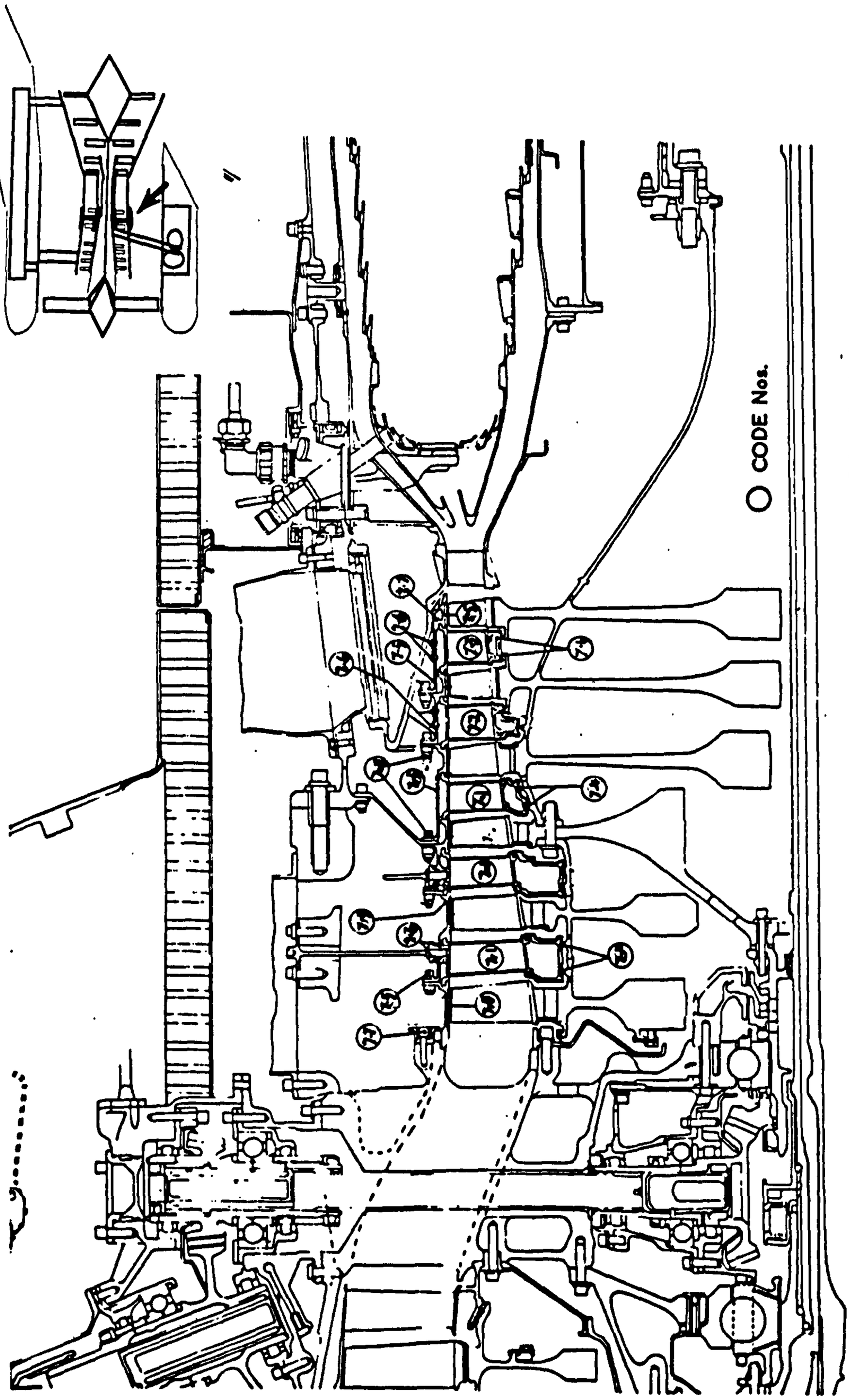



FIGURE G.13 HP COMPRESSOR STATOR

THIS PAGE INTENTIONALLY BLANK

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 7.1 Stator vanes (stages 1 to 3) | *Compress core air* | Fatigue | Cracking and detachment of aerofoil | HP blading damage<br>Titanium fire | IFSD<br>Fire | *Major*<br>*Hazardous* | 50<br><.5 | MISC 61 |
| 7.2 Stator vanes (stage 4) | *Compress core air* | Fatigue | Cracking from brazed joint at inner/outer platform | HP blading damage | IFSD | *Major* | 200 | MISC 61 |
| 7.3 Stator vanes (stage 5) | *Compress core air* | Fretting | Wear of vane t-slot locating tangs, allowing interference of stator and rotor blades | HP blading damage | IFSD | *Major* | 1.6 | MISC 61 |
| 7.4 Stator inner shroud rings | *Form abradable seal between compressor stages* | Wear | Excessive rub by rotor drum fins and detachment of abradable lining | Leakage of air from next compressor stage. Performance loss | IFSD | *Minor* | 20 | MISC 61 |
| | | | | Spacer overheating and distortion | IFSD | *Major* | 20 | |
| | | | | Disc failure | Uncontained | *Hazardous* | <.1 | |
| | | | | Titanium fire | Fire | *Hazardous* | <.1 | |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 7.5 Stator support casings | *Contain flow of core air. support abradable lining seal preventing forward airflow between stages. Transmit torque and axial loads.* | Bolt failure | Multiple bolt failure allows flange separation and leakage of HP air into IP delivery duct or HP3 turbine cooling air. | Performance reduction, turbine disc overheat | IFSD | *Major* | <.01 | MISC 61 |
| | | | | HP rotor blade damage | IFSD | *Major* | <.006 | |
| | | | | Titanium fire | Fire | *Hazardous* | <.001 | |
| | | Fatigue | Major casing cracking allows leakage of HP air into IP delivery duct or HP3 turbine cooling air | Performance reduction, turbine disc overheat | IFSD | *Major* | <.01 | MISC 61 |
| | | | | HP rotor blade damage | IFSD | *Major* | <.002 | |
| | | | | Titanium fire | Fire | *Hazardous* | <.0001 | |
| 7.6 Stator vane stop | *Locate and retain vanes* | Rivet failure | Rivet (stage 3) enters core gaspath and damages rotor blades | HP blade damage | IFSD | *Major* | 2 | MISC 61 |



*CONTAINS RR PROPRIETARY DATA*

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 7.7 Front and rear sealing rings | *Prevent forward leakage of air at front and back of HP rotor (outside diameter of compressor )* | Wear | Excessive wear at rear sealing ring allows leakage of HP delivery air into HP3 turbine sealing air. | Performance reduction | IFSD | *Minor* | <1 | MISC 61 |
| | | Fatigue | Retaining plate failure on bayonet ring securing rear sealing ring. Leakage of HP delivery air into HP3 turbine sealing air. | Ingestion of retaining plate pieces, blading damage. | IFSD | *Minor* | <.01 | MISC 61 |



CONTAINS RR PROPRIETARY DATA

THIS PAGE INTENTIONALLY BLANK

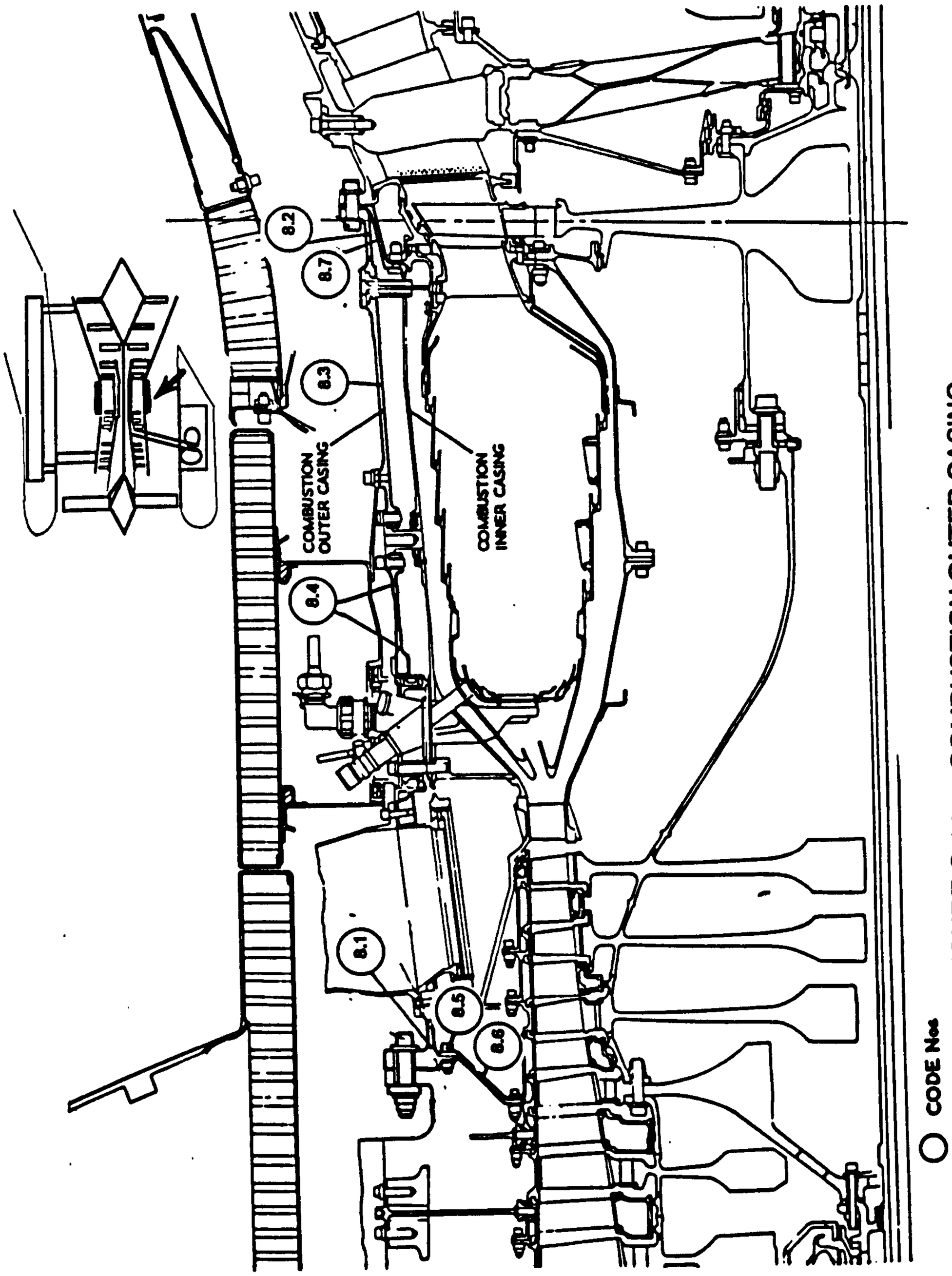



FIGURE G.14 COMBUSTION OUTER CASING

THIS PAGE INTENTIONALLY BLANK

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 8.1 Flange to intermediate casing | *Transmits axial and torque loads. Contains IP air* | Bolt fracture or fatigue | Multiple bolt failure and progressive overload | Separation of casing joint, leakage of IP air into zone 2. Impaired structure transmitting thrust and aerodynamic loads to rear mount. Severe damage to rotors. | IFSD | *Major* | <.01 | MISC 61 |
| | | Fatigue | Major circumferential cracking | Casing rupture, leakage of HP3 air into zone 2, fairing overpressure. | IFSD | *Major* | <.02 | MISC 61 |
| | | | | Casing flexure and blade rubs | | | | |
| | | | | Loss of turbine sealing air, turbine disc growth. | | | | |
| | | | | HP turbine disc failure | Uncontained | *Hazardous* | <.001 | |
| | | | | Explosive casing rupture | Explosion | *Hazardous* | <.004 | |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 8.1 cont. | | Fatigue | Major axial cracking | Casing rupture, leakage of HP3 air into zone 2, fairing overpressure.<br>Casing flexure and blade rubs<br>Loss of turbine sealing air, turbine disc growth.<br>HP turbine disc failure<br>Explosive casing rupture | IFSD<br><br><br><br><br>Uncontained<br>Explosion | *Major*<br><br><br><br><br>*Hazardous*<br>*Hazardous* | <.01<br><br><br><br><br><.001<br><.004 | MISC 61 |
| 8.2 Flange to turbine casing | *Transmits axial and torque loads. Contains HP3 air* | Bolt fracture or fatigue | Multiple bolt failure and progressive overload | Separation of casing joint, leakage of HP3 air into zone 2. Impaired structure transmitting thrust and aerodynamic loads to rear mount. Severe damage to rotors. | IFSD | *Major* | <.01 | MISC 61 |



*CONTAINS RR PROPRIETARY DATA*

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 8.2 cont. | | Fatigue | Major circumferential cracking | Casing rupture, leakage of HP3 air into zone 2, fairing overpressure. Casing flexure and blade rubs Loss of turbine sealing air, turbine disc growth. | IFSD | *Major* | <.02 | MISC 61 |
| | | | | HP turbine disc failure | Uncontained | *Hazardous* | <.001 | |
| | | | | Explosive casing rupture | Explosion | *Hazardous* | <.004 | |
| | | | | Flame tube overheat and flame breakout | Fire | *Hazardous* | <.01 | |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 8.2 cont. | | | Major axial cracking | Casing rupture, leakage of HP3 air into zone 2, fairing overpressure. Casing flexure and blade rubs Loss of turbine sealing air, turbine disc growth. | IFSD | *Major* | <.01 | MISC 61 |
| | | | | HP turbine disc failure | Uncontained | *Hazardous* | <.001 | |
| | | | | Explosive casing rupture | Explosion | *Hazardous* | <.004 | |
| | | | | Flame tube overheat and flame breakout | Fire | *Hazardous* | <.005 | |
| 8.3 Combustor casing drum | *Transmits axial and torque loads. Contains HP3 air* | Fatigue | Major circumferential cracking | As above | As above | As above | <.02<br><.002<br><.004<br><.01 | MISC 61 |
| | | Fatigue | Major axial cracking | As above | As above | As above | <.04<br><.004<br><.012<br><.02 | MISC 61 |



*CONTAINS RR PROPRIETARY DATA*

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 8.3 cont. | | Tensile failure | Flame breakout from combustion inner casing impinges on outer casing. | Hot turbine cooling air, HPTdisc growth and burst. | IFSD | *Major* | 4 | MISC 61 |
| | | | | Outer casing burn-through, cowl over-pressure | Uncont'd Fire | *Hazardous* | .4 | |
| | | | | Explosive failure of outer casing | Explos'n | *Hazardous* | 2.4 | |
| | | | | | | | .04 | |
| 8.4 Casing sole-plate inserts | *Admit burners, air offtakes and borescope access to combustor section* | Fatigue | Cracking from welds propagating into casing | Casing rupture, leakage of HP3 air into zone 2, fairing overpressure. | IFSD | *Major* | 0.2 | MISC 61 |
| | | | | Loss of turbine sealing air, turbine disc growth. | | | | |
| | | | | HPT disc failure | Uncont'd | *Hazardous* | .02 | |
| | | | | Explosive casing rupture | Explo-sion | *Hazardous* | .04 | |
| | | | | Flame tube overheat and flame breakout | Fire | *Hazardous* | .1 | |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 8.5 Flange to HP compressor support panel | *Locates HP compressor stator casing. Transmits axial and torque loads* | Fracture | Multiple bolt failure | Loss of HPC stator casing location.<br>HP compressor damage, titanium fire | IFSD<br>Fire | *Major*<br>*Hazardous* | .05<br>.001 | MISC 61 |
| | | Fatigue | Major cracking and flange failure | Loss of HPC stator casing location.<br>HP compressor damage, titanium fire | IFSD<br>Fire | *Major*<br>*Hazardous* | <.02<br><.01 | MISC 61 |
| 8.6 HP compressor support panel | *Transmits loads between external structural casing and HP compressor pressure casing* | Fatigue | Major cracking and loss of pressure sealing | Loss of HP3 air to turbines<br>Recirculation of air into HP compressor inlet<br>HP turbine disc failure | IFSD<br>Surge<br>Uncontained | *Minor*<br>*Major*<br>*Hazardous* | 10<br>10<br>1 | MISC 61 |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 8.7 Combustor casing rear support panel | *Locates rear end of combustion chamber and NGVs* | Fatigue | Major cracking and failure | Loss of location of chamber and NGVs. HP NGV overheating, airflow distortion in flame tube and overheating. | IFSD | *Major* | 10 | MISC 61 |
| | | | | Flame break out, casing burn-through | Fire | *Hazardous* | 3 | |
| | | | | Leakage of hot air into HP3 disc-cooling air, HP turbine disc failure | Uncontained | *Hazardous* | 0.5 | |



CONTAINS RR PROPRIETARY DATA

THIS PAGE INTENTIONALLY BLANK

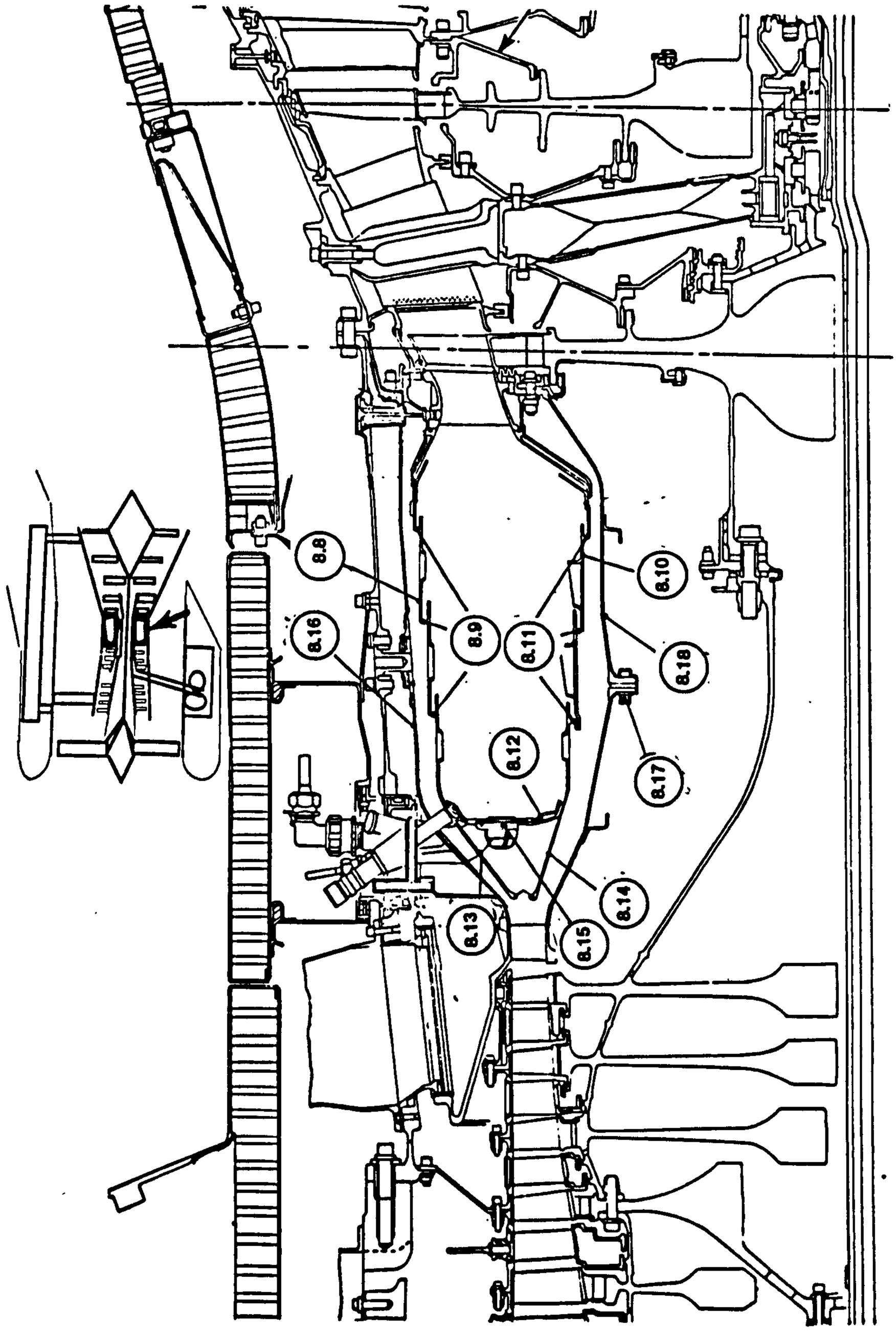



FIGURE G.15 COMBUSTION CHAMBER

THIS PAGE INTENTIONALLY BLANK

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 8.8 Flame tube outer wall | *Directs combustor airflow aft. Supports cooling rings* | Overheat/ burning | Tube distortion and airflow maldistribution | Hot streaks in gas burn NGVs.<br>Combustion casing burnthrough | IFSD<br>Fire | *Major*<br>*Hazardous* | 490<br>70 | MISC 61 |
| | | Thermal fatigue | Tube cracking allows distortion and airflow maldistribution | Hot streaks in gas burn NGVs.<br>Combustion casing burnthrough | IFSD<br>Fire | *Major*<br>*Hazardous* | 210<br>30 | MISC 61 |
| 8.9 Outer wall cooling rings | *Meter and direct cooling/dilution airflow into combustion region* | Overheat/ burning | Tube distortion and airflow maldistribution | Hot streaks in gas burn NGVs.<br>Combustion casing burnthrough | IFSD<br>Fire | *Major*<br>*Hazardous* | 490<br>140 | MISC 61 |
| | | Thermal fatigue | Tube cracking allows distortion and airflow maldistribution | Hot streaks in gas burn NGVs.<br>Combustion casing burnthrough | IFSD<br>Fire | *Major*<br>*Hazardous* | 210<br>60 | MISC 61 |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 8.10 Flame tube inner wall | *Directs combustor airflow aft. Supports cooling rings* | Overheat/ burning | Tube distortion and airflow maldistribution | Hot streaks in gas burn NGVs.<br>Combustion casing burnthrough | IFSD<br>Fire | *Major*<br>*Hazardous* | 630<br>7 | MISC 61 |
| | | Thermal fatigue | Tube cracking allows distortion and airflow maldistribution | Hot streaks in gas burn NGVs.<br>Combustion casing burnthrough | IFSD<br>Fire | *Major*<br>*Hazardous* | 500<br><.01 | MISC 61 |
| | | | Multiple locating bolt failure | Flame tube loses location<br>Hot streaks in gas burn NGVs.<br>Combustion casing burnthrough | IFSD<br><br>Fire | *Major*<br><br>*Hazardous* | .02<br><br><.01 | MISC 61 |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 8.11 Inner wall cooling rings | *Meter and direct cooling/dilution airflow into combustion region* | Overheat/ burning | Tube distortion and airflow maldistribution | Hot streaks in gas burn NGVs. | IFSD | *Major* | 700 | |
| | | | | Combustion casing burnthrough | Fire | *Hazardous* | <.01 | |
| | | Thermal fatigue | Tube cracking allows distortion and airflow maldistribution | Hot streaks in gas burn NGVs. | IFSD | *Major* | 200 | |
| | | | | Combustion casing burnthrough | Fire | *Hazardous* | <.01 | |
| 8.12 Flame tube heat shield | *Directs cooling air around exterior of flame tube* | Overheat/ burning | Loss of cooling flow to flame tube | Overheating of flame tube walls and airflow distortion. NGV damage. | IFSD | *Major* | 500 | MISC 61 |
| | | | | Combustion casing burnthrough | Fire | *Hazardous* | 10 | |
| | | Thermal fatigue | Loss of cooling flow to flame tube | Overheating of flame tube walls and airflow distortion. | IFSD | *Minor* | 800 | MISC 61 |
| | | | | NGV damage (burning and debris impact). | IFSD | *Major* | 800 | |
| | | | | Combustion casing burnthrough | Fire | *Hazardous* | 8 | |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 8.12 cont. | *As above* | Carbon deposition | Fuel spray deflection. | Flame tube burnthrough and overheat of HP3 air. | IFSD | *Minor* | 300 | MISC 61 |
| | | | | NGV damage. | IFSD | *Major* | 500 | |
| | | | | Combustion casing burnthrough | Fire | *Hazardous* | 10 | |
| | | Fatigue | Multiple rivet failure | Overheating of flame tube walls and air-flow distortion. | IFSD | *Major* | 100 | MISC 61 |
| | | | | NGV damage (burning and debris impact). | IFSD | *Major* | 90 | |
| | | | | Combustion casing burnthrough | Fire | *Hazardous* | 1 | |
| 8.13 Flame tube diffuser outer wall | *Directs cooling air around exterior of flame tube* | Fatigue | Cracking and distortion reduces airflow to outer annulus. | Overheating of flame tube walls and air-flow distortion. | IFSD | *Major* | 400 | MISC 61 |
| | | | | NGV damage (burning and debris impact). | IFSD | *Major* | 280 | |
| | | | | Combustion casing burnthrough | Fire | *Hazardous* | 40 | |



*CONTAINS RR PROPRIETARY DATA*

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 8.14 Flame tube diffuser inner wall | *Directs cooling air around inner wall of flame tube* | Fatigue | Cracking and distortion reduces airflow to inner annulus. | Overheating of flame tube walls and air-flow distortion. | IFSD | *Major* | 400 | MISC 61 |
| | | | | NGV damage (burning and debris impact). | IFSD | *Major* | 280 | |
| | | | | Internal overheat warning from flame breakout | IFSD | *Major* | <.01 | |
| 8.15 Fuel spray nozzles | *Meter and atomize fuel for combustion* | Carbon deposition | Hot streaks in combustor exit air | NGV damage. Flame tube overheat. Flame break out | Fire | *Hazardous* | <.1 | MISC 61 |
| | | Fatigue | Pintle failure and fuel spray distortion | NGV damage. Flame tube overheat. | IFSD | *Major* | 7 | MISC 61 |
| | | | | Flame break out | Fire | *Hazardous* | <.1 | |
| | | | Internal fuel leakage | As above | Fire | *Hazardous* | 10 | MISC 61 |

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 8.16 Combustion casing outer annulus | *Contains HP compressor delivery air* | Overheating/ distortion | Casing distortion and maldistribution of cooling air | NGV damage from hot streaks | IFSD | *Major* | 2 | MISC 61 |
| | | Fatigue | Casing major cracking | HP3 air overheat<br>NGV damage from hot streaks<br>Flame breakout and explosive casing failure | IFSD<br>IFSD<br>Fire Explosion | *Major*<br>*Major*<br>*Hazardous* | <.02<br><.01<br><.01 | MISC 61 |
| | | Fatigue | Multiple bolt failure and loss of fuel tube location | Fuel feed pipe failure<br>Fuel fire | IFSD<br>Fire | *Minor*<br>*Hazardous* | .08<br>.08 | MISC 61 |
| | | | Multiple bolt failure and loss of casing location at rear flange | Cooling air leakage and temperature increase | IFSD | *Minor* | .01 | MISC 61 |
| | | | | Turbine damage<br>Combustor assembly damage | IFSD<br>Fire | *Major*<br>*Hazardous* | .01<br>.005 | |



*CONTAINS RR PROPRIETARY DATA*

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 8.17 Combustion casing inner annulus (front) | *Contains HP compressor delivery air.* | Fatigue / loosening | Single bolt failure | Impact damage to HP turbine rotor bore. Vibration | IFSD | *Major* | 80 | MISC 61 |
| | | | Multiple bolt failure | Loss of location of NGVs, fuel burners and flame tube, consequent damage | IFSD | *Major* | .01 | MISC 61 |
| 8.18 Combustion casing inner annulus (rear) | *Contains HP compressor delivery air.* | Overheat/ distortion | Disturbance of cooling airflow | NGV damage from hot streaks.<br>Flame breakout | IFSD<br>Fire | *Major*<br>*Hazardous* | 9<br><.01 | MISC 61 |
| | | Fatigue | Cracking of casing and disturbance of cooling airflow | NGV damage from hot streaks.<br>Flame breakout | IFSD<br>Fire | *Major*<br>*Hazardous* | 4<br><.01 | MISC 61 |



CONTAINS RR PROPRIETARY DATA

THIS PAGE INTENTIONALLY BLANK

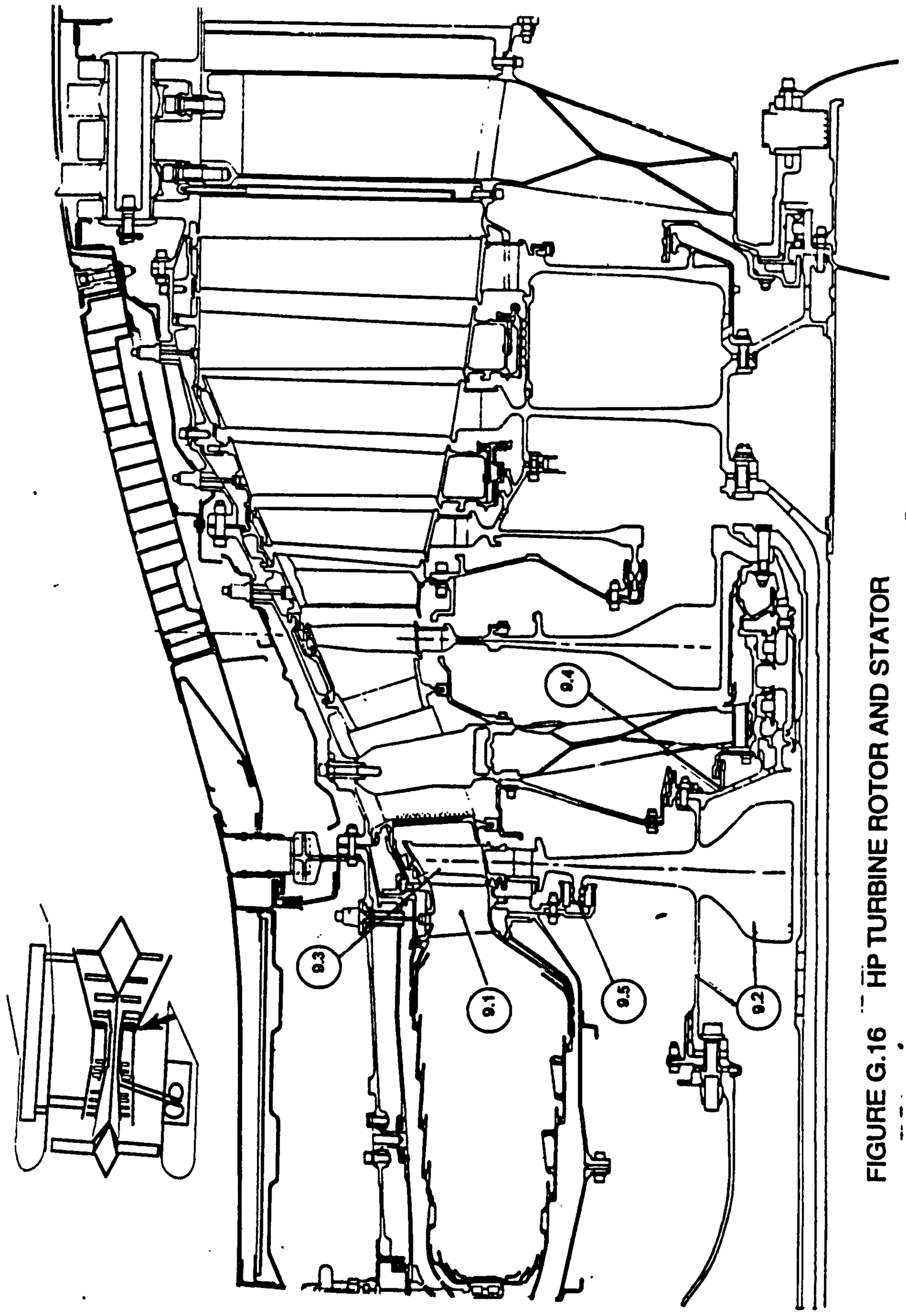



FIGURE G.16 – HP TURBINE ROTOR AND STATOR

THIS PAGE INTENTIONALLY BLANK

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 9.1 HP nozzle guide vanes | Direct combustor air into turbine. | Burning | Portion of vane breaks away | Consequent damage to turbine blades | IFSD | *Major* | 15 | MISC 61 |
| | | Overheat/ distortion | Portion of vane breaks away | Consequent damage to turbine blades | IFSD | *Major* | .5 | MISC 61 |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 9.2 HP turbine disc | *Retains turbine blades against radial loads. Transmits turbine torque to HP shaft. Transmits axial loads to location bearing* | *Fatigue* | Release of turbine blades from disc rim failure | Unbalance, engine fire | IFSD Fire | *Major Hazardous* | 0.1 | SER 90074 Iss 1, SER 90074 Iss 2 |
| | | *Creep* | *Release of blades as blade root disengages and blade rubs* | As above | As above | *As above* | .1 | SMK |
| | | *Fatigue* | Disc rupture | Uncontained failure | Uncontained | *Hazardous* | 0.1 | SER 90074 Iss 1, SER 90074 Iss 2 |
| | | *Creep* | As above | As above | As above | *As above* | .1 | |
| 9.3 HPT front shaft | *Transmits torque to HP compressor transmits axial load to location bearing* | *Fatigue* | Shaft failure allows compressor deceleration, turbine acceleration. Aft movement of turbine | Blade/vane interference and seal rubs. | IFSD | *Major* | 10 | SER 90074 Iss 1, SER 90074 Iss 2 |



*CONTAINS RR PROPRIETARY DATA*

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 9.4 HP turbine blades | *Convert energy of gaspath air into torque* | *Fatigue* | Blade failure | Impact damage to IP and LP turbines. Increased air temperature. | *IFSD* | *Major* | 10 | SER 90074 Iss 1, SER 90074 Iss 2 |
| | | *Creep* | *Blade stretching and eventual failure from tip-rub* | *Impact damage to IP and LP turbines. Increased air temperature.* | *IFSD* | *Major* | *10* | *SMK* |
| | | *Burning* | *Blade burning and reduced efficiency* | *Increased turbine air temperature. Casing overheat* | *IFSD* | *Major* | *10* | *SMK* |
| | | *Blockage* | *Cooling passage blockage by foreign material allows blade overheat and creep* | *As for creep* | *IFSD* | *Major* | *10* | SER 90074 Iss 1, SER 90074 Iss 2 |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| *9.5 HP turbine rear stubshaft* | *Locates HPT rotor radially by transmitting loads to roller bearing* | *Fatigue* | *Stubshaft cracking and failure* | Loss of radial location, unbalance and vibration. Rotor will run on seals and blade tips | IFSD | *Major* | 10 | SER 90074 Iss 1, SER 90074 Iss 2 |
| *9.6 HP turbine airseal* | *Prevents airflow between turbine bore and turbine NGV exit* | *Wear* | *Seal allows core air to leak to front face of HP turbine* | *HP turbine disc overheat (signaled by overheat detector, IFSD)*<br>*Disc burst* | *IFSD*<br>*Uncontained* | *Major*<br>*Hazardous* | *10*<br>*0.1* | *SMK* |



CONTAINS RR PROPRIETARY DATA

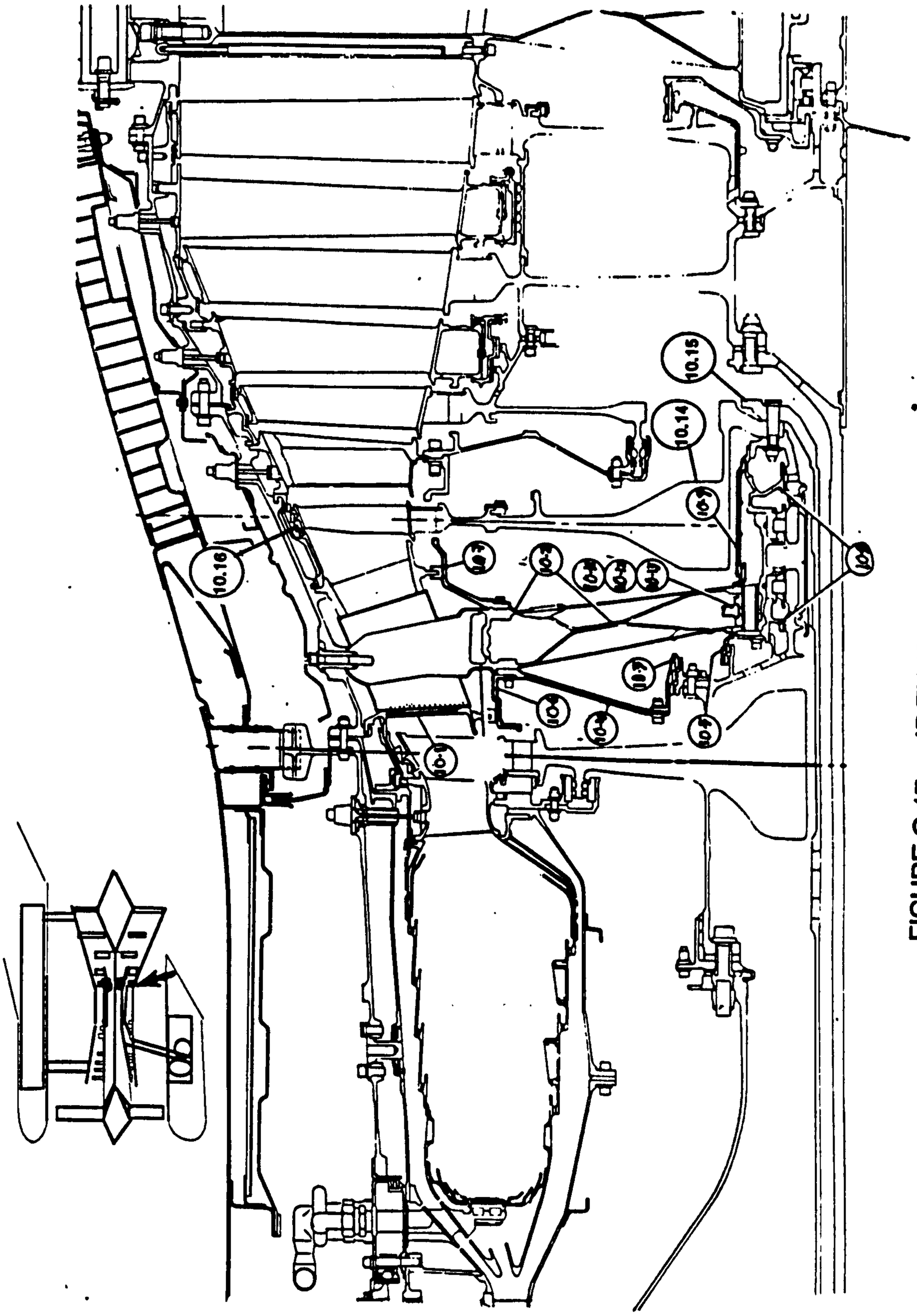



FIGURE G.17 IP TURBINE ROTOR AND STATOR

(10) CODE Nos.

THIS PAGE INTENTIONALLY BLANK

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 10.1 IP Nozzle Guide Vane | *Direct core air into IP turbine/ transmit load from bearings to casings* | Fatigue | Cracking and fracture of vane | Impact damage to IP and LP turbine blades | IFSD | *Major* | 1 | MISC 61 |
| | | Creep | Vane distortion. | Rub on IP turbine inner platform | IFSD | *Minor* | .5 | MISC 61 |
| 10.2 Nozzle Guide Vane support panels | *Transmit loads between bearing and NGVs* | Fatigue | Cracking in welded joints | Loss of bearing location, shaft and blade tip rubs. | IFSD | *Major* | 0.2 | MISC 61 |
| | | | | Oil fire | Fire | *Hazardous* | 0.2 | |
| 10.3 Outer stepped air seal | *Seals core air from bore of turbine* | Fatigue | Seal fin cracking and disintegration | Inward flow of HPT delivery air down rear face of HPT disc, overheat detection allows IFSD. | IFSD | *Major* | 15 | MISC 61 |
| | | | | Disc overheat and rim failure | Uncontained | *Hazardous* | 15 | MISC 61 |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 10.4 Outer stepped air seal support | *Supports air seal (10.3)* | Fatigue | Cracking and conical support failure | Ingestion of HPT delivery air down rear face of HPT disc, overheat detection allows IFSD.<br>Disc overheat and rim failure | IFSD<br>Uncontained | *Major*<br>*Hazardous* | .3<br>.3 | MISC 61 |
| 10.5 Inner stepped air seal | *Controls airflow to turbine bearing chamber* | Fatigue | Seal cracking and failure | Oil leakage from bearing chamber.<br>Oil fire | IFSD<br>Fire | *Minor*<br>*Hazardous* | 6<br>6 | MISC 61 |
| 10.6 Front NGV seal support ring | *Supports seal between HP3 cooling air and turbine gaspath* | Fatigue | Ring cracking and partial detachment | Damage by debris to disc and blades. Increase in HP3 airflow aft of HPT | IFSD | *Minor* | 6 | MISC 61 |
| 10.7 Rear NGV seal support ring | *Supports seal preventing recirculation of turbine gaspath air* | Fatigue | Ring cracking and partial detachment | Damage by debris to IPT disc and blades. Reduced HP3 airflow to rear face of HPT disc, signaled by overheat detector | IFSD | *Major* | 6 | MISC 61 |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 10.8 Bearing chamber oil seals | *Control bearing chamber pressure balance* | Wear | Loss of abradable seal lining | Oil system contamination by debris. | IFSD | *Minor* | 10 | MISC 61 |
| | | | | Oil leakage | IFSD | *Minor* | 10 | |
| 10.9 Outer sealing sleeve | *Controls IPT cooling air flow* | Fatigue | Cracking and air leakage | Drop in sealing air pressure forward of IPT disc. Recirculation of HPT delivery air and IPT disc rim overheat | IFSD | *Major* | 0.1 | MISC 61 |
| 10.10 not used | | | | | | | | |
| 10.11 Bearing oil feed | *Controls and meters oil flow to turbine roller bearings* | Fatigue | Oil pipe cracking | Oil leak into HP3 air. | IFSD | *Minor* | .1 | MISC 61 |
| | | | | Oil fire in turbine bore | Fire | *Hazardous Major* | .07 | |
| | | | | Bearing failure | IFSD | | .02 | |
| | | Leakage | Pipe joint leaking at spherical joint | External oil leak | IFSD | *Minor* | 1 | MISC 61 |
| | | | | Bearing failure | IFSD | *Major* | .2 | |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 10.12 Bearing oil scavenge | *Conducts hot oil and sealing air from bearing chamber* | Fatigue | Oil pipe cracking | Oil accumulation in bearing chamber and leakage through chamber seals. | IFSD | *Minor* | .07 | MISC 61 |
| | | | | Oil fire | Fire | *Hazardous* | .03 | |
| | | Leakage | Pipe joint leaking at spherical joint | Oil accumulation in bearing chamber and leakage through chamber seals. | IFSD | *Minor* | .7 | MISC 61 |
| | | | | Oil fire | Fire | *Hazardous* | .3 | |
| 10.13 Bearing chamber vent | *Conducts sealing air from bearing chamber* | Fatigue | Pipe cracking | Bearing chamber pressure increase and possible oil leakage. | IFSD | *Minor* | .1 | MISC 61 |
| | | | | Oil fire | Fire | *Hazardous* | .03 | |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 10.14 IP turbine disc | *Retains turbine blades against radial loads. Transmits turbine torque to IP shaft. Transmits axial loads to location bearing* | *Fatigue* | Release of turbine blades from disc rim failure | Unbalance, engine fire | IFSD Fire | *Major Hazardous* | 0.1 | SER 90074 Iss 1, SER 90074 Iss 2 |
| | | *Creep* | *Release of blades as blade root disengages and blade rubs* | As above | As above | *As above* | 0.1 | SMK |
| | | *Fatigue* | Disc rupture | Uncontained failure | Uncont'd | *Hazardous* | 0.1 | SER 90074 Iss 1, SER 90074 Iss 2 |
| | | *Creep* | *As above* | As above | As above | *As above* | 0.1 | |
| | | *Fatigue* | *Disc drive arm or multiple drive arm bolt failure* | *Loss of radial location. Turbine overspeed and blade release* | *IFSD* *Uncontained* | *Major* *Hazardous* | *.1* *.1* | *SMK* |
| 10.15 IPT shaft | *Transmits torque to IP compressor transmits axial load to location bearing* | *Fatigue* | Shaft failure allows compressor deceleration, turbine acceleration. Aft movement of turbine | Blade/vane interference and seal rubs. Turbine overspeed and blade release | IFSD Uncontained | *Major* *Hazardous* | .1 .1 | SER 90074 Iss 1, SER 90074 Iss 2 |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 10.16 IP turbine blades | *Convert energy of gaspath air into torque* | *Fatigue* | Blade failure | Impact damage to LP turbine. Increased air temperature. | *IFSD* | *Major* | .1 | SER 90074 Iss 1, SER 90074 Iss 2 |
| | | *Creep* | *Blade stretching and eventual failure from tip-rub* | *As above* | *As above* | *As above* | *.1* | *SMK* |
| | | *Burning* | *Blade burning and reduced efficiency* | *Increased turbine air temperature. Casing overheat* | *IFSD* | *Major* | *.1* | *SMK* |
| | | *Blockage* | *Cooling passage blockage by foreign material allows blade overheat and creep* | *As for creep* | *IFSD* | *Major* | *.1* | *SMK* |



CONTAINS RR PROPRIETARY DATA

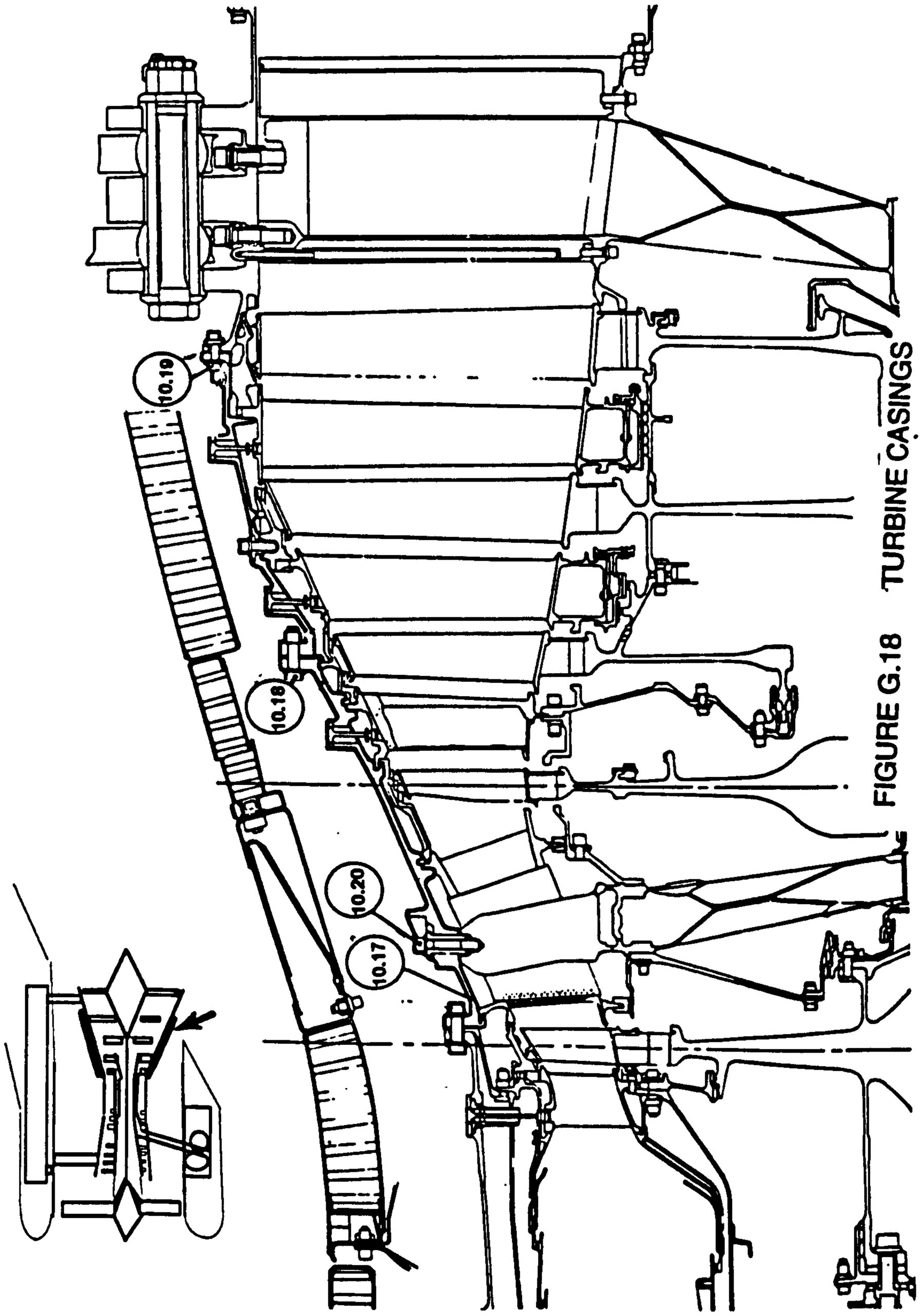



FIGURE G.18 TURBINE CASINGS

THIS PAGE INTENTIONALLY BLANK

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 10.17 HP/IP turbine casing front flange | *Secures turbine casing to combustion outer casing* | Loosening/fracture | Multiple progressive bolt failure and joint separation | Breakdown of engine carcase structure, severe damage to rotors | IFSD Explosion | *Hazardous* | <.01 | MISC 61 |
| | | Fatigue | Major circumferential cracking and casing failure | Leakage of HP3 air into zone 2, fairing failure | IFSD | *Major* | <.02 | MISC 61 |
| | | | | Casing flexure and severe rotor/stator rubs. | IFSD | *Major* | <.008 | |
| | | | | Loss of turbine cooling air, HPT and IPT disc rim overheat | IFSD | *Major* | <.016 | |
| | | | | HPT disc failure | Uncontained | *Hazardous* | <.002 | |
| | | | | Explosive casing rupture | Explosion | *Hazardous* | <.004 | |
| | | | | Flame tube overheat and flame breakout | Fire | *Hazardous* | <.01 | |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 10.17 cont. | | Fatigue | Major axial cracking and casing failure | Leakage of HP3 air into zone 2, fairing failure | IFSD | *Major* | <.01 | MISC 61 |
| | | | | Loss of cooling air, HPT/IPT disc rim overheat | IFSD | *Major* | <.007 | |
| | | | | HPT disc failure | Uncontained | *Hazardous* | <.001 | |
| | | | | Explosive casing rupture | Explosion | *Hazardous* | <.003 | |
| | | | | Flame tube overheat and flame breakout | Fire | *Hazardous* | <.005 | |
| | | Impact | Cracking from impact of released blade | Casing deformation and cracking | IFSD | *Major* | 10 | MISC 61 SER 90074 Iss 1, SER 90074 Iss 2 |
| 10.18 HP/IP turbine casing aft flange | *Secures HP/IP turbine casing to LP turbine casing* | Loosening/fracture | Multiple progressive bolt failure and joint separation | Breakdown of engine carcase structure, severe damage to rotors | IFSD Explosion | *Hazardous* | <.01 | MISC 61 |

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 10.18 cont. | As above | Fatigue | Major circumferential cracking and casing failure | Casing rupture and leakage of LPT air into zone 2 | IFSD | *Major* | <.02 | MISC 61 |
| | | | | Casing flexure, severe rotor rubs, bearing failures | IFSD | *Major* | <.014 | |
| | | | | Explosive casing rupture | Explosion | *Hazardous* | <.006 | |
| | | Fatigue | Major axial cracking and casing failure | Casing rupture and leakage of LPT air into zone 2 | IFSD | *Major* | <.01 | MISC 61 |
| | | | | Casing flexure, severe rotor rubs, bearing failures | IFSD | *Major* | <.003 | |
| | | | | Explosive casing rupture | Explosion | *Hazardous* | <.007 | |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 10.19 LP turbine casing aft flange | *Secures LP turbine casing to rear suspension casing* | Loosening/fracture | Multiple progressive bolt failure and joint separation | Breakdown of engine carcase structure, severe damage to rotors | IFSD Explosion | *Hazardous* | <.01 | MISC 61 |
| | | Fatigue | Major circumferential cracking and casing failure | Casing rupture and leakage of LPT air into zone 2 | IFSD | *Major* | <.02 | MISC 61 |
| | | | | Casing flexure, severe rotor rubs, bearing failures | IFSD | *Major* | <.014 | |
| | | | | Explosive casing rupture | Uncontained | *Hazardous* | <.006 | |
| 10.20 Radial bolted joint at HP NGVs | Secures HP/IP bearing support structure to casings | Loosening/fracture | Multiple progressive bolt failure and joint separation | Bearing failure. Turbine blade tip rubs. | IFSD | *Major* | .04 | MISC 61 |
| | | | | Loss of axial location, IPT disc rubs | IFSD | *Major* | .02 | |

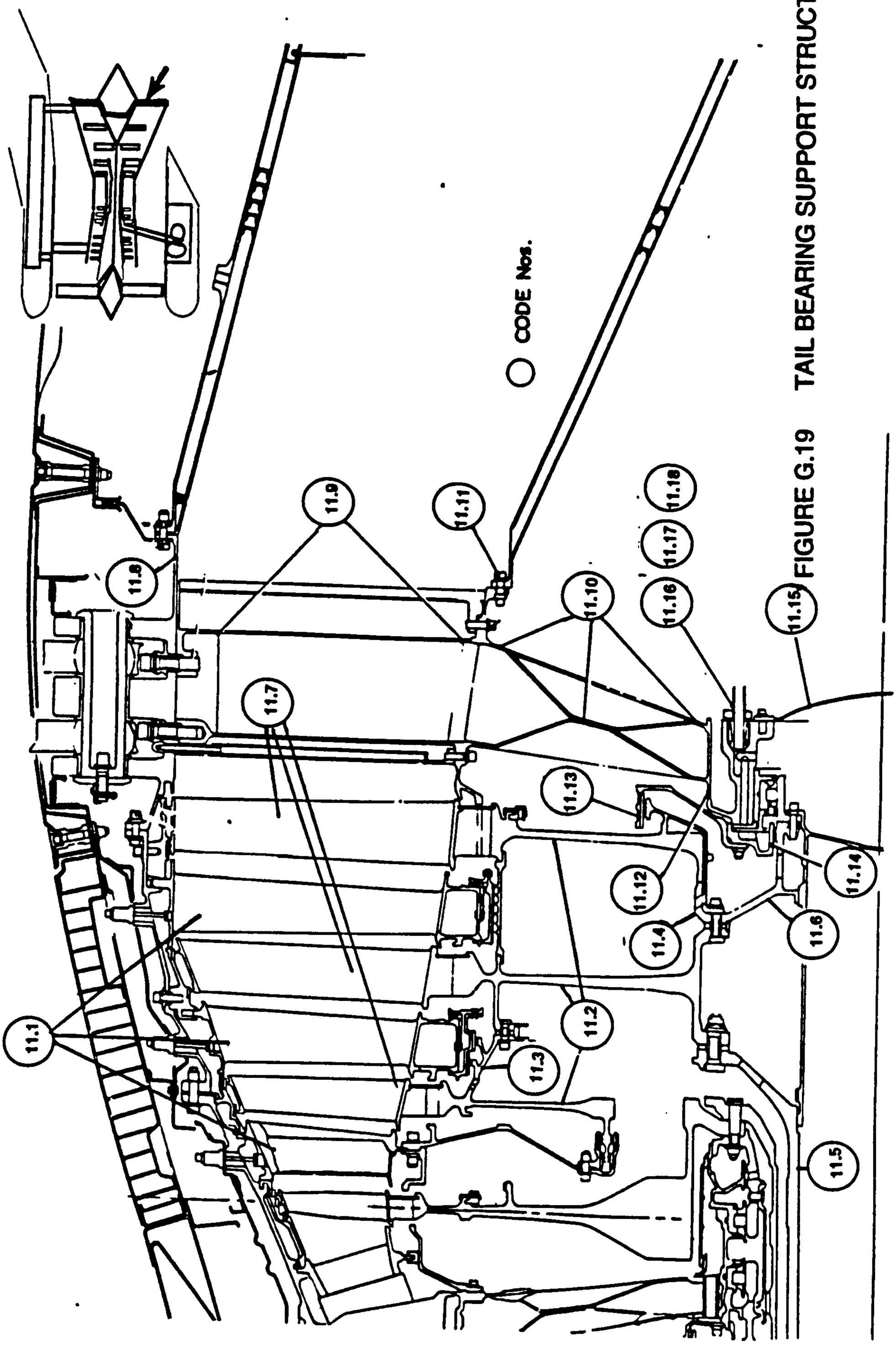



FIGURE G.19 TAIL BEARING SUPPORT STRUCTURE

THIS PAGE INTENTIONALLY BLANK

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| *11.1 LP nozzle guide vanes* | *Redirect circumferential turbine airflow to travel axially* | *Burning* | *Portion of vane breaks away* | Consequent damage to downstream turbine blades. Unbalance, vibration | *IFSD* | *Major* | 10 | SER 90074 Iss 1, SER 90074 Iss 2 |
| | | *Fatigue* | *As above* | As above | *IFSD* | *Major* | 10 | SER 90074 Iss 1, SER 90074 Iss 2 |
| | | *Impact from upstream debris* | *As above* | As above | *IFSD* | *Major* | 10 | SER 90074 Iss 1, SER 90074 Iss 2 |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 11.2 LP turbine discs | *Retain turbine blades against radial loads. Transmit turbine torque to LP shaft. Transmit axial loads to location bearing* | *Fatigue* | Release of turbine blades from disc rim failure | Unbalance, engine fire | IFSD Fire | *Major Hazardous* | 0.1 | SER 90074 Iss 1, SER 90074 Iss 2 |
| | | *Creep* | *Release of blades as blade root disengages and blade rubs* | As above | As above | *As above* | 0.1 | *SMK* |
| | | *Fatigue* | Disc rupture | Uncontained failure | Uncontained | *Hazardous* | 0.1 | SER 90074 Iss 1, SER |
| | | *Creep* | As above | As above | As above | | 0.1 | 90074 Iss 2 |
| 11.3 First stage disc drive arm | *Transmits torque from first stage of LPT to LP shaft* | *Fatigue* | Separation of first stage from LPT. | Overspeed and failure of first stage disc | Uncontained | *Hazardous* | 0.1 | SER 90074 Iss 1, SER 90074 Iss 2 |
| 11.4 Third stage disc drive arm | *Transmits torque from third stage of LPT to LP shaft. Locates third stage axially* | | Separation of third stage from LPT. | Heavy axial rubs of third stage against tail bearing support structure. Overspeed and blade release | Uncontained | *Hazardous* | 0.1 | SER 90074 Iss 1, SER 90074 Iss 2 |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 11.5 LPT shaft | *Transmits torque to LP compressor transmits axial load to location bearing* | *Fatigue* | Shaft failure allows compressor deceleration, turbine acceleration. Aft movement of turbine | Blade/vane interference and seal rubs. | Uncontained | *Hazardous* | 0.1 | SER 90074 Iss 1, SER 90074 Iss 2 |
| 11.6 LPT stubshaft | *Provides radial location to aft end of LP turbine* | *Fatigue* | Stubshaft failure and radial movement of turbine rotor | Blade tip and seal rubs. Vibration | Uncontained | *Hazardous* | 0.1 | SER 90074 Iss 1, SER 90074 Iss 2 |
| 11.7 LP turbine blades | *Convert energy of gaspath air into torque* | *Fatigue* | Blade failure | Increased air temperature. Vibration | *IFSD* | *Major* | .1 | SER 90074 Iss 1, SER 90074 Iss 2 |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 11.8 Rear suspension casing aft flange | Secures exhaust casing to rear suspension casing | Loosening/ fracture | Multiple progressive bolt failure and joint separation | Exhaust casing, nozzle and thrust reverser separate from airplane | IFSD | *Major* | <.01 | MISC 61 |
| | | Fatigue | Circumferential cracking at flange and joint failure | Exhaust casing, nozzle and thrust reverser separate from airplane | IFSD | *Major* | <.02 | MISC 61 |
| 11.9 Support spokes | Locate tail bearing housing concentric with casings. | Fatigue | Major cracking of multiple spokes | Casing distortion and LPT blade tip rubs | IFSD | *Major* | 1 | MISC 61 |
| 11.10 Tail bearing housing support panels | Locate tail bearing housing concentric with casing | Fatigue | Major cracking at welds | Casing distortion and LPT blade tip rubs. Oil leakage | IFSD | *Major* | 0.2 | MISC 61 |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 11.11 Flange to exhaust cone | *Secures exhaust cone to engine* | Fatigue | Major cracking at flange and joint failure | Cone separates from aircraft | IFSD | *Major* | <.01 | MISC 61 |
| 11.12 Tail bearing hub | | Fatigue | Major cracking of weld to diaphragm | Structure distortion, heavy unbalance, LPT blade tip rubs. Oil leaks | IFSD | *Major* | 1 | MISC 61 |
| 11.13 Air seal member | *Forms seal between bearing housing and LPT3 disc* | Fatigue | Seal member failure and disruption of air sealing flow. | LPT gas ingestion and disc rim overheat. Oil leak<br>LPT disc rim failure<br>Oil fire | IFSD<br>Uncontained<br>Fire | *Minor*<br>*Hazardous*<br>*Hazardous* | 20<br>5<br>5 | MISC 61 |
| 11.14 Bearing chamber oil seal | *Controls sealing airflow into bearing chamber* | Wear | Loss of pressure balance across seal. | Oil leak. | IFSD | *Minor* | 10 | MISC 61 |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 11.15 Rear cover | *Seals aft end of bearing chamber from exhaust cone* | Fatigue | Cracking | Oil leakage from bearing chamber. Oil fire in tailpipe | IFSD Fire | *Hazardous* | 1 | MISC 61 |
| 11.16 Oil feed to bearing | *Supplies oil* | Fatigue | Cracking of welded joint | Oil leakage into exhaust cone and tailpipe. Oil fire | IFSD Fire | *Hazardous* | .1 | MISC 61 |
| | | Leakage | Leak from spherical joint | As above | IFSD Fire | *Hazardous* | 10 | |
| 11.17 Oil scavenge from bearing | *Removes oil/air mix from bearing chamber* | Fatigue | Cracking of welded joint | Increase in bearing chamber pressure. Oil leak. | IFSD | *Minor* | .07 | MISC 61 |
| | | | | Oil fire at LPT3 disc | Fire | *Hazardous* | .02 | |
| | | Leakage | Leak from spherical joint | As above | As above | *Hazardous* | 7<br>2 | |
| 11.18 Bearing chamber vent | *Removes excess sealing air from bearing chamber* | Fatigue | Cracking of welded joint | Increase in bearing chamber pressure. Oil leak. | IFSD | *Minor* | .1 | MISC 61 |
| | | | | Oil fire at LPT3 disc | Fire | *Hazardous* | .02 | |
| | | Leakage | Leak from spherical joint | As above | As above | *Hazardous* | 10<br>2 | |

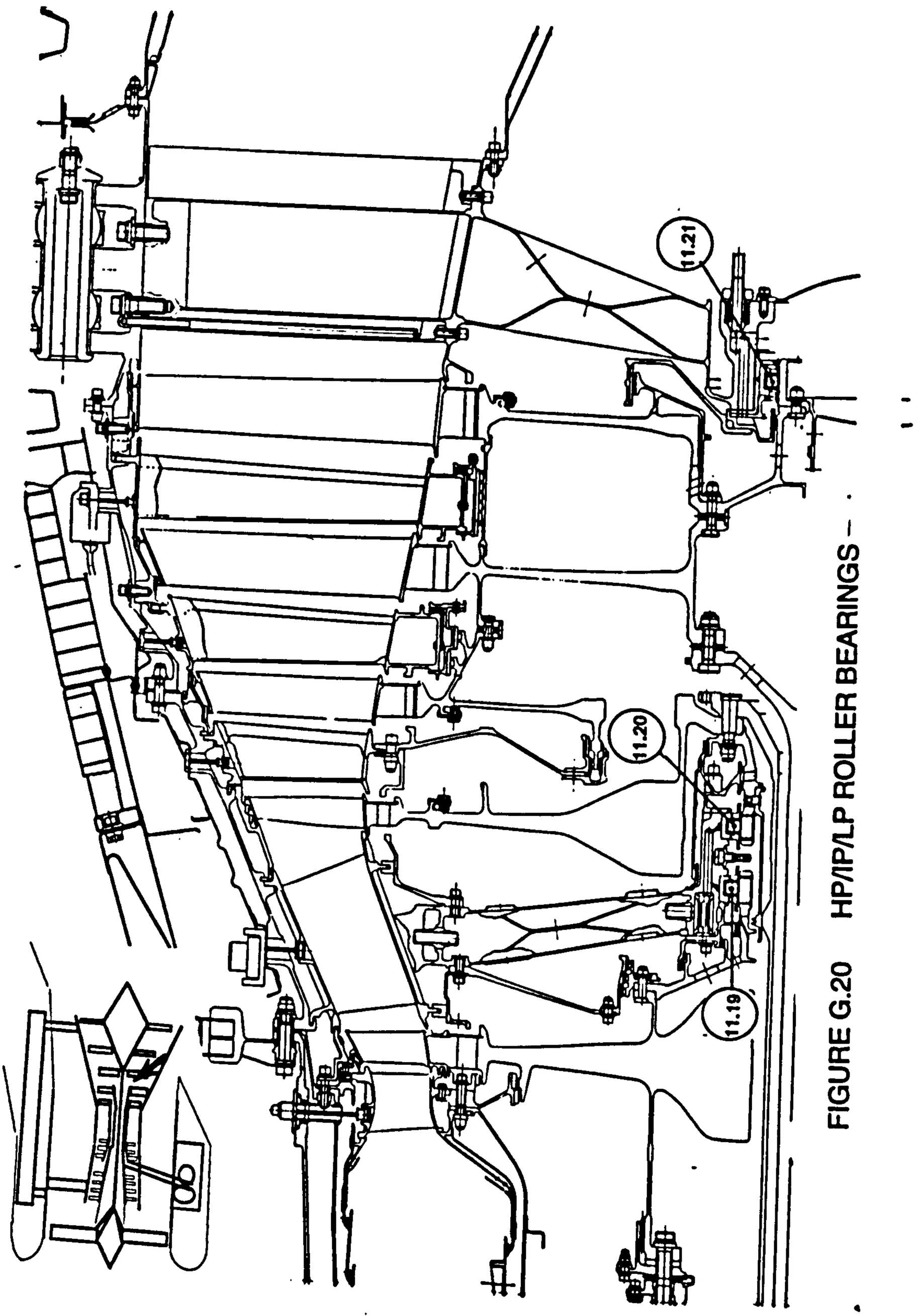



FIGURE G.20 HP/IP/LP ROLLER BEARINGS

THIS PAGE INTENTIONALLY BLANK

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 11.19 HP turbine roller bearing | Locates aft end of HP rotor radially, transfer radial rotor loads to engine carcase | Fatigue | Break up of tracks and rollers | Seal and blade tip rubs. Vibration. | IFSD | *Minor* | 5 | MISC 61 |
| | | | | Reduced turbine cooling air | IFSD | *Major* | 5 | |
| | | | | Oil leak | IFSD | *Minor* | 3 | |
| | | | | Oil fire | Fire | *Hazardous* | <.01 | |
| | | | | IP shaft overheat and failure | Uncontained | *Hazardous* | <.01 | |
| | | Poor oil supply | Break up of tracks and rollers | Seal / blade tip rubs. | IFSD | *Minor* | 20 | MISC 61 |
| | | | | Reduced turbine cooling air | IFSD | *Major* | 20 | |
| | | | | Oil leak | IFSD | *Minor* | 8 | |
| | | | | Oil fire | Fire | *Hazardous* | <.01 | |
| | | | | IP shaft overheat and failure | Uncontained | *Hazardous* | <.01 | |
| | | Skidding | Damage of tracks and rollers | Seal/ blade tip rubs. | IFSD | *Minor* | 20 | MISC 61 |
| | | | | Reduced turbine cooling air | IFSD | *Major* | 20 | |
| | | | | Oil leak | IFSD | *Minor* | 12 | |
| | | | | Oil fire | Fire | *Hazardous* | <.01 | |
| | | | | IP shaft overheat and failure | Uncontained | *Hazardous* | <.01 | |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 11.19 cont. | *As above* | Fatigue | Cage or rivet failure | Seal and blade tip rubs. Vibration. | IFSD | *Minor* | 20 | MISC 61 |
| | | | | Reduced turbine cooling air | IFSD | *Major* | 20 | |
| | | | | Oil leak | IFSD | *Minor* | 12 | |
| | | | | Oil fire | Fire | *Hazardous* | <.01 | |
| | | | | IP shaft overheat and failure | Uncontained | *Hazardous* | <.01 | |
| 11.20 IP turbine roller bearing | Locates aft end of IP rotor radially, transfers radial rotor loads to engine carcase | Fatigue | Break up of tracks and rollers | Seal / blade tip rubs. | IFSD | *Minor* | 1 | MISC 61 |
| | | | | Reduced turbine cooling air | IFSD | *Major* | 1 | |
| | | | | Oil leak | IFSD | *Minor* | .6 | |
| | | | | Oil fire | Fire | *Hazardous* | <.01 | |
| | | | | IP shaft overheat and failure | Uncontained | *Hazardous* | <.01 | |
| | | Poor oil supply | Break up of tracks and rollers | Seal and blade tip rubs. Vibration. | IFSD | *Minor* | 20 | MISC 61 |
| | | | | Reduced turbine cooling air | IFSD | *Major* | 20 | |
| | | | | Oil leak | IFSD | *Minor* | 8 | |
| | | | | Oil fire | Fire | *Hazardous* | <.01 | |
| | | | | IP shaft overheat and failure | Uncontained | *Hazardous* | <.01 | |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 11.20 cont. | *As above* | Skidding | Damage of tracks and rollers | Seal and blade tip rubs. Vibration. | IFSD | *Minor* | 20 | MISC 61 |
| | | | | Reduced turbine cooling air | IFSD | *Major* | 20 | |
| | | | | Oil leak | IFSD | *Minor* | 12 | |
| | | | | Oil fire | Fire | *Hazardous* | <.01 | |
| | | | | IP shaft overheat and failure | Uncontained | *Hazardous* | <.01 | |
| | | Fatigue | Cage or rivet failure | Seal and blade tip rubs. Vibration. | IFSD | *Minor* | 20 | MISC 61 |
| | | | | Reduced turbine cooling air | IFSD | *Major* | 20 | |
| | | | | Oil leak | IFSD | *Minor* | 12 | |
| | | | | Oil fire | Fire | *Hazardous* | <.01 | |
| | | | | IP shaft overheat and failure | Uncontained | *Hazardous* | <.01 | |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 11.21 LP turbine roller bearing | Locates aft end of LP rotor radially, transfer radial rotor loads to engine carcase | Fatigue | Break up of tracks and rollers | Seal and blade tip rubs. Vibration. | IFSD | *Minor* | 5 | MISC 61 |
| | | | | Reduced turbine cooling air | IFSD | *Major* | 5 | |
| | | | | Oil leak | IFSD | *Minor* | 3 | |
| | | | | Oil fire | Fire | *Hazardous* | <.01 | |
| | | | | LP shaft overheat and failure | Uncontained | *Hazardous* | <.01 | |
| | | Poor oil supply | Break up of tracks and rollers | Seal / blade tip rubs. | IFSD | *Minor* | 20 | MISC 61 |
| | | | | Reduced turbine cooling air | IFSD | *Major* | 20 | |
| | | | | Oil leak | IFSD | *Minor* | 8 | |
| | | | | Oil fire | Fire | *Hazardous* | <.01 | |
| | | | | LP shaft overheat and failure | Uncontained | *Hazardous* | <.01 | |
| | | Skidding | Damage of tracks and rollers | Seal / blade tip rubs. | IFSD | *Minor* | 20 | MISC 61 |
| | | | | Reduced turbine cooling air | IFSD | *Major* | 20 | |
| | | | | Oil leak | IFSD | *Minor* | 12 | |
| | | | | Oil fire | Fire | *Hazardous* | <.01 | |
| | | | | IP shaft overheat and failure | Uncontained | *Hazardous* | <.01 | |



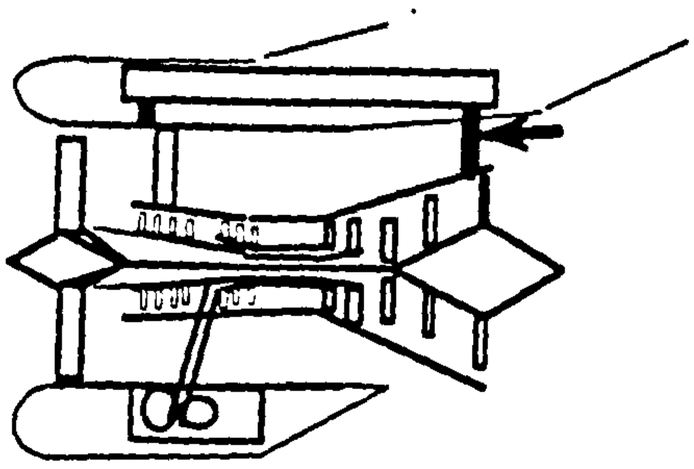
CONTAINS RR PROPRIETARY DATA

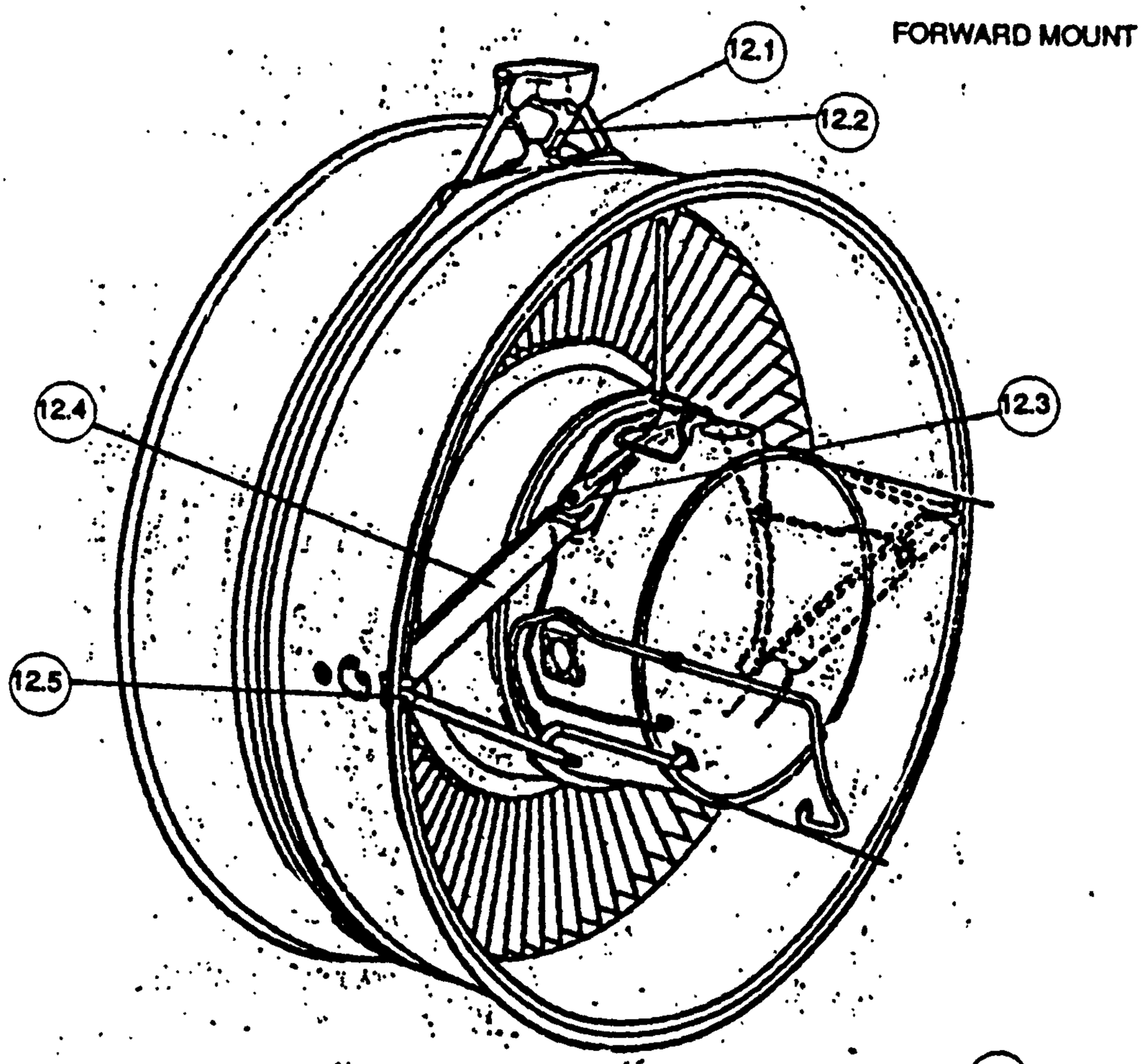
| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 11.21 cont. | As above | Fatigue | Cage or rivet failure | Seal and blade tip rubs. Vibration. | IFSD | *Minor* | 20 | MISC 61 |
| | | | | Reduced turbine cooling air | IFSD | *Major* | 20 | |
| | | | | Oil leak | IFSD | *Minor* | 12 | |
| | | | | Oil fire | Fire | *Hazardous* | <.01 | |
| | | | | IP shaft overheat and failure | Uncontained | *Hazardous* | <.01 | |



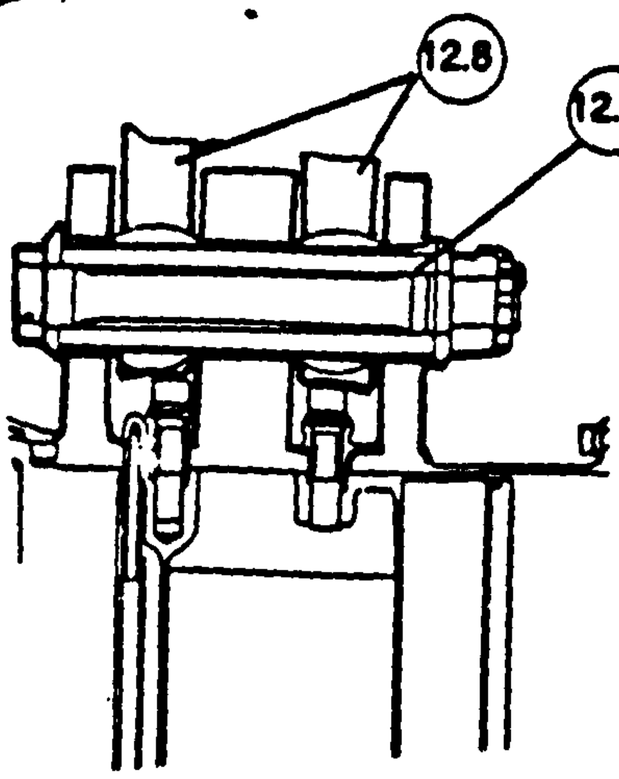
CONTAINS RR PROPRIETARY DATA

THIS PAGE INTENTIONALLY BLANK






FORWARD MOUNT




AFT MOUNT (SIDE LINKS NOT SHOWN)

**FIGURE G.21 ENGINE MOUNTS**

THIS PAGE INTENTIONALLY BLANK

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 12.1 Side link and pin | *Transfer downward and sideways loads to pylon from fan case* | *Fatigue* | Single link or pin failure | Engine carcase drops and weight is carried on thrust link fail-safe pin | None | *Minor* | 0.1 | SER 90074 Iss 1, SER 90074 Iss 2 |
| 12.2 Thrust link and bracket | *Transfers axial thrust load to pylon* | *Fatigue* | Link or bracket failure releasing thrust spigot | Engine moves forward and thrust is carried by front and rear suspension links and remaining thrust link, or fail-safe pin | None | *Minor* | 0.1 | SER 90074 Iss 1, SER 90074 Iss 2 |
| | | | Link or bracket failure releasing rear axial pin | Engine moves forward until thrust link trunnion reaches bore of housing | None | *Minor* | 0.1 | SER 90074 Iss 1, SER 90074 Iss 2 |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 12.3 A-frame bolt retaining pin/ lug | *Attach struts to compressor intermediate casing* | Fatigue | Pin or lug failure | Redistribution of load between port and starboard A-frames | None | *Minor* | .1 | MISC 61 |
| 12.4 A-frame strut | *Transmits side couple from fan case to core, and transmits upward force from bending moment produced by thrust (in parallel with fan OGVs)* | Fatigue | Strut fracture | Vertical load capability reduced. Load transferred to fan OGVs, fan case deformation and fan blade tip rubs | None | *Minor* | 0.5 | MISC 61 |
| 12.5 Pin/ bolt at fan case | *Attach struts to fan case* | Fatigue | Pin or bolt failure | As above | None | *Minor* | <.05 | MISC 61 |

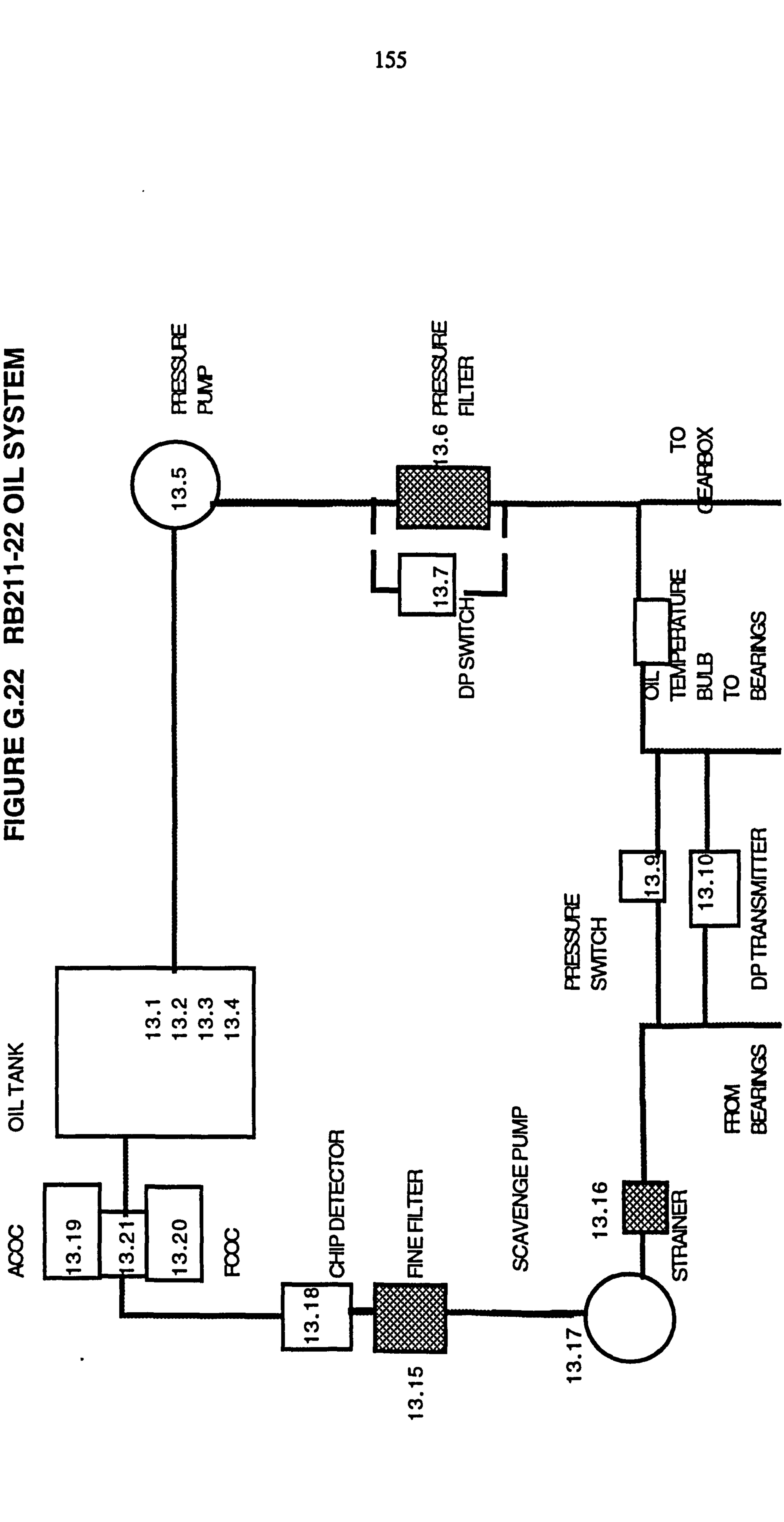


CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 12.6 Side link | *Carries vertical and sideways loads from engine carcase to pylon* | *Fatigue* | Single link failure | Load transferred to remaining link | None | *Minor* | 0.1 | SER 90074 Iss 1, SER 90074 Iss 2 |
| 12.7 Side link pin/ lug | *Attach side link to engine carcase* | *Fatigue* | Lug or pin failure releasing one pin | Engine moves down/sideways and vertical load transfers to remaining side link and torque links | None | *Minor* | 0.1 | SER 90074 Iss 1, SER 90074 Iss 2 |
| | | | | Further link failure allows engine separation | Engine departure | *Hazardous* | 0.1 | SER 90074 Iss 2 |
| 12.8 Centre link | *Reacts torque about engine axis* | *Fatigue* | Single link failure | Load transferred to remaining link | None | *Minor* | 0.1 | SER 90074 Iss 1, SER 90074 Iss 2 |
| 12.9 Centre link pin/ lug | *Attach centre links to engine carcase* | *Fatigue* | Lug or pin failure releasing one pin | Engine can swing laterally. | None | *Minor* | 0.1 | SER 90074 Iss 1, SER 90074 Iss 2 |
| | | | | Further link failure allows engine separation | Engine departure | *Hazardous* | 0.1 | |

THIS PAGE INTENTIONALLY BLANK

FIGURE G.22 RB211-22 OIL SYSTEM



THIS PAGE INTENTIONALLY BLANK

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| *13.1 Oil tank and filler cap* | *Contains oil for engine lubrication and cooling* | *Leakage* | *Leaking cap allows oil to escape into nacelle* | *Low oil quantity and IFSD. Possible nacelle fire* | *IFSD* | *Minor* | *10b,e** | *MISC 61 Sn 2.3* |
| | | | | | *Fire* | *Hazardous* | *.0001a* | *IAR 60190* |
| | | *Impact* | *Cracked tank leaks oil* | *As above* | *IFSD* | *Minor* | *10b,e** | *MISC 61 Sn 2.3* |
| | | | | | *Fire* | *Hazardous* | *.0001a* | *IAR 60190* |
| *13.2 Dipstick* | *Measures depth of oil during maintenance* | *Leakage* | *Oil escapes into nacelle* | *Low oil quantity and IFSD. Possible nacelle fire* | *IFSD* | *Minor* | *10b.e** | *MISC 61 Sn 2.3* |
| | | | | | *Fire* | *Hazardous* | *.0001a* | *IAR 60190* |
| *13.3 Deaerator* | *Separates out air entrained in scavenge oil* | *Fatigue* | *Deaerator tray cracks ; pieces released into tank. Highly aerated tank oil, incorrect oil quantity reading , low oil flow* | *Reduced bearing life. Indicated oil quantity fluctuation. Possible IFSD* | *IFSD* | *Minor* | *14d* | *NPRD-1 RADC* |
| *13.4 Oil level transmitter* | *Measures depth of oil in tank, for transmission to flight deck* | *Switch failure* | *False low oil quantity False high oil quantity No quantity indication* | *Possible IFSD* | *IFSD None* | *Minor* | *0.1d* | *MISC 61 Sn 2.3* |
| | | *Wiring failure* | | | *IFSD* | *Minor* | *.05b* | |

* Oil tank impact considered Remote ($10^{-5}$). Routine maintenance breaking/making seal is assigned a severity factor of 10 compared to undisturbed seal.

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| *13.5 Oil pressure pump* | *Pumps oil from tank to gearbox and core engine bearings* | *Wear* | *Spline wear on pump drive-shaft and complete loss of oil flow. Low oil pressure.* | *IFSD. Bearing failures* | *IFSD*<br>*IFSD* | *Minor*<br>*Major* | *6d*<br>*.006e* | *Total failure rate 18.5 (ref. 98)* |
| | | *Cavitation* | *Debris released downstream. Reduced oil flow., filter clogging* | *IFSD. Reduced bearing life* | *IFSD* | *Minor* | *6d* | |
| | | *Leakage* | *Oil leak into nacelle. Low oil quantity* | *IFSD for low oil. Possible oil fire* | *IFSD*<br>*Fire* | *Minor*<br>*Hazardous* | *1b*<br>*1E-5a* | *MISC 61 Sn 2.3 IAR 60190* |
| | | *Fatigue* | *Bearing fatigue and failure generates local friction and high temperatures.* | *IFSD for high oil temperature. Gearbox fire* | *IFSD*<br>*Fire* | *Minor*<br>*Hazardous* | *6d*<br>*.06e* | *Engineering estimate that 1 in 100 produces gearbox fire* |

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| *13.6 Pressure filter* | *Filters out debris from oil supplied to engines* | *Blockage* | *Filter accumulates debris and blocks up. Bypass valve opens and unfiltered oil is circulated to engine* | *IFSD for filter blockage light. Bearings and gearbox protected by individual filters* | *IFSD* | *Minor* | *33d* | *Filter total failure rate 66; NPRD-1 (RADC)* |
| | | *Disintegration* | *Filter element sheds debris* | *Blockage of individual filters begins.* | *None* | | *32d* | |
| | | *Jamming* | *Bypass valve jams shut, so that filter blockage cuts off oil supply.* | *IFSD for low oil pressure* | *IFSD* | *Minor* | *8d* | *Valve total failure rate 9; NPRD-1. Valve normally open.* |
| | | | *Bypass valve jams open, so that unfiltered oil is circulated to engine* | *IFSD for filter blockage light. Bearings and gearbox protected by individual filters* | *IFSD* | *Minor* | *1d* | |
| | | *Leakage* | *Oil leak into nacelle* | *IFSD for low oil quantity.* | *IFSD* | *Minor* | *1b* | *MISC 61 Sn 2.3 IAR 60190* |
| | | | | *Possible oil fire* | *Fire* | *Hazardous* | *1E-5a* | |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| *13.7 Differential P switch* | *Measures pressure drop across filter for transmission to flight deck* | *Open circuit* | *Switch fails open. No indication if filter blocked* | *None* | | | *20d* | *Switch failure rate 40; NPRD-1* |
| | | *Short circuit* | *Switch fails closed. False indication of filter blockage* | *IFSD for filter blockage* | *IFSD* | *Minor* | *20d* | |
| | | *Leakage* | *Oil leak into nacelle* | *Low oil quantity and IFSD. Possible nacelle fire* | *IFSD Fire* | *Minor Hazardous* | *1b 1E-5a* | *MISC 61 Sn 2.3 IAR 60190* |
| *13.8 Oil temperature bulb* | *Measures oil temperature for transmission to flight deck* | *Biased low* | *Reads low oil temperature.* | *None* | *None* | | *43d* | *Bulb failure rate 87; NPRD-1* |
| | | *Biased high* | *Reads high oil temperature* | *IFSD for high oil T* | *IFSD* | *Minor* | *43d* | |
| | | *Wiring failure* | *Gives no reading of oil temperature* | *Possible IFSD* | *IFSD* | *Minor* | *.05b* | *MISC 61 Sn 2.3* |
| | | *Leakage* | *Oil leak into nacelle* | *Low oil quantity and IFSD. Possible nacelle fire* | *IFSD Fire* | *Minor Hazardous* | *1b 1E-5a* | *MISC 61 Sn 2.3 IAR 60190* |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| *13.9 Pressure switch* | *Measures oil pressure for transmission to flight deck* | *Biased low*<br>*Biased high*<br>*Wiring failure*<br>*Leakage* | *Reads low oil pressure.*<br>*Reads high oil pressure*<br>*Gives no reading of oil pressure*<br>*Oil leak into nacelle* | *Possible IFSD*<br>*None*<br>*None*<br>*Low oil quantity and IFSD. Nacelle fire* | *IFSD*<br>*None*<br>*IFSD*<br>*IFSD Fire* | *Minor*<br>*Minor*<br>*Hazardous* | *20d*<br>*20d*<br>*.05b*<br>*1b*<br>*1E-5a* | *Switch failure rate 40, NPRD-1*<br>*MISC 61 Sn 2.3*<br>*MISC 61 Sn 2.3 IAR 60190* |
| *13.10 Differential P transmitter* | *Measures pressure drop for transmission to flight deck* | *Open circuit*<br>*Short circuit*<br>*Leakage* | *As 13.7* | *As 13.7* | *None*<br>*IFSD*<br>*IFSD Fire* | *Minor*<br>*Hazardous* | *27d*<br>*27d*<br>*1b*<br>*1E-5a* | *Failure rate 54; NPRD-1*<br>*MISC 61 Sn 2.3 IAR 60190* |
| *13.11 Bearings* | *Oil supply, scavenge addressed above* | | | | | | | |
| *13.12 Gearbox* | *Oil supply; ; scavenge addressed above* | | | | | | | |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| *13.13 Lines and fittings (24 lines external to casings)* | *Conduct oil between components* | *Leakage* | *Oil leaks from fitting . Low oil quantity* | *IFSD for low oil. Bearing failure* | *IFSD* | *Major* | *1b* | *MISC 61 Sn 2.3* |
| | | *Blockage* | *Possible interruption of oil supply to bearing.* | *Bearing failure* | *IFSD* | *Major* | *3a* | *MISC 61 Sn 2.3* |
| | | | *Possible build-up of oil in bearing chamber* | *Leakage from chamber seals. Oil fire* | *Fire* | *Hazardous* | *1.5b* | *MISC 61 Sn 6.1* |
| | | *Fracture* | *Rapid oil loss. Low oil quantity* | *IFSD for low oil. Bearing failure* | *IFSD* | *Major* | *24a* | *MISC 61 Sn 2.3* |
| | | | | *Possible nacelle fire* | *Fire* | *Hazardous* | *.5* | |
| *13. 14 Differential P switch* | *Measures pressure drop across scavenge filter, for transmission to flight deck* | *Open circuit* | *As 13.7* | *None* | | | *20d* | *NPRD-1* |
| | | *Short circuit* | | *IFSD for filter blockage* | *IFSD* | *Minor* | *20d* | *NPRD-1* |
| | | *Leakage* | | *IFSD for low oil. Possible nacelle fire* | *IFSD Fire* | *Minor Hazardous* | *1b 1E-5a* | *MISC 61 Sn 2.3 IAR 60190* |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| *13.15 Scavenge filter and bypass valve* | *Traps debris from scavenge oil, for inspection during maintenance* | *Blockage* | *Filter accumulates debris and blocks up. Bypass valve opens and unfiltered oil is circulated to heat exchangers* | *Heat exchanger clogging or damage, possible blockage or leak.* | *IFSD* | *Minor* | *33d* | *NPRD-1* |
| | | | | *Bearing failure* | *IFSD* | *Major* | *3e* | *Engineering est. IAR 60190* |
| | | | | *Fire from leak* | *Fire* | *Hazardous* | *1E-5a* | |
| | | *Disintegration* | *Filter element sheds debris which damages/ clogs heat exchangers* | *As above* | *IFSD* | *Minor* | *32d* | *NPRD-1* |
| | | | | | *IFSD* | *Major* | *3e* | |
| | | | | | *Fire* | *Hazardous* | *1E-5a* | *IAR60190* |
| | | *Jamming* | *Bypass valve jams shut, so that filter blockage cuts off oil scavenge flow.* | *Possible build-up of oil in bearing chamber, leakage through chamber seals and oil fire* | *IFSD* | *Minor* | *8d* | *MISC61* |
| | | | | | *Fire* | *Hazardous* | *4b,d* | *Sn 6.1* |
| | | | *Bypass valve jams open, so that unfiltered oil is circulated to heat exchangers* | *Heat exchanger clogging or damage, possible blockage or leak.* | *IFSD* | *Minor* | *1d* | |
| | | | | *Bearing failure* | *IFSD* | *Major* | *.01e* | *Engineering est. IAR 60190* |
| | | | | *Fire from leak* | *Fire* | *Hazardous* | *1E-5a* | |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| *13.16 Coarse filter* | *Protect scavenge pumps by trapping large pieces of debris from scavenge oil* | *Blockage* | *Severe contamination blocks coarse filter, loss of scavenging* | *Contamination will affect other components first.* | *None* | | *33d* | *NPRD-1* |
| | | *Disintegration* | *Debris released into scavenge pump, possible pump failure* | *Oil build-up in bearing chamber. Leakage and fire* | *Fire* | *Hazardous* | *.5bx32d =16* | *MISC 61 Sn 6.1* |
| | | *Leakage* | *Pump leaks oil into nacelle.* | *Low oil quantity, IFSD.* | *IFSD* | *Minor* | *1b* | *MISC 61 Sn 2.3* |
| | | | | *Possible nacelle fire* | *Fire* | *Hazardous* | *1E-5a* | *IAR60190* |
| *13.17 Scavenge pumps* | *Pump scavenge oil and entrained air from bearings and gearbox, to return to tank* | *Wear* | *Spline wear on drive-shaft and complete loss of scavenging, all pumps* | *All pumps run off same drive-shaft; IFSD for low pressure* | *IFSD* | *Minor* | *6d* | *Ref. 98* |
| | | *Cavitation* | *Debris released, blocks heat exchangers.* | *Fine scavenge filter protects heat exchangers. As 13.16* | *IFSD Fire* | *Minor Hazardous* | *6d 1E-5a* | *IAR60190* |
| | | *Leakage* | *Oil leak into nacelle* | *IFSD for low oil. Possible nacelle fire* | *IFSD Fire* | *Minor Hazardous* | *1b 1E-5a* | *MISC 61 Sn 2.3* |
| | | *Fatigue* | *Bearing fatigue and failure, high temperatures.* | *IFSD for high oil temperature. Gearbox fire* | *IFSD Fire* | *Minor Hazardous* | *6d .06e* | *IAR 60190* |

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| *13.18 Chip detectors* | *Trap pieces of ferro-magnetic debris for inspection during maintenance* | *Leakage* | *Oil leak past seal. Low oil quantity.* | *IFSD for low oil Possible nacelle fire. Bearing failure* | *IFSD Fire* | *Major Hazardous* | *1b 1E-5a* | *MISC 61 Sn 2.3 IAR60190* |
| | | *De-magnetisation* | *Debris not detected.* | *Incipient bearing or gearbox failure progresses to further engine damage* | *None* | | *10* | |
| *13.19 Air cooled oil cooler and bypass valve* | *Cools oil using fan air Allows oil to bypass if pressure drop through cooler is too high* | *Fatigue* | *Oil leaks into cooling air* | *Oil loss overboard* | *IFSD* | *Minor* | *3d* | *Ref. 47c* |
| | | | *Oil leaks into nacelle* | *Possible nacelle fire* | *Fire* | *Hazardous* | *3E-5a* | *IAR60190* |
| | | *Jamming* | *Valve sticks open, oil inadequately cooled* | *Reduced bearing life. IFSD* | *IFSD* | *Minor* | *1d* | *NPRD-1* |
| | | | *Valve sticks shut, oil flow through engine reduced if cooler is blocked* | *Low oil P, bearing failure* | *IFSD* | *Minor* | *8d* | |



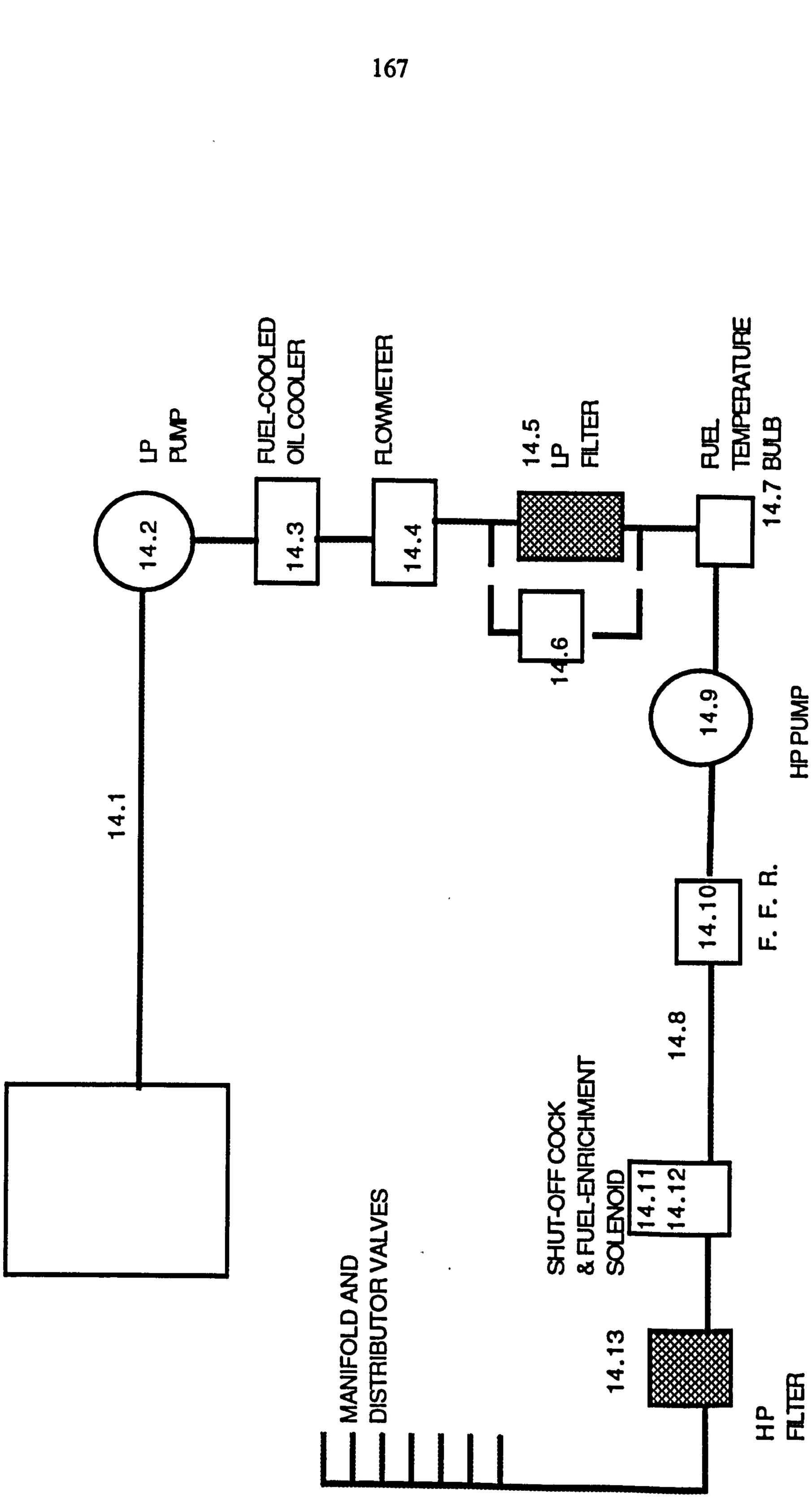
CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| *13.20 Fuel cooled oil cooler and bypass valve* | *Cools oil using fuel Allows oil to bypass if pressure drop through cooler is too high* | *Fatigue* | *Fuel leaks into oil.* | *Bearing failures. Fuel fire in IP/HP bearing chambers.* | *IFSD Fire* | *Major Major* | *$3_a$ $3_a$* | *IRR 60001* |
| | | | *Fuel or oil leak into nacelle* | *Possible fire* | *Fire* | *Hazardous* | *$2E\text{-}5_a$* | *IAR60190* |
| | | *Jamming* | *Valve sticks open, oil inadequately cooled* | *Reduced bearing life. IFSD* | *IFSD* | *Minor* | *$1_d$* | *NPRD-1* |
| | | | *Valve sticks shut, oil flow through engine reduced if cooler is also blocked* | *Low oil P, bearing failure* | *IFSD* | *Minor* | *$8_d$* | |
| *13.21 Cooler control unit* | *Shuts off oil flow to air cooled cooler at low fuel temperatures* | *Jamming* | *Spring or translating spool jam, Closed (insufficient cooling at normal fuel temperatures)* | *Oil temperature rise. IFSD* | *IFSD* | *Minor* | *$12_d$* | *Unit failure rate 25; ref. 47c* |
| | | | *Open (too much cooling at low fuel temperatures)* | *Low oil temperature. Possible cooler bypass.* | *None* | *Minor* | *$12_d$* | |
| | | *Leakage* | *Connection to oil line leaks* | *Low oil quantity and IFSD. Possible fire* | *IFSD Fire* | *Minor Hazardous* | *$1_b$ $1E\text{-}5_a$* | *MISC 61 Sn 2.3 IAR 60190* |



CONTAINS RR PROPRIETARY DATA

**FIGURE G.23 RB211-22 FUEL SYSTEM**



THIS PAGE INTENTIONALLY BLANK

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| *14.1 Fuel inlet line (airframe supply)* | *Conducts fuel from airframe firewall to engine LP fuel pump.* | *Chafing* | *Chafing against other components wears hole in flexible line, allowing fuel leak into nacelle* | *Fuel leak into nacelle, high fuel flow and IFSD. Nacelle fire.* | *IFSD*<br>*Fire* | *Minor*<br>*Hazardous* | *$1_e$*<br>*$1E\text{-}5_a$* | *SMK*<br>*IAR60190* |
| | | *Leakage* | *Leakage at connection seal allows fuel to escape into nacelle* | *Fuel leak into nacelle, high fuel flow and IFSD. Nacelle fire.* | *IFSD*<br>*Fire* | *Minor*<br>*Hazardous* | *$1_b$*<br>*$1E\text{-}5_a$* | *Misc 61 Sn 2.3*<br>*IAR60190* |
| *14.2 Low Pressure fuel pump* | *Pumps fuel from airframe into engine LP fuel system* | *Fatigue* | *Bearing fatigue and failure generates friction and local high temperatures.* | *Fuel fire. IFSD for high fuel T* | *Fire IFSD* | *Minor Hazardous* | *$6_d$ $0.6_e$* | *Ref. 98 Engineering judgement* |
| | | *Cavitation* | *Debris released downstream, loss of pump efficiency* | *Debris caught by filter. Reduced LP pressure, engine power reduction IFSD* | | | *6* | |
| | | *Leakage Wear* | *Fuel leak to nacelle from connections Pump drive splines wear and pump no longer driven from gearbox* | *Nacelle fire. Reduced LP fuel pressure, reduction in available engine power.* | *IFSD Fire* | *Minor Hazardous* | *$1_b$ 1E-5a $6_d$* | *Misc 61 Sn 2.3 IAR60190* |

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| *14.3 Fuel/oil cooler* | *See 13.20* | | | | | | | |
| *14.4 Fuel flowmeter* | *Measures fuel flow for transmission to cockpit* | *Biased high* | *False high fuel flow indication* | *Possible IFSD* | *IFSD* | *Minor* | *100d* | *NPRD-1* |
| | | *Biased low* | *False low fuel flow indication* | *None* | | | *100d* | |
| | | *Leakage* | *Fuel leak into nacelle from connection* | *Possible nacelle fir. Possible IFSD* | *Fire* | *Hazardous* | *1E-5a 1b* | *IAR60190 Misc 61 Sn 2.3* |
| *14.5 Fuel filter and bypass* | *Filters out debris from fuel. Allows fuel to bypass filter if filter clogs.* | *Blockage* | *Filter clogs. Bypass valve opens and dirty fuel is supplied to system* | *IFSD for high dP Contamination of FFR, fuel mis-scheduling* | *IFSD. Stall or roll-back* | *Minor* | *16d* | *Ref. 47c; total rate is 33* |
| | | *Disintegration* | *Filter element sheds debris* | *FFR contamination* | *Stall or roll-back* | *Minor* | *16d* | |
| | | *Jamming* | *Bypass valve jams shut, so that filter blockage cuts off fuel supply* | *Engine shuts down after progressive power loss* | *IFSD* | *Minor* | *8d* | *NPRD-1* |
| | | | *Bypass valve jams open, dirty fuel supplied to system* | *FFR contamination* | *Stall or roll-back* | *Minor* | *1d* | |
| | | *Leakage* | *Fuel leakage from connection into nacelle* | *Possible nacelle fire* | *Fire* | *Hazardous* | *1E-5a* | *Misc 61 Sn 2.3 IAR60190* |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| *14.6 Differential P switch* | *Annunciates filter clogging to flight deck.* | *Open circuit* | *Switch fails open. No indication for blocked filter* | *None* | *None* | | *20d* | *NPRD-1* |
| | | *Short circuit* | *Switch fails closed. False indication of filter blockage* | *IFSD for filter blockage* | *IFSD* | *Minor* | *20d* | |
| *14.7 Fuel temperature bulb* | *Measures fuel temperature for transmission to flight deck* | *Biased low* | *Reads low* | *None* | | | *41d* | *NPRD-1* |
| | | *Biased high* | *Reads high* | *None* | | | *41d* | *Misc 61 Sn 2.3* |
| | | *Wiring failure* | *No reading of fuel temperature* | *None* | | | *.05b* | *IAR 60190* |
| | | *Leak* | *Fuel leak into nacelle* | *Nacelle fire* | *Fire* | *Hazardous* | *1E-5a* | |
| *14.8 Pipes and fittings* | *Conduct fuel between components* | *Fatigue* | *Pipe cracks in fatigue. allowing fuel leak.* | *High fuel flow, flame-out.* | *IFSD* | *Minor* | *20b* | *Misc 61 Sn 2.3 20* |
| | | | | *Nacelle fire* | *Fire* | *Hazardous* | *.1* | *pipes* |
| | | *Chaf g* | *Pipe wears against hardware; fuel leak.* | *As above* | *IFSD* | *Minor* | *20e* | *1 pipe in core* |
| | | | | | *Fire* | *Hazardous* | *.1* | *comp't.* |
| | | *Leak* | *Fitting damage allows fuel leak* | *As above* | *IFSD* | *Minor* | *40b* | *IAR60190* |
| | | | | | *Fire* | *Hazardous* | *.2* | |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| *14.9 High Pressure fuel pump* | *Raises fuel pressure* | *Fatigue* | *Bearing fatigue generates friction and local ignition points* | *Fuel fire. IFSD for high fuel T* | *IFSD Fire* | *Minor Hazardous* | *6d .6a* | *Ref. 98 IAR60190* |
| | | *Cavitation* | *Debris released downstream, loss of pump efficiency* | *Debris caught by filter. Reduced HP pressure, engine power reduction* | | | *6d* | |
| | | *Leakage* | *Fuel leak to nacelle from connections* | *Nacelle fire. Possible IFSD* | *Fire* | *Hazardous* | *1E-5a* | *MISC 61 Sn 2.3 IAR60190* |
| | | *Wear* | *Pump drive splines wear and pump no longer driven* | *Engine flameout* | *IFSD* | *Minor* | *6d* | |
| | | *Jam* | *Spill valve jams at take-off position* | *Pump burst, fuel fire* | *Fire* | *Hazardous* | *1* | *TDR 7537* |
| *14.10 Fuel Flow Regulator (FFR)* | *Meters fuel flow in response to throttle setting* | *Wear* | *Fuel flow too high* | *Turbine blade overheat, thrust high* | *IFSD* | *Major* | *0.1c* | |
| | | | *Fuel flow too low* | *Engine rollback and IFSD* | *IFSD* | *Minor* | | |
| | | | *Wrong acceleration schedule* | *Stall* | *IFSD* | *Minor* | | |
| | | *Jamming* | *As above* | *As above* | *IFSD* | *Major* | *1b* | |
| | | | | | *IFSD* | *Minor* | | *MISC 61 Sn2.3 IAR60190* |
| | | | | | *IFSD* | *Minor* | | |
| | | *Leakage* | *Fuel leak to nacelle from connections* | *Nacelle fire* | *Fire* | *Hazardous* | *1E-5a* | |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| *14.11 HP shut-off cock* | *Closes off fuel to HP system on engine shut-down signal* | *Jamming* | *Valve jams open.* | *Engine runs until fuel downstream of LP cock (on airframe) has been consumed* | *None* | *None* | *9.5d* | *NPRD-1* |
| | | | *Valve jams closed* | *Inability to start engine* | *None* | *None* | *9.5d* | *Misc 61 Sn 2.3* |
| | | *Wiring failure* | *As above* | *As above* | *None* | *None* | *.05b* | |
| *14.12 Fuel enrichment solenoid* | *Valve provides richer fuel flow for engine start* | *Solenoid failure* | *Valve cannot be powered open* | *Poor/no starting capability* | *None* | *None* | *1b* | *NPRD-1 Misc 61 Sn 2.3* |
| | | *Jamming* | *Valve sticks closed* | *As above* | *None* | *None* | *9.5d* | |
| | | | *Valve sticks open* | *Hot streaks in combustor exit gas, eventual NGV damage* | *None* | *None* | *9.5d* | |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| *14.13 HP Fuel filter* | *Filters out debris from fuel.* | *Blockage* | *Filter clogs. Reduced fuel flow to engine* | *Engine shuts down after progressive power loss* | *IFSD.* | *Minor* | *16d* | |
| | | *Disintegration* | *Filter element sheds debris* | *Contamination of distributor valves and spray nozzles* | *IFSD or reduced power* | *Minor* | *16d* | |
| | | *Leakage* | *Fuel leakage from connection into nacelle* | *Nacelle fire* | *Fire* | *Hazardous* | *1E-5a* | *Misc 61 Sn 2.3 IAR60190* |
| *14.14 Fuel manifold and distributor valves* | *Distributes fuel to fuel spray nozzles* | *Leakage* | *Fuel leakage from connection into nacelle* | *Nacelle fire* | *Fire* | *Hazardous* | *1a* | *IAR60190* |
| | | *Fatigue* | *Manifold failure and fuel leak into the nacelle* | *Nacelle fire* | *Fire* | *Hazardous* | *.6e* | *Engineering judgement* |
| | | *Blockage* | *Fuel deposits jam valve open/closed* | *Open valve ,tailpipe fire on shutdown.* | *Fire* | *Major* | *2d* | *NPRD-1* |
| | | | | *Closed valve reduces fuel ;power loss* | *IFSD* | *IFSD* | *2d* | *NPRD-1* |
| | | *Jam* | *Distributor valve spring jams valve in open/ closed position* | *As above* | *Fire IFSD* | *Major IFSD* | *2d 2d* | *NPRD-1 NPRD-1* |
| *14.15 Fuel spray nozzles* | *Addressed in section 8* | | | | | | | |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 14.16 Fuel control system | *Schedules fuel flow to engine based on altitude, temperature, airspeed and throttle setting. Prevents hazardous engine overspeed* | Amplifier failure | Loss of fan speed and TGT limit logic, engine controlled to pressure ratio | Engine overspeed within rotor capability. | IFSD | Major | $12_a$ | TDR 7537 ADR 60027 |
| | | P1 probe failure | Incorrect pressure ratio transmitted to flightdeck | Low engine thrust | No safety effect | None | TBD | ORR 60031 |
| 14.17 Throttle control linkage | *Transmits pilots throttle setting to fuel control unit* | Disconnection | Throttle movement not transmitted to fuel control unit | No engine response to throttle movement | IFSD | *Minor* | $0.3_a$ | ORR 60020/3 |
| | | Seizure | As above | As above | IFSD | *Minor* | $.1_a$ | ORR60020/3 |



CONTAINS RR PROPRIETARY DATA

THIS PAGE INTENTIONALLY BLANK

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| *15.1 Start ducting* | *Carries air from airframe or ground supply to starter* | *Fatigue* | *Duct cracks and fails Slow crack growth* | *Slow starting or hung start. Accessory overheat, possible fire warning* | *No safety effect* | *Minor* | *1e* | *Engineering estimate* |
| | | | *Rapid crack growth* | *Cowl overpressure. Fire warning. Flailing duct may damage adjacent components.* | | *Minor* | *.02b* | *Analogy to TDR 5796* |
| *15.2 Start valve* | *Opens to allow air to drive the starter. Indicates valve position to flight deck.* | *Jamming* | *Valve jams closed.* | *Engine cannot be started.* | *No safety effect* | *Minor* | *0.5d* | *NPRD-1* |
| | | | *Valve jams open.* | *Starter continues to run after engine start. Starter failure possible.* | *IFSD* | *Minor* | *0.5d* | |
| | | *Wiring failure* | *No indication of valve position.* | *None* | | *Minor* | *.05b* | *MISC 61 Sn 2.3* |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| *15.6 Igniter plugs* | *Provide high energy spark in combustor to ignite fuel for engine starting or in inclement weather.* | *Carbon deposition* | *Carbon bridges contacts, preventing spark.* | *Remaining igniter will start engine* | *None* | *None* | *100a* | *MISC 61 Sn 5.4* |
| | | *Overheat* | *Overheat and cracking of insulation allows voltage discharge outside gas path* | *Remaining igniter will start engine* | *None* | *None* | *.1a* | *MISC 61 Sn 5.4* |
| | | *Loosening* | *Plug loosening allows high pressure air leak from core* | *Fire warning, IFSD* | *IFSD* | *Minor* | *1e* | |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| *15.3 Starter* | *Turbine rotates and drives engine via external gearbox, to start engine* | *Fatigue* | *Starter turbine disintegrates, debris is contained.* | *Engine cannot be started.* | *No safety effect* | *Minor* | | |
| | | *Binding* | *Starter clutch remains engaged above engine idle, starter driven by engine until turbine fails* | *As above* | | | | |
| *15.4 Ignition units* | *Convert aircraft low-voltage power to high voltage for spark ignition of fuel* | *Wiring failure* | *No power supplied to unit* | *None (remaining unit and igniter plug ignite fuel)* | *No safety effect* | *Minor* | *.05b* | *MISC 61 Sn2.3* |
| | | *Short circuit* | *Short circuit across capacitor supplies continuous low voltage power to igniter plug* | *As above* | | | | |
| *15.5 Igniter leads* | *Transmit high voltage to igniter plugs* | *Short circuit* | *No power to igniter plug* | *Possible sparks in nacelle. Possible fire. Remaining plug ignites burners* | *Fire* | *Hazardous* | *.05b* | *MISC 61 Sn 2.3* |
| | | *Open circuit* | *As above* | *As above* | *Fire* | *Hazardous* | *.05b* | |



CONTAINS RR PROPRIETARY DATA

THIS PAGE INTENTIONALLY BLANK

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| *16.1 HP shaft speed* | *Measures HP spool speed for transmission to flight deck* | *Vibration* | *High N3 indication*<br>*Low N3 indication* | *Possible IFSD or RTO*<br>*Possible RTO* | *IFSD* | *Minor* | $5_e$ | *SMK* |
| *16.2 IP shaft speed* | *Measures IP spool speed for transmission to flight deck* | *Vibration* | *High N2 indication*<br>*Low N2 indication* | *No effect*<br>*No effect* | *None* | | $5_e$ | *SMK* |
| *16.3 LP shaft speed* | *Measures LP spool speed for transmission to flight deck* | *Vibration* | *High N1 indication*<br>*Low N1 indication* | *Possible IFSD or RTO*<br>*Possible RTO* | *IFSD* | *Minor* | $5_e$ | *SMK* |
| *16.4 Turbine Gas Temperature* | *Indicates TGT to flight deck and to fuel control unit (see section 14)* | *Open circuit* | *Thermocouple harness open circuit lets TGT read high*<br>*Open circuits in TGT indicator lets TGT read low* | *Pilot may shut down engine*<br>*No crew action* | *IFSD*<br>*None* | *Minor*<br>*None* | $4_a$<br>$28_a$ | *ADR 60027* |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| 16.5 Integrated Exhaust Pressure Ratio | *Indicates engine thrust to flight deck, for pilot to set throttle* | Blockage (P1, PE) | IEPR reads high | Engine thrust set too low | IFSD | *Minor* | $10_a$ | ORR 60031 |
| | | Leakage (PF) | IEPR reads low | Engine thrust set too high | | | $10_a$ | |
| *16.6 Vibration* | *Indicates engine vibration to flight deck* | *Induced voltage* | *Signal noise interpreted as vibration* | *Engine shut down* | *IFSD* | *Minor* | *72d* | *47c* |
| *16.7 Oil temperature* | *Addressed in 13.8* | | | | | | | |
| *16.8 Oil pressure* | *Addressed in 13.10* | | | | | | | |
| *16.9 Oil low pressure* | *Addressed in 13.9* | | | | | | | |
| *16.10 Oil quantity* | *Addressed in 13.4* | | | | | | | |
| *16.11 Oil filter p'sure drop* | *Addressed in 13.7* | | | | | | | |



CONTAINS RR PROPRIETARY DATA

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| *16.12 Fuel temperature* | *Addressed in 14.7* | | | | | | | |
| *16.13 Fuel low pressure* | *Warns flight crew of low fuel pressure* | *Short circuit* | *Switch failure closed gives false warning light* | *Pilot shuts down engine* | *IFSD* | *Minor* | *10* | *SMK* |
| | | *Open circuit* | *No warning available* | *No effect* | | | | |
| *16.14 Fuel filter p'sure drop* | *Addressed in 14.6* | | | | | | | |
| *16.15 Cooling air overheat* | *Warns flight crew of overheat in turbine cooling system* | *Leakage* | *Leak in HP3 line allows only IP air to be sensed* | *No overheat protection* | *None* | | | *SMK* |
| | | | *Leak in IP line allows only HP3 air to be sensed* | *Overheat incorrectly signalled* | *IFSD* | *Minor* | *10* | |
| | | | *Switch fails open or closed* | *No effect (dual switches and test circuitry* | *None* | | | |
| *16.16 Fuel flow* | *Addressed in 14.4* | | | | | | | |



CONTAINS RR PROPRIETARY DATA

THIS PAGE INTENTIONALLY BLANK

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| *17 .1 Anti-ice duct* | *Supplies anti-icing air to nose cowl* | *Fatigue* | *Rapid crack growth and hot air leak into fan zone* | *Fire warning. Duct flailing may damage adjacent components* | *IFSD* | *Minor* | *.02b* | *Analogy to TDR5796* |
| *17.2 Anti-ice duct valve* | *Admits anti-ice air to nose cowl* | *Jamming* | *Valve fails closed* | *Nose cowl accumulates ice in flight, which sheds into engine. Vibration and IFSD* | *IFSD* | *Minor* | *1.3d* | *NPRD-1* |
| | | | *Valve fails open* | *Possible nose cowl overheat.* | *None* | | *1.3d* | *NPRD-1* |
| *17.3 Spinner anti-ice supply* | *Addressed in section 1* | | | | | | | |
| *17.4 P1 probe anti-icing* | *Addressed in section 14* | | | | | | | |



CONTAINS RR PROPRIETARY DATA

THIS PAGE INTENTIONALLY BLANK

| COMPONENT | FUNCTION | FAILURE MODE | | SYSTEM EFFECT | ENGINE EFFECT | CRITICALITY | PROBABILITY PER MILLION ENGINE HOURS | ANALYSIS SOURCE |
|---|---|---|---|---|---|---|---|---|
| | | MECHANISM | PROPAGATION | | | | | |
| *18.1 HP air duct* | *Supplies air to airframe for pressurisation, anti-icing, etc.* | *Fatigue* | *Rapid crack propagation and duct failure.* | *Increased bleed extraction from engine, causing TGT rise. Possible overheat indication and IFSD. Cowling overpressure.* | *IFSD* | *Minor* | *.02a* | *TDR 5777 MDR 60289* |
| *18.2 IP air duct* | *Supplies air to airframe for pressurisation, anti-icing, etc.* | *Fatigue* | *Rapid crack propagation and duct failure.* | *Increased bleed extraction from engine, causing TGT rise. Possible overheat indication and IFSD* | *IFSD* | *Minor* | *.02a* | *TDR 5796* |
| *18.3 Starter duct* | *See section 15* | | | | | | | |
| *18.4 Anti-ice duct* | *See section 17* | | | | | | | |



CONTAINS RR PROPRIETARY DATA

THIS PAGE INTENTIONALLY BLANK

# APPENDIX H

# EFFECT OF MINOR DESIGN CHANGES

THIS PAGE INTENTIONALLY BLANK

# APPENDIX H: EFFECT OF SMALL DESIGN CHANGES

## Hi Introduction

It is common practice within the aircraft engine industry to produce higher-thrust versions of an engine model as experience is gained in service by the baseline model, and confidence in the basic design increases. The likely reliability and safety of higher-thrust derivative engines has been the occasion of considerable debate. It has been argued that an increase in engine thrust must necessarily involve reduced margins for such design parameters as rotor speed, turbine gas temperature and compressor delivery pressure, and that therefore reliability must necessarily be reduced. Conversely, it has been claimed that incorporation of lessons learned from the original engine model will eliminate many problems and produce an engine with greater reliability than the original, providing that margins for physical parameters conform to accepted design standards, and that few causes of engine failures are directly linked to engine thrust.

Given this fundamental disagreement upon the effect of thrust growth, it is not surprising that guidance should be lacking upon the extent of design change which would necessitate a modification to the safety analysis. If the safety analysis is to provide useful information to the design community, it is essential to establish how small changes in design or operation are likely to impact the validity of a previous safety analysis.

## Hii Engine selection

The Spey engine was used to study the effect of thrust growth upon engine failure rates. The Spey has been in service since the 1960s; the Spey 505, Spey 506, Spey 511 and Spey 512 offer progressively greater take-off thrust ratings and the Spey 555 represents a greater departure from the baseline design, being both lighter and simpler. The Spey 555 formed the basis for the core of the recently offered Tay high bypass-ratio engine, with considerable increases in thrust offered.

The Tay 610/611 and Tay 620 are physically identical; the Tay 650 features fan, combustor and high pressure turbine changes to accommodate higher thrust. The Spey/Tay family, therefore, permits assessment of thrust growth effects and also the effects of major redesign, in the case of the Spey 555 and Tay engines.

The record of in service events (IFSDs etc) analysed in this study was provided by Rolls Royce for the purpose of this specific study and is proprietary to Rolls Royce.

## Hiii Reliability/safety parameter

Two measures of engine reliability were initially chosen for making comparisons between engine models; the in-flight shutdown rate and the rate of unscheduled engine removals. Both of these were calculated annually, per engine operating hour. The selection was heavily influenced by the availability of service data; it is conceded that these parameters provide a better measure of reliability than of safety as such. The rarity of purely safety-related events, however, introduces considerable random scatter in event rates from year to year, rendering trending of rates a questionable exercise, and making small differences in event rates (such as might be seen between two engine models) difficult to assess. The validity of this approach was tested by reviewing the incidence of rotor bursts in the Spey, using a series of FAA studies ((54) through (63)). Rotor burst, although not necessarily resulting in uncontained failure, is clearly related to engine safety. Figure H.1 illustrates the variation in rotor burst incidence from year to year.

[1]
When a mean rotor burst rate was calculated for each of the models assessed, the ratio of the rates (555/506 rate) was approximately 0.29. Comparison of equivalent IFSD rates gives a value of 0.4, and comparison of UER rates gives a ratio of 0.5 for these two engine models. It can therefore be concluded that analysis of IFSD rates and of UER rates gives some indication of relative engine safety, although more credence is to be placed in the IFSD rate than the UER rate, both intuitively (an IFSD approaches closer to an emergency than does a UER) and statistically (the IFSD ratio described above is closer to the rotor burst ratio, which has a direct safety relationship, than is the UER ratio.)

## Hiv Variation of failure rates with time

The IFSD rates and UER rates for civil Spey engine models from 1967 to 1993 are shown in Figures H.2 and H.3. Although all the data available from Rolls-Royce has been used to generate these figures, the apparent low failure rates in the 1960s and early 1970s do not reflect the actual performance of the fleet, but rather the difficulties associated with a manual data-storage system. Introduction of an electronic data storage system in the late 1970s enabled a much greater proportion of events to be recorded in an accessible form. The effect of recording systems' influence upon the study has been minimised by using data from 1980 onwards for comparison of failure rates. It should also be noted that several models are in the process of going out of service, greatly reducing the number of fleet hours per year for the 1990s. Error bars indicate the change in rate

---

[1]The absolute values of the rates shown should not be considered, since they were calculated using a subset of rotor bursts (those in the USA) divided by world fleet engine operating hours, but the rates serve to compare the incidence of rotor burst from one model to the next.

attributable to one more or one less IFSD or UER in the later years; clearly the absolute magnitude of the failure rate should be treated with some caution where the size of the error bar approaches the difference in failure rates between models.

Subject to the above caveats, the following points are clear from inspection of Figs H.2 and H.3; the Spey 505 experienced the highest rates of IFSDs and UERs, followed by the Spey 512, the Spey 506 and 511, and the lowest rates were experienced by the Spey 555, in general (the order may vary in individual years, but is generally valid for the time period 1980 - 1990).
It has been hypothesized that the earlier models would have the highest failure rates, and there would be a steady improvement from model to model as design problems were addressed and as design techniques improved in sophistication. This did not prove to be universally true, as demonstrated by the relatively high failure rate[2] of the Spey 512 (see Fig H.4).

It might be argued that comparison of failure rates versus calendar time is inappropriate, since the engine models were introduced into service in different years, and have accrued experience at different rates, not only do the different models have differing maturity at the outset, but the relationships between models also vary with time. The failure rates were therefore plotted against fleet hours, as shown in H.5 and H.6. Unfortunately, data corresponding to similar fleet maturities were unavailable for all five models, rendering true comparison impossible, but it seems unlikely upon reviewing the figures that the putative correlation between thrust and failure rate would obtain.

---

[2]Hourly IFSD rates and UER rates averaged (total events/total hours) over the experience of the fleet since the beginning of 1980

## Hv Relationship between failure rates and basic physical parameters

It appears intuitively obvious that higher thrust settings, involving higher core air pressures and temperatures and higher rotor speeds, would produce higher failure rates, other factors being equal. Figures H.7 to H.10 show mature average failure rates with respect to rated thrust, compressor delivery pressure (T/O power), core engine speed (T/O power) and turbine gas temperature. The Spey 505 and 512 generally exhibited higher failure rates than would be anticipated from consideration of basic engine parameters. Review of the Tay IFSD rates (see Table H.1) confirmed that there was no strong relationship between failure rates and basic engine parameters between one model and the next.

| **TAY MODEL** | **610/ 611** | **620** | **650** |
|---|---|---|---|
| IFSD RATE (/MILLION HOURS) | 10.4 | 27.8 | 16.1 |
| THRUST (LB) SLS | 12420 | 13850 | 14000 |
| N2 AT TAKEOFF (RPM) | 12234 - 12446 | 12550 | 12560 |
| COMPRESSOR DELIVERY PRESSURE (PSI) | 232 | 232 | 238 TO 244 |
| | | | |

TABLE H.1

As a final check, a similar table was constructed for a completely unrelated engine family, the CFM56. No clear relationship between engine-caused IFSD rates and basic parameters was evident (table H.2).

| CFM56 MODEL | CFM56-2 | CFM56-3 | CFM56-5A | CFM56-5C |
|---|---|---|---|---|
| ENGINE-CAUSED IFSD RATE (/MILLION HOURS) | 8 | 2 | 5 | 8 |
| THRUST (LB) SLS | 22000 | 20100 | 25000 | 31000 |
| EGT (CELSIUS) | 905 | 930 | 905 | 905 |
| COMPRESSOR DELIVERY PRESSURE (PSI) | 367 | 441 | 460 | 550 |

TABLE H.2

A more detailed study of the Spey and Tay IFSDs was undertaken, separating the IFSDs by cause into four system groups; those attributable to instrumentation errors and false fire or overheat warnings, those attributed to the fuel or oil systems, those attributed to turbomachinery (including bearing and gearbox failures) and all others (mainly associated with the bleed system). The results are shown in Figures H.11 to H.16.

The following points are of considerable significance:

Turbomachinery failures were not the dominant contributor to the IFSD rate. Instrumentation faults and fuel/oil system problems each made similar contributions to the overall IFSD rate.

Those models with high overall IFSD rates (the 506 and 512) had high rates of IFSDs caused by instrumentation as well as those caused by turbomachinery. The rates of instrumentation problems might have been expected to be similar from one engine to the next.

The IFSD rate caused by turbomachinery alone was not strongly related to any engine basic parameter.

The Tay IFSD rates for instrumentation and for fuel/oil systems were comparable to those of Spey engines. The Tay turbomachinery IFSD rate was an order of magnitude better than that of the Spey.

Significant improvements in the reliability of turbomachinery appear to result from major redesigns (Spey 555 and Tay 610/611).

Hvi Installation effects

It was proposed that the number of engines in the aircraft installation could have a significant effect upon the IFSD rate, since the crew would be less likely to perform a precautionary shut down on an engine of a twin than of a tri-jet. All IFSDs caused by instrumentation/false warnings can be considered precautionary shutdowns; those caused by turbomachinery or fuel/oil system failures are generally likely to have led to an IFSD regardless of the crew's reluctance to shut down an engine (with certain exceptions).
If the crew of a 3-engined aircraft is more disposed to precautionary shutdowns than the crew of a twin, then the ratio of IFSDs caused by false warnings or instrumentation faults should be higher for the 3 engined airplane, other factors being equal (the crew of the twin will verify an apparent problem by reference to other engine parameters before shutting down). The Spey 512 is installed on both twin engined and 3-engined aircraft. Review of the causes of Spey 512 IFSDs, from 1980 to 1990, showed that for twins, faulty instrumentation/false warnings caused 25% of all IFSDs, and for 3-engined airplanes, these causes accounted for 19% of all IFSDs. This difference can easily be explained by such factors as selection of different instrument vendors by different airplane companies, but there does not appear to be a significantly greater likelihood of a precautionary IFSD for a tri-jet than a twin.

The Tay appeared to experience a significantly greater number of IFSDs attributable to instrumentation/false warnings when installed in the F100 than the GIV. It must be recognised that the operational environment of a short-range commercial transport is very different from that of a business jet, and high usage might increase the number of IFSDs attributable to limited troubleshooting or hurried maintenance.

Hvii Design margin

It had been suggested that design margin would provide a better indicator of engine safety/reliability than absolute levels of any physical parameter. This possibility is difficult to evaluate directly without access to detailed design studies. The Tay turbomachinery-related IFSD rate increased from 1/million hours to 1.5/million hours when the same turbomachinery was run at higher thrust and design margin can be presumed to be smaller (Tay 611 vs. 620). However, this effect is negligible compared with the IFSD contribution from instrumentation and fuel/oil systems.

## Hviii Conclusions

There is no clear relationship between increased thrust (or core speed, or turbine gas temperature, or compressor discharge pressure) and turbomachinery-caused IFSD[3] rate. The overall IFSD rate is strongly influenced by instrumentation faults and problems with ancillary systems such as fuel and engine oil, which would not be expected to be closely linked to engine thrust levels. The contribution of turbomachinery to the IFSD rate is much smaller for recent engine models than for those entering service thirty years ago, to the extent that it could be claimed that turbomachinery is an insignificant contributor to the IFSD rate.
Turbomachinery failures are nevertheless the major contributor to other safety related failures such as uncontained failures and casing rupture, but the relationship between these and increased thrust is yet to be established.

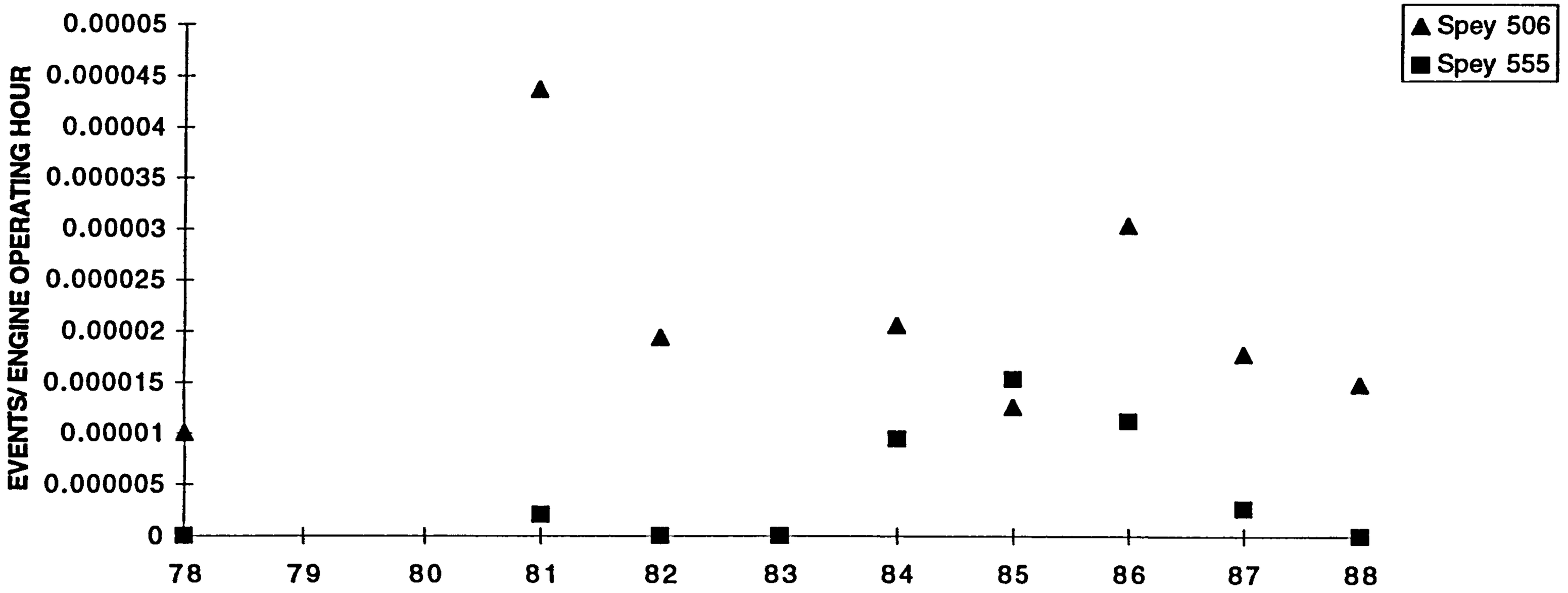
This study was initiated to attempt to establish the effect upon the engine safety of a small design change such as a thrust bump, and the necessity or otherwise of modifying the safety analysis. Generally, the qualitative portion of the analysis does not consider such factors as thrust levels in the prediction of failure progressions. It appears from this study that there is no clear means of forecasting the effect on failure rates of a design change such as a throttle push. The original study should therefore remain valid, except for any specific failure modes which have been precluded (or enabled) by changes to the hardware.

---

[3] The concept of using a base failure rate with severity factors applied to different environments is immediately called into question

THIS PAGE INTENTIONALLY BLANK

## ROTOR BURST RATES* FOR SPEY FROM FAA STUDY




*Absolute values of rates should not be used; based on an incomplete sample.

FIGURE H.1

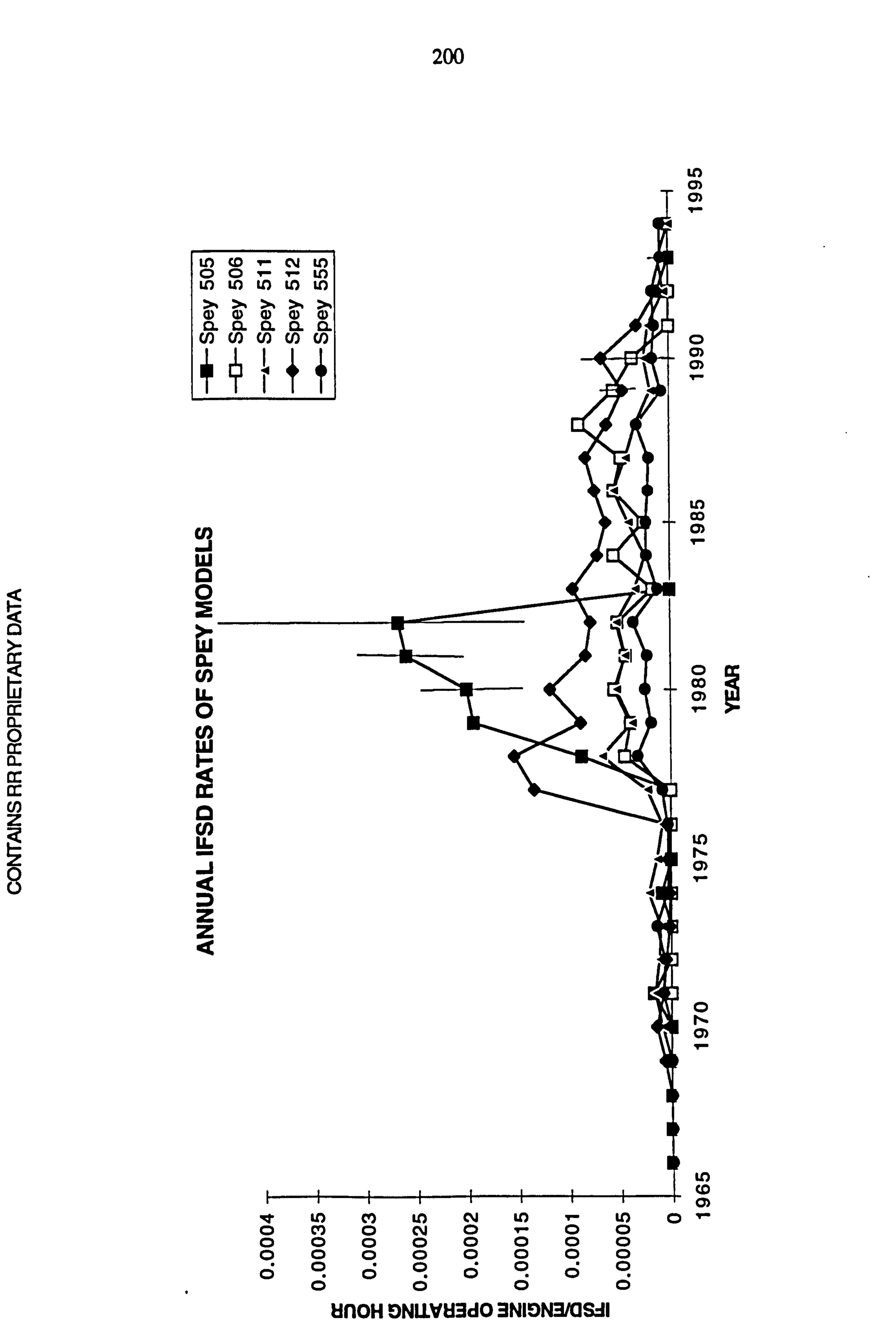

CONTAINS RR PROPRIETARY DATA
ANNUAL IFSD RATES OF SPEY MODELS
Spey 505
Spey 506
Spey 511
Spey 512
Spey 555
IFSD/ENGINE OPERATING HOUR
0.0004
0.00035
0.0003
0.00025
0.0002
0.00015
0.0001
0.00005
0
1965
1970
1975
1980
1985
1990
1995
YEAR

FIGURE H2

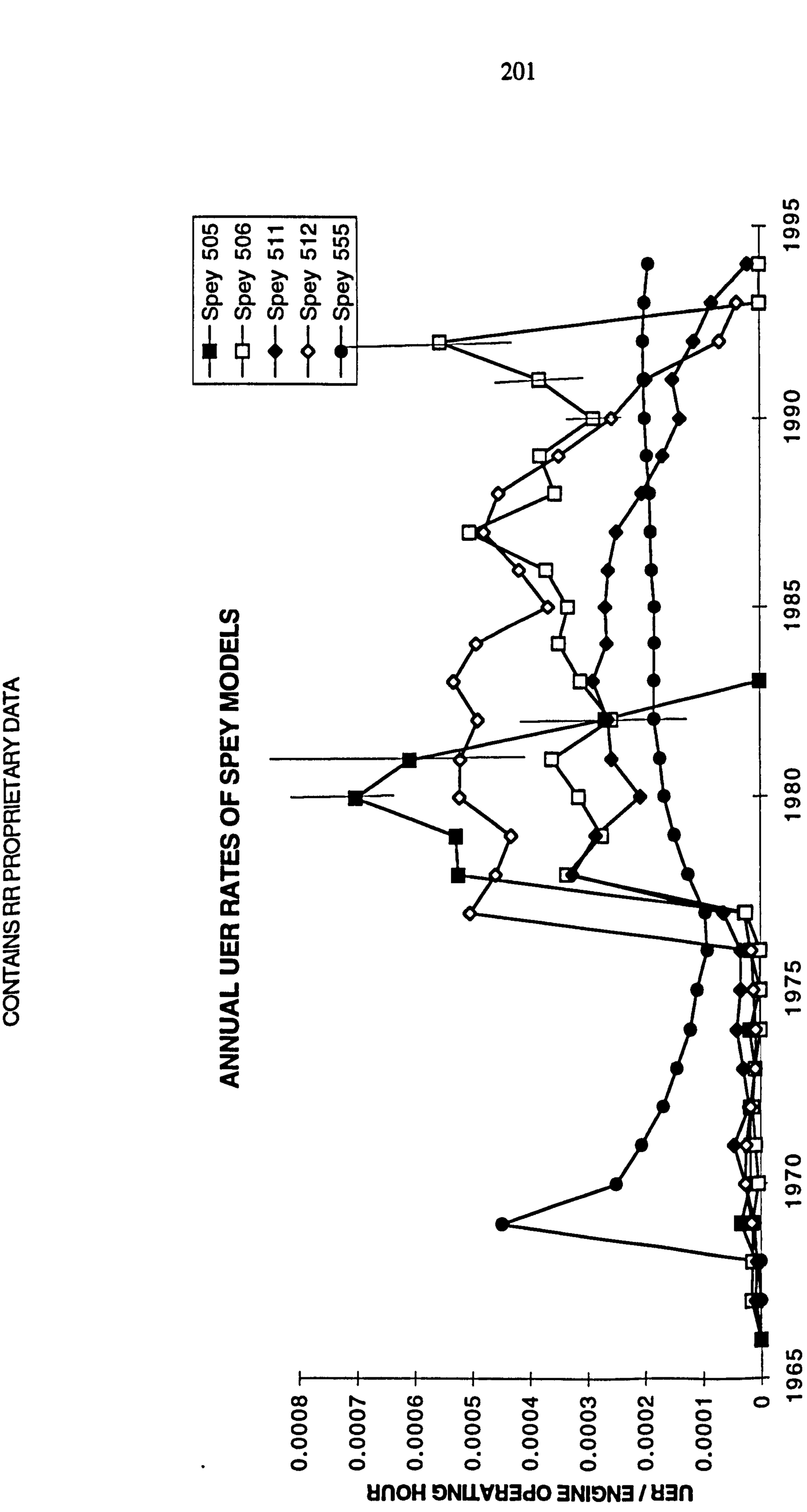

Spey 505
Spey 506
Spey 511
Spey 512
Spey 555
ANNUAL UER RATES OF SPEY MODELS
CONTAINS RR PROPRIETARY DATA
UER / ENGINE OPERATING HOUR
0.0008
0.0007
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0
1965
1970
1975
1980
1985
1990
1995
YEAR

FIGURE H.3

## MATURE FAILURE RATES VS DATE OF ENTRY INTO SERVICE FOR SPEY MODELS

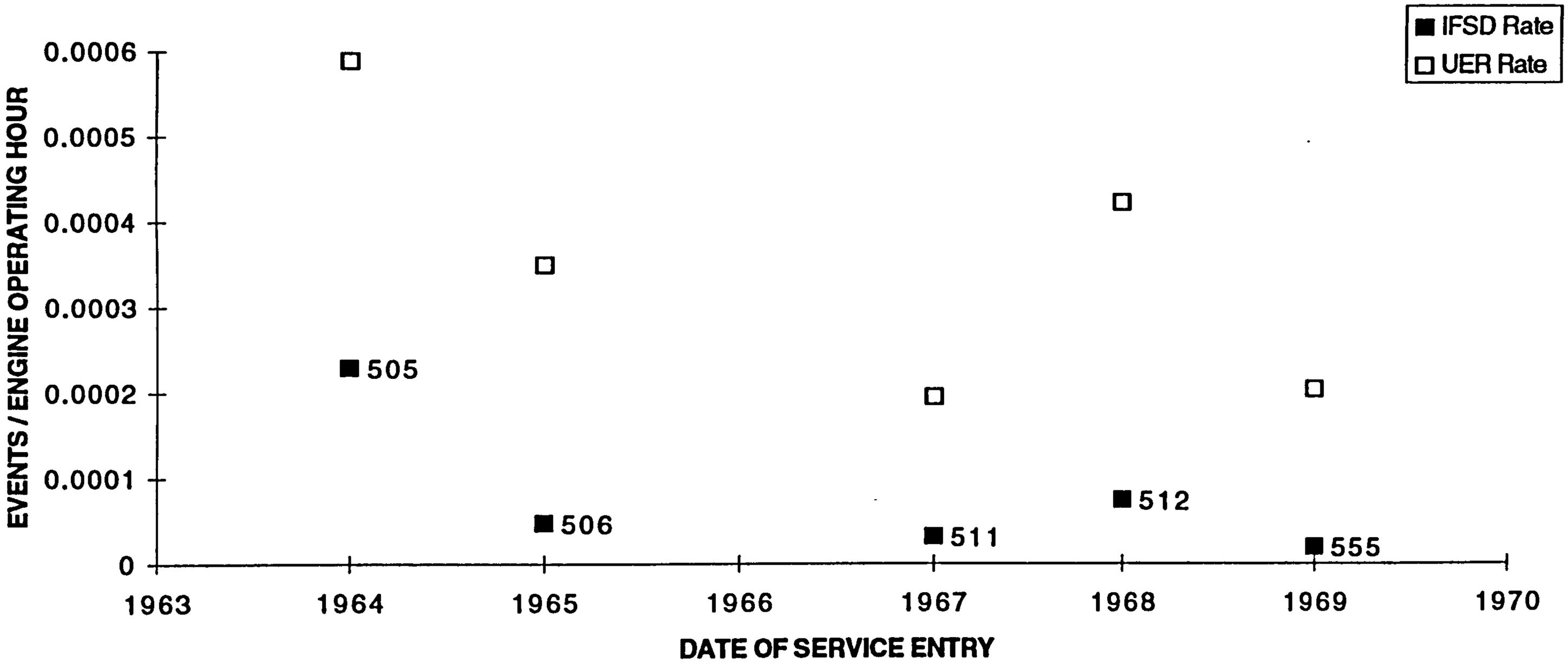





*FIGURE H.4*

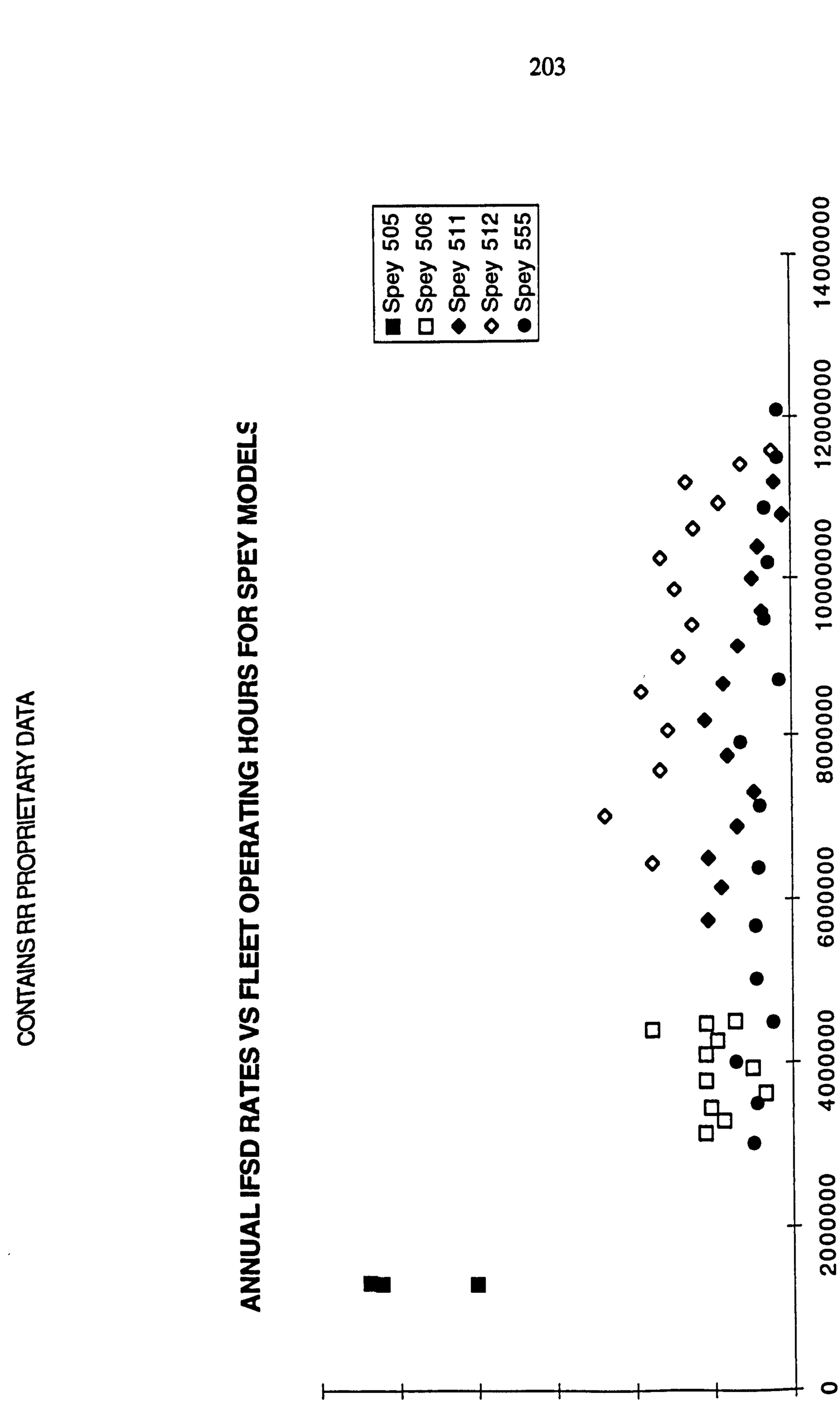

CONTAINS RR PROPRIETARY DATA
ANNUAL IFSD RATES VS FLEET OPERATING HOURS FOR SPEY MODELS
Spey 505
Spey 506
Spey 511
Spey 512
Spey 555
IFSD/ENGINE OPERATING HOUR
0.0003
0.00025
0.0002
0.00015
0.0001
0.00005
0
MODEL FLEET HOURS
0
2000000
4000000
6000000
8000000
10000000
12000000
14000000

FIGURE H5

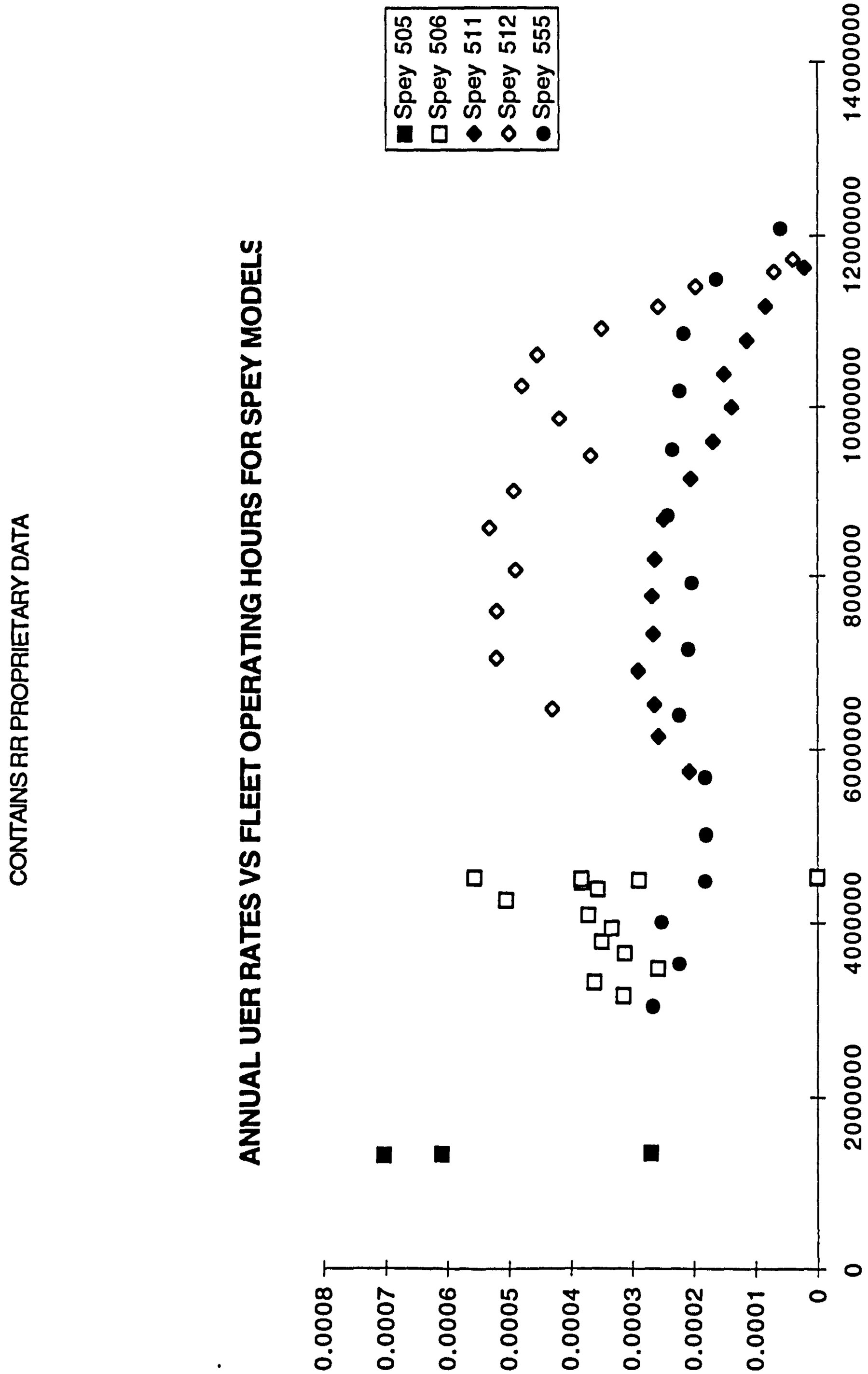

CONTAINS RR PROPRIETARY DATA
ANNUAL UER RATES VS FLEET OPERATING HOURS FOR SPEY MODELS
Spey 505
Spey 506
Spey 511
Spey 512
Spey 555
0.0008
0.0007
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0
UER / ENGINE OPERATING HOUR
0
2000000
4000000
6000000
8000000
10000000
12000000
14000000
MODEL FLEET HOURS

FIGURE H.6

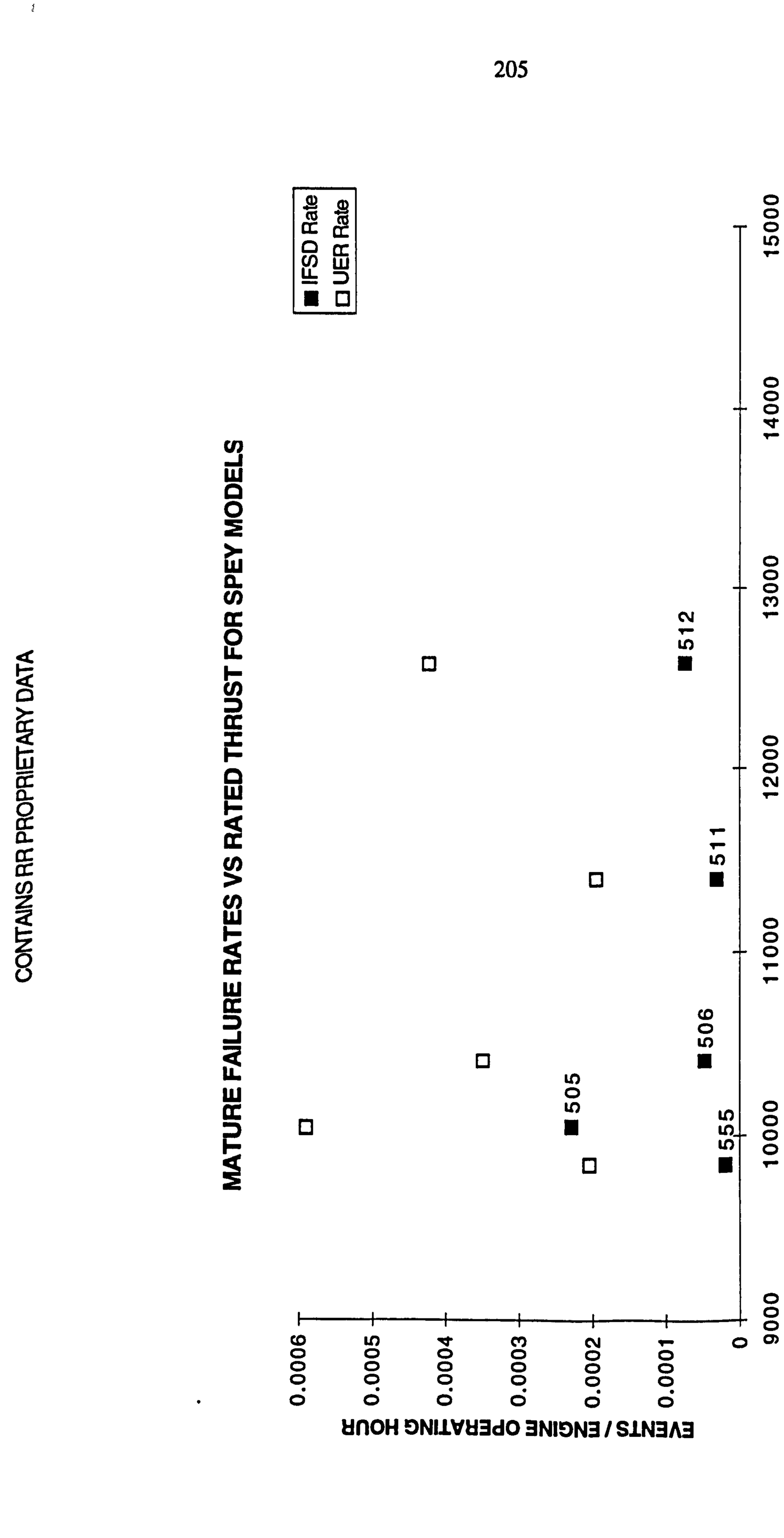

CONTAINS RR PROPRIETARY DATA
MATURE FAILURE RATES VS RATED THRUST FOR SPEY MODELS
IFSD Rate
UER Rate
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0
9000
10000
11000
12000
13000
14000
15000
LB THRUST (TAKE OFF)
EVENTS / ENGINE OPERATING HOUR
555
505
506
511
512

FIGURE H.7

CONTAINS RR PROPRIETARY DATA

**MATURE FAILURE RATES VS COMPRESSOR DELIVERY PRESSURE FOR SPEY MODELS**

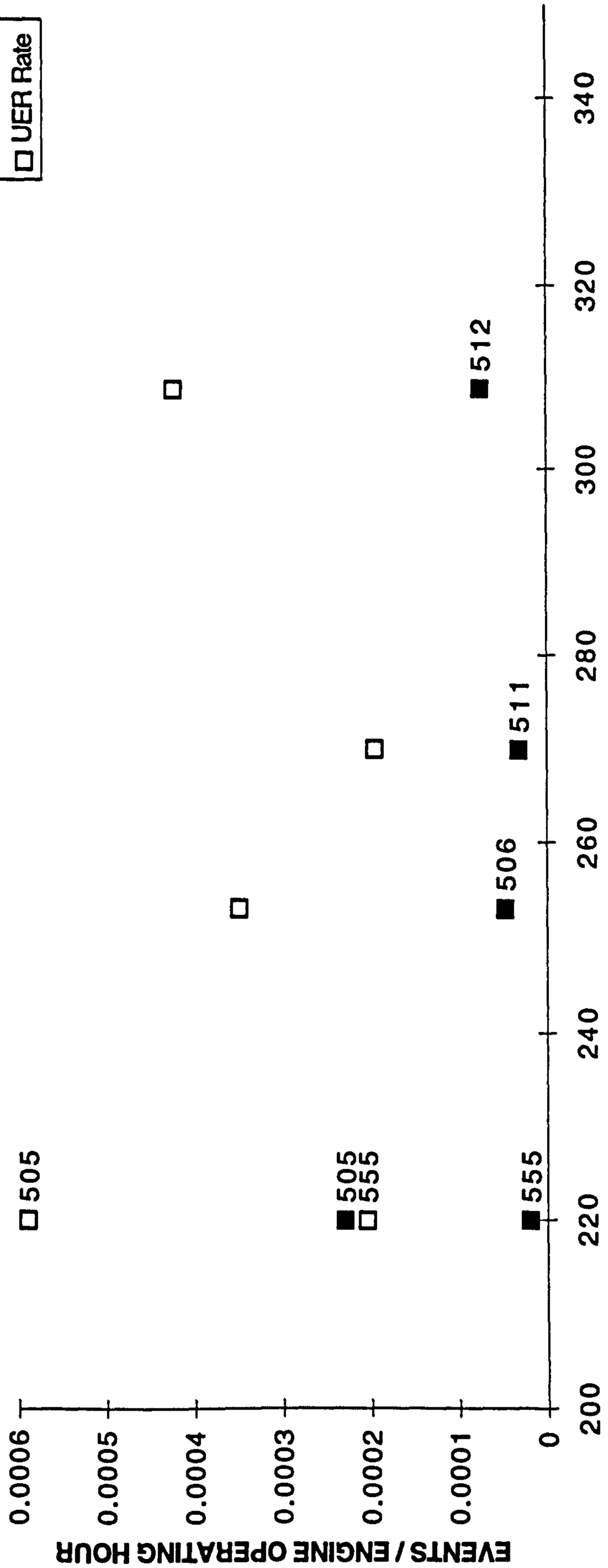



FIGURE H.8

CONTAINS RR PROPRIETARY DATA

**MATURE FAILURE RATES VS CORE SPEED FOR SPEY MODELS**

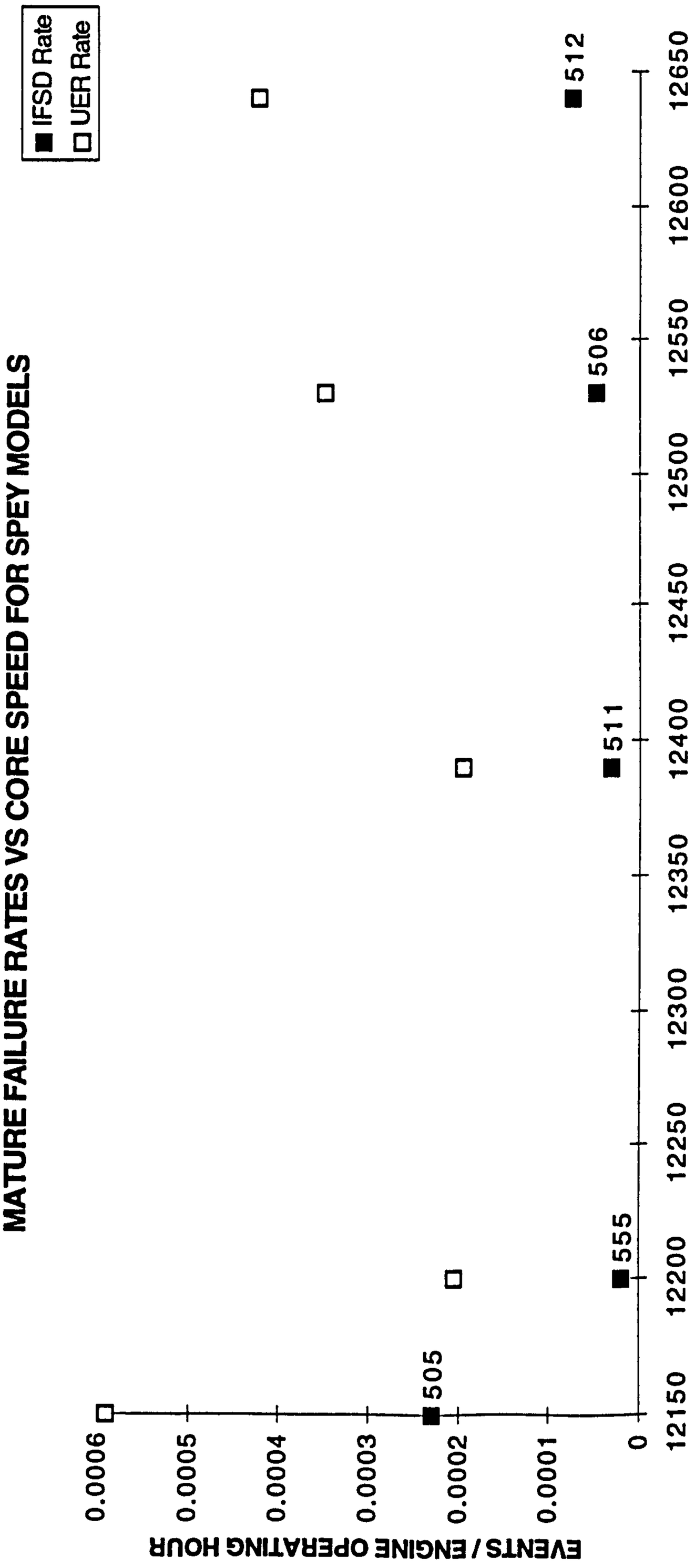
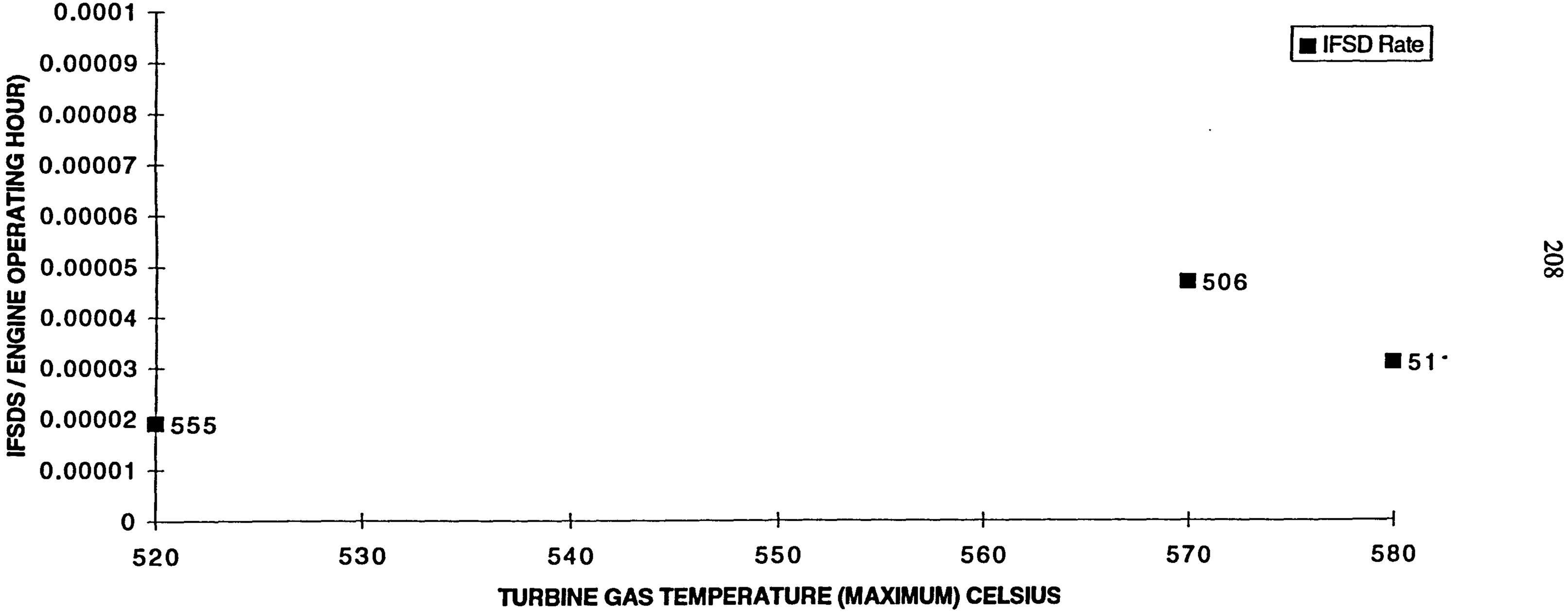



FIGURE H.9

CONTAINS RR PROPRIETARY DATA

## MATURE FAILURE RATES VS TGT FOR SPEY MODELS




208

FIGURE H.10

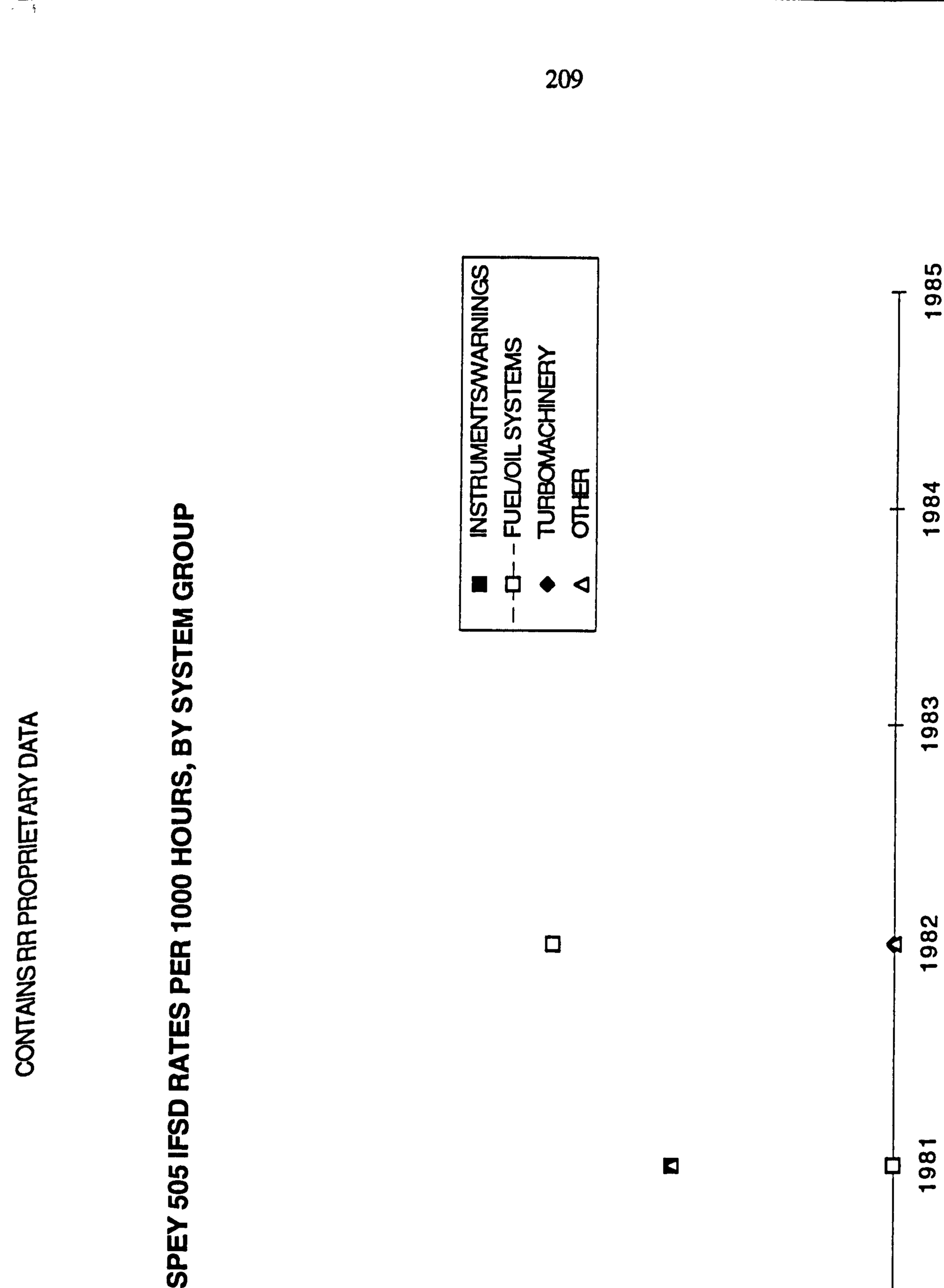

SPEY 505 IFSD RATES PER 1000 HOURS, BY SYSTEM GROUP
CONTAINS RR PROPRIETARY DATA
INSTRUMENTS/WARNINGS
FUEL/OIL SYSTEMS
TURBOMACHINERY
OTHER
IFSD/ 1000 ENGINE HOURS
0.25
0.2
0.15
0.1
0.05
0
1980
1981
1982
1983
1984
1985
YEAR

FIGURE H.11

CONTAINS RR PROPRIETARY DATA

**SPEY 506 IFSD RATES PER 1000 HOURS, BY SYSTEM GROUP**

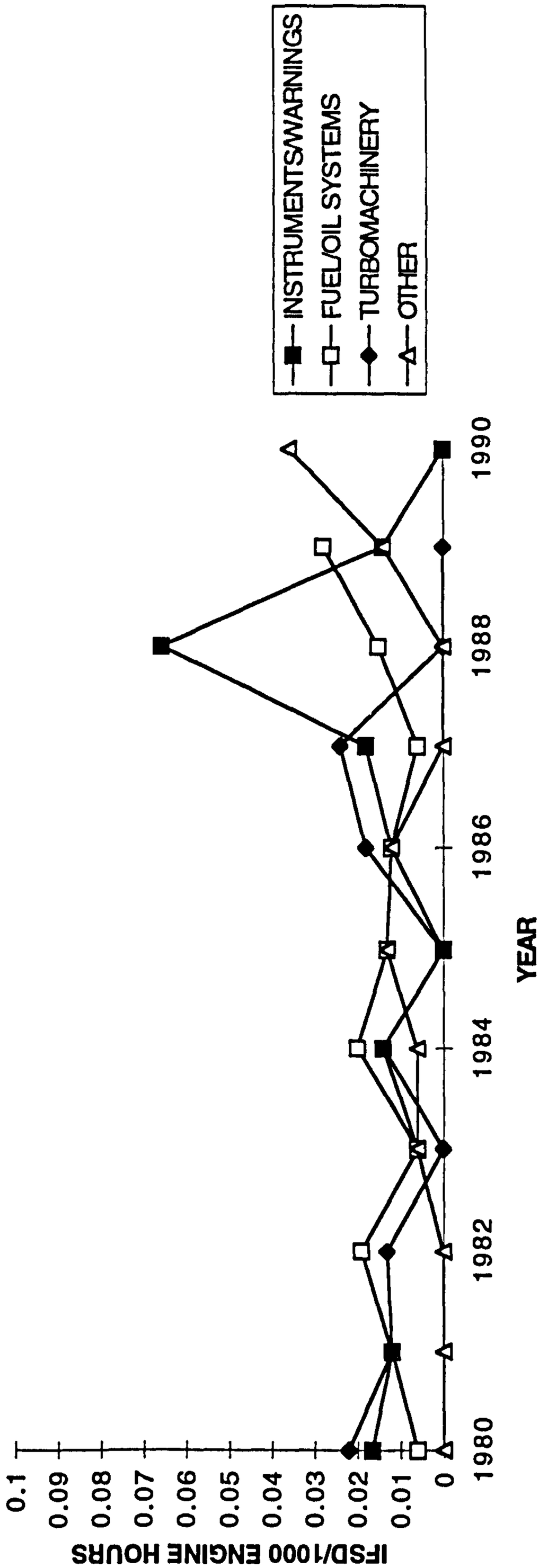



FIGURE H.12

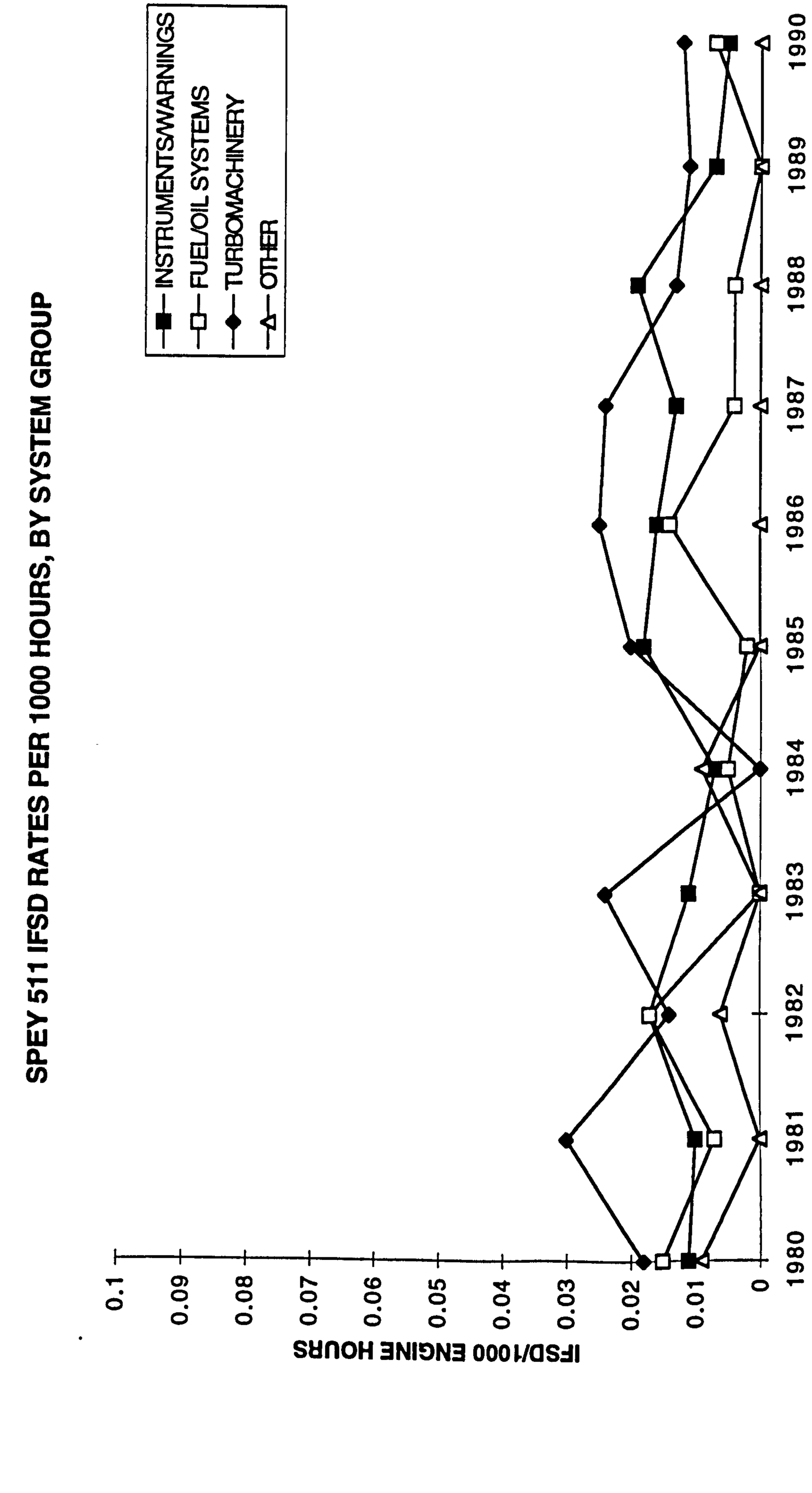

CONTAINS RR PROPRIETARY DATA
SPEY 511 IFSD RATES PER 1000 HOURS, BY SYSTEM GROUP
INSTRUMENTS/WARNINGS
FUEL/OIL SYSTEMS
TURBOMACHINERY
OTHER
IFSD/1000 ENGINE HOURS
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
1980
1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
YEAR

FIGURE H.13

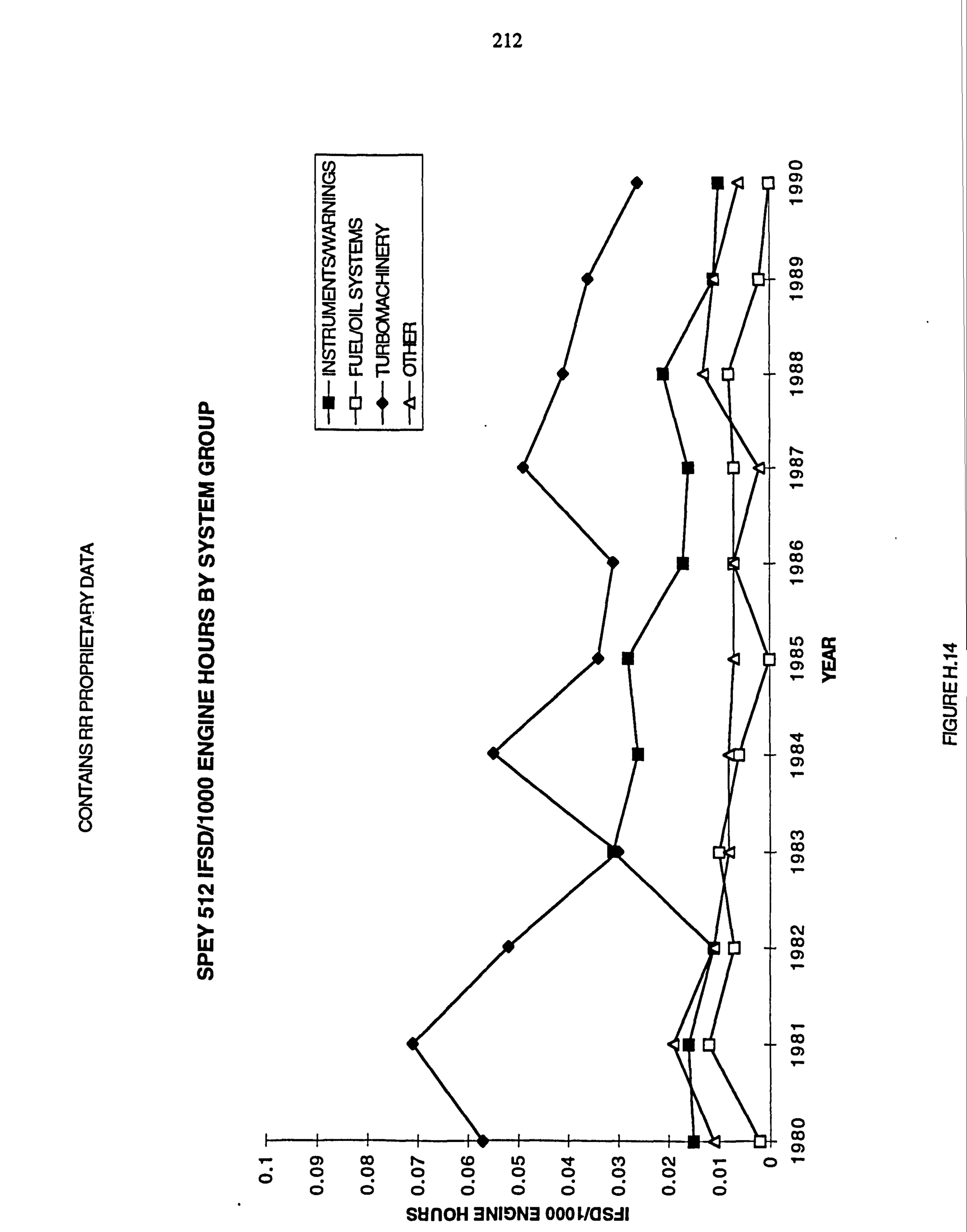

CONTAINS RR PROPRIETARY DATA
SPEY 512 IFSD/1000 ENGINE HOURS BY SYSTEM GROUP
INSTRUMENTS/WARNINGS
FUEL/OIL SYSTEMS
TURBOMACHINERY
OTHER
IFSD/1000 ENGINE HOURS
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
1980
1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
YEAR

FIGURE H.14

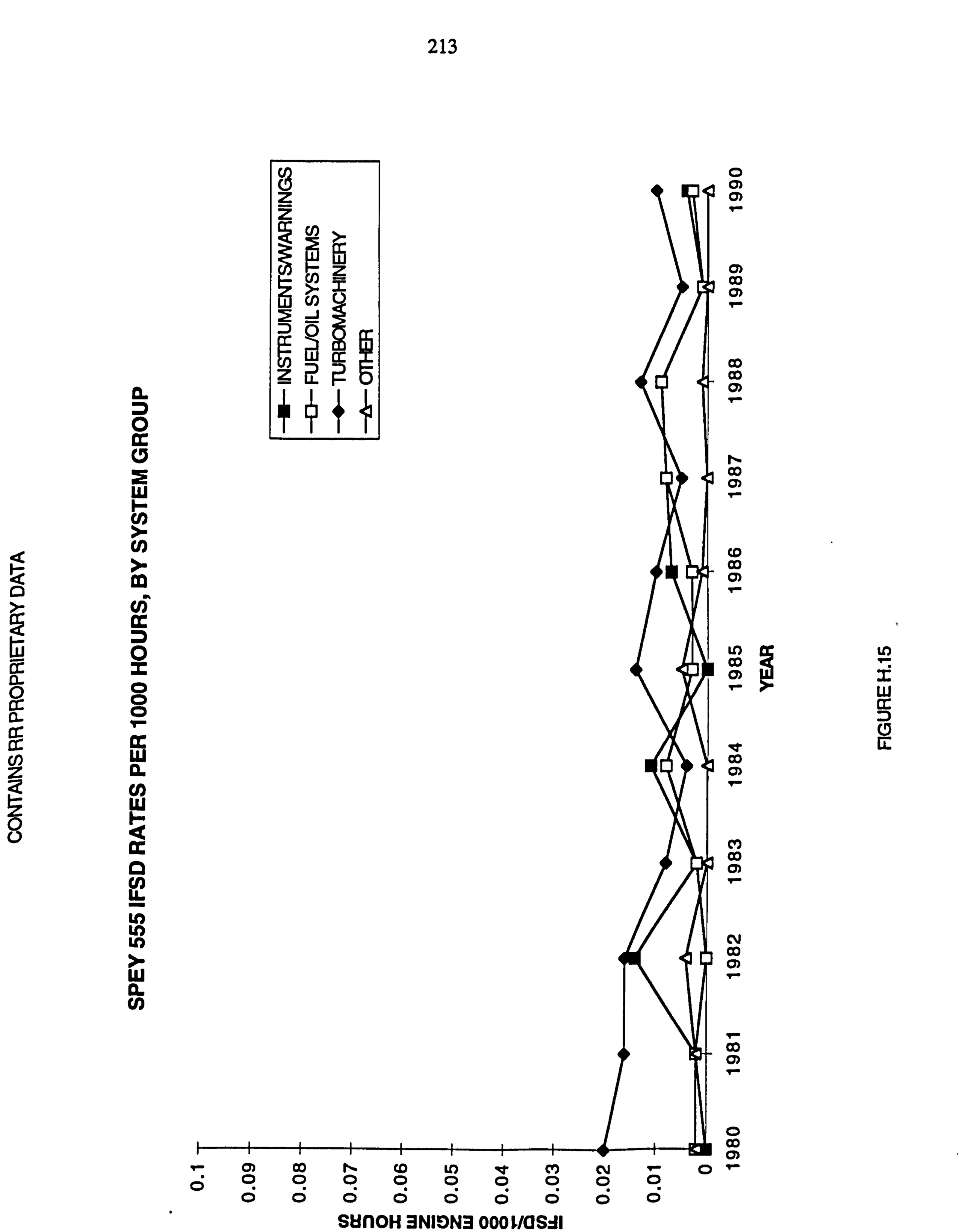

CONTAINS RR PROPRIETARY DATA
SPEY 555 IFSD RATES PER 1000 HOURS, BY SYSTEM GROUP
INSTRUMENTS/WARNINGS
FUEL/OIL SYSTEMS
TURBOMACHINERY
OTHER
IFSD/1000 ENGINE HOURS
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
1980
1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
YEAR

FIGURE H.15

## TAY IFSD RATES BY MODEL AND BY SYSTEM GROUP

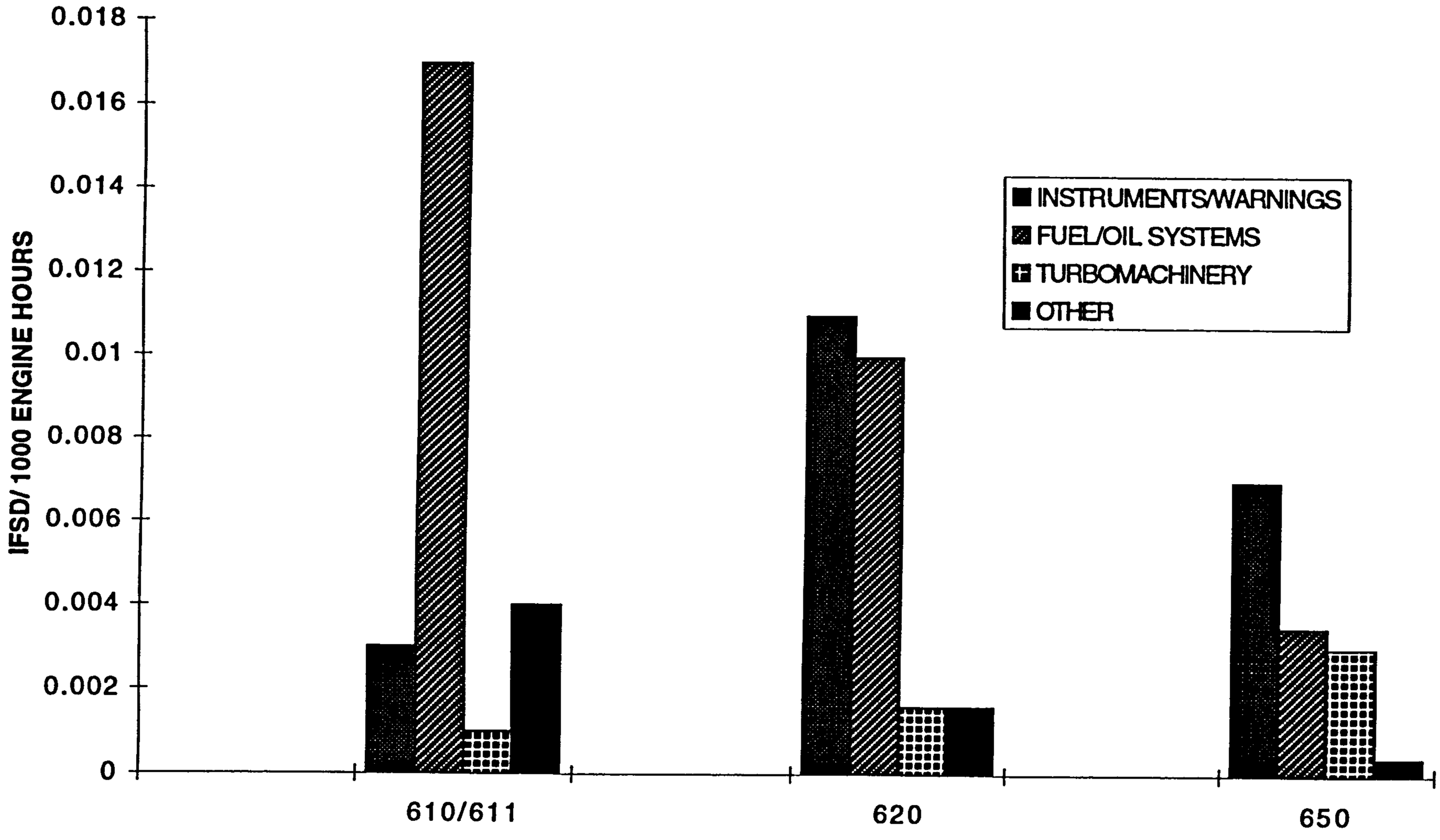



FIGURE H.16

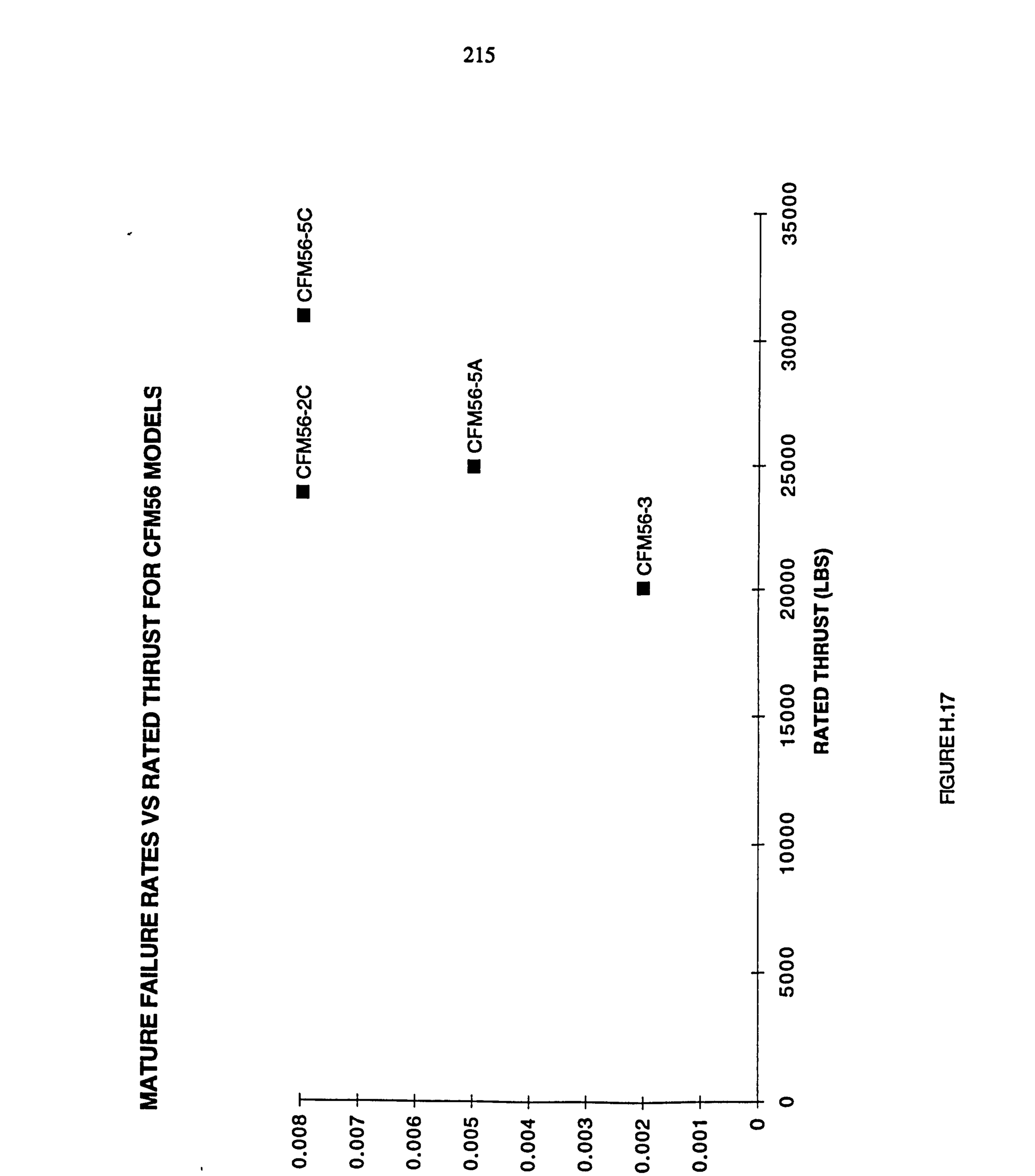



FIGURE H.17 IMMATURE FAILURE RATES VS RATED THRUST FOR CFM56 MODELS

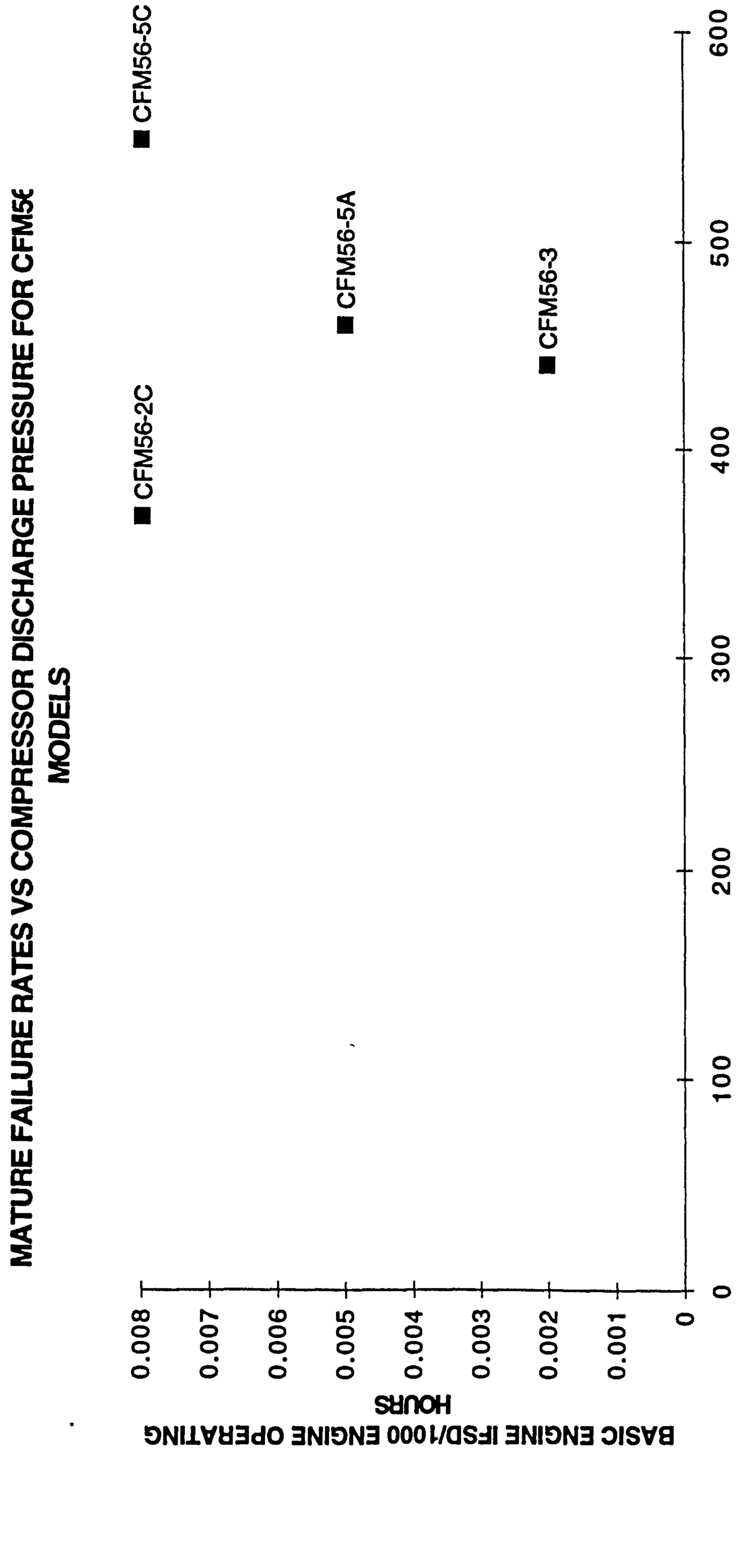

MATURE FAILURE RATES VS COMPRESSOR DISCHARGE PRESSURE FOR CFM56
MODELS
BASIC ENGINE IFSD/1000 ENGINE OPERATING HOURS
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
0
100
200
300
400
500
600
COMPRESSOR DISCHARGE PRESSURE (PSI)
CFM56-2C
CFM56-3
CFM56-5A
CFM56-5C

FIGURE H.18

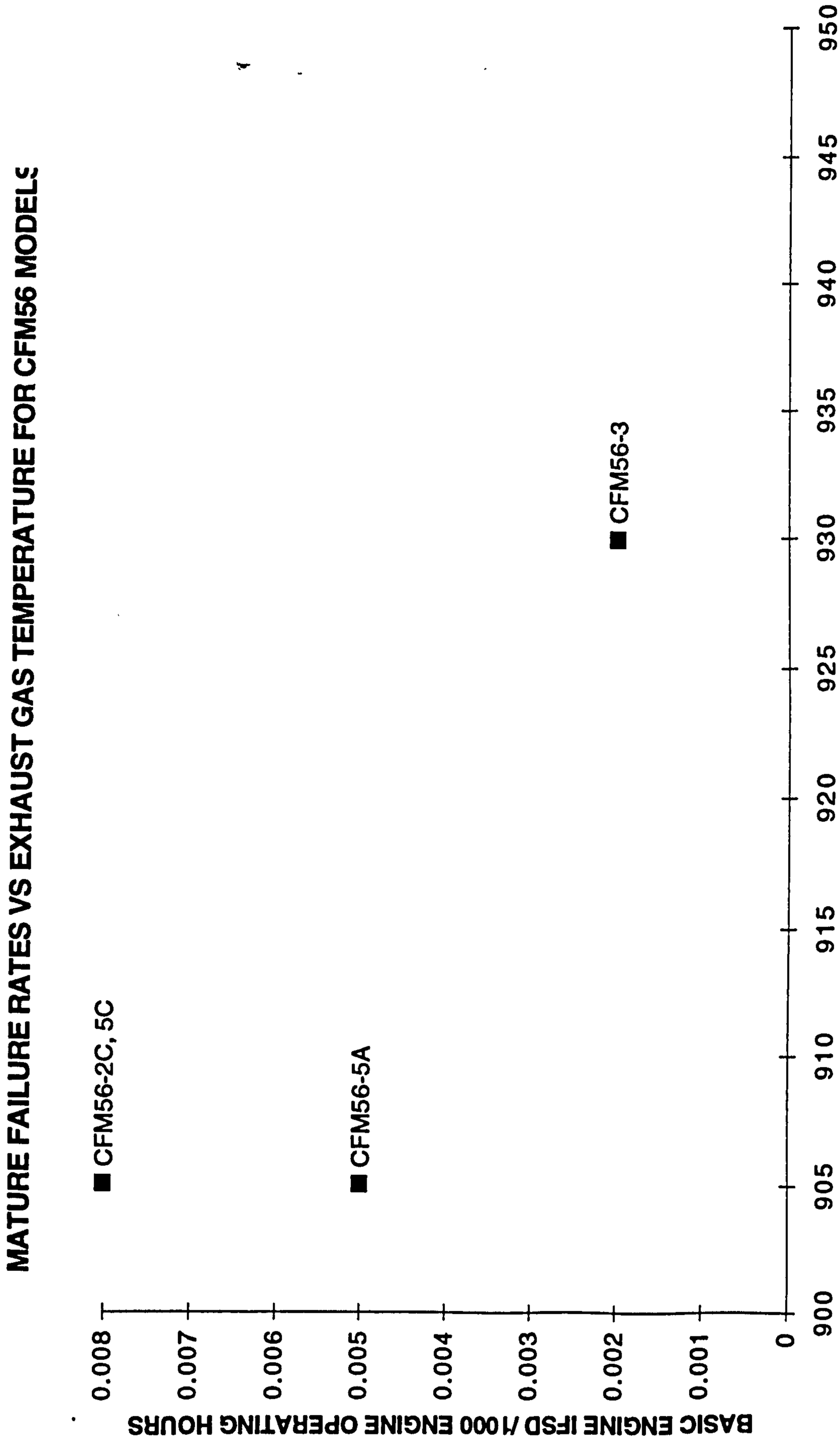

MATURE FAILURE RATES VS EXHAUST GAS TEMPERATURE FOR CFM56 MODELS
CFM56-2C, 5C
CFM56-5A
CFM56-3
BASIC ENGINE IFSD /1 000 ENGINE OPERATING HOURS
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
900
905
910
915
920
925
930
935
940
945
950
EGT (CELSIUS)

FIGURE H.19