

CRANFIELD UNIVERSITY



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**PERFORMANCE AND CFD ANALYSES FOR A NOVEL AND
EXISTING THRUST REVERSER DESIGNS**

SCHOOL OF ENGINEERING

PhD THESIS

CRANFIELD UNIVERSITY

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DEPARTMENT OF ENERGY, POWER AND PROPULSION

PhD THESIS

2009-2014

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**PERFORMANCE AND CFD ANALYSES FOR A NOVEL AND
EXISTING THRUST REVERSER DESIGNS**

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April 2014

This thesis is submitted in fulfilment of the requirements for the degree of
Doctor of Philosophy

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Acknowledgements

First of all, I would like to express my sincere gratitude to my academic supervisors, Dr. Vishal Sethi and Dr. A. J. B. Jackson, for their continuous valuable guidance and support throughout the entire period of my research activities at Cranfield University. I also wish to extend my thanks and gratitude to Professor P. Pilidis from the department of Power & Propulsion, for providing me with the opportunity to pursue a PhD degree at Cranfield University. Thanks are also due to my work colleague Sanjay Mata for his numerous technical discussions on my PhD topic.

I am forever indebted to my parents for all their love, understanding and encouragement towards overcoming boundaries in pursue of self-development. The magnitude of their contribution to the current status of my life has been truly significant and I will forever be grateful.

I would also like to mention my gratitude and admiration towards my sisters for their inimitable support and encouragement during my studies.

I would also like to sincerely thank my wife Wardah Tashfeen for her indispensable support and understanding during my studies.

Last but not least, I would like to thank all of my colleagues and friends at Cranfield, for all the beautiful moments we shared throughout the three year period of my studies. In particular, I want to express my gratitude to my friends;

Atma Prakash
Bhupendra Khandelwal
Fakhre Ali
Karan Patra
Rajeev Verma
Uyioghosa Igie

Abstract

The landing phase of any flight is the most important one with respect to safety. For a high bypass ratio turbofan engine, aircraft deceleration can be achieved by the use of thrust reversers, lift spoilers and brakes. The use of thrust reversers naturally contributes to a reduction in engine life while the use of brakes has operational limitations with respect to aircraft “turn-around times”. With a drive towards improved engine efficiency and lower overall weight, research into novel thrust reverser concepts is imperative to identify designs which offer improved reverser effectiveness and lower weight as well as ease of installation and storage.

The main contributions to knowledge of this PhD research are related to feasibility assessments of the following two thrust reverser concepts:

- A novel vane target type hybrid reverser (VTTHR) design concept has been conceived and evaluated (at a preliminary level) by the author. The design incorporates a target type thrust reverser with cascade vanes. This idea may be patentable.
- NASA has developed and tested a core mounted target type thrust reverser (CMTTTR) for which experimental data is available in the public domain. The second contribution to knowledge of this PhD research is extensive studies of this design. These studies comprise 2D and 3D CFD analyses to assess design feasibility and provide an understanding of performance and flow physics of this thrust reverser for both static and landing conditions (not available in public domain).

In addition to these studies, comprehensive studies of the impact of thrust reverser deployment on overall engine and component performance (for both a mixed and a separate exhaust high bypass ratio turbofan engine) were performed.

The preliminary feasibility studies of the VTTHR, which were performed using 2D CFD, suggest that this new design may offer benefits in terms of greater reverser efficiency, weight and ease of storage, relative to conventional designs. Additionally, it was deduced from a large number of CFD investigations that this may be the only feasible “core mounted” thrust reverser design concept for future high bypass ratio engines. There are of course several additional studies (aerodynamic and structural) that need to be performed to mature this technology but the preliminary studies performed provide a good foundation for these. The use of a VTTHR reverser concept relocates reverser hardware to the core cowl, offering potential reductions in reverser and nacelle weight while allowing the nacelle lines to be optimized. Also, installation of VTTHR would benefit aircraft cruise performance, as during cruise flight there will be no losses due to flow leakage and pressure drops that normally occur across the stowed reverser hardware for conventional cascade type thrust reversers, thus, an improvement in specific fuel consumption and therefore mission fuel burn is expected.

The CMTTTR models developed were successfully validated using experimental data. However it was concluded that this design may not be feasible because of issues related to reverser effectiveness, mass flow compatibility and runway clearance.

Contents

Acknowledgements	ii
Abstract	i
List of Figures	viii
List of Tables.....	xvii
Abbreviations	xix
Chapter 1. Introduction and Background.....	1
1. General Context	1
1.1 Background of the Study	1
1.1.1 Target Type Thrust Reverser	3
1.1.2 Cascade Type Thrust Reverser	3
1.2 Statement of the Problem	4
1.3 Aims and Objectives.....	5
1.4 Thesis Structure	7
Chapter 2. Civil Aircraft Thrust Reversers.....	9
2.1 Types of Thrust Reversers	10
2.1.1 Cascade Type Thrust Reverser	10
2.1.2 Pivoting door type thrust reverser	11
2.1.3 Target Type Thrust Reverser	12
2.1.4 Clamshell and Bucket Door Type Thrust Reverser	13
2.2 Thrust Reverser Utilization	14
2.2.1 Thrust Reverser Utilisation Survey at Heathrow Airport	16
2.3 Thrust Reverser Problems and Related Accidents.....	19
Chapter 3. Thrust Reverser Design and Aerodynamics – Literature Review.....	20
3.1 Early Thrust Reverser Concept Selection Research by Boeing.....	20
3.2 Early Research Conducted by NACA on Cascade Type Thrust Reverser	21
3.3 Early Research Conducted by NACA on Target Type Thrust Reverser Concept	27
3.4 Early Research Conducted by NACA on Cylindrical Type Thrust Reverser	29
3.5 Thrust Reverser as a Modulating Device	33
3.6 Early Research Conducted by NACA on a Full Scale Target Type Thrust Reverser	34
3.7 Early Research Conducted by NACA on a Full Scale Cascade Type Thrust Reverser	37

3.8	Thrust Reverser Application for Aircraft Manoeuvrability	40
3.9	F-100F Aircraft Equipped with Cascade Type Thrust Reversers.....	41
3.10	Early Development and use of Thrust Reversers on Civil Aircraft	43
3.11	Thrust Reverser Installation on the First Long Range Four Engine Aircraft - B707 and DC8	44
3.12	Review of Early Thrust Reverser Design and Performance	45
3.13	Thrust Reverser for McDonnell Douglas DC-10 Aircraft.....	48
3.14	Rolls-Royce Reviews Thrust Reversers of the 1960s.....	50
3.15	Thrust Reverser for Concorde Aircraft.....	50
3.16	Thrust Reverser Study for Civil STOL Aircraft.....	52
3.17	Target Type Thrust Reverser for the TFE-731 Turbofan Engine	53
3.18	Experimental Performance of Cascade Thrust Reversers at Forward Velocity.....	55
3.19	Cascade Type Thrust Reverser Installation Implications	61
3.20	Thrust Reverser for Cessna Citation Aircraft.....	68
3.21	Thrust Reversal Using Variable Pitch Fan	70
3.22	Aft-Mounted Twin Engine Aircraft Thrust Reverser	74
3.23	Introduction and Development of a Pivoting Door Type Reverser	79
3.24	Six Innovative Thrust Reverser Concepts.....	82
3.24.1	Forward thrust – Separate flow exhaust model.....	83
3.24.2	Conventional Cascade Reverser	84
3.24.3	Cascade Reverser with Porous Fan-Duct Blocker	85
3.24.4	Blocker-less Thrust Reverser Concept.....	85
3.24.5	Core-Mounted Annular Target Reverser	86
3.24.6	Core-Mounted Fabric Target Reverser.....	87
3.24.7	Multi-Door Crocodile Thrust Reverser	87
3.24.8rd	Wing Mounted Thrust Reverser.....	89
3.25	Thrust Reverser Wind Tunnel Testing for Civil Aircraft.....	90

Chapter 4. CFD Analysis for Thrust Reversers – Literature Review 96

4.1	Introduction to CFD Analysis for Thrust Reverser	96
4.2	2D CFD Analysis of Reversing Pitch Fan Blade Thrust Reverser	96
4.3	CFD Analysis to Investigate Aerodynamic Behaviour of an Installed Thrust Reverser	99
4.4	Three dimensional CFD Analyses for a High Bypass Ratio Turbofan Engine Thrust Reverser	102
4.5	Multidisciplinary Optimization Approaches for Thrust Reverser Design	105
4.6	Aircraft Thrust Reverser Evaluation Using CFD	106

4.7	Numerical Simulation of Vortex Flows for Airplanes in Ground Operations	110
4.8	Study of the Influence of Aircraft Geometry on the Computed Flow field during Thrust Reversers Operation	113
4.9	Numerical Simulation of Thrust Reverser for Rear Mounted Engine.....	115
4.10	Observations on the Design of Cascade-less Thrust Reversers – CFD Analysis	117

Chapter 5. Thrust Reverser Performance at Integrated Aircraft-Engine Level- Separate Exhaust Turbofan 119

5.1	Introduction	119
5.2	Engine Components Overview	120
5.3	Engine Design Point and Off-Design Study.....	121
5.4	Compressor Off-design Performance	122
5.4.1	SLS	125
5.4.2	Take-off	125
5.4.3	Cruise	126
5.4.4	Landing	126
5.4.5	Reverse thrust condition	127
5.4.6	Thermal and Propulsive Efficiency between $M=0.211 - 0.09$ (140 – 60 knots)	127
5.5	Turbine Off-Design Performance	129
5.5.1	Take-off	131
5.5.2	Cruise.....	131
5.5.3	Landing.....	131
5.5.4	Reverse Idle.....	131
5.5.5	Maximum Reverse Thrust between 140 – 60 knots ($M=0.211 - 0.09$)	131
5.7	Thrust Reverser Performance.....	134
5.10	Conclusion	135

Chapter 6. Thrust Reverser Performance at Integrated Aircraft-Engine Level- Mixed Exhaust Turbofan 136

6.1	Introduction	136
6.2	High Bypass Ratio Mixed Turbofan Engine	137
6.3	Engine Performance.....	138
6.3.1	Engine Design Point and Off-Design Study.....	140
6.3.2	Compressor Performance	141
6.3.3	Turbine Performance.....	148
6.4	Thrust Reverser Performance.....	156

6.5	2D Numerical Analyses for a Mixed Exhaust Thrust Reverser.....	158
6.5.1	Grid and Boundary Conditions.....	160
6.5.2	Static Pressure	161
6.5.3	Total Pressure	161
6.5.3	Total Temperature	162
6.5.4	Velocity Vectors.....	163
6.6	Aircraft Performance	164
6.6.1	Aircraft Deceleration Time	164
6.6.2	Calculation of Aircraft Ground Roll Distance	165

Chapter 7: CFD Analyses of a Core-Mounted Target Type Thrust Reverser in Stowed and Deployed Conditions 168

7.1	Introduction	168
7.2	Structure of the Chapter.....	169
	Advantages of performing CFD Analysis	169
7.3	Advantages of Performing CFD Analysis for Thrust Reverser Study	170
7.4	CAD Design and Modelling	171
7.4.1	Building CAD Models	171
7.4.2	Geometric Parts Description	172
7.5	3D Meshing.....	177
7.6	CFD Methodologies.....	184
7.6.1	The CFD methodology involves the following steps.....	184
7.6.2	In FLUENT the following needs to be ensured	184
7.7	Main Objectives of the CFD Study	185
7.8	Part 1 – CFD Analyses at Static Condition, $M=0.0$	186
7.8.1	CFD Analyses at Reverser Stowed Condition, $M=0.0$ (Baseline)	186
7.9	Results and Discussion.....	190
7.9.1	40 Degree Core Mounted Target Type Reverser Aerodynamics at $M=0.0$	192
7.9.2	40 Deg Core Mounted Target Type Thrust Reverser Aerodynamics at $M=0.211$	201
7.8.2.1	Results and Discussion.....	201
7.10	CFD Results Validation against the Experiments	206
7.10.1	Experimental Testing.....	206
7.10.2	CFD Measurements and Data Extraction	208
7.11	Target Reverser at 40 Deg – Comparison of Experiment vs. CFD.....	209
7.12	Target Reverser at 40 Deg with Kicker Plate – Comparison of Experiment vs. CFD	211
7.13	Results and Discussion for 3D CFD Analyses	214

7.13.1	Introduction	214
7.14	Results and Discussion for the Forward Thrust Configuration at Static Conditions, (M=0.0) 214	
7.15	Results and Discussion for the Core Mounted Target Type Thrust Reverser with and without kicker plate at Static Conditions (M=0.0).....	215
7.16	Results and Discussion for the Forward Thrust Configuration at Landing Conditions, (M=0.211).....	220
7.17	Results and Discussion for the Core Mounted Target Type Thrust Reverser with and without kicker plate at Landing Conditions (M=0.211)	220
7.18	Design Feasibility Study for the Core Mounted Target Type Thrust Reverser	223
7.18.1	A 2D CFD Study for Forward Thrust at (M=0.211)	224
7.18.2	A 2D CFD Study for Core Mounted Target Type Thrust Reverser at (M=0.211)	225
Chapter 8	A Novel Hybrid Thrust Reverser Design	230
8.1	Target Type Hybrid Reverser.....	233
Chapter 9	Conclusions	238
Chapter 10	Proposals for Future Work	241
References		242
APPENDICES		247
Appendix A1: Thrust Reverser Actuation and Control Systems		248
A.1	Types of Thrust Reverser Actuation Systems.....	248
A.2	Hydraulic Actuation System	248
A.3	Pneumatic Actuation System	248
A4	Thrust Reverser Lever	250
A5	Control System for a Pivoting Door Type Thrust Reverser – A320	251
A6	Control System for a Cascade Type Thrust Reverser – B777	253
A7	Control System for a Target Type Thrust Reverser – B737-100/200.....	255
Appendix A2: CFD Theory		257
A2.2	Pressure Based Solver	257
A 2.5	General Scalar Transport Equation: Discretization and Solution	259
	Evaluation of Gradients and Derivatives	261
A2.13	Steady-State Iterative Algorithm.....	262

A2.17 Modeling Turbulence	263
Appendix A3: Forward Thrust Contours of Static and Total Pressure and Streamlines, M = 0.0 Static	272
Appendix A3.1 – Static Pressure Contours	272
Appendix A3.2 – Total Pressure Contours	274
Appendix A3.3 Streamlines Plot	276
Appendix A4: Reverse Thrust 40 Degree with and without kicker plate at Static Condition, M=0.0	284
Appendix A4.1 –Static Pressure Contours	284
Appendix A4.2 – Total Pressure Contours	286
Appendix A4.3 – Streamlines Plot.....	289
Appendix A4.4 – Static Pressure Contours with Kicker Plate, M=0.0	296
Appendix A4.5 – Total Pressure Contours with Kicker Plate, M=0.0	298
Appendix A4.6 – Streamlines Plot with Kicker Plate, M=0.0.....	300
Appendix A5: Reverse Thrust 40 Degree with and without kicker plate at Static Condition, M=0.211.....	314
Appendix A5.1 –Static Pressure Contours	314
Appendix A5.2 – Total Pressure Contours	318
Appendix A5.3 – Streamline Plots.....	322
Appendix A5.4 – Static Pressure Contours with Kicker Plate, M=0.211	330
Appendix A5.5 – Total Pressure Contours with Kicker Plate, M=0.211	332
Appendix A5.6 – Mach Number with Kicker Plate, M=0.211	334
Appendix A5.7 – Total Pressure Contours	336
Appendix A6: Reverse Thrust 40 Degree with and without kicker plate at Static Condition, M=0.211.....	352
Appendix A6.1 –Streamlines Plots	352

List of Figures

Chapter 1

Figure 1.1: (L) Hans von Ohain with his turbofan engine. (R) Sir Frank Whittle with his prototype Whittle engine. Images adopted from [Ref.1].	1
Figure 1.2 (L) Landing run required with different braking devices, (R) Comparison of an aerodynamic speed brake and a thrust reverser. Approximate aircraft weight=20,000 lbs, Images adopted from [Ref. 2].	2
Figure 1.3: Thrust reverser contribution in decreasing stopping distance on dry and icy runway, Images adopted from [Ref. 3].	2
Figure 1.4: (L) Target type reverser (a) hemisphere and (b) half cylinder. (R) Cascade reverser, Images adopted from [Ref. 2].	4

Chapter 2

Figure 2.1: (TL) The sliding cascade reverser [Ref. 8]. (TR) Cascade type thrust reverser operating on fan stream [Ref. 10]. (BL) Fixed and movable structure on the cascade type thrust reverser [Ref. 9]. (BR) Shows the reverser cascade blocks, they go around the circumference as per the design location, images adopted from [Ref. 11].	11
Figure 2.2: (TL) Pivoting door type reverser design [Ref. 9]. (TR) Pivoting door reverser with kicker plate installed [Ref. 9]. (TB) Mixed exhaust engine using pivoting door reverser operating on fan stream only [Ref. 12]. (RB) Separate exhaust engine for an A320 using a pivoting door type thrust reverser. Images adopted from [Ref. 13].	12
Figure 2.3: Target type thrust reverser in operation on Fokker aircraft. Images adopted from [Ref. 14].	13
Figure 2.4: (L) Shows the Tornado aircraft employing the bucket door type thrust reverser during landing [Ref. 15]. (R) The difference between the Clamshell reverser employed on the Viggen aircraft and the Bucket door type thrust reverser employed on the Tornado aircraft. Images adopted from [Ref. 16].	14
Figure 2.5: Weathervaning–Effect of reverse thrust on a slippery runway with crosswind (B727). Image adopted from [Ref. 18].	15
Figure 2.6: (L) Typical engine operating levels and limitations during reverse thrust operation. (R) Sample of engine power levels and cut-off speeds used by some airlines. Images adopted from [Ref. 18].	16

Chapter 3

Figure 3.1: Dry runway landing with brakes alone, Icy runway landing with brakes alone and Icy runway landing with thrust reversers deployed. Images adopted from [Ref. 20].	20
Figure 3.2: Shapes of likely reversers tested by Boeing. Image adopted from [Ref. 20].	21
Figure 3.3: Summary of various thrust reverser performance. Image adopted from [Ref. 20].	21
Figure 3.4: Tail pipe cascade reverser. Image adopted from [Ref. 21].	22
Figure 3.5: (L) Symmetrical cascade blades. (R) Asymmetrical cascade blades. Images adopted from [Ref. 21].	22
Figure 3.6: Effect of cascade design on performance of tail pipe cascade thrust reversers. Tail pipe Mach no=0.2; 100 percent tail pipe blockage. Images adopted from [Ref. 21].	23

Figure 3.7: Effect of cascade solidity on performance of tail pipe cascade thrust reverser; tailpipe blockage 100 percent [10]. Image adopted from [Ref. 21].	24
Figure 3.8: Performance of tail pipe thrust reverser with external guidance doors and no cascades. 100 percent tail pipe blockage. Door length to diameter ratio set as 0.98 and design turning angle, 150° deg. Image adopted from [Ref. 21].	25
Figure 3.9: Effect of tail pipe blockage on performance of cascade thrust reverser; Pressure ratio 2.0. Image adopted from [Ref. 21].	25
Figure 3.10: Reversed flow field from the tail pipe cascade thrust reverser with impulse and reaction blading; tail pipe pressure ratio, 2.0. Images adopted from [Ref. 21].	26
Figure 3.11: (L) The typical geometry for a hemisphere reverser and (R) the geometries created by installing flat plates in the back of hemispherical and cylindrical reversers. Images adopted from [Ref. 22].	27
Figure 3.12: Configurations used to study effects of boat tail shape on reverse thrust ratio. Images adopted from [Ref. 22].	27
Figure 3.13: Minimum spacing required for fixed nozzle operation and reverse thrust ratios obtained for various size hemispherical reversers; exhaust nozzle pressure ratio, 2.0. Images adopted from [Ref. 22].	28
Figure 3.14: Cylindrical thrust reversers. Image adopted from [Ref. 23]	29
Figure 3.15: Variation in reversed flow field with width to height ratio. Exhaust nozzle pressure ratio 2.0; reverser frontal area ratio 3.17; lip angle 180°; end plate angle 180°; full end plates. Image adopted from [Ref. 23]	30
Figure 3.16: Variation in reverse flow field with end plate depth. The Exhaust nozzle pressure ratio≈2.0; reverser frontal area≈3.17; width to height ratio≈1.6; lip angle≈180°; end plate angle≈180°. Image adopted from [Ref. 23].	31
Figure 3.17: Thrust modulation characteristics of a cylindrical target type thrust reverser. Exhaust nozzle pressure ratio, 2.0; reverser frontal area ratio, 3.17; width to height ratio, 1.6; lip angle, 146°; end plate angle, 180°; nonconcentric end plates. Image adopted from [Ref. 23].	32
Figure 3.18: Thrust modulation characteristics for various thrust reverser designs. Image adopted from [Ref. 27].	34
Figure 3.19: Target configurations used in full-scale thrust reverser investigation. Image adopted from [Ref. 28]	35
Figure 3.20: (L) Comparison of reverse thrust ratio with engine speed for full depth and modified hemispheres. (R) Comparison of reverse thrust ratio with nozzle pressure ratio for full depth and modified hemispheres. Image adopted from [Ref. 28].	35
Figure 3.21: (L) Installation of survey rake for measurement of reverser discharge flow angle. (R) Variation of thrust reverser discharge flow angle with nozzle pressure ratio for full depth hemisphere. Image adopted from [Ref. 28]	36
Figure 3.22: (L) Variation of thrust reverser discharge flow angle with nozzle pressure ratio for a modified hemisphere. (R) Relationship of nozzle pressure ratio and engine speed for a turbojet engine with and without modified hemisphere reverser. Image adopted from [Ref. 28].	37
Figure 3.23: Overall view of aircraft with thrust reverser installed. Image adopted from [Ref. 29].	38
Figure 3.24: Vane type thrust reverser installation on a fighter type jet aircraft. Image adopted from [Ref. 29].	38
Figure 3.25: External view of the tail pipe arrangement before and after modifications. Image adopted from [Ref. 29]	38
Figure 3.26: Thrust reverser turning vane details. Image adopted from [Ref. 29].	39
Figure 3.27: Tethering cable arrangement used to measure thrust. Image adopted from [Ref. 29].	39

Figure 3.28: Bicycle-wheel arrangement used to measure ground speed and elapsed distance. Image adopted from [Ref. 29].	40
Figure 3.29: F-100F aircraft in the wind tunnel for cascade type thrust reverser testing. Image adopted from [Ref. 31].	41
Figure 3.30: Thrust reverser configurations [31].	42
Figure 3.31: (L) Sketch drawing and (R) side view of an installed thrust reverser [31].	42
Figure 3.32: (L) Thrust reverser on a Comet aircraft. (R) Thrust reverser landing sequence. Image adopted from [Ref. 32]	44
Figure 3.33: Thrust reversers on a four engine aircraft. Flow pattern at different landing speed. Image adopted from [Ref. 32].	45
Figure 3.34: (L) Target door reverser on Boeing 727. (R) Target reverser with long duct fan engine on Lockheed C-141. Images adopted from [Ref. 33].	46
Figure 3.35: (L) Target reverser on fan and cascade reverser on turbine exhaust, Boeing 720B. (R) Cascade reverser mounted aft of tailpipe exit plane, North American F-100. Images adopted from [Ref. 33].	46
Figure 3.36: (L) Dual target reverser, Lockheed Jet star business jet. (R) Target thrust reverser on Grumman Gulfstream II business jet. Images adopted from [Ref. 33]	46
Figure 3.37: (L) Modulation performance of target type reverser at take-off power. (R) In flight performance of a target type reverser. Image adopted from [Ref. 33]	47
Figure 3.38: (L) Landing roll performance (15,000lb landing weight). (R) Rejected take-off performance (decelerate stop distance). Images adopted from [Ref. 33].	48
Figure 3.39: (L) DC-10 general arrangement and (R) engine installation. Image adopted from [Ref. 34].	48
Figure 3.40: (L) Reverser schematic. (R) Reverser control and actuation system. Images adopted from [Ref. 34].	49
Figure 3.41: (L) Stowed cascade spoiler. (R) Plug stowed cascade. Images adopted from [Ref. 34].	50
Figure 3.42: (L) Concorde thrust reverser efflux angles [36]. (R) Top, Cascade type thrust reversers for the Concorde prototype aircraft. Bottom, target thrust reversers for Concorde aircraft. Images adopted from [Ref. 37].	51
Figure 3.43: (L) Control system for a typical STOL aircraft. (R) Typical control system for conventional aircraft. Images adopted from [Ref. 38].	52
Figure 3.44: Pivoted target thrust reverser installed on a TFE-731 turbofan. Image adopted from [Ref. 39].	53
Figure 3.45: TFE-731 turbofan engine thrust reverser deployed geometry. Image adopted from [Ref. 39].	53
Figure 3.46: Target spacing ratio. Image adopted from [Ref. 39]	54
Figure 3.47: (L) Thrust reverser doors closed. (R) Thrust reverser doors open. Images adopted from [Ref. 39].	55
Figure 3.48: Fan inlet and thrust reverser section – Experimental test rig. Image adopted from [Ref. 40].	56
Figure 3.49: Thrust reverser blade section. Image adopted from [Ref. 40].	57
Figure 3.50: (L) Schematic of static stand test. (R) Thrust reverser model in low speed tunnel. Image adopted from [Ref. 40].	57
Figure 3.51: Configurations tested and static reverser efficiency. Image adopted from [Ref. 40].	58
Figure 3.52: Variation of reverser efficiency with forward velocity for different configurations. Image adopted from [Ref. 30]	59

Figure 3.53: Variation of reverser efficiency with yaw angle for different configurations. Image adopted from [Ref. 40].	60
Figure 3.54: Variation of stator exit pressure for different configurations and test conditions. Image adopted from [Ref. 40].	61
Figure 3.55: Forward and reverse thrust model with flight type inlets. Image adopted from [Ref. 41]	62
Figure 3.56: (Top) Section of a model with flight type inlet and no stator cascade spacer. (Bottom) Section of the model shows the cascade spacer. Image adopted from [Ref. 41].	63
Figure 3.57: Average stator exit static pressure ratio variation as function of normalised rotational speed. Image adopted from [Ref. 41].	64
Figure 3.58: Total pressure ratio variation as a function of normalized rotation speed. Image adopted from [Ref. 41]	65
Figure 3. 59: Fan mass flow variation as a function of normalized rotational speed. Image adopted from [Ref. 41].	65
Figure 3.60: Fan performance map for bellmouth inlet with recirculation shield and normalized stator spacing distance b_s/d of 0.52. Image adopted from [Ref. 41].	66
Figure 3.61: Variation of fan characteristics as a function of normalized cascade length for normalized rotational speed $N/N_d=0.98$. Image adopted from [Ref. 41].	67
Figure 3.62: Variation of stator exit distortion parameters as a function of normalised cascade length for normalized rotational speed N/N_d of 0.98. Image adopted from [Ref. 41].	67
Figure 3.63: Design configuration summary of thrust reverser development tests. Image adopted from [Ref. 42].	68
Figure 3.64: Installation of Rohr thrust reverser on Cessna Citation 500. . Image adopted from [Ref. 42]	70
Figure 3.65: Engine cross-section. Image adopted from [Ref. 43].	71
Figure 3.66: Engine test stand. (L) Front view (R) Aft view. Image adopted from [Ref. 44].	71
Figure 3.67: Station designation reverse thrust. Image adopted from [Ref. 34].	72
Figure 3.68: Fan rotor blade. Image adopted from [Ref. 44].	72
Figure 3.69: (L) Schematic of fixed 30° exlet. (R) Fixed 30° exlet on a test bed. Images adopted from [Ref. 44].	73
Figure 3.70: (L) Reverse thrust fan speed characteristics. (R) Reverse thrust fan blade angle characteristics. Images adopted from [Ref. 44].	74
Figure 3. 71: Photograph of the McDonnell Douglas MD-89 jet transport model with engine simulators as mounted in test section of Langley 14 by 22 foot subsonic tunnel. Images adopted from [Ref. 45].	75
Figure 3.72: Cascade thrust reverser plenums. Images adopted from [Ref. 45].	76
Figure 3.73: (L) Sketches of thrust reverser simulators. (R) Target thrust reverser plenums Images adopted from [Ref. 45].	76
Figure 3.74: (L) Three configurations of the four door thrust reverser design. (R) Four door thrust reverser plenums. Images adopted from [Ref. 45].	77
Figure 3.75: Test section configuration when investigated effects of moving belt ground plane. All dimensions are in feet. Image adopted from [Ref. 45].	77
Figure 3.76: Sketch of pressure instrumented ground board showing location of pressure orifices. Image adopted from [Ref. 45].	78
Figure 3.77: (L) Showing water supply lines for cascade thrust reverser. (R) Water injection flow visualization for cascade thrust reverser. Images adopted from [Ref. 45].	78
Figure 3.78: Pivoting door reverser deflection of fan duct flow. Images adopted from [Ref. 46].	80

Figure 3.79: (L) Pivoting door thrust reverser for the Trent engine. (R) Blow up of the reverser. Images adopted from [Ref. 46].	80
Figure 3.80: (L) Reverser door structure. (R) Inner fixed structure. Images adopted from [Ref. 46].	81
Figure 3.81: Typical setup of separate flow exhaust system model installed on the propulsion simulation system. Images adopted from [Ref. 47].	84
Figure 3.82: Sketch of a separate flow exhaust model. Image adopted from [Ref. 47].	84
Figure 3.83: (L) Sketch of a cascade reverser model. (R) Cascade thrust reverser model. Images adopted from [Ref. 47].	85
Figure 3.84: (L) Sketch of cascade vanes segment with variable leakage door. (R) Photograph of the cascade reverser model [Ref. 47].	85
Figure 3.85: (L) shows the sketch of blocker-less thrust reverser model. (R) Sketch of the fluidic injector assembly . Images adopted from [Ref. 47].	86
Figure 3.86: (L) The sketch of the metal target thrust reverser model. (R) The annular target geometry. Images adopted from [Ref. 47].	87
Figure 3.87: (L) Sketch of fabric thrust reverser. (R) Fabric target thrust reverser model. Images adopted from [Ref. 47].	87
Figure 3.88: (Top-L) Sketch of multi-door crocodile thrust reverser, (Top-R) Reverser port details. (Bottom-L) Photograph of multi-door reverser side view, (Bottom-R) Front quarter view. Images adopted from [Ref. 47].	88
Figure 3.89: (Top-L) Sketch of the wing mounted thrust reverser model. (Top-R) Wing mounted reverser model assembly during testing. (Bottom-L) Top view of the wing mounted reverser. (Bottom-R) details of the deflector assembly. Images adopted from [Ref. 48].	89
Figure 3.90: Blown nacelle for thrust reverser test in wind tunnel. Images adopted from [Ref. 49].	91
Figure 3.91: Thrust reversers for wind tunnel tests, (a) Blown cascade, (b) TPS cascade, and (c) four pivoting door reverser. Images adopted from [Ref. 49].	91
Figure 3.92: (L) Installation of the blown nacelle in the wind tunnel model, simulating the aft mounted of aircraft engines. (R) Steam visualization of thrust reverser flow pattern. Blown nacelle technique with aft mounted engine simulators [Ref. 49].	93
Figure 3.93: Dorsal sting supported Airbus A380 above the Moving Belt Ground Plane in DNW-LLF. Image adopted from [Ref. 49].	94
Figure 3.94: The experimental arrangement for the photo above with boundary layer scoop in red and moving belt in blue. Images adopted from [Ref. 49].	95

Chapter 4

Figure 4.1: (L) Turbofan geomtry. (R) Computaitonal area for numerical analysis. Images adopted from [Ref. 51].	97
Figure 4.2: Physical representation of actuator disk – reverser pitch. Image adopted from [Ref. 51].	97
Figure 4.3: (L) Static pressure profile for case 1. (R) Velcoity vectors for case 1. Images adopted from [Ref. 51].	98
Figure 4.4: (L) Stagnation pressure for case 2. (R) Velocity vectors for case 2. Images adopted from [Ref. 51].	98
Figure 4.5: (L) Stagnation pressure for case 3. (R) Velocity vectors for case 3 . Images adopted from [Ref. 51].	99
Figure 4.6: (L) Front view with grid. (M) Close-up view. (R) Side view with grid. Images adopted from [Ref. 52].	101

Figure 4.7: Computed exhaust plume trajectory (Mach 0.15, ground effect. Image adopted from [Ref. 52].	101
Figure 4.8: (L) Structured mesh. (M) Surface unstructured mesh. (R) Surface mesh of the airplane with runway, downstream and symmetry plane. Images adopted from [Ref. 53].	103
Figure 4.9: (L) Frontal view with efflux from the cascade reverser. (R) Another frontal view with reverser efflux in particle traces. Images adopted from [Ref. 53].	104
Figure 4.10: (L) Frontal view with reverser efflux at $M=0.2$. (R) Frontal view with reverser efflux at $M=0.076$. Images adopted from [Ref. 53].	104
Figure 4.11: Geometric representation of a thrust reverser cascade. Images adopted from [Ref. 54].	106
Figure 4.12: Example of cascade boxes angles changed axially and radially respectively (20 boxes, 10 per nacelle side. Images adopted from [Ref. 55].	107
Figure 4.13: (L) Aircraft CAD model, showing the surfaces. (R) Aircraft triangular. Images adopted from [Ref. 55].	108
Figure 4.14: (L) Thrust reverser plume, isosurface of total temperature. (R) Thrust reverser streamlines coloured by velocity. Images adopted from [Ref. 55].	108
Figure 4.15: Pathlines of particles released from the reverser for the two alternative reverser cascade configurations. Images adopted from [Ref. 55].	109
Figure 4.16: (L) Water spray test on EMB 170 aircraft. (R) 10 μ m droplets trajectory released from the ground for the CFD analysis. Images adopted from [Ref. 55].	109
Figure 4.17: Effects of thrust reversers on vortex structure. Images adopted from [Ref. 56].	111
Figure 4.18: Streamtube capture area under thrust reverser operation. Images adopted from [Ref. 56].	112
Figure 4.19: Comparison of numerical simulations with observed vortical systems. Images adopted from [Ref. 56].	112
Figure 4.20: Meshes (a) basic configuration, (b) intermediate configuration, and (c) complete configuration [Ref. 57].	113
Figure 4.21: (L) Iso-surface of total temperature at 290K for the three configurations: (a) basic, (b) intermediate, and (c) complete, for landing speeds of 50 knots (left side) and 60 knots (right side). (R) Contours of total temperature in the plane of the fan face for three configurations: (a) basic, (b) intermediate, and (c) complete, for landing speeds of 50 knots (left) and 60 knots (right side) [Ref. 57].	115
Figure 4.22: Installed engine whole computational domain and zoom on the reverser [Ref. 58].	115
Figure 4.23: Total pressure iso-contours, and, engine jet streamlines [Ref. 58].	117
Figure 4.24: (L) Natural blockage reverser. (R) Cascade type reverser. Images adopted from [Ref. 59].	117
Figure 4.25: (T-Left) Baseline case, (T-Midd) Case 1, (T-Right) Case 2, (B-Left) Case 3, (B-Midd) Case 4, (B-Right) Case 5. Images adopted from [Ref. 59].	118

Chapter 5

Figure 5.1: The cascade type thrust reverser. Images adopted from [Aircraftengines.net].	120
Figure 5.2: B777 landing with deployed thrust reverser. Image adopted from [www.flickr.com]	120
Figure 5.3: GE90-94B nacelle longitudinal cross section. Image adopted from [Ref. 62].	121
Figure 5.4: Fan PR against the corrected mass flow for different engine operating conditions	124
Figure 5.5: LPC PR against the corrected mass flow for different engine operating conditions.	124
Figure 5.6: HPC PR against the corrected mass flow for different engine operating conditions.	125
Figure 5.7: Variation of propulsive efficiency with aircraft landing speed (sea level).	128

Figure 5.8: Variation of thermal efficiency with aircraft landing speed (sea level).....	128
Figure 5.9: Pressure ratio across the HPT at different operating conditions.....	130
Figure 5.10: Pressure ratio across the LPT at different operating conditions.	130
Figure 5.11: Variation in pressure ratio across the bypass nozzle at different operating conditions.	133
Figure 5.12: Variation in pressure ratio across the core nozzle at different operating conditions.	133
Figure 5.13: Shows the reverse thrust force components. Images adopted from [Ref. 57].....	134

Chapter 6

Figure 6.1: Deployed thrust reverser on a mixed exhaust engine. Reverser is operating only on fan stream flow. Images adopted from [Ref. 65].	136
Figure 6.2: Longitudinal section of a mixed exhaust CFM56-5C used on A340. Lower half reverser in operation. Images adopted from [Ref. 69].	137
Figure 6.3: Longitudinal cross section of TRENT 700 nacelle. Image adopted from [Ref. 69].	140
Figure 6.4: Fan P.R against the fan corrected mass flow for different operating conditions.	142
Figure 6.5: IP compressor P.R against the IP compressor corrected mass flow for different operating conditions.	142
Figure 6.6: HP compressor P.R against the HP compressor corrected mass flow for different operating conditions.	143
Figure 6.7: Variation of propulsive efficiency with aircraft landing speed (sea level).....	146
Figure 6.8: HP turbine pressure ratio against the HP turbine corrected mass flow at different operating conditions.	149
Figure 6.9: IP turbine pressure ratio against the IP turbine corrected mass flow at different operating conditions.	150
Figure 6.10: LP turbine pressure ratio against the LP turbine corrected mass flow at different operating conditions.	150
Figure 6.11: Common nozzle pressure ratio against the corrected mass flow at different operating conditions.	154
Figure 6.12a: Core nozzle pressure ratio against the core nozzle corrected mass flow during reverse thrust. Figure 6.12b: reverser pressure ratio against the reverser corrected mass flow during reverse thrust.	155
Figure 6.13: Reverse thrust force components in 3D and 2D. Images adopted from [Ref. 65].	158
Figure 6.14: Grid and boundary conditions for the stowed reverser (magnified image).....	160
Figure 6.15: Grid for deployed thrust reverser (magnified image).	160
Figure 6.16: Contours of static pressure at forward idle, reverse idle and maximum reverse.	161
Figure 6.17: Contours of total pressure at forward idle, reverse idle and maximum reverse.	162
Figure 6.18: Contours of total temperature at forward idle, reverse idle and maximum reverse. ...	162

Chapter 7

Figure 7.1: (L) A typical geometry used for wind tunnel testing. (R) Geometry schematic [Ref. 33]	171
Figure 7.2: (Top) An isometric view of a complete CFD Domain. (Bottom) Top view.	173
Figure 7.3: (Top) Close view of a typical geometry used.	174
Figure 7.4: A 3D CAD model for a forward thrust configuration with transparency.....	174
Figure 7.5: Top and bottom view for a core mounted target thrust reverser installation.	175

Figure 7.6: Isometric view of a core mounted target thrust reverser configuration.	176
Figure 7.7: A close view of a 3D CAD model for a 40 degree core mounted target type thrust reverser with kicker plate.	176
Figure 7.8: A 3D view of a 40 degree target type thrust reverser configuration.	177
Figure 7.9: Shows a surface mesh for a 40 degree target type thrust reverser. (Top) with kicker plate and (Bottom) without kicker plate.	178
Figure 7.10: Typical surface mesh on wing suction surface.	179
Figure 7.11: Aft view, showing the surface mesh for the wing trailing edge, exhaust plug and rear of the core mounted reverser.	179
Figure 7.12: (Top) Surface mesh of the reverser, nacelle external surface and pylon are visible. (Bottom) Close view of the nacelle external mesh, pylon and kicker plate.	180
Figure 7.13: Shows the surface mesh on individual components. (Top) shows a surface mesh for fan nacelle internal surface, and for forward nacelle internal surface. (Bottom) shows the mesh on core external surface. Also visible on both figures are the refined mesh on the nacelle inlet regions.	181
Figure 7.14: (Top) surface mesh on the core internal surface. (Bottom) surface mesh on the core mounted reverser, kicker plate, and exhaust plug.	182
Figure 7.15: (Top) shows typical density mesh regions. (Middle) Close view of the density mesh regions. (Bottom) typical prism mesh for a forward nozzle baseline configuration.	183
Figure 7.16: (Top) shows a 7.9% scale model of a GE90 engine. (Bottom) shows a full scale 3D CFD model.	185
Figure 7.17: (Top) shows a wind tunnel model for a forward thrust configuration. (Bottom) shows a schematic of the vertical cut plane of the model tested [Ref. 8].	187
Figure 7.18: Shows the residuals.	188
Figure 7.19: Mass flow for the fan outlet.	188
Figure 7.20: Typical examples of residuals and mass flow observations for solution convergence.	189
Figure 7.21: Shows a typical Y^+ contours plot. The acceptable range is between 30 and 300. However, in all the CFD cases, the Y^+ values were in the acceptable range.	189
Figure 7.22: Streamline forward thrust, horizontal plane, $M=0.0$	191
Figure 7.23: Streamline forward thrust, vertical plane, $M=0.0$	191
Figure 7.24: 3D Streamlines for the forward thrust configuration at $M=0.0$, $FNPR=1.504$	192
Figure 7.25: (Top) shows a wind tunnel mode for a forward thrust configuration. (Bottom) shows a schematic of a vertical cut plane of the model tested [Ref. 8].	193
Figure 7.26: Zone 10 shows the recirculating region for a kicker plate configuration, $M=0.0$	196
Figure 7.27: Shows the re-circulation zone formed between the core external and the reverser surface and the fan flow turning at the reverser exit, $M=0.0$	197
Figure 7.28: Streamlines in the external far field region, horizontal plane, $M=0.0$	197
Figure 7.29: Streamlines plot showing the external and internal flow field regions, $M=0.0$	198
Figure 7.30: Streamlines plot for the external flow field during reverser deployment, vertical plane, $M=0.0$	198
Figure 7.31: Streamlines plot for the external and internal flow fields, vertical plane, $M=0.0$	199
Figure 7. 32: Streamlines plot in the external far field region at low thrust setting during thrust reverser deployment, vertical plane, $M=0.0$	199
Figure 7. 33: 3D streamline plots for the core mounted target type thrust reverser at $M=0.0$, $FNPR=1.504$	200
Figure 7.34: Streamlines plot for the external flow field with thrust reverser deployed, horizontal plane, $M=0.211$	202

Figure 7. 35: Streamlines plot for the external and internal flow field for the thrust reverser deployed configuration, high thrust settings, horizontal plane, $M=0.211$.	202
Figure 7.36: Streamlines plot for the external and internal flow field for the thrust reverser deployed configuration, at low thrust setting, horizontal plane, $M=0.211$.	203
Figure 7.37: Streamlines plot for the external flow field for the thrust reverser deployed configuration, vertical plane, $M=0.211$.	203
Figure 7.38: Streamlines plot for the external and internal flow field for the thrust reverser deployed configuration, vertical plane, $M=0.211$.	204
Figure 7.39: 3D streamlines for the core mounted target type thrust reverser with kicker plate at $M=0.211$, $FNPR=1.50$.	205
Figure 7.40: Shows a 14 degree clockwise plane which is used for static pressure measurement.	207
Figure 7.41: Shows a cut-plane and the location of the static pressure orifice for a 40 degree core mounted target type thrust reverser.	207
Figure 7.42: A 14 degree cut plane, similar to the experimental tests was taken for the CFD static pressure measurements.	209
Figure 7.43: CFD and Experimental comparison for the static pressure values at different $FNPR$ s for Core External Surface, for 40 degree target thrust reverser configuration.	209
Figure 7.44: CFD and Experimental comparison for the static pressure values at different $FNPR$ s for Fan Nacelle Internal 1, for 40 degree target thrust reverser configuration	210
Figure 7.45: CFD and Experimental comparison for the static pressure values at different $FNPR$ s for Fan Nozzle Internal 2, for 40 degree target thrust reverser configuration.	210
Figure 7.46: CFD and Experimental comparison for the static pressure values at different $FNPR$ s for 40 Deg Target Reverser Internal Surface, for 40 degree target thrust reverser configuration .	211
Figure 7.47: CFD and Experimental comparison for the static pressure values at different $FNPR$ s for Core External Surface, for 40 degree target thrust reverser with kicker plate, $M=0.0$.	211
Figure 7.48: CFD and Experimental comparison for the static pressure values at different $FNPR$ s for Fan Nacelle Internal, for 40 degree target thrust reverser with kicker plate, $M=0.0$.	212
Figure 7.49: CFD and Experimental comparison for the static pressure values at different $FNPR$ s for Fan Nozzle Internal Surface, for 40 degree target thrust reverser with kicker plate, $M=0.0$.	212
Figure 7.50: CFD and Experimental comparison for the static pressure values at different $FNPR$ s for Target Reverser with Kicker Plate internal surface. $M=0.0$.	213
Figure 7.51: Shows the variation in fan gross thrust against the $FNPR$, $M=0.0$.	215
Figure 7.52: Comparison between the results obtained from the 3D CFD analyses against those performed by NASA in the wind tunnel. Also, shown in the figure is the variation in reverse thrust if the pressure thrust is also accounted. (L) 40 degree core mounted target thrust reverser. (R) 40 degree core mounted target thrust reverser with Kicker Plate.	218
Figure 7.53: Shows a comparison of overall reverser efficiency against the $FNPR$ s at static and forward landing conditions.	221
Figure 7.54: Shows a 2D axisymmetric design of a core mounted target type thrust reverser.	223
Figure 7.55: Shows the 2D mesh for the forward thrust configuration.	225
Figure 7.56: Shows total pressure contours for the baseline configuration.	225
Figure 7.57: Shows a typical 2D unstructured mesh used for the CFD simulations.	226
Figure 7.58: Shows a 2D streamline plot for the baseline configuration.	226

List of Tables

Chapter 2

Table 2.1: Shows the runway lengths for the major airports in United Kingdom.	17
Table 2.2: Survey results for thrust reverser use and runway occupancy time averages. Adopted from [Ref. 19].	18

Chapter 4

Table 4.1: Engine flow Conditions. Table adopted from [Ref. 52].	100
Table 4.2: Component breakdown of computed total braking force (per engine). Table adopted from [Ref. 52].	101
Table 4.3: (L) Boundary conditions for the unstructured mesh. (R) Boundary conditions for the structured mesh. Tables adopted from [Ref. 53].	103

Chapter 5

Table 5.1: CUTS_TF Design Point and Off-Design Study	122
Table 5.2: Compressor Pressure Ratios at Different Operating Conditions	123
Table 5.3: SLS design point values of isentropic efficiencies, specific work and r.p.m	123
Table 5.4: Turbine pressure ratio variation at different engine operating conditions	129
Table 5.5: SLS design point values of isentropic efficiencies, specific work and r.p.m	130
Table 5.6: Variation in pressure ratio across the bypass and core nozzle	132
Table 5.7: The time required for the flaps and brakes to be effective.	134

Chapter 6

Table 6.1: Engine design point at SLS condition and off-design at take-off, cruise, landing, idle-reverse, and maximum reverse conditions.	140
Table 6. 2: Compressor pressure ratios at different operating conditions	141
Table 6.3: SLS design point values of assumed isentropic efficiencies, specific work and r.p.m.	141
Table 6.4: Typical times required for lift dumpers and brakes to be effective and to reduce the engine thrust to reverse idle [13].	144
Table 6.5: Variation in Fan Performance Parameters Relative to Design Values	147
Table 6.6: Variation in IP compressor Performance Parameters Relative to Design Values	147
Table 6.7: Variation in HP compressor Performance Parameters Relative to Design Values	148
Table 6.8: Turbine pressure ratios at different operating conditions	149
Table 6.9: SLS design point values of assumed isentropic efficiencies, specific work and power	149
Table 6.10: Variation in HP turbine Performance Parameters Relative to Design Values	151
Table 6.11: Variation in IP turbine Performance Parameters Relative to Design Values	152
Table 6.12: Variation in LP turbine Performance Parameters Relative to Design Values	153
Table 6.13: Common nozzle performance parameters – Mixed Exhaust	153
Table 6. 14: Core nozzle and reverser exit performance parameters at different operating conditions.	154
Table 6.15: Variation in Common nozzle Performance Parameters Relative to Design Values	156

Table 6.16: The time required for the flaps and brakes to be effective and to reduce the engine thrust to idle.	157
Table 6.17: Thrust reverser deployment time.....	165
Table 6.18: Aircraft landing distance with maximum and idle reverse thrust	166

Chapter 7

Table 7.1: shows the major differences between the experiment and the CFD tests.....	185
Table 7.2: Shows the Results from the 3D CFD Analyses for the Forward Thrust Configuration at Static Conditions ($M=0.0$).	215
Table 7.3 :3D CFD Results for the Core Mounted Target Type Thrust Reverser at Static Conditions ($M=0.0$)	219
Table 7.4: 3D CFD Results for the Core Mounted Target Type Thrust Reverser with Kicker Plate at Static Conditions ($M=0.0$)	219
Table 7.5: Shows the Results from the 3D CFD Analyses for the Forward Thrust Configuration at Landing Conditions ($M=0.211$)	220
Table 7.6: 3D CFD Results for the Core Mounted Target Type Thrust Reverser at landing Conditions ($M=0.211$).....	222
Table 7.7: 3D CFD Results for the Core Mounted Target Type Thrust Reverser with Kicker Plate at landing Conditions ($M=0.211$).....	222
Table 7.8:Shows the 2D CFD results for the forward flight condition ($M=0.211$) at different FNPRs.	224
Table 7.9: Compares the performance of various thrust reversers	228

Abbreviations

<i>Alt</i>	Altitude, m
<i>ABS</i>	Auto Brake System
<i>APU</i>	Auxiliary Power Unit
<i>BPR</i>	Bypass Ratio
<i>CMTTTR</i>	Core mounted target type thrust reverser
<i>CUTEA</i>	Cranfield University Twin Engine Aircraft
<i>CFD</i>	Computational Fluid Dynamics
<i>CUTS_TF</i>	Cranfield University Three Spool Turbofan
<i>D</i>	Drag, kN
<i>DP</i>	Design Point
<i>ECAM</i>	Engine Centralized Aircraft Monitor
<i>EPR</i>	Engine Pressure Ratio
<i>EGT</i>	Exhaust Gas Temperature
<i>FAA</i>	Federal Aviation Administration
<i>FADEC</i>	Full Authority Digital Engine Control
<i>FEA</i>	Finite Element Analysis
<i>FOD</i>	Foreign Object Damage
<i>FNPR</i>	Fan Nozzle Pressure Ratio
F_x	Reverse thrust axial component, kN
F_y	Reverse thrust vertical component, kN
F_z	Reverse thrust side force component, kN
<i>HP</i>	High pressure
<i>IAS</i>	Indicated Air Speed
<i>IGV</i>	Inlet guide vane
<i>IP</i>	Intermediate pressure
<i>L</i>	Aircraft lift, kN
<i>LP</i>	Low pressure
<i>LVP</i>	Low Visibility Procedures
<i>M</i>	Mach number
M_{cold}	Mach number, cold flow
M_{hot}	Mach number, hot flow
M_{mixed}	Mach number, mixed flow
<i>MAX</i>	Maximum
<i>MAESTO</i>	Modified engine acceleration schedule for take-off
<i>N</i>	Mechanical speed, rpm
<i>NACA</i>	National Advisory Committee for Aeronautics
<i>NASA</i>	National Aeronautics and Space Administration
<i>OPR</i>	Overall pressure ratio
P_{core}	Total Pressure Core Exit, kPa
P_{fan}	Total Pressure Fan Exit, kPa
<i>P.R</i>	Pressure Ratio
<i>r.p.m</i>	Revolution Per Minute
<i>RTO's</i>	Refused Takeoffs
<i>RET's</i>	Rapid Exit Takeoffs
<i>SFC</i>	Specific Fuel Consumption
<i>SLS</i>	Sea Level Static
<i>S</i>	Aircraft Wing Area, m ²
<i>STOL</i>	Short Takeoff Landing
S_1	aircraft free roll distance, m
S_2	aircraft distance with reverser deployed
S_3	aircraft distance travelled with brakes
S_{Total}	aircraft stopping distance, m
<i>t</i>	Time, seconds

TOGA	Take-off or Go Around
T_1	Temperature at fan entry, K
TET	Turbine entry temperature, K
VIGV	Variable inlet guide vanes
VSV	Variable stator vane
VTTHR	Vane target type hybrid thrust reverser
V	Velocity, m/s
V_j	Reverser flow exit jet velocity, m/s
V_{TD}	The touchdown velocity, m/s
V_{brake}	Velocity at breaking point, m/s
W_{force}	Aircraft downward force, kN
Θ	Pivoting door angle relative to axial, deg
Φ	3D flow angle, deg
ρ	Density, kg/m ³
μ_{r1}	Runway rolling coefficient of friction
μ_{r2}	Braking coefficient of friction

Chapter 1. Introduction and Background

1. General Context

At the start of the last century aircraft came into service and with continuous research and development became a permanent part of the major air forces. Initially, piston engine aircraft came into service and were the major players during WWI. However, the ever needed requirement for speed, agility and manoeuvrability give rise to a new generation of aircraft called jet aircraft. The early development of the jet engines took place during the period of World War II. The pioneers for turbojet engine were Frank Whittle from United Kingdom and Hans Joachim Pabst von Ohain from Germany, as shown in (Figure 1.1). Turbojet engines came into service during the 1940s and became the major players for the fighter aircraft during and after WWII.

Early day's fighter aircraft were mainly single engine and the engines were normally integrated into the aircraft fuselage. The turbojet engine developments were based solely on military requirements, and the initial applications of the jet engine were for high speed military aircraft. The early engines had shorter lives, poor reliability and very high fuel consumption. A great deal of development was necessary before the technology reached the level where it could be used in civil aviation, and the first civil aircraft applications appeared in the early 1950s. Once the new power plant (jet engines) become established it rapidly made the piston engines obsolete, and today the piston engines are restricted to a small market for light aircraft [Ref 2].

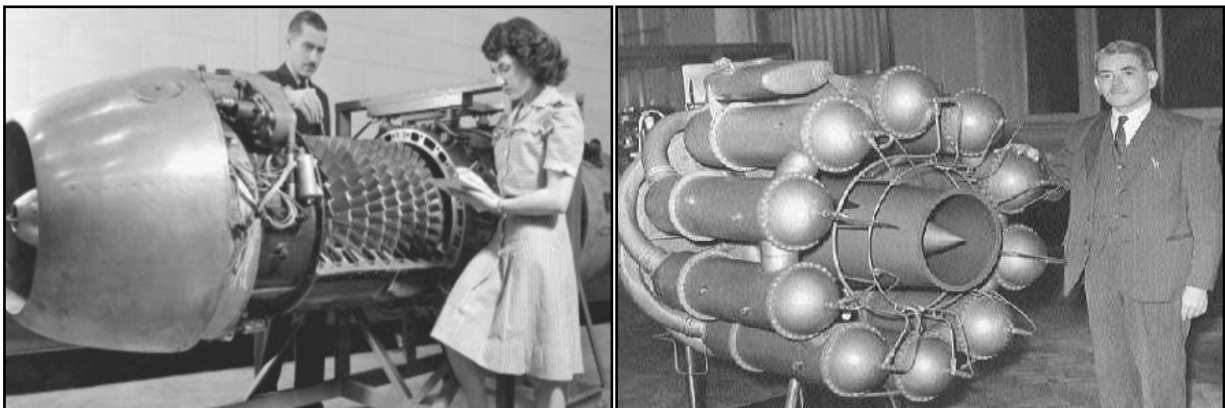


Figure 1.1: (L) Hans von Ohain with his turbofan engine. (R) Sir Frank Whittle with his prototype Whittle engine. Images adopted from [Ref.1].

1.1 Background of the Study

If a flight phase of an aircraft is considered, the landing phase of any flight is the most important one from the standpoint of safety. In early years, propeller reversing has been employed effectively to assist in braking the aircraft during the landing. However, with the advent of jet engines, engineers and scientists realised that a similar thrust reverser device would be equally useful and this can be achieved by reversing the direction of the engine exhaust during landing.

In the early days of turbojet development (early 1950s) the safe landing distance requirement was very clear. With the landing speeds of jet aircraft ever increasing, the required landing distances were becoming prohibitively long. Also important was the aircraft landing on, short runways, during

adverse weather conditions i.e. on wet or icy runways, in naval applications landing in the shortest time was also very critical due to the limited runway length. Landing speeds are high for two reasons: first, aerodynamic reasons such as high wing loadings and low maximum-lift coefficients, and second, the necessity for making the final approach at a relatively high engine speed in preparation for a possible wave-off.

These requirements lead to the concept of using brake plus a retarding force such as a parachute. It was clear to engineers that they need to find innovative ways to reduce the landing distance for an aircraft. This led to massive research and development in the area of thrust reversing using the parachute as a stopping force and using the engine exhaust flow as the reverse thrust. The thrust reverser has the advantage of providing the required reverse thrust (at rated engine conditions) with assurance that full forward thrust can be regained rapidly if the need arises. A drag parachute can be used to reduce final approach speed by increasing drag, but it must be cut loose in case of a wave-off and will not be available for the next attempted landing. Figure 1.2L shows the benefit of thrust reverser. In addition to reducing landing roll on dry runways, the thrust reverser is also far superior to wheel brakes on wet or icy runways. Also, it is conceivable that a thrust reverser can be used as a speed brake. With a reverser used in this manner, the aerodynamic speed brakes could be removed from the airplane to compensate for the weight of the reverser. The effectiveness of a thrust reverser as a speed brake has also been computed as shown in (Figure 1.2R) and is superior to an aerodynamic speed brake.

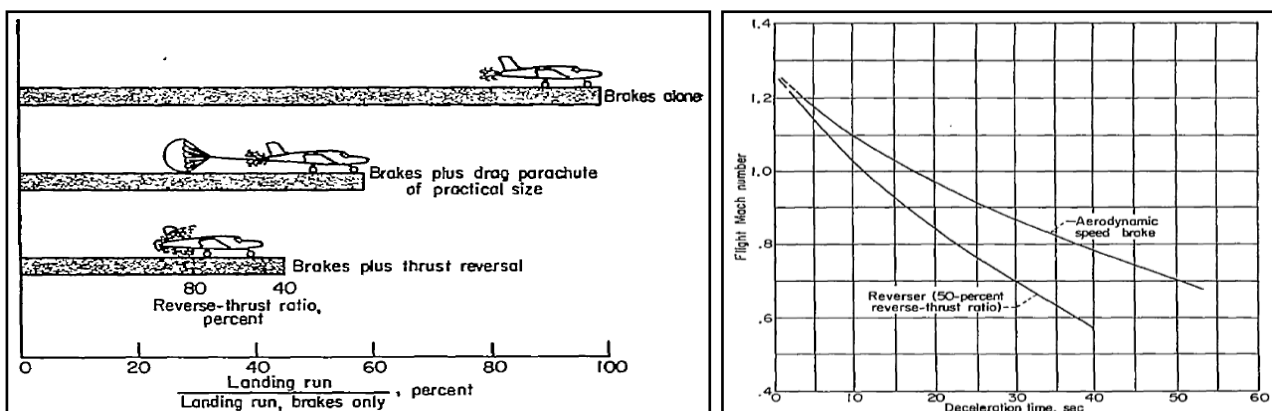


Figure 1.2 (L) Landing run required with different braking devices, (R) Comparison of an aerodynamic speed brake and a thrust reverser. Approximate aircraft weight=20,000 lbs, Images adopted from [Ref. 2].

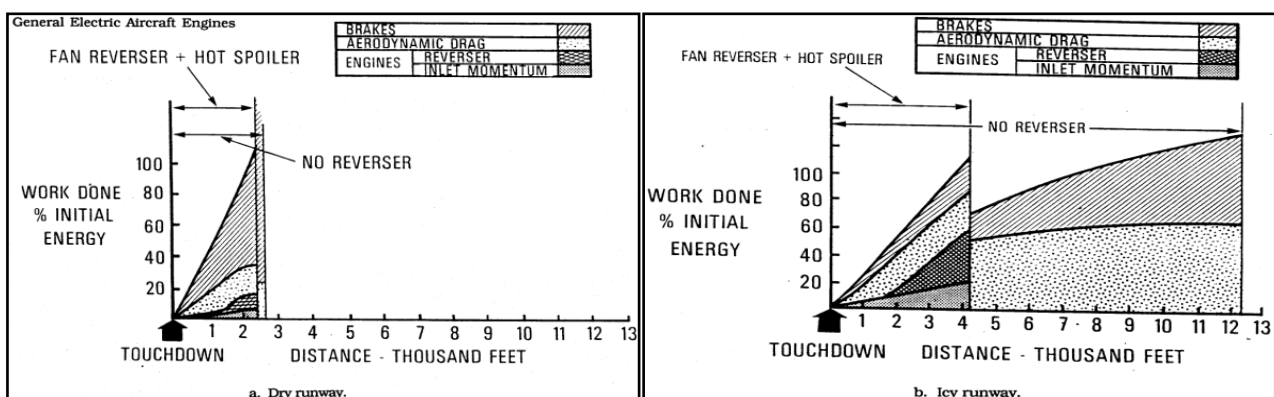


Figure 1.3: Thrust reverser contribution in decreasing stopping distance on dry and icy runway, Images adopted from [Ref. 3].

The selection of the thrust reverser design on the early aircraft was based on the potential ability to fulfil several practical requirements. The first of these is that the reverser be 'fail-safe'. This term is usually considered to mean that in the event of a reverser-actuating-mechanism failure the reverser will return to a forward thrust position from gas forces alone. Secondly, the reverser should have no effect on engine performance in order that the full thrust of the engine will be available for reversing. Thirdly, the retracted reverser should have low internal drag and suitable external shape. Lastly, the reverser should produce a minimum of 40 percent reverse thrust; normally a 40 percent reverse thrust will be sufficient to stop future jet aircraft within the confines of existing runways.

In the early days two basic type of thrust reverser were investigated, target type and cascade type. These two reverser types can be located at various positions on the aircraft.

1.1.1 Target Type Thrust Reverser

The initial concept was a target type thrust reverser. The target type thrust reversers were so designated because the jet is turned by a target positioned behind the exhaust nozzle. Two general configurations of target type reverser, the hemisphere and the half cylinder, are illustrated in [Figure 1.4]. The hemisphere can be designed similar to a clamshell nozzle so that the gas forces acting on the reverser segments are very nearly balanced during actuations. This results in low actuation forces. The cylindrical or circular arc reverser was expected to have desirable jet directional qualities with respect to avoiding control surfaces because of long flow path of the gases along the length of the cylinder.

1.1.2 Cascade Type Thrust Reverser

The second group of thrust reverser investigated in the early 1950s was the tailpipe cascade type. The operation of the tail pipe cascade reverser requires that the cascade be unblocked and the tailpipe blocked, thus forcing the gas into the cascades. The Mach number in the tail pipe just ahead of the cascades was about 0.2 in this case. The early tests on these reverser cascades indicated that high reversal (≈ 80 percent) and the gas turning angles close to designs are obtainable with the simple sheet metal blades. Modification of the blade shapes from reaction to impulse type had negligible effect on gas turning efficiency. Changing the cross section of the cascade to an aerofoil shape with increased thickness likewise had only a small effect on gas turning efficiency and in no case increased the reversal by more than 5 percent. Relocation of the cascade to a high Mach number region (about 0.5) comparable with that immediately downstream of the turbine resulted in a drop in reversal of up to 5 percent. The shape length to width ratio of the cascade likewise appeared to have negligible effect as long as the cascade was correctly sized to pass the desired gas flow [Ref. 4].

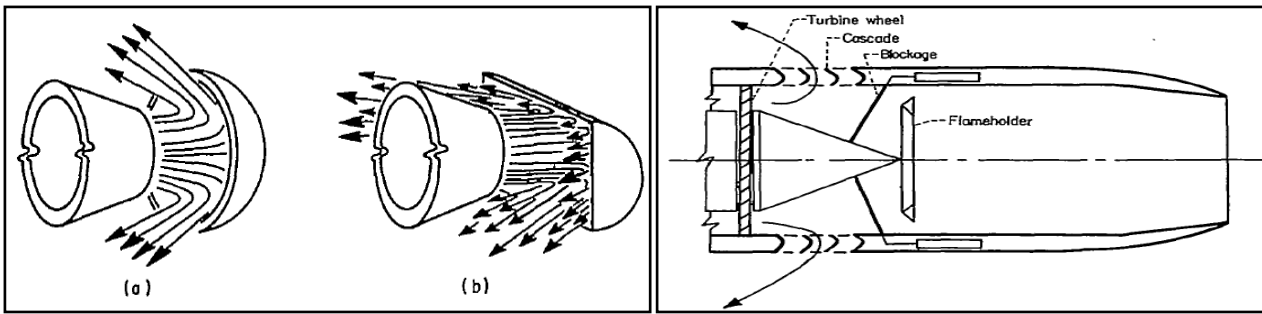


Figure 1.4: (L) Target type reverser (a) hemisphere and (b) half cylinder. (R) Cascade reverser, Images adopted from [Ref. 2].

1.2 Statement of the Problem

The recent high bypass ratio turbofan engines such as TRENT900 (A380), TRENT1000 (B787), GP7200 (A380) and GENx (B787) have BPR values between 9 and 11.

In order to satisfy the demands of higher thrust, increased propulsive efficiency, η_p , and lower Specific Fuel Consumption (SFC), it is very likely that this trend of higher bypass ratios would continue to increase for the future turbofan engines. Future turbofan engines are likely to have BPR values somewhere between 12 and 15. BPR greater than 15 would not be suitable as at higher bypass ratios there will be large shift in fan working line as the speed increases. This affect is so severe at high bypass ratios that engine instability would take place, if no action is taken. Variable bypass nozzle is the most effective way to counteract this problem. Interested reader can get further information from [Ref 5]

The interest in innovative thrust reverser systems is based on the premise that high reverser effectiveness may not be required with very high bypass ratio engines to achieve necessary aircraft stopping force. This is because a substantial amount of the aircraft stopping force is achieved from the ram drag of the large engine nacelles when the thrust is spoiled. In light of this, there is a tremendous incentive to investigate the potential for simpler, lighter weight thrust reverser systems [Ref. 4].

Thrust reversers are mainly installed in an engine nacelle, and are important for aircraft and passenger safety during landing and aborted take-off. However, they are normally not used during the other segments of the flight. During normal landing thrust reversers operates for approximately 19 seconds [Ref. 10]. Thus, thrust reversers come into operation for a very short period of time. Although used for a fraction of an aircraft operating time, the impact of thrust reverser systems on commercial aircraft nacelle design, weight, engine maintenance, aircraft cruise performance, and overall operating and maintenance cost is significant [Ref 8]. The past few decades shows that there has been no significant change in thrust reverser design and cascade, pivoting and target type reversers are still widely use.

The aim of this research is to carry out a preliminary study on a future thrust reverser design that should potentially offer weight savings. NASA carried out a performance study in which six innovative thrust reverser concepts were looked at. One of those six thrust reverser concepts is a Core Mounted Target Type Thrust Reverser. During this PhD, Core Mounted Target Type Thrust Reverser concept is studied in great detail. A 3D CAD model of the thrust reverser is built which is similar to that tested by NASA. 3D CFD analyses will be performed to investigate the reverser

performance, develop an understanding of the reverser aerodynamics, and compare the CFD results with the experiments. A design feasibility study for the future thrust reverser concept will also be performed.

Also, thrust reverser deployment effects on engine performance will be studied for both the mixed and separate exhaust engines. The engine configuration selected for the separate exhaust study is similar to the GE90-94B engine and that for the mixed exhaust engine is similar to the Trent 700 engine. Also, 2D CFD analyses for the mixed exhaust engine were carried out during thrust reverser deployment.

A novel thrust reverser concept is also proposed. Using CFD analyses it will be shown that this novel thrust reverser concept will satisfy the engine performance criteria, provide sufficient reverse thrust, and will offer potential weight savings.

1.3 Aims and Objectives

The main aims of this research are the following:

- i) Perform a performance study on thrust reversers for mixed and separate exhaust engines. The purpose of this study is to show how the deployment of a thrust reverser affects the performance of other engine components such as the compressor, turbine and the nozzle.

As per the data available in the public domain, no work is published which highlights the effect of thrust reverser deployment on over all engine performance. In this regard the performance study is carried out for both the mixed and separate exhaust engines.

A study on a separate exhaust engine with a $BPR \approx 9$ was carried out and is published in this thesis. The reason for this study is firstly, because it represents an advanced high bypass ratio engine, and secondly a similar engine model was used by NASA for thrust reverser testing. An engine CAD model with a similar bypass ratio ($BPR \approx 9$) was constructed for the CFD analyses. Therefore, the boundary conditions obtained from the performance study would later be used for the CFD analyses. A similar study on the medium bypass ratio engine ($BPR \approx 6$) was published in ASME conference in the year 2011 [Ref 6].

A performance study on the mixed exhaust engine is also performed. The purpose of this study is to understand how the performance of the engine components is affected due to deployment of the thrust reverser. A medium bypass ratio engine was selected for this study, which is similar to TRENT 772. During the thrust reverser deployment the engine will change configuration and will act as a separate exhaust engine, this is because reverse thrust is only provided by the fan stream. To understand the core stream behaviour during thrust reverser deployment a 2D CFD study is also carried out.

- ii) The second aim of this research is to carry out a performance and CFD study on a core mounted target type thrust reverser design. Core mounted target type thrust reverser concept is for future high bypass ratio turbofan engines. The future thrust reverser design should offer weight savings and it must be capable to provide sufficient reverse thrust to stop the aircraft within the desired landing distance. The new reverser design must be compatible, so the required reverse thrust can be achieved with minimum effect on engine

performance. The reverser design should have low internal drag and suitable external shape.

During this PhD, Core Mounted Target Type Thrust Reverser concept is looked into greater detail. A 3D CAD model assembly of the thrust reverser along with the wing, external nacelle, and pylon will be built which will be similar to that tested by NASA. Also, a forward thrust configuration will be tested. The comparison between the forward and reverser thrust configuration is important performance criterion that must be satisfied.

Initially, a 3D CFD study will be performed for the reverser stowed condition, i.e. forward thrust configuration. The CFD analyses will be performed at different thrust settings (ideal to maximum). Also, the study is carried out at static ($M=0.0$) and at aircraft landing conditions, $M=0.211$.

3D CFD analyses will also be performed to investigate two different target type thrust reverser designs. The two target type thrust reverser designs are both at 40 degree; one of the reverser design is installed with a kicker plate and the other is without. CFD analyses will be performed at different thrust settings. The study is carried out at both static and aircraft landing conditions.

- iii) From the 3D CFD study, the reverser efficiency and performance will be estimated; CFD study would also allow an understanding of the reverser aerodynamics at both static and at forward landing condition. A comparison of the CFD results against the experiments will also be performed.
- iv) 2D CFD analyses will be performed to conduct a design feasibility study for the future core mounted target type thrust reverser concepts.
- v) 2D CFD analyses will be performed to conclude a novel thrust reverser concept.

1.4 Thesis Structure

The thesis is structured such that all the elements of the research are properly presented to facilitate maximum understanding and comprehension. The thesis structure is presented below.

Chapter 1

The 1st chapter is dedicated to provide an introduction to the content of work dealt within this Thesis. An overview of the underlying context is presented along with the problem statement of the developed methodology. The objectives of the undertaken project are discussed in detail along with the Thesis structure.

Chapter 2

The 2nd chapter provides a broad description of several different types of operational/existing civil thrust reversers; their application, design and safety concerns are also briefly highlighted for greater understanding.

Chapter 3

The 3rd chapter provides a comprehensive literature review corresponding to thrust Reverser Design and Aerodynamics.

Chapter 4

The 4th chapter provides a comprehensive literature review corresponding to the application of Computational Fluid Dynamics to Thrust Reverser Design and Aerodynamics.

Chapter 5

The 5th chapter provides comprehensive analyses related to thrust reversing techniques for a separate exhaust high bypass ratio turbofan engine and its deployment effect on aircraft and engine performance. Chapter 5 subsequently elaborates on the performance implications of thrust reverser deployment on individual component characteristics e.g. compressor, turbine, nozzle etc.

Chapter 6

The 6th chapter provides comprehensive analyses related to thrust reversing techniques for a mixed exhaust high bypass ratio turbofan engine and its effect on integrated aircraft-engine performance. Chapter 6 subsequently elaborates on the performance implications of thrust reverser deployment on individual engine component characteristics e.g. compressor, turbine, nozzle etc. Also, results from the 2D CFD analyses are discussed and presented for a mixed exhaust high bypass ratio turbofan engine at landing condition with thrust reverser deployed.

Chapter 7

In chapter 7, 3D CFD results are presented for the forward and reverse thrust configurations. CFD study is presented for a core mounted target type thrust reverser at static ($M=0.0$) and forward landing condition ($M=0.211$). CFD results for the static condition are extensively validated against

the wind tunnel experiments performed by NASA. The associated flow physics for the 3D CFD analyses has also been discussed.

A design feasibility study was also undertaken for the core mounted target type thrust reverser; 30 different reverser designs were investigated using 2D CFD analyses.

Chapter 8

In chapter 8, the design specifics of the proposed novel Vane Target Type Hybrid Thrust Reverser (VTTHR) configuration are discussed and presented; along with the noticeable improvement in reverser overall performance.

Chapter 9

The 9th chapter recapitulates the most important conclusions of this research and identifies the fulfilment of the Thesis objectives.

Chapter 10

The chapter 10 elaborates on various research aspects that have not been tackled within the work presented in this thesis, due to the time constraints. New areas of research with respect to both potential improvements as well as application of the developed approach are proposed, for the consideration of future work.

Chapter 2. Civil Aircraft Thrust Reversers

Civil aircraft thrust reversers have three key functions, first, to provide a continuous external aerodynamic surface for the nacelle, second, to provide a fan flow path for the engine in forward thrust mode and finally but most importantly to reverse the exhaust flow after the aircraft touchdown, and to assist with aircraft deceleration. Thrust reversers for high bypass ratio engines are integrated into the engine nacelle and contribute to about 30% to the overall nacelle weight [Ref. 5].

Thrust reversers increase the aircraft deceleration and are mandatory on all civil aircraft engines. This increase in deceleration force is vital for aircraft and passenger safety especially on contaminated runways with water, slush or even ice – and thrust reverser also improves rejected take-off margins in similar conditions. The use of thrust reversers also increase the brake life, hence reducing maintenance intervals and saving maintenance cost, however, this all comes at an expense of extra thrust reverser weight that the aircraft has to carry. In civil applications, no certification credit on landing distances is given for thrust reverser fitment; an aircraft landing distance will be determined by the use of anti-lock brakes and aerodynamic drag devices such as flaps and airbrakes. Most large turbo fan engines have 'C' duct thrust reverses that are split into two halves and hinged to the aircraft pylon, providing access to the engine core components. [Ref 6 and 7]

Part of the thrust reverser optimisation process includes ensuring that the hot air/gases neither impinge on the aircraft wing or fuselage nor are re-ingested into the engine intake, which could cause engine surge. It is also important to minimise any lift component from the thrust reverser in order to maximise braking efficiency. Typically, most thrust reverser units are constructed from carbon composite panels, aluminium structural beams, a metal firewall bulkhead, and a suitable thermal blanket (usually stainless steel) on the inner wall to ensure the epoxy in the carbon composite can withstand the combustion and turbine case temperatures. Actuation of the translating sleeves or pivot doors could be electric, hydraulic, or pneumatic and three separate locks are provided to ensure there is no thrust reverser deployment in flight. One of these locks will be separately operated, while the other two will be operated and controlled by the engine [Ref 6].

The two main types of thrust reversers installed on the civil aircraft turbo fan engines are the cascade type thrust reverser, which are commonly found on civil aircraft engines with ($6 < \text{BPR} < 12$), and the pivoting door type thrust reverser which are mainly installed on medium bypass ratio engines ($\text{BPR} \approx 6$). Low bypass ratio turbofan engines makes use of the target type thrust reversers. These are normally aft mounted. Target type thrust reversers are also common on business jets aircraft. Cascade and pivoting door type thrust reversers mainly operates on the fan stream.

On large turbofan engines thrust reverses make use of bypass flow and produce a rearward acting force. Only the fan bypass flow is normally re-directed by the thrust reversers because this gas flow generates the large portion of the engine thrust. To achieve this it re-directs the exhaust gas flow at an angle. On large turbofan engines the bypass stream contributes to approximately 74 per cent of the total thrust, hence, using thrust reverser to convert this thrust as a rearward acting thrust for decelerating the aircraft can be very beneficial for a safer landing.

If the total flight time for a civil aircraft is considered, thrust reversers deployment represent only a small fraction of the flight operating time. Even though the thrust reversers operate for a very short

duration, they are still considered a critical component as their installation on aircraft engines offers the safety of aircraft and the passengers. Also, thrust reverser installation and use affects the nacelle design, propulsion weight, aircraft cruise performance, engine maintenance expenses, and also installation of a thrust reverser system can apparently increase the engine SFC as a result of leakage and pressure drops [Ref. 8]. Manufacturing and design of thrust reversers are mostly not carried out by the gas turbine manufacturers but are out sourced mainly to other companies whose prime purpose is to carry research and development, design, testing and manufacturing of such products. Some of the renowned suppliers in this market are Hispano-Suiza, Aircelle, Goodrich and Honeywell.

2.1 Types of Thrust Reversers

Currently, four types of thrust reversers are in use today, namely, the cascade type, pivoting door type, target type and clamshell door type thrust reversers. A brief description of each reverser design is given below. The two most common thrust reverser types in use on high bypass ratio engines are the cascade type thrust reverser using translating sleeve and pivoting door type thrust reverser.

The details related to the thrust reverser Actuation and Control Systems are provided in (Appendix A1).

2.1.1 Cascade Type Thrust Reverser

The cascade type thrust reversers are mainly installed on high bypass ratio turbofan engines. For very high bypass ratio turbofan engines i.e. $BPR > 6$, the cascade type thrust reversers are always installed. In a cascade type thrust reverser the blocker door blocks the fan stream and divert it through the cascade vanes to produce reverse thrust. Figure 2.1, shows the cascade type thrust reverser. The cascade type thrust reverser has movable translating sleeves, which slides reward to uncover the cascades installed on the fixed structure around the secondary airflow. Blocker doors are installed on the translating sleeves. During deployment the doors are pivoted into the airflow while the translating sleeves move aft ward. In the deployed position the blocker doors block the airflow passage to the rear. Thus, allowing the bypass flow of the engine to exit through the cascades, which deflect and accelerate the airflow into its final direction. This type of reverser creates low actuator loads and allows a very precise control of the airflow during reverse thrust operation.

Cascade thrust reversers are known for their high degree of structural integrity, reliability, and their tolerance to various aircraft applications. Also, in Figure 2.1, it was shown that the cascade type reverser has a fixed and a movable structure. The cowling of a turbofan engine covers the core engine and also forms the gas path for the secondary airflow from the fan frame (or intermediate case) to the nozzle with its outer shell or barrel. It is designed in two halves and hinged to the engine pylon. Thus the cowling can easily be opened for maintenance access to the core engine. The airflow deflection system of the thrust reverser is integrated into the outer barrel of the cowling. Thus this cowling is often called the reverser cowling. The structure of the reverser cowling consists of the fixed structure and the movable structure. The fixed structure is formed by the inner barrel, the forward frame, the longitudinal beams and dependent on the design parts of the outer barrel. The forward frame stiffens the whole structure together with longitudinal beams and transfers the operating loads to the fan frame of the engine. It is attached to the fan frame with a positive-locking fit. In the forwards thrust position the translating sleeve covers the cascade and the blocker doors are positioned flush with the inner surface of the translating sleeve. In the reverse

thrust position the cascades are exposed and the blocker doors have pivoted into the gas path to block the airflow to the rear. Thus, the secondary airflow of the engine exits the gas path through the cascades into the direction enforced by the cascades [Ref 9].

On cascade type reversers Linear Variable Differential Transformers (LVDTs) are used for the sensing of the translating sleeve position by the Full Authority Digital Engine Control (FADEC) computer [Ref.9]. Conventional cascade type thrust reversers are commonly used on commercial aircraft equipped with high bypass ratio turbofan engines i.e. $5 < \text{BPR} \leq 11$.

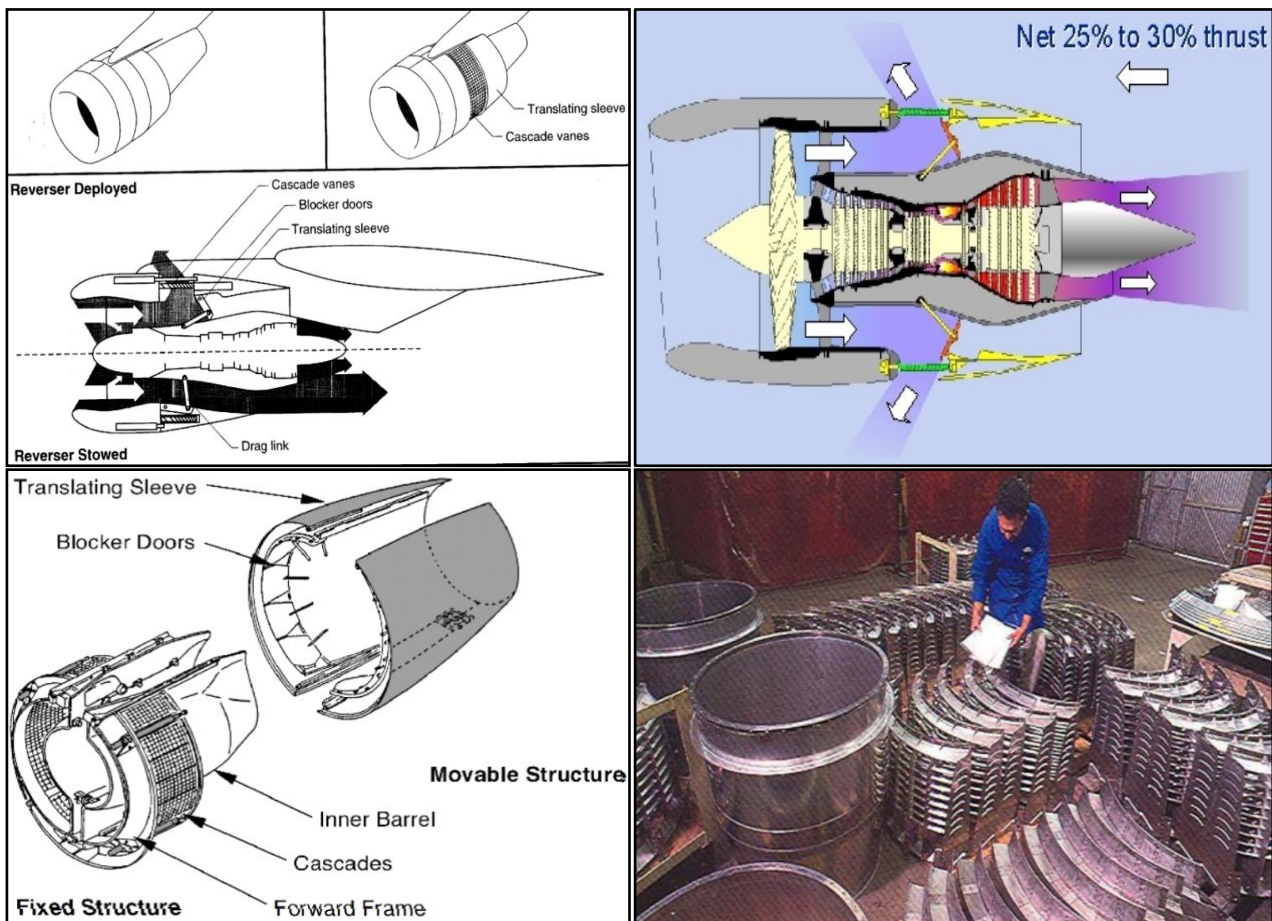


Figure 2.1: (TL) The sliding cascade reverser [Ref. 8]. (TR) Cascade type thrust reverser operating on fan stream [Ref. 10]. (BL) Fixed and movable structure on the cascade type thrust reverser [Ref. 9]. (BR) Shows the reverser cascade blocks, they go around the circumference as per the design location, images adopted from [Ref. 11].

2.1.2 Pivoting door type thrust reverser

Pivoting door type thrust reversers are the second most widely used thrust reverser design on high bypass ratio turbofan engines. However, their use is limited to the engine size and is commonly installed on engines with a bypass ratio of 6 or less. Pivoting door type reverser can be used for both the mixed and the separate exhaust engine configurations. Typical example of a mixed exhaust engine with pivoting door type reverser is the RR TRENT 700. Typical example for the separate exhaust engine (CFM56-5A/5B for A320) is shown in (Figure 2.2). On a pivoting door type thrust reverser normally the four pivoting doors are the movable structure. Figure 2.2, also shows the cross section of a pivoting door type reverser with a pivoting door in the deployed position. In the forward thrust position the doors cover the openings in the fixed structure. In the

reverse thrust position they deflect the secondary airflow of the engine into the direction enforced by the door angle and the sharp edge (kicker plate) at the front end of the door. The thrust reverser designer also ensures that there is sufficient clearance between the pivoting doors and the ground. Whereas, the pivoting doors should not produce any lifting force while in operation. Door leakages when the reverser is in stowed position should be kept to minimum. Finally, the engine designer and the control engineer need to ensure that the doors will not deploy during flight as it could be catastrophic.

Pivoting door type thrust reversers have fewer moving parts and simpler kinematics compared to the cascade type reversers. Additionally the required stiffness of the fixed structure can be achieved at a lower weight. It creates a higher drag in the fully deployed position and the actuator loads are higher compared to the cascade type reverser of the same size. Pivoting door type thrust reversers were first used on the Airbus A320. They are also in service on the A340-200/300 aircraft with CFM56-5C engines and on the Airbus A330 aircraft with TRENT700 engines.

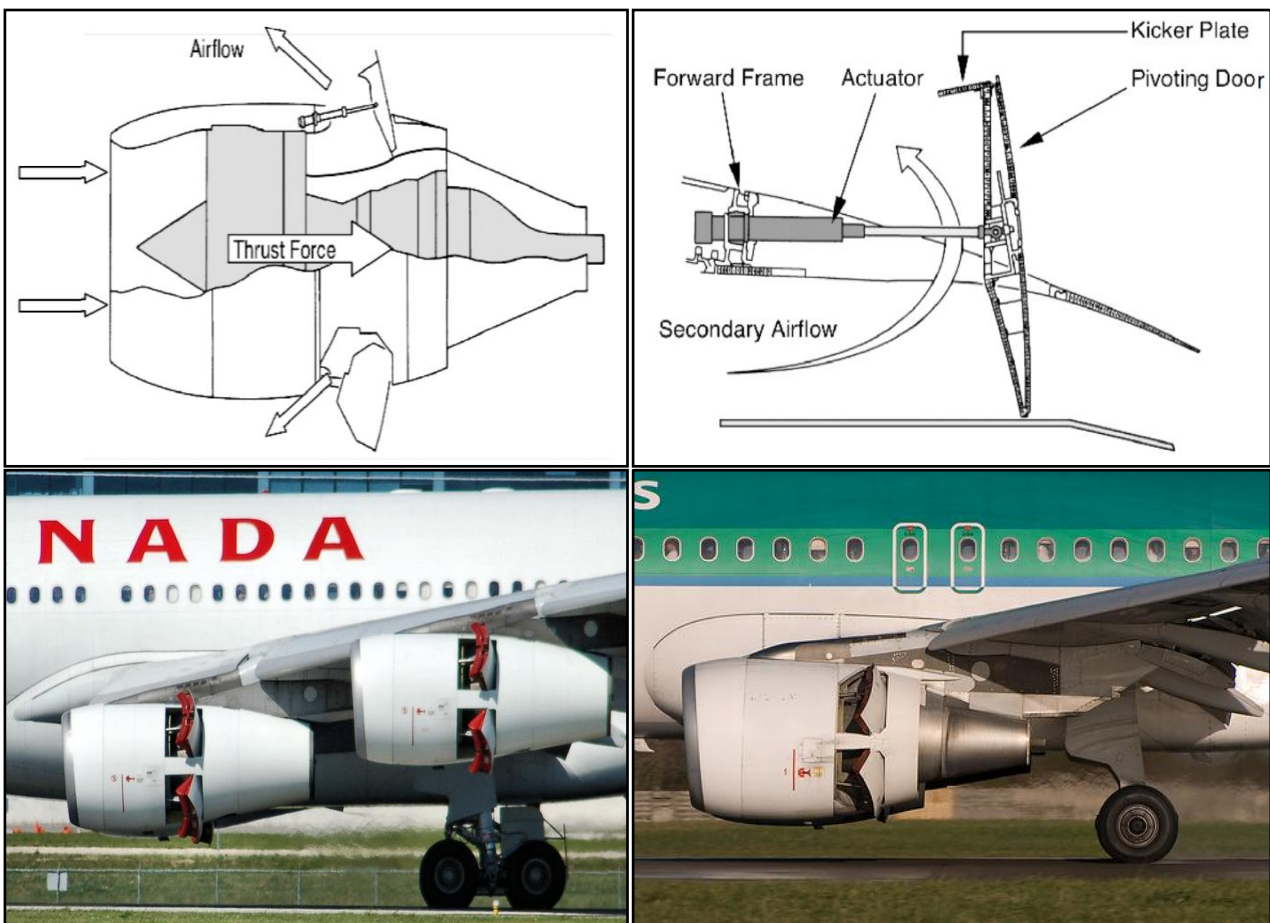


Figure 2.2: (TL) Pivoting door type reverser design [Ref. 9]. (TR) Pivoting door reverser with kicker plate installed [Ref. 9]. (TB) Mixed exhaust engine using pivoting door reverser operating on fan stream only [Ref. 12]. (RB) Separate exhaust engine for an A320 using a pivoting door type thrust reverser. Images adopted from [Ref. 13].

2.1.3 Target Type Thrust Reverser

The most common type of thrust reverser for low bypass ratio turbofan engine is the 'target type thrust reverser'. Small turbofan engines are mostly equipped with internal mixers; they are mainly installed on business and regional jets. In the target type reverser the translating and rotating part

of the exhaust nozzle creates a bucket at the rear end of the engine that redirects the (mixed) fan and core exhaust flows. A typical example is shown in (Figure 2.3). Target type reversers are commonly found on aircraft such as Gulfstream and Fokker 100, 70.



Figure 2.3: Target type thrust reverser in operation on Fokker aircraft. Images adopted from [Ref. 14].

2.1.4 Clamshell and Bucket Door Type Thrust Reverser

The only two current military aircraft which are installed with thrust reversers are the Saab Viggen aircraft employing the Volvo RM8 turbofan engine which is a derivative of the Pratt and Whitney JT8D, and, Panavia Tornado aircraft employing the, Rolls Royce RB199, turbo fan engine. Both of these aircraft have thrust reversers and afterburners.

On RB199 engine the thrust reverser design is similar to the target type thrust reverser used on commercial aircraft, and is mainly referred to as bucket door type thrust reverser when employed on a military engine. The design of the exhaust nozzle parts are such that the bucket is formed by their rotation, this then reverses the engine flow. The bucket target system is a hydraulically actuated system. The bucket doors are actuated by a conventional hydraulic powered pushrod system. The actuator incorporates a mechanical lock in the extended position. In the forward thrust mode the bucket doors form the convergent-divergent final nozzle for the engine. When the thrust reverser is deployed, the reverser automatically opens to form a 'bucket' approximately three-fourth to one nozzle diameter at the rear of the engine exhaust nozzle. Figure 2.4 shows a Tornado aircraft making use of a bucket door type thrust reverser during landing.

Saab Viggen aircraft are installed with clamshell door type thrust reversers. The clamshell door on this aircraft is pneumatically operated. Normal engine operation is not affected by this installation, because the ducts through which the exhaust gases are deflected remain shut until reverser thrust is activated by the pilot. When this happens, the clamshell doors rotate to uncover the ducts and close the normal exit. Engine flow is then directed by the cascade vanes; the reverse thrust produced opposes the aircraft motion (Figure 2.4). In contrast to the RB199, engine the thrust reverser for the Volvo RM8 engine is integrated within the engine i.e. in exhaust pipe and is not visible during landing.

The main reason for not employing thrust reversers on other military aircraft engines is weight of the thrust reversing buckets and the hydraulics; as they weights significantly more than a parachute or a hook. Also, the military engines are mixed-exhaust and thrust reversers will be located at the rear of the engine; thus the exhaust gases could be at a very high temperature and could damage and/or affect the aircraft control surfaces.

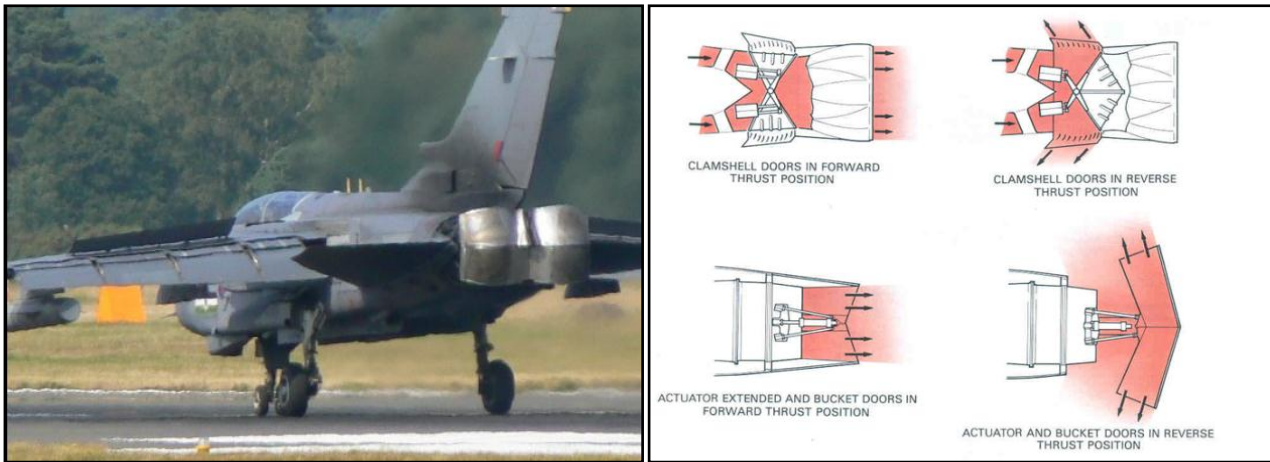


Figure 2.4: (L) Shows the Tornado aircraft employing the bucket door type thrust reverser during landing [Ref. 15]. (R) The difference between the Clamshell reverser employed on the Viggen aircraft and the Bucket door type thrust reverser employed on the Tornado aircraft. Images adopted from [Ref. 16].

2.2 Thrust Reverser Utilization

Most airlines deploy thrust reversers on every landing. The guidelines for thrust are well established and are typically based on inputs from the airframe manufacturers. Although most airline pilots deploy thrust reversers on every landing, the level of reverse thrust used is left to pilots' discretion. Hence, the pilot discretion means that if the aircraft landing field is short the pilot would than deploy the thrust reversers and maintain full power; whereas if the runway is long and dry then full reverse thrust may not be necessary. It should be noted that most airlines recognize that since thrust reversers are available they should be used to reduce brake wear. Pilots are therefore instructed to use thrust reverser early in landing sequences (high speed) to minimize the amount of brake wear. At maximum reverse thrust the engine operates at around 80 percent power; reverse thrust is cancelled at speeds of around 80 to 60 knots to prevent problems associated with engine surge, re-ingestion and tail blanking.

Weathervaning in crosswinds is likely to affect the thrust reverser operation. Weathervaning is defined as the condition where the reverse thrust side force component, F_z , combines with crosswind component to cause the airplane to yaw into wind (Figure 2.5). This condition is controlled and prevented by reducing the reverser thrust level and compensating with opposite rudder or differential braking. Refused Take-offs (RTO's) are also identified as a primary reason for having thrust reversers on commercial transport aircraft, the frequency of RTO's average about 2 per 10,000 take-offs [Ref. 18].

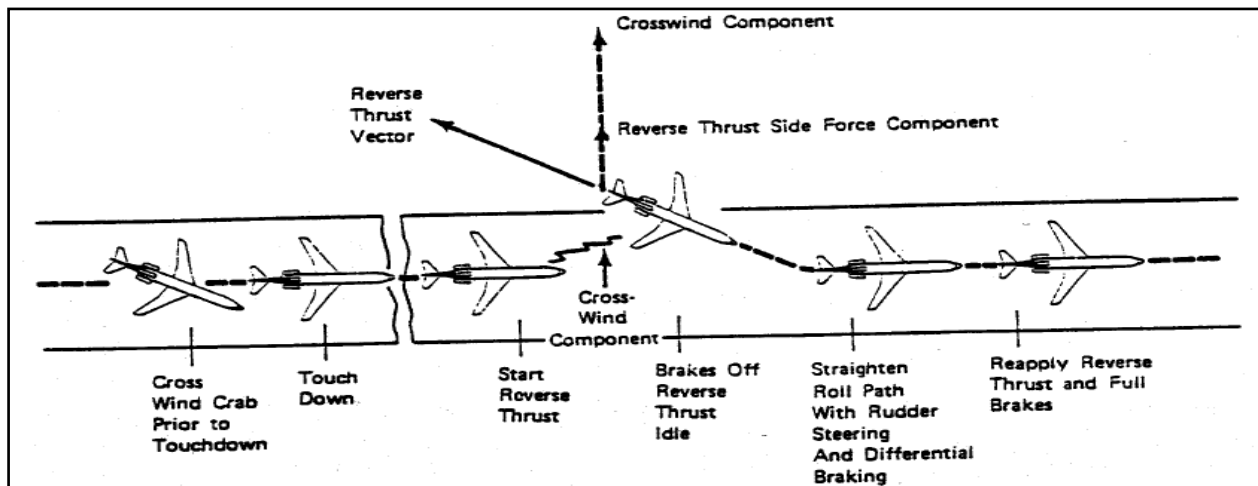


Figure 2.5: Weathervaning—Effect of reverse thrust on a slippery runway with crosswind (B727). Image adopted from [Ref. 18].

The typical brake system for an aircraft consists of an Anti-Skid System (ASS) and an Auto-Brake System (ABS), each operates independent of the other. The function of the anti-skid system is to modulate the individual wheel brake pressure to achieve maximum brake effectiveness for the current runway condition. The anti-skid system senses wheel speed and adjust brake pressure accordingly to prevent wheel lockup. The availability and/or use of thrust reversers have no impact at all on the design and function of the anti-skid system. The auto-brake system senses aircraft deceleration rate and modulates brake system pressure to maintain a constant preselected deceleration rate.

The application of reverse thrust will result in reduced braking by the ABS system. Therefore, the availability of the thrust reverser indirectly affects the use of auto-brake system in that the braking action required for a given deceleration rate is reduced when thrust reverser are used. To save on brake wear some airlines instruct their pilots not to use ABS except during adverse weather conditions. Another advantage of thrust reversers on small aircraft is to fulfil the requirement of power back from the terminal gate. A small minority of airlines do power back to minimize ground handling equipment and ground crew personnel requirements. In practice, power backs are typically limited to aircraft with relatively small (low thrust) tail mounted engines (B727, DC9, MD80, F100). For reasons of ground safety, noise, and air pollution most airlines do not use thrust reversers for power back. Power back is not used on aircraft with larger high bypass turbofans engines because of the large amount of air movement involved.

The installation and use of thrust reversers increase the engine maintenance cost; this is due to the increase in engine operating cycles. Engine maintenance schedules are typically based on a combination of engine hours and cycles. In effect, the engine cycles per flight are factored into the flight hour reference maintenance schedules for each aircraft type. It should also be noted that an engine cycle is defined as a flight cycle which includes the take-off, climb, cruise, descent and landing. The deployment of the thrust reverser and a change in engine power setting during landing is not considered an additional engine cycle if the engine is not brought up to the maximum power during reverse thrust. An engine ground run-up for maintenance checkout would also not be counted as an engine cycle. This definition is used throughout the airline industry [Ref. 18].

Engine cycles are important when it comes to the turbine disc and the number of mechanical cycles experienced. Turbine blade tip wear due to thermal cycles is critical to engine performance, not to mechanical reliability. Tip wear causes engine performance losses which show up as higher

exhaust gas temperatures (and eventually an over temperature) when setting maximum power [Ref. 18]. Figure 2.6L, shows the engine power level during reverse thrust operation. Figure 2.6R, shows the different engine speeds and cut-off speeds used by airlines during thrust reverser operation.

The level of reverse thrust required can be divided into three categories, Minimum (MIN), Medium (MED), Maximum (MAX). They are all function of runway length and surface condition. The amount of reverse thrust to be use depends on the length of the runway and runway surface conditions, but the final decision on the level of reverse thrust to be used is the pilot decision.

The following describes the engine power during reverse operation with runway length. MAX mode is not recommended on dry runways. The use of ABS is recommended for landing on wet, slippery and contaminated runways or runways close to minimum runway length. Normally, the landing speed for civil aircrafts is between 120 knots – 145 knots [Ref. 10]. The aircraft touches the ground at high angle of attack; once the brakes and the lift dumpers becomes effective the pilot sets the engine forward thrust lever to idle and make use of the reverse thrust lever to apply reverse thrust. On a dry runway, when the thrust reverser is deployed, the pilot does not apply the brakes, once the aircraft speed is reduced below 100 knots. The pilot applies the brake pressure, the reverse thrust is cancelled between the speeds of 80 knots – 60 knots and the engine power is changed back to forward-idle. At a speed of 60 knots the engine thrust is set to forward-idle and only the brake force is than applied to decelerate the aircraft. At a speed of 20 knots which is a normal aircraft taxi speed the aircraft departs towards the designated gate assigned by the Air Traffic Controller.

- MIN – when available runway length is >9750 ft.
- MED – when available runway length is 7800 to 9750 ft.
- MAX – when available runway length < 7800 ft.

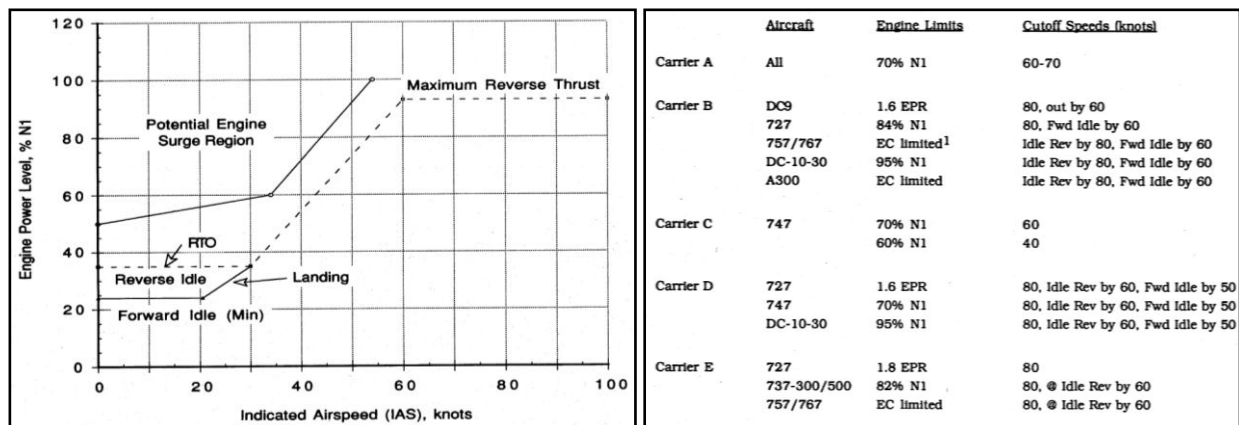


Figure 2.6: (L) Typical engine operating levels and limitations during reverse thrust operation. (R) Sample of engine power levels and cut-off speeds used by some airlines. Images adopted from [Ref. 18].

2.2.1 Thrust Reverser Utilisation Survey at Heathrow Airport

A survey was carried out at London Heathrow Airport by British Airways and BAA to gain more information about the use and duration of the thrust reversers for both British Airways and other

operators for input into modelling of local air quality impact of aircraft landing operations on October 26th and Nov 1st 2005.

Observations were made and recorded by hand for landings that took place on runway 27L and 27R at Heathrow Airport. The length of the runway from the [Table 2.1] is about:

- London Heathrow, Runway, 09/27R = 12,802 ft.
- London Heathrow, Runway, 09/27L = 12,000 ft.

The technical report as per [Ref.19] suggests that the majority of the airline pilots i.e. around (60%) use only the idle reverse thrust during the landing. The average duration of thrust reverser utilisation on these occasions was approximately 19 second. The runway length at London Heathrow Airport is greater than 9,750 ft. (Table 2.1). Therefore, depending on the aircraft landing weight, the idle-reverse thrust may be sufficient on a dry runway.

Country	Airport Name	Runway Length	Runway Elevation	T/Reverser Use on Dry Runway
United Kingdom	London Heathrow, 09L/27R	3902m x 50m (12802ft x 164ft)	80 ft	Min
United Kingdom	London Heathrow, 09R/27L	3658m x 45m (12000ft x 148ft)	80 ft	Min
United Kingdom	London Heathrow, Runway Length 23	1962m x 45m (6437ft x 148ft)	80 ft	Max
United Kingdom	London Gatwick, 26L/08R	3316m x 46m (10879ft x 151ft)	196ft	Min
United Kingdom	London Gatwick, 26R/08L	2565m x 45m (8415ft x 148ft)	196ft	Med
United Kingdom	London Stanstead, 05/23	3048m x 46m (10000ft x 151ft)	348ft	Min
United Kingdom	London Luton, 08/26	2160m x 46m (7086ft x 151ft)	526ft	Max
United Kingdom	Manchester, 05L/23R	3048m x 48m (10000ft x 157ft)	257ft	Min
United Kingdom	Birmingham Int, 15/33	2605m x 46m (8547ft x 151ft)	325ft	Min
United Kingdom	Edinburgh, 06/24	2560m x 46m (8399ft x 151ft)	135ft	Min

Table 2.1: Shows the runway lengths for the major airports in United Kingdom.

In total about 170 observations were made at London Heathrow Airport; this was to observe thrust reverser utilization on various different aircraft. The results are presented in (Table 2.2), the table shows the number of observations made, percentage using greater than reverse-idle, average time when reverse thrust was greater than idle (sec) and the average time for landing roll-out on runway (sec). All the observations were made during the daytime, between 09:00 and 13:00 local time, so that no special rules regarding the use of reverse thrust at night were in force. Also the runway state remained DRY, with no Low Visibility Procedure (LVP) in place, which again meant that normal procedure were being used and were not affected by the ambient conditions prevailing at the time. The time from wheel touchdown (identified by tyre smoke) until turn-off from the runway was recorded and the time for any thrust reverser operation was also noted. Identification of whether the landing aircraft utilised reverser thrust above the idle power setting was relatively straightforward, as the rise in noise associated with power increase during the reverser thrust operation was clearly noticeable and obvious. Two locations were chosen, one for 27L and one for

27R such that the point of touchdown on the runway to the end of the landing rollout where the aircraft turned off onto the taxiways was visible. A note on the aircraft type was made so that any trend in reverser operation due to different types might be identified, and BAA Heathrow also noted the operator of the aircraft for future analysis [Ref.19].

Approximately 40% of aircraft landings observed were identified as using reverse thrust at more than idle power, with the other 60% at reverse idle. The average time spent with reverse power operating was about 19 seconds; and reverse thrust, appeared to be initiated approximately 3 seconds from touchdown. The average duration of the ground rollout for all types was about 38 seconds. There was quite a variation in both the use and duration of reverse thrust used between types with a few recordings (mainly Boeing 757 and 777 aircraft) using no more than 2 or 3 seconds of reverser power before retarding the throttles to idle. Other aircraft, principally the older Boeing 747's and A340 and the Gulfstream IV (biz jet), used a significant amount of reverse thrust coupled with a long rollout along the runway to one of the Rapid Exit Turnoffs (RET's) further down the runway.

Aircraft type	No. of observations	Percentage using greater than reverse idle	Average time in reverse greater than idle (sec)	Average time for landing roll-out on runway (sec) 2005 survey	Average time for landing roll-out on runway (sec) 2001 survey
A300	0	--	--	--	45
A310	1	100%	27	57	--
A319	33	15%	16	32	36
A320	32	59%	18	37	36
A321	23	35%	21	34	36
A330	3	67%	19	46	--
A340	2	50%	32	64	45
B737	15	93%	19	40	35
B747 "Classics"	2	100%	33	55	57
B747-400	13	23%	21	48	49
B757	13	8%	2	37	35
B767	8	38%	16	38	46
B777	16	31%	17	45	54
BAe 146	0	n/a*	n/a*	--	--
Canadair RJ	1	?	?	30	--
DC10	0	--	--	--	56
EMB 145	1	100%	13	27	--
F70/100	1	0%	0	36	--
MD11	1	100%	24	47	44
MD80/90	4	25%	16	34	--
Biz jets (e.g., Learjet)	1	100%	33	59	37
Props (e.g. F50)	0	--	--	--	--
Airport average	170	40%	19 sec	38 sec	

Table 2.2: Survey results for thrust reverser use and runway occupancy time averages.
Adopted from [Ref. 19].

2.3 Thrust Reverser Problems and Related Accidents

The types of problems typically encountered with thrust reverser systems are as follows:

- Indicator problems
- Inability to Deploy or Stow
- Mechanical failure: Actuator, Blockers, Linkages, Cascades
- Wear, De-lamination of acoustic treatments
- Leaks

Landing with thrust reversers locked out should not pose a problem for the safe operation of the aircraft on a dry runway, as per the Federal Aviation Administration (FAA) certification requirements the aircraft should be able stop within the safe landing distance only on wheel brakes [1]. However, thrust reverser in flight deployment due to control system or other engine malfunction could be catastrophic for both the aircraft and passengers. The un-commanded deployment of thrust reversers up to the time of writing this thesis had reportedly resulted in four fatal air crashes the brief detail of which are as follows:

Un-commanded Deployment:

1. 9-February-1982 - Japan Airline Flight 350, DC-8, thrust reverser intentional deployment cause death of 24 passengers
2. 29-August-1990 - Lockheed C5A thrust reverser un-commanded deployment cause 13 deaths
3. 26- May-1991 - Lauda Air flight, Boeing 767-300, un-commanded deployment of one of the thrust reversers caused 223 deaths
4. 31-October-1996 - TAM Linhas Aereas Flight 402 – Fokker 100, un-commanded deployment of thrust reverser caused 96 deaths

Late Deployment:

Similarly, late deployment of thrust reverser up to this day has reportedly caused three accidents resulting in 200 fatalities the brief detail of which are as follows:

1. 8-December-2005 - Southwest Airlines Flight 1248 overran the runway killing a 6 year old boy, cause of the accident was mainly due to late deployment of thrust reverser.
2. August–2005 - Air France Flight 358, the airplane skids past 200 meters down the runway; no one was killed, due to late thrust reverser deployment.
3. 17 – July - 2007 - TAM Airlines Flight 3054, Airbus A320, was not able to stop while landing killing 187 people on board and 12 on ground. One inoperative thrust reverser played a role in the crash.

Chapter 3. Thrust Reverser Design and Aerodynamics – Literature Review

The first technical work on thrust reversers was officially published by National Advisory Committee for Aeronautics (NACA) in the year 1954. Initially, the early research on thrust reversers was on a single engine turbojet military aircraft.

3.1 Early Thrust Reverser Concept Selection Research by Boeing

The Boeing Airplane Co had a vast experience with reversible propellers and was the first one along NACA to carry out the research on turbojet thrust reversers. Boeing started the initial testing of thrust reversers on turbojet engines in the year 1951; however, the work was first published in the year 1954 by the SAE (Society of Automotive Engineering). The parachute chutes were common to improve the stopping capability on turbojet aircraft such as the Boeing B-47. However, the parachute chutes do have limitations which reduce operational flexibility. Once the chute is deployed, facilities outside the airplane are necessary to handle it. Another disadvantage of the chute is that it has to be deployed quite close to touchdown to be fully effective, since the drag effect is a function of air speed. Boeing, thus, realised that reverse thrust would have to be developed for jet engines if jet transports are to have the operational flexibility. Figure 3.1, shows that if a dry concrete runway is assumed, and brakes only are used to stop than an adequate margin in stopping distance exists. If an icy runway is assumed, a large part of the margin is used up. However, with the thrust reverser deployed on an icy runway the margin in stopping distance is more than equal to that achieved on a dry runway using brakes alone [Ref. 20].

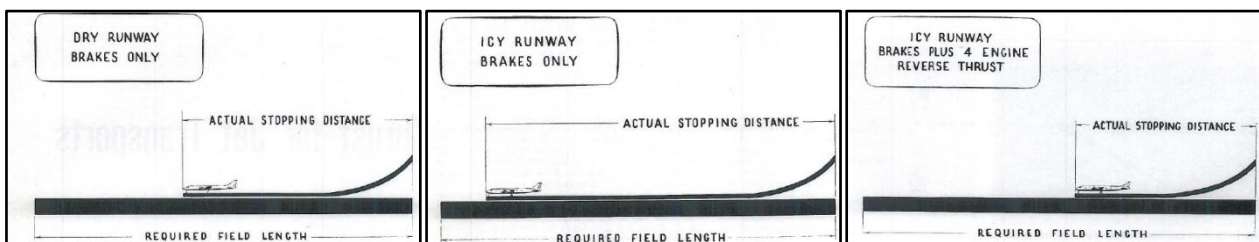


Figure 3.1: Dry runway landing with brakes alone, Icy runway landing with brakes alone and Icy runway landing with thrust reversers deployed. Images adopted from [Ref. 20].

Boeing started the research on thrust reversers by setting up design objectives. The primary objective was to design a device which would be inherently safe and reliable. It was desired that these qualities should be achieved through basic design and simple structural locks. The second objective was that the reverse thrust should be in the order of 40% of maximum forward thrust. Third that the reverse thrust should be used for ground run control only. Using reverse thrust for glide path control could increase the probability of failure in flight. The fourth objective requires that the reverser should not affect engine economy when the reverser is not in operation. In addition, the reverser should not adversely affect engine life or engine control characteristics when in operation [Ref. 20].

Tests of many shapes of likely reversers were conducted using the Boeing Nozzle test facility (Figure. 3.2 and 3.3). The research provided a useful outcome that about 45 to 50% reversal from the exhaust flow is possible with reversers that could reasonably fit into the space available near the engine tailpipe. The clam-shell type reverser showed the greatest promise from the standpoint of meeting the design objectives and from the standpoint of mechanical simplicity, installed weight,

and aircraft stowage. The clamshell design arrangement was capable of achieving the necessary stopping distances on icy conditions. The research also concluded that the reverser effectiveness is proportional to the deflection angle of the exhaust flow and the exhaust flow clears the adjacent structure by considerable margin. The clamshell reverser has no effect on engine characteristics during normal forward thrust operation since no part of the device extends into the jet blast [Ref. 20].

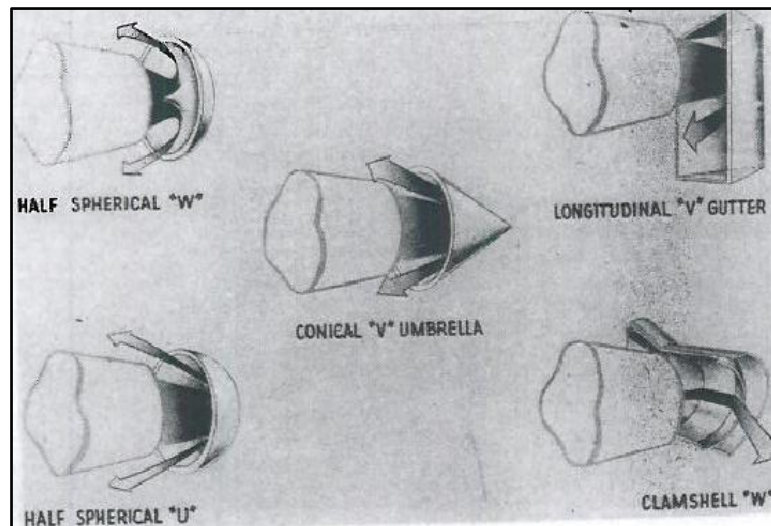


Figure 3.2: Shapes of likely reversers tested by Boeing. Image adopted from [Ref. 20].

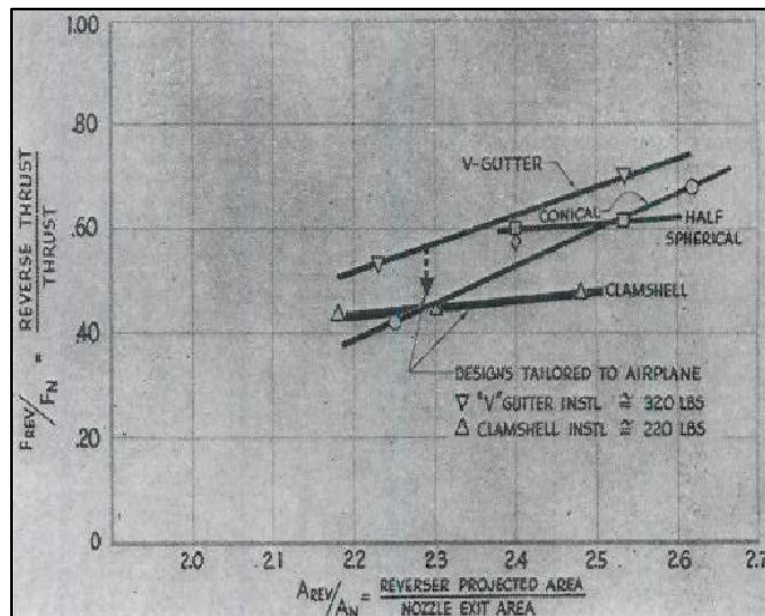


Figure 3.3: Summary of various thrust reverser performance. Image adopted from [Ref. 20].

3.2 Early Research Conducted by NACA on Cascade Type Thrust Reverser

Since the early 1950s, NACA was actively involved in the design and experimental research on thrust reversers, and has published many good quality technical reports which have certainly led to the thrust reverser designs on modern civil aircraft. Because thrust reversal is a desirable or necessary feature of high speed or all weather jet aircraft, a research program on thrust reversal was inaugurated at the NACA.

The first research on the cascade type model thrust reversers was published in the year 1955 by NACA. The cascade type thrust reversers are located at the upstream of the jet engine exhaust nozzle i.e. in the tail-pipe (Figure. 3.4). Reference 21, provides details of such a cascade type reverser experiment where 15 different tail pipe cascade configurations were investigated in quiescent external flow conditions. Symmetrical cascade blade shape models in both thin (single curvature) and thick (double curvature) were studied. The symmetrical blades configuration have equal entrance and exit angles and, as a result, have equal entrance and exit effective flow areas (Figure 3.5L). However, for the asymmetrical blades the entrance and exit angles were not equal; as a result, the entrance and exit effective flow areas would also be different (Figure 3.5R).

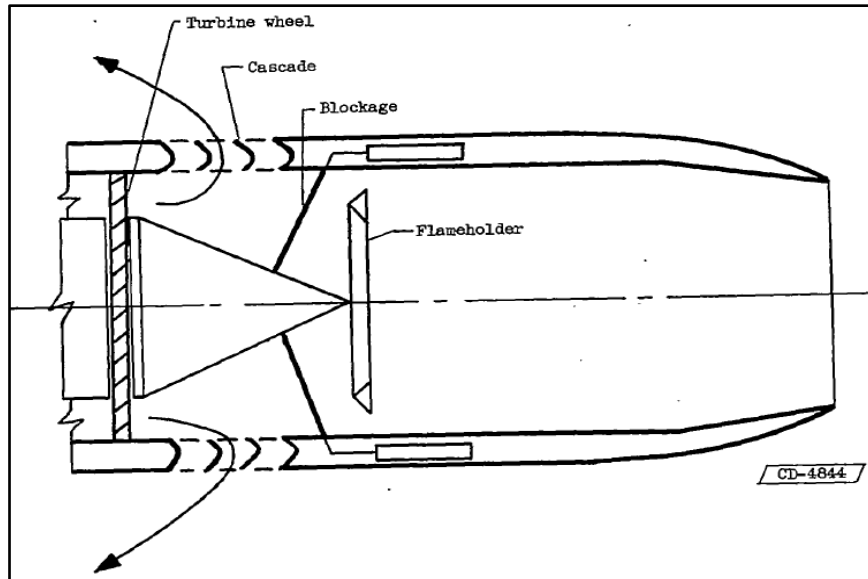


Figure 3.4: Tail pipe cascade reverser. Image adopted from [Ref. 21].

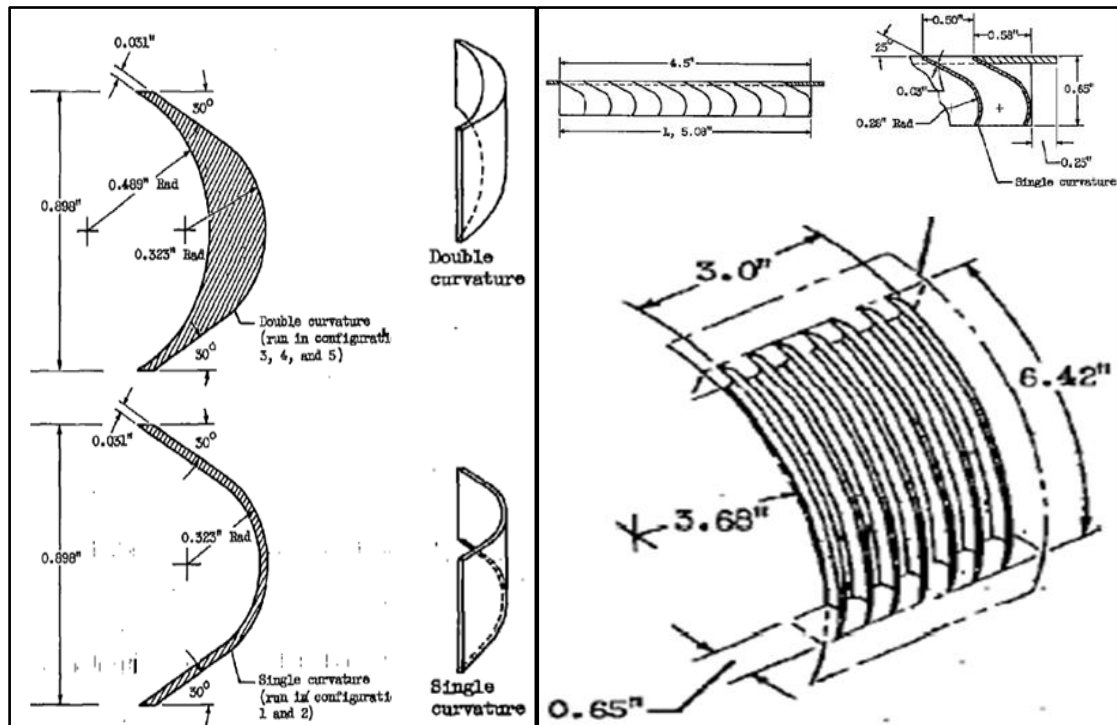


Figure 3.5: (L) Symmetrical cascade blades. (R) Asymmetrical cascade blades. Images adopted from [Ref. 21].

It was investigated that the maximum reverse thrust ratio on a full scale thrust reverser occurs when the effective area of the cascade reverser is equal to the effective area of the exhaust nozzle; also the limiting tail pipe pressure and temperature needs to be taken into account. The experiments were performed over a range of cascade exhaust nozzle pressure ratios from about 1.2 to 2.4. The research in [Ref. 21] summarises that the maximum reverse thrust with a thin symmetrical cascade will be about 74 percent, however, that for the thick symmetrical cascade the maximum reverse thrust ratio would be about 76 percent. Thus, the thin and thick symmetrical reverser cascades would achieve approximately similar reverse thrust values. The asymmetrical reverser cascade blades on the other hand would achieve a higher reverse thrust ratio of about 88 percent.

The operation of the tail pipe cascade reverser requires that the cascade be unblocked and the tail pipe blocked, thus forcing the gas into the cascade. Typical performance of several tail pipe cascade reversers obtained with the tail pipe completely blocked is illustrated in (Figure. 3.5 and 3.6). Curves of reverse thrust ratio against tail pipe pressure ratio are presented for sheet metal cascade using a 'reaction' type (minimum area at blade exit) blade of 1.65 solidity and an 'impulse' (minimum area at blade inlet) type of 1.5 solidity. Sketches showing cross sections through the blades are also included. The Mach number in the tail pipe just a head of the cascades was about 0.2 in this case.

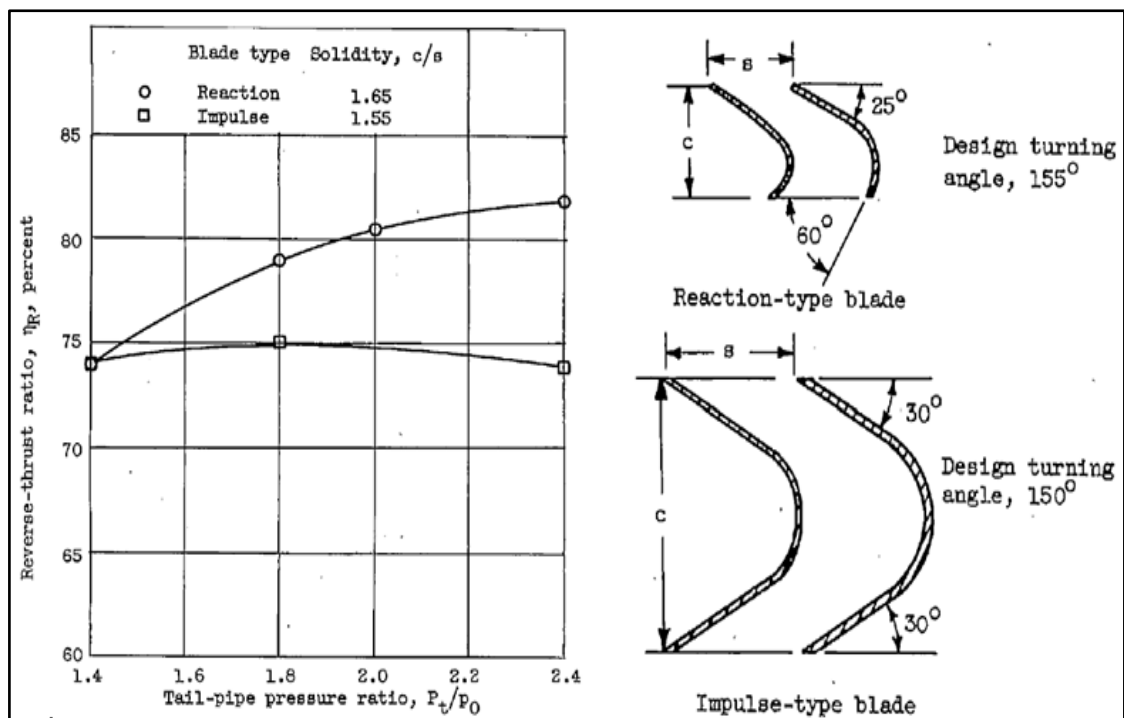


Figure 3.6: Effect of cascade design on performance of tail pipe cascade thrust reversers. Tail pipe Mach no=0.2; 100 percent tail pipe blockage. Images adopted from [Ref. 21].

The test with these cascades indicated that high reversal (over 80 percent) and gas turning angles close to design are obtained with these simple sheet metal blades. Modification of the blade shape from reaction to impulse type had negligible effect on gas turning efficiency because the difference between the curves at higher pressure ratios can be accounted for by the difference in blade exit angle and solidity. Changing the cross section of the blade from that indicated to an aerofoil shape with increased thickness likewise had only a small effect on gas turning efficiency and in no case increased the reversal by more than 5 percent. Relocation of the cascade to a high Mach number region (about 0.5) comparable to that immediately downstream of the turbine resulted in a drop in

reversal of up to 5 percent. The shape (length to width) ratio of the cascade likewise appeared to have negligible effect as long as the cascade was correctly sized to pass the desired gas flow [Ref. 21].

The cascade solidity is defined as the ratio of the cascade height to the distance between the two cascades (Figure 3.7). The effect of cascade solidity on reverse thrust ratio is considerable as shown in (Figure 3.7) for two different blade cross sections. Reverse thrust ratio increases about 10 percent as the solidity is increased from 1.11 to 1.55.

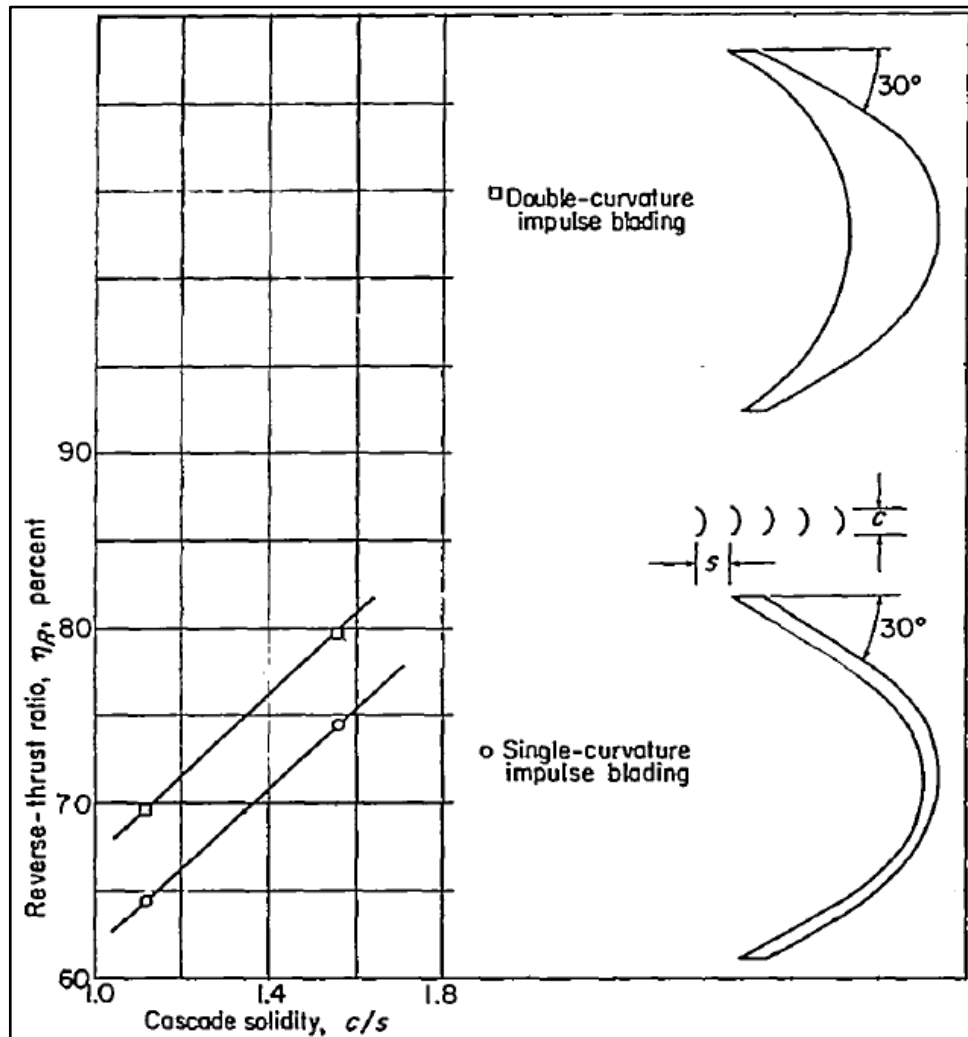


Figure 3.7: Effect of cascade solidity on performance of tail pipe cascade thrust reverser; tailpipe blockage 100 percent [10]. Image adopted from [Ref. 21].

For one series of tests the cascades were completely removed, and an external door was used to guide the flow (Figure 3.8). With doors of 0.98 length– diameter ratio set for a 150° turning angle, a reverse thrust ratio of 55 percent was obtained at a tail pipe pressure ratio of 2.0. This is about 20 percent less than that obtained with from an impulse cascade reverser with a cascade solidity of 1.55 designed for the same turning angle.

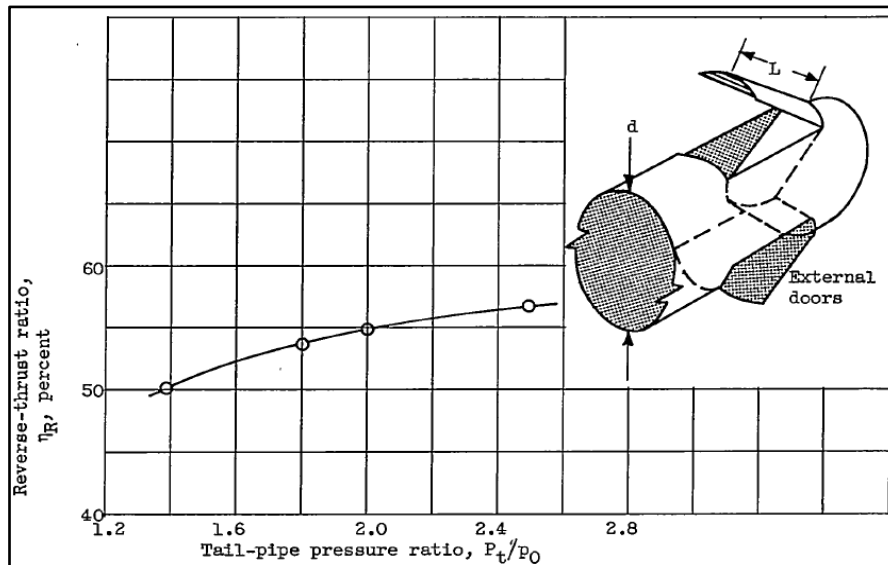


Figure 3.8: Performance of tail pipe thrust reverser with external guidance doors and no cascades. 100 percent tail pipe blockage. Door length to diameter ratio set as 0.98 and design turning angle, 150° deg. Image adopted from [Ref. 21].

The effect of varying the tail pipe blockage on the reverse thrust obtained with a typical cascade reverser is illustrated in (Figure 3.9). The cascades were covered as the blockage was decreased so that the effective flow area of the system remained constant. As, expected the reverse thrust decreases as tail pipe blockage is decreased. A reverse thrust ratio of 40 percent can be obtained with a blockage of 64 percent. Thus, it is not necessary to completely block the tail pipe to obtain useful values of thrust reversal.

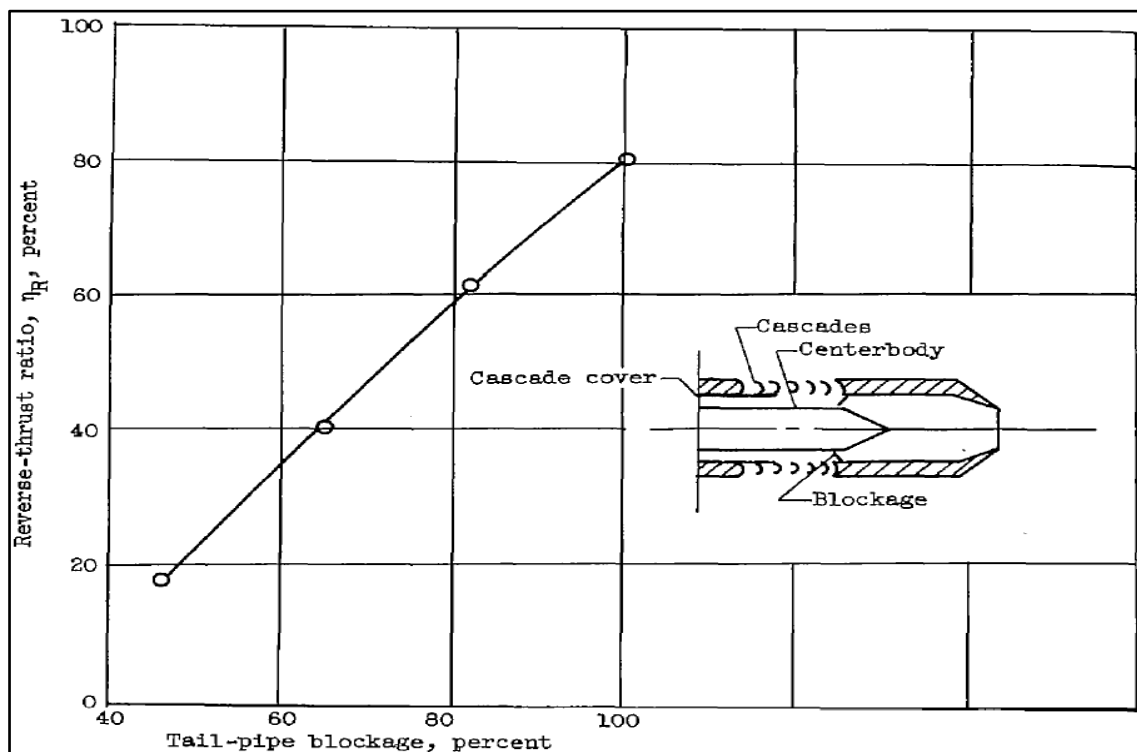


Figure 3.9: Effect of tail pipe blockage on performance of cascade thrust reverser; Pressure ratio 2.0. Image adopted from [Ref. 21].

The external flow fields of the cascade reversers were of considerable interest; and thus, typical external-velocity patterns are presented in (Figure 3.10). The profiles at the top of the figure were determined for an impulsive type cascade that produced 73 percent reversal at a pressure ratio of 2.0, and those at the bottom were determined for a reaction type cascade that produced 81 percent reversal at the same pressure ratio. The essential difference between the two is that, although the design turning angles of the cascades were about the same, the flow from the reaction type blades was attached to the external fairing, whereas that from the impulse type blade were not. Although the exact reason for this phenomenon is not known, it is suspected that the location of the minimum flow area of the blade row is the main contributing factor. It will be recalled that the reaction type cascade has its minimum area at the exit of the blade row, whereas the impulse type has its minimum area at the entrance Ref. 21].

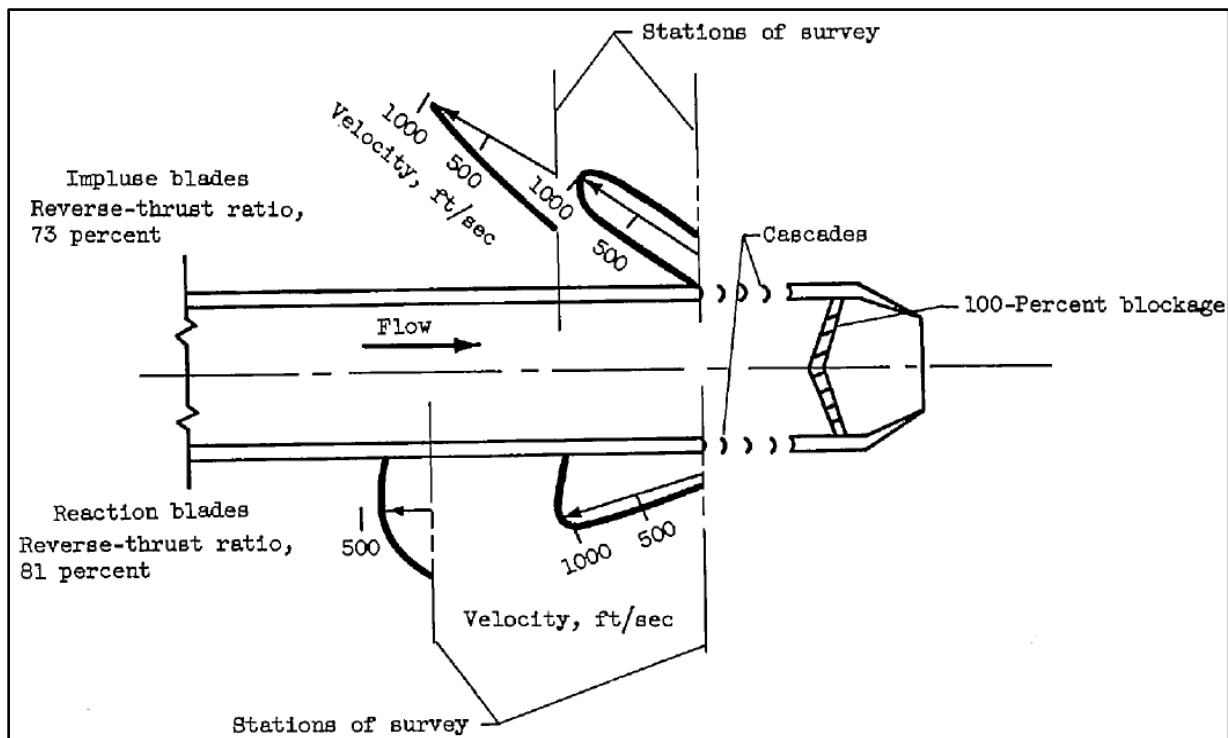


Figure 3.10: Reversed flow field from the tail pipe cascade thrust reverser with impulse and reaction blading; tail pipe pressure ratio, 2.0. Images adopted from [Ref. 21].

A brief investigation was undertaken to determine if the flow from the reaction type blades could be made to detach from the cowl. Several devices and methods, both external and internal were tested. Increasing the length to width ratio for a cascade may not affect the reverse thrust, but could detach the external flow from the surface. With a large length to width ratio, the width of the reversed jet was less and more easily separable from the skin by a layer of air at atmospheric pressure. Parallel cascade end plates as opposed to radial cascade end plates also tended to detach the reversed flow. With parallel end plates little diffusion of the radial velocity component occurs, and thus the direction of the resultant velocity remains approximately fixed. Cascade blade design, cascade length to width ratio, and cascade end plates have small effect on maximum reverse thrust ratio but considerable effect on the reverse thrust ratio at which the reversed flow attached to the cowl.

3.3 Early Research Conducted by NACA on Target Type Thrust Reverser Concept

The first technical report discussing the hemispherical target type thrust reversers was published by NACA in the year 1955 [Ref. 22]. The typical geometry of the hemispherical reverser is shown in (Figure 3.11). The geometry of the reverser was created by installing a flat plate at the back of a hemisphere reverser as shown in (Figure 3.11). A flat plate was installed because its shape makes the reverser more adaptable to stowage and jet directional control than a conventional hemispherical type. The various boat tail configurations tested are shown in (Figure 3.12). Except for the tests run specifically to evaluate the effect of boat-tail shape on performance, all tests were run with convex boat-tail shown in (Figure 3.12). The ratio of the reverse jet thrust for a given configuration at a given pressure ratio to the forward jet thrust for a nozzle alone at the same pressure ratio was thus obtained and defined as the basic reverse thrust ratio.

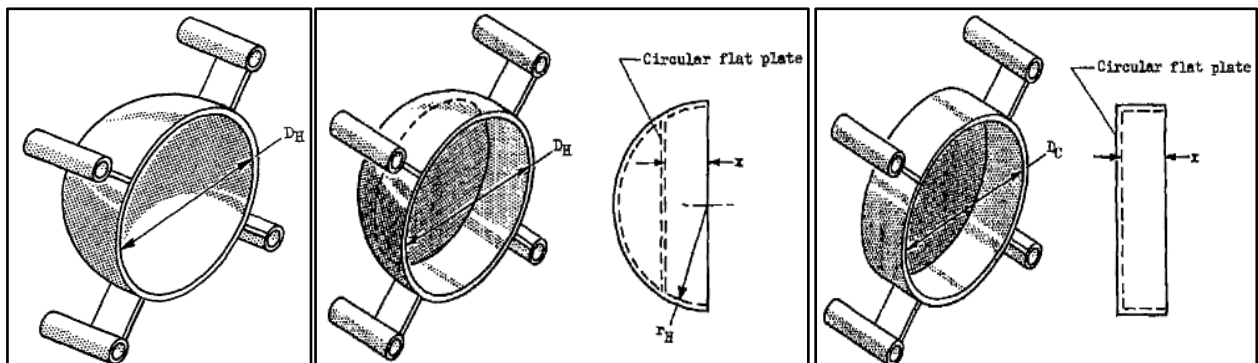


Figure 3.11: (L) The typical geometry for a hemisphere reverser and (R) the geometries created by installing flat plates in the back of hemispherical and cylindrical reversers. Images adopted from [Ref. 22].

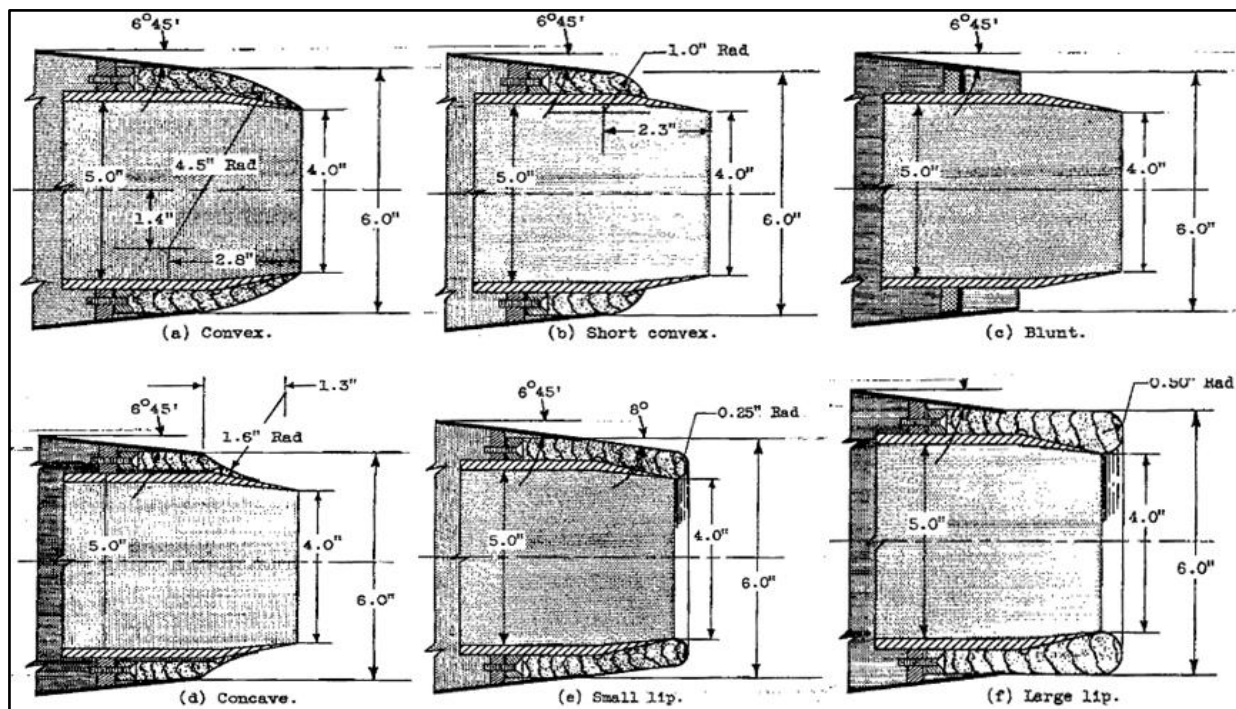


Figure 3.12: Configurations used to study effects of boat tail shape on reverse thrust ratio. Images adopted from [Ref. 22].

There is a range of spacing for which the reverse thrust ratio of target type reversers will generally remain about constant or increase slightly as spacing is reduced. However, a spacing would eventually be reached at which the mass flow through the engine would reduce, would also cause engine surge and in the case of a turbojet engine installation, the turbine temperature would increase. The spacing can be decreased further without encountering turbine over temperature if the engine exhaust nozzle is opened [Ref. 22].

The minimum spacing that can be used on an engine with a fixed area exhaust nozzle as dictated by limiting turbine temperature is shown in (Figure 3.13a) as function of hemisphere diameter. Spacing is presented as ratio of the spacing to the diameter of the exhaust nozzle, l/D_n . As might be expected, the minimum spacing decreases as the hemisphere diameter increases. The accompanying variation in reverse thrust ratio with hemisphere diameter is shown in (Figure 3.13b). Reverse thrust ratio increases rapidly with an increase in hemisphere diameter and reaches a maximum of about 82 percent with a hemisphere to nozzle diameter ratio of 1.8. Closer spacing than the ones shown in (Figure 3.13) can be used if the exhaust nozzle is opened. However, the experimental study performed in [Ref. 22] concludes that the gains in reverse thrust ratio which results from the close spacing with a fixed area nozzle are small and a maximum of 3 percent increase is possible. Therefore, the small increase in reverse thrust ratio is insufficient to justify the installation of a variable area nozzle [Ref. 22].

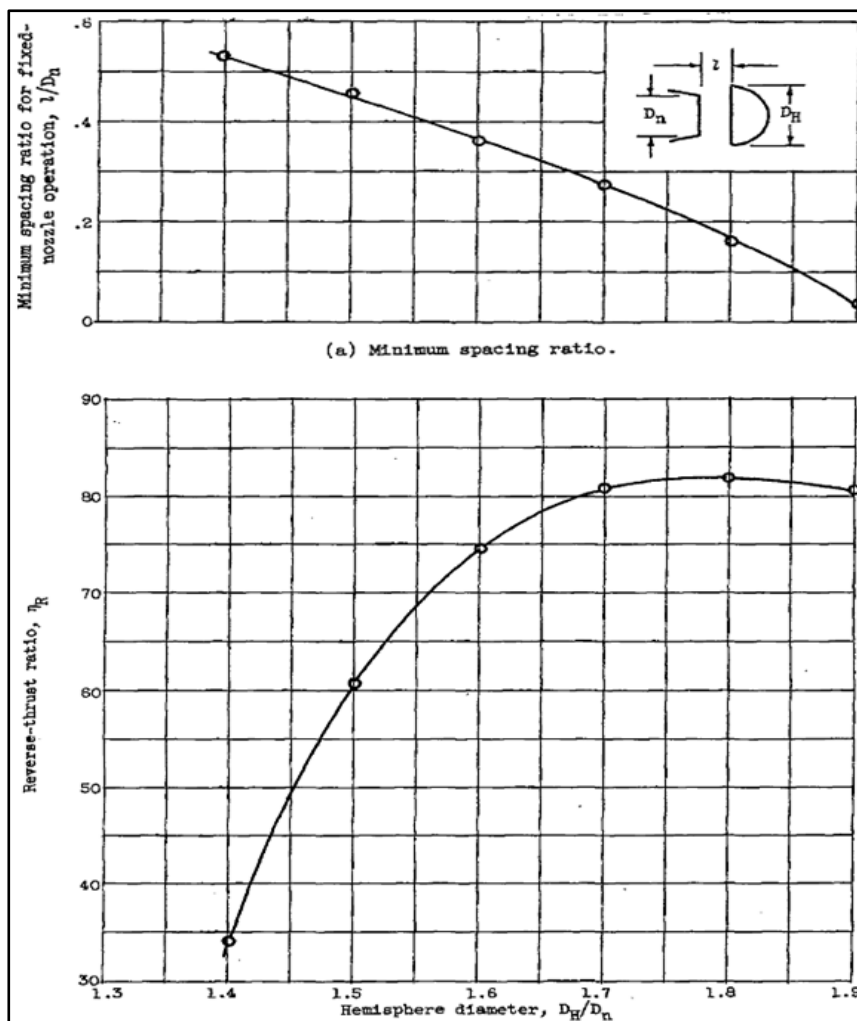


Figure 3.13: Minimum spacing required for fixed nozzle operation and reverse thrust ratios obtained for various size hemispherical reversers; exhaust nozzle pressure ratio, 2.0. Images adopted from [Ref. 22].

The reverse thrust ratio is a function of the flow turning angle. An experimental study was carried out to study the effect on reverse thrust ratio due to the flow turning angle. It was noticed that as the spacing ratio is decreased, the mean turn angle and the reverse thrust ratio also decreases. On the other hand, a big hemisphere turns the flow through a high angle and gives a large reverse thrust ratio. The high flow turning angle is caused by a large force produced by pressure acting over the big reverser frontal area. This principle applies to the turning surfaces of any reverser. In addition to hemisphere spacing and diameter, the lip angle of the spherical surface also affects the flow turning angle and thus the reverse thrust ratio. Also, for high values of reverse thrust ratios, it is necessary to turn the flow through a large angle, and with this type of reverser, the flow is directed very close to the nacelle or fuselage surface [Ref. 22].

An experimental study to investigate the effect of boat-tail shapes (Figure 3.12) on reverse thrust ratios was also carried out in [Ref. 22]. An interesting outcome from this study was that the maximum increase in reverse thrust due to the change in boat-tail shape would only be between 3 to 7 percent. Thus, it was concluded that the best solution would be to use the conventional convex configuration (Figure 3.12a). Also, the use of a large lip boat-tail (Figure 3.12, f) would cause an unstable flow field that may result in destructive vibration.

3.4 Early Research Conducted by NACA on Cylindrical Type Thrust Reverser

The first technical report discussing the cylindrical type thrust reversers was published by NACA in the year 1956 [Ref.23]. The purpose of the investigation was to determine the performance of cylindrical type thrust reversers and the effects of several modifications on their performance. All tests were run in quiescent air with cold airflow. The geometries of the cylindrical thrust reversers used in this investigation are shown in (Figure 3.14).

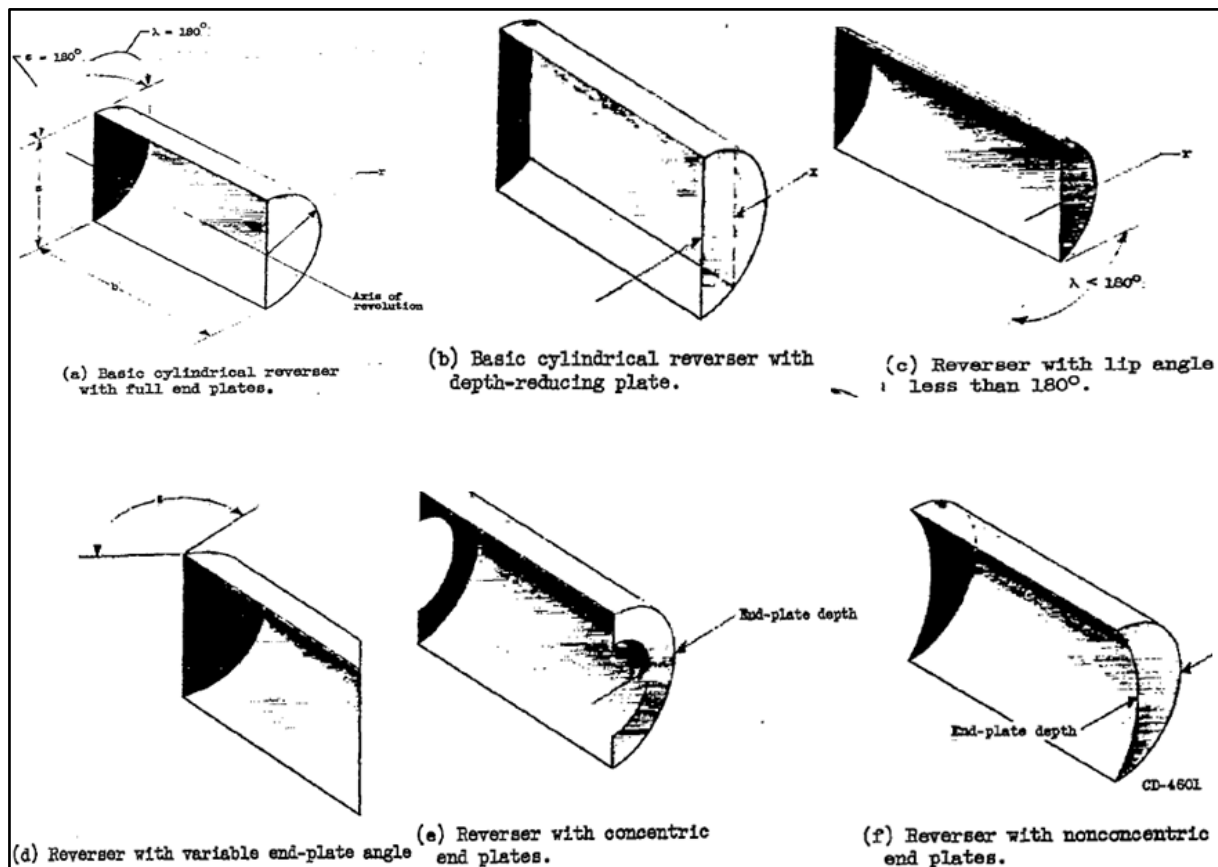


Figure 3.14: Cylindrical thrust reversers. Image adopted from [Ref. 23]

The purpose of the investigation was to determine the performance of cylindrical type thrust reversers and the effects of several modifications on their performance. These modifications include changes in frontal area, width to height ratio, depth, lip angle, end plate depth and end plate shape. The effects of exhaust nozzle pressure ratio on reverse thrust ratio and spacing ratio required for unrestricted nozzle flow are similar to those that occur with hemispherical reversers [Ref. 22].

The frontal area ratio is defined as the ratio of the frontal area of the reverser to the exhaust nozzle area A_r/A_n . The reverse thrust ratio obtained from the cylindrical target type thrust reverser with full end plates is primarily a function of the frontal area ratio of the reverser. Width to height ratio is defined as the ratio of projected width to projected height b/a . It was investigated that a reverser with a frontal area ratio of about 3 to 4 appears to be optimum and produces a reverse thrust ratio of 84 percent. The spacing ratio is defined the same as that for hemispherical reversers. The minimum spacing ratio generally increases with a decrease in frontal area ratio. Decreasing the width to height ratio below 1.6 does not affect the minimum spacing ratio. Increasing the width to height ratio above 1.6, however, increases the minimum spacing ratio.

The study of width to height ratio for cylindrical reversers shows that a reverser with width to height ratio less than 1.0 would cause flow instability. The gas would discharge alternately from the top and bottom of the reverser in puffs, rather than in continuous stream, and may cause induce vibrations [Ref. 23].

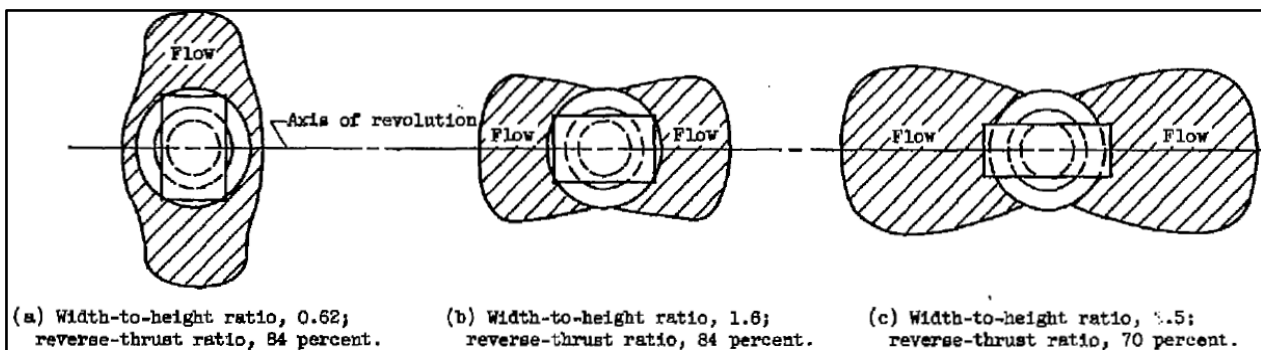


Figure 3.15: Variation in reversed flow field with width to height ratio. Exhaust nozzle pressure ratio 2.0; reverser frontal area ratio 3.17; lip angle 180° ; end plate angle 180° ; full end plates. Image adopted from [Ref. 23]

The effect of decreasing the depth of the cylindrical reversers by insertion of a flat plate was also studied. The decrease in depth to 38 percent of its original value decreases the reverse thrust by only 10 percent. However, the minimum spacing would need to be increased by 29 percent for unrestricted nozzle flow. Similarly, a decrease in the lip angle of the reverser results in a decrease in the reverse thrust ratio. Changing the lip angle from 180° to 146° decrease the reverse thrust by about 15 percent. The nozzle spacing would need to be increased by 32 percent for the nozzle to accommodate the change in lip angle for an unrestricted nozzle flow [Ref. 23].

The effect of decreasing the end plate angle from 180° to 120° reduces the reverse thrust from 84 percent to 55 percent. The minimum spacing ratio would increase from 0.17 to 0.45. Reducing the end plate depth may facilitate retraction and stowage. The reverse thrust ratio, however, decreases as the end plate depth is reduced. The effects of using the concentric and nonconcentric end

plates would be the same. The minimum spacing would not be affected by the end plate depth. Decreasing the end plate depth, however, is effective in detaching the reversed flow from the cowl [Ref. 23].

Lastly, the thrust modulation characteristics for a cylindrical target type thrust reverser were found. In the reverse thrust position, the reverser had a projected frontal area 3.17 times as large as the exhaust nozzle area and a width to height ratio of 1.6. In the forward thrust position, the reverser formed a large diameter i.e. long ejector. Reverse thrust ratio was plotted against the angular position of the reverser (Figure 3.17). Negative values of reverse thrust ratio are equivalent to percentages of forward thrust. Sketches of reverse flow boundaries are also shown. The shading within the reverse flow boundaries indicates the relative magnitude of the reversed flow velocity. For the first 15° of actuation the jet is not intercepted by the reverser. From about 30° to 75° , a 1° change in actuation angle causes approximately a 3 percent change in thrust. At 75° , maximum reverse thrust is obtained, but the flow is attached to the cowl. By actuating the reverse to 90° position, the maximum reverse thrust ratio is maintained, and the flow is detached from the cowl.

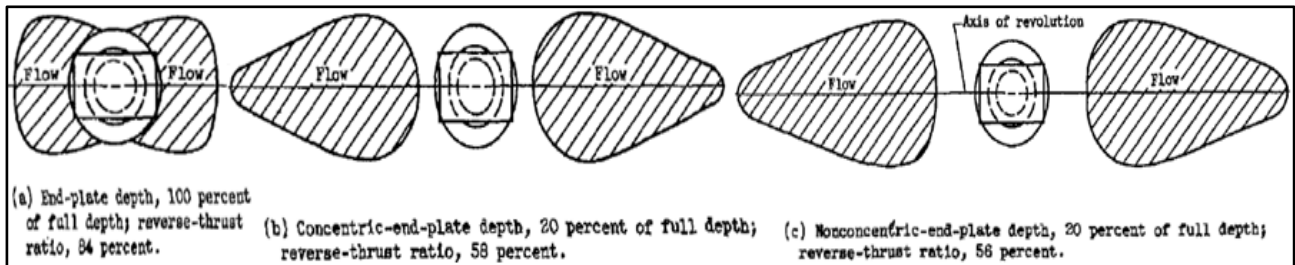


Figure 3.16: Variation in reverse flow field with end plate depth. The Exhaust nozzle pressure ratio ≈ 2.0 ; reverser frontal area ≈ 3.17 ; width to height ratio ≈ 1.6 ; lip angle $\approx 180^\circ$; end plate angle $\approx 180^\circ$. Image adopted from [Ref. 23].

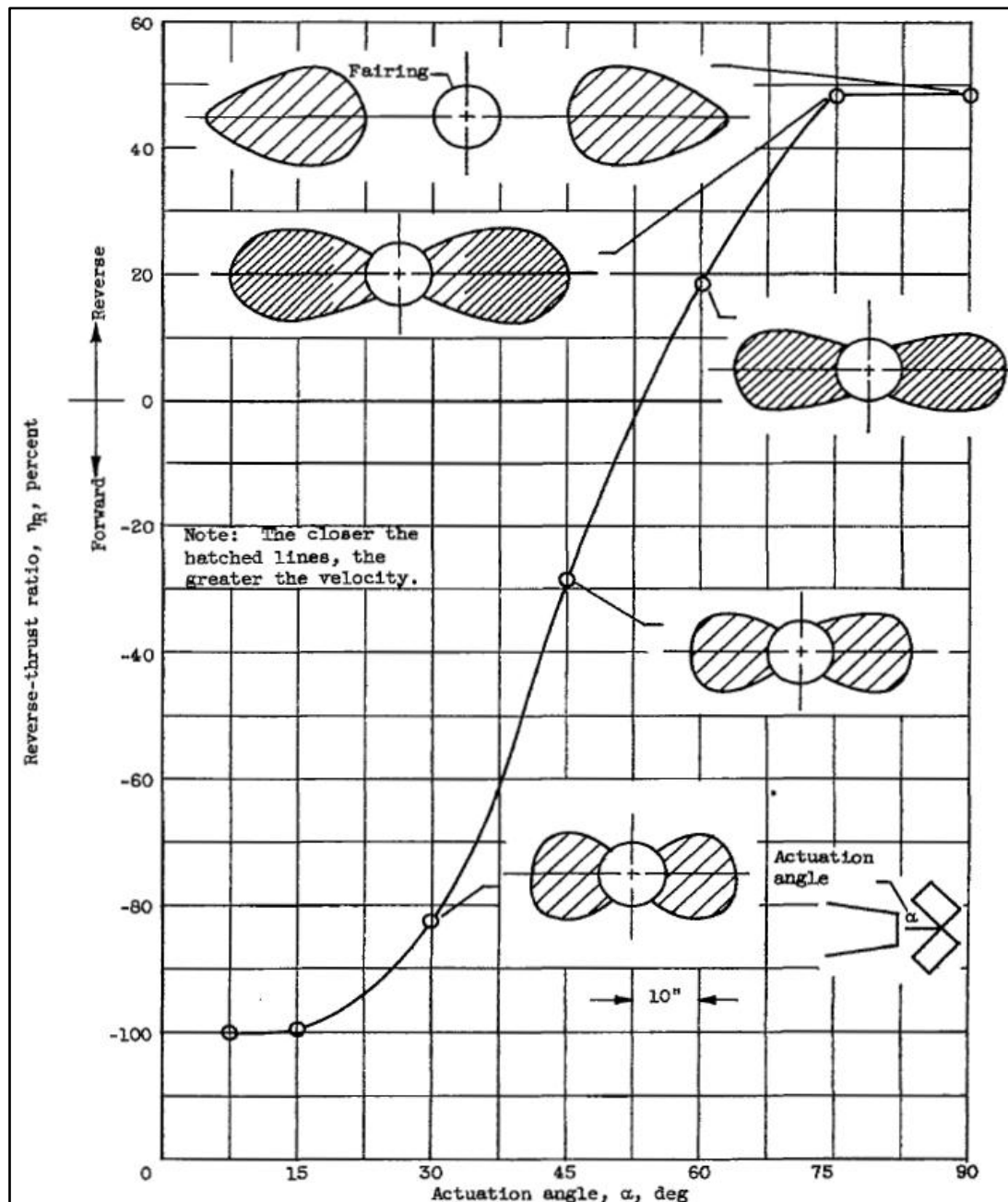


Figure 3.17: Thrust modulation characteristics of a cylindrical target type thrust reverser. Exhaust nozzle pressure ratio, 2.0; reverser frontal area ratio, 3.17; width to height ratio, 1.6; lip angle, 146° ; end plate angle, 180° ; nonconcentric end plates. Image adopted from [Ref. 23].

The summary of important results and considerations for the hemispherical and cylindrical type thrust reverser experiments discussed above are presented in [Ref 24]. The results indicate that the length to width ratio of the cylinder has only a small effect on the reverser performance, and the effect of cross sectional area ratio is about the same for both the hemispherical and cylindrical type reverser. Reduction in size or cross sectional area has only a small effect on reverser thrust ratio until a value equal to about the 2.5 times the nozzle area is reached. Below this value, the fall-off in reversal is quite rapid. The depth of either the reverser or end plate could be reduced to 50 percent of full depth without a severe loss in reverse thrust ratio. Forty percent reversal was still obtained with a reversal depth of 14 percent or an end plate depth of 10 percent.

3.5 Thrust Reverser as a Modulating Device

Thrust reversers may be classified in one or two categories: an on-off device that provides full forward or full reverse thrust, or a modulating device that, in addition to the preceding, will also provide desired intermediate values of thrust.

With a modulating type reverser an aircraft could make a landing approach with engines running at full speed and with required amount of forward or reverse thrust. Upon touchdown only reverser actuation time would elapse before full reverse or forward thrust could be obtained, because the engine would already be at full speed. With a strictly on-off device, however, the engine speed of a standard engine would have to be reduced during final approach. After touchdown, a time consuming engine acceleration would be required before full reverse thrust (or forward thrust in the case of a wave-off) could be obtained. If modulating the thrust with a reverser does not change the effective flow area through the engine, no new engine control problems are introduced. The mechanical design of some reversers, however, may be such that the effective flow area is changed during the modulation cycle.

If the effective flow area is increased, engine speed can be maintained if the fuel flow is reduced. Although the thrust output of the engine will decreased, changes in thrust can still be obtained rapidly because the engine speed will not have been changed. On the other hand, if the effective flow area is reduced during the modulation cycle, both the fuel flow and the engine speed will have to be decreased. Thus, changes in thrust will be accompanied by changes in engine speed, and the response to changes in thrust setting will be slow. Therefore, a reverser should be designed to maintain a constant effective flow area or, at worst, increase the effective flow area during the modulation cycle. A reverser should not be designed so that the effective flow area will be decreased during modulation.

The thrust modulation characteristics of the three thrust reverser configurations described above are presented in (Figure 3.18). The performance is shown as a plot of reverse thrust ratio against percentage of actuation (the latter is defined as the ratio of reverser position to the final position). In each case the performance curve is continuous and has sufficient slope such that it should not be difficult to set any desired value of thrust. Thus, all these configurations have desired modulation characteristics.

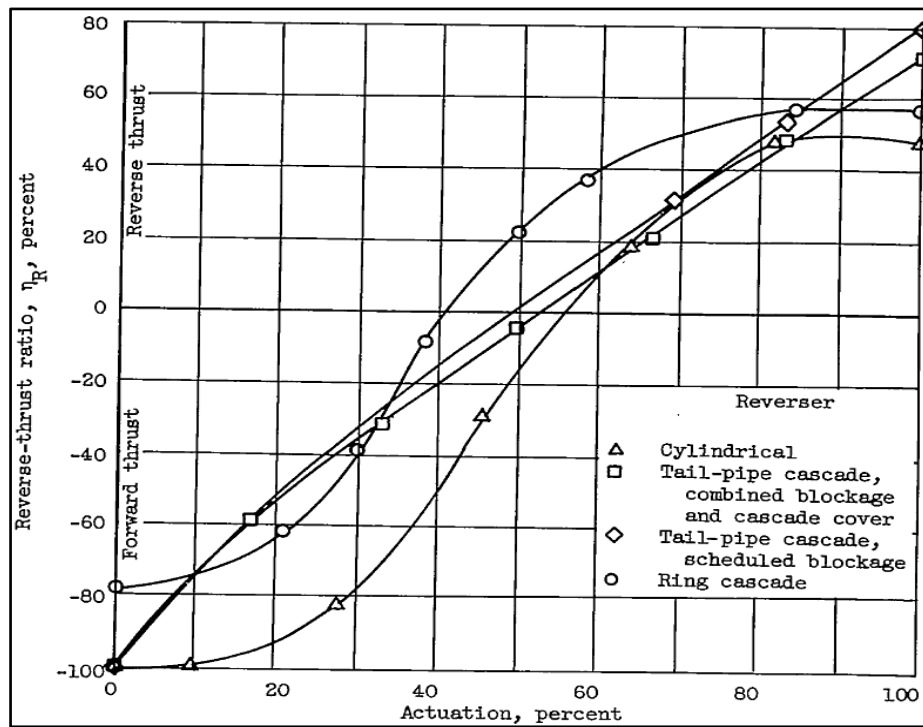


Figure 3.18: Thrust modulation characteristics for various thrust reverser designs. Image adopted from [Ref. 27].

3.6 Early Research Conducted by NACA on a Full Scale Target Type Thrust Reverser

The first full-scale jet engine thrust reverser performance and operational experimental study was performed by NACA and the report was published in the year 1956 [Ref. 25]. The experimental aircraft used for this study was the Fairchild C-82 aircraft employing an under wing pylon mounted axial flow turbojet engine. A hemispherical target type thrust reverser was used for this study and was operated at both stationary and taxi condition, but the aircraft was not flown. The data obtained from this full scale study was compared with the results obtained from the wind tunnel model study performed also by NACA [Ref. 27].

The internal diameter of the hemisphere was 0.631 m (24.86 inches), which closely corresponds to 1.5 times the jet nozzle diameter. The hemispherical thrust reverser model studies [Ref. 14] performed prior to full scale hemispherical thrust reverser tests have shown that for the hemispherical thrust reversers the 1.5 nozzle diameter size represents a reasonable compromise between the improved performance of larger targets and the bulk of the target. Bulk must be considered in terms of stowage volume required at the rear of the engine. In order to move the target in and out of the nozzle exhaust stream, the hemisphere was split into two equal sections. The double-wall construction was used in the fabrication of the reversers as they would offer some advantage from the standpoint of strength to weight ratio. A full-depth hemisphere and a modified hemisphere i.e. employing a flat plate were used for the full-scale investigation (Figure 3.19a) [Ref. 17]. The target was positioned 0.26m (10.25 inches) downstream of the plane of the jet nozzle exit. This distance divided by the nozzle diameter 0.419m (16.5 inches) is 0.621 and is the spacing ratio. The effects of spacing ratio on the engine flow were investigated in [5] and the tests indicated that a spacing ratio of 0.621 would be more than sufficient to avoid flow restriction; thus, it was used on the full scale testing.

The modified thrust reverser i.e. with a flat plate installed normal to the thrust line at a depth within the hemisphere indicated that during the full scale test the performance penalties were not large. The target, however, was spaced a little farther behind the nozzle exit plane in the full scale tests (Figure 3.19b) [Ref. 28].

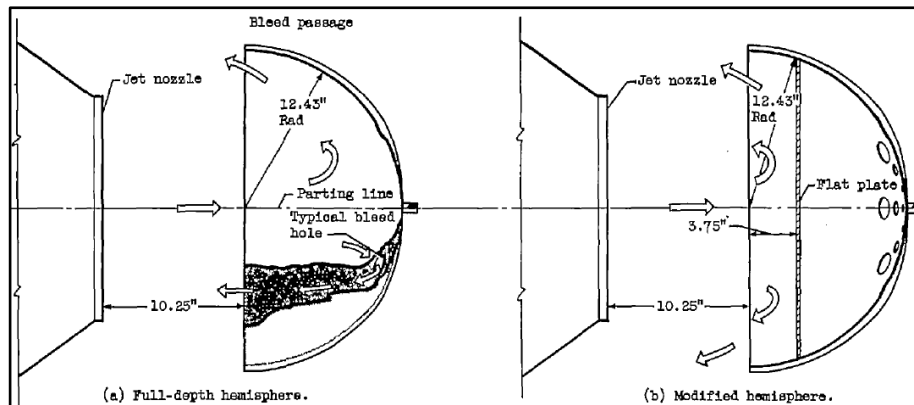


Figure 3.19: Target configurations used in full-scale thrust reverser investigation. Image adopted from [Ref. 28]

Reverse thrust ratio is expressed as a percentage of the corrected forward thrust at the same corrected engine speed as shown in (Figure 3.20). Reverse thrust ratio increases with corrected engine speed. A maximum reverse thrust ratio value of 58 percent was obtained for the full depth hemisphere thrust reverser at corrected engine speed 100 percent of maximum rpm. The maximum reverse thrust ratio developed at maximum corrected engine speed by the shallower target reverser i.e. modified hemisphere reverser was about 52 percent (Figure 3.20L).

The nozzle pressure ratios for the full depth hemispherical thrust reverser and the modified hemispherical thrust reverser were plotted against the corrected engine speed (Figure 3.20R). The data points represented a compilation of measurements obtained in several stationary test operations. The peak nozzle pressure ratio of 1.78 for the full depth reverser and maximum nozzle pressure ratio of 1.8 for the modified thrust reverser were obtained at a corrected engine speed of 100 percent rpm (Figure 3.20R).

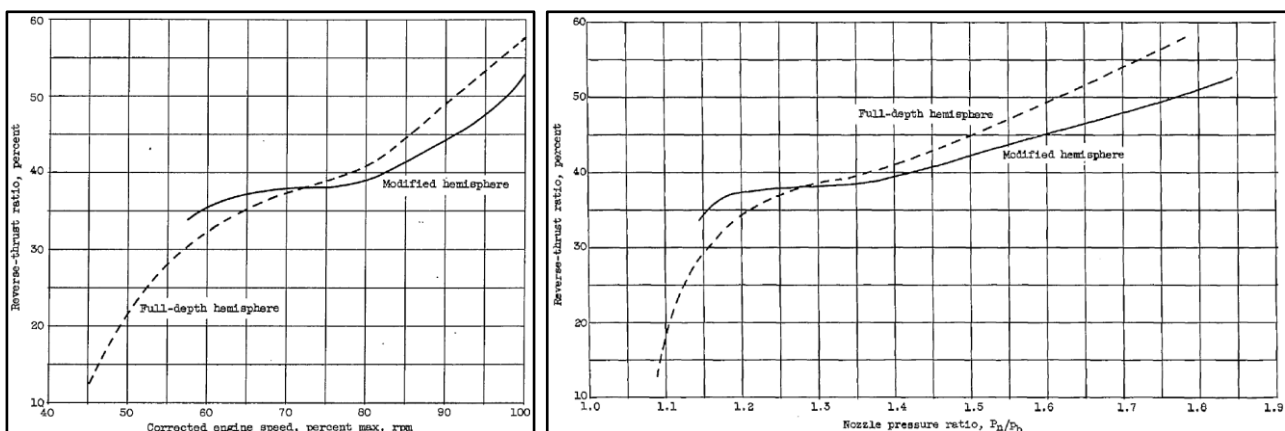


Figure 3.20: (L) Comparison of reverse thrust ratio with engine speed for full depth and modified hemispheres. (R) Comparison of reverse thrust ratio with nozzle pressure ratio for full depth and modified hemispheres. Image adopted from [Ref. 28].

The variation of reverse thrust ratio with nozzle pressure ratio depends largely upon the angle through which the gas is turned by the thrust reversing device. In the full scale test a flow survey was made in which the turning angle of the reversed gas was measured. The survey rake was used for this study (Figure 3.21L). Each tube in the survey rake was directed at the same point on the lip of the hemisphere. All tubes were located in the same horizontal plane at a radius of 1.5 nozzle diameters from the target lip. The variation of turning angle with nozzle pressure ratio is shown in (Figure 3.21R). The survey also indicates that the flow discharges from the thrust reverser in the form of a conical sheet. The turning angle increases with nozzle pressure ratio. For example at a nozzle pressure ratio of 1.43 the average flow turning angle was about 120° , whereas at a nozzle pressure ratio of 1.69 the average turning flow angle increased to 143° .

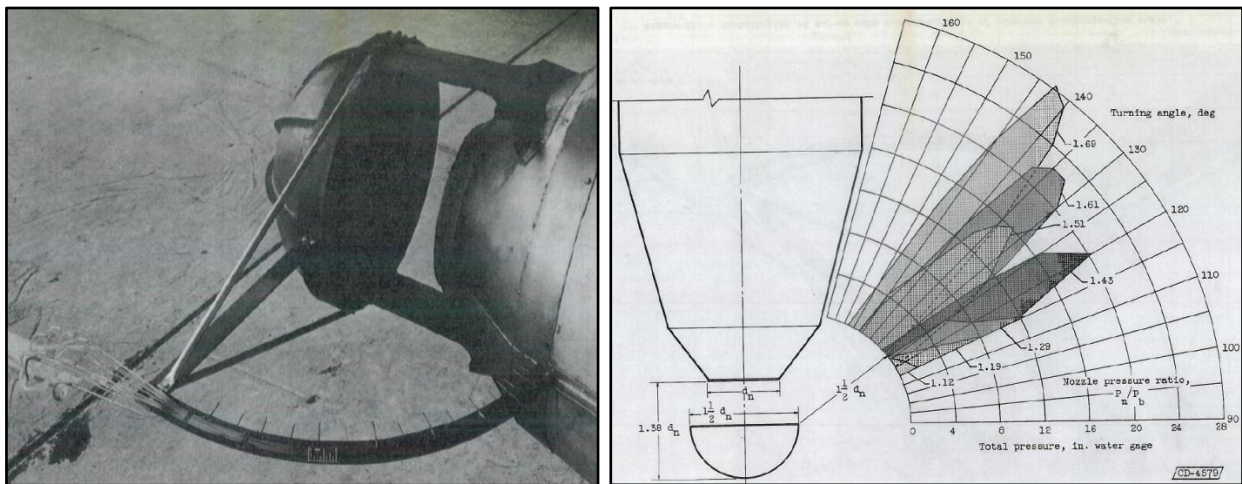


Figure 3.21: (L) Installation of survey rake for measurement of reverser discharge flow angle. (R) Variation of thrust reverser discharge flow angle with nozzle pressure ratio for full depth hemisphere. Image adopted from [Ref. 28]

Figure 3.20 shows the relationship between the reverse thrust ratio against the engine speed and the relationship between the reverse thrust ratio against the nozzle pressure ratio. From (Figure 3.20) the reverse thrust values for a modified reverser are slightly lower than the full depth hemisphere i.e. between 5 and 8 percent. At higher engine speeds and nozzle pressure ratios the reduction in reverse thrust ratio with the truncated hemisphere is attributed for the most part, to the smaller angle through which the reverser flow is turned. Target efflux flow angle surveys for a flat plate hemisphere reverser for several engine nozzle pressure ratios is shown in (Figure 3.22L). When compared with the discharge angle surveys for the full depth hemisphere (Figure 3.21R), the patterns obtained with the truncated hemisphere shows that the flow turning angle was reduced by about 5° at the lower nozzle pressure ratios and about 25° at the higher nozzle pressure ratios. At the lower engine speeds, the truncated hemisphere caused a reduction in the weight flow through the engine. Evidence of this can be seen in the engine nozzle pressure ratio characteristics shown in (Figure 3.22R). Blockage, which cause a rise in the nozzle pressure ratio, is indicated at engine speeds of up to 85 percent of maximum rpm. These data verify the results of model tests of several target configurations [Ref. 14] where the flow reduction became increasingly severe as the nozzle pressure ratio was lowered.

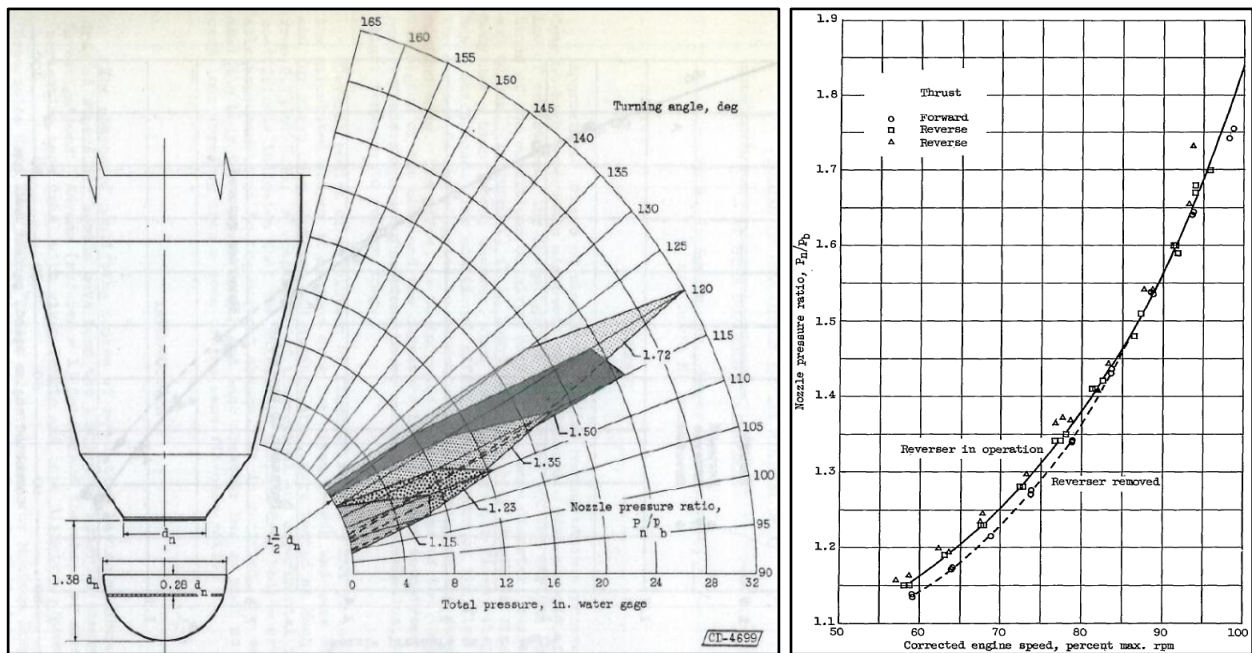


Figure 3.22: (L) Variation of thrust reverser discharge flow angle with nozzle pressure ratio for a modified hemisphere. (R) Relationship of nozzle pressure ratio and engine speed for a turbojet engine with and without modified hemisphere reverser. Image adopted from [Ref. 28].

3.7 Early Research Conducted by NACA on a Full Scale Cascade Type Thrust Reverser

The data available in the public domain highlights the fact that the first full scale cascade type thrust reverser testing was conducted by NACA Lewis Laboratory and the technical report discussing the testing was published in the year 1957 [Ref. 29]. The technical report in [Ref. 18] discusses the cascade type reverser three-tenth scale model design and testing. The technical report also discuss in detail the first full scale installation of the cascade type reverser on the single engine, subsonic, turbojet fighter. The report discusses the design, performance and operational characteristics of the installed thrust reverser.

The aircraft was not flown. The thrust reverser installation was designed to fit into the existing aircraft with minimal structural modifications or change in the fuselage contour. Reverser thrust was produced by opening the tailpipe and moving the vanes outward to form cascades that intercepted the rearward gas flow and turned it through approximately 150° . Variation of the forward and rearward thrust with engine speed was measured with the airplane held stationary. Taxi tests were conducted on a dry runway in order to provide data with which to compare the distances required to bring the airplane to stop using (1) the wheel brakes only, (2) reverser thrust only and (3) a combination of wheel brakes and reverse thrust. An overall view of aircraft with thrust reverser installed is shown in (Figure 3.23). Reverse thrust was produced by a twin set of turning vanes which deflected the engine exhaust gas. External views of the thrust reverser in the forward and reverse thrust positions are shown in (Figure 3.24). Figure 3.25, shows a cross sectional view of the tail pipe arrangement before and after modifications. Turning vane details are shown in (Figure 3.26).

A calibrated strain-gage load cell was used to measure the tension in a steel cable that tethered the airplane to a tie down ring. The cable was attached to each of the main landing gear struts

(Figure 3.27). During the taxi runs, the actual ground speed and elapsed distance were measured by means of a bicycle wheel attached to the left landing gear (Figure 3.28).

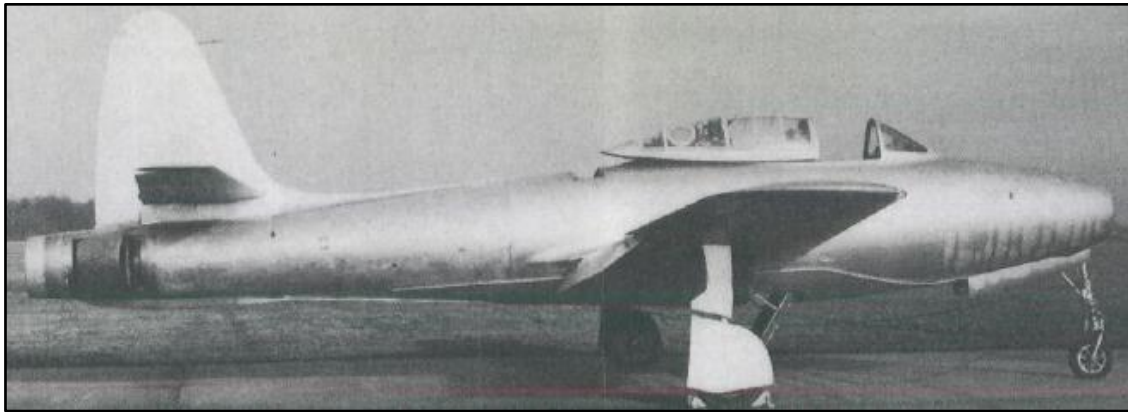


Figure 3.23: Overall view of aircraft with thrust reverser installed. Image adopted from [Ref. 29].

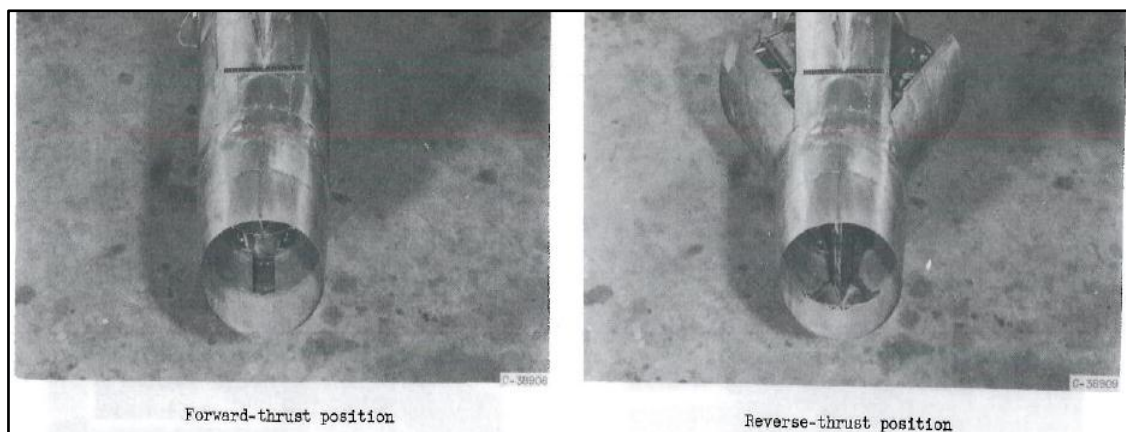


Figure 3.24: Vane type thrust reverser installation on a fighter type jet aircraft. Image adopted from [Ref. 29].

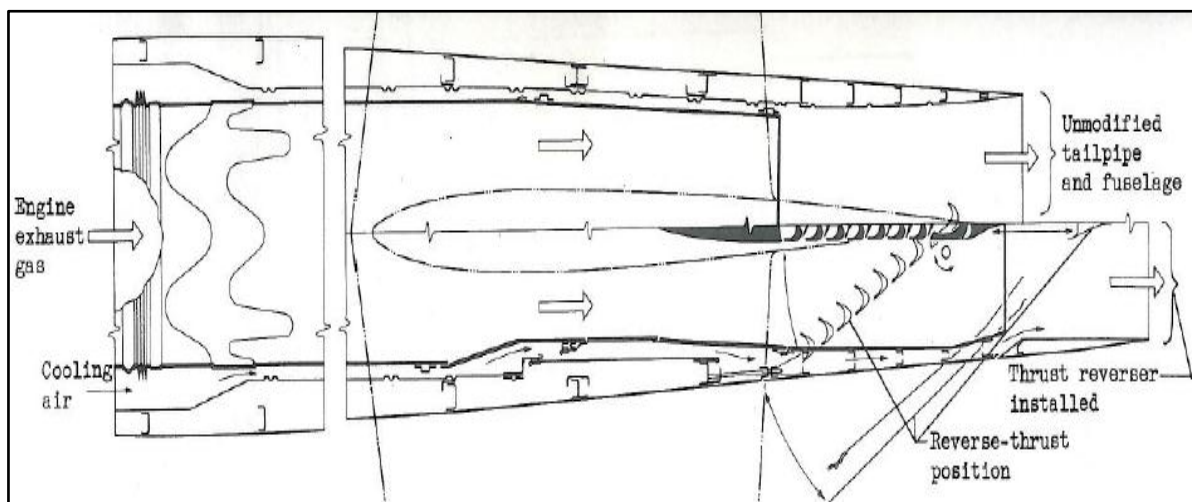


Figure 3.25: External view of the tail pipe arrangement before and after modifications. Image adopted from [Ref. 29]

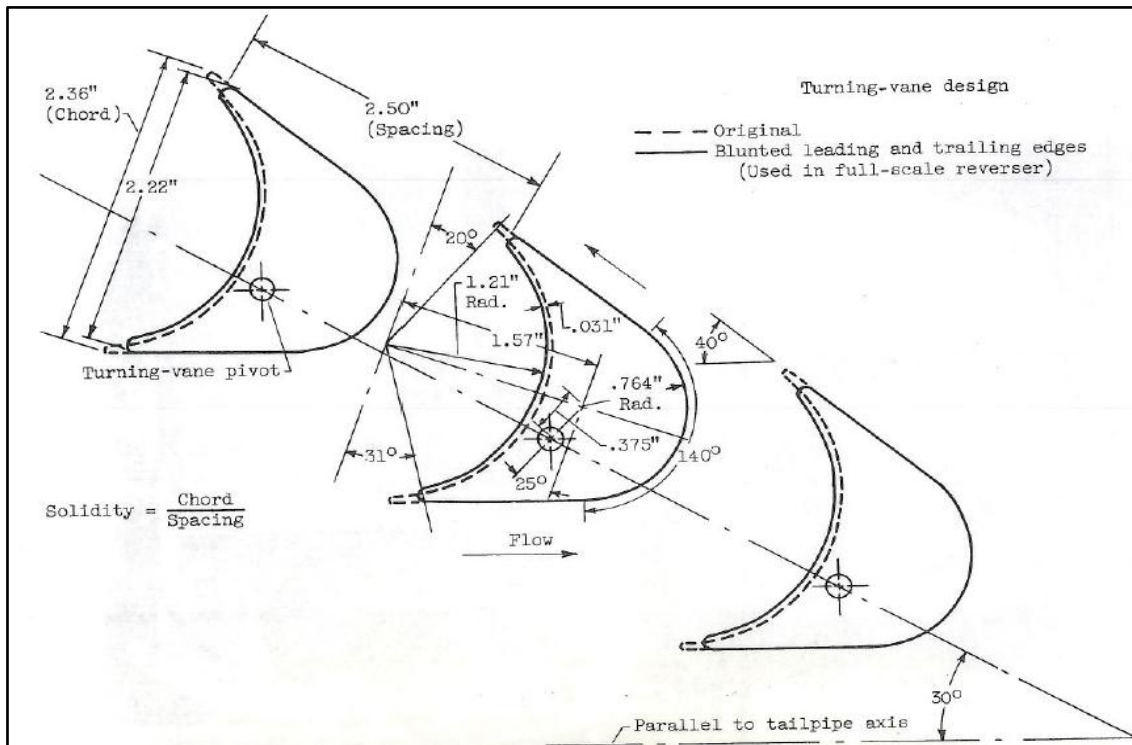


Figure 3.26: Thrust reverser turning vane details. Image adopted from [Ref. 29].

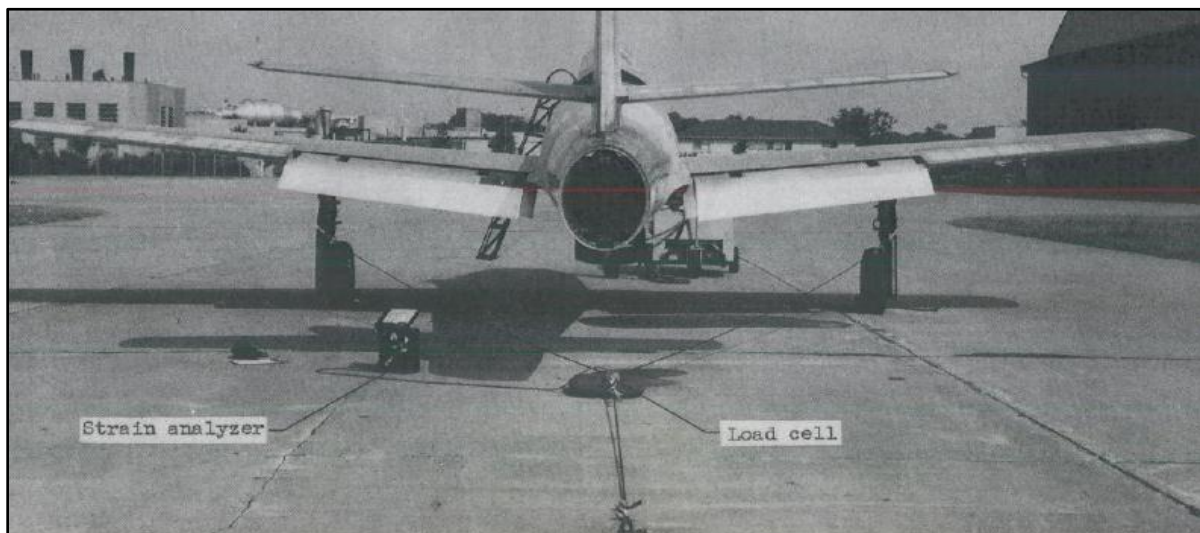


Figure 3.27: Tethering cable arrangement used to measure thrust. Image adopted from [Ref. 29].

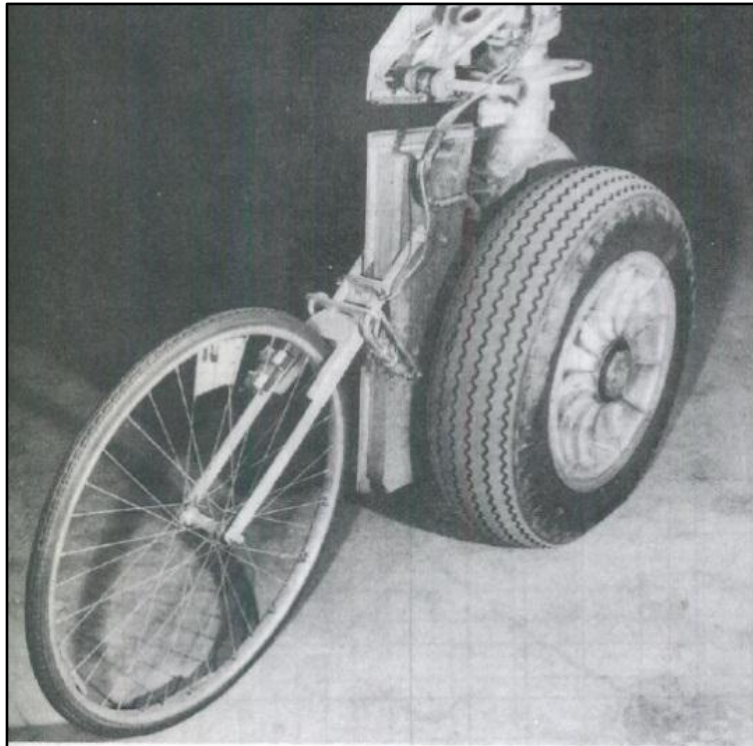


Figure 3.28: Bicycle-wheel arrangement used to measure ground speed and elapsed distance. Image adopted from [Ref. 29].

The turning vanes solidity of the full scale installation was 0.89. At values of solidity less than 0.76, the reverser thrust ratio diminishes because of poor turning effectiveness. The design and use of this full scale cascade reverser aggregates several types of losses, among which are the internal flow loss due to the presence of the stowed vanes, leakage loss through the tailpipe and thrust reverser seals and the nozzle loss. The loss of forward thrust associated with internal vane stowed is estimated to be in the order of 3 percent at full engine speed.

In designing the thrust reverser, it was necessary to arrive at a compromise value for the flow velocity at the thrust reverser inlet. High flow velocities were required to reduce the diameter of the tailpipe, whereas low flow velocities were desirable in order to keep the flow losses to minimum which results from the internal vane stowage. With these requirements in mind, a design Mach number of 0.7 at the thrust reverser inlet was selected.

A maximum reverse thrust ratio of about 35 percent at full engine speed was obtained with a splitter vane width at the design value of 2.34 inches. Taxi tests on a dry runway indicated that the average deceleration was about 0.11 g's when using either the thrust reverser or wheel brakes to stop the airplane. When the thrust reverser and wheel brakes were used in combination, the average deceleration was almost doubled.

3.8 Thrust Reverser Application for Aircraft Manoeuvrability

In addition to the interest in the thrust reverser as a landing aid, there has been an interest expressed in using the thrust reverser as a speed brake during the flight. It might be used during combat manoeuvring, during steep descent from high altitudes, and during the approach to landing. These effects were investigated in the [Ref. 30] in the year 1957. The study was carried

out on a single engine fighter model in the Langley 16-foot transonic tunnel at Mach numbers from 0.2 to 1.05 at 0° angle of attack. The data was also obtained at Mach numbers of 0.8, 0.92, and 1.05 and the angle of attack was varied from 0° to 5° at these Mach numbers. However, no reliable reverser thrust data was obtained during this investigation.

A year later a similar study was conducted by NASA in the Ames 40 by 80 feet wind tunnel on a full scale F-86D airplane along with the J-34 turbojet engine. The aircraft was also equipped with a target type reverser to determine the effects of the reverser operation on the static stability and control of the aircraft. The target was a semi-cylinder with partial end plates with axis of revolution mounted horizontally and normal to the engine thrust axis. Large pitch nose-down pitching moments were encountered with the reverser in operation. These pitching moments were found to depend on both reverser thrust and forward velocity. The large changes in the pitching moment due to reverser operation were associated with distortion of the flow field near the horizontal tail. Under certain conditions of operation, these distortions increased the angle of attack at the tail sufficiently to stall the horizontal tail. Generally, it may be stated that the magnitude and direction of the pitching moment due to reverser operation on a single engine aircraft is dependent on the location of the horizontal tail relative to the reverser. For the configuration tested, the horizontal tail was above the reverser gases, and a pitch down resulted. If the tail had been below the reversed gases, the flow surveys indicate that a pitch up would have resulted. Placing the tail high on the vertical fin or relatively far forward would have minimized the change in pitching moment due to reversed thrust.

3.9 F-100F Aircraft Equipped with Cascade Type Thrust Reversers

A technical study on a full scale cascade type thrust reverser was conducted by NASA, Ames Research Centre, in the year 1960. The technical report presents results of a full scale wind tunnel investigation of an F-100F aircraft equipped with a cascade type thrust reverser. The purpose of this investigation was to develop a thrust reverser satisfactory for use during landing approach [Ref. 31]. Figure 3.29, shows the aircraft F-100F installed in the wind tunnel.



Figure 3.29: F-100F aircraft in the wind tunnel for cascade type thrust reverser testing. Image adopted from [Ref. 31].

The afterburner ordinarily used on the aircraft was removed, and the jet engine tail pipe was ducted into the reverser assembly. The blocker doors at the rear of the reverser could be set at any position from open to full closed, thereby providing a continuous variation of thrust from full forward to full reverse. The reverser was also equipped with various set of turning vanes which made it possible to adjust the direction of the exhaust gases. The tests were set at vanes angles which progressed from 65° at the front port of the reverser to 41° at the rear port. Details of the thrust reverser are shown in (Figure 3.30). All the data was obtained with the aircraft in landing configuration.

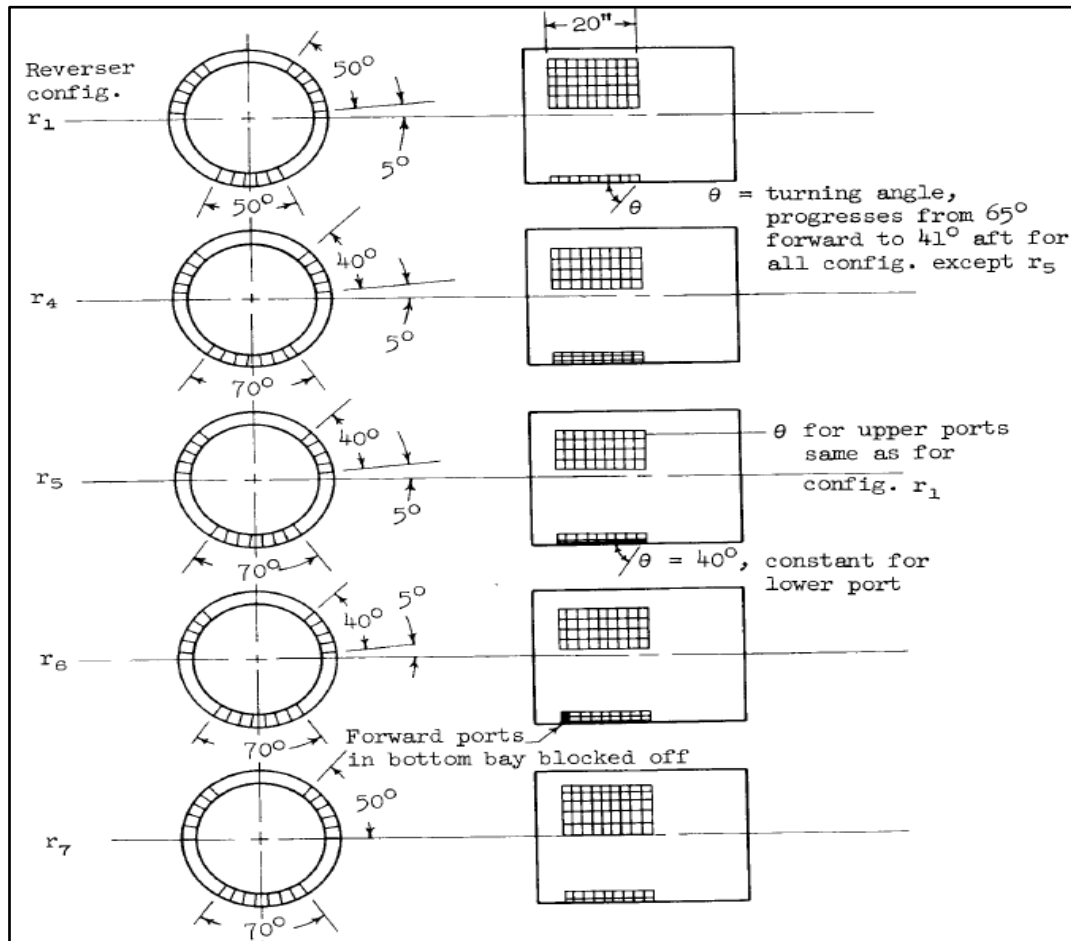


Figure 3.30: Thrust reverser configurations [31].

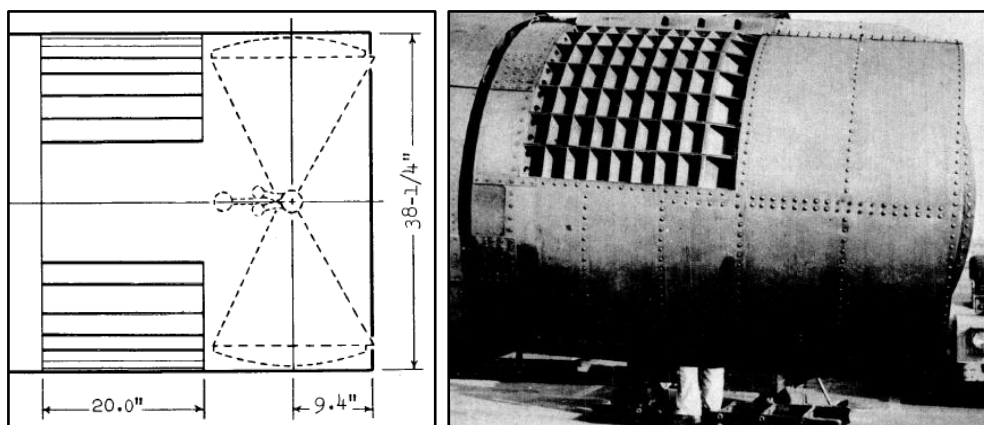


Figure 3.31: (L) Sketch drawing and (R) side view of an installed thrust reverser [31].

Along with the cascade type reverser study the purpose of the testing was also to come up with a reverser design that would possibly avoid the large nose up or nose down pitching moments that were experienced in [Ref. 29] and [Ref. 30]. First, configuration r_1 , (Figure 3.30) was tested and a large nose up pitching moment was found. To eliminate the nose up pitching moment the size of the upper exhaust ports of the reverser should be decreased while that of the lower port should be increased. Since the directional stability data indicated that the reverser had a deleterious effect on the flow around the vertical fin, the upper ports were also moved downward away from the vertical fin. The resulting reverser configuration was r_4 (Figure 3.30). Operation of this reverser produced a nose down increment, which indicated that the reverser geometry changes were in the right direction but too large in magnitude. In order to reduce the nose down moment, the turning vanes in the bottom port were replaced with a set that had a higher turning angle ($\theta=40^\circ$) that reduced the vertical thrust component. This is reverser configuration r_5 (Figure 3.30). It was found that operation of this reverser produced a nose up pitching moment and also decreased directional stability. The decrease in directional stability was quite surprising since the geometry of the upper ports was identical to that of reverser configuration r_4 (Figure 3.30) which had no deleterious effect on directional stability. It is reasoned that the turning vanes with increased turning angle used in the lower exhaust port for reverser r_5 (Figure 3.30) reduced the effective flow area of that port; with the result that the moment of the exhaust gases from the upper ports was increased sufficiently to distort the flow over the vertical fin. The original turning vanes were replaced in the lower port of the reverser, but the area of this port was decreased as shown in configuration r_6 (Figure 3.30). The results for r_6 (Figure 3.30) were similar to that for r_4 (Figure 3.30). This similarity indicated that the nose up pitching moment increment could not be eliminated by available changes in reverser geometry, and that the best that could be hoped for was to minimize the sudden nose-down change in pitching moment.

Analysis of engine data indicated that there was a slight back pressure on the engine with all of the reverser configurations tested. It was therefore desired to test a reverser configuration having a large exit area in the hope that the engine back pressure could be eliminated without seriously compromising the effectiveness of the reverser or its effects on stability and control. The lower port was already opened to its maximum available area, so the only resource was to increase the area of the upper ports as much as possible. The upper ports were also moved downwards away from the vertical as far as possible to reduce the nose up moment and also to keep the exhaust gases away from the vertical fin. The resulting geometry is shown in (Figure 3.30) as configuration r_7 . The magnitude of the pitching moment increments due to the thrust reverser operation is believed to be acceptable at least for a research aircraft. For yaw, angles up to 4° , the directional stability appeared unaffected by the thrust reverser. At higher yaw angles a loss in directional stability is indicated. However, it is believed that the indicated loss in directional stability at high angles of yaw will not seriously affect the flying qualities of the aircraft.

The study highlights the complexities associated in designing a typical cascade type thrust reverser. A good and acceptable thrust reverser design needs to be sufficiently effective and should also satisfy the aircraft stability and control. Thus, it was not possible to predict either analytically or from the available experimental data, a reverser configuration which would eliminate these effects, and the reverser configuration had to be modified by a trial and error process.

3.10 Early Development and use of Thrust Reversers on Civil Aircraft

From the data available in the public domain it seems that the first application of a thrust reverser in civil aviation was on Comet II aircraft powered by Rolls-Royce Avon RA9 engines (Figure 3.32) [Ref. 32]. Thrust reversers were installed to deal with the situations such as take-off abandoned

near the critical speed and a late landing touchdown. The additional hazards of lost braking power owing to mechanical failure or iced or water laden runways serve to underline the desirability, on all aircraft, of an absolutely assured means of bringing the aircraft to rest. Such assurance is obtainable only by providing alternative means of braking with power equivalent to or better than wheel brakes [Ref. 32].

Certification authorities at the time demand a 3 second interval after touchdown to ensure that all wheels shall be on the ground before selecting reverser, leading to the typical sequence of 3 seconds elapse before reverse selection, followed by another 7 to 10 seconds before achieving maximum engine speed (Figure 3.32). A typical value for the reverser cross sectional area to final nozzle area was 1.5, giving a maximum Mach number in the duct of about 0.43.

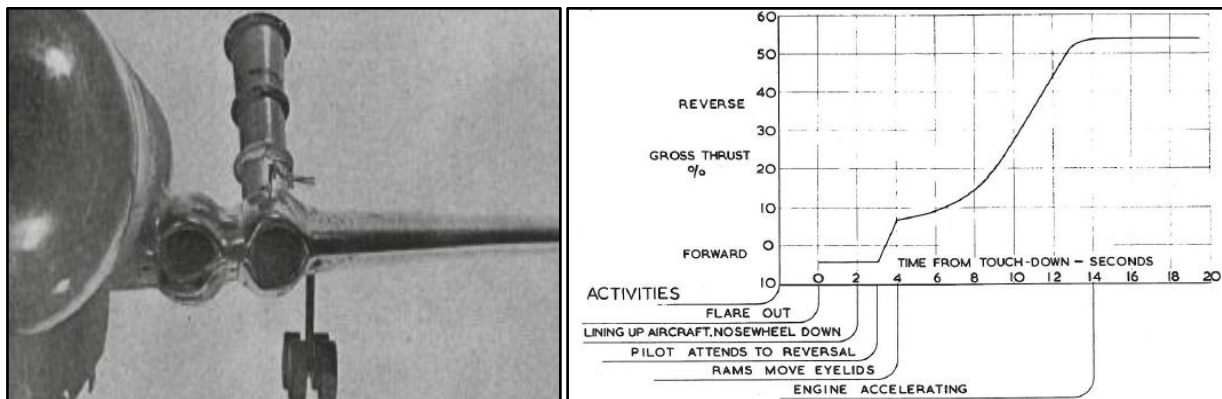


Figure 3.32: (L) Thrust reverser on a Comet aircraft. (R) Thrust reverser landing sequence. Image adopted from [Ref. 32]

The two severe problems in the early 1960s that were experienced due to thrust reversers were hot gas and stone ingestion. It was observed that at low speeds with reverser running at high r.p.m the engine would surge due to engine ingesting its own high temperature gas. This was dealt by cutting the reverser off at an aircraft speed of 50 knots. [Ref. 32], discusses the techniques that Rolls-Royce and Sud-Aviation developed to study in detail the trajectories of the loose stones on runway during thrust reverser operation. Interested readers could refer to [Ref. 32] for more detail.

3.11 Thrust Reverser Installation on the First Long Range Four Engine Aircraft - B707 and DC8

The era of late 1950's and 1960's saw the development of long range aircraft. The two famous examples were Boeing B707 and McDonnell Douglas DC8 aircraft. They both used four Pratt and Whitney, JT3D or Rolls Royce Conway turbofan engines. Cascade type thrust reversers were installed on DC8, [Ref. 32] discusses it along with the tests that were carried out to find a suitable reverser for high bypass ratio turbofan engines ranging from BPR 5 to 8.

Design trends for four-engine subsonic transport aircraft indicated that turbofan engines with bypass ratio (BPR) in the region of 3:1 to 8:1 would be suitable, with 65 to 85% of forward thrust supplied by fan exhaust. The engine installations will feature short or moderate length fan ducts exhausting from a plane forward of the gas generator exhaust. The ducts may be lengthened moderately to provide for incorporation an acoustic treatment to reduce fan exhaust noise. The engines will be fitted with thrust reversers with the objectives of braking on the ground during landing or aborted take-off and for rough air slowdown or rapid descent in flight. Figure 3.33,

shows thrust reverser flow characteristics on low bypass ratio turbofan engines with both fan and core flows reversed.

In order to operate thrust reversers only on fan stream for future high BPR engines, a test was initially carried out on the DC-8 aircraft with only the fan stream reversed. It was observed that the outboard engine will not surge and that the inter engine ingestion of fan air is tolerable, and that, from this standpoint, full reverse power may be maintained on all four engines. It was also assumed that the cascade type reverser effectiveness should be in the range of 35 – 40%. It was decided that the cascade type reverser perform well at low pressure ratio levels that are typically experienced in fan exhaust ducts. A summary of the cascade type reverser selection and experimental tests that were carried out on the 23% thrust reverser scale model is well presented in [Ref. 32]

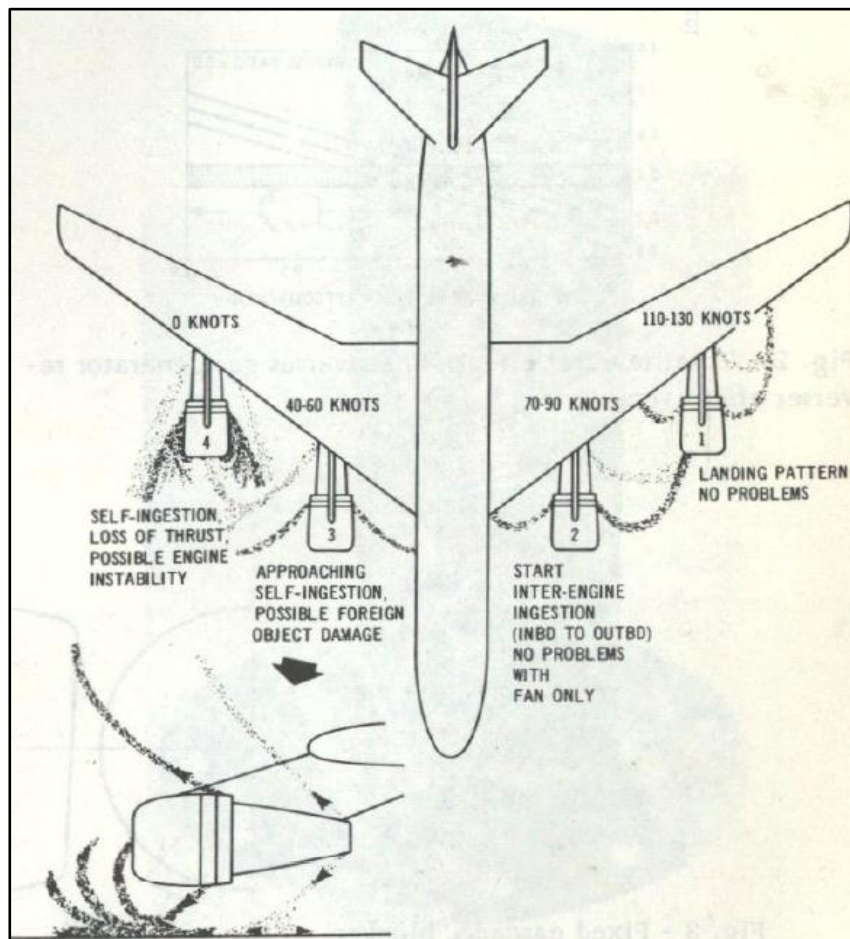


Figure 3.33: Thrust reversers on a four engine aircraft. Flow pattern at different landing speed. Image adopted from [Ref. 32].

3.12 Review of Early Thrust Reverser Design and Performance

Principles of thrust reversing were reviewed along with descriptions of most common types of thrust reversers in [Ref. 33]. Specific use of target type thrust reversers on business jets and the resulting performance gains were also demonstrated. Figure 3.34 to 3.36, are photographs of both the cascade and target type reversers on various aircraft. Although, the reversers are quite different in appearance, all employ either cascade or target principle or combination of both. Specifically, each reverser must be tailored to suit the aircraft configuration and the engine type [Ref. 33].

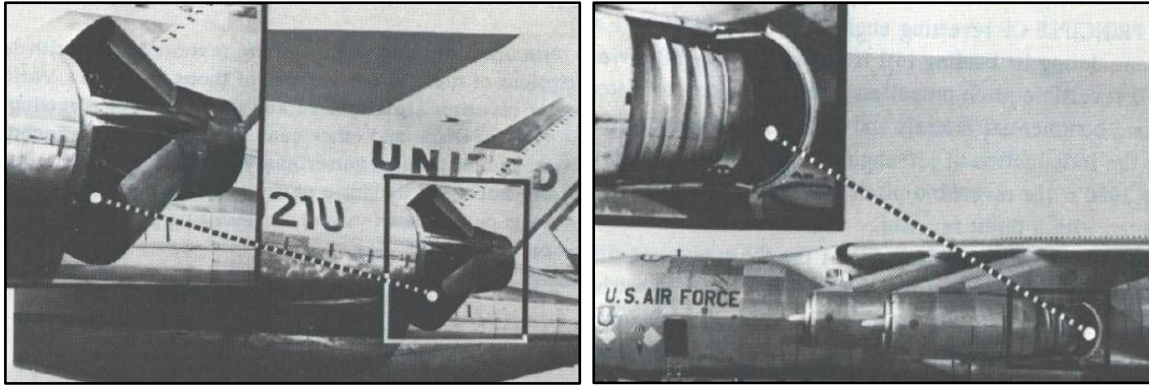


Figure 3.34: (L) Target door reverser on Boeing 727. (R) Target reverser with long duct fan engine on Lockheed C-141. Images adopted from [Ref. 33].

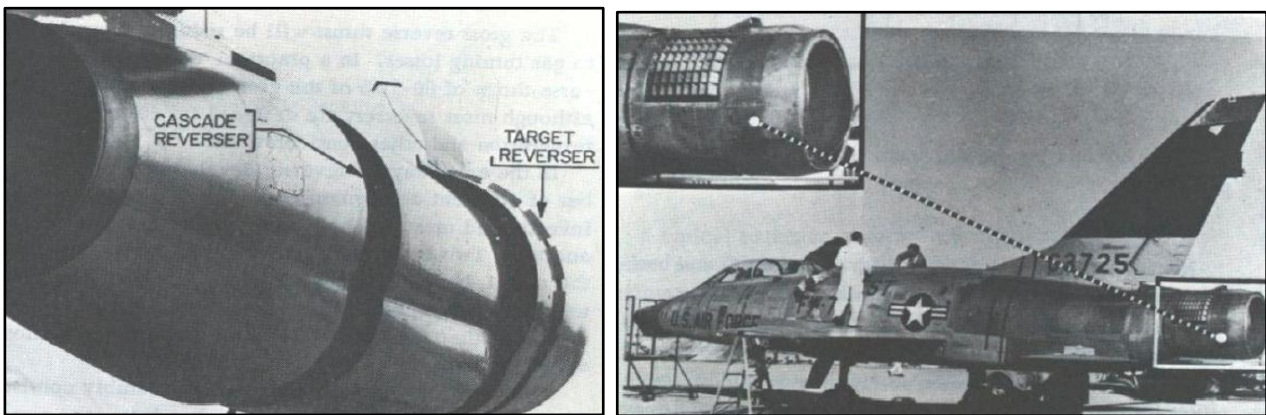


Figure 3.35: (L) Target reverser on fan and cascade reverser on turbine exhaust, Boeing 720B. (R) Cascade reverser mounted aft of tailpipe exit plane, North American F-100. Images adopted from [Ref. 33].



Figure 3.36: (L) Dual target reverser, Lockheed Jet star business jet. (R) Target thrust reverser on Grumman Gulfstream II business jet. Images adopted from [Ref. 33]

Target type thrust reversers are mainly a common choice for business aircraft. Ref 33, discusses the design considerations, principles and advantages of using target type reversers. Some of the most important elements considered in target type reverser design are:

1. Distance behind the tailpipe exit plane.

2. Acute angle between thrust axis and reverser door.
3. Length of endplate.

Distance behind the exhaust plane is most important consideration since it affects both the amount of reverse thrust obtainable for a given reverser geometry and determines whether there will be a back pressure on the engine. It is desirable to place the reverser as close as possible to the tail pipe to keep actuation linkages short and thereby reduce weight. If it is placed too close, however, the reversed gases cannot escape readily enough and a higher than ambient pressure will exist downstream of the nozzle reducing the effective pressure ratio and resulting in reduced air mass flow and over temperature at the turbine inlet. The acute angle between the forward thrust axis and reverser door is important in controlling the amount of reversed thrust and in preventing dynamic oscillation of the reverser assembly. Although, forward sweep of the doors plays an important part in determining the amount of the reverser thrust, the end plate size and shape plays the dominant role; the longer the endplate, the more effective the reverse thrust. It is the endplate that gives the gases their final forward kick [Ref. 33].

Thrust reversers are ordinarily designed for actuation in 1 – 2 sec either from forward to reverse or reverser to forward thrust. Figure 3.37, is a curve showing the modulation characteristics of a typical target type reverser. This is a typical of the initial reverser action that would occur when it is used to stop an aircraft on rejected take-off. With the engine at full take-off power, the reverser doors begin transition to the reverse position and there is little effect until the doors begin entry into the exhaust stream. This occurs at about one third door position. As the doors continue into stream, a zero thrust condition is reached at about 60% closure, followed by increasing reverse thrust to the final door position. It will be noted that the effective part of the modulation curve is fairly straight line with steep slope characteristics which gives smooth and rapid reverse thrust response.

A thrust reverser operates as a function of gross thrust, rather than the net thrust, and aerodynamic drag. Reverser effectiveness is greater at higher aircraft velocity. This is shown in (Figure 3.37). The gross thrust increases with increased aircraft velocity, and also the aerodynamic drag on the thrust reverser doors increases with velocity. Considering these conditions, it is possible for a reverser which is used in flight at high velocity to have more than 100% of the static engine thrust in the reverse direction. This effect can be quite useful in slowing the aircraft down to maximum allowable gust speed or in executing an emergency descent.

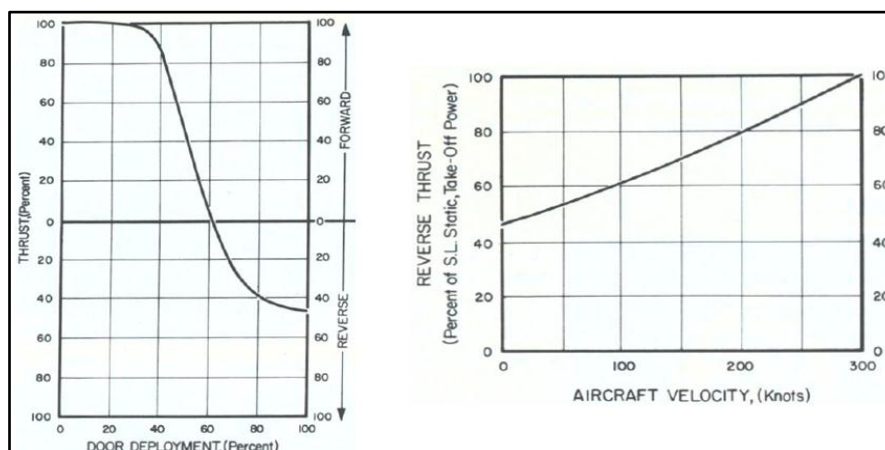


Figure 3.37: (L) Modulation performance of target type reverser at take-off power. (R) In flight performance of a target type reverser. Image adopted from [Ref. 33]

The most common use of a reverser is reduction of the ground roll distance during landing. In addition to the safety of shorter field landings on dry, wet and icy runways, the aircraft also enjoys less wear on the tires and braking system. Figure 3.38, shows comparative landing distances from touchdown to complete stop, with and without thrust reversers, for the three runway conditions. It will be noted that with thrust reversers, the landing distance on a dry runway is 56% of that without and on the wet runway only 35%. A large benefit is shown on the icy runway which is only 18% of the landing distance without thrust reversers. These comparisons are calculated on the basis that the reverser is stowed at 40 knots. A thrust reverser can also be useful and is ordinarily designed to assist in stopping during a rejected take-off. The reduction in rejected take-off distance for a typical 15,000lb aircraft is shown in (Figure 3.38).

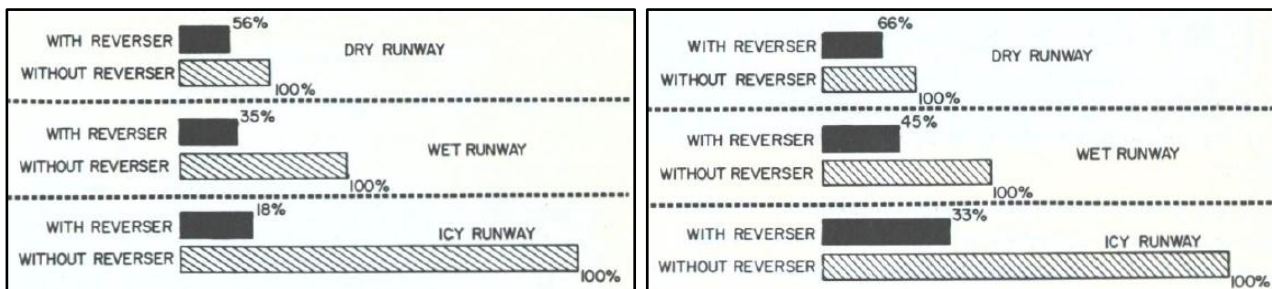


Figure 3.38: (L) Landing roll performance (15,000lb landing weight). (R) Rejected take-off performance (decelerate stop distance). Images adopted from [Ref. 33].

Another use of the thrust reverser while on the ground is to spoil idle thrust so that the desired taxi distance can be maintained without excessive use of wheel brakes. Reversers are also used, by utilising low power settings, to back up the aircraft, such as into a parking position. Inflight use of thrust reverser would help to decelerate the aircraft from cruise to maximum allowable gust speed in typically 44% less time. Emergency descent, in the event of cabin depressurization or oxygen system failure, from 40,000ft to 10,000ft, can be accomplished in 47 seconds less with reverse thrust than without [Ref. 33].

3.13 Thrust Reverser for McDonnell Douglas DC-10 Aircraft

Design features of the CF6 thrust reverser and spoiler is presented in [Ref. 25] CF6 engine was introduced into airline service as the power plant for the McDonnell Douglas DC-10. The DC-10 aircraft has three engines, two were pylon mounted pods under the wing and the third located above the fuselage aft of the tail vertical stabilizer (Figure 3.39).

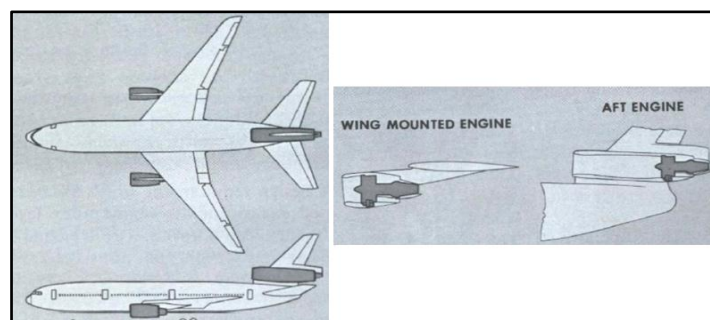


Figure 3.39: (L) DC-10 general arrangement and (R) engine installation. Image adopted from [Ref. 34].

The DC-10 is designed to provide a minimum reverse thrust of 40% of maximum take-off forward thrust. This reverse thrust is achieved by two systems; a core engine thrust spoiler which provides 100% spoilage of core engine thrust and a thrust reverser which provides 48.5% reverse thrust on the fan stream. In the forward thrust mode, the reverser and spoiler must function as exhaust nozzles and inherently must have high thrust coefficients. This requires smooth and properly contoured flow paths with minimum drag and leakage losses. The importance of this is illustrated by the fact that a 1% penalty in fan nozzle thrust coefficient results in a 2.2% increase in specific fuel consumption at cruise flight conditions. The noise requirements for the CF6 engine have a significant impact on the thrust reverser configuration selected. One additional major requirement, which needs no discussion, is achieving minimum weight.

The design selection of the reverser was performed after numerous trade-off studies. The reverser configuration as shown in (Figure 3.40) was selected because it met the requirement of minimum weight consistent with reverser and exhaust system performance requirements. A series of aerofoil turning vanes are mounted around the outer circumferential of the fan nacelle. The vanes are surrounded by a cowl which provides a smooth high performance flow path for both internal fan exhaust and the external airstream.

Aft translation of the outer cowl uncover the turning vanes; and a series of doors (16) total, flush mounted by hinges to the cowl and attached to links extending from the inner cowl, are automatically pivoted inward to block the fan flow through the fan exhaust nozzle. The cowl translation is accomplished by rotating ball screws which are driven by flexible shafts connected to a pneumatic motor mounted in the pylon (Figure 3.40).

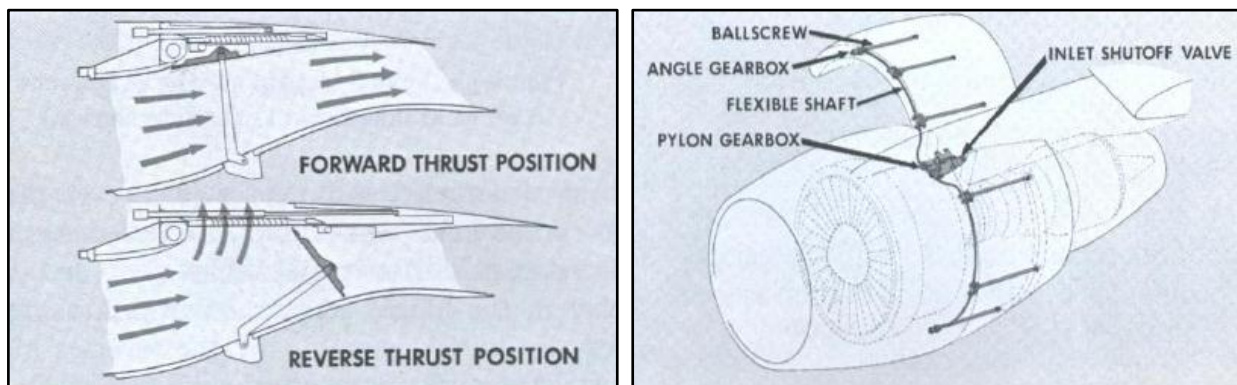


Figure 3.40: (L) Reverser schematic. (R) Reverser control and actuation system. Images adopted from [Ref. 34].

The thrust spoiler is a post nozzle exit, cascade type design as illustrated schematically in (Figure 3.41). Two cascade elements (turning vanes) are mounted on a fixed pivot aft of the core nozzle exit and are enclosed in a fairing which forms an aerofoil shaped plug. Aft transition of the fairing uncovers the cascades which open across the nozzle exit and divert the core exhaust flow radially outward and slightly forward in the horizontal direction. A very desirable feature of this location is the fact that the outer nozzle structure is not disrupted and no seals are required.

The design of the spoiler as shown in (Figure 3.41) consists of a conical inner flow path wall of Inconel 718 with conical outer nacelle fairing made of titanium. The cascade fairing extends up inside the nozzle such that the leading edge is an area of lower velocity. This fairing supports an inner plug which mates through a slip joint with engine rear frame. The cascades are mounted to a cross member which is supported by two beams extending aft from the nozzle. This provides a

rigid support for the cascades for both manoeuvre and aerodynamic loading. The cascade doors are identical pieces with beams extending lengthwise along the cascades to provide the required structural stiffness and support of the vanes. The vanes are modified aerofoil elements with an extension on each end which mates with slots in the axial beams. The aerodynamic forces in both the fairing and the cascades are relatively low and, as a result low actuation forces are required.

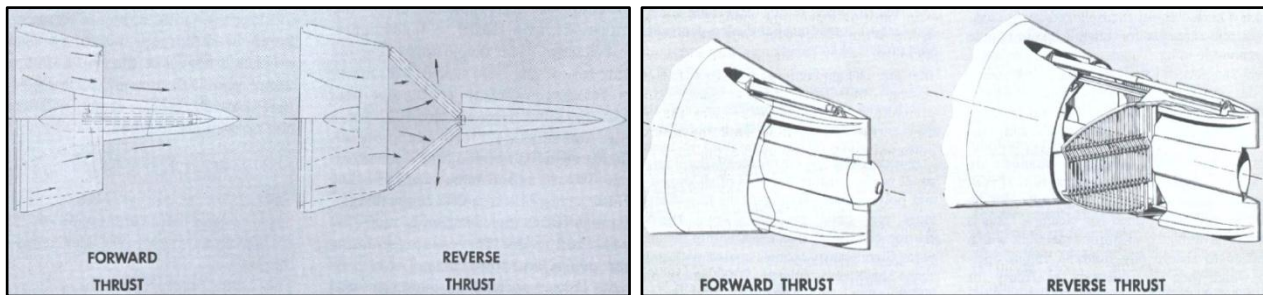


Figure 3.41: (L) Stowed cascade spoiler. (R) Plug stowed cascade. Images adopted from [Ref. 34].

Reference 34, also discusses the installation problems on the reverser along with thrust reverser load paths, structural analysis, actuation and control systems, acoustic treatment, reverser development testing and mechanical properties of the CF-6 engine thrust reverser. The author here has briefly described the important features; detail description can be found in [Ref. 34].

3.14 Rolls-Royce Reviews Thrust Reversers of the 1960s.

Rolls-Royce published a technical paper in the year 1969 where thrust reverser designs and service experience for the Avon engine installed on the Comet and Caravelle aircraft, Conway engine for the Boeing 707 and Vickers VC10 aircraft, SPEY engine for the HAS Trident and BAC 1-11 aircraft, and RB211 for the Lockheed CL 1011 are discussed. The general thrust reverser designs are similar to those described above; however, the paper is well written and could be a good read for anyone interested in the detail of the subject [Ref. 35].

3.15 Thrust Reverser for Concorde Aircraft

Concorde aircraft was one of the major breakthroughs in the civil aviation market. Concorde makes use of the Olympus engine which was jointly built by Rolls Royce and SNECMA. A study on thrust reverser design, development and testing was carried out by SNECMA for Concorde aircraft as discussed in [Ref. 36]. Concorde was a very special aircraft with supersonic cruise capability, thus, it is worth mentioning the thrust reverser capabilities of Concorde.

The technical requirements from the thrust reverser system was firstly, to provide a reverse thrust during landing and secondly, to slow down the aircraft in flight from a Mach no of around 0.9. Since the Concorde engines were two spool straight flow turbo jets, the only possible thrust reversal gases were the exhaust gases. Figure 3.42, shows the Concorde thrust reversal efflux angles [Ref. 36]. Therefore, the system had to be designed to withstand the high temperature at the take-off condition ($T_{\text{jet,exhaust}} \geq 700^{\circ}\text{C}$) and to meet the requirements of decelerating the aircraft on the ground, in normal landing or in emergency conditions. In addition to these performance requirements, the thrust reverser system had to be incorporated in the geometry of an exhaust system where:

1. A variable area convergent nozzle is needed for use of reheat, and for optimum matching of the engine along the flight plan.
2. For performance purposes in flight, the optimization of the convergent divergent system had been achieved, and implied a relative arrangement which could not be transgressed.
3. The secondary airflow, the pressure of which has a major effect on the internal losses of the exhaust system, had to be as clean as possible.

The prototypes aircraft were fitted with cascade type reverser. However, the cascade type reverser has issues during in flight deployment. It was investigated from the wind tunnel tests that the cascade reversers had a very marked effect on the pitching moment, particularly at high C_L , and these effects too are proportionally stronger at low reverser efflux pressure. The effects on the outer engines in reverser were somewhat smaller than those for the inners in reverse. The results from the wind tunnel data indicate that a cascade type reverser should be restricted to speeds above 220 knots ($C_L \approx 0.4$), and idling engines only.

The introduction of a target type reverser moves the reverser efflux further aft on the wing; thus, the interference of the reversed flow with the pitching moment was reduced significantly. Target type reversers, had a very small effect on lift. There was no sign of pitch up effects at high C_L . Thus, a Concorde thrust reverser system is comprised of the following components, thrust reverser buckets, bucket seals, bucket actuators, bucket locking system, pneumatic control system.

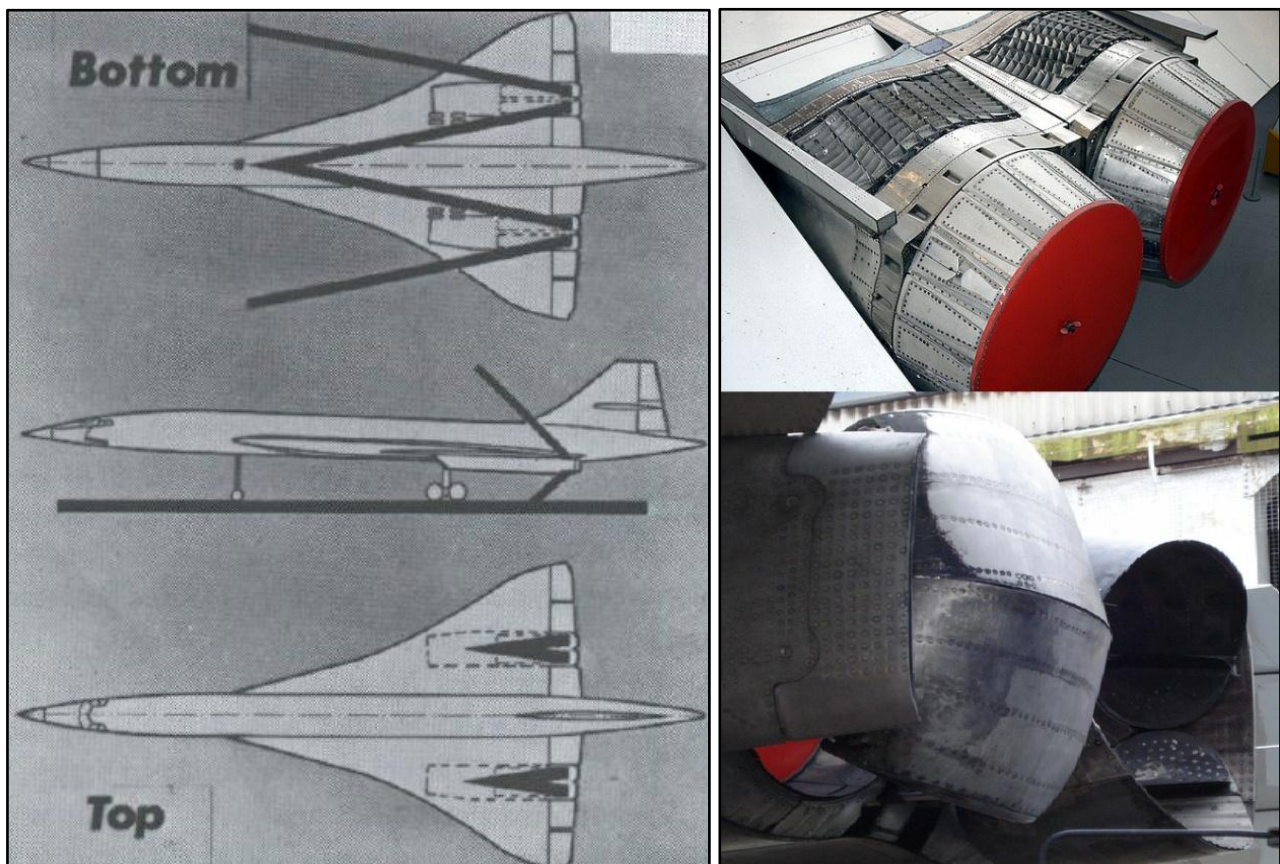


Figure 3.42: (L) Concorde thrust reverser efflux angles [36]. (R) Top, Cascade type thrust reversers for the Concorde prototype aircraft. Bottom, target thrust reversers for Concorde aircraft. Images adopted from [Ref. 37].

3.16 Thrust Reverser Study for Civil STOL Aircraft

A thrust reverser study for civil STOL (short take-off and landing) aircraft was carried out by Rolls-Royce and is presented in [Ref. 38]. Civil Short Takeoff Landing (STOL) aircraft typical landing speeds are around 90 knots; these lower speeds imply very low wing loadings, causing in-flight passenger discomfort. Descent and approach flight path angles may be twice those of conventional aircraft. Static thrust/weight ratio is likely to be 0.45 – 0.5, appreciably higher than conventional aircraft, which are generally in the band 0.25 – 0.35. The method of lift augmentation selected by the manufacturers of STOL aircraft affects the cycle and operating mode of the engine. On a STOL aircraft the full reverse thrust position should be achievable within 2 sec after touchdown. Since the engine will already be at an intermediate power setting and accelerating during reverser travel, full reverse thrust should be attainable within the next 2 sec, thus full reverser thrust should be achieved in approximately 4 seconds from touchdown. It is also important for STOL aircraft to use thrust reversers up to a speed of 30 knots; this is considerably lower than that for the conventional aircraft where the reversers are stowed at speeds of around 60 knots. Also, a study of the basic thrust reverser designs for the STOL aircraft is given in [Ref. 38].

Conventional reverser control systems are unsuitable for STOL aircraft for two reasons; first the procedure of throttling back to idle and then operating a separate lever to select reverse and (after waiting for full deployment) reaccelerating the engine takes around 10 sec, which is much too slow for aborted take-off and normal landing. Secondly, conventional systems do not permit thrust reverser modulation. Thus, for STOL aircraft a completely new concept is needed that avoids these two deficiencies and fulfils the safety criteria and meets pilot's requirements that all engines and reversers must be controllable by one hand. As shown in (Figure 3.43), each engine in this new system will have a power lever and a thrust lever, with corresponding levers for other engines ranges alongside for one handed operation. Figure 3.43, also shows a schematic of a typical control system. The power lever will select the basic engine speed or power level and in addition may have other functions (for example start and shut-off positions) depending on engine requirements. The thrust lever will both control the reverser and modify the power set by the power lever. When the thrust lever will be fully forward, it will provide take-off power irrespective of the power lever setting. Moving it back to the flight position (Figure 3.43) will progressively reduce power to the level set by the power lever. Further movement will cause the reverser to deploy progressively at the selected power level, and the final travel will bring power up again to maximum reverse. The reverser may reach its full reverse position at some point along this final travel.

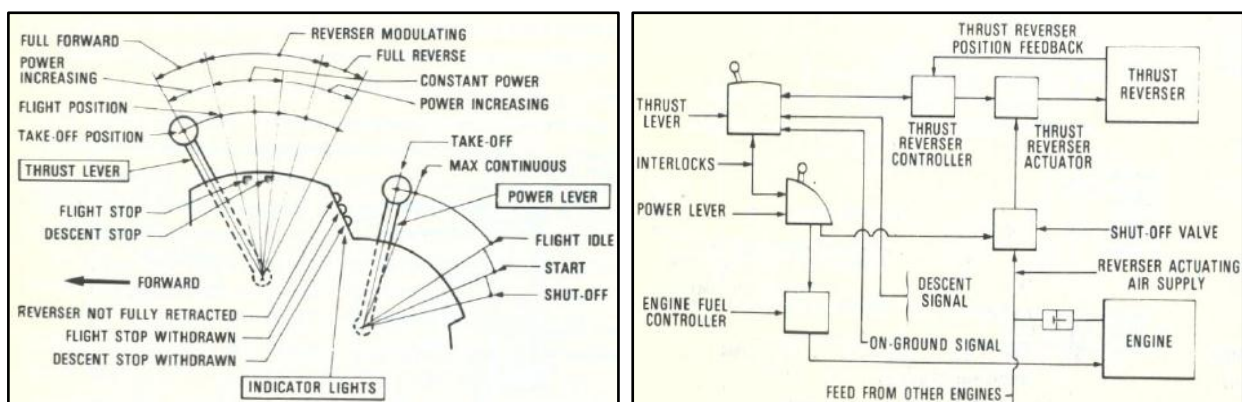


Figure 3.43: (L) Control system for a typical STOL aircraft. (R) Typical control system for conventional aircraft. Images adopted from [Ref. 38].

3.17 Target Type Thrust Reverser for the TFE-731 Turbofan Engine

A target thrust reverser was developed by Grumman Aerospace for the TFE-731 turbofan engine. TFE-731 turbofan was used on Dassault Falcon 10, Gates Lear jet 35/36 and West wind 1124 aircraft and was design and built by Garrett Air Research now known as Honeywell Aerospace. The three aircraft are twin engine business jets capable of carrying 6-8 passengers.

Grumman Aerospace space selected pivoted target thrust reverser design for the TFE-731 turbofan engines. Figure 3.44, shows a pivoted target thrust reverser installed in the stowed position. The reverser extends downstream and forms a 'fish mouth' nozzle. The fish mouth shape is dictated by the sweep angle that the target doors must have when they pivot to meet in the deployed position. The external surfaces of the target doors extend downstream of the conventional tailpipe exhaust blend with the re-contoured nacelle to form an improved fineness ratio and local boat tail angle. Internal surfaces of the fish mount mate with the exit diameter of the fan nozzle without restricting nozzle exit flow area. Some mixing or ejector action takes place as the hot and cold flows pass through the fish mouth; however when target doors are in stowed position the reverser parts are exposed only to fan stream. Because of the medium bypass ratio and the non-mixed exhaust other types of thrust reversers are not as suitable for this installation. Target thrust flow has interesting characteristics (Figure 3.45), it appears that the hot core stream is turned and follows along the door centreline. But the fan stream is split by the turned core flow and stays near the outer edges of the door.

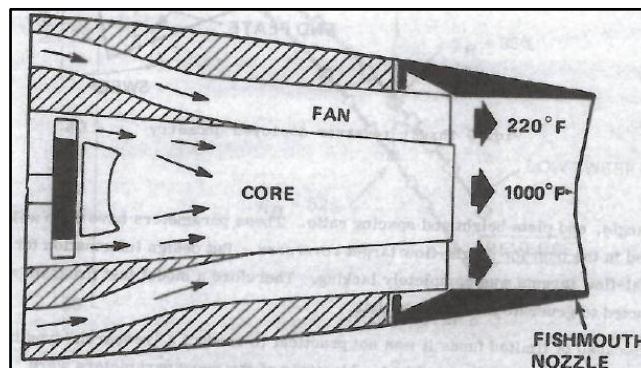


Figure 3.44: Pivoted target thrust reverser installed on a TFE-731 turbofan. Image adopted from [Ref. 39]

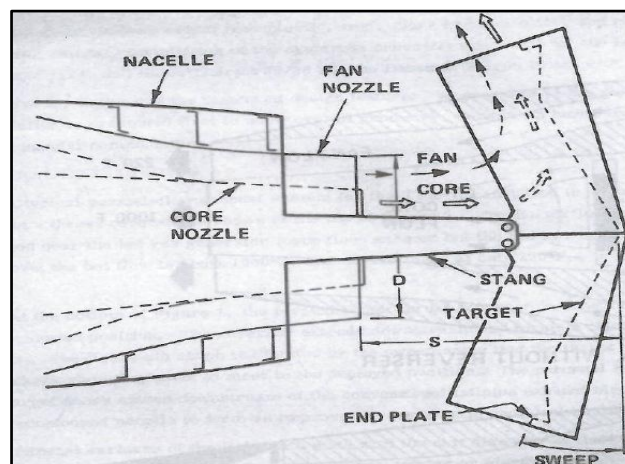


Figure 3.45: TFE-731 turbofan engine thrust reverser deployed geometry. Image adopted from [Ref. 39]

Reverse thrust effectiveness is a function of engine power setting and geometrical parameters such as door size, sweep angle, side angle, end plate height and spacing ratio. These parameters have been well defined in the past for single flow target reversers. But design information for coaxial flow targets was completely lacking. Therefore, a model test program was conducted by Grumman Aerospace to generate the required data. A 1/7th scale model of this configuration was built and tested with two sweep angles.

Spacing ratio was found to be much more critical for the TFE-731 type engine than for turbojet or mixed flow low bypass engines. This is due to the fact that TFE-731 operates with un-choked nozzles at sea level static conditions and is therefore more sensitive to backpressure effects than if the nozzles were choked. When the discharge coefficient decreases below that measured without thrust reverser, the TFE-731 would start to feel back pressure. The spacing ratio of the design must be greater than 1.10 to avoid backpressure. The full design has the target located at a spacing ratio of 1.15 to provide some margin (Figure 3.46).

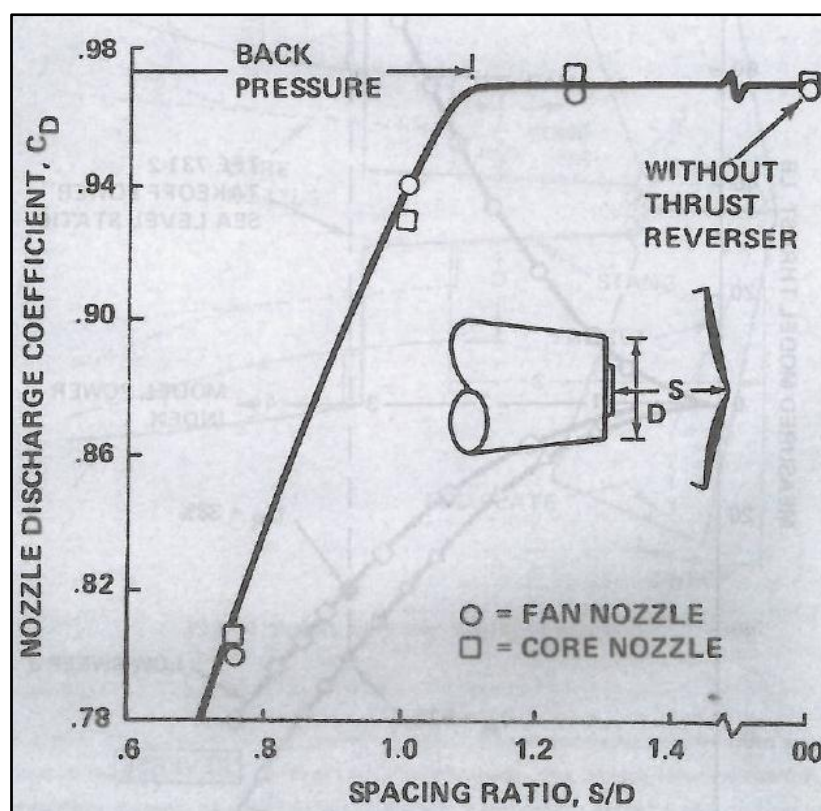


Figure 3.46: Target spacing ratio. Image adopted from [Ref. 39]

Stowed thrust reverser geometry can influence cruise performance (thrust loss or drag increase) and engine operation (rotor speed mismatch). Analysis in [Ref. 39] indicates that the improved pivoted target thrust reverser has a very small thrust loss that is more than offset by nacelle drag reduction. The internal thrust loss was also checked on the 1/7th scale model by testing a conventional coaxial tailpipe and then adding stowed reverser fish mouth. Although, minimum data scatter were observed, no thrust difference (loss) was found between the two model configurations.

The thrust reverser assembly is designed to bolt directly to the engine outer fan case which supports the entire thrust reverser. The turbine exhaust system mounts to the engine completely independent of the reverser. The basic hardware consists of door support structure, two doors, and actuation and control system. The door support structure consists of two stang beam integral with

the aft cowl, one inboard and one outboard of the engine centreline. Housed between the upper and lower stang beams are the thrust reverser actuator, actuator fluid lines, deploy switch, secondary latch solenoid. Stow switches are mounted through both the upper and lower stang beams. Thrust reverser doors are designed as neutral doors i.e. the same door can be used for an upper or lower left or right hand installation. The door structure is made of A286 stainless steel, the outer skin of the door is aluminium alloy. When deployed, the upper and lower doors lean on each other along their aft canted frames. Reverse thrust efficiency is improved by addition of an endplate mounted onto the forward frame and extending beyond the inside skin [Ref. 39].

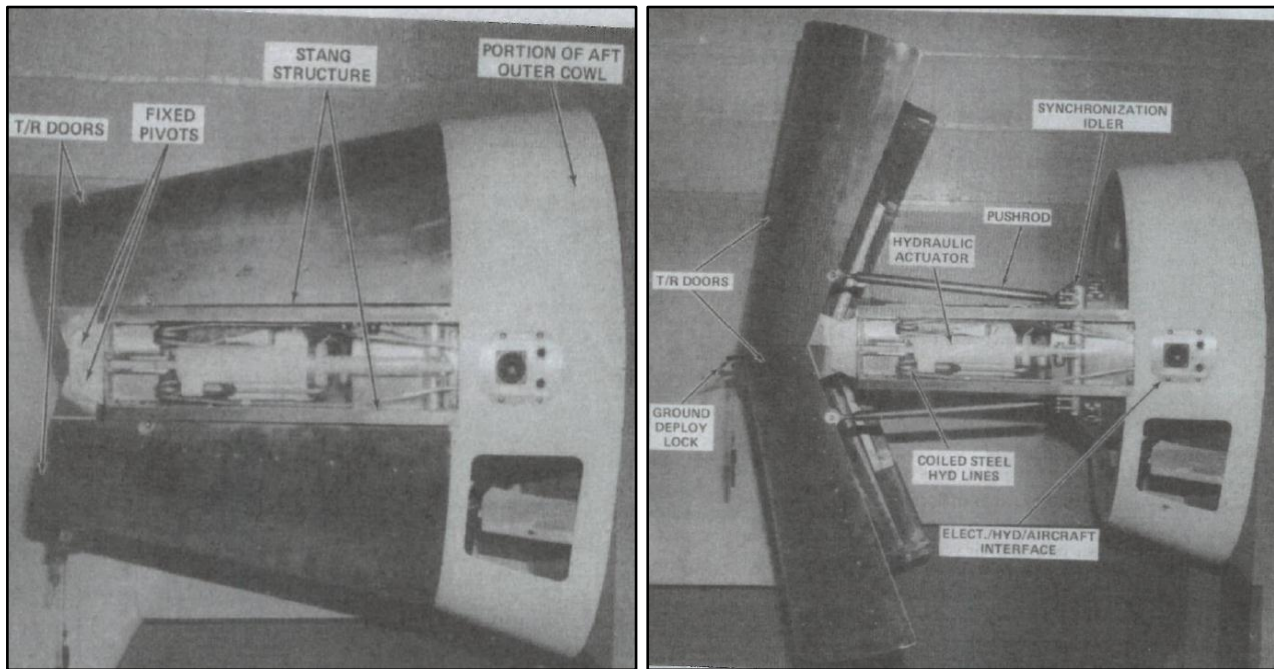


Figure 3.47: (L) Thrust reverser doors closed. (R) Thrust reverser doors open. Images adopted from [Ref. 39].

3.18 Experimental Performance of Cascade Thrust Reversers at Forward Velocity

Experimental performance of cascade thrust reverser at forward velocity was studied in [Ref. 40]. A series of static and wind tunnel tests were performed on four cowl cascade thrust reverser configurations which had various reversed jet emission patterns. The study was initiated to investigate the performance of a model fan reverser system. The work was performed using a fan model which was 14.0 centimetres in diameter and passed a fan mass flow of 2.49 kg/s at an approximate fan pressure ratio of 1.22 and fan corrected rotational speed of 35,800 rpm. The thrust reverser configurations considered in the study were the cowl mounted cascade thrust reversers and were conducted with low pressure ratio model fan. The objective of the study was to determine both the thrust reverser efficiency and the variation of the fan duct static pressure. Wind tunnel tests were conducted for a range of yaw angles from 0° to 90° and forward velocities from static to 35 meters per second [Ref. 40].

The thrust reverser section consisted of eight replaceable cascade sectors (Figure 3.48), the forward and aft housing rings, and two axial support rails located 180° apart. Each cascade sector subtended an azimuth angle of 42.5° and was replaceable by a solid sector which provided azimuth blockage of the flow for some configurations. Since each sector contained end rails, the azimuth flow angle of each sector was 40.2°. The fan flow was turned through the cascade reversers by a blocker door which had a forward sloping surface of 45° and seals to prevent flow

leakage axially. The blocker door was axially translatable, thus making the effective fan exit area and mass flow adjustable. The cascade reverser blades were designed according to the following procedure. To reduce losses through the cascade blades, it was estimated that a minimum Reynolds number of 10^5 based on the blade chord and the fan duct velocity was required. A solidity of 1.3, an approximate turning angle of 135° , and 15 percent thick blade contour having a chamber of 110° were selected. The blade section is illustrated in (Figure 3.49). The angle between the chord line of the reverser blade and the fan centreline was 75° . Accounting for radial divergence in flow area through the blades, this design incorporates a cross-sectional flow passage that converges. This feature helps avoid flow separation. From the blade design, the cascade discharge coefficient was estimated to be 0.55 [Ref. 40].

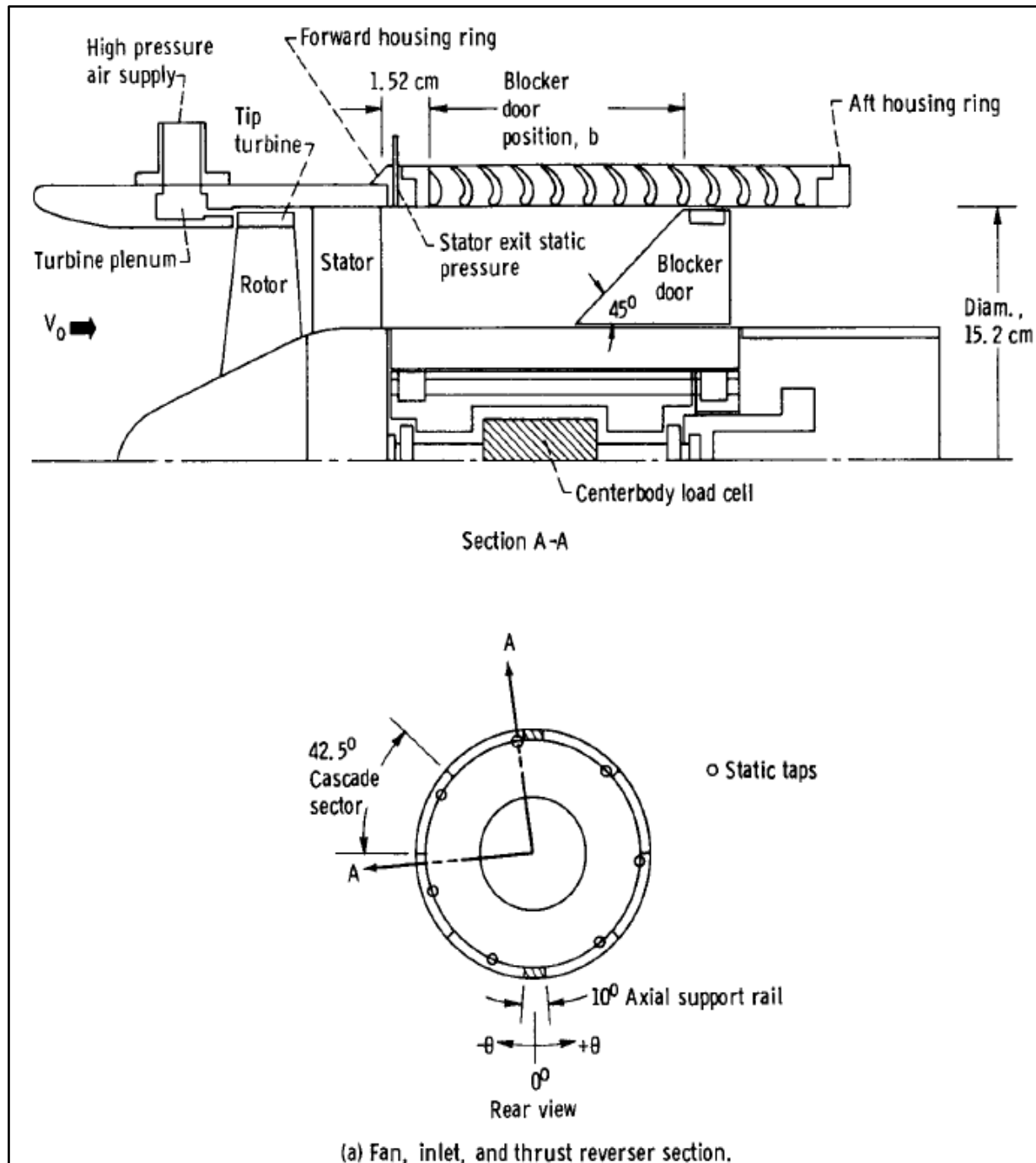


Figure 3.48: Fan inlet and thrust reverser section – Experimental test rig. Image adopted from [Ref. 40].

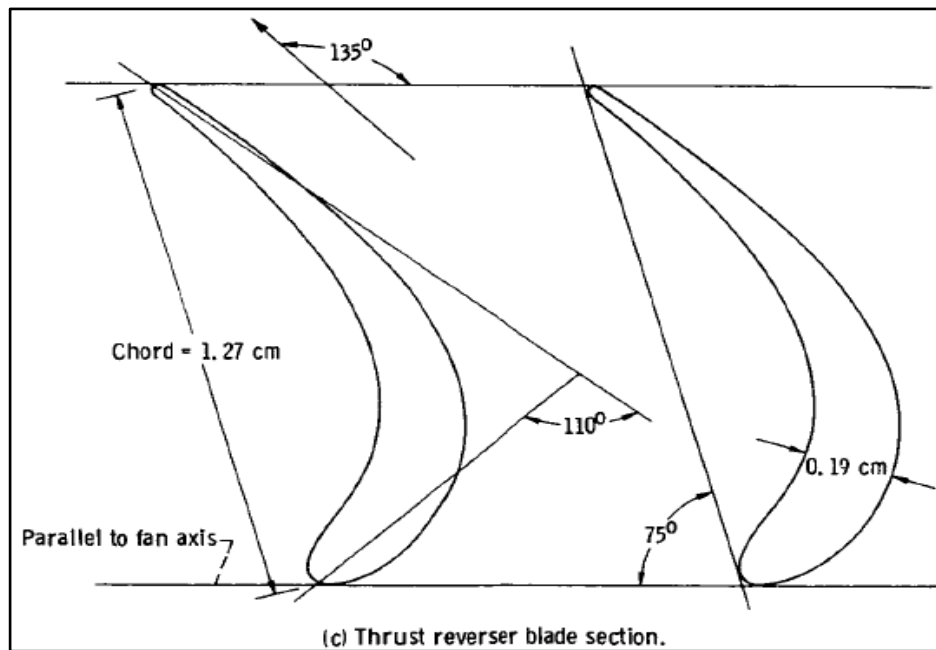


Figure 3.49: Thrust reverser blade section. Image adopted from [Ref. 40].

The instrumentation is also illustrated in (Figure 3.48). A single component load cell was located in the model centre body and was used to measure the total axial force during the wind tunnel tests. The model centre body also contained a light sensitive cell to measure fan rotational speed. Seven static pressure taps were located in the outer passage wall between the stator exit plane and the thrust reverser section. Two test facilities were used during the test series: the static test stand and the Lewis 2.74 by 4.57 meters low speed wind tunnel (Figure 3.50) [Ref. 40].

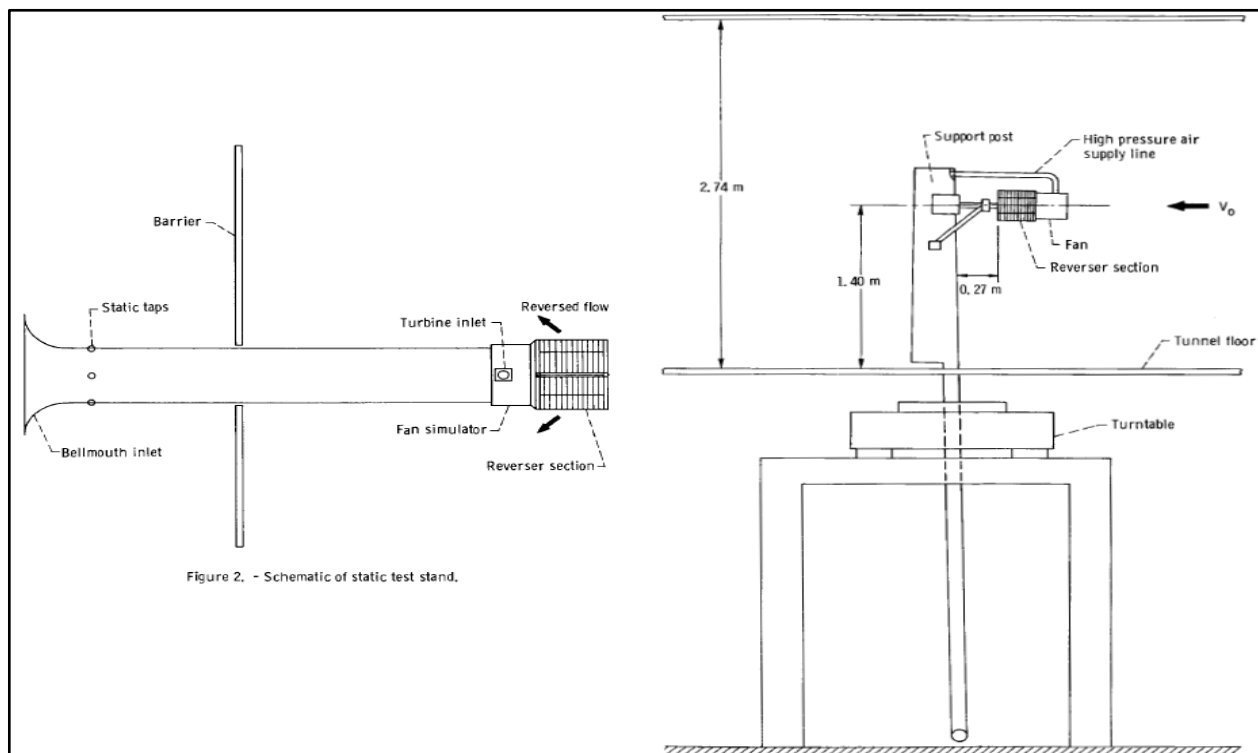


Figure 3.50: (L) Schematic of static stand test. (R) Thrust reverser model in low speed tunnel. Image adopted from [Ref. 40].

Figure 3.51, shows the five configurations tested: one configuration using a standard forward exit and four reverser configurations. For the reverse configurations, the model allowed both the number of cascades and the blocker door position to be varied. The first reverser configuration used all the eight cascade sections and had a total azimuth emission angle of 321.6° . The second reverser configuration had approximately 33 percent of the circumferential blockage giving a total emission angle of 241.2° . The remaining two configurations had more than half the circumference blocked giving a total emission angle of 160.8° . The difference between the last two was the geometrical arrangement.

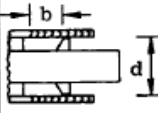
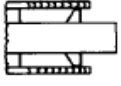
Exit configuration identification	Configuration schematic		Total emission angle, deg	Normalized blocker door position, b/d	Static thrust reverser efficiency (N = 36 000 rpm)	
	Side view	Rear view			With barrier ^a	Without barrier
Standard exit			----	----	----	----
Full emission reverser			321.6	0.37	0.74	0.42
Partial emission reverser			241.2	0.59	0.69	0.58
Partial emission reverser			160.8	0.75	----	0.54
Partial emission reverser			160.8	0.75	0.65	0.60

Figure 3.51: Configurations tested and static reverser efficiency. Image adopted from [Ref. 40].

Figure 3.52, presents the variation of thrust reverser efficiency as a function of free stream velocity for two yaw angles and two fan rotational speeds. The increase in thrust reverser efficiency with forward velocity for a given configuration was due to the increase in inlet ram drag and base drag with forward speed and to any reduction of the amount of exhaust flow being re-ingested. The highest thrust reverser efficiency was observed in the present test series was for a configuration with a total emission angle of 160.8° divided into two sectors oriented 180° apart.

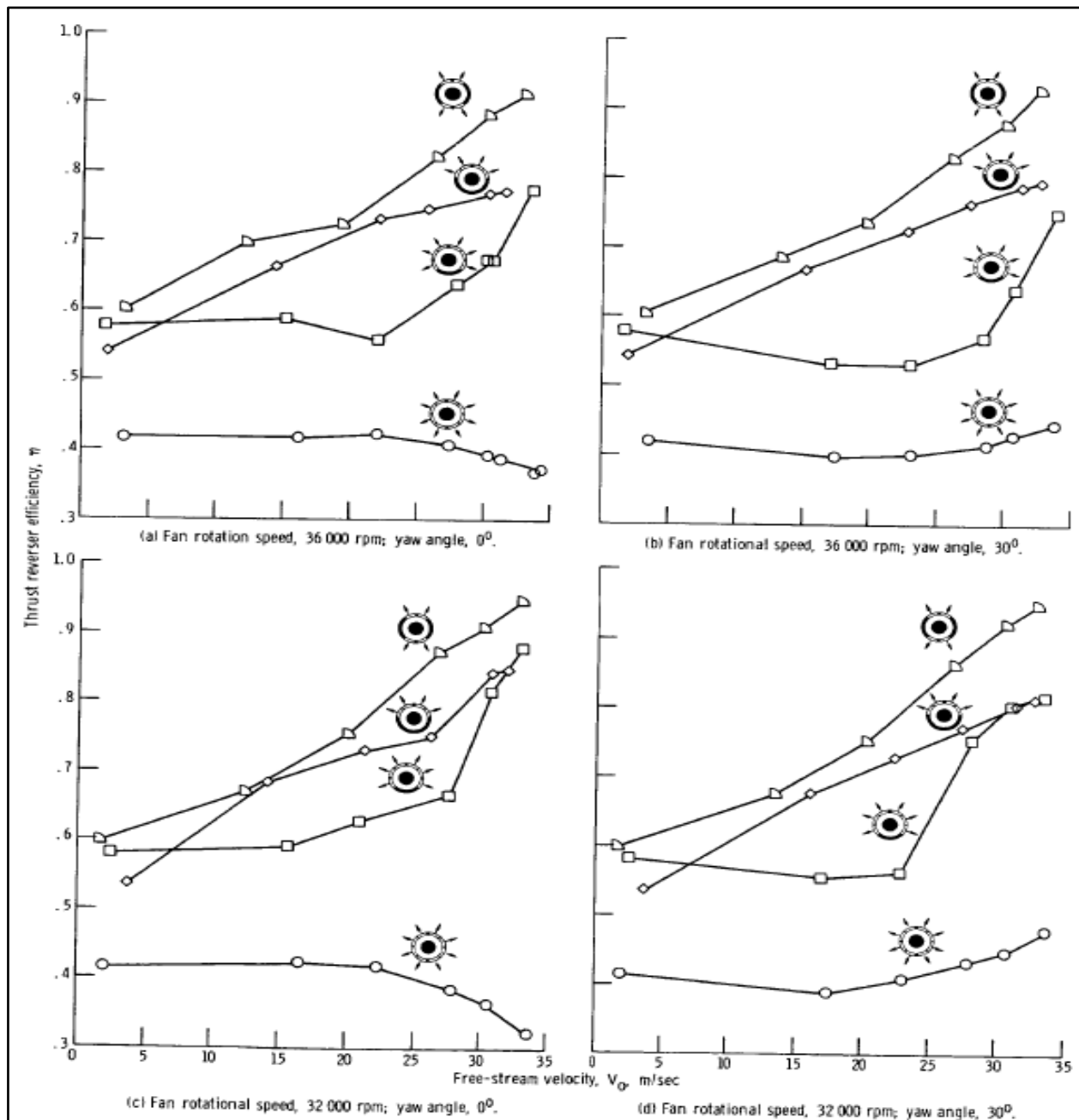


Figure 3.52: Variation of reverser efficiency with forward velocity for different configurations. Image adopted from [Ref. 30]

Figure 3.53, shows the effect of yaw angle on thrust reverser efficiency. For configurations with high efficiency, the efficiency decreased with increasing yaw angle. This is attributed to decrease in component of the inlet momentum drag along the fan axis and any decrease of inlet performance with increasing yaw angle. For configurations with lower efficiency and large recirculation, flow angle has little effect on the efficiency [Ref. 40].

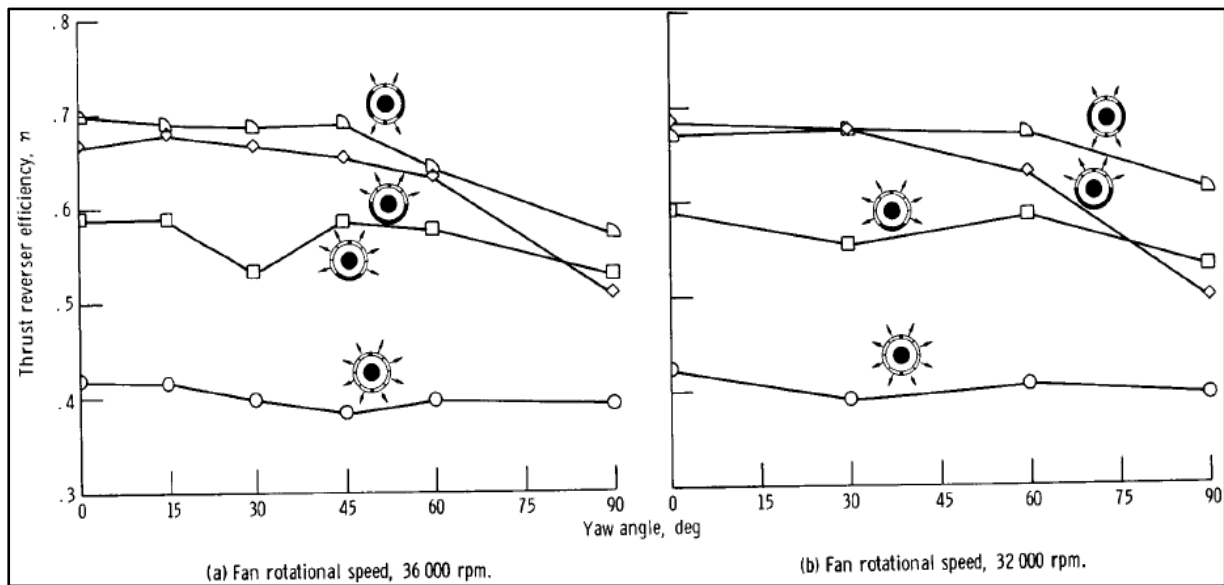


Figure 3.53: Variation of reverser efficiency with yaw angle for different configurations.
Image adopted from [Ref. 40].

Figure 3.54, presents the azimuthal variation of the internal static pressure between the stator exit plane and the reverser section. In all cases, the static pressure is normalised by the free stream static pressure. For a uniform fully circumferential exhaust discharge, no circumferential variation in static pressure was expected. The small variations in static pressure for the configuration which has a 321.6° emission angle shows the effect of the axial support at $\theta=0^\circ$ and 180° . For the configuration with approximately 95° blockage at the bottom of the model, there was a large rise in static pressure in the vicinity of the blockage. For the next configuration with 180° of blockage, both the extent and magnitude of the static pressure rise increased. Breaking the same circumferential blockage into two sectors significantly reduced the static pressure variation. The data in (Figure 3.54) also shows that the internal static pressure variation is essentially unaffected by the free-stream flow velocity (Figure 3.54a), the flow angle (Figure 3.54b), or fan rotational speed (Figure 3.54c). In general, the internal static pressure distribution was determined only by the thrust reverser geometry.

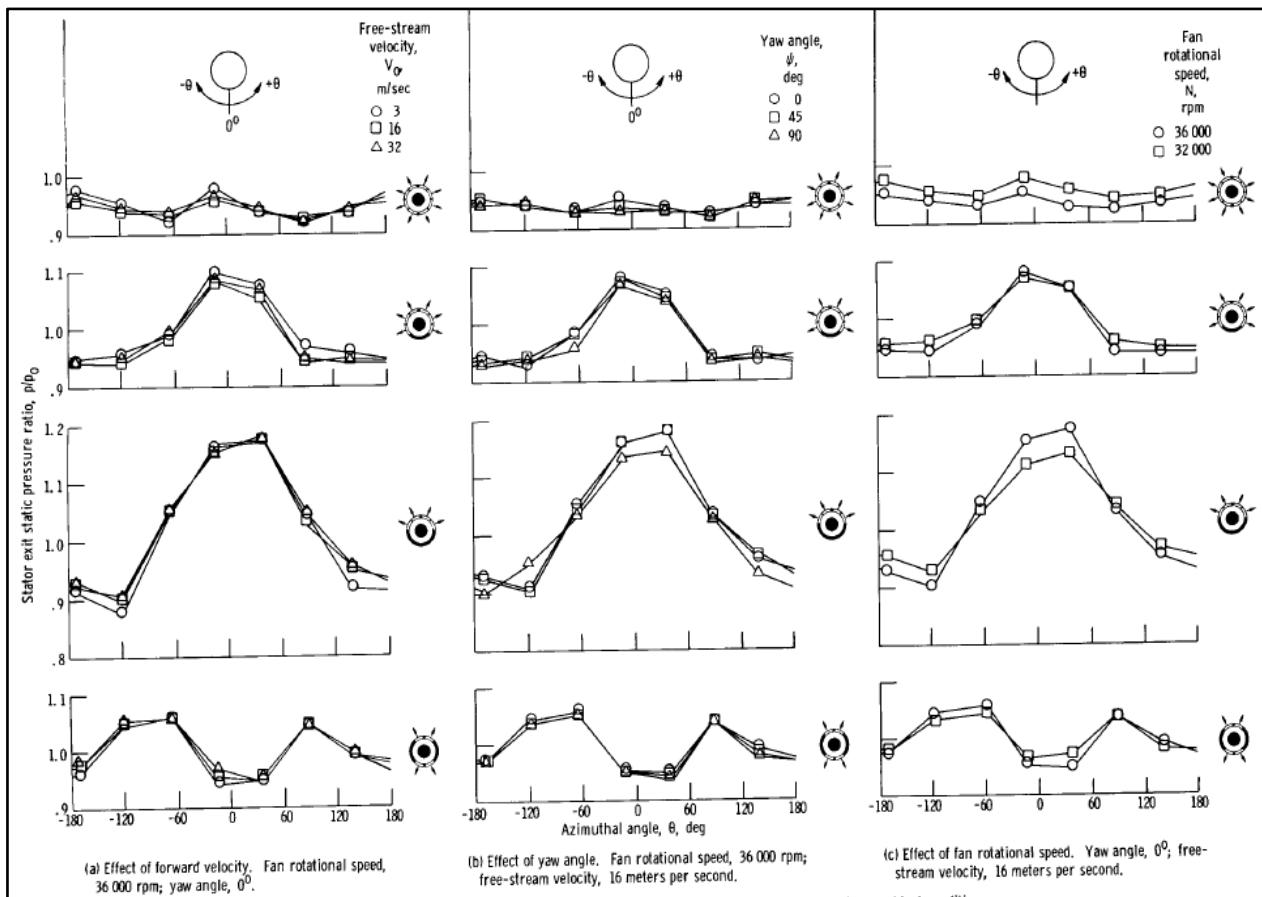


Figure 3.54: Variation of stator exit pressure for different configurations and test conditions. Image adopted from [Ref. 40].

3.19 Cascade Type Thrust Reverser Installation Implications

The effect on fan internal flow characteristics due to the length and axial location of a cascade thrust reverser is discussed in [Ref. 41]. The study looked into the fan overall operating characteristics, inlet static pressure contours, fan exit total and static pressure contours, and fan exit pressure distortion parameters due to the operation of a cascade thrust reverser. Also, cascade thrust reversers make use of large circumferential blocker doors which can induce a significant fan flow distortion and back pressure. Thus, the effect of blocker doors was also considered in [Ref. 41].

A reverser model similar to that used in [Ref. 40] was used for this study. A fan rotor with a tip diameter of 14.0 centimetres, design rotational speed of 35,800 rpm, mass flow of 2.49 kg/s and which has a design pressure ratio of 1.25 was used. Tests were performed on nine thrust reverser configurations each of which had the same geometrical emission pattern and a total circumferential angle of 241.2° . All tests were performed statically over a range of fan rotational speed from 60 to 100 percent of the fan design speed. Figure 3.55, shows the forward and reverser thrust configurations.

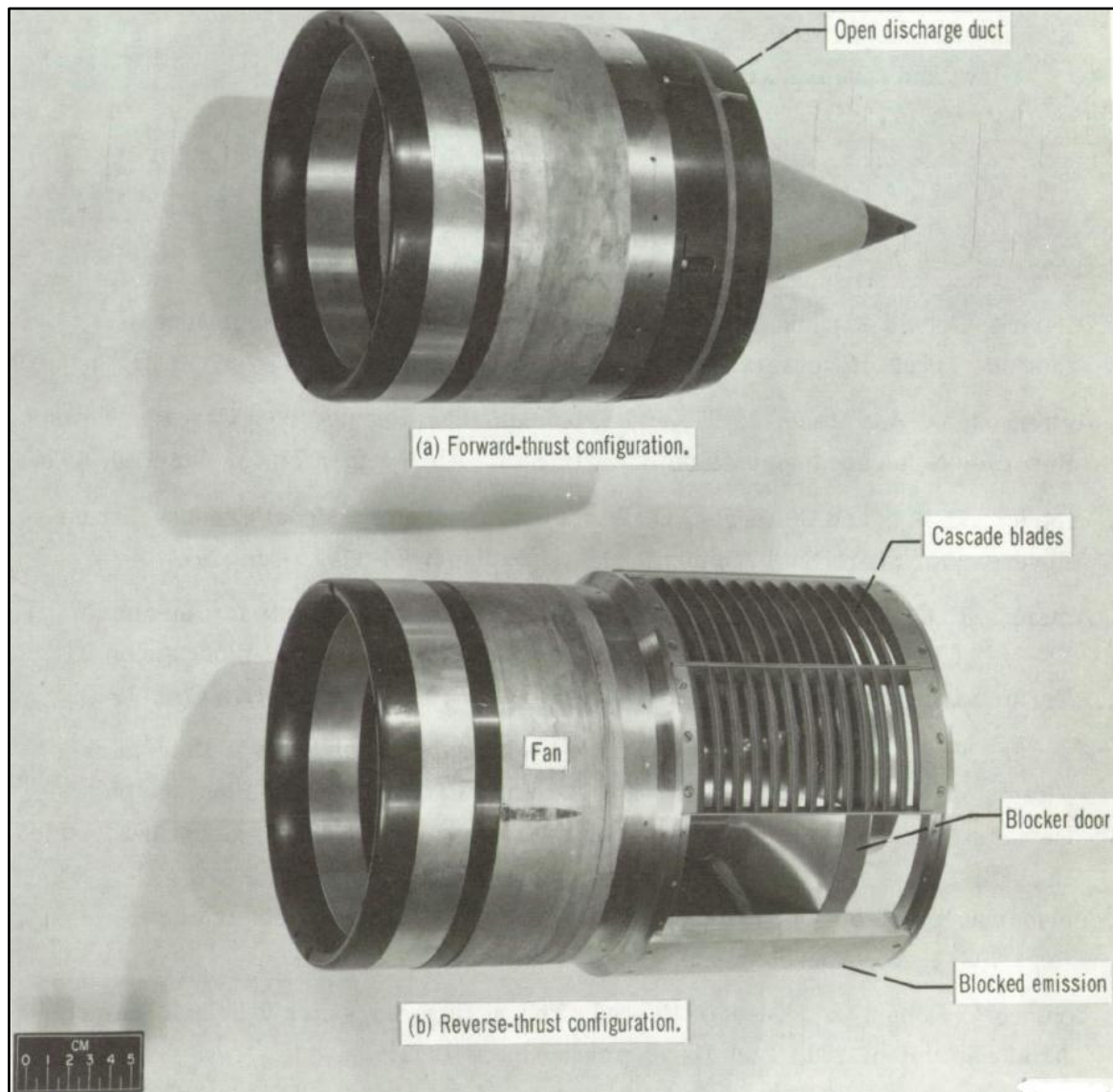


Figure 3.55: Forward and reverse thrust model with flight type inlets. Image adopted from [Ref. 41]

Two cascade axial locations were investigated. The first is the close spacing configuration which has the shortest length possible between stator trailing edge and cascade inlet. The second configuration of the model was accomplished by the addition of a spacer which was 6.35 centimetres long (Figure 3.56). The addition of the spacer changed the spacing distance, which was the distance from the stator trailing edge to reverser leading edge from 0.10 to 0.52 fan duct diameter (i.e., $b_s/d = 0.10$ and 0.52). The cascade reverser blade geometry was similar to that discussed in [Ref. 40]. The instrumentation used is illustrated in (Figure 3.56).

Three variables of the test configurations were the axial cascade length (axial position of the blocker door), the axial distance between the stator and reverser, and the type of inlet. The total emission angle for all the configurations was 241.2° , and the geometric arrangement of the emission pattern was fixed. The emission geometry had a single blockage of 95° centred about the 0° circumferential position plus a small 10° blockage at 180° (Figure 3.56). Varying the blocker door position changed the axial length of the cascade section.

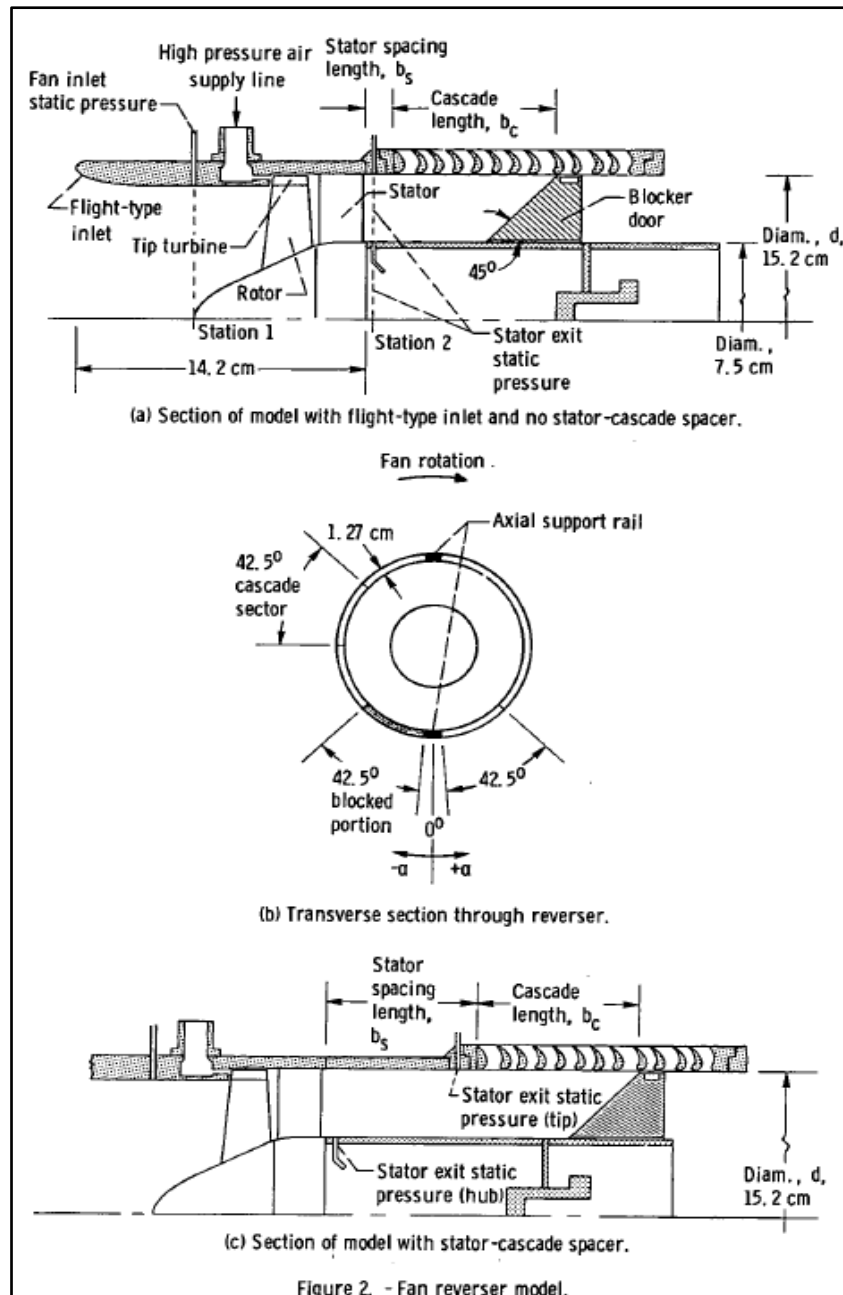


Figure 3.56: (Top) Section of a model with flight type inlet and no stator cascade spacer. (Bottom) Section of the model shows the cascade spacer. Image adopted from [Ref. 41]

Figure 3.57, is an arithmetic average of the stator exit static pressure measurements rationed to the ambient pressure as a function of normalized rotational speed N/N_d for each configuration. The stator exit pressure ratio represents the back pressure on the fan stage and determines the fan operating point. The solid symbols of (Figure 3.57) are the data for the representative forward thrust and the open symbols are for the reverser configurations. There is a general trend for the stator exit static pressure with increasing rotational speed and as expected with increasing cascade length (increasing b_c/d) or increasing reverser exit area. For the same value of cascade length parameter b_c/d increasing the normalized spacing distance b_s/d from 0.10 to 0.52 significantly decreases the stator exit pressure as may be seen by comparing (Figure 3.57a and b). Also, the flight type inlet gives a lower stator exit static pressure than the bellmouth inlet plus recirculation shield (Figure 3.57c) [Ref. 41].

The reverser cascade length may be selected on the basis of having the same stator exit static pressure ratio (the same operating point) during reversing as that of the forward thrust case. Therefore, the cascade length (b_c/d) may be selected as 0.58 when the normalized stator spacing distance $b_s/d=0.10$ (Figure 3.57a) and selected as 0.54 when $b_s/d=0.52$. This indicates that the required reverser cascade length to maintain the same fan operating point is reduced as the stator spacing distance is increased [Ref. 41].

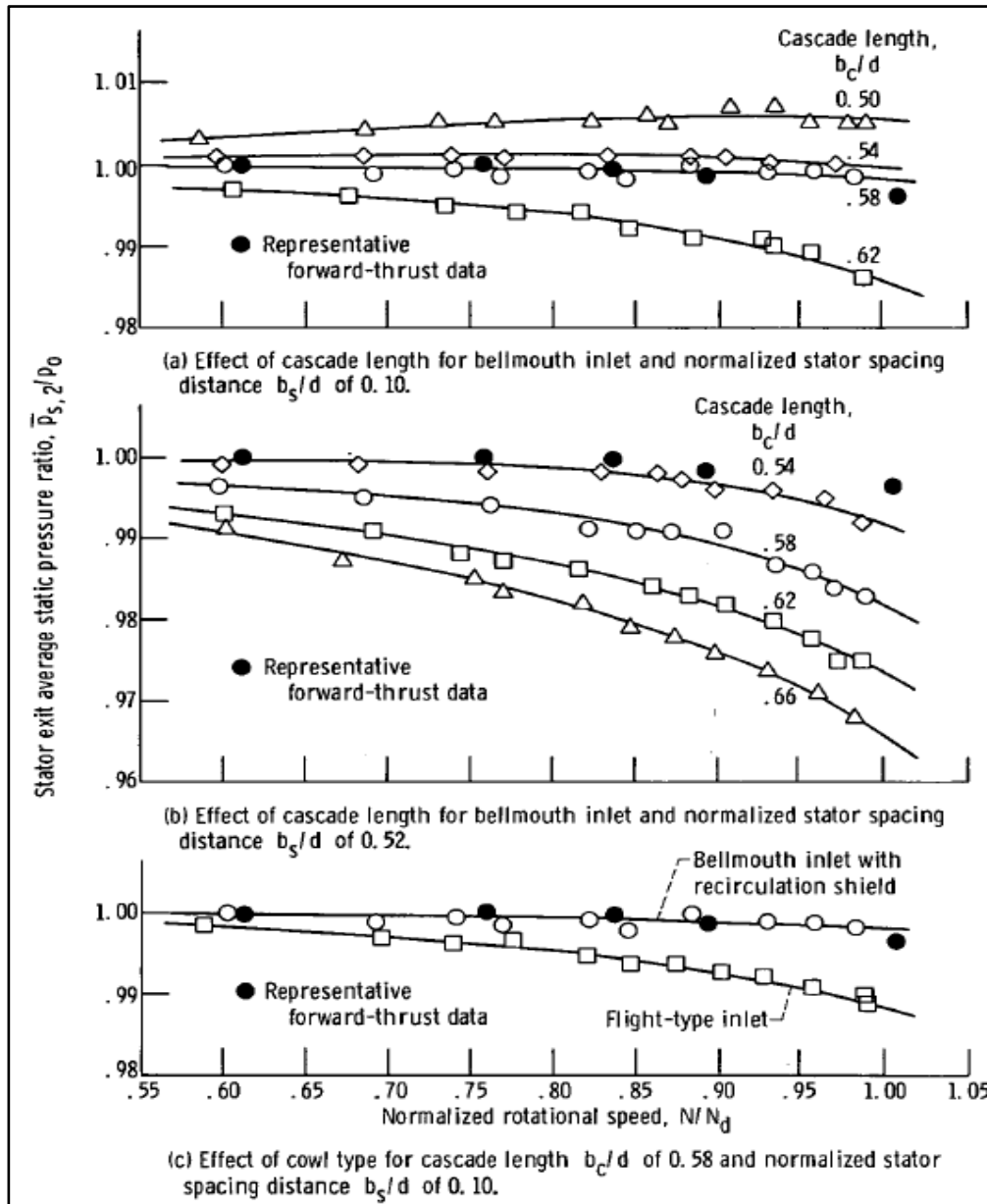


Figure 3.57: Average stator exit static pressure ratio variation as function of normalised rotational speed. Image adopted from [Ref. 41].

The total pressure ratio remains essentially unchanged as the cascade length is changed, as shown in (Figure 3.58). A comparison of the data shows a small increase in total pressure ratio when normalized spacing distance is increased from 0.10 to 0.52. The effect on the flight type inlet (Figure 3.58c) is to significantly reduce the total pressure ratio compared to the bellmouth inlet. The reduction in total pressure ratio is attributed to a reduction in the inlet pressure recovery associated with the smaller lip radius of the flight type inlet and possible also to a small amount of exhaust jet re-circulation.

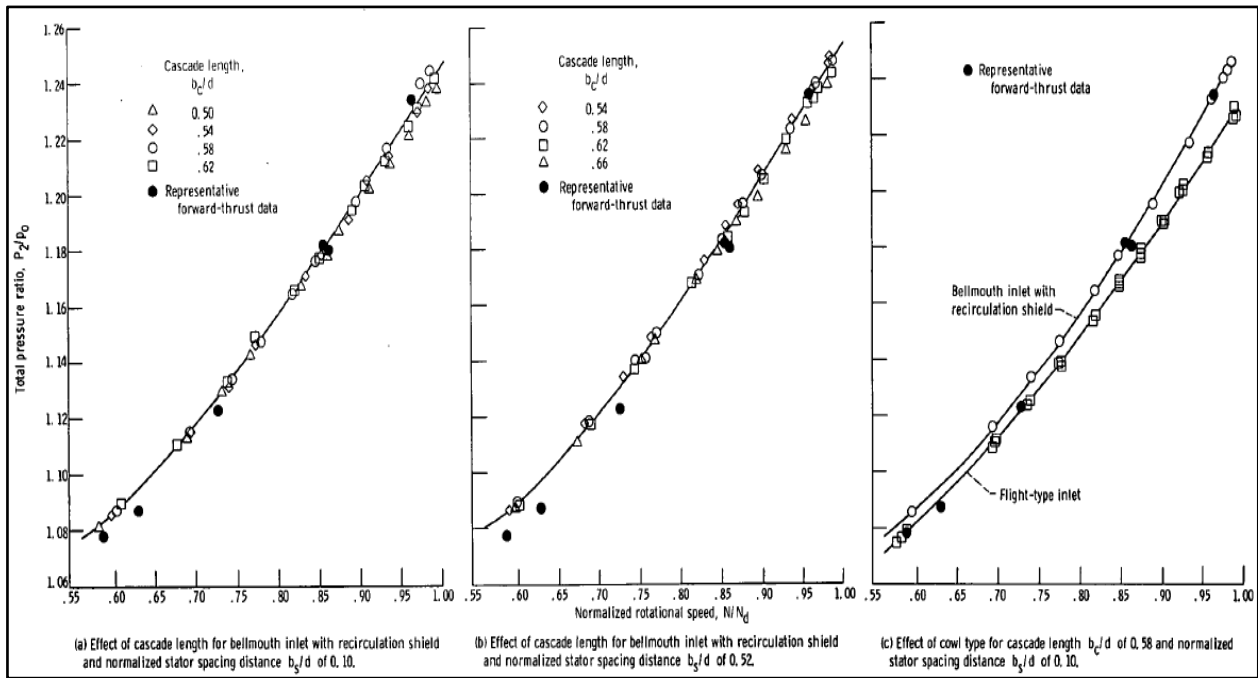


Figure 3.58: Total pressure ratio variation as a function of normalized rotation speed. Image adopted from [Ref. 41]

Contrary to the effect of the total pressure ratio, there is a significant increase in fan mass flow as either the cascade length or the normalized spacing distance is increased. This result is expected since, for these same changes in the cascade length or spacing distance, the stator exit static pressure (fan back pressure) is decreased. Similar, to the case of total pressure ratio, the effect of the flight type inlet is to reduce the fan mass flow compared to the bellmouth inlet (Figure 3.59).

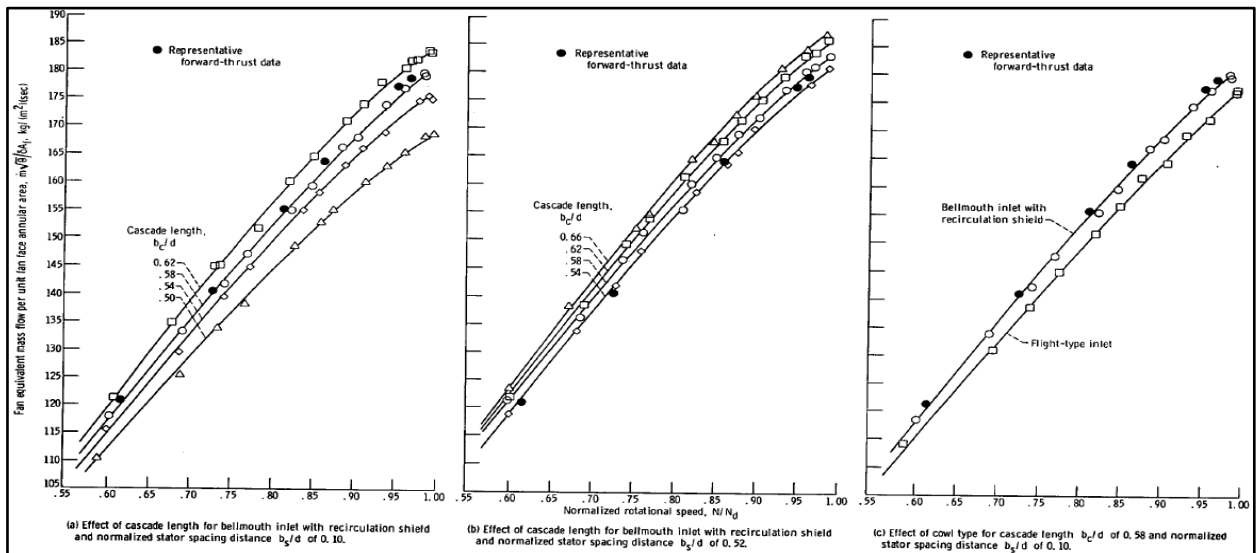


Figure 3.59: Fan mass flow variation as a function of normalized rotational speed. Image adopted from [Ref. 41].

Shown in (Figure 3.60) is the variation of the total pressure ratio P_2/P_0 with fan equivalent mass flow per unit fan face annular area for all the extended spacing ($b_s/d=0.52$) configurations. It is evident that a decrease in cascade length (exit area) drives the fan in the direction of stall. In

summary, the overall fan plus inlet performance characteristics have shown that the cascade acts as a throttle to the fan and there is a need to relate the forward thrust data to the reverse thrust data to establish the proper operating point. In general, a reverser cascade length can be selected in conjunction with a reverser spacing distance which will yield the same fan back pressure, total pressure ratio, and fan mass flow as the forward thrust case [22]. Also, Compressor surge could occur if b_c/d is too small.

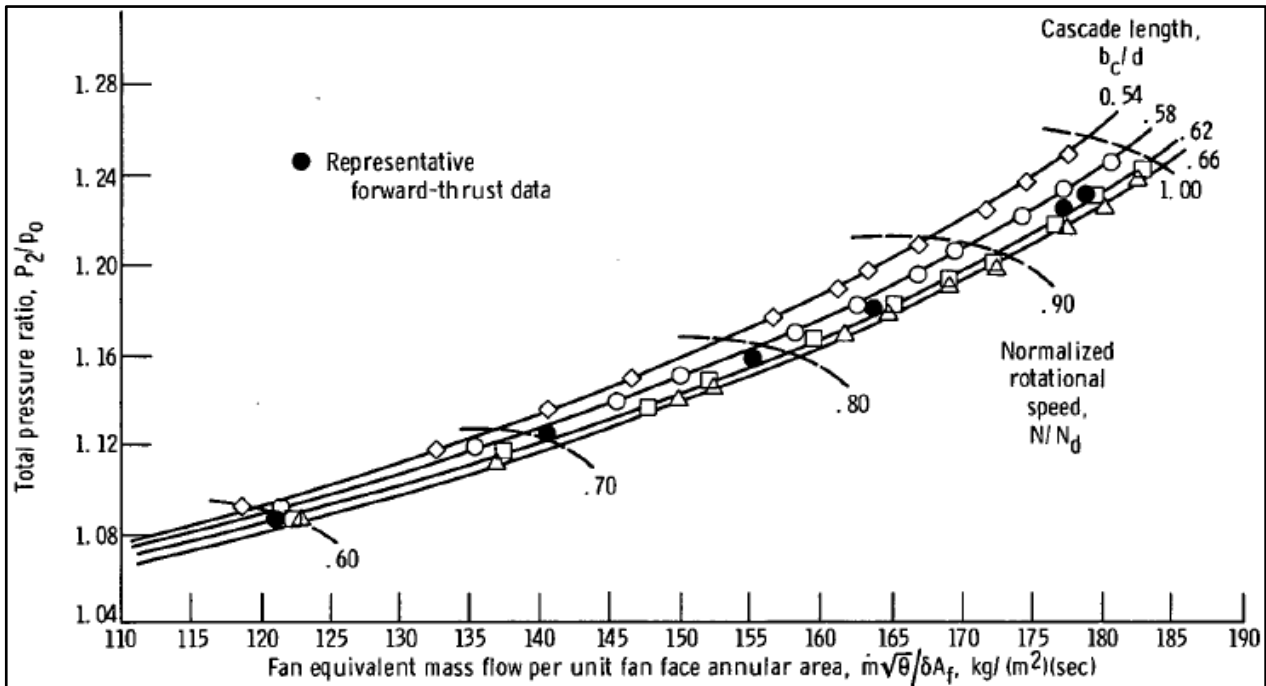


Figure 3.60: Fan performance map for bellmouth inlet with recirculation shield and normalized stator spacing distance b_s/d of 0.52. Image adopted from [Ref. 41].

As shown previously, the cascade exit area affects primarily the fan stage back pressure and mass flow with little effect on the fan total pressure ratio. Therefore, the stator exit static pressure ratio may be used in determining the matching conditions of the forward and reverse thrust operating points. As shown in (Figure 3.61), increasing the normalized stator spacing, b_s/d , results in a decrease in the stator exit static pressure and an increase in both the fan mass flow and exhaust momentum flux. Therefore, in order to match the forward and reverser thrust operating points, the close spacing ($b_s/d=0.10$) configuration requires a significant longer cascade length than the extended spacing ($b_s/d=0.52$) configuration. However, the total aft length must be considered in the comparison of the various configurations. The close spacing does require a longer cascade length ($b_c/d=0.58$), but has a total aft cowl length ratio ($b_s + b_c)/d$ of 0.68. The extended spacing configuration can have a shorter cascade length ($b_c/d=0.54$), but the total cowl length ratio becomes 1.06. Consideration of the total aft cowl length is important since added length due to the reverser would lead to an increase in weight.

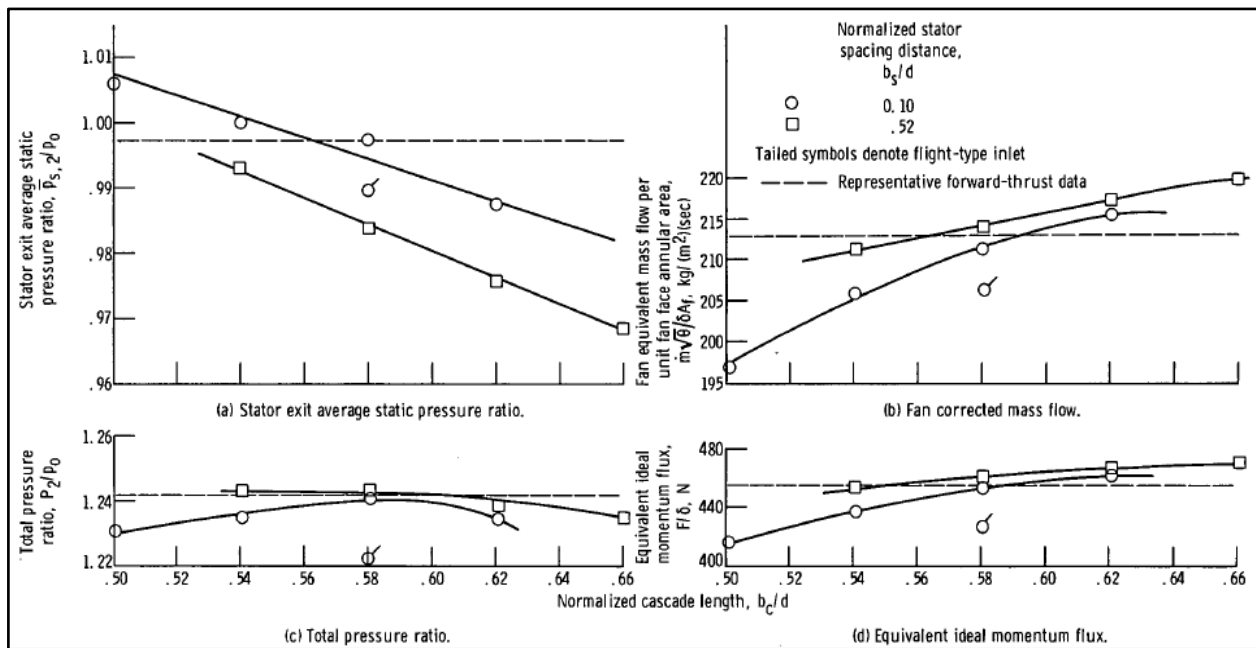


Figure 3.61: Variation of fan characteristics as a function of normalized cascade length for normalized rotational speed $N/N_d=0.98$. Image adopted from [Ref. 41].

Figure 3.62, presents the stator exit distortion parameters as a function of the normalized cascade length b_c/d for all the configurations at a constant normalized rotational speed of $N/N_d=0.98$. As shown in (Figure 3.62), the close spacing configurations produce high values of all internal flow distortion parameters. An increase in the internal flow distortion may increase the reverser related noise. The extended spacing configurations tend to reduce the distortion parameters and may reduce the noise due to both reduced cascade length and reduced fan flow distortion. Thus, a compromise between distortion, noise, and weight is required [Ref. 41].

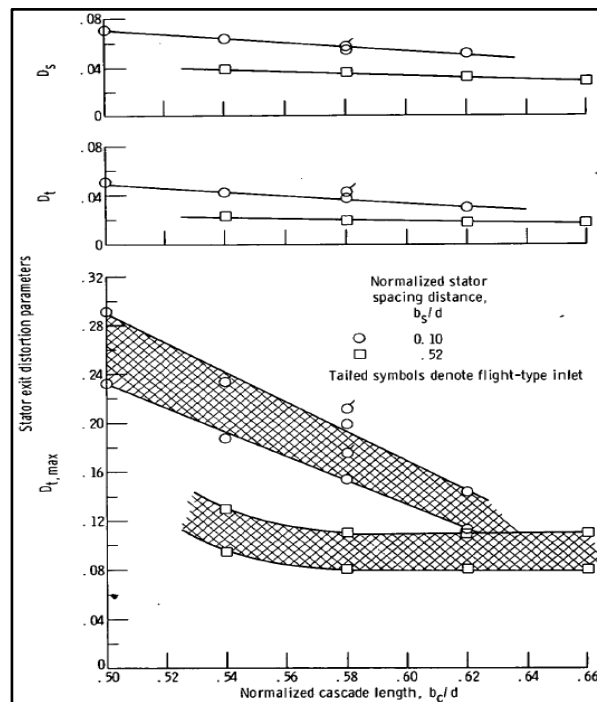


Figure 3.62: Variation of stator exit distortion parameters as a function of normalised cascade length for normalized rotational speed N/N_d of 0.98. Image adopted from [Ref. 41].

3.20 Thrust Reverser for Cessna Citation Aircraft

Cessna Citation is a very successful business jet aircraft. The Cessna aircraft make use of a Williams FJ44 two spool turbofan engine, which has a BPR $\approx$ 3.28 and was manufactured by Williams International/Rolls-Royce. Two reverser concepts were initially considered for application to the Cessna Citation. One was a post exit target type and the other was a fan cascade reverser used in conjunction with a primary exhaust spoiler. Trade studies showed a cost, weight and reliability advantage in selecting the target reverser. Production scheduled dictated that the final thrust reverser design be established in the first four months of the program. In order to meet this schedule a series of development test were initiated to investigate, reverser performance, reverser/engine compatibility, reverser/aircraft compatibility and to calibrate the exhaust system in the forward thrust mode [Ref. 42].

A series of taxi tests were conducted with the Cessna prototype aircraft with a fixed deployed target thrust reverser installed on the left hand engine. The purpose of these tests were to determine the reverse thrust exhaust flow path, establish the target door configuration that would minimize foreign object ingestion during reverser operation and establish a minimum cut-off speed to prevent exhaust gas re-ingestion. The 18 target type reverser configurations which were tested are shown in (Figure 3.63) [Ref. 42].

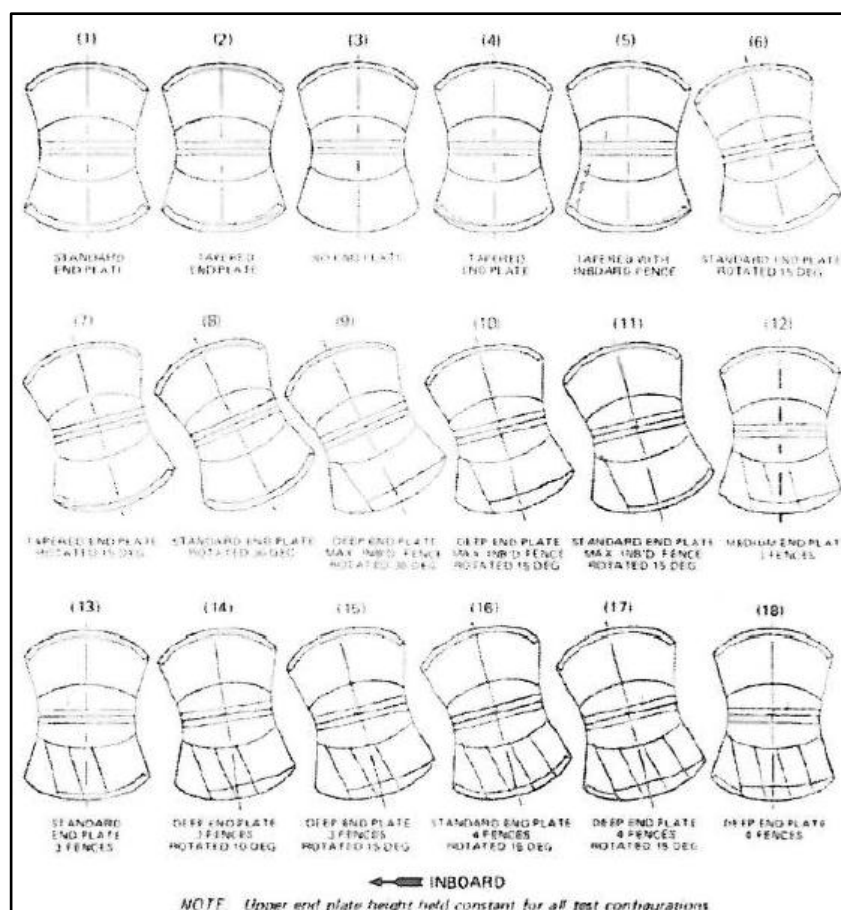


Figure 3.63: Design configuration summary of thrust reverser development tests. Image adopted from [Ref. 42].

The first series of tests, configuration 1 through 5, established the requirement for directing the plume outboard by the addition of an inboard aerodynamic fence. The next series of tests,

configuration 6 through 8, investigated the effect of clocking or rotating to skew the lower plume outboard and resulted in minimal gains in reducing the cut off speed. During subsequent reviews of the test data, it was decided to redesign the lower door to more effectively direct the plume outboard by additional aerodynamic fences and deeper end plates. The final series of tests were used to develop a configuration that would provide the lowest normalized cut off speed with the greatest reduction in landing distance. Configuration 18 was selected for final design. It has a modified lower door contour with four aerodynamic fences and a notched end plate for vortex generation. The doors were vertically orientated to simplify installation and avoid impingement of the upper plume on the rudder [Ref. 42].

Ground static tests were performed at Rohr Industries Brown Field Test Facility with a production thrust reverser model installed on a JT15G-1 turbofan engine. The purpose of the ground static tests was to demonstrate structural and mechanical soundness, engine compatibility and compliance with FAR Parts 33.97 and 25.933. The certification test consisted of 200 reverse thrust cycles simulated 175 normal landings and 25 aborted take-offs. Structural problems encountered during preliminary testing had been anticipated. The inner skins on both the upper and lower doors ruptured after 35 full power cycles. Analysis indicated that the failure was caused by the sonic fatigue. Corrective action was taken by increasing the material thickness of the inner skins. Every component in the thrust reverser system assembly completed 200 full power cycles without failure and many completed over 300 cycles without failure.

Slush spray tests were also conducted. The purpose of these tests was to determine that the aircraft can operate at maximum reverser thrust settings at speed ranging from landing speed down to the minimum cut-off speed of 55 knots through three quarters of an inch of water and/or slush, without causing the engine to flame out or otherwise inhibit its operation. A review of high speed movies taken during the tests show that the gases discharged from the thrust reverser deflect very little water forward of the wing leading edge or over the upper surface of the wing. The films also show that very little of the spray which does go over the wing including water spray from the nose wheel at the critical speed of 70 knots, is ingested into the engine and does not cause any adverse effects on engine performance.

Flight tests for thrust reverser certification to FAR Part 25 were conducted to demonstrate performance, cut-off speeds, actuation times, controllability, ground handling characteristics and inflight deploy and restore capability. These tests were conducted at Wichita Mid-Continent Airport. Ground roll controllability was demonstrated at 110 knots indicated airspeed by simulating the greatest asymmetrical thrust case, one reverser deployed and the other engine in forward thrust, with both engines set at maximum thrust setting. In addition to demonstrating controllability with maximum asymmetric thrust, ground handling was demonstrated satisfactorily with both reversers deployed under cross wind conditions. Landing with a cross wind component of 22 knots with gusts to 27 knots were demonstrated.

The FAA requires that an inadvertent inflight deploy and re-stow on one engine be demonstrated to prove the structural capability, actuation system and controllability of the aircraft with one reverser deployed at idle power. One thrust reverser was deployed in flight at speeds up to 180 knots. In flight re-stow was demonstrated at minimum climb speeds (V_2) of 125 and 150 knots at 15,000 feet. To complete the flight test demonstrations, an approach and landing with one reverser deployed on a shut-down engine was flown to establish that the aircraft could be safely landed under this condition at the selected reference velocity.

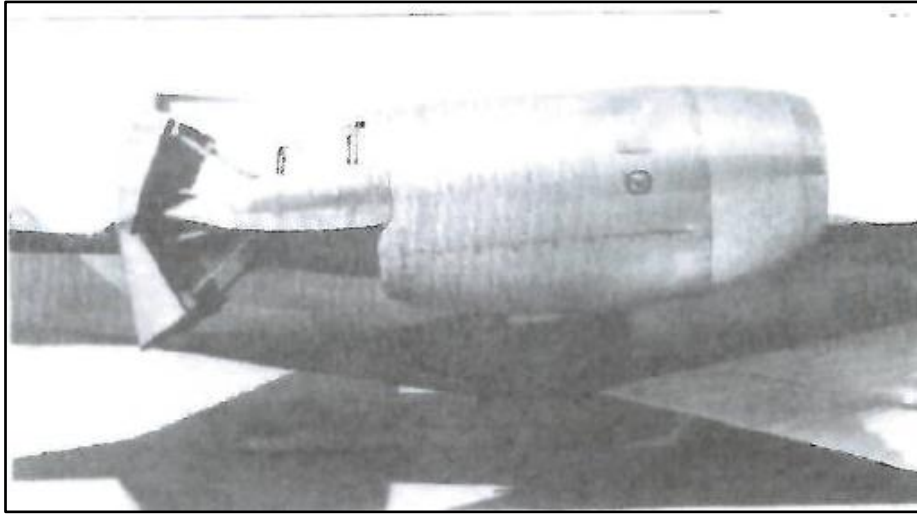


Figure 3.64: Installation of Rohr thrust reverser on Cessna Citation 500. . Image adopted from [Ref. 42]

Thrust reversers for the Cessna Citation 500 (Figure 3.64) were certified by the FAA for both new production and retrofit in January 1976. Results of the model test, taxi tests and ground static test indicated that a landing distance reduction of 43% on an icy runway was accomplished at a minimum cut-off speed of 60 knots.

3.21 Thrust Reversal Using Variable Pitch Fan

Variable pitch fan engines may be attractive for aircraft if sufficient reverse thrust is available for aircraft deceleration after touchdown. Thrust reversal is obtained in these engines by changing fan blade pitch about 90 degrees, which causes the fan airflow to enter the fan duct nozzle and exhaust through the fan inlet. This capability will eliminate the heavy and costly thrust reverser systems required for current fixed pitch turbofan engines. The NASA Lewis Research Centre has supported the development of advanced technology for a quiet, clean, high bypass ratio turbofan engine for future short haul aircraft. A major portion of this effort is the Quiet, Clean, Short Haul Experimental Engine (QCSEE) Program [Ref. 43].

The potential advantage of using a variable pitch fan is the elimination of the conventional heavy, high-maintenance target or cascade thrust reversal hardware plus the added benefit of improved thrust response time. One of the potential problems in operation of variable pitch fans is difficulty in establishing reverse thrust at certain reverse blade angles. This problem is aggravated when reversing with forward velocity. Experimental propulsion system (Figure 3.65) was designed to provide 81.4 kN (18,300 lb.) of uninstalled thrust and 77.4kN (17,400 lb.) of installed forward thrust at take-off on a 305.6 °K (90°F) day. Reverse thrust goal was set as 35% of forward take-off thrust. Specific engine features include: a composite structure high Mach (accelerating) inlet; a gear driven variable pitch fan with composite fan blades; a composite fan frame; an acoustically treated fan duct with an acoustic splitter ring; a variable geometry fan exhaust nozzle, an advanced (F101) core engine and low pressure turbine; an acoustically treated core exhaust nozzle, top mounted engine accessories and a digital electronic control system combined with hydro-mechanical fuel control. The engine has a bypass ratio of 11.8 and a fan pressure ratio at take-off of 1.27. A primary requirement of the control system was the capability of achieving a thrust response of 1.0 sec for approach to take-off thrust and 1.5 seconds for approach to reverse thrust [Ref. 44].

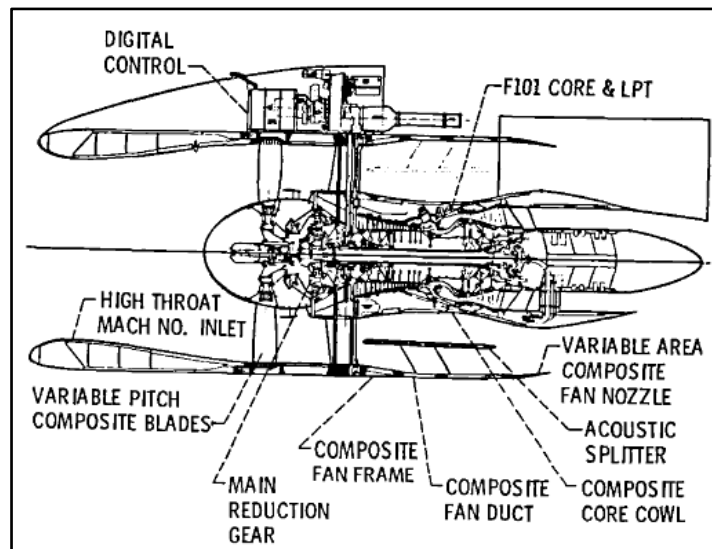


Figure 3.65: Engine cross-section. Image adopted from [Ref. 43].

The variable pitch turbofan engine was tested for reverser performance at a NASA Lewis outdoor engine test stand. Detailed instrumentation, data reduction, and test procedures were incorporated to define steady state reverse thrust performance and forward to reverse thrust transient characteristics. The engine test stand was designed specifically for test of the QCSEE engines. The stand was designed to enable measurement of forward, reverse and side loads (Figure 3.66) [Ref. 44].

A schematic of the reverse thrust configuration along with engine station designations is shown in (Figure 3.67). In the reverse thrust mode, flow enters the engine at the fan nozzle, passes through aft fan duct and fan bypass outlet guide vanes and then separates into two streams; one stream passing through the fan rotor and discharging out the engine inlet, and other stream turning 180° and entering the gooseneck to the core compressor [Ref. 44].

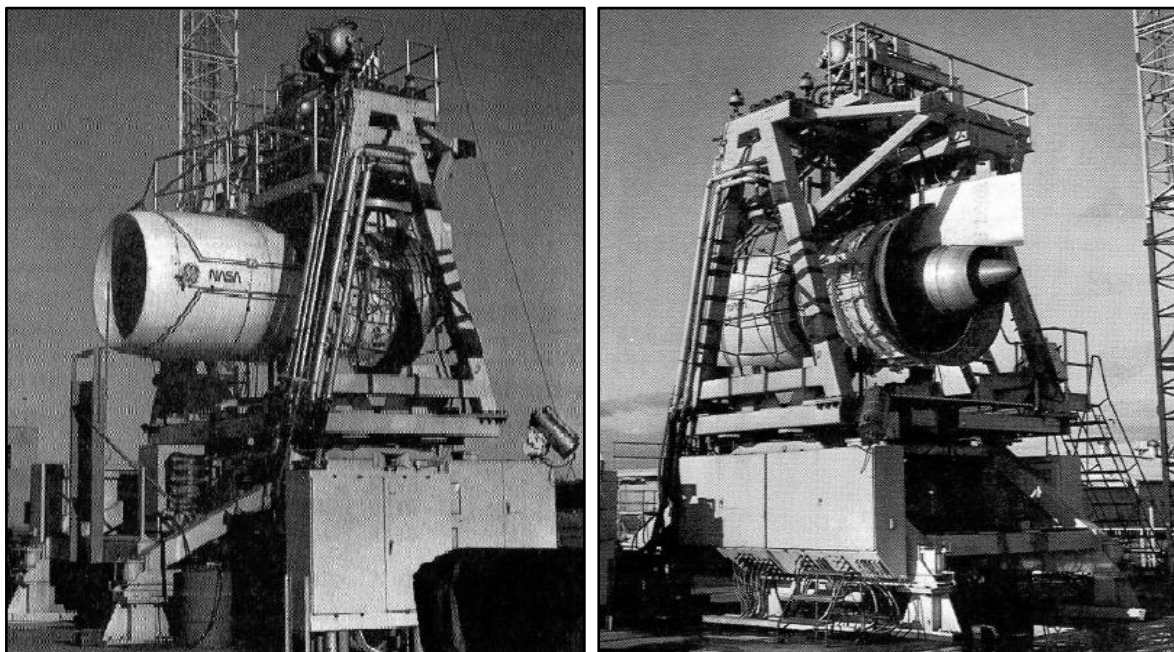


Figure 3.66: Engine test stand. (L) Front view (R) Aft view. Image adopted from [Ref. 44].

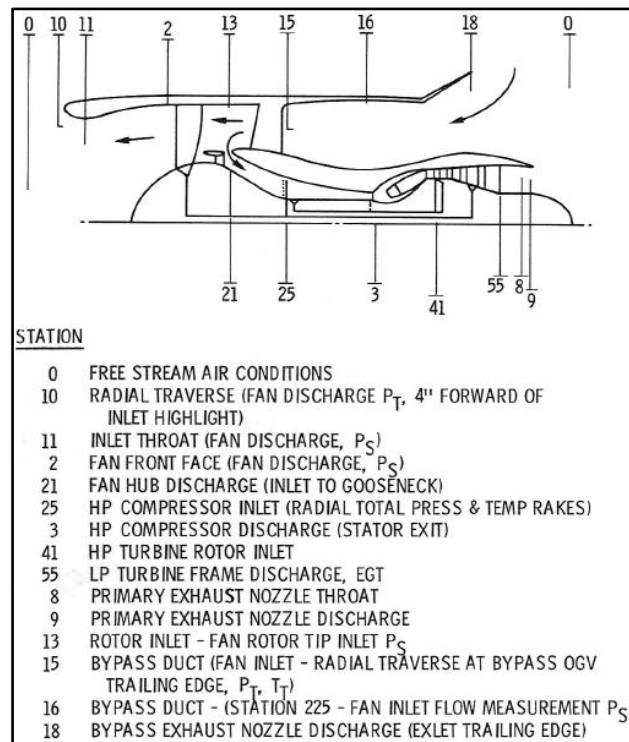


Figure 3.67: Station designation reverse thrust. Image adopted from [Ref. 34].

Although the QCSEE design was capable of fan blade pitch change in either direction, reverse through stall was found to provide improved performance and therefore was used in these tests. In this direction the blades are opened about 100° ($\beta_F = -100^\circ$) from the forward thrust design blades angle ($\beta_F = 0^\circ$) (Figure 3.68) [Ref. 44].

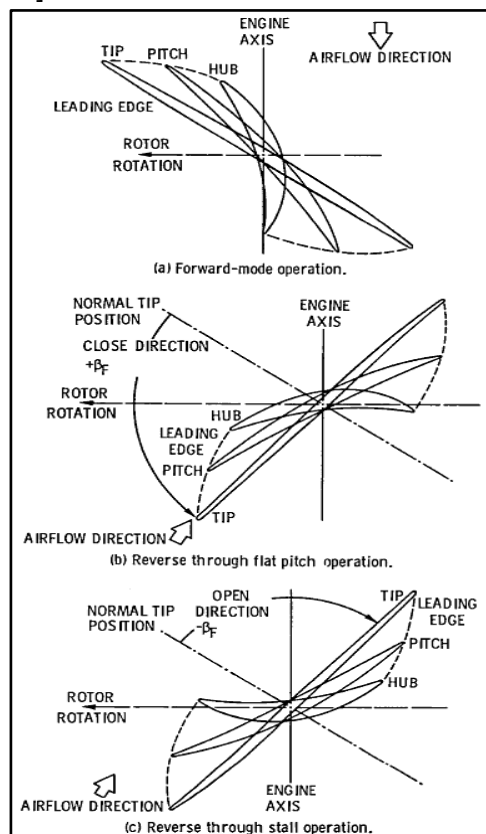


Figure 3.68: Fan rotor blade. Image adopted from [Ref. 44].

All forward to reverse thrust transients included an automatic change in fan nozzle area from a forward thrust setting (convergent nozzle) to an open, approximately 30° half angle flared position to provide an inlet for reverse flow (exlet). Simultaneously, the fan blade pitch was changed on the order of 100° from a forward thrust to reverse thrust setting. The transients were performed from nominal forward idle, approach and take-off power to various levels of reverse thrust. Other variations included final reverse fan blade angle, blade angle overshoot, and fuel scheduling (fuel interlock setting) during transient [Ref. 44].

Steady state reverser testing reported in (Ref. 43) included back to back tests with the fixed 30° exlet and the movable flaps. All forward to reverse transients were made with movable flaps. A schematic of the fixed 30° exlet and a photograph of it on test are shown in (Figure 3.69) [Ref. 44].

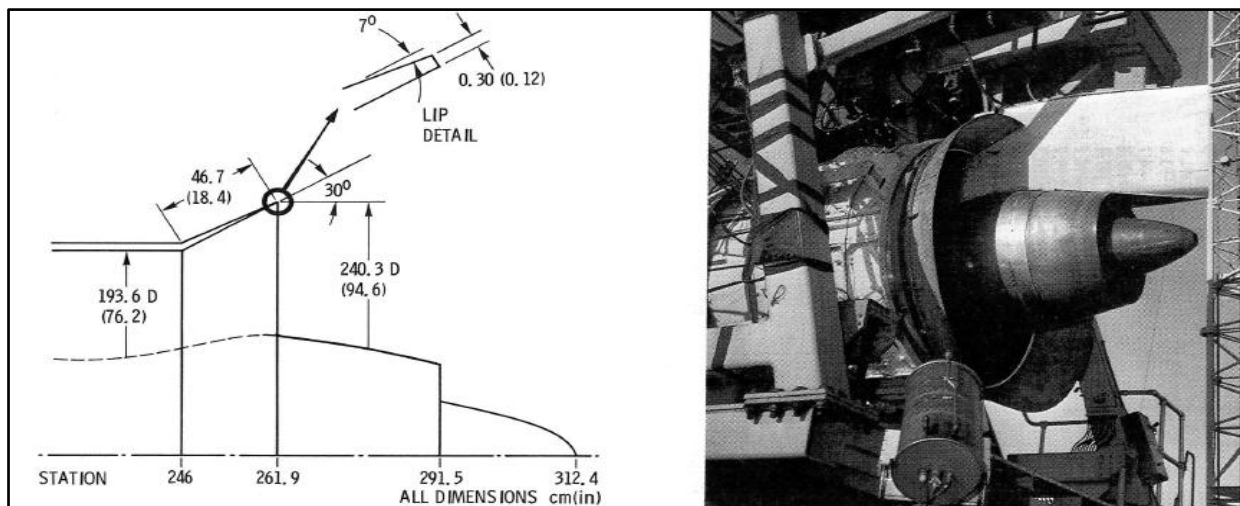


Figure 3.69: (L) Schematic of fixed 30° exlet. (R) Fixed 30° exlet on a test bed. Images adopted from [Ref. 44].

Reverser thrust performance was obtained with the engine at steady state operating conditions. Variation of corrected reverse thrust with fan speed is shown in (Figure 3.70) for both the fixed 30° exlet and movable flap configurations. At fan speed up to 79% of the design thrust peaked at a fan blade angle of -93.6° for the fixed exlet; at higher speeds, and $\beta_F = -93.6^\circ$, turbine temperature limits were reached. As fan blade angle was held constant, reverse thrust increased almost linearly with increasing fan speed and began to level off above 80%. The 27.1kN (6090 lb.) thrust goal was attained with the fixed 30° exlet while slightly exceeding the turbine temperature limit. At a similar condition and with movable flap configuration installed, only about 22.2kN (5000 lb.) reverse thrust was obtained [Ref. 44].

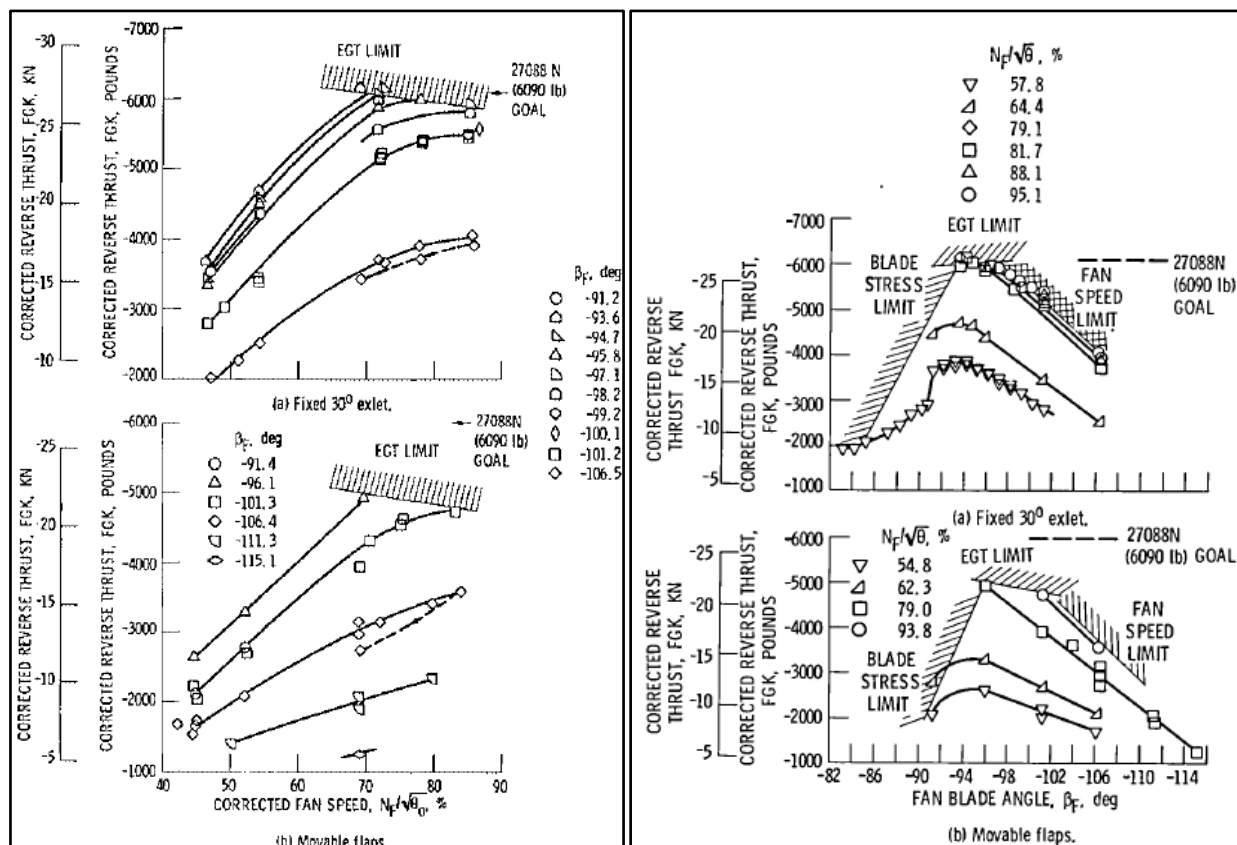


Figure 3.70: (L) Reverse thrust fan speed characteristics. (R) Reverse thrust fan blade angle characteristics. Images adopted from [Ref. 44].

Performance comparison at constant fan speed for the two exlet configurations are presented in (Figure 3.70). Only small gains in reverse thrust with increases in fan speed above 81% are evident as seen by the collapsing speed lines. Maximum reverse thrust was limited by the boundaries, namely, blade stress at low fan blade angles, core EGT limits near maximum reverse thrust blade angles, and fan speed limits at higher off-loaded blade angles. At higher fan speeds, the sensitivity was about 890N (200 lb.) of reverse thrust per degree of fan blade angle for both configurations. At 58% fan speed, a fan blade angle hysteresis check was made with the fixed 30° exlet (Figure 3.70). The data indicated less than 1° of hysteresis with blade angle at this speed. At blade angles from -83° to 91° significantly lower but measurable reverse thrust along with high blade stresses indicated the blades were in a partially stalled mode [Ref. 44].

During these tests consistently higher reverse thrust was obtained with a fixed 30° exlet in comparison to the movable flaps at all fan speeds and fan blade angle. In addition, lower blade stresses, lower engine vibrations, and more stable reverse flow were observed. The reverse thrust objectives can only be achieved with the fixed 30° exlet configuration while slightly increasing the turbine temperature limit [Ref. 44].

3.22 Aft-Mounted Twin Engine Aircraft Thrust Reverser

Thrust reverser flow investigation on a twin engine transport aircraft is discussed in [Ref. 45]. The technical paper deals in great detail particularly with regards to the wind tunnel tests carried out for different thrust reverser designs on an aft mounted engine. An investigation was conducted in the

Langley 14 by 22 foot subsonic tunnel to study the effects of engine thrust reversing on an aft mounted twin engine transport and to develop effective testing techniques. Testing was done over a fixed and moving belt ground plane. Free stream dynamic pressure was set at a value of 12.2 psf, which correspond to a maximum Reynolds number based on mean aerodynamic chord of 7.65×10^5 . The thrust reversers examined include cascade, target, and four door configurations. The investigation focused on the range of free stream velocities and engine thrust reverser flow rates that would be typical for landing ground roll conditions. Flow visualization techniques were investigated, and the use of water or smoke injected into the reverser flow proved effective for determining the forward progression of the reverser flow and reingestion limits [Ref. 45].

When investigating a thrust reverser in ground effect in a wind tunnel, the accuracy of engine simulation is particularly important. The forward progression of the reversed flow and any exhaust flow ingested into the inlet will depend heavily on both the reverser and inlet flow simulators. Simultaneously, matching engine inlet and exhaust mass flows and exhaust pressure ratio with model engine simulators is usually very difficult on powered wind tunnel models. The effects of flaps and spoilers were investigated for landing conditions at deflection angles of 40° and 60° , respectively [Ref. 45].

The configuration used in this investigation was a 9 percent scale model of a McDonnell Douglas MD-89 twin engine jet transport. A photograph of the entire test setup is presented in (Figure 3.71). The engine simulation system is approximately 10.5ft long and contains separately driven inlet and reverser systems. Primary emphasis during this investigation was placed on obtaining data with the model at a height and attitude representing roll-out on the runway following aircraft touchdown. To simulate these conditions, angle of attack was held constant at -1° and sideslip was fixed at 0° . All data in ground effect were obtained with the tunnel boundary layer removal system in operation [Ref. 45].

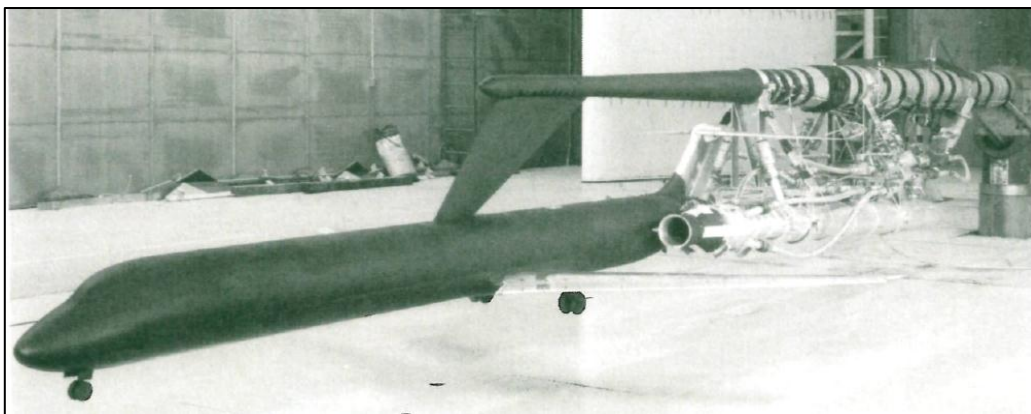


Figure 3. 71: Photograph of the McDonnell Douglas MD-89 jet transport model with engine simulators as mounted in test section of Langley 14 by 22 foot subsonic tunnel. Images adopted from [Ref. 45].

A cascade reverser consisted of three reverser sections and three wood filler blocks as shown in (Figure 3.72), a target reverser consisted of two reverser sections and two wood filler blocks as shown in (Figure 3.73), and a four door reverser consists of four reverser sections (Figure 3.74) [Ref. 45].

The cascade reverser has been tailored to reduce exhaust gas interactions with fuselage, wing, and tail surfaces. The upper and lower outboard reverser sections deflect reversed flow 45° ,

whereas the lower inboard reverser section performs more like a spoiler with 75° deflection angle. These angles are based on 0° deflection being for reversed flow that directly opposes the free stream [Ref. 45].

The target reverser has two reverser sections that are 180° apart. This reverser was tested in vertical orientation and was then rotated 15° and 22.5° (with the lower reverser section being moved outboard) in an attempt to minimize exhaust gas re-ingestion [Ref. 45].

The four door reverser system consisted of four separate reverser sections. The configuration tested contains two sections that have a folding door with side fences, one section that has a folding door with 30° turning vanes and one section that has a non-folding door. The folding doors are set at 30° angle as shown in (Figure 3.74) and deflect the exhaust flow forward, whereas the non-folding door allows the exhaust flow to progress outward perpendicular to the free stream flow. Each reverser section is one quarter of an annulus; therefore, the four door plenums can be configured in several different ways. Three configurations of this four door reverser system were studied in this investigation and their orientations are shown in (Figure 3.74) [Ref. 45].

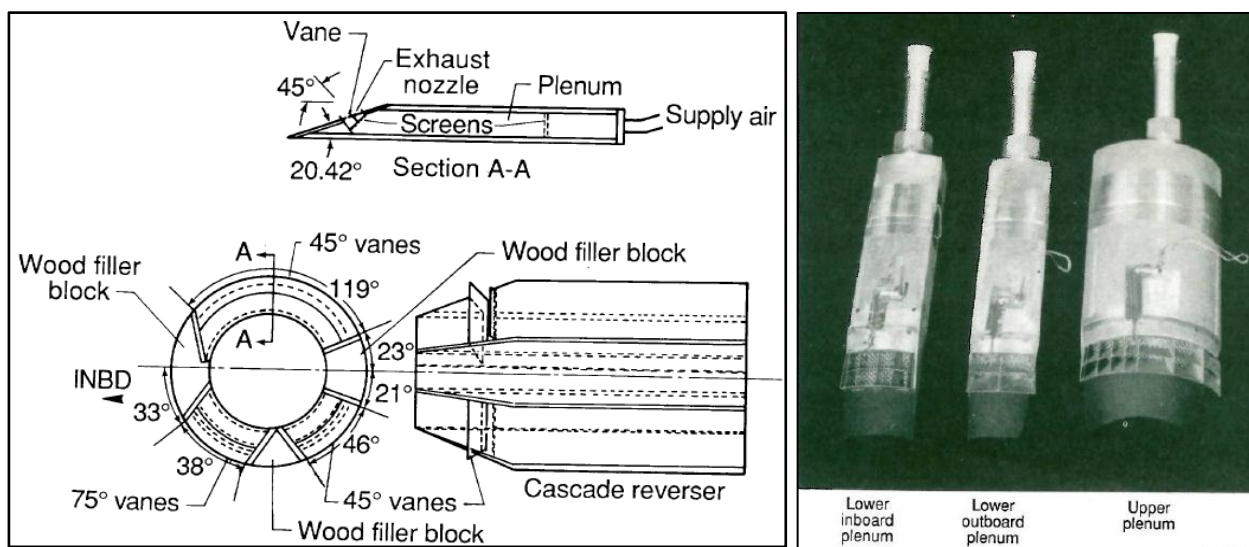


Figure 3.72: Cascade thrust reverser plenums. Images adopted from [Ref. 45].

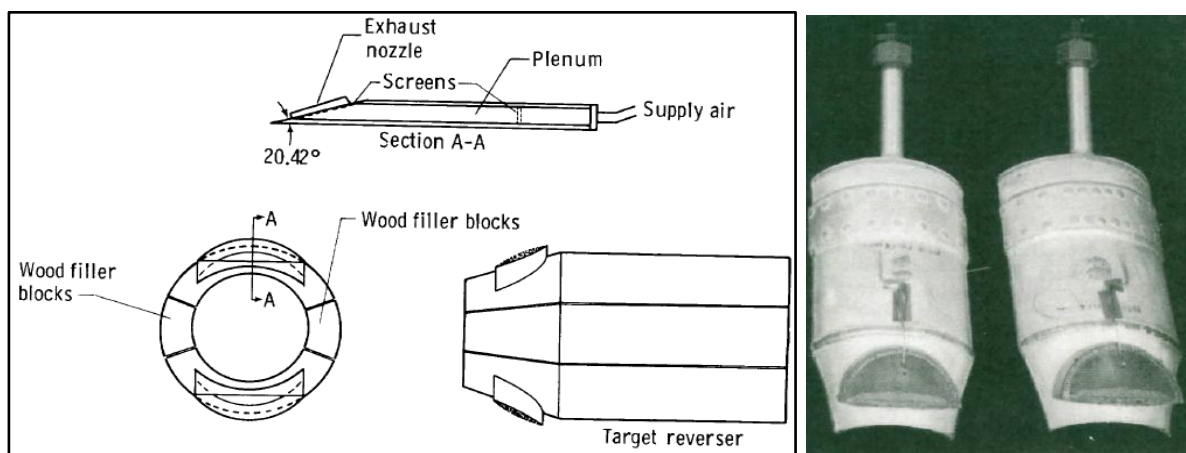


Figure 3.73: (L) Sketches of thrust reverser simulators. (R) Target thrust reverser plenums Images adopted from [Ref. 45].

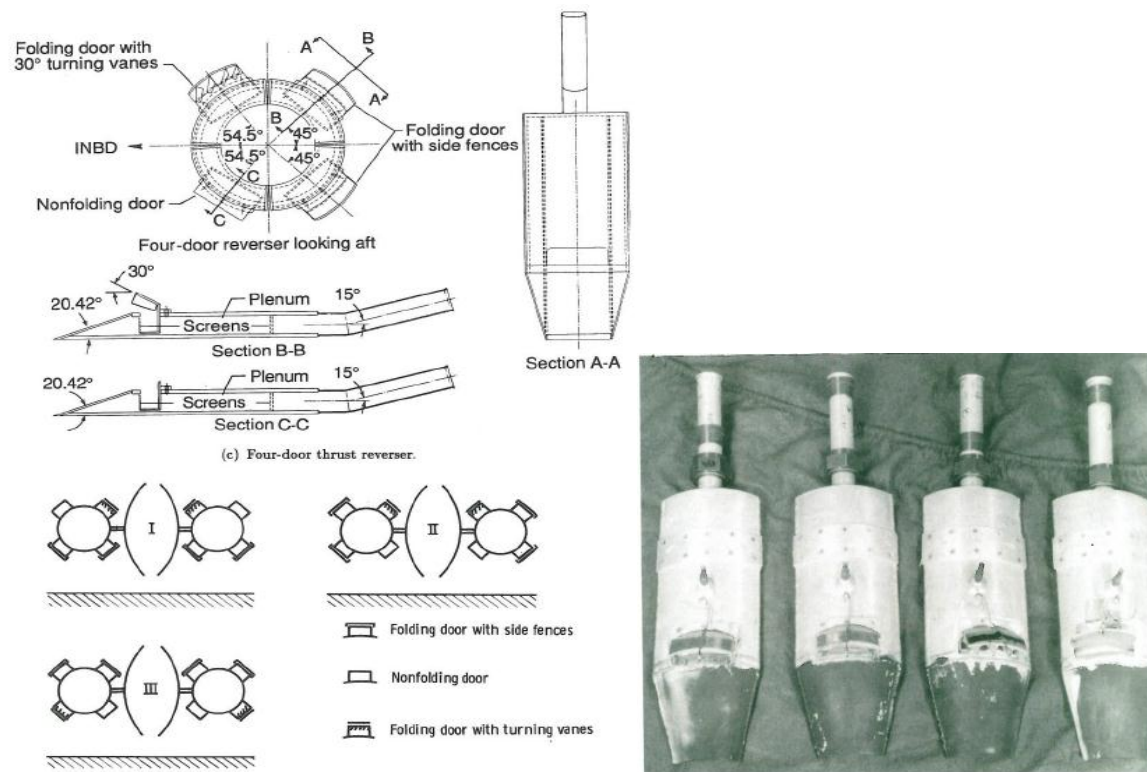


Figure 3.74: (L) Three configurations of the four door thrust reverser design. (R) Four door thrust reverser plenums. Images adopted from [Ref. 45].

The wind tunnel investigation was divided into three major phases. The first phase consisted of investigating flow visualization techniques over a fixed ground plane as shown in (Figure 3.71) above. In the second phase, the effects of a moving belt ground plane were investigated. The moving belt surface was 14ft wide and 20ft long, and the model was centred over it as shown by the tunnel test section configuration presented in (Figure 3.75). The third phase consisted of obtaining pressure measurements in the ground plane of the reverser flow field to determine the reversed flow ground impingement point, the extent of the forward progression of the reversed flow, and its velocity on the tunnel floor. This testing was conducted over a pressure instrumented ground board as shown in (Figure 3.76). Only the left hand side of the ground board was instrumented. All pressure orifices had an inner diameter of 0.04in.

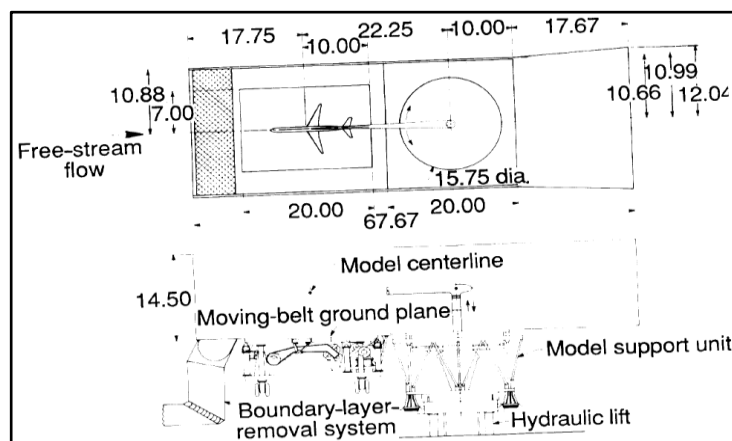


Figure 3.75: Test section configuration when investigated effects of moving belt ground plane. All dimensions are in feet. Image adopted from [Ref. 45].

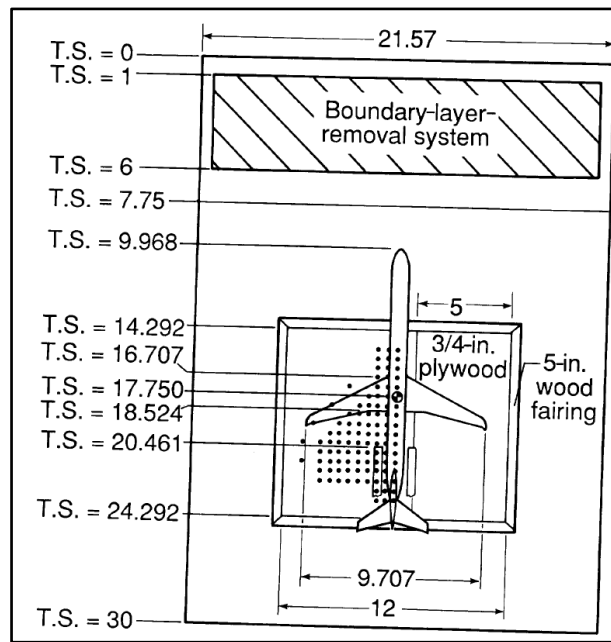


Figure 3.76: Sketch of pressure instrumented ground board showing location of pressure orifices. Image adopted from [Ref. 45].

When testing over a fixed ground plane, the reverser exhaust plumes were made visible by injecting water into the reversed flow (Figure 3.77). All configurations and reverser flow rates were tested with a standard 60 psi water supply system.

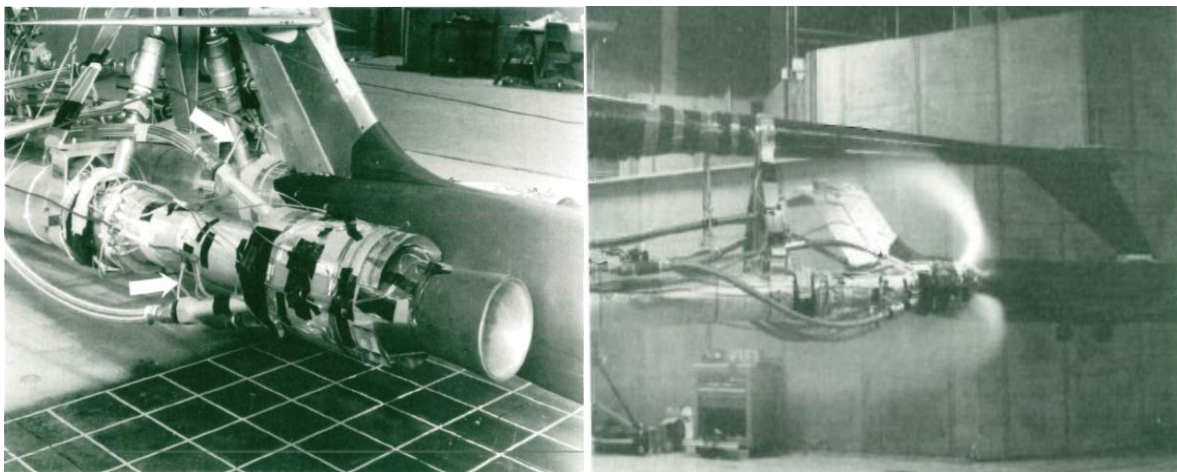


Figure 3.77: (L) Showing water supply lines for cascade thrust reverser. (R) Water injection flow visualization for cascade thrust reverser. Images adopted from [Ref. 45].

For the cascade reverser configurations it was found that the reversed flow was making contact with the vertical tail at all free stream speeds. Thus, the cascade reverser design may not be suitable for this aircraft configuration.

Target thrust reversers were investigated for 15° and 22.5° configurations. When the lower target exhaust jet is angled outboard 15° it was found that this design would minimize both the reverser flow interactions with airframe and reingestion from the lower exhaust plume. However, the upper target exhaust jet is angled inboard 15° , and this can be seen to promote interactions with the tail surfaces. For the 22.5° rotated target thrust reverser, the maximum amount of usable reverse

thrust without reingestion would be obtained by throttling back the engines as the aircraft slows to keep the reversed flow out of the inlet plane. However, in all cases, the flow from the upper reverser appears to interact with the tail surfaces. Thus, target reverser may not be a suitable reverser design.

All three configurations for the four door reverser were tested. The flow results for (configuration 1) reveals that the upper inboard reversed flow was grazing the side of the fuselage and as the flow velocity of the free stream reduces, this direct contact of the reversed flow with the fuselage becomes even greater. Flow visualization for (configuration 2) shows that for high reverser mass flow the reversed flow comes in contact with the wing. These conditions illustrate the potential for both re-ingestion problems and foreign object damage. However, when the reverser massflow is reduced, the reingestion does not appear to be present. Results for (configuration 3) reveals that the reversed flow disrupts the normal free stream flow over the wing and conditions suitable for reingestion and foreign object damage are present. However, as the mass flow for the reverser decreases there would be no danger of reingestion. One problem noted on (configuration 3) of the four door thrust reverser was that the upper inboard plenum with a folding door and side fences directs the reversed flow into the fuselage, this would be unacceptable. However, it may be acceptable with 30° turning vanes. When all three of the four door reverser configurations are compared, (configuration 2) has the least disruptive reverse flow pattern.

3.23 Introduction and Development of a Pivoting Door Type Reverser

Hurel-Dubois patented a new concept of thrust reverser in 1981 known as 'the forward reverser'. The concept of pivoting-door reverser was proposed by Hurel-Dubois in 1981, to the aircraft and engine manufacturers. It gives numerous advantages over the conventional cascade reverser, and in particular the reverser weight is inherently lighter. The extensive use of advanced materials has allowed a highly competitive weight to be achieved along with other qualities such as the simplicity, efficiency and ease of maintainability. The pivoting doors were first selected to equip the Airbus A320/CFM56-5A1 in 1984, then the Airbus A340/CFM56-5C2 in 1988. In 1988, Rolls-Royce launched a TRENT program for the Airbus A330. The development of this kind of very large engine, demanding improvements concerning weight and efficiency, led Airbus and GE/Snecma to choose Hurel-Dubois pivoting door reverser [Ref. 46].

In the pivoting door system the fan flow is reversed by means of large doors which rotate about fixed pivots. These doors when stowed provide a major part of both the outer nacelle surface and the fan duct outer wall. When deployed they rotate such that:

1. The aft section blocks the fan flow to the discharge nozzle.
2. An alternative discharge orifice is created.
3. The forward section turns the fan flow to provide a forward thrust component.

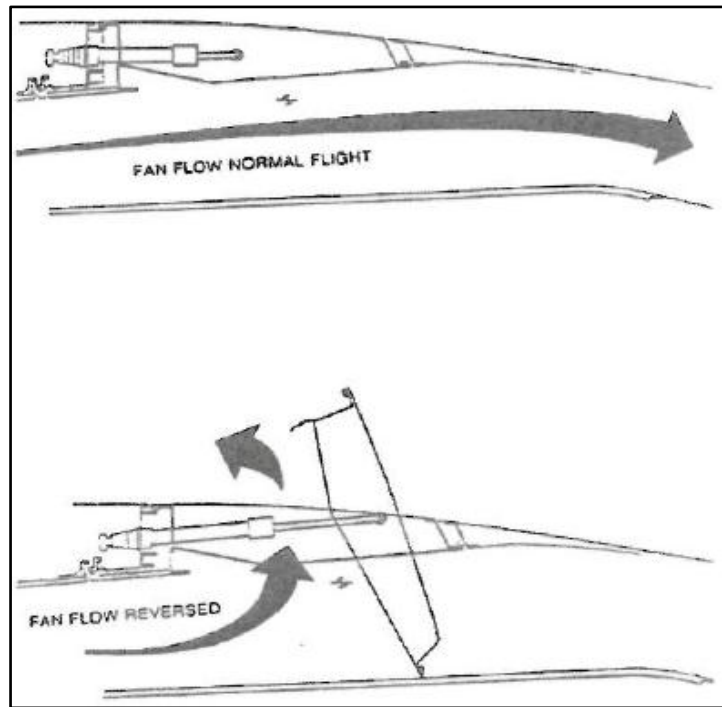


Figure 3.78: Pivoting door reverser deflection of fan duct flow. Images adopted from [Ref. 46].

The inner faces of the doors on the A320 have metallic punched sheet and a carbon epoxy perforated skin on the A340. The A340 reverser doors are totally composite. The reverser for the A330/Trent 700 is part of the nacelle with long after body and mixed flow. It is of D-duct type as show in (Figure 3.79), the diameter of the reverser is about 3m and the length is around 2.5m.

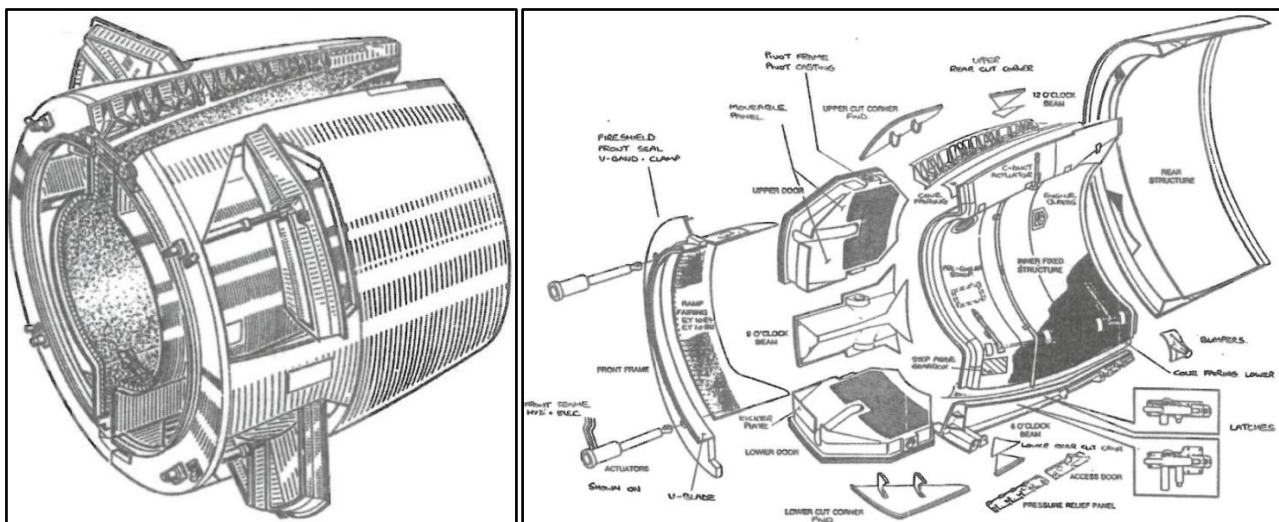


Figure 3.79: (L) Pivoting door thrust reverser for the Trent engine. (R) Blow up of the reverser. Images adopted from [Ref. 46].

Figure 3.80, shows the door structure. All the elements defined are generally of a box type construction comprising panels enclosing side wall and stiffener sub-structure. Except for the attachment/mounting points for such items as door pivots, actuators, latches, etc. all parts are of composite construction. Outer and inner skins are of honeycomb construction and other parts are

monolithic. The inner panels of the fan duct are acoustically perforated. The inner fixed structure is of a one piece composite sandwich construction and forms one half of the inner fan duct wall, from the 12'o clock beam, around the engine core to 6'o clock beam. The inner structure is acoustically treated, and is protected from the engine core harsh environment by a thermal blanket [Ref. 46].

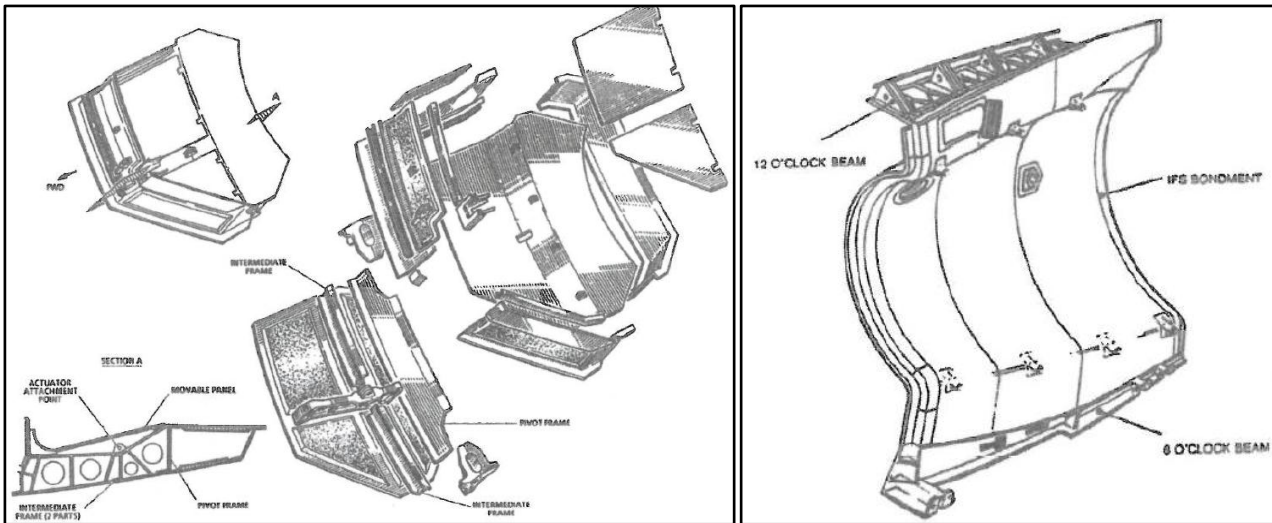


Figure 3.80: (L) Reverser door structure. (R) Inner fixed structure. Images adopted from [Ref. 46].

The main material used for the construction of the elements described previously is T300/914 carbon/epoxy. The limitations of more wide spread usage of composite materials on the A320/CFM56-5A reverser were the difficulty of manufacturing sound attenuation structures with good mechanical and aerodynamic properties and the inability of these composite materials to withstand high temperatures [Ref. 46].

On Rolls Royce Trent 700 (A330) the reverser has to meet noise suppression requirements, the fan duct section includes extensive acoustic structures of increasing complexity. A total effective area of 15m² within the fan duct section of the reverser must carry acoustic treatment. This is achieved by structural honeycomb sandwich panels, perforated on air swept surfaces. The bismaleimide family of resins has been chosen mainly for its ease of manufacturing, and its better conformity with safety regulations in the workshop. The selection was made according to the temperature performances and the existing acquired experiment action with a range of products. The improvement of the temperature allows the use of bismaleimide resin up to 210°C [Ref. 46].

The first application of pivoting door reverses was in the year 1984 on the CFM56-5A (A320) thrust reverse. Pivoting door reversers were installed on many other engines including the TRENT 700 (A330) reverser. Since 1980s composite components have greatly improved. The ratio of composite weight to reverser total weight has increased from 20% to 45%. With the introduction of new advanced composites like bismaleimide carbon and development of advanced acoustic treatment methods, the use of composite components in reverser technology is rapidly increasing [Ref. 46].

3.24 Six Innovative Thrust Reverser Concepts

In response to the challenges from the industry to provide a 'technology injection' to thrust reverser design, the NASA Langley Configuration Aerodynamics Branch conducted a cooperative test program with industry to investigate innovative thrust reverser concepts that offer potential weight savings and/or design simplifications over conventional cascade thrust reverser systems. Industry partners in the test program were Allison, BF Goodrich Aerospace, Boeing, General Electric, Northrop-Grumman, Pratt & Whitney, and Rolls-Royce. Six of the most promising concepts were down selected for testing (Figure 3.81). The concepts tested consisted of a conventional cascade thrust reverser model, cascade reverser with porous fan-duct blocker, a blocker-less thrust reverser, metal target thrust reverser, fabric target thrust reverser, multi-door crocodile thrust reverser, and a wing mounted thrust reverser.

These innovative concepts attempt to simplify thrust reverser design, reduce weight, and/or improve overall propulsion system performance by eliminating some of the mechanisms and nacelle design compromises that cause engine performance losses during cruise operation. Testing was conducted in the Jet Exit Test Facility at NASA Langley Research Centre using a 7.9% scale exhaust system model with fan to core by pass ratio of approximately 9.0. All tests were conducted with no external flow and high pressure air was used to simulate core and fan exhaust flows.

Although thrust reversers are used for only a fraction of airplane operating time, their impact on nacelle design, weight, engine maintenance, airplane cruise performance, and overall operating and maintenance costs is significant. The renewed interest in alternative thrust reverser systems is based on the premise that high thrust reverser effectiveness levels may not be required with high bypass ratio engines to achieve the necessary stopping force. In this regard, there is tremendous incentive to investigate the potential for simpler, lighter weight thrust reverser systems [Ref. 47]. However, no attempt was made to address the practicality of these thrust reverser concepts in regards to mechanical complexity such as actuation linkages and kinematics, structural / thermal considerations and integration with airframe and aircraft/engine systems other than the knowledge that these issues do exist and represent challenges to the successful implementation of these concepts [Ref. 47].

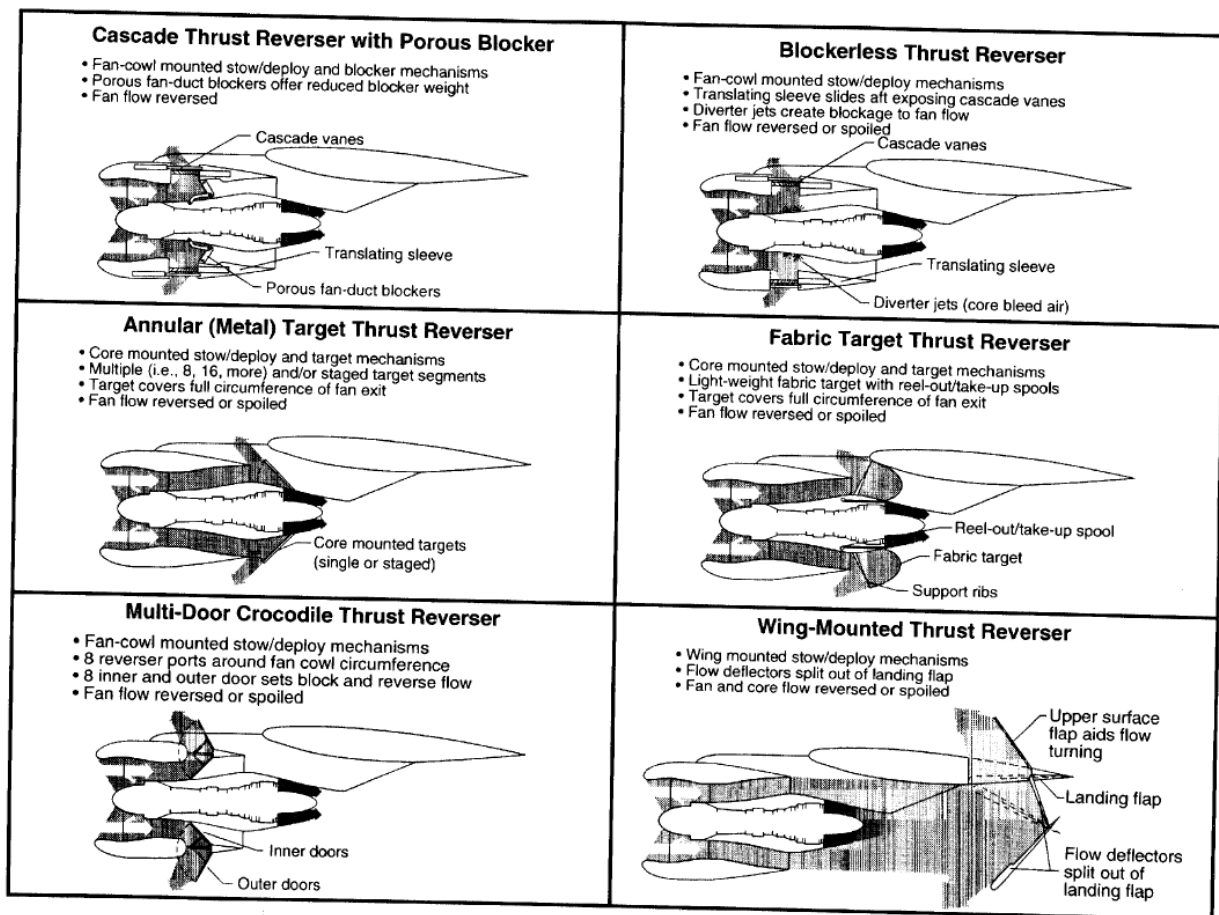


Figure 3.47: Shows the six innovative thrust reverser concepts that were tested by NASA in the Jet-Exit Test Facility at NASA Langley Research Centre. Images adopted from [Ref. 47].

The details of the experimental setup and reverser testing are given below:

3.24.1 Forward thrust – Separate flow exhaust model

Typical setup of the high bypass ratio separate flow exhaust system model installed on the propulsion simulation system is shown in (Figure 3.82). The separate flow exhaust nozzle model was installed on the downstream end of the instrumentation section (MS 33.750) (Figure 3.82). The core and fan nozzle contours (internal and external) were based on preliminary BPR $\approx$ 9.0 exhaust nozzle design provided by General Electric. The core section consists of a core nozzle, core cowl, and exhaust plug. The core cowl was split to permit installation of the fan duct blocker and to facilitate modifications of the core cowl section for testing of core mounted thrust reverser concepts. The fan section was comprised of the fan nozzle and the fan nozzle annulus. The fan nozzle separated from the nozzle annulus to facilitate installation of cascade vane sections. For structural integrity, the fan nozzle pylon/bifurcator section interfaced directly with fan nozzle annulus. The separate flow nozzle was tested in the forward thrust mode to provide reference thrust levels to access reverser effectiveness.

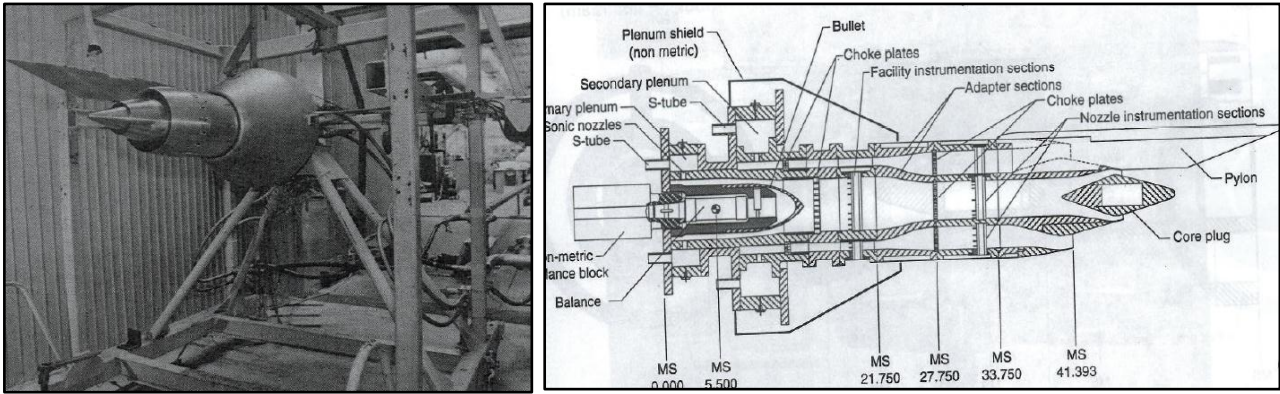


Figure 3.81: Typical setup of separate flow exhaust system model installed on the propulsion simulation system. Images adopted from [Ref. 47].

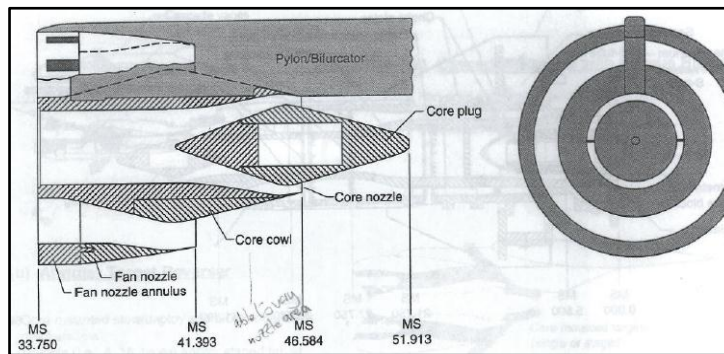


Figure 3.82: Sketch of a separate flow exhaust model. Image adopted from [Ref. 47].

3.24.2 Conventional Cascade Reverser

Details of the cascade thrust reverser configuration are presented in (Figure 3.84). This configuration represents the current state of the art thrust reverser system for turbofan engines. Test results for this configuration are used as a baseline to assess the effectiveness of the novel thrust reverser concepts. Twelve cascade vanes segments were mounted around the circumference of the fan nozzle to direct the fan exhaust flow forward. The cascade vanes (provided by Pratt & Whitney) were configured with an array of 7 longitudinal ports having cant and skew angles representative of a right wing nacelle installation. The nominal flow area of the cascades with all ports open was 104% of the fan nozzle area. A cascade port filler plate mounted on the front side of the blocker was used to close off the aft cascade port and vary the cascade area up to 92% of the fan nozzle throat area [Ref. 47].

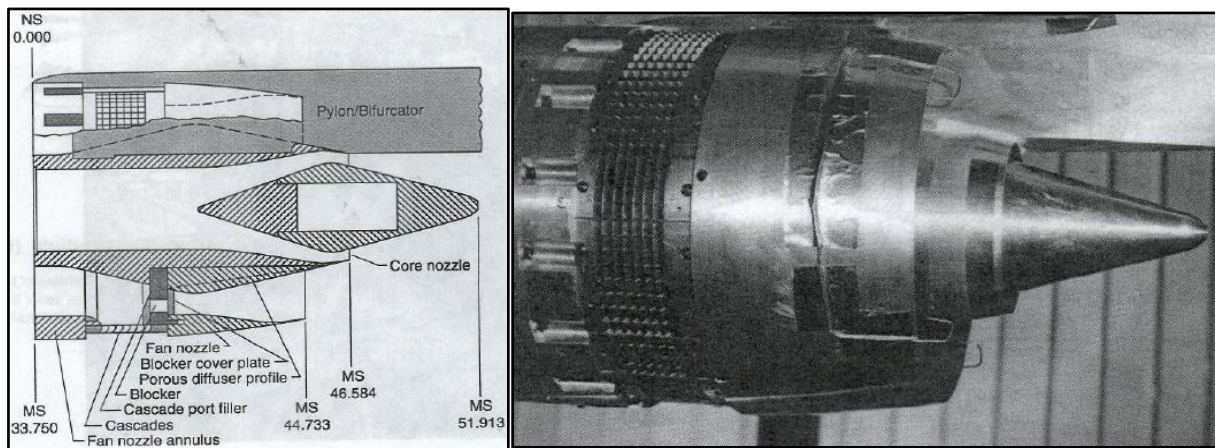


Figure 3.83: (L) Sketch of a cascade reverser model. (R) Cascade thrust reverser model. Images adopted from [Ref. 47].

3.24.3 Cascade Reverser with Porous Fan-Duct Blocker

The porous blocker concept offers a reduction in blocker weight. A photograph of the porous fan duct blocker is presented in (Figure 3.85). Functionally, the porous blocker replaced the variable leakage blocker used with the conventional cascade thrust reverser configuration. Blocker porosities representing flow areas of 25% and 50% of fan duct cross-sectional area were tested.

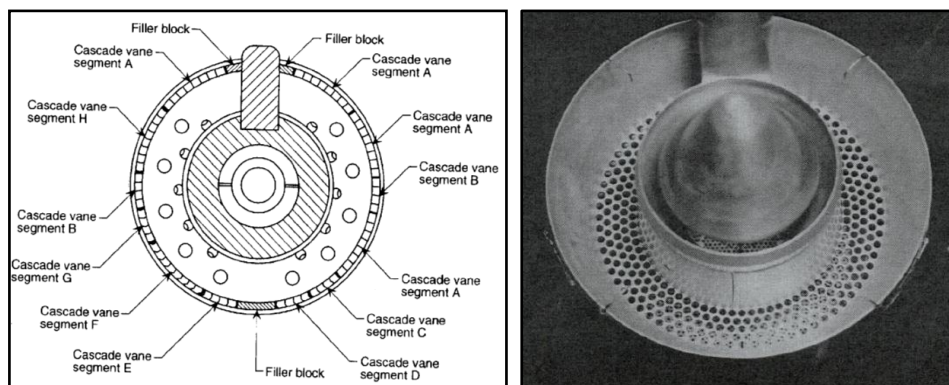


Figure 3.84: (L) Sketch of cascade vanes segment with variable leakage door. (R) Photograph of the cascade reverser model [Ref. 47].

3.24.4 Blocker-less Thrust Reverser Concept

In this design the blocker doors are eliminated (Figure 3.86) and the reverse thrust is obtained by extracting a small quantity of high pressure air from the core flow and introducing it as a diverter in the fan duct to block and divert the fan flow. This concept offers the potential of weight savings over a conventional cascade thrust reverser by eliminating the blocker doors. Improvement in the performance of forward thrust would also result from eliminating the blocker doors thus eliminating the losses associated with blocker door hardware. This design requires an alternate pylon assembly. Figure 3.86, below shows the sketch of the blocker-less thrust reverser model. A fluidic injector assembly was installed in place of the core hardware. The bullnose fairing was added to the forward fan nozzle smoothly turn the fan flow into the cascades. The fluidic injector assembly used a series of interchangeable injector rings to vary the fluidic injection port geometry at each of five injection locations. Important point to note is that the core flow was not simulated and that the

practical injection weight-flow ratio for blocker-less thrust reverser configurations was assumed to be 0.05. Both single injection and multiple injections were tested. In multiple injections three locations were tested at mid, aft and throat on a blocker-less thrust reverser at an injection pressure ratio (IPR) of 12.0 with slot width $w_s = 0.025$ in and 45° injection angle (θ) [Ref. 47].

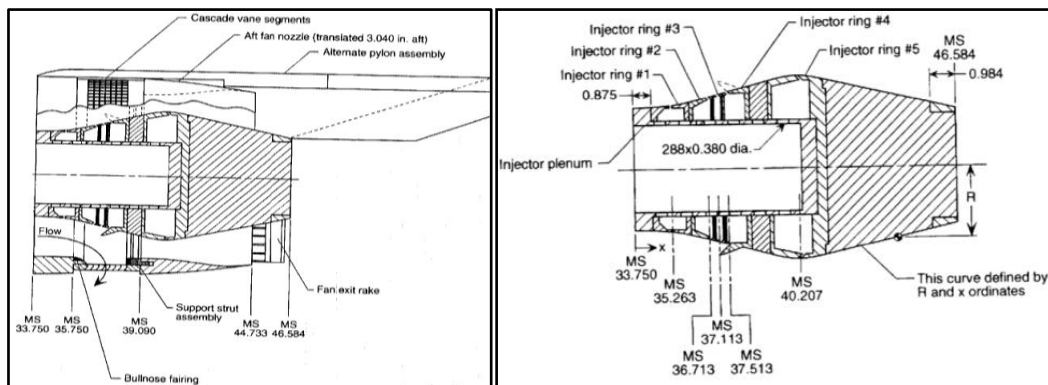


Figure 3.85: (L) shows the sketch of blocker-less thrust reverser model. (R) Sketch of the fluidic injector assembly . Images adopted from [Ref. 47].

3.24.5 Core-Mounted Annular Target Reverser

Details of the core-mounted annular target reverser configurations are shown in (Figure 3.87). The annular targets covered the full circumference of the fan exit and represented a blocker arrangement with no leakage. Two primary design parameters investigated with the annular target reverser were the reverser Area Ratio (AR) and the target angle (Φ). The reverser exit (a conic surface) is defined by a line drawn perpendicular to the inner (forward) surface of the target and intersecting the fan cowl lip. The reverser exit area is the minimum area aft of the fan nozzle exit. The reverser area ratio is defined as the ratio of the reverser exit area and the fan nozzle throat area (A_{fan}). Reverser AR of 1.05, 1.15, and 1.25 were tested. Spacers were used to reposition the targets on the core nozzle section and vary the reverser exit area. The target angle (Φ) is defined as the angle between the inner surface of the target and a vertical plane perpendicular to the thrust axis. This is also the nominal reverser efflux angle, the angle of the vector drawn normal to the reverser exit. As shown in (Figure 3.87), two annular targets with angles of 20° and 40° were built for testing. To evaluate the effect of the target length (diameter) an extension piece was built for the 40° target and tested with the target in the AR=1.25 position. Kicker plates (end plates) have shown to increase reverser effectiveness on conventional low by-pass ratio target reverser systems. Endplates also offer performance advantages on concepts which use short targets that do not have exit areas perpendicular to the target panel. The kicker plate can also be used to locally trim the reverser efflux pattern.

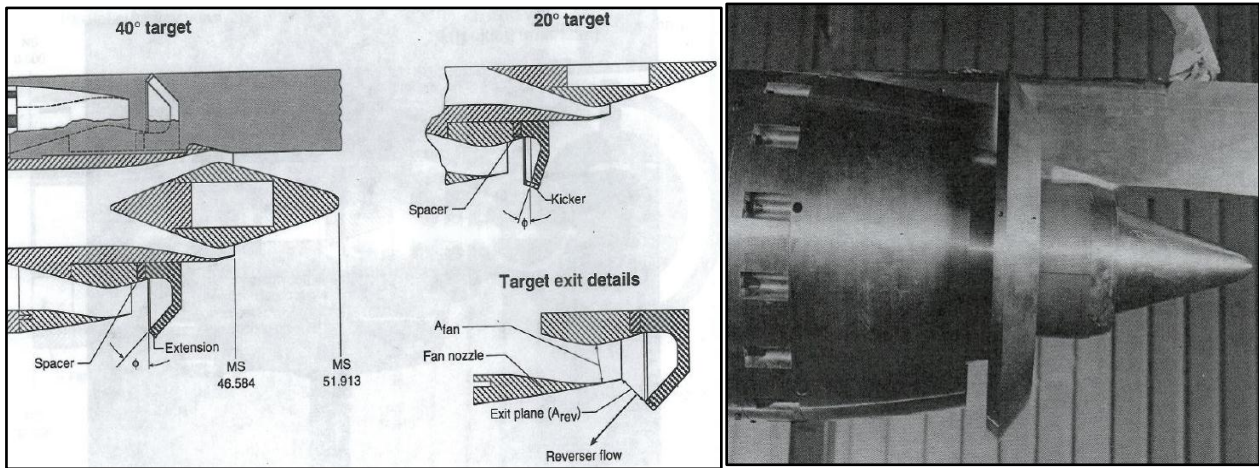


Figure 3.86: (L) The sketch of the metal target thrust reverser model. (R) The annular target geometry. Images adopted from [Ref. 47].

3.24.6 Core-Mounted Fabric Target Reverser

The fabric target thrust reverser concept represents a lightweight design based on the core-mounted annular (metal) target thrust reverser, with consideration given to how the device might be deployed and stowed. This concept has been patented by Pratt and Whitney. The fabric target thrust reverser configurations were designed for a reverser area ratio, AR, of 1.15 and nominal exit angles of 20° and 40°. The inside edge (along the core) of the fabric target was secured below the core surface; no attempt was made to attach the fabric target to the pylon. The nominal fabric target shape was established by the reverser exit angle and a circular arc matched to the slope of the core surface and nominal target exit angle. Short and long fabric lengths were tested for target to determine the effects of fabric length at angles of 20° and 40°. The fabric material used in this test was KEVLAR 840 (provided by Hexcel Corp.) with porosity of 1.08ft³/min/ft² and a weight of 7 oz/yd². The unloaded (jet-off) shape of the fabric targets were essentially the same as the metal targets described previously. The inflation characteristics (loaded shape) of the fabric target are important to the operation of this concept.

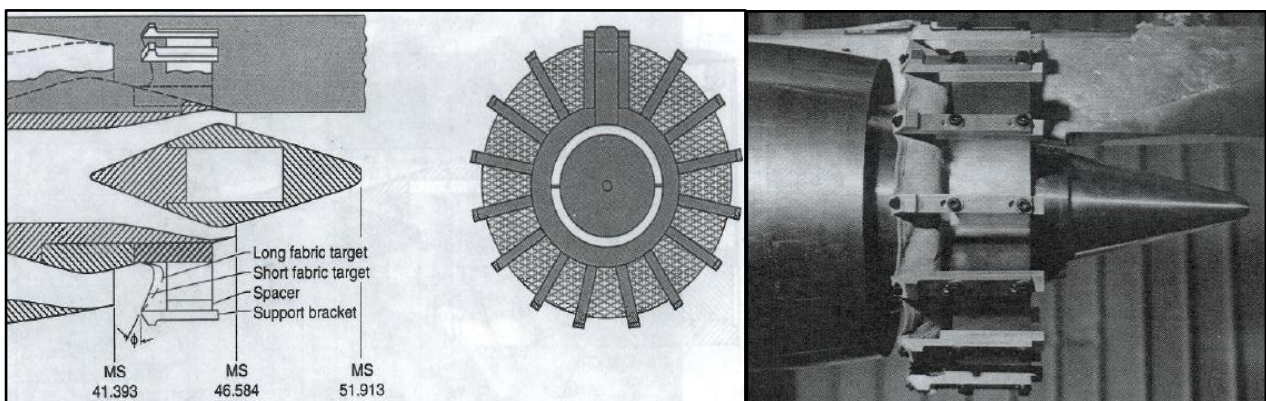


Figure 3.87: (L) Sketch of fabric thrust reverser. (R) Fabric target thrust reverser model. Images adopted from [Ref. 47].

3.24.7 Multi-Door Crocodile Thrust Reverser

Details of the multi-door crocodile thrust reverser concept developed by Rolls-Royce and Rohr are presented in (Figure 3.89). The concept employs set of inner and outer doors that are hinged at the

door panel trailing edge. The inner doors rotate to block the fan duct and the outer doors open outward to deflect the fan flow forward. The configuration tested employs eight door sets (reverser ports) located symmetrically around the circumferential of the fan cowl. Design variables investigated for the fully deployed configuration include pylon/bifurcator filler plates, reverser port bullnose radius, reverser port area, kicker plate length, outer door cutback (size). Partially deployed reverser configurations were also tested [Ref. 47].

The shape of the reverser port is trapezoidal, with the width larger at the aft end. The reverser port area is defined as the product of the average port width and port length. Variations in reverser port area were achieved by installing spacers in front of the bullnose inserts, thereby reducing the length of the reverser port. Three reverser area ratios were investigated: 1.67, 1.60, and 1.52. The smaller area ratios correspond to a 4.4% and 9.4% reduction in port area. Selected configurations were tested without kicker plates and with long and extra-long kickers [Ref. 47].

For a conventional subsonic transport nacelle installation it is likely that the outer door panels at the top and bottom of the nacelle will require cutback to provide clearance with the ground and wing leading edge slats (when deployed). Combinations of outer and inner door deployment angles were tested. Fixed door brackets were used to vary the outer door deployment angle (Φ) from 10° to 60° in 10° increments, and the inner door deployment angle (δ) from 6° to 36° in 6° increments. The majority of testing was done with the inner doors set to the fully deployed 36° position while the outer door position was varied between 40° , 50° , and 60° to determine the optimum door position. Combinations of inner and outer door positions were also tested to simulate partial deployment configurations [Ref. 47].

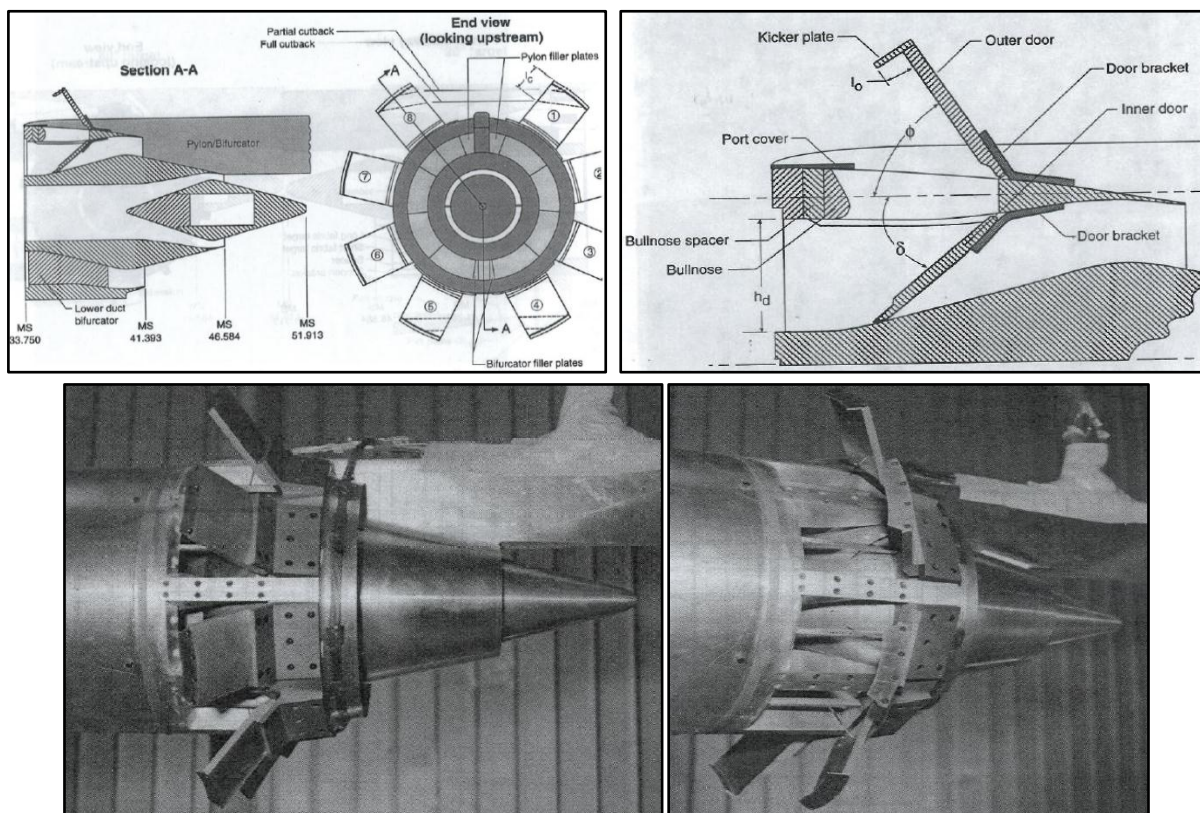


Figure 3.88: (Top-L) Sketch of multi-door crocodile thrust reverser, (Top-R) Reverser port details. (Bottom-L) Photograph of multi-door reverser side view, (Bottom-R) Front quarter view. Images adopted from [Ref. 47].

3.24.8rd Wing Mounted Thrust Reverser

One of the limitations of fan-cowl mounted (cascade or multi-door) and core-mounted (target) thrust reverser systems is that only the fan flow is reversed. With the wing-mounted thrust reverser concept both the core and fan flow can be captured and reversed, and thrust reverser effectiveness can be improved. By removing the thrust reverser system from the nacelle, the wing-mounted thrust reverser concept offers the nacelle designer more options for improving nacelle aerodynamics and propulsion airframe integration, simplifying nacelle structural designs, reducing nacelle weight, and improving engine maintenance access. Conceptually, the wing-mounted thrust reverser concept would use one or more flow deflectors deployed from the wing to capture and reverse the engine flow. Kinematically, these flow deflectors could operate in a variety of different ways. One possibility would be to use the airplane high lift systems to form flow deflectors by either splitting or over turning one or more of the flap elements (Figure 3.90). Another possibility would be to deploy the deflector(s) from the lower wing surface. The model used in this investigation is representative of typical wing mounted thrust reverser system. Geometric variations of key design parameters investigated for the wing mounted thrust reverser concept include flow deflector angles and chord length, optional deflector fences, and the mount angle of the deflector system (normal to the engine centreline or parallel to the wing trailing edge). The deflector assembly as shown in (Figure 3.90) was mounted to the wing section in either the normal or parallel mount positions. The deflector were sized to a width twice that of the maximum nacelle diameter or $2.0D_{max}$.

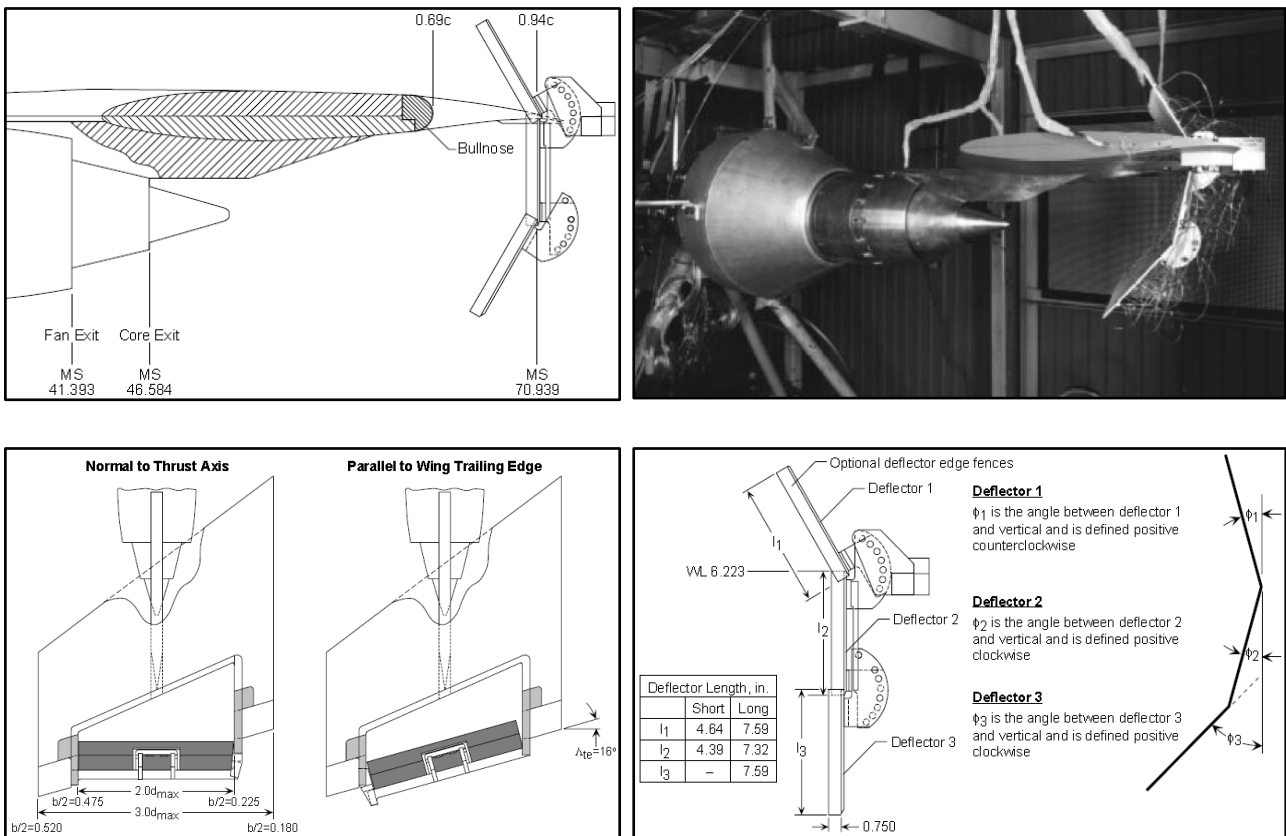


Figure 3.89: (Top-L) Sketch of the wing mounted thrust reverser model. (Top-R) Wing mounted reverser model assembly during testing. (Bottom-L) Top view of the wing mounted reverser. (Bottom-R) details of the deflector assembly. Images adopted from [Ref. 48].

The data from the test conducted showed that the highest value of overall thrust reverser effectiveness, η_{rev} , occurs for configurations with $\psi_3 = 30^\circ$, while ψ_2 has the most substantial effect

on, η_{rev} , the highest value of, η_{rev} generally occurs for configurations with ψ_2 of 0° or less. The overall thrust reverser effectiveness level for configurations with $\psi_2 \leq 0^\circ$ ranges from about 0.3 to 0.44 at $FNPR \approx 1.1$ and decreases with increasing $FNPR$ (Fan Pressure Ratio). This performance is competitive with cascade type thrust reverser systems, which have, η_{rev} , values on the order of 0.35 to 0.4.

There are three deflector angle combinations that depending on the $FNPR$ produce the highest values of η_{rev} . At $FNPR$ values from 1.1 to about 1.25 the configuration with $\psi_1 = 60^\circ$, $\psi_2 = -15^\circ$ and $\psi_3 = 30^\circ$ has the highest values η_{rev} . At $FNPR$ values from 1.25 to 1.5 the configuration with $\psi_1 = 60^\circ$, $\psi_2 = 0^\circ$ and $\psi_3 = 30^\circ$ has the highest values η_{rev} . At remaining $FNPR$ values from 1.5 to about 1.6 the configuration with $\psi_1 = 45^\circ$, $\psi_2 = 0^\circ$ and $\psi_3 = 30^\circ$ has the highest value of η_{rev} . Removing the deflector edge fences results in a substantial drop in overall reverser effectiveness but produces only small changes in force and moment coefficients; the drastic reduction in η_{rev} that occurs when the fences are removed is a result of increased exhaust flow spreading / spillage in the lateral direction. Exhaust flow which is not captured by the deflectors would produce forward thrust and will result in reduce value of η_{rev} .

Test results have shown that these innovative thrust reverser concepts do achieve thrust reverser effectiveness levels which, when considering the potential for system simplification and reduced weight, may make them competitive with current state of the art thrust reverser systems. Although the configurations investigated were primarily conceptual, the results obtained provide a data base from which to access thrust reverser performance and conduct primarily design trade-offs for some of the more important geometric parameters. The favourable results obtained also justify further concept refinement and to carry out detailed systems studies to identify and better the actual system trade-offs.

3.25 Thrust Reverser Wind Tunnel Testing for Civil Aircraft

In spite of progress in CFD, wind tunnel testing is still indispensable in the process of the development and checkout of thrust reverser designs. Few of the reasons for the wind tunnel testing are: the interaction of the reverser efflux with the airframe and other high lift systems, the deployment of a thrust reverser may introduce engine surge at low speeds due to temperature distortions resulting from flow ingestion and also the possibility of F.O.D at low speeds. Thrust reverser design is a very complex and challenging task. The reverser efflux can interact with the control elements and lifting surface of the airplane, thereby changing its behaviour. It can also, when directed strongly forward, re-enter the engine and thereby affects its intake air properties. German-Dutch Wind Tunnels (DNW) has built up testing methodologies in such a way as to be able to simulate the engine thrust reverser action both with blown nacelles as well as with the turbine powered simulators (TPS). Reference 39 discusses thrust reverser wind tunnel testing criteria for civil aircraft [Ref. 49].

Smaller by pass ratio turbofan engines are mostly equipped with internal mixers and are used for powering business and regional jets. Smaller bypass ratio mixed exhaust engines are normally equipped with the target type reverser. Translating and rotating part of the exhaust nozzle creates a bucket at the rear end of the engine that redirects the (mixed) fan and core exhaust. A typical wind tunnel model of a target type reverser is shown in (Figure 3.91). Relevant reverser elements are shown in (Figure 3.91). The design of an exhaust nozzle is such that after deployment a bucket shape is formed; the engine exhaust flow is then blocked and re-directed forward by the target assembly. This type of thrust reversing is common on business jet aircraft such as Gulfstream, and also on the aft mounted engines on regional jet aircraft such as Fokker 100, 70 or others. In the

wind tunnel this type of thrust reversal is generally simulated with the so-called blown nacelle type simulator [Ref. 49].

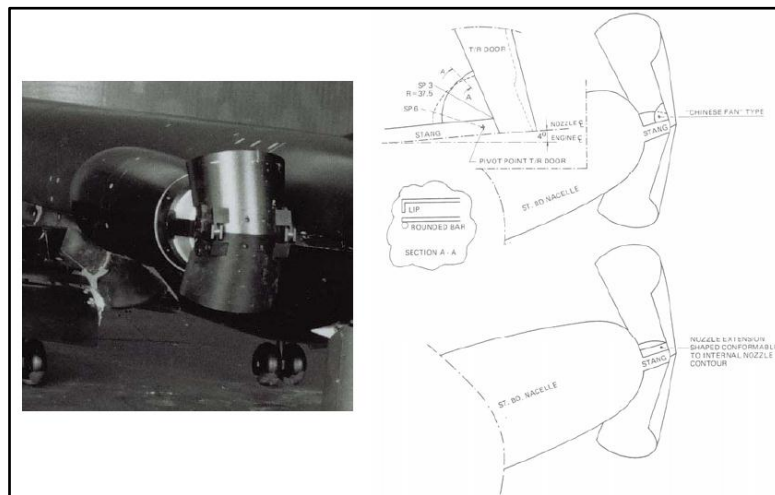


Figure 3.90: Blown nacelle for thrust reverser test in wind tunnel. Images adopted from [Ref. 49].

For larger jet engines with high bypass ratios sufficient forward thrust can be generated by reversing the fan flow only. Examples of the cascade openings, in the configurations used in wind tunnel testing with blown nacelles and with TPS (Turbofan Propulsion Simulator) are shown in (Figure 3.92a and b). The other type has (typically four) circumferential distributed pivoting doors as shown in (Figure 3.92c). The pivoting doors combine the blocking function with that of directing the efflux upstream. The thrust reversers utilizing the cascade openings are common on larger civil transport aircraft, such as the Airbus family of aircraft [Ref. 49].

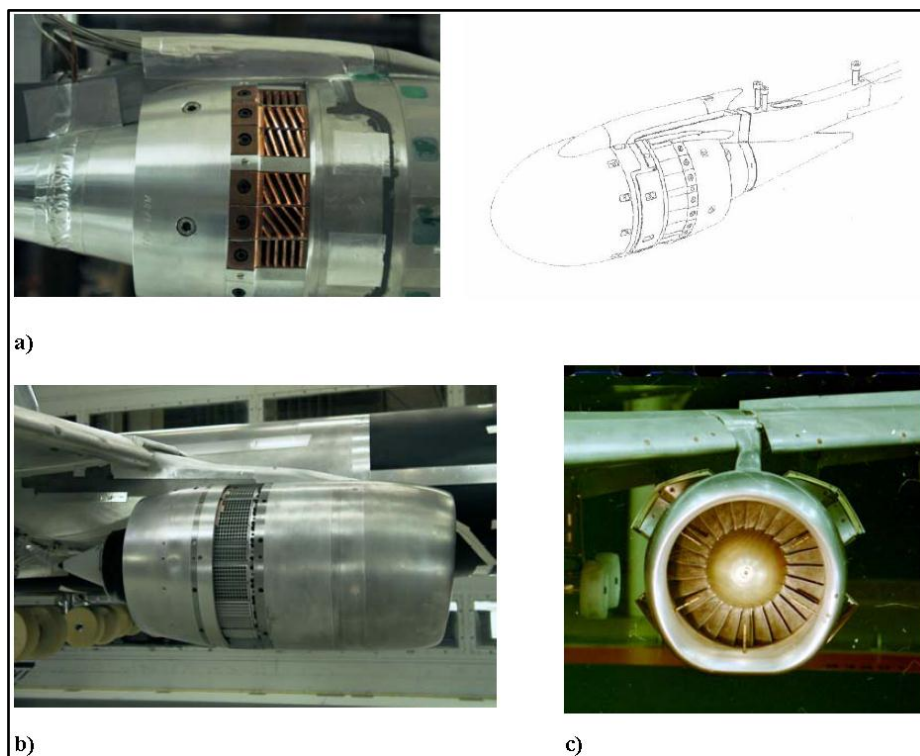


Figure 3.91: Thrust reversers for wind tunnel tests, (a) Blown cascade, (b) TPS cascade, and (c) four pivoting door reverser. Images adopted from [Ref. 49].

In general, as with all aspects of engine simulation in wind tunnels, there are limitations imposed by the experimental infrastructure upon the range of thrust reverser simulations that can be performed. One of these is the amount of compressed air that can be delivered to the simulators. This amount can be limited by either the compressor capacity or the model dimensions restricting air delivery to the engine simulators. For simulation of the intake flow the restrictions posed by the model are often even more severe. The relatively low pressure of the intake flow requires large piping. As in all wind tunnel testing, appropriate scaling laws have to be given due consideration [Ref. 39]. For the correct duplication of the geometric pattern of the thrust reverser flow, the ratio of the momentum of the exhaust jet flow to the tunnel flow $(\rho V^2)_j / (\rho V^2)_{\text{tunnel}}$ should be duplicated. In addition, the flow ratio $(V_{\text{throat}} / V_{\text{tunnel}})$ must be duplicated for the proper stream tube contraction of the fan incoming flow towards the inlet throat (the narrowest part of the inlet duct ahead of the fan). The latter is simulated by setting the intake mass flow equal to the exhaust mass flow. Experience also indicates that the wind tunnel test results agree better with full-scale results when one takes buoyancy forces of the hot exhaust air into account. This means that the balance between the energy transport by convection and inertial phenomenon should be maintained. It can be shown that this requirement is satisfied, when the Froude number similarity relationship is fulfilled. Since the model jet temperatures are generally lower than those of the full scale jet, the requirements for mass flux and wind tunnel speed in the experiment are reduced. The Froude number similarity can be safely ignored, when the tests involves only cold gas, as is the case only fan flow is reversed. Further to these momentum and energy transport considerations, the geometrical conditions must be properly simulated as well. The inlet lip and cowling of the engine have to be correctly designed [Ref. 49].

The balance between the reversed jet momentum and the momentum of the oncoming flow governs onset of re-ingestion. In ground proximity the absence or presence of the boundary layer on the ground cannot be neglected. Contrary, to real situation, on the test section floor of the wind tunnel there is a relatively thick boundary layer. The simplest solution to have a boundary layer as thin as possible is to use a ground board and ground boards have been used in the DNW-LST and DNW-LLF for the tests. But even with ground board there will be a boundary layer. A further reduction in boundary layer thickness is achieved in the DNW-LST by tangential blowing or moving belt floor in the LLF [Ref. 49].

In the standard procedure of the development cycle a first series of testing is aimed at finding a geometry that gives the highest reverser efficiency compatible with the engine cycle. In this phase of development a static test bench is used, as the effects of external flow are neglected at this stage. The thrust reversal strength can vary significantly depending on the geometrical configuration. Here, the velocity reversal coefficient of the isolated engine simulator with thrust reversers deployed in various configurations is plotted against the nozzle pressure ratio of the engine simulator. For installation on an aircraft, an intermediate condition is typically chosen. This is because the maximum reversal configuration will typically lead to an early re-ingestion of the engine exhaust air when interacting with the oncoming flow in a landing situation. The geometry optimized in isolation is next tested in a wind tunnel and mounted on the aircraft model to investigate the installation effects. The most common elements of such a wind tunnel test are measurements of overall forces and moments, determination of re-ingestion onset and the measurements of the (unsteady) effect on the structure. The thrust reverser simulation is generally performed as part of an overall engine integration study. The simplest solution is to simulate the exhaust flow by means of compressed air leading to the so called blown nacelle technique (Figure 3.91 and 3.92) above. When the objective is to investigate the interaction of the reverser efflux on the airframe this is the most obvious choice. For the target type reversers it is mandatory to heat

the compressed air. Heating the compressed air permits one also to study the heat efflux to the bucket doors [Ref. 49].

A more detailed description of one of the blown nacelle setups in DNW is given in (Figure 3.93) where the air supply through the model mount as well as the model for simulation of aft mounted engines are depicted. The model is mounted on an external balance, which is equipped with a low reaction airline crossover via the hollow strut. In this way the overall model forces and moments including the thrust developed by the blown nacelles is directly measured by the balance. At the same time an internal balance measures the model forces and moments generated by the flow and exhaust plumes (except the thrust and aerodynamic forces on the nacelles). In the test setup the goal is to study the exhaust interaction with the airframe and its effect upon the handling capabilities of the aircraft. The blown nacelle technique with compressed air supply was also applied during visualization of the flow pattern (Figure 3.93). For visualization steam is injected into the simulated exhaust jet in the plane just after the flow rectifier. The mass fraction of the steam is sufficiently low not to affect the momentum balance in any significance, in this way the visualization is a reflection of the proper relationship [Ref. 49].

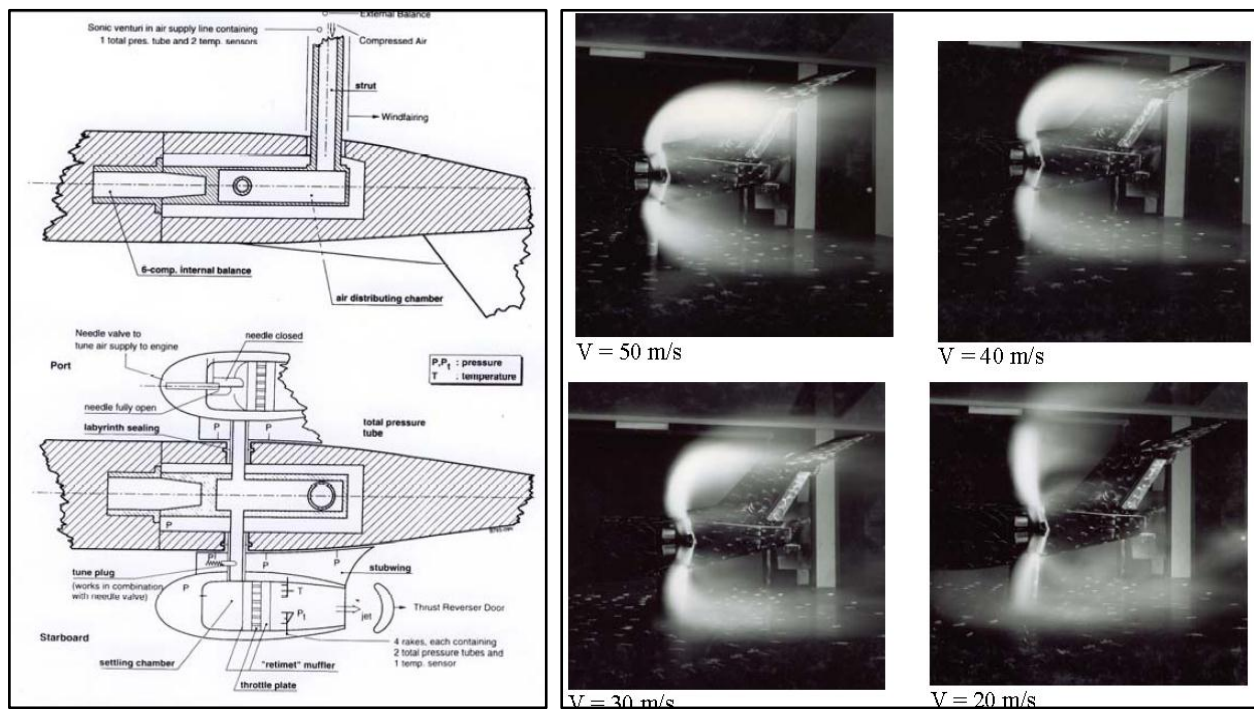


Figure 3.92: (L) Installation of the blown nacelle in the wind tunnel model, simulating the aft mounted of aircraft engines. (R) Steam visualization of thrust reverser flow pattern. Blown nacelle technique with aft mounted engine simulators [Ref. 49].

Another example of the blown nacelle technique as applied in DNW is in combination with a sucked inlet technique. For re-ingestion investigation the blown exhaust nozzle must be combined with a sucked inlet. (Figure 3.94) shows a photograph of a typical test setup with combined sucked inlet / blown nacelle in the DNW-LST. The reverser efflux is again visualized by means of steam. The suction is performed by an auxiliary suction pump. The inlets for this type of tests are instrumented with temperature rakes in a manner similar to the instrumentation in the exhaust plane. A temperature rake is also visible in (Figure 3.92c), here in connection with a TPS thrust reverser. The temperature sensors can detect the onset of engine exhaust re-ingestion by detecting the temperature changes in the incoming intake airflow [Ref. 49].

To completely avoid ducting the intake mass flow through the model a Turbofan Propulsion Simulator (TPS) can be used. A TPS consists of a scaled inlet fan connected to compressed air driven turbine. In general the massflow to drive the turbine is much less than the compressed air required for a blown nozzle. The only limiting factor in applying TPS units for reverser testing is the limited number of standard sizes. An advantage of utilizing the TPS for thrust reverser simulation is that since only the fan flow is used, the temperature ratio (and thus the buoyancy effect, which is absent) for free flight condition is duplicated identically. No scaling for this parameter is required in the test. Care should still be exercised in the scaling of the geometry of the reverser cascade. Geometric reduction may lead to problems with structural strength of the cascades. Generally the solution to this problem lies in the reduction of the cascade elements and corresponding strengthening of the structure. In the reduction of the number of cascade it should be guaranteed that the efflux pattern of the 'scaled' cascade is identical to the original one. This often requires an extra test in which the pattern of the two are compared. Still, the critical opening of the cascades in combination with the fan entry flow is a strong requirement. This means that the reverser discharge coefficient should be close to fan nozzle discharge coefficient. If the cascade choke, the TPS may incur the structural damage due to fan stall [Ref. 49].

For a more complete boundary layer removal without formation of a new boundary layer the DNW-LLF has made recourse to a moving belt system. The Moving Belt Ground Plane (MBGP) fits in the $8 \times 6 \text{ m}^2$ test section of the DNW-LLF. This setup has been used for reverser testing of wide variety of Airbus models starting from the Airbus A320 till Airbus A380. The setup for these tests is shown in (Figure 3.94 and 3.95). In addition to removing the tunnel boundary by a mechanical scoop and letting a new boundary layer start only at the lip of this ground plane, the rolling of the belt acts in such a way as to let negligible new boundary layer establish. This corresponds to the real runway situation. The re-ingestion can be delayed by approximately 10 knots with moving belt. This simulation provides the designer with extra margin for the thrust reversers [Ref. 49].



Figure 3.93: Dorsal sting supported Airbus A380 above the Moving Belt Ground Plane in DNW-LLF. Image adopted from [Ref. 49].

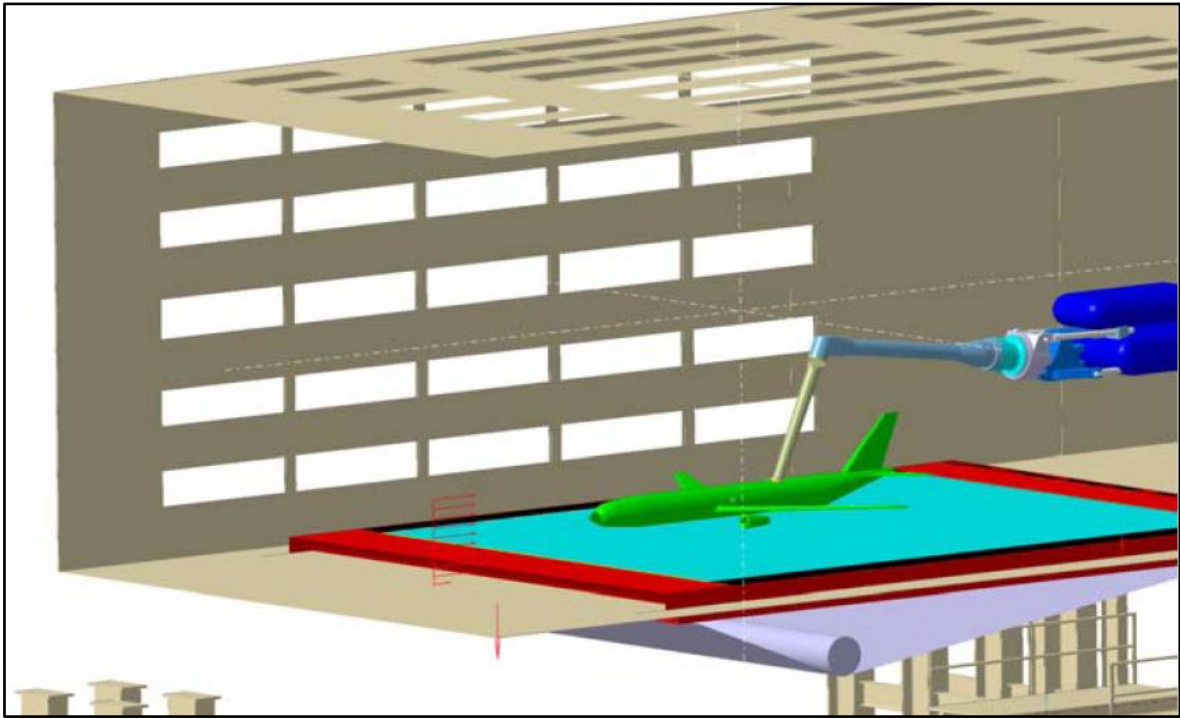


Figure 3.94: The experimental arrangement for the photo above with boundary layer scoop in red and moving belt in blue. Images adopted from [Ref. 49].

Chapter 4. CFD Analysis for Thrust Reversers – Literature Review

4.1 Introduction to CFD Analysis for Thrust Reverser

Computational fluid dynamics is today an equal partner with pure theory and pure experiment in the analysis and solution of fluid dynamic problems. The future advancement of fluid dynamics will rest upon a proper balance of all three approaches, with computational fluid dynamics helping to interpret and understand the results of theory and experimental, and vice versa. In 1950s, there was no CFD in the way that we think of it today. The early development of CFD in the 1960s and 1970s was driven by the needs of the aerospace community. In 1970, there was CFD, but the type of computers and algorithms that existed at the time limited all practical solutions essentially to two-dimensional flows. The real world of fluid dynamic machines – compressors, turbines, flow ducts, airplanes, etc. – is mainly a three dimensional world. In 1970, the storage and speed capacity of digital computers were not sufficient to allow CFD to operate in any practical fashion in this three dimensional world. By 1990s, however, this story had changed substantially. The instrument which has allowed the practical growth of CFD is the high speed digital computer. CFD solutions generally require the repetitive manipulation of many thousands, even millions, of numbers, a task that is humanly impossible without the aid of a computer. Therefore, advances in CFD, and its applications to problems of more and more detail and sophistication, are intimately related to advances in computer hardware, particularly in regard to storage and execution speed. This is why the strongest force driving the development of new supercomputers is coming from the CFD community [Ref. 50].

4.2 2D CFD Analysis of Reversing Pitch Fan Blade Thrust Reverser

The early work published on the numerical analysis of thrust reverser was in the year 1987 by Boeing. A 2D axisymmetric CFD study was carried out on the thrust reverser concept which involves reversing the pitch of the fan blade to cause flow reversal in the fan duct. The nozzle will be required to act as an inlet. An experimental work on this concept was carried out in the year 1979 and 1980 by NASA. The Reynolds-averaged Navier-Stokes equations together with turbulence modelling were used. An implicit procedure was used to solve the flow variables. Theoretically, an implicit formulation could reach the steady state limit much faster (hence less expensive) than an explicit analysis [Ref. 51].

The physics of the compressible, viscous flow is described by time-dependent, Reynolds-averaged, Navier-Stokes equation. The Navier-Stokes equations, in two dimensional compressible form can be written as:

$$\frac{\partial U}{\partial t} + \frac{\partial F}{\partial X} + \frac{\partial G}{\partial Y} = 0 \quad [\text{Equation 4.1}]$$

A typical turbofan engine installation is shown schematically in (Figure 4.1). For the purpose of the study the effects of the wing and pylon are neglected. The flow domain is divided up into quadrilateral control volumes as illustrated in (Figure 4.1). The finite volume method is employed to calculate the fluxes of mass, momentum, and energy into each control volume. This is done in a manner consistent with (Equation 4.1).

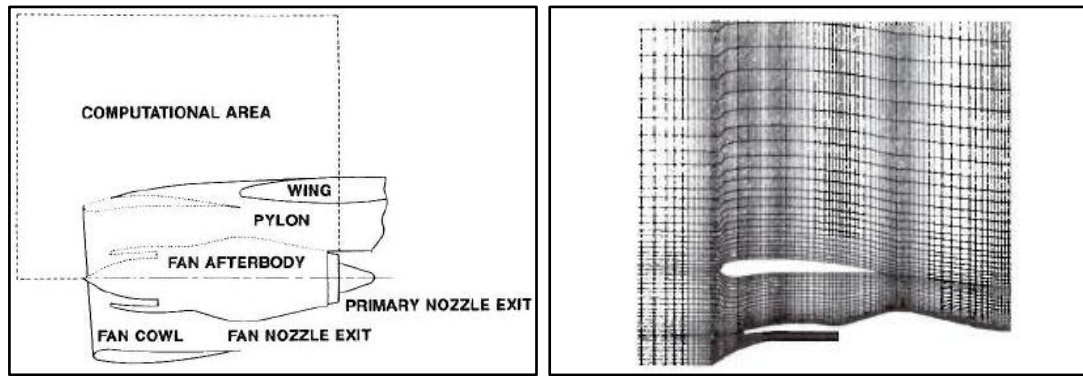


Figure 4.1: (L) Turbopan geomtry. (R) Computaitonal area for numerical analysis. Images adopted from [Ref. 51].

An actuator disk is used to model the physics at the fan face. The actuator disk is a disk of zero thickness across which the stagnation pressure and stagnation temperature increases to model the performance of the fan. Figure 4.2, illustrates the situation at the actuator disk. Cell 1 is on the right-hand side of the actuator disk and contains fluid at certain levels of velocity, pressure, etc. as shown, while cell 2 is on the left and has fluid property values shown. The cell interface, which contains the actuator disk, is shown parted for illustration purposes. There is a flux of fluid across the interface:

$$q = \vec{V} \cdot d\vec{A} \quad [\text{Equation 4.2}]$$

where, A is the area of the cellular interface. The variation in stagnation properties is used to model the pumping characteristics of the fan.

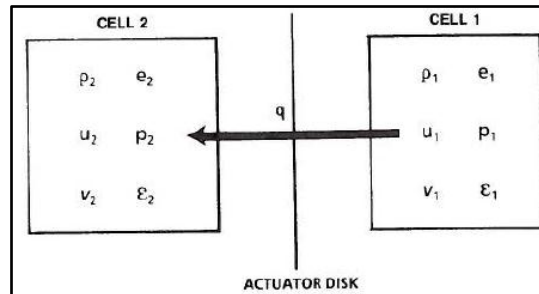


Figure 4.2: Physical representation of actuator disk – reverser pitch. Image adopted from [Ref. 51].

Three cases were studied. In the first, a typical forward-thrust fan nozzle configuration is analysed in reverse fan pitch. In the second case the effect on the reverse flow field due to the addition of a 9-inch circumferential fan cowl slot with 4 inch diverter doors is analysed. The first two cases are compared at a free stream velocity of 33 knots. The third case presents the results for a typical landing speed of 132 knots. A reverse fan blade pitch with 9inch slot and diverter door is modelled in case 3.

Case 1: Figure 4.3, presents the static pressure contours for a 33 knots free stream velocity. Examination of that figure reveals that, with the flight nozzle flow are fixed; the fan has pumped the pressure in the fan duct to a value lower than ambient. The stagnation pressure contours revealed that there is only a small region where stagnation pressure is sufficient to cause reverse flow from the inlet. Even with the enforced increase in stagnation pressure across the actuator disk, the

resulting downstream stagnation pressure is largely too low to overcome the free stream dynamic head, and thus stable reverser thrust fan operation is unlikely. From the velocity vectors, the right of the actuator disk effectively closes off the fan duct allowing only the small reverse flow jet.

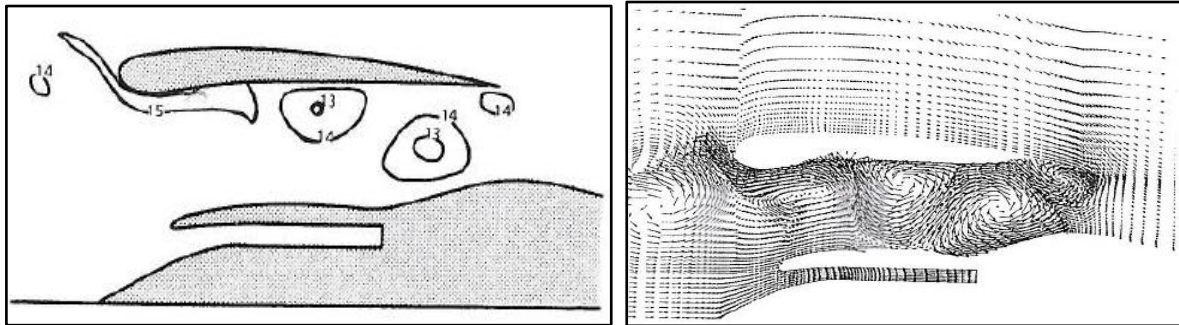


Figure 4.3: (L) Static pressure profile for case 1. (R) Velocity vectors for case 1. Images adopted from [Ref. 51].

Case 2: In an attempt to increase the inflow area in reverse fan blade pitch operation, a 9in slot is opened in the fan cowl. The slot is formed by translating the rear portion of the cowl aft 9in. To improve the quality of the flowfield into the slot, 4inch diverter doors are included. The doors extend above and below the downstream edge of the slot. A high stagnation pressure region (nearly free stream) is seen to extend from the slot to the actuator disk (Figure 4.4). A strong high stagnation pressure jet is seen to extend upstream from the actuator disk. The reverser flow jet can also be seen in the velocity vector diagram. No separation is evident at the core cowl inlet.

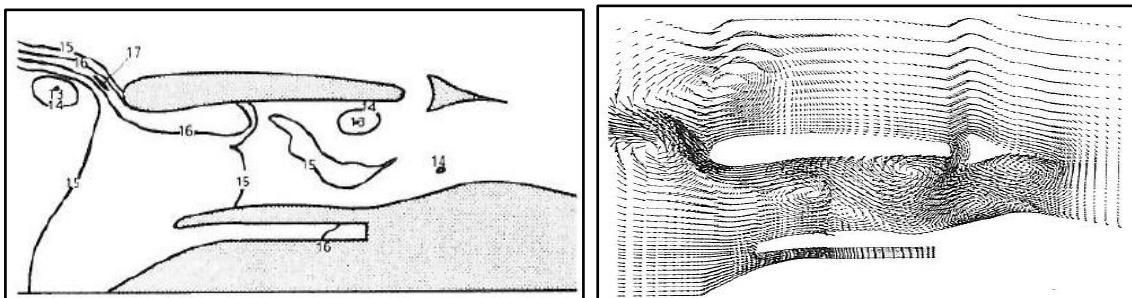


Figure 4.4: (L) Stagnation pressure for case 2. (R) Velocity vectors for case 2. Images adopted from [Ref. 51].

Case 3: To illustrate the flow characteristics at conditions representative of landing speed, an analysis was carried out at 132 knots using the slot and diverter door configuration described above. The stagnation pressure contours are shown in (Figure 4.5). A nearly free stream stagnation pressure is seen in the duct for the nozzle to the actuator disk. This results in a strong jet to the left of the actuator disk. A strong reverser flow is seen in the velocity vector presented in (Figure 4.5). No separation is evident in the core inlet.

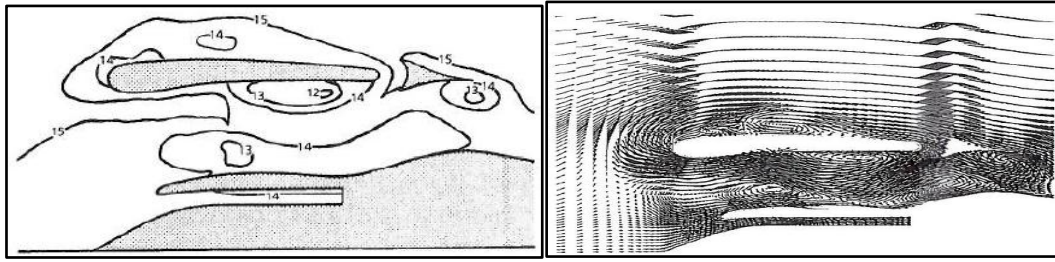


Figure 4.5: (L) Stagnation pressure for case 3. (R) Velocity vectors for case 3 . Images adopted from [Ref. 51].

4.3 CFD Analysis to Investigate Aerodynamic Behaviour of an Installed Thrust Reverser

One of the most challenging problems for the modern CFD methods is the accurate calculation of an installed thrust reverser performance. In [Ref. 52], a 3D cartesian grid Euler method is used to compute the flow about a contemporary business jet with thrust reversers deployed in ground effect. While the entire aircraft is included in this simulation, the multigrid procedure facilitates grid refinement near the thrust reverser components.

Numerical solutions of thrust reverser operations are extremely complicated in that the geometries are complex and the flow is strongly three dimensional and highly turbulent. For example the interaction between the vectored exhaust plume and the freestream flow is dominated by turbulent mixing and the leeward side of the reverser door may be immersed in separate flow. Generally, the fine geometric details such as kicker plates that are required in reverse simulaitons preclude the use of body fitted grid methods in a design environment. The work reported in [Ref. 52] uses a 3D Cartesian Euler method to investigate the aerodynamic behaviour of an installed, deployed thrust reverser with kicker plates. While viscous effects are undoubtely important in determining some local surface pressures and in computing heat transfer, jet plume effects and component load estimations for installed thrust reversers can be predicted with an Euler method. Furthermore, because of the simplicity of the method employed in [Ref. 52], preliminary design simulaitons of installed thrust reversers are practical on existing computers.

The computer code employed in this work uses a multigrid calculation procedure with an equally spaced cartesian mesh strucuture to discretize the governing Euler equations for an inviscid compressible flow. Within the multigrid algorithm, the discretized Euler equations iteratively approach steady state via a four-stage Runge-Kutta scheme. The present technique allows local refinement through multiple, aligned or no-aligned, grid-block embedding which reduces the total number of grid points by concentrating the grid in regions of primary interest (e.g. high flow gradients, fine geometric features, etc.). Thus, this method has the advantage of convergence acceleration present in classical multigrid techniques, without the expense of extensive grid refinement throughout the flow domain. The Euler equations that are solved by the present method govern inviscid, compressible fluid motion and are written in integral form for the general control volume, V , whose surface, S , has an outward unit normal, n , as:

$$\frac{\partial}{\partial t} \iiint_{vol} F \cdot dv + \iint_S \vec{E} \cdot n dS = 0$$

where F is the vector dependent variable,

$$F^T = \{\rho, \rho u, \rho v, \rho w, \rho e, \}$$

and E is the flux vector.

$$\vec{E} = \begin{pmatrix} \rho \vec{q} \\ \rho u \vec{q} + p e_x \\ \rho v \vec{q} + p e_y \\ \rho w \vec{q} + p e_z \\ \rho h \vec{q} \end{pmatrix}$$

with unit vectors e_x , e_y , and e_z along the coordinate axes and $\vec{q}$ the velocity vector with cartesian components (u, v, w). The expression represents a system of equations corresponding to conversation of mass, momentum, and energy. Here, the cartesian coordinate system is denoted by (x, y, z); q is magnitude of the velocity vector $\vec{q}$; p and ρ are the pressure and density; and h is the total enthalpy.

Calculations were performed at two flight conditions: a ground effect condition at a free stream Mach number of 0.15 and a worst case two door inadvertent deployment, full power condition at a free stream Mach number of 0.6. The inflow speed and the fan and core pressure and temperature ratios for each case are prescribed according to the wind tunnel test data and are presented below in Table 5.1 [Ref. 52].

Table 4.1: Engine flow Conditions. Table adopted from [Ref. 52].

Description	Inflow Speed (Ft/Sec)	Fan Exit		Primary Exit	
		Pt/Pinf	Tt/Tinf	Pt/Pinf	Tt/Tinf
Ground Effect	337.6	1.52	1.19	1.40	2.62
Inadvertent Deployment	526.1	1.87	1.23	1.67	2.74

For subsonic boundary conditions, the Euler equations require four specified variables at the engine exhaust face and one at the engine inlet boundary. The boundary conditions allowed by the current method require that the radial components of velocity on the inflow and outflow faces are zero. Further, for both calculations the circumferential components of velocity on the inflow and outflow faces were neglected. The ground effect case was the more computationally challenging of the two due to the close ground proximity and the low Mach number [Ref. 52].

The installed thrust reverser is presented in (Figure 4.6) with the cartesian grid layout. The thrust reverser doors which include an advanced kicker plate geometry are deployed at 60 degrees to the engine exhaust flow. The test results primarily consisted of elements of the thrust reverser breaking force and a qualitative description of the plume trajectory. This numerical model consists of nearly 2 million grid points. The computation time for the Mach 0.15 and 0.6 flight conditions was about 18 and 10 hours, respectively, on a Cray J90.

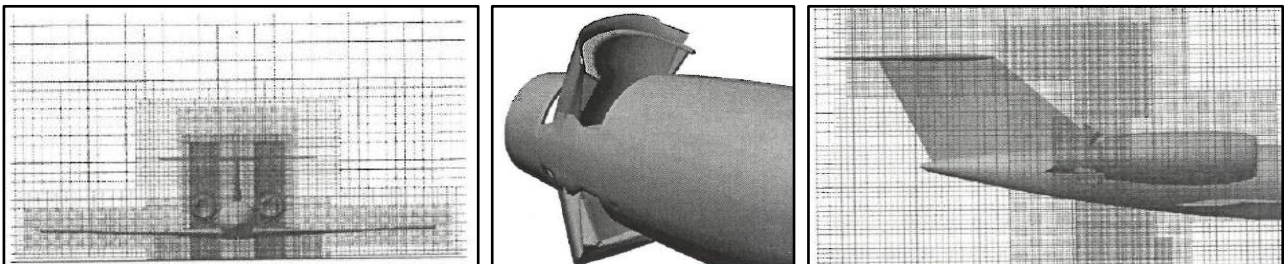


Figure 4.6: (L) Front view with grid. (M) Close-up view. (R) Side view with grid. Images adopted from [Ref. 52].

The plume trajectory in the presence of the complete aircraft is displayed in (Figure 4.7) for the ground effect condition. Although the computed plume trajectory is qualitatively similar to that observed under test conditions, there are quantitative differences between the two. The effects of the close proximity of the wind tunnel ceiling, deployed wing spoilers and non-moving ground plane on wind tunnel test trajectories are not clear [Ref. 52].

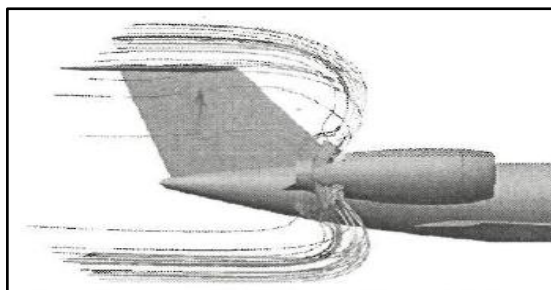


Figure 4.7: Computed exhaust plume trajectory (Mach 0.15, ground effect. Image adopted from [Ref. 52].

Because the thrust reverser doors have sharp edges that provide fixed flow separation boundaries and produce a separated flow that is dominant by large scale vortical structures, an Euler method should be capable of accurately computing the total braking force. While viscous effects are undoubtedly important in determining the detailed pressure distribution on the lee side of the doors, the Euler method should also capture the nominal pressure level on the aft faces. Furthermore, since the door loads are predominately driven by the high pressure jet, and errors in the aft face pressure distribution will not contribute significantly to the total braking force. The total braking force has three primary elements as summarized in (Table 4.2). The present computations predict that 85% of the net braking force is associated with that part of the thrust reverser doors facing into the engine exhaust plume. Here, the plume has travelled on the order of one jet diameter downstream and is comprised of a potential core. Thus, the viscous effects are minimal in this region. Integration of the aft facing door pressures indicate that this component represents approximately 10% of the braking force. Consequently, these two components make up over 95% of the total braking force with the remaining contribution coming from the struts, core cowl, etc. The computed total single engine integrated braking force acting on the engine components aft of the exhaust exit is 18,097 lbf which is about 2% higher than the test results. Also, the measured ISA-SLS reverser efficiency, C_v , is 35.9% while the computed efficiency is 36.6% [Ref. 52].

Table 4.2: Component breakdown of computed total braking force (per engine). Table adopted from [Ref. 52].

Engine Component	Braking Force (lbf)	% of Total
T/R Doors Forward Face	15,306	85
T/R Doors Aft Face	1,860	10
Other Components	931	5
Total	18,097	100

Grid sensitivity studies and solution histories of residuals, integrated force components, and surface pressure demonstrate that the Euler solution is stable and converged. Comparison with wind tunnel test data have shown that the computed exhaust plume geometry is qualitatively similar to that observed in tests on similar installations. Furthermore, the computed pressure distribution on the windward side of the upper thrust reverser door compares favorably with the available test data. Quantitatively, the differences between the computed and measured pressures are about 10% for the lower three quarters of the doors and increase to roughly 30% at the base of the kicker plate. These differences are most likely due to physical differences in the numerical and experimental models related to the flow leakage around the thrust reverser doors. Also, the present inviscid method failed to predict the presence of a vortex at the base of the kicker plate [Ref. 52].

4.4 Three dimensional CFD Analyses for a High Bypass Ratio Turbofan Engine Thrust Reverser

Three dimensional CFD analysis were performed to investigate thrust reverser flows in [Ref. 43]. The paper discusses high bypass ratio turbofan engine exhausts operating in reverse thrust at various aircraft speeds, and inlet duct flow fields of Auxiliary Power Units (APUs). Three geometries were analyzed, the first included a typical commercial twin engine transport, including engine struts and ground plane with a clean wing with reverse thrust operating; the second configuration was similar to the first but with leading and trailing edge high lift devices deployed on wing and tail surfaces; the third configuration was a typical APU with a section of the fuselage surface scoop inlet, S-duct, plenum, plenum structure ribs and bellmouth [Ref. 53].

To deal with complex geometries, the methods used included both structured and unstructured mesh approaches. For the first case of clean wing geometry, a structured multiblock grid approach was used. For the second case of deployed high lift surfaces, an unstructured mesh was used. Both types of meshes were obtained using the ICEM/CAE grid generator software. The structured mesh flow fields were obtained using the TLNS3D-MB Navier-Stokes solver. The unstructured mesh flow fields were obtained using commercial CFD software FLUENT. The objective of the study is to develop a complete CFD procedure for accurately predicting the effects of the thrust reverser efflux on the aircraft. These include impingement on the aircraft surfaces, re-ingestion of reversed flow and the effect of the fan pressure profile, landing conditions and various cascade pattern on the nacelle of the aircraft.

In the past, designers relied on wind tunnel testing to verify their designs. One involves the problem of scaling and the accuracy of the model measurements. Secondly, it is difficult to visualize the entire flow field of the plumes in the wind tunnel environment. The third problem is the high cost and long turn around time. The fourth problem with wind tunnel testing is that it is usually performed only near the end of the design process rather than earlier, where it could provide design guidance. Finally, if a problem with the thrust reverser flow was not detected in the wind tunnel and only showed up during flight testing, the consequences would be serious. Therefore, such thrust reverser related problems should be avoided before an aircraft design enters the flight test mode.

These drawbacks prompted the Boeing Company to develop a Computational Fluid Dynamics (CFD) process as a thrust reverser design tool. Solutions from CFD provide much better insight and views than values from the wind tunnels tests giving as much better understanding of the

underlying physics and facilitates superior design as compared to model testing alone. The Boeing Company initiated research in 1995 to investigate feasibility of CFD tools to model complex fields.

The complete computational process consists of the following sequential tasks: 1. Geometry creation / cleanup 2. Meshing 3. Numerical computation and 4. Post processing. To simplify the process and limit the number of tools involved, ICEM-CFD was selected for tasks 1 and 2, while FLUENT V5 was selected for the unstructured mesh for tasks 3 and 4.

In previous work at Boeing, it has taken up to six weeks to create a reasonable quality structured mesh for the thrust reverser and surrounding areas of a complete underwing twin nacelle aircraft. This limits the usefulness of structured CFD as a tool for guiding designers. While an unstructured mesh can place a greater burden on the solver, accuracy is less of an issue when simulation is limited to momentum and heat transfer, as was the case for the thrust reverser. If, in addition, the geometry is complex, containing regions of vastly different scale, the unstructured mesh is clearly a better approach. Figure 4.8, shows a surface mesh for a typical twin engine strut, nacelle and runway. This multi-block point matched structured mesh was developed using ICEM. The mesh contains 105 blocks with a total of approximately 1.9 million points. For the more complex geometry with fuselage, spoilers, wing, engine strut, nacelle, chine/starkem horizontal tail, vertical tail and the runway unstructured mesh was used. For the purpose of investigating the effect of mesh sizing and parallel computation of unstructured mesh, four unstructured meshes of mesh sizes 1.9, 2.58, 3.70 and 6.28 million cells were constructed.

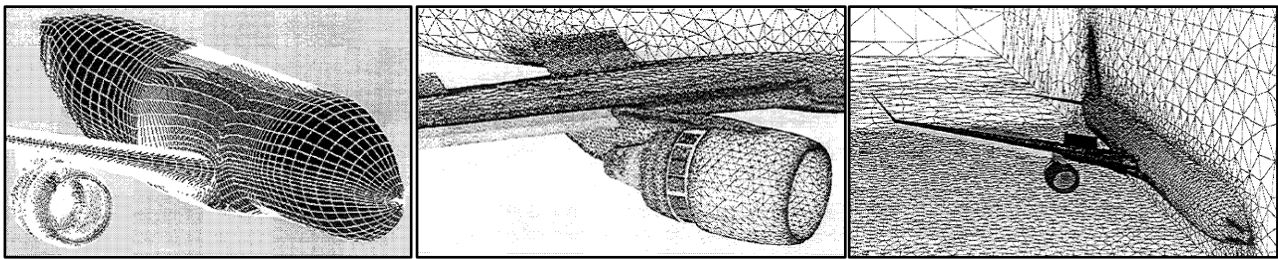


Figure 4.8: (L) Structured mesh. (M) Surface unstructured mesh. (R) Surface mesh of the airplane with runway, downstream and symmetry plane. Images adopted from [Ref. 53].

For the cases studied, the airplane landing speed was assumed to be about 130knots ($M=0.20$) at standard sea level conditions. The airplane was at zero angle of attack, pitch and yaw. The flow boundary conditions for the structured and unstructured meshes are show in (Table 4.3).

Table 4.3: (L) Boudnary conditions for the unstructured mesh. (R) Boundary conditions for the structured mesh. Tables adopted from [Ref. 53].

	$M_{ts}=0.20$ Case		Case 1 $M_{ts}=0.076$	Case 2 $M_{ts}=0.22$
Free Stream speed	50 Knots	Free Stream speed	50 Knots	140 Knots
Exit Pressure	14.7 Psi	Exit Pressure	14.6 Psi	14.6 Psi
Reverser P/P_{ts}	1.42	Reverser P/P_{ts}	1.64	1.64
Reverser T/T_{ts}	1.12	Reverser T/T_{ts}	1.18	1.18
Core Nozzle P/P_{ts}	1.16	Core Nozzle P/P_{ts}	1.30	1.30
Core Nozzle T/T_{ts}	2.56	Core Nozzle T/T_{ts}	2.78	2.78
Fan Nozzle P/P_{ts}	1.02	Fan Nozzle P/P_{ts}	1.008	1.008
Fan Nozzle T/T_{ts}	1.006	Fan Nozzle T/T_{ts}	1.17	1.17
Nacelle Inlet P	13.2	Nacelle Inlet P	12.4	12.4
Ground Speed	130 Knots	Ground Speed	50 Knots	140 Knots

TLNS3D solver was used for the structured mesh case. Figure 4.9, shows the front view of the aircraft engine with efflux discharge from the cascade thrust reverser for the structured mesh case. The exhaust flow from the reverser is bent back due to the forward speed ($M=0.20$) of the airplane. Due to lack of a viscous surface mesh, it is not possible to investigate potential flow separation close to the airplane surfaces, a potential source of re-ingestion.

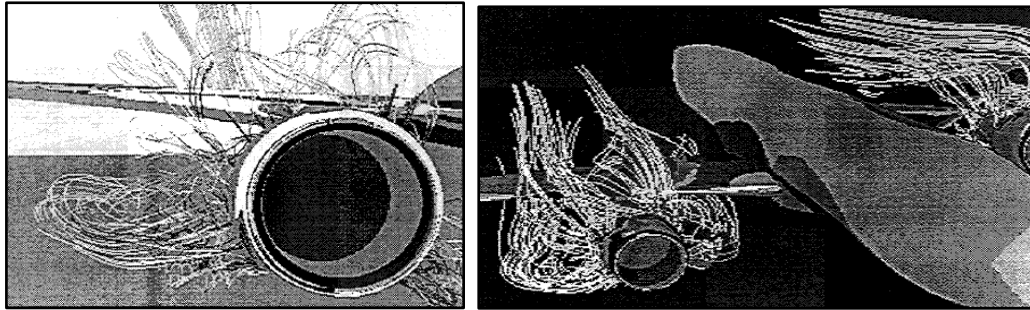


Figure 4.9: (L) Frontal view with efflux from the cascade reverser. (R) Another frontal view with reverser efflux in particle traces. Images adopted from [Ref. 53].

For unstructured mesh calculations, the FLUENT V5 was used. For the two cases studied, the airplane landing speed was set at 50 knots ($M=0.076$) and 140 knots ($M=0.22$) with standard sea level conditions. The cascade reverser modeled in the unstructured mesh cases are of different design as compared with the design in the structured mesh case. A two-equation k-e turbulence model was used. Figure 4.10, shows the flow pattern of the reverser at 140 and 50 knot speeds.

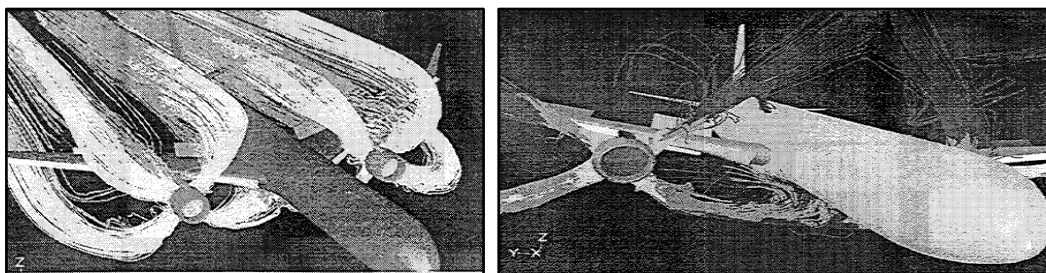


Figure 4.10: (L) Frontal view with reverser efflux at $M=0.2$. (R) Frontal view with reverser efflux at $M=0.076$. Images adopted from [Ref. 53].

The CFD procedure is flexible, fast by reason of parallel computing, and ready for use in modern day airplane product development. This procedure provides an analysis capability that gives the designers a fast, cost effective means of optimizing the aerodynamic configuration of the thrust reverser. It also raises the possibility of reducing if not eliminating, expensive and time consuming model testing. Since the entire CFD analysis cycle can be completed in about three days, designers can use this tool to examine numerous configurations during the design cycle. The designer can easily map the performance of the reverser against wide ranges of engine power setting and airplane forward velocity. With this CFD procedure, tests that involve geometry changes such as the repositioning of the cascades or the nacelle relative to the wing, or validation of the cascade angles, can be accomplished with minimal remeshing and recalculation.

4.5 Multidisciplinary Optimization Approaches for Thrust Reverser Design

An increasingly competitive market place has brought about the need for the aerospace industry to improve the efficiency of its product development methods. With fewer new products entering the market place, innovation is starting to switch from product to process technologies such as design, improve efficiency and reduce cost. This can be achieved by acquiring more knowledge about the design as early as possible in the development process and by allowing more freedom to alter the design later in the design cycle, if required. The process of achieving these improvements can be referred to as multidisciplinary design optimisation which seeks to provide the designer with improved tools for achieving better design. When designing aircraft components the differing approach taken by the aerodynamic and structural design methods means that the simulation models tend to diverge as the design process progresses and becomes more complex. Modern aircraft design relies heavily on simulation to predict aircraft performance. The simulation methods available to the designer include finite element analysis (FEA) for structural analysis and computational fluid dynamics (CFD) for aerodynamic simulations [Ref. 54].

Ref 5, discusses such a multidisciplinary optimization process for thrust reverser design. The paper focuses on the development of effective and efficient methodologies for the structural analysis. The methodologies used for comparison include the element type used for structural simulations and the methods of geometry and load transfer between a 2D aerodynamic simulation and the structural models. The aerodynamic simulation was carried out first using FLEUNT, to determine the resultant static pressure distribution around each of the vanes in the cascade for an arbitrary set of operating conditions. Structural models were then setup in PATRAN using beam, shell and 3D solid elements representing the cascade itself. The models were analysed using NASTRAN [Ref. 54].

The results from the 2D aerodynamic analysis yielded a load distribution for the cascade which took the form of a resultant pressure for each of the nodal positions around the perimeter of the individual vanes. In each of the proposed structural idealisations one of the key tasks was the appropriate abstraction of the pressure data on the structure model. For the beam model a statically equivalent force and moment was applied. For the shell and solid element models, the pressures were applied using the load table within PATRAN.

Cascade geometry will heavily affect the aerodynamic performance of the thrust reverser. It is important that having carried out the initial aerodynamic simulation using un-deformed cascade geometry, that the simulation should be re-run taking into account the deformations predicted by the structural analysis. This results in the need for an efficient means of transferring the deformed cascade geometry from the structural model back into the aerodynamic model. For the purpose of this work the results from the 3D, solid element model, represented the best opportunity for transferring the deformed cascade shape back into the CFD package for the re-assessment of aerodynamic performance using the 2D sectional model. Although, PATRAN could not output deformed nodal data in a form which could be transferred directly to FLUENT, it was possible to isolate sectional deformation data from any point along the vane sections within PATRAN. This was written to a text file which was then, re-formatted to give deformed nodal positions in the form of a PATRAN neutral file. This file was then used as the basis for a deformed cascade shape for re-run of the aerodynamic analysis. Although, the solid element model, provided the most direct route for data transfer back to the CFD simulation, it would also be possible to transfer the results from the, beam, and, shell models. This process would also require the development of automated methods for data transfer between FLUENT and PATRAN [Ref. 54].

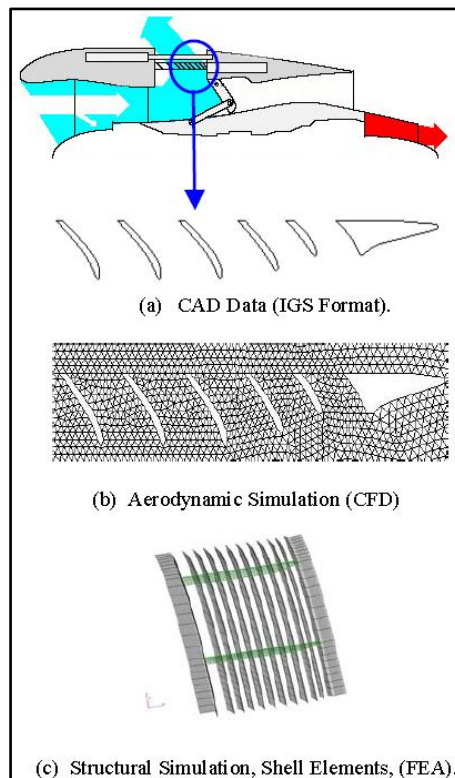


Figure 4.11: Geometric representation of a thrust reverser cascade. Images adopted from [Ref. 54].

4.6 Aircraft Thrust Reverser Evaluation Using CFD

CFD analyses were performed on the complete Embraer EMB170 aircraft. The aircraft model includes fuselage, wing, pylon, deployed slats, flaps spoilers, landing gears, empennages and nacelle with thrust reverser. Three thrust reverser configurations were evaluated in [Ref 55] to check before hand for installation effects and possibility of reingestion, jet impingement on aircraft surfaces, buoyancy, controllability degradation and spoilers drag wipe out.

One of the solutions to minimize reverser aerodynamical problems, improving efficiency and control over the direction of the reversed flow is the use of cascade boxes – vanes grouped together circumferentially around the nacelle. The reverser is comprised of different cascade boxes, each cascade box has its own vane angle that turn the flow to the predefined circumferential and axial directions (Figure 4.12). There are three different solutions that can be implemented on a particular cascade box, that can be; to close a box on the bottom side of the nacelle to avoid debris; change the angle axially in order to avoid the jet impingement on particular surfaces or buoyancy and/or change the angle radially in order to avoid the jet impingement on particular surfaces or buoyancy. In any case the cascade configuration must be such that during the period of reversing neither the engine operating point nor the nacelle internal flow quality should be adversely affected [Ref. 55].

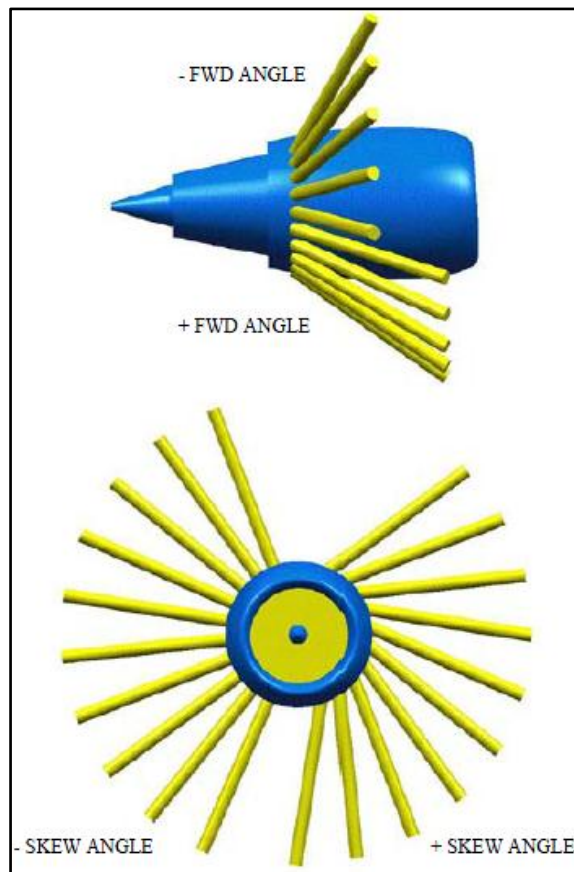


Figure 4.12: Example of cascade boxes angles changed axially and radially respectively (20 boxes, 10 per nacelle side. Images adopted from [Ref. 55].

Thrust reverser wind tunnel tests are typically used to provide valuable information for the cascade configuration design. Fan operating point, noise impacts, reversed thrust and ideal engine thrust setting are some of the important data that can be gathered from the wind tunnel tests. On the other hand, there are several challenges and problems associated with such wind tests, such as problems due to scaling and accuracy of reverser model measurements, difficult to visualise the entire reverser flow field of the plumes in the wind tunnel environment, high cost and high turn around time, performed generally late on the design phase rather than earlier when it could provide design guidance. The use of CFD as a guidance in order to anticipate problems with cascade configurations seems to be an attractive option. CFD analyses can provide a fairly good idea of flow field complexity with easy visualisation of individual cascade influences, while also allowing testing of many different configurations [Ref. 55].

Preliminary cascade designs were defined by the engine/nacelle manufacturer based on its previous experience and results from reverse thrust stand tests. At the beginning of the conceptual and definition phase there were about 50 different cascade boxes configurations considered. Most of them were tested individually in a thrust test bench. Based on this 6 best configurations were selected and 3 of them were chosen for the development test on the aircraft during ground and flight test campaign. These designs presented the best trade off between reversed thrust and ability to overcome aircraft and engine operational problems [Ref. 55].

The condition chosen for the analysis was the landing configuration at a reverser cut off speed (60 knots). The low speed is more critical for engine reingestion and buoyancy. Initial evaluation did not require the assessment of crosswind effects therefore only half aircraft model with symmetry

was used. The mesh comprised about 1.4 million tetrahedral elements adapted to y^+ in near wall regions. The landing gear geometry was simplified and the flap track fairings and winglets were not included.

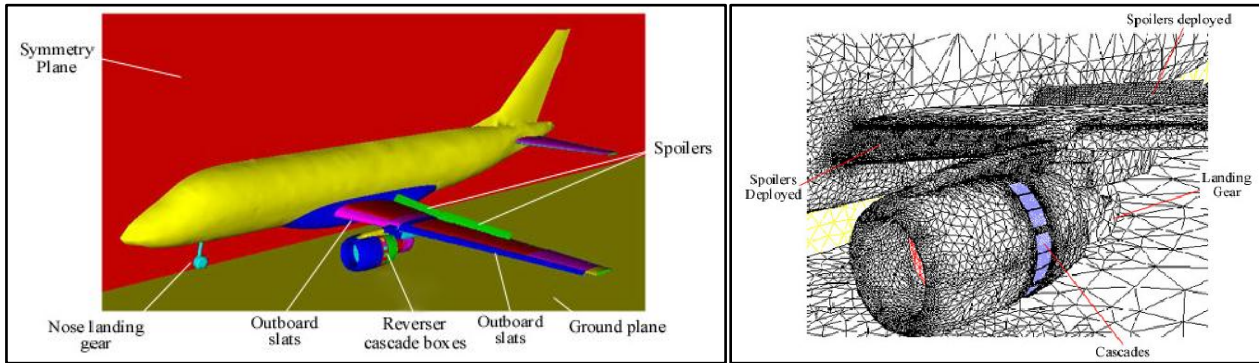


Figure 4.13: (L) Aircraft CAD model, showing the surfaces. (R) Aircraft triangular. Images adopted from [Ref. 55].

The Reynolds averaged Navier-Stokes equations were solved for an ideal gas, with a coupled, density based, finite volume formulation. Upwind scheme with second order spatial interpolation and turbulence closure through the realizable k- ϵ model was used. Boundary conditions were set individually for each of the 18 engine's cascades in terms of total pressure, total temperature and flow angles, so that the maximum reverse thrust was obtained with the right efflux mass flow and pattern. The fan inlet and exhaust jet conditions were imposed according to the engine thermodynamic cycle deck. The ground was treated as moving wall at 60 knots. Outer boundaries were treated as pressure farfield with 60 knots flow speed, null angle of attack and sea level standard atmosphere pressure and temperature conditions [Ref. 55].

Three thrust reverser cascade configurations were tested. The first is the baseline configuration, the other two configurations are compared against this baseline model. Figure 4.14, shows an isosurface of total temperature just above the ambient temperature. This is a spatial way to visualize the envelope affected by the reverser plume. It can be seen that the reasonable part of the bottom of the fuselage is under the influence of the reverse efflux, this may indicate the presence of buoyancy and controllability problems. On the other hand it is shown that with this cutoff speed there is no risk of reingestion by the engine inlet. The streamlines originated on the reverser cascades coloured by velocity magnitude. In comparison the volume encompassed by iso surface is bigger than the one occupied by the streamlines, this is due to the re-circulations induced on the front of the reverser flow that diffuses the flow temperature to the front. The streamline analysis shows that actually the reverser flow meets the symmetry plane far from the nose landing gear, considerably reducing the expected buoyancy effects [Ref. 55].

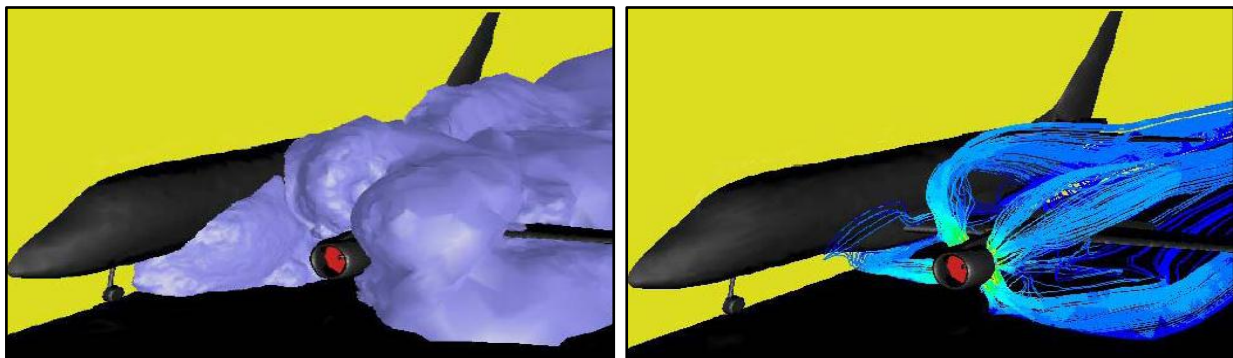


Figure 4.14: (L) Thrust reverser plume, isosurface of total temperature. (R) Thrust reverser streamlines coloured by velocity. Images adopted from [Ref. 55].

CFD analysis were also performed for the other two configurations. The difference between the baseline and these configurations is in reverse flow angles at the lower inboard boxes. The cascade vane forward angles at this region were reduced, the objective being to have less probability of reingestion and buoyancy problems compared to the baseline configuration. Therefore in case any of these issues is detected during flight test with the baseline cascade set, the use of alternative configurations would correct the problems. But these lower cascade vanes forward angles also reduce reversed thrust available. Thus, one of the alternatives configurations has greater engine speeds than the other configurations in order to recover the original thrust. Figure 4.15 shows the pathlines of these reverser cascades coloured by velocity magnitude.

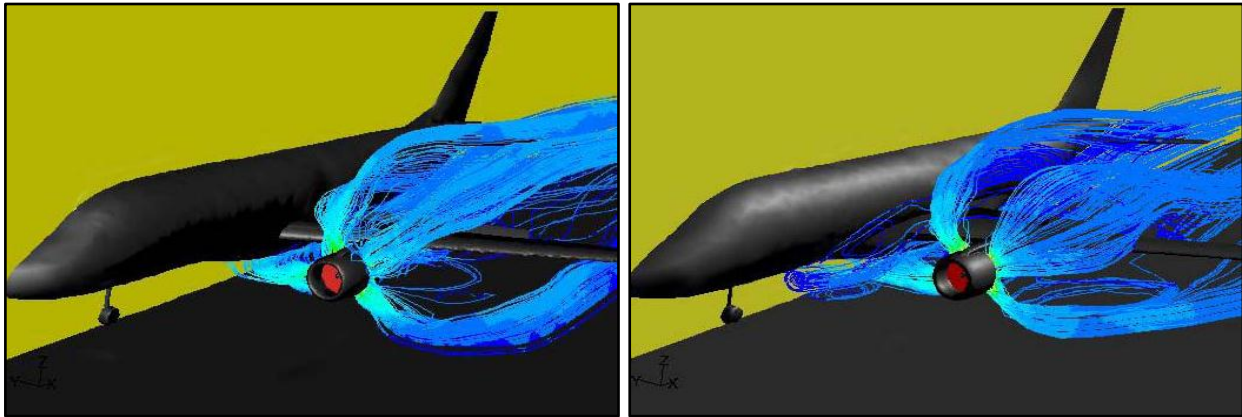


Figure 4.15: Pathlines of particles released from the reverser for the two alternative reverser cascade configurations. Images adopted from [Ref. 55].

Because the lower inboard cascade angles are less forward than the baseline configuration the flow meets the fuselage slightly closer to the wing root. Due to the higher thrust, i.e. the higher momentum the flow leaves the engine; the second alternative configuration has a more open plume, higher pressures levels on the fuselage and outboard slats, and a strong flow recirculation is induced below the fuselage before the nose landing gear.

Aircraft landing on wet runways affects aircraft operation, including the engine. Thus, certification tests are required for many different aircraft and engine configurations including the thrust reverser deployed. These tests have already been performed on the EMB-170. Figure 4.16, shows that water spray could generate during one of these tests using the reverser as well as a CFD result containing the trajectory of 10 μ m water droplets released just above the ground, coloured by velocity magnitude. One can notice that (Figure 4.16) (L) and (R) suggests a quite similar path of water particles. It is important to remark that in the CFD model the landing gear wheels were not spinning, but this seems to have no strong influence on the overall results.

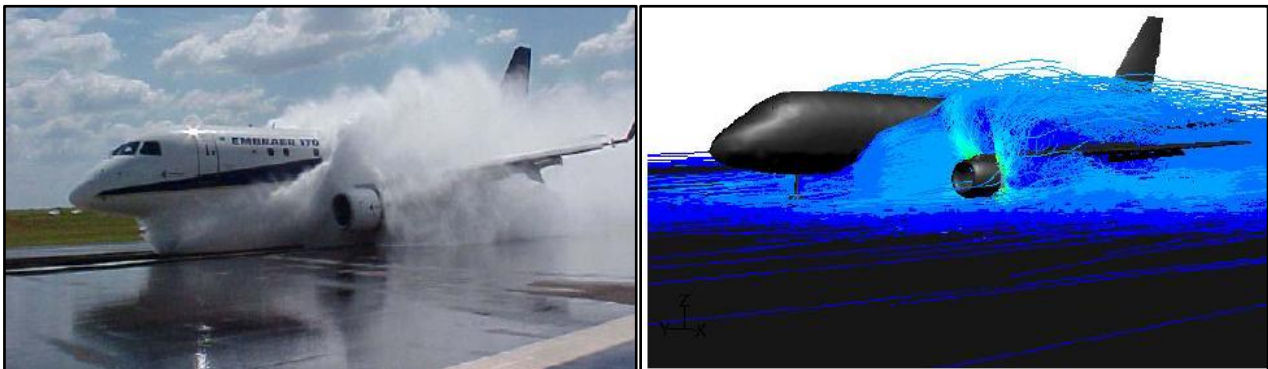


Figure 4.16: (L) Water spray test on EMB 170 aircraft. (R) 10 μ m droplets trajectory released from the ground for the CFD analysis. Images adopted from [Ref. 55].

4.7 Numerical Simulation of Vortex Flows for Airplanes in Ground Operations

An important part of the operational envelope for aircraft is maneuvering on the ground at low speed and high engine power setting. Military transport aircraft use thrust reversers to taxi around the ramp and backup into parking or loading areas. At these operating conditions the aircraft are subject to complex set of vortical flow activities. Additionally, the thrust reverser plumes interact with the vortical flow and might impinge on various airplane structures. [Ref. 56], carried out a CFD analysis to study the vortical system around a four engine aircraft operating on the ground with thrust reversers deployed. The analysis of such flows are complex. The flow is highly unsteady involving high speed jets, multiple vortices, unsteady ambient flow conditions and structural vibrations of aircraft components.

The rotational flow field induced by the inlet ground vortex can kick up dust, dirt and small debris off the ground that can be ingested into the engine, causing damage to the blades, reducing the life span of the engine and degrading its performance. Under certain conditions the vortex can be strong enough to dislodge sizeable objects from the ground (e.g. rocks, chunk of ice, concrete or asphalt) which can be ingested into the engine and cause Foreign Object Damage (FOD). The inlet vortex can also create severe inlet distortion that can cause engine surge and blades failure. This problem is amplified when the thrust reversers are deployed on the ground [Ref. 56].

The ability to understand and control inlet vortices around an aircraft is critical from both operational and economical points of view but the complex features of the flow are major obstacles to achieve it. The flow is highly unsteady with sporadic movement of the vortices on the ground and around the aircraft, depending on the ambient conditions. The unsteadiness is commonly caused by gusts of varying strength and directions, structural excitation of the aircraft airframe and unsteadiness caused by turbulence mixing of the thrust reverser plumes. In addition, the vortices are invisible and can be observed only when they contain dust particles or water droplets. Also, if the humidity level in prevailing flow is high, the vortices are rendered visible due to condensation in the low pressure regions of their cores. Engine integration issues associated with these types of flows have been traditionally addressed by employing cut and try approaches or knowledge based engineering obtained from experiments. Unfortunately, tests in controlled laboratory do not represent realistic conditions. Compounding the problem is complexity and cost associated with testing powered engines and thrust reversers. On the other hand, conducting full scale experiments requires subjecting the test aircraft to conditions that might damage the engine due to F.O.D and engine surge [Ref. 56].

The presence of circulation in the flow is necessary for the formation of inlet vortex. Circulation may be generated by the asymmetry in the configuration layout or the direction of the oncoming flow. The suction provided by the engine results in contraction of the streamlines towards the engine inlet. The angular momentum due to the turning of the flow in combination with the stagnation streamlines off the ground plane leads to the creation of the ground vortex. This mechanism can usually be considered as an inviscid phenomenon. Other sources of circulation are wind gusts, ground turbulence, wake flow of neighbouring aircraft components (i.e. wing, fuselage and empennage) and mixing of thrust reverser plumes when the reversers are deployed. Vortex elements can be formed between the engine and solid surfaces that are sufficiently close. For example, vortices can be formed between the engine and the fuselage, or between two adjacent engines [Ref. 56].

The complexity of a full scale aircraft required a general CFD code. In this study the OVERFLOW code was chosen due to its ability to handle arbitrary geometries and the vast experience in using it in many applications. The code computes solutions for the full Navier-Stokes equations using the overset grid system. The results presented in [Ref. 56] were computed using ARC3D diagonal scheme and a third order Roe scheme. A local time stepping scheme, a multigrid procedure and a low Mach number preconditioning were employed in order to accelerate the convergence to steady state. Turbulence was introduced into the ambient flow through the use of the field turbulence model, k- ϵ in OVERFLOW. The modelling doesnot include the engine internal flow. An inlet boudnary condition is used to establish the engine mass flow rate. The thrust reversers are modeled by imposing jet boundary conditions on the reverser openings on the engine cowl. Both core and fan reversers are included in the current model [Ref. 56].

An aircraft configuration that include a wing, fuselage and empennage was used to investigate the effects due to thrust reverser operations. Both core and fan thrust reversers were simulated and results for tail and headwinds are presented in (Figure 4.17). Contours of vorticity magnitude are plotted on the ground plane and the fuselage. In addition, the openings of the thrust reversers are colored by the Mach number. Streamtraces released on the ground plane show the ground vortex that exists under the inboard engine. The structure of the plume described by the streamlines released from the reverser openings (Figure 4.17b) is very similar in both conditions but the footprints on the ground (Figure 4.17c) are completely different. It is striking that the ground streamlines near the engines (inside the marked box) are almost identical in the two cases even though they orginate at the opposite ends of the flow domain. These results show that the thrust reversers play a profound role in establishing the flow structure by creating a barrier around the configuration, forcing the capture streamtube to approach the engines from a locally restricted direction, independent of the far field flow [Ref. 56].

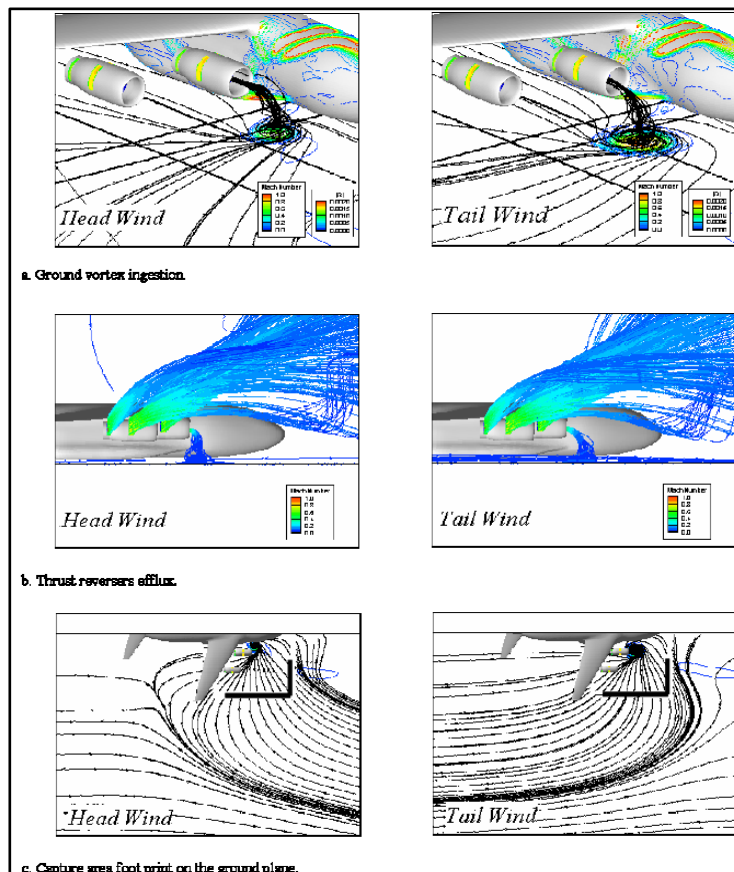


Figure 4.17: Effects of thrust reversers on vortex structure. Images adopted from [Ref. 56].

Further insight into the flow structure can be gained by examining the capture streamtubes as shown in (Figure 4.18). Red and blue streamlines terminate at the inboard and outboard engines inlets representing the respective capture streamtubes. Green and black streamlines originate at the inboard and outboard thrust reversers, respectively. Note that the blue streamlines do not touch the ground at either flow condition; hence no inlet vortex forms underneath the outboard engine.

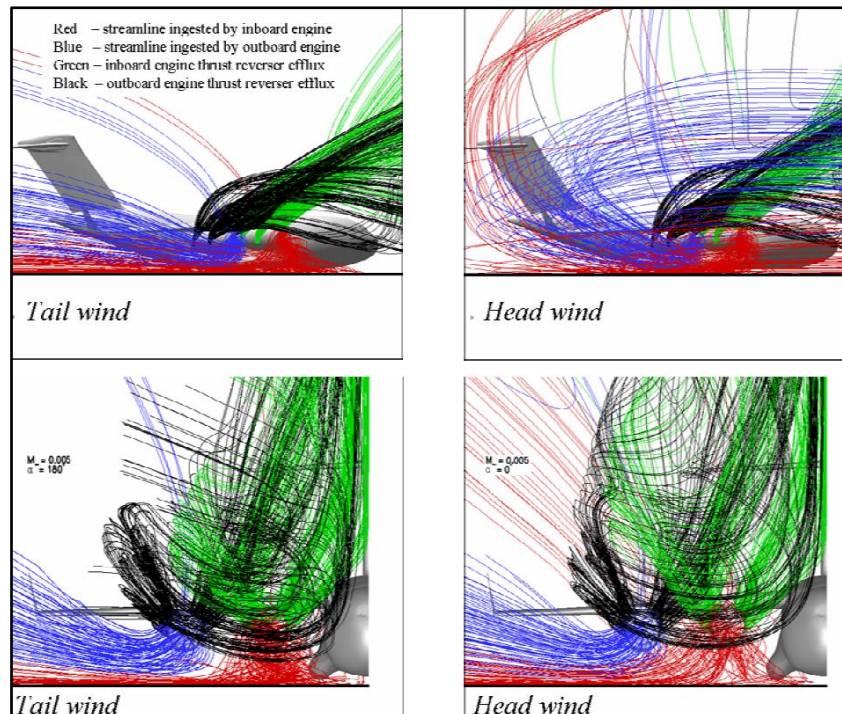


Figure 4.18: Streamtube capture area under thrust reverser operation. Images adopted from [Ref. 56].

Comparisons of the numerical simulations with observations of vortical flow around full scale aircraft are presented in (Figure 4.19). Here, the exact conditions in which these aircraft operated are not known, but the general structure and the locations of the inlet ground vortex systems are very similar to the compound flow fields. Note that for the aircraft shown at the bottom of (Figure 4.19) the actual thrust reversers plumes are visible due to the dust particles ingested by the engine [Ref. 56].

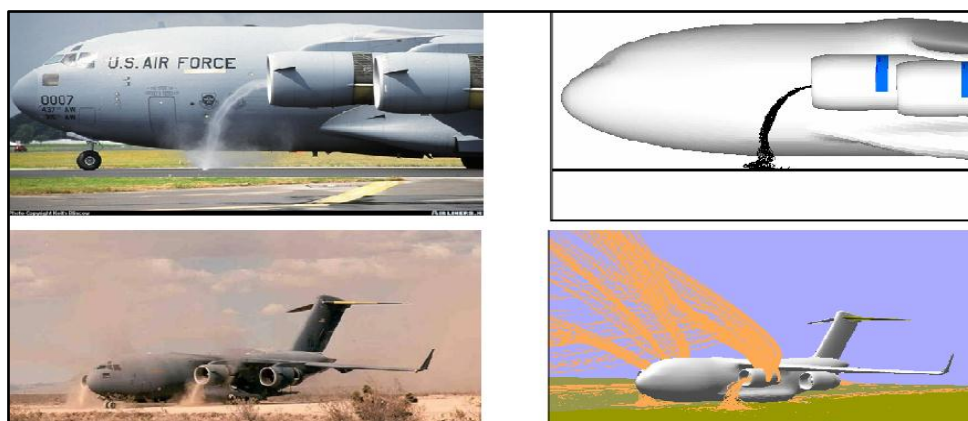


Figure 4.19: Comparison of numerical simulations with observed vortical systems. Images adopted from [Ref. 56].

4.8 Study of the Influence of Aircraft Geometry on the Computed Flow field during Thrust Reversers Operation

In Ref 8, the effects of the geometric configurations of the aircraft on the computed flow field during thrust reverser operation were evaluated. Three different configurations, representative of a regional aircraft with wing-mounted engines in landing with using a cascade thrust reverser, were defined: (i) baseline geometry with clean wing configuration and without landing gears and spoilers, (ii) an intermediate geometry containing the baseline with wingtips, flaps, and slats deployed, (iii) a complete configuration including landing gears and spoilers to the intermediate geometry [Ref. 57].

For each configuration a tetrahedral mesh was generated attempting to preserve similar levels of refinement in the regions that were not modified from one configuration to the other. The baseline mesh had around 1.6 million cells, the mesh for the intermediate configuration had 3 million cells and the complete geometry 5 million cells. Figure 4.20, shows the surface meshes for the basic, intermediate and complete cases [Ref. 57].

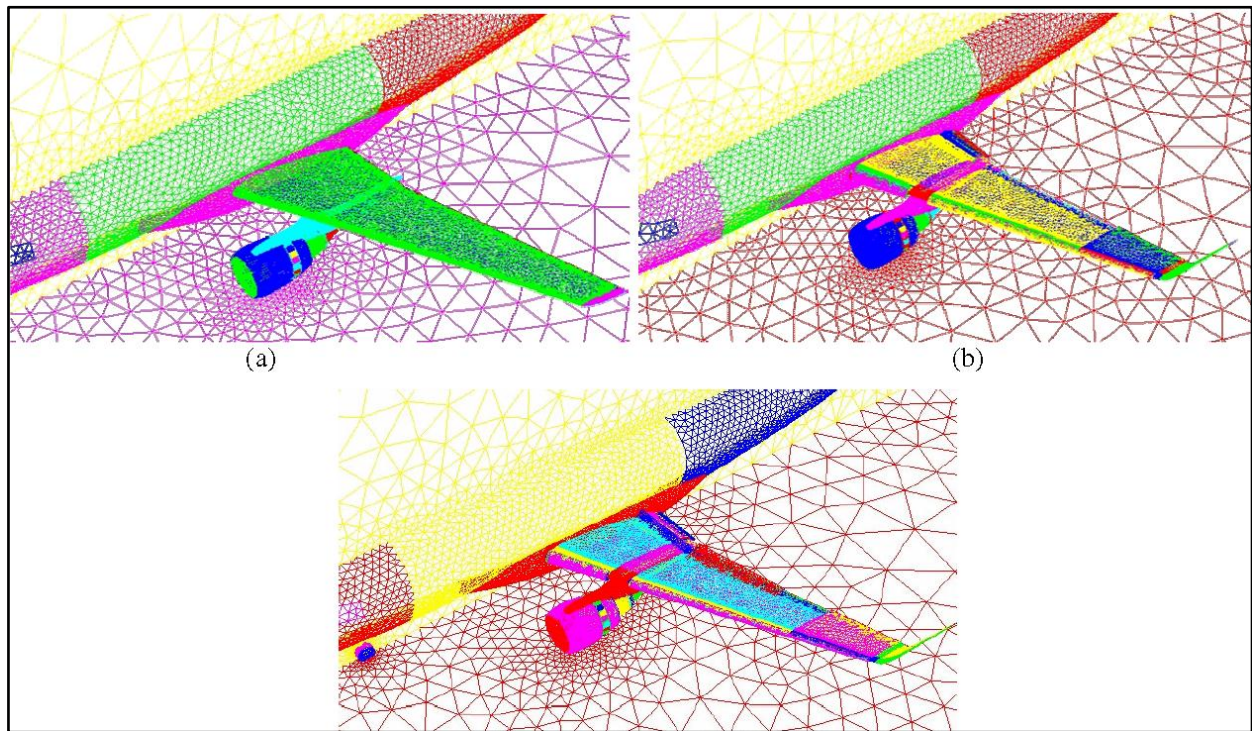


Figure 4.20: Meshes (a) basic configuration, (b) intermediate configuration, and (c) complete configuration [Ref. 57].

A commercial CFD package, FLUENT was used to analyse all the configurations considering aircraft landing speeds of 50 knots (25.7m/s) and 60 knots (30.9m/s). The models were 3D, steady state models, and, an implicit, coupled solver was used to solve the governing equations, together with a realizable k- ϵ turbulence model with standard wall functions. The interpolation scheme used for the convection term, discretization of turbulence kinetic energy and turbulence dissipation the First-Order Upwind Scheme was used. The algorithm applied for the pressure-velocity coupling is SIMPLE. The convergence criteria for the thrust reverser applications was established for the point when the residuals for continuity, x, y, and z velocity components and energy were below 10^{-3} . This is the default value in FLUENT which was considered satisfactory due to the complexity of the problem. The convergence is achieved when the residuals are stable and no longer change with

iterations. For the turbulence quantities, the turbulent kinetic energy, k , and turbulent dissipation rate, ϵ , the convergence was achieved when the residuals were below 10^{-5} [Ref. 57].

The external domain is considered a pressure far field boundary, with sea level pressure and standard atmospheric temperature. The gauge pressure is 101,325 Pa. The fluid (air) velocity is considered only in the x-direction, which is aligned with the fuselage axis. The ground is treated as moving ground, moving with the same velocity and direction as the relative wind. The static temperature is 288 K. A target mass-flow rate representative of a thrust reverser operation condition was prescribed for the nacelle inlet. Total pressure and total temperature values corresponding to thrust reverser operation were imposed at the engine core exhaust while components of velocity and static temperature were prescribed for each reverser panel.

The iso-surface of total temperature allows observing the envelope affected by the reverser plume. Figure 4.21L, shows the iso-surface of total temperature (290K) for basic, intermediate and complete configuration, and for landing speeds of 50 knots and 60 knots. The basic and intermediate cases show that at 60 knots there is no risk of ingestion. On the other hand, the complete configuration, which includes the landing gear, shows that the flow is affected by the change in the geometry, but still maintains the result of no re-ingestion of the reverser plume originated from the region between the nacelle and fuselage. However, at 50 knots the temperature contours show flow re-ingestion at all three configurations.

Figure 4.21R, shows the contours of total temperature on plane coincident with the fan face for the three configurations and the two landing speeds. Regarding the 60 knots case it is possible to confirm in (Figure 4.21R), the influence of the landing gear on the different format of the plume present in this configuration, as it pushes the plume of the reverser and spreads it around the region between the nacelle and the fuselage. Thus, it seems that an adequate representation of the landing gear in the CFD model is definitely necessary for computations of thrust reverser flows. Again, a final conclusion could only be stated after comparison with experimental results [Ref. 57].

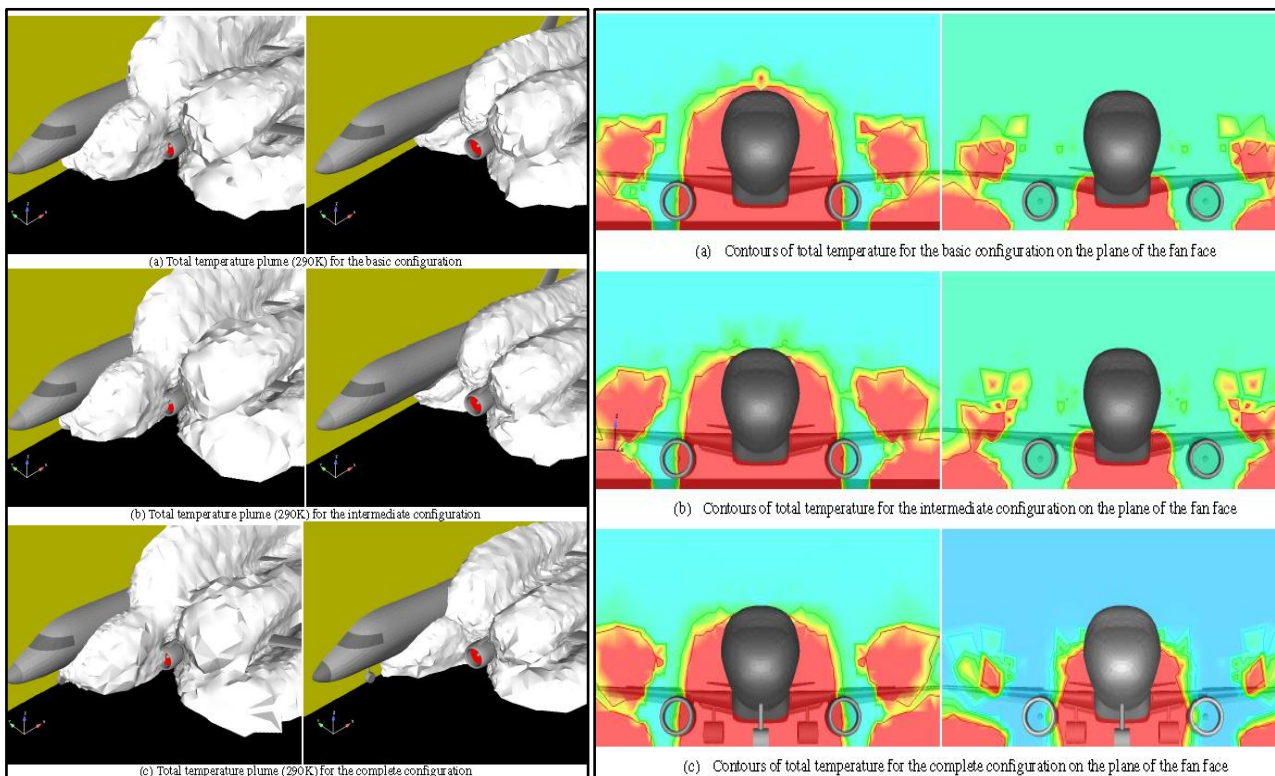


Figure 4.21: (L) Iso-surface of total temperature at 290K for the three configurations: (a) basic, (b) intermediate, and (c) complete, for landing speeds of 50 knots (left side) and 60 knots (right side). (R) Contours of total temperature in the plane of the fan face for three configurations: (a) basic, (b) intermediate, and (c) complete, for landing speeds of 50 knots (left) and 60 knots (right side) [Ref. 57].

4.9 Numerical Simulation of Thrust Reverser for Rear Mounted Engine

The objectives of the study carried out in [Ref. 58] were to establish the feasibility, including robustness and accuracy, of the evaluation of the performances of thrust reverser systems through numerical simulations. The approach consisted to start with an isolated engine configuration, then to apply numerical settings to a generic rear mounted engine configuration. Due to the complex geometrical arrangements of the system under scrutiny, the choice of the unstructured code CEDRE developed by Onera was made. CEDRE is a multiphysics computational tool for numerical simulations in the field of energetics (with particular emphasis on propulsion application) developed and validated by Onera. The code can handle several coupled physical subsystems through internal or external couplings. It solves the multi-species, reactive Navier-Stokes equations, thanks to an iterative implicit time marching algorithm (GMRES). Auto-adaptive local time stepping algorithms can be used for steady state computations. This considerably enhances the code robustness. The spatial discretization relies on second order flux splitting MUSCL schemes. Several turbulence models can be activated, comprising an in house (k, L) RANS model, complemented by ad-hoc wall treatments, which was used for the present works [Ref. 58]. Only the results for the half aircraft with installed engine and reverser are presented (Figure 4.22).

Due to the symmetry, one simulated only half of the aircraft. The aircraft was placed inside a box. This box is a computational domain. The 3D hybrid unstructured mesh was built constituted of tetrahedrons and prisms.

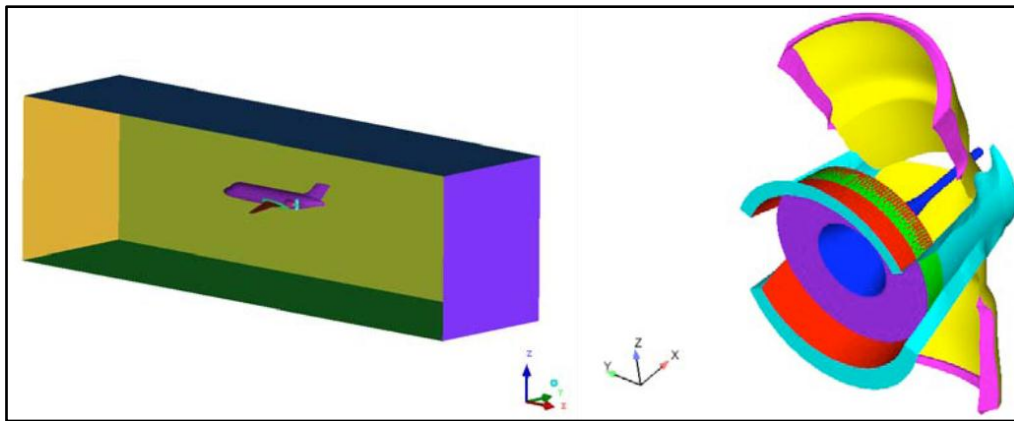


Figure 4.22: Installed engine whole computational domain and zoom on the reverser [Ref. 58].

The boundary conditions were specified at the engine air intake plane (representative of the engine operating point) and the engine exit plane was chosen as the mixer exit plane where the boundary condition was constructed from the first configuration computation. This permitted to run the installed configuration with realistic engine data. The solution was run on sixty four CPUs, and the

physical time of the computation on the cluster was roughly fourteen hours. This duration was judged compatible with industrial processes [Ref. 58].

The solution convergence criteria is set by considering the global inlet/outlet mass flow rate convergence. The reverse thrust convergence was also observed. Here, the x-momentum fluxes on boundaries are direct output from CEDRE code. Let one introduces, F'_x , sum of x-momentum fluxes on well chosen boundaries.

$$F'_x = \int_{\text{Jet inlets} + \text{Specific Engine Walls}} (P n_x + \rho(\vec{v} \cdot \vec{n}) v_x) ds$$

Moreover, one can write an expression of the reverse thrust:

$$F_x = \int_{\text{Engine Outlet Section}} ((P - P_a) n_x + \rho(\vec{v} \cdot \vec{n}) v_x) ds$$

And on the closed surface, one can write:

$$F_x + F'_x - \int_{\text{Jet inlets} + \text{Specific Engine Walls}} P_a n_x ds = 0$$

Then, one can write an expression of the reverser thrust F_x , supplied by CEDRE:

$$F_x = - \int (P n_x + \rho(\vec{v} \cdot \vec{n}) v_x) ds + P_a \int n_x ds$$

As P_a is a constant, one can consider that F_x convergence is achieved when F'_x convergence is achieved. Though, the evaluation of the P_a term in the equation above is necessary to evaluate the value of the reverse thrust, and its convergence level in percentage [Ref. 58].

Rather good convergence was obtained, with small residual fluctuations due to low frequency wake instabilities behind the thrust reverser doors.

Figure 4.23, shows total pressure iso-contours, and, engine jet streamlines. On the left side, one can see that total pressure iso-contours are fairly similar to those obtained in the isolated case. On the right side, one verified that the hot jet do not interfere with critical plane walls, such as the rear end and vertical tail.

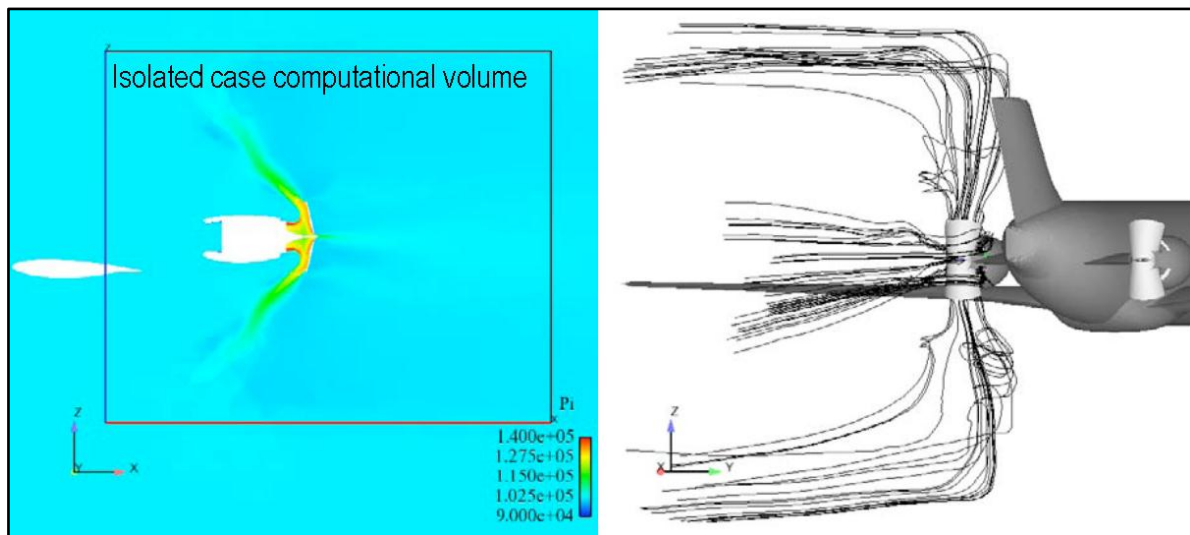


Figure 4.23: Total pressure iso-contours, and, engine jet streamlines [Ref. 58].

4.10 Observations on the Design of Cascade-less Thrust Reversers – CFD Analysis

Cascade-less thrust reverser offers the potential both to save weight and to simplify the construction of a nacelle. Potential issues inherent in the concept however relate to the difficulty of flow turning and efflux tailoring. Cascade-less thrust reverser is also commonly known as natural blockage thrust reverser. The thrust reverser operates on the fan stream, and the concept was first used on Bombardier aircraft. The Bombardier natural blockage thrust reverser design for the CRJ700/900 has increased reverse thrust efficiency, allowing the engine to run slower in reverse mode. It also has a novel counter-balance mechanism, which eliminates the need for powered door operation. Studies, on natural blockage thrust reverser have found that the flow entering the fan duct is presented with a rapid expansion, while the reverser is fully deployed. A typical natural blockage reverser along with a base line cascade reverser is shown in (Figure 4.24).

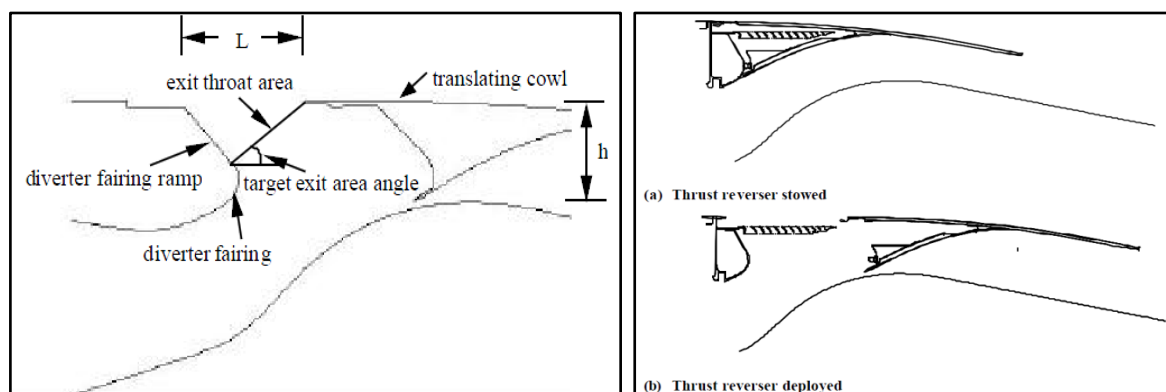


Figure 4.24: (L) Natural blockage reverser. (R) Cascade type reverser. Images adopted from [Ref. 59].

CFD simulation were performed on a two dimensional model using FLUENT in order to understand the aerodynamic performance of the natural blockage thrust reverser. First, CFD analyses were run on the baseline configuration, than five other CFD cases were run for the natural blockage

reverser as shown in (Figure 4.25). Ref 10, defines five principles to be followed in order to satisfy the design of a natural blockage reverser. It can be seen from (Figure 4.25) that case 5 meets all the principles with the result that the flow pattern is the best from all of the natural blockage thrust reverser configurations tested.

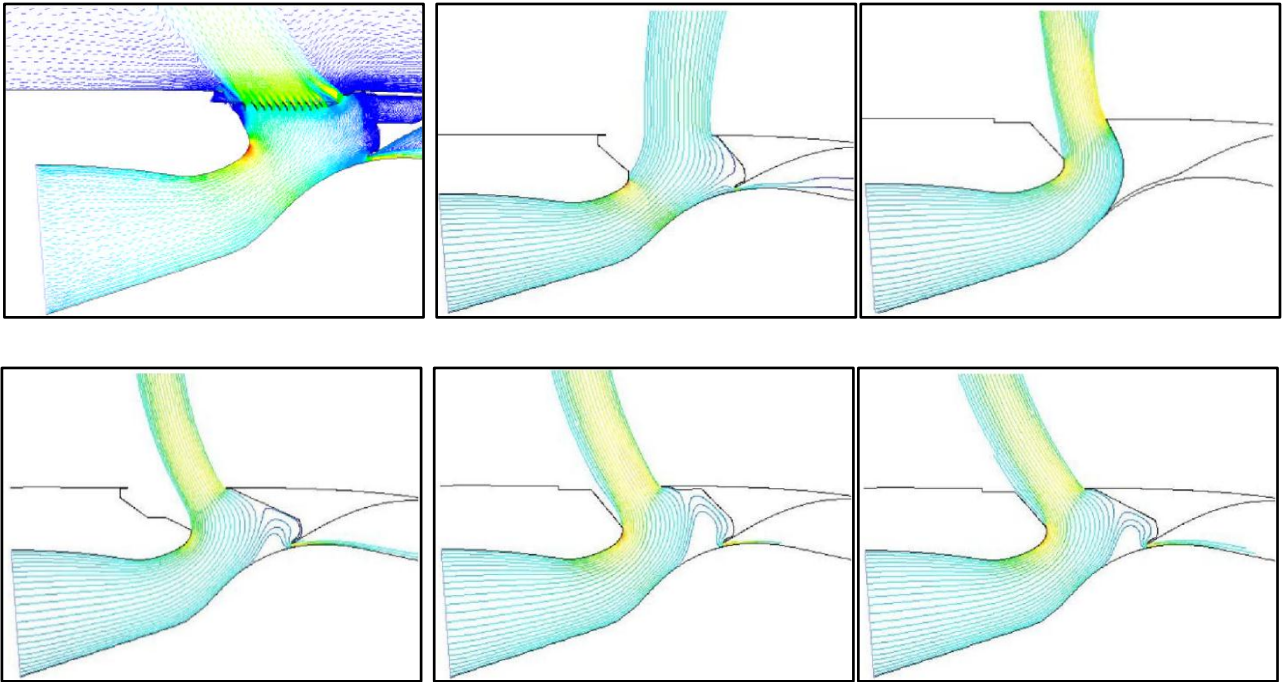


Figure 4.25: (T-Left) Baseline case, (T-Midd) Case 1, (T-Right) Case 2, (B-Left) Case 3, (B-Midd) Case4, (B-Right) Case 5. Images adopted from [Ref. 59].

Chapter 5. Thrust Reverser Performance at Integrated Aircraft-Engine Level- Separate Exhaust Turbofan

This chapter discusses thrust reversing techniques for a separate exhaust high bypass ratio turbofan engine and its effect on aircraft and engine performance. Cranfield University is developing suitable thrust reverser performance models. These thrust reverser performance models will subsequently be integrated within the TERA (Techno-economic Environmental Risk Analysis) architecture thereby allowing for more detailed and accurate representations of aircraft and engine performance during the landing phase of a typical civil aircraft mission.

The turbofan engine chosen for this study was CUTS_TF (Cranfield University Twin Spool Turbofan) which is similar to the GE90-94B engine and the information available in the public domain is used for the engine performance analysis along with the Gas Turbine Performance Software, 'GasTurb 10' [Ref. 60]. The CUTEA (Cranfield University Twin Engine Aircraft) which is similar to the Boeing B777 is used alongside with the engine model for the thrust reverser performance calculations. The aim of this research is to investigate the effects on aircraft and engine performance characteristics due to the cascade type thrust reverser deployment. The chapter will look into the overall engine performance characteristics and how the engine components get affected when the thrust reversers come into operation. This includes the changes into the operating point of fan, booster, HP compressor, HP turbine, LP turbine, bypass nozzle and core nozzle. Also, thrust reverser performance analyses were performed (at aircraft/engine system level) by varying the reverser exit area by $\pm 5\%$ and its effect on aircraft deceleration rate, deceleration time and landing distances were observed.

5.1 Introduction

A thrust reverser system is designed to operate mainly when the aircraft touches ground during landing. On large turbofan engines with separate exhausts, when thrust reversers get deployed they produce a rearward acting force using the fan-stream flow. This study is carried out on an engine model similar to the GE90-94B engine which makes use of a cascade type thrust reverser as shown in (Figure 5.1). The cascade thrust reverser uses the blocker doors, actuated by the motion of translating sleeve to block the engine fan flow. The cascade type reverser has movable translating sleeves which slide rearward to uncover the cascades installed on the fixed structure around the fan flow. Blocker doors are installed on the translating sleeves. They are pivoting into the airflow while the translating sleeves are moved aft. In this position the blocker doors are blocking the airflow passage to the rear. Thus, the fan flow of the engine exits through the cascades, which deflect and accelerate the airflow into its final direction. The cascade type thrust reverser, creates low actuator loads and allows a very precise control of the airflow during reverse thrust operation. Cascade thrust reversers are known for their high degree of structural integrity, reliability and tolerance to various aircraft applications. On cascade type reversers LVDTs are used for the sensing of the translating sleeve position by the FADEC computer [Ref. 9]. Conventional cascade type thrust reversers are commonly used on commercial aircraft equipped with high bypass ratio turbofan engines.

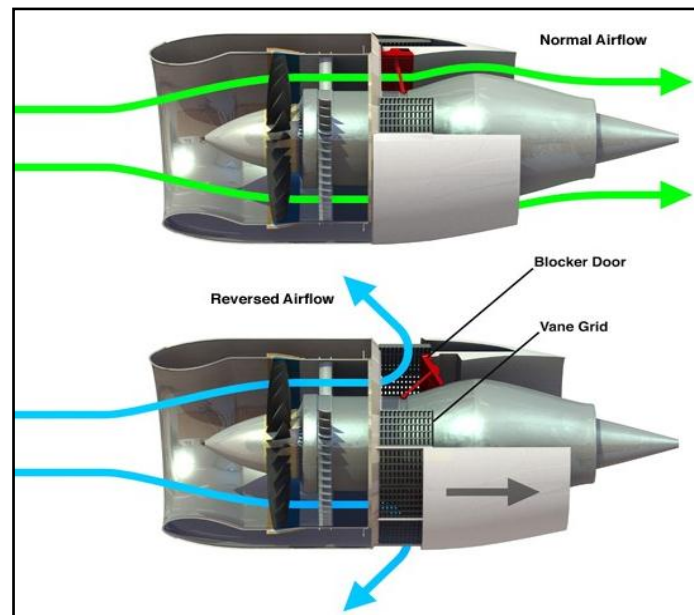


Figure 5.1: The cascade type thrust reverser. Images adopted from [Aircraftengines.net].



Figure 5.2: B777 landing with deployed thrust reverser. Image adopted from [www.flickr.com]

5.2 Engine Components Overview

The CUTS_TF turbofan engine is similar to the GE90-94B engine (Figure 5.3). The CUTS_TF is a two shaft turbofan engine of high bypass ratio. The engine comprises a single stage fan with a diameter of approximately 3.124m (123 in). The fan has 22 shroudless wide-chord blades made of intermediate modulus graphite/epoxy composite with replicable titanium leading edge guards and a polyurethane coating on the concave side. Each blade weighs approximately 15.4kg (34lb). The outlet guide vanes are structural and the fan case incorporates a pylon mount with an integrally stiffened structure which bypasses loads around the core. Three stage LP compressor (booster) rotating with the fan thus, at low rpm and moderate pressure ratios. Ten stage HP compressor, employing a Variable Inlet Guide Vane (VIGV) and five stages of Variable Stator Vanes (VSVs). Dual Annular Combustor (DAC), inner and outer chambers are perforated by many thousands of holes drilled by laser at an acute angle. Each has its thirty air spray fuel nozzles. The double annulus has been specifically designed for minimum NO_x emissions. During starting and low power operation, the engine is fuelled by the outer nozzles only. At take-off and during cruise, both rings of nozzles are in operation. Two stage HP turbine of small diameter with cast mono crystal blades

of N5 material with laser drilled cooling air holes held in powdered metal (Rene R88DT) boltless discs with smooth side plates for minimum windage losses. Six stages of large and increasing diameter LP turbine, the casing has active clearance control. The use of six stages on LP turbine provides low stage loading for improved efficiency and reduced noise. The nacelle incorporates a translating cowl and cascade type reverser. The FADEC system provides enhanced diagnostics and also controls fuel flow, variable IGV scheduling and active clearance control [Ref 62].

The CUTS_TF engine also incorporates bleed valves at the end of LP compressor, third stage of the HP compressor and at the end of HP compressor. When the bleed valves downstream of a compressor are opened the compressor map is left unaffected but the working line shows a steep change away from surge, thus maintaining acceptable part surge margin. Handling bleed valves downstream of the compressor may be opened at part power. This has the effect of requiring a higher compressor mass flow thus lowering the working line to a satisfactory level. The disadvantage of bleed valve is that they increase SFC and TET at the given part power level of thrust, as well as adding cost, complexity and weight. Variable stator vanes are closed at part power, sliding the compressor map to the left (lower flow). The stability state working line is unchanged and so more low power stability margin is available. Variable stator vanes do not have the performance penalty associated with the handling bleed valves, but can be of higher cost, complexity and weight.

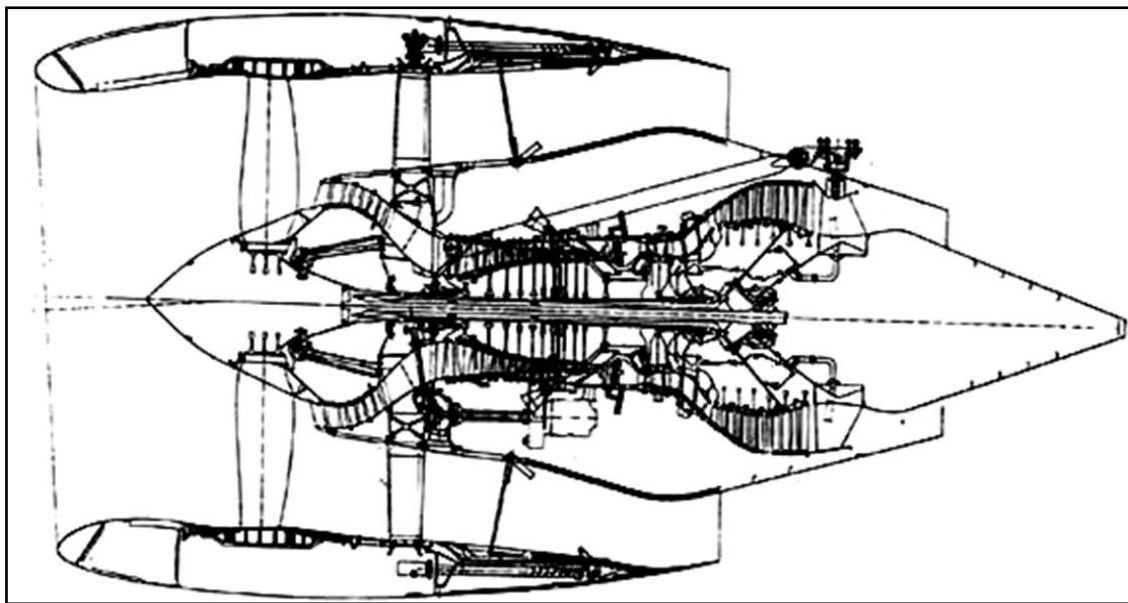


Figure 5.3: GE90-94B nacelle longitudinal cross section. Image adopted from [Ref. 62].

5.3 Engine Design Point and Off-Design Study

Initially, an engine design point study was carried out for the CUTS_TF engine at sea level static (SLS) condition i.e. maximum power; that is when it is operating at a particular speed, turbine entry temperature (TET), pressure ratio (P.R), and mass flow (W) for which the components were designed [Table 5.1]. The variation of performance of the gas turbine over the complete operating range of speed and power output, normally referred to as the off-design engine performance, was also performed at take-off, cruise, landing, reverse idle, and maximum reverse thrust mode. The data available in the public domain was used for this study together with the performance software 'GasTurb 10'. Performance graphs for the fan, LP compressor, HP compressor, HP turbine, LP turbine, bypass and core nozzles were then plotted.

The design and off-design performance studies are beneficial as they allow a comparison of thrust reverser operation with other operating conditions. The compressor, turbine and nozzle design and off-design study are described below in section 5.4, 5.5 and 5.6. The off-design operating conditions such as take-off, cruise, landing etc. are abbreviated by suffix 5.4.2, 5.4.3, 5.4.4 and so on.

Table 5.1: CUTS_TF Design Point and Off-Design Study

Engine Parameters	Design Point	Off-Design				
	DP SLS Max Power	Take-off M=0.24	Cruise Alt=10,670m M=0.80	Forward Idle Thrust M=0.221	Idle Rev/Thrust M=0.211	Max Rev/Thrust M=0.211
Engine Mass Flow (kg/s)	1467	1521.9	575.7	807.9	944.79	1407.4
BPR	8.4	8.47	8.1	11.9	11.69	9.5
OPR	39.6	39.17	42.96	12.94	15.8	31.6
TET (K)	1712	1712	1584	1250	1300	1580
EPR	1.39	1.35	1.25	1.03	1.06	1.24
s.f.c	8.3	11.04	15.6	11.91	10.94	10.02
$V_{\text{Bypass}} / V_{\text{Core}}$	0.82	0.84	0.8	1.23	-	-
Propulsive Efficiency	0	0.41	0.76	0.57	0.538	0.408
Thermal Efficiency	0.537	0.54	0.59	0.36	0.37	0.52
Fan Nozzle Effective Area (m ²)	3.6	3.6	3.6	3.6	3.78	3.78
Core Nozzle Effective Area(m ²)	1.011	1.011	1.011	1.011	1.011	1.011
Fan Gross Thrust (kN)	359.2	385.6	188.8	123.1	-	-
Core Gross Thrust (kN)	57.56	60.4	30.4	9.22	12.98	41.62
Net Forward Thrust (kN)	416.8	321.2	82.56	74.68	-	-
Gross Reverse Thrust(kN)	-	-	-	-	128.09	263.45
Net Reverse Thrust (kN)	-	-	-	-	182.56	322.3

5.4 Compressor Off-design Performance

In this section the performance of Fan, LP compressor and HP compressor are discussed. The compressor rotor is driven by the turbine, via connecting shaft. It is rotated at high speed by the turbine causing air to be continuously induced into the compressor. The pressure rise results from the energy imparted to the air by the rotor. The air is passed through the downstream stator, where swirl is removed and rise in static pressure is achieved. The rise in the stage total pressure is proportional to the change in tangential or whirl velocity across each stage. As the air passes through each stage the air pressure and temperature increases progressively. It must be realized at the outset, however, that any compressor will be required to operate at conditions far removed from the design point including engine starting, idling, reduced power, maximum power,

acceleration and deceleration. Thus, it is clear that the compressor must be capable of satisfactory operation over a wide range of rotational speeds and inlet conditions. With the compressor blading and annulus dimensions chosen to satisfy the design point condition, it is obvious that these will not be correct for conditions far removed from the design. Compressor blading had a limited range of incidence before losses became unacceptably high, resulting in low compressor efficiency. Also, blade stalling may lead to surging of the compressor. The HP compressor speed lines are not distributed linearly with the flow; this is because the CUTS_TF, HP compressor, is a ten stage compressor with the first five stages variable i.e. fitted with variable stators. These VSVs are open progressively as speed increases, causing an exaggerated increase in flow in the medium to high speed region. At low speeds, the variable stators are locked causing a more linear relationship between speed and flow. Also, note that beyond 100% flow the speed lines for fan, booster and HP compressor closes rapidly due to choking. Beyond choke any further increase in speed will generate no further increase in airflow. The slightly curved, near vertical, lines on the main part of the compressor map are the (constant rotational) corrected speed lines. They are a measure of a rotor blade tip Mach number.

The variation of mass flow and pressure ratio with rotational speed of the compressor is plotted (Figure 5.4, 5.5 and 5.6). The operating point on the compressor is primarily dictated by the components surrounding it, as opposed to the compressor itself; where the constant speed lines become vertical on the basis when the inlet is choked. The equilibrium running points for a series of speeds at sea level static (SLS) and cruise conditions are plotted and joined up to form an equilibrium running line. Figure 5.4, 5.5 and 5.6 also shows the proximity of the operating line or zone to the compressor surge line. The pressure ratios obtained at various operating conditions are presented in [Table 5.2].

Table 5.2: Compressor Pressure Ratios at Different Operating Conditions

Engine Operating Conditions	Fan P.R.	LPC P.R.	HPC P.R.
Sea Level Static (max-power)	1.69	1.1	23.0
Take off (M=0.24, 160knots)	1.68	1.12	22.5
Cruise (Alt=10,670, M=0.8)	1.76	1.11	23.9
Landing at (M=0.211,145knots)	1.25	1.04	12.5
Idle Reverse Thrust (at M=0.211)	1.19	1.04	10.8
Maximum Reverse Thrust, area 5% increased (at M=0.211)	1.54	1.09	20.2
Maximum Reverse Thrust, area 5% increased (at M=0.09, 60knots)	1.54	1.08	20.5

Table 5.3: SLS design point values of isentropic efficiencies, specific work and r.p.m

Compressor Components	Assumed Isentropic Efficiency	Specific work (kW/(kg/s))	R.P.M
Fan	0.92	50.85	2465
LP compressor	0.91	10.14	2465
HP compressor	0.91	542.13	9411

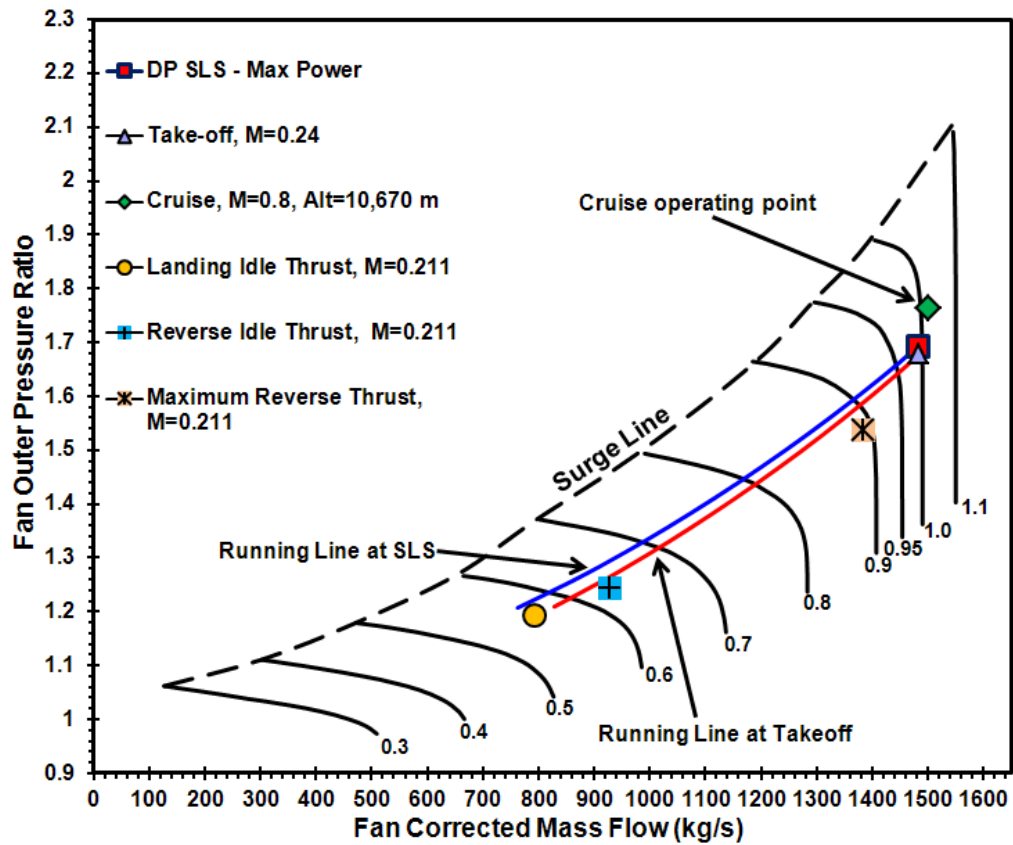


Figure 5.4: Fan PR against the corrected mass flow for different engine operating conditions

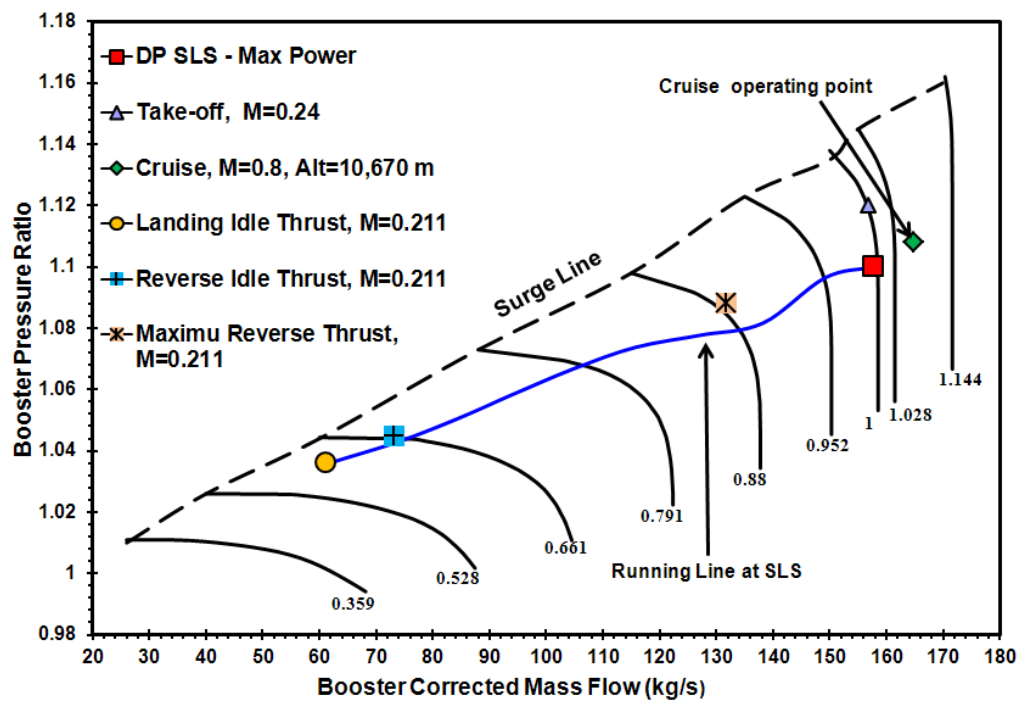


Figure 5.5: LPC PR against the corrected mass flow for different engine operating conditions.

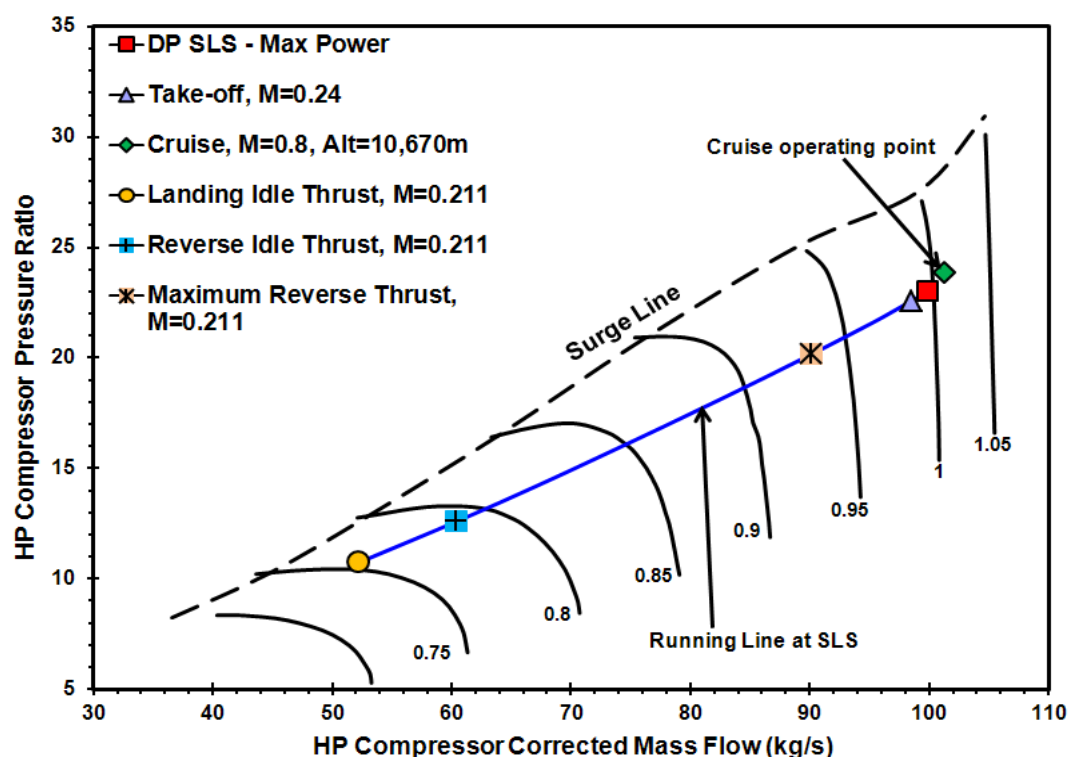


Figure 5.6: HPC PR against the corrected mass flow for different engine operating conditions.

5.4.1 SLS

Once the passengers have boarded the aircraft and the aircraft doors are closed; pilot completes his 'Before Start' check list. The next step is to shut down the APU and perform 'after start check list' and then request taxi clearance. The pilot then releases brakes and taxi to the assigned runway. Idle thrust is sufficient to keep the aircraft rolling.

5.4.2 Take-off

Once the aircraft is cleared for take-off, the pilot brings the engine to 60% rpm of low pressure turbine (this is done to prevent flame out on take-off due to compressor stall). The aircraft accelerates along the ground at a nearly constant angle of incidence which is determined by the design of the undercarriage and by the distribution of the aircraft weight upon it. At a speed of about 0.12 M (80 knots) the pilot hits the TO/GA (take-off and go around) switch to set take-off thrust. The engine thrust then increases to the computed take-off power i.e. the aircraft high management computer will determine the power needed by engines to take-off based on a number of factors such as runway length, wind speed, ambient temperature, and most importantly the weight of the aircraft. At this point the aircraft is accelerating at maximum power. Once the aircraft successfully exceeds the decision speed, V_1 , and reach the rotation speed V_R the pilot uses the elevator control to begin the rotation of the aircraft in the nose-up sense, usually achieving a mean rate of rotation in the region of $2.5^\circ - 3^\circ$ per second. As the rotation begins the angle of incidence and lift coefficient increases and soon after the start of the rotation the nose wheel leaves the ground. As the lift becomes equal to and then exceeds the aircraft weight the main wheels leave the ground, the speed at which this occurs is the lift-off speed, V_{LO} . The take-off condition was considered at 0.24 M (160 knots). At take-off, both the fan and core nozzles are unchoked and have an effect on the fan and booster running lines (Figure 5.4 and 5.5). The aircraft acceleration from zero to a take-off speed of 0.24 M pushes the fan running line away from the surge line

(Figure 5.4). Fundamentally, the increase of ram pressure means the fan utilises a low pressure ratio to push the required flow i.e. the fan pressure ratio reduces [Table 5.2]. This allows an increase in the engine mass flow, bypass ratio (BPR), propulsive efficiency and the fan gross thrust [Table 5.1].

A reduction in fan pressure ratio at take-off will be compensated by the increase in pressure ratio across the LP compressor. This will cause an increase in the stagnation temperature ratios. The temperature change across the LP compressor will also increase, thus increasing the specific work. Therefore, the rpm for the LP shaft will increase and the operating point on the LP compressor map at take-off will be slightly higher than that at SLS condition (Figure 5.5).

Although, the HP compressor inlet mass flow is greater than that at SLS condition the corrected mass flow will reduce along with the pressure and temperature ratios. Hence, the operating point at take-off will be shift down to a slightly lower value (Figure 5.6). The running line at take-off for the HP compressor is not plotted as it will be similar to that at SLS condition.

5.4.3 Cruise

At cruise the aircraft is in steady flight and the operating conditions were considered to be at an altitude and aircraft speed of Alt=10,670m and 0.8 M. The high aircraft forward speed together with low ambient pressure at cruise altitude will give rise to an increase in ram pressure. The value of TET/T_1 will be higher at cruise due to very low T_1 , thus, there will be a higher pressure ratio across the fan, IP compressor and HP compressor [Table 5.2]. The engine mass flow decreases significantly at cruise altitude due to the decrease in ambient pressure and density. The products of the LP turbine and fan bypass efficiencies define the optimum ratio of bypass jet velocity to that of the core velocity; from [Table 5.1] the value of V_{Bypass} / V_{Core} is about 0.8.

The fan compressor map (Figure 5.4) shows that at cruise operating point the non-dimensional mass flow will increase, there will also be a slight increase in the fan pressure ratio (FPR). The fan nozzle will be choked.

The HP compressor operating point at cruise is close to that at SLS condition. The values of bypass ratio and overall pressure ratio (OPR) will be greater at cruise when compared with the values at SLS. The cruise calculations do take into account the customer over board bleed (cabin pressurisation).

5.4.4 Landing

A practical limitation of the descent performance is often required. In the case of a transport aircraft cabin pressure changes must be limited to 300ft/min. The minimum engine thrust setting may be limited by the need to supply aircraft system with power. The thrust setting can still be very low on descent but is not negligible. The CUTEA aircraft will descend up to 0.48 M (320 knots), at which point the pilot will throttle down to 0.468 M (310 knots). As the aircraft passes through flight level of 5486m i.e.18,000 ft. the pilot will reduce speed down to 0.41 M (270 knots). Below 4572m (15,000 ft.) the pilot will throttle down to 0.38 M (250 knots) and below 12,000 ft. to 0.36 M (240 knots). Below 3,048 m (10,000 ft.) the landing lights and the seat belt sign will be put ON. The aircraft will glide slope with flaps at 15° and at 0.241 M (160 knots) the flaps will be at 20°. The undercarriage is lowered and the flaps are set to the landing configuration while the aircraft is at least 300m (948 ft.) above the sea level. The aircraft is then held in a straight glide path, usually at an angle of 3° to the horizontal, and as the height falls below 60m (197 ft.) the speed is gradually reduced [Ref 68 and 75].

The aircraft approaches the runway initially along the straight path, but if this straight approach were continued all the way to the ground the vertical component of velocity on impact would be unacceptably high and it is necessary to introduce a 'flare' in which the flight path curves upward. At approximately 15.24m (50 ft.) radio altitude, the autopilots start the flare manoeuvre. During flare, between 15.24m – 7.62m (50ft. and 25 ft.) radio altitude, the auto-throttle begins retarding the thrust levers to idle. In manual landing the pilot will retard throttle at 3.05 m (10 ft.) i.e. the thrust is set at idle just before the touchdown [Ref 75].

In the flare the pilot aims to reduce the vertical component of the velocity so that it is no more than about 0.5 m/s when the main wheels touch the runway, although the undercarriage is usually designed for a much higher vertical velocity component, of order 3 m/s. The point at which this occurs is known as the touchdown point, but at this stage the nose wheel will still be well above the runway and it is necessary to rotate the aircraft in the nose down sense before effective braking can be assisted by lift dumpers to reduce wing lift and thus increase the ground reaction, while also increasing the drag, and reversed thrust from the engine. At specific threshold or screen height, usually taken to be either 9.1m (30ft) the approach speed is required to be not less than 1.3 times the stalling speed, V_s [Ref 75].

The aircraft lands at a speed of about 0.211 M (140 knots). The operating point for the fan, LP compressor and HP compressor at this idle thrust setting are shown in (Figure 5.4, 5.5 and 5.6). The selection of idle thrust reflects several engine issues, including combustor stability, engine temperatures and surge margin levels. In addition certain applications impose their own particular requirements. The idle thrust is assumed at about 17% engine power. This will ease the change of thrust from forward to reverse thrust. At idle thrust the operating point for the fan has sufficient surge margin (Figure 5.4). The surge margin for the LP and HP compressors have reduced; the CUTS_TF engine incorporates the VIGVs, VSVs and variable bleed valves; thus, it is believed that in this regard the variable geometry will assist the LP and HP compressors at low power settings to overcome the surge problems.

5.4.5 Reverse thrust condition

After landing, the pilot will change the thrust from forward idle to reverse idle after both the main and nose landing gears have touched down on the runway (not before) and the lift dumpers become effective. As the pilot changes the thrust from forward idle to reverse idle the auto-throttle will disconnect automatically. The idle reverse thrust will be at a slightly higher power setting than the forward idle (Figure 5.4, 5.5 and 5.6) and [Table 5.2].

The pilot will then increase the reverse thrust from reverse idle to maximum reverse thrust. In this study, the maximum reverse thrust is assumed to be at 80% power [Table 5.1]; this is normally the case when the runway is short or when the runway is contaminated i.e. wet or icy. The operating points for the fan and HP compressor at maximum reverse thrust condition ($M=0.211$) shows that the surge margin will be sufficient. However, for the LP compressor the operating point at maximum reverse will move close to the surge. During the thrust reverser operation the TET will remain constant. The operating points at maximum reverse thrust are shown for the fan, LP and HP compressors (Figure 5.4, 5.5 and 5.6). The corrected mass flow and pressure ratio values will be much lower than that at SLS condition.

5.4.6 Thermal and Propulsive Efficiency between $M=0.211 - 0.09$ (140 – 60 knots)

The propulsive efficiency during aircraft landing will be about 0.62 i.e. about 78% of that at cruise. The higher the propulsive efficiency the greater the reverser thrust, and from (Figure 5.7) the value

is higher at high speeds and falls significantly as the aircraft speed falls. Therefore, it is due to this effect that pilots are advised to use thrust reversers as soon as the aircraft lands i.e. at high landing speeds. The thermal efficiency on landing, on the other hand, will be 0.35 i.e. about 65% to what it was as SLS condition. The thermal efficiency during the thrust reverser mode increases at reverse idle to what it initially was at landing. As the reverse thrust increases to maximum, the thermal efficiency raises to 0.52 an increase in comparison to the value at landing.

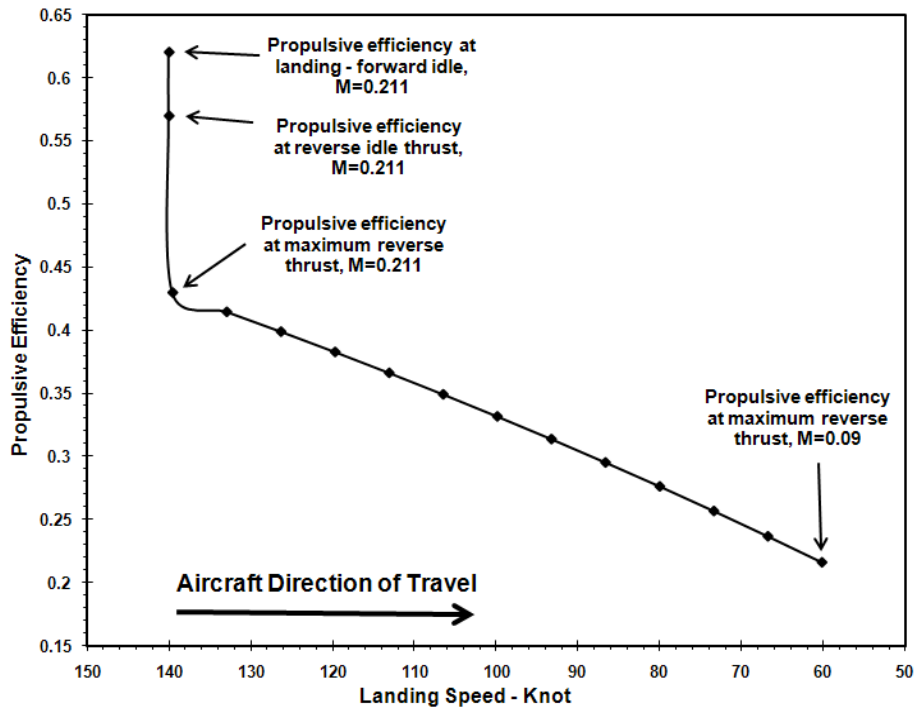


Figure 5.7: Variation of propulsive efficiency with aircraft landing speed (sea level).

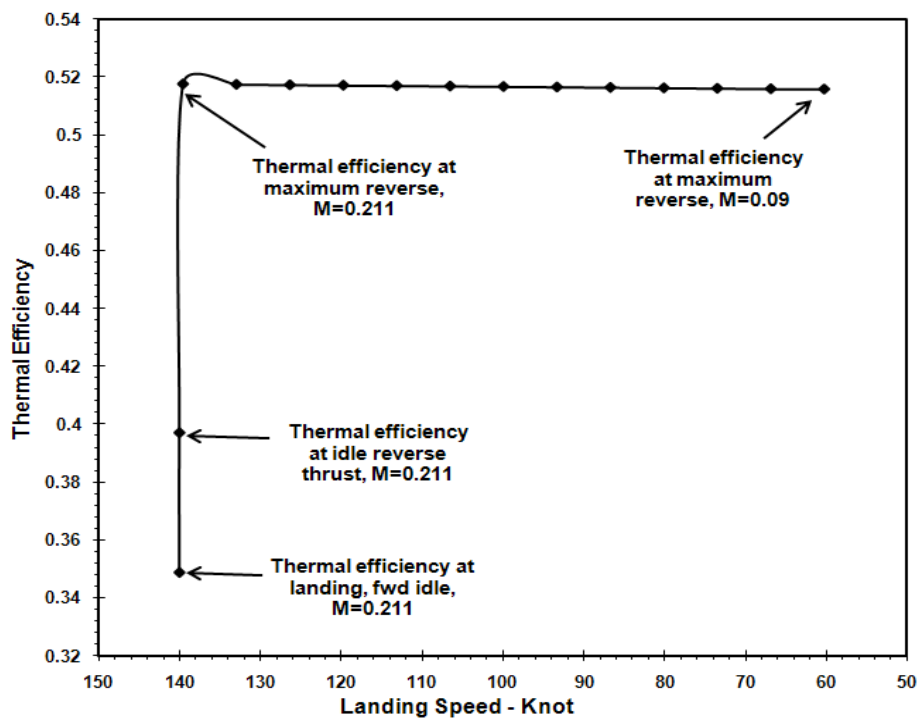


Figure 5.8: Variation of thermal efficiency with aircraft landing speed (sea level).

5.5 Turbine Off-Design Performance

The turbine assembly is downstream of the combustor forming a rear third of the jet engine when viewed as a whole. Having been highly compressed, mixed with vaporized fuel and ignited, the hot gas following the combustion process is forced through the combustor discharge nozzles into the HPT NGVs where, because of their aerodynamic convergent shape it is accelerated to about the speed of sound (about 850 m/s at a high turbine entry temperature) [Ref 76]. Simultaneously, the gas is swirled in the direction of the turbine blades' rotation. As the tailored gas flow enters and passes through the turbine blades the energy is extracted, their aerodynamic form creates torque, a rotational reaction force across each blade, causing them to turn the disc and shaft assembly driving the compressor.

The flow characteristics of a turbine must be carefully matched with those of the compressor to achieve efficiency and performance targets. If the turbine components allowed too low a maximum flow, then a back pressure would build up in the engine causing the compressor to surge. Conversely, too high a flow would cause the compressor to choke, where the total gas flow entering the compressor is greater than its working capacity due to imbalance between the two systems. Either condition would induce a loss in engine efficiency and performance. Every design is a compromise and the design methodologies used often require a lengthy iteration process to achieve the best overall solution. This series of iterative loops is required because of each component's inter relationship with other components [Ref. 54]. Once the turbine geometry has been fixed at the design point then the turbine map may be generated to define its performance under all off design conditions. It is often found in practice that turbines do not exhibit any significant variation in non-dimensional flow with non-dimensional speed, and in most cases the turbine operating region is severely restricted by another component downstream [Ref. 55]. The turbine map is represented by a series of curves as shown in (Figure 5.9). The map also shows a running line at SLS condition and at cruise operating point. There is no surge line in the turbine as surge does not occur in the accelerating flow.

Table 5.4, shows the pressure ratios across the HP turbine at different engine operating conditions. It is noticed that the turbine pressure ratio remains constant for all the operating conditions apart from the idle thrust where it reduces slightly. The HPT remains choked for the entire engine operating conditions, as long as the LPT turbine is choked. The HP turbine will operate at the fixed non-dimensional point i.e. at $PR \approx 4.2 - 4.8$ as shown in (Figure 5.9). The HP turbine will remain choked at all condition. The pressure ratio across the LP turbine vary as shown in the [Table 5.4], however, the LP turbine remains choked for all the engine operating conditions apart from idle thrust at which it operates unchoked. The maximum pressure ratio across the LPT is controlled by swallowing capacity of the downstream component i.e. the core nozzle.

Table 5.4: Turbine pressure ratio variation at different engine operating conditions

Engine Operating Conditions	HPT P.R	LPT P.R
Sea Level Static (max-power)	4.42	6.09
Take off (M=0.24, 160knots)	4.42	6.19
Cruise (Alt=10,670m, M=0.8)	4.42	7.35
Landing at (M=0.211, 140knots)	4.16	3.37
Idle Reverse Thrust (at M=0.211)	4.02	2.93
Maximum Reverse Thrust, area 5% increased (at M=0.211)	4.39	5.45
Maximum Reverse Thrust, area 5% increased (at M=0.09)	4.39	5.41

Table 5.5: SLS design point values of isentropic efficiencies, specific work and r.p.m

Turbine Components	Assumed Isentropic Efficiency	Specific work (kW/(kg/s))	Power (kW)
HP turbine	0.95	563.51	84,627
LP turbine	0.96	471.7	75,263

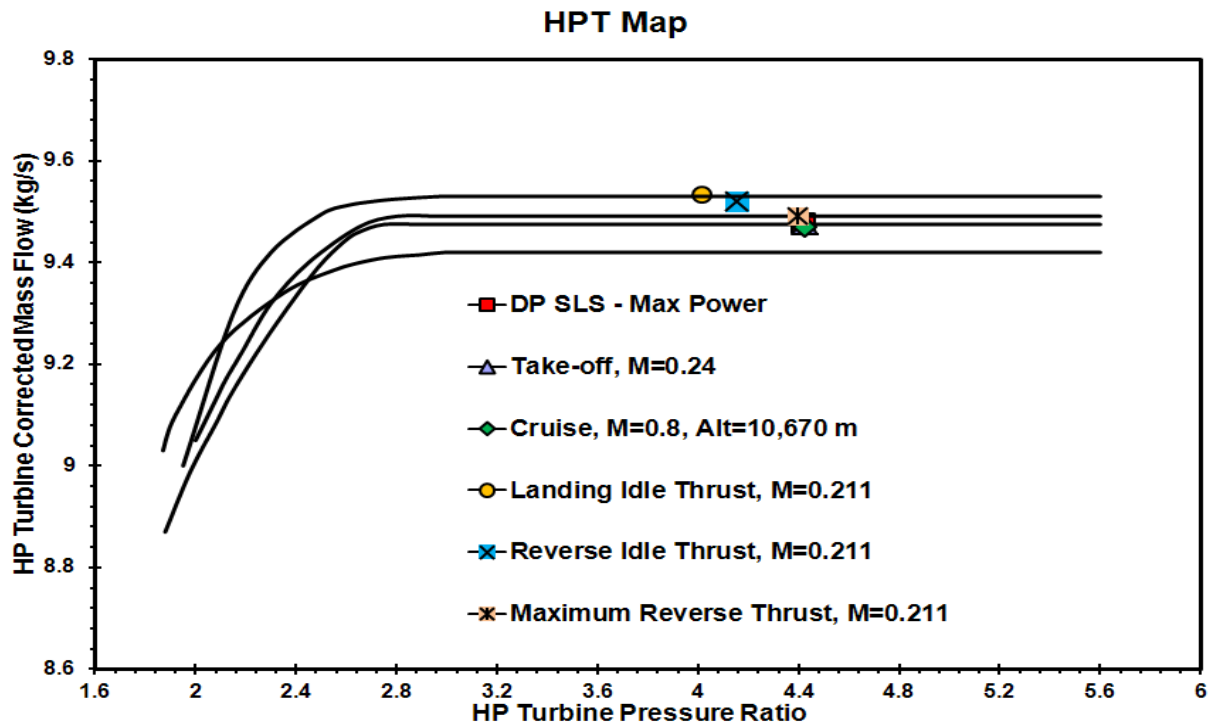


Figure 5.9: Pressure ratio across the HPT at different operating conditions.

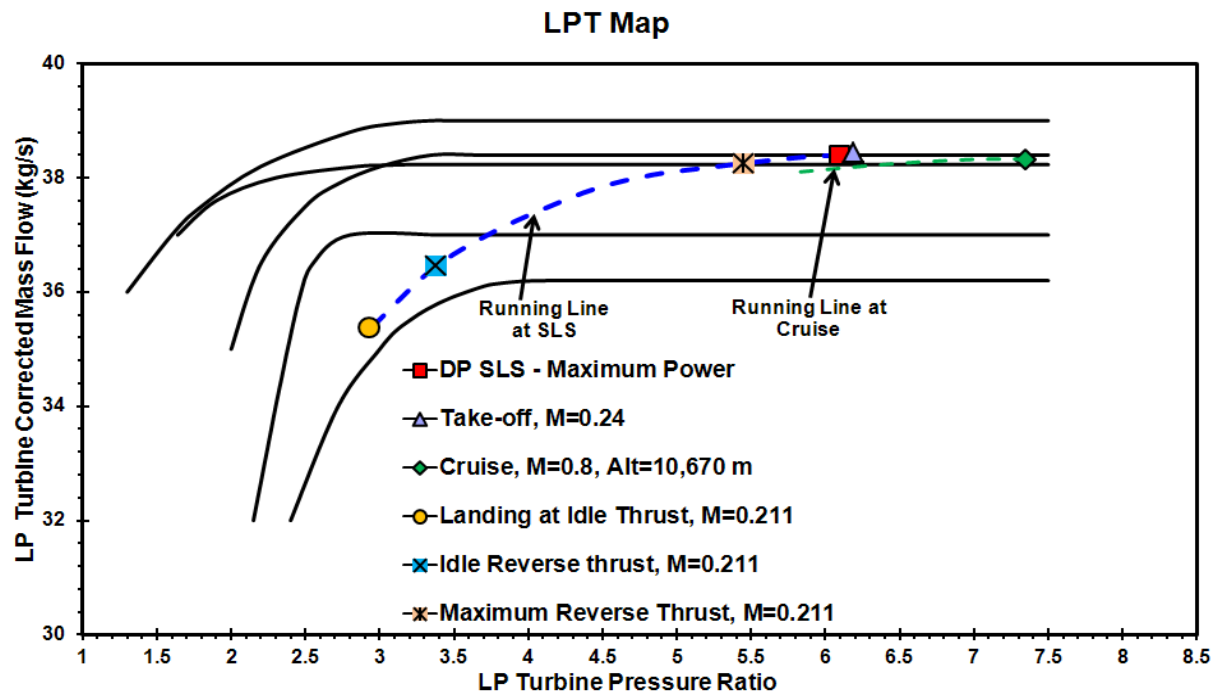


Figure 5.10: Pressure ratio across the LPT at different operating conditions.

5.5.1 Take-off

At take-off (0.24 M), the mass flow relative to the design point increases across the HP and LP turbines. The corrected mass flow, however, remains constant. The pressure ratio across the HP turbine remains unchanged, operating as choked. However, the common nozzle is unchoked (Figure 5.12) which causes the LP turbine pressure ratio to increase by a very small amount (Figure 5.10).

5.5.2 Cruise

At cruise (0.82 M) the mass flow and corrected mass flow relative to the design point reduces across the HP and LP turbines (Figure 5.9 and 5.10). The decrease in corrected mass flow, by a very small amount, is due to the c_p effect. The pressure ratio across the HP turbine remains at almost the same value as that in SLS conditions, however, the LP turbine pressure ratio increases.

5.5.3 Landing

At landing (0.211 M), the mass flow relative to the design point reduces across the HP and LP turbines. The corrected mass flow across the LP turbine and pressure ratios across the HP and LP turbines will reduce (Figure 5.9 and 5.10). The HP turbine will still be choked; however, the LP turbine will operate as unchoked at landing (Figure 5.9).

5.5.4 Reverse Idle

At reverse idle (0.211 M), the mass flow, corrected mass flow and the pressure ratio across the HP and LP turbines will increase when compared with the forward idle landing condition. The HP turbine will operate as choked, however, the LP turbine will be unchoked (Figure 5.9 and 5.10).

5.5.5 Maximum Reverse Thrust between 140 – 60 knots ($M=0.211 - 0.09$)

The corrected mass flow across the HP will reduce slightly and will increase for the LP turbine when compared with the SLS condition. The mass flow and pressure ratio will increase for the HP and LP turbines when compared with the reverse idle condition. Both the HP and LP turbines will operate as choked (Figure 5.9 and 5.10).

5.6 Nozzle Performance

The performance analyses were carried out for both the bypass and the core nozzles and the variation in pressure across the nozzles at different engine operating conditions is shown in [Table 5.6]. The propelling nozzle area for a jet engine is determined from the design point calculations, and once the nozzle size has been fixed it has a major influence on the off-design operation. During take-off conditions it was observed that the pressure ratios across the two nozzles are slightly higher than that at SLS. The jet engine, of course is intended for flight at high speeds and it is necessary to consider the effect of forward speed on the equilibrium running line. It is most convenient to express the forward speed in terms of Mach number for the matching calculations, and this can readily be converted to velocity for calculation of the momentum drag and thrust. At cruise altitude the low ambient pressure along with the high forward speed produces a ram pressure ratio which is a function of both flight Mach number and intake efficiency. This ram effect will give rise to an increase in compressor delivery pressure, which will in turn lead to higher pressure before the propelling nozzle, thereby increasing the nozzle pressure ratio. Once the nozzle is choked, however, the nozzle non-dimensional flow will reach its maximum value and will

then be independent of the nozzle pressure ratio and therefore of forward speed. The significance of this is that the turbine operating point will then also be unchanged, because of the requirement for compatibility of flow between the turbine and the nozzle. It follows that as long as the nozzle is choked the equilibrium running line will be uniquely determined by the fixed turbine operating point and will be independent of flight speed. Any increase in overall expansion ratio across the nozzle due to increasing ram effect will therefore result in an increase in overall nozzle pressure ratio with the turbine pressure ratio unaffected [Ref. 55]. At cruise, both the core and bypass nozzles are choked, thus, the turbine capacity, expansion ratio and hence work parameter of the HPT and LPT sensibly remain constant. Also, when the nozzles are choked there will be an additional pressure force due to static pressure in the exit plane being greater than the ambient pressure acting upon the equal area at the front of the engine.

Thus, in our case the nozzle is unchoked during SLS, take-off, landing and thrust reverse operation. Although, the civil aircraft engine spend most time at cruise i.e. nozzle choked; it is important to consider the effect of low forward speed on the fan running line under conditions where the nozzle is unchoked because it is at low rotational speeds that the running line is in close proximity to the surge line (Figure 5.4, 5.5 and 5.6). It should be noted that increasing the Mach number pushes the equilibrium running line away from the surge line at low compressor speeds. Fundamentally, this is because the ram pressure rise allows the compressor to utilise a lower pressure ratio for pushing the required flow through the nozzle.

During landing configuration both the bypass and the core nozzles will be unchoked (Figure 5.11 and 5.12), and in order to deploy the thrust reverser the engine thrust will be reduced to idle at which point the pressure ratios across both the nozzles will be significantly reduced. Once the thrust reverser is deployed the engine thrust will be increased, thus increasing the nozzle pressure ratio. As previously discussed the beneficial effects of increasing the nozzle area during thrust reverser operation will give a better surge margin for the fan and booster (Figure 5.4, 5.5 and 5.11). Figure 5.11, shows the effect of increasing the bypass nozzle area by 5% to its current value [Table 5.6].

Increasing the bypass nozzle area decreases the pressure ratio across the bypass nozzle and a slight increase in core nozzle pressure ratio. At a fixed value of N_H any increase in nozzle area will cause an increase in N_L , the physical reason being that opening the nozzle will increase the pressure ratio across the LP turbine, thus, causing an increase in LP rotor torque. This will also cause an increase in engine mass flow and an increase in total gross thrust as will be shown in the next section. Thus, increase in bypass nozzle area is not only beneficial for increasing the surge margin for the Fan and Booster but also has a favourable effect of increasing the reverse thrust.

Table 5.6: Variation in pressure ratio across the bypass and core nozzle

Engine Operating Condition	Bypass Nozzle Pressure Ratio	Core Nozzle Pressure Ratio
Sea Level Static (max-power)	1.63	1.36
Take off (M=0.24, 160knots)	1.69	1.38
Cruise (Alt=11,000m, M=0.8)	2.60	1.86
Landing at (M=0.211)	1.26	1.08
Idle Reverse Thrust (at M=0.211)	1.20	1.06
Maximum Reverse Thrust, area 5% increased (at M=0.211)	1.53	1.26
Maximum Reverse Thrust, area 5% increased (at M=0.09)	1.50	1.25

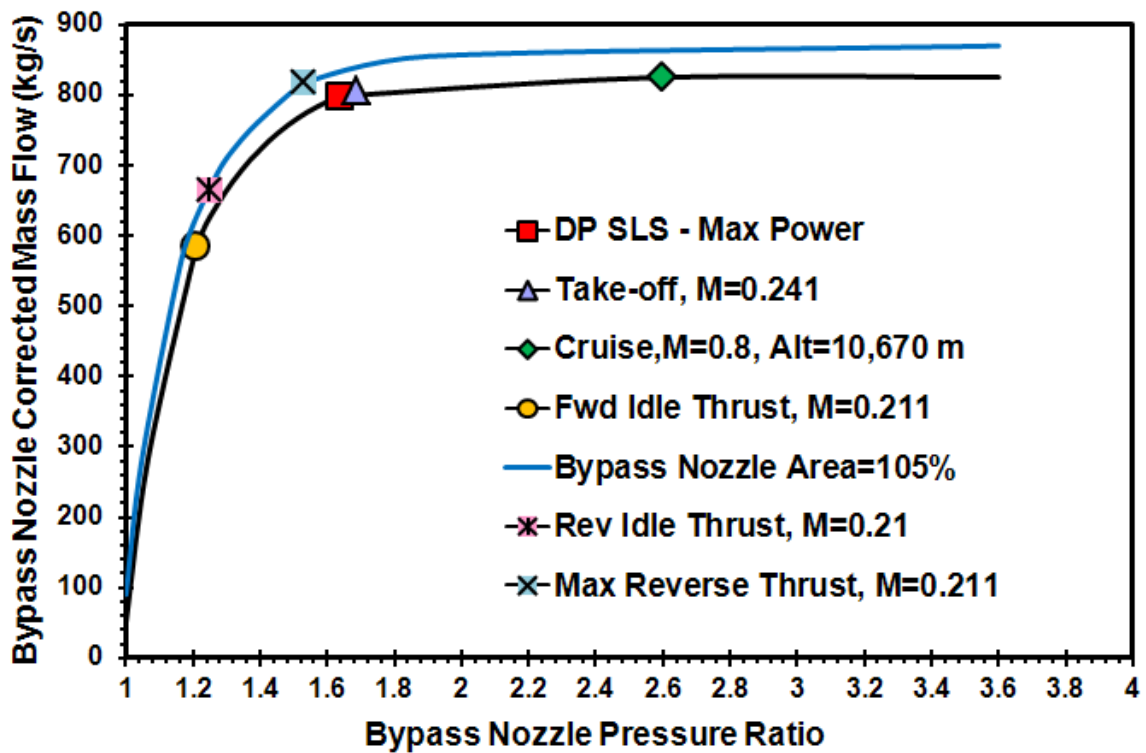


Figure 5.11: Variation in pressure ratio across the bypass nozzle at different operating conditions.

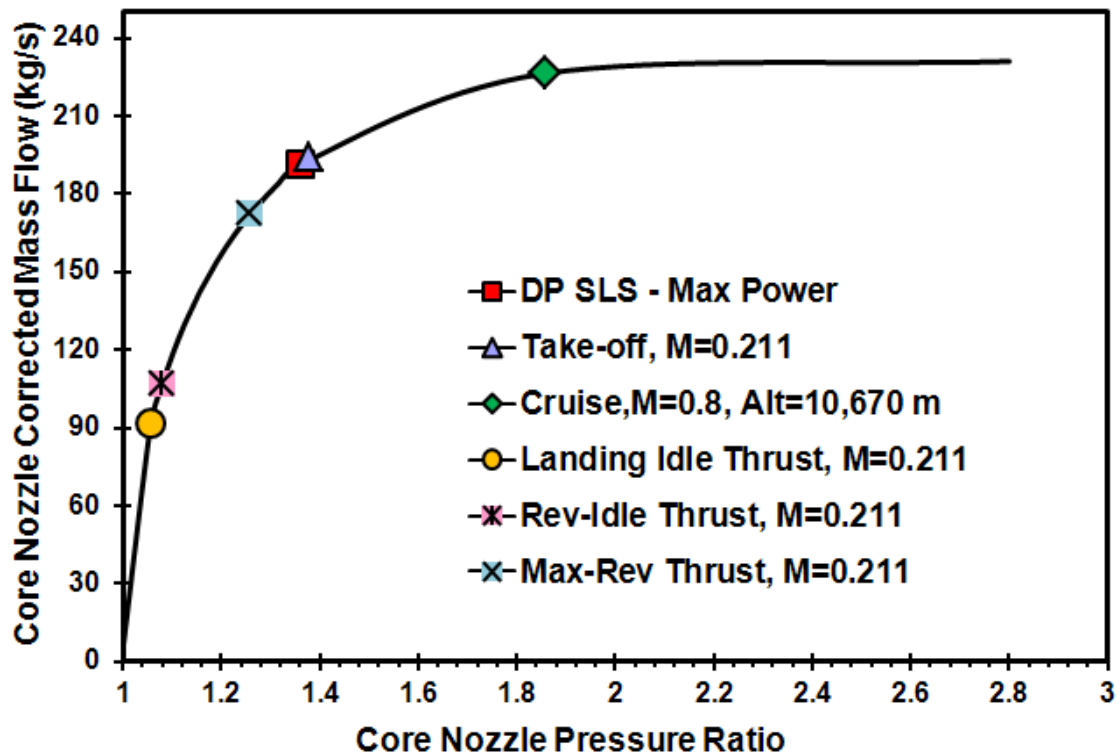


Figure 5.12: Variation in pressure ratio across the core nozzle at different operating conditions.

5.7 Thrust Reverser Performance

Part of the thrust reverser optimisation process includes ensuring that the hot air/gases neither impinge on the aircraft wing or fuselage nor are re-ingested into the engine intake, which could cause engine surge and F.O.D. It is also important to minimize any lift component from the thrust reverser in order to maximize braking efficiency. In this section the performance of the thrust reverser is carried out at different landing speeds.

Majority of the Boeing 777 landing takes place at Auto-throttle setting. At landing the pilot deploys the thrust reversers once the flaps and brakes become effective. Table 5.7, shows that it takes about 1.5 seconds for the flaps and lift dumpers to be aerodynamically effective for the landing configuration and the wheel brakes to become effective is about 2 seconds. In the next 1.5 seconds the pilot reduces the engine forward thrust to idle and select reverse idle thrust. Once the aft nacelle is translated and the cascade reverser block segments are exposed, the reverse thrust is established on the fan stream (Figure 5.13). This thrust is different from that coming out from a convergent nozzle which in civil application is almost always axial. As shown in (Figure 5.13) the reverser thrust will have force components in all the three axes i.e. it will have an axial component, F_x , a vertical component F_y , and a side force component, F_z .

Table 5.7: The time required for the flaps and brakes to be effective.

Procedure	Time (sec)
From main gear touchdown to lift dumper effective	1.5
From main gear touchdown to brakes effective	2
From main gear touchdown to ground idle	3.5

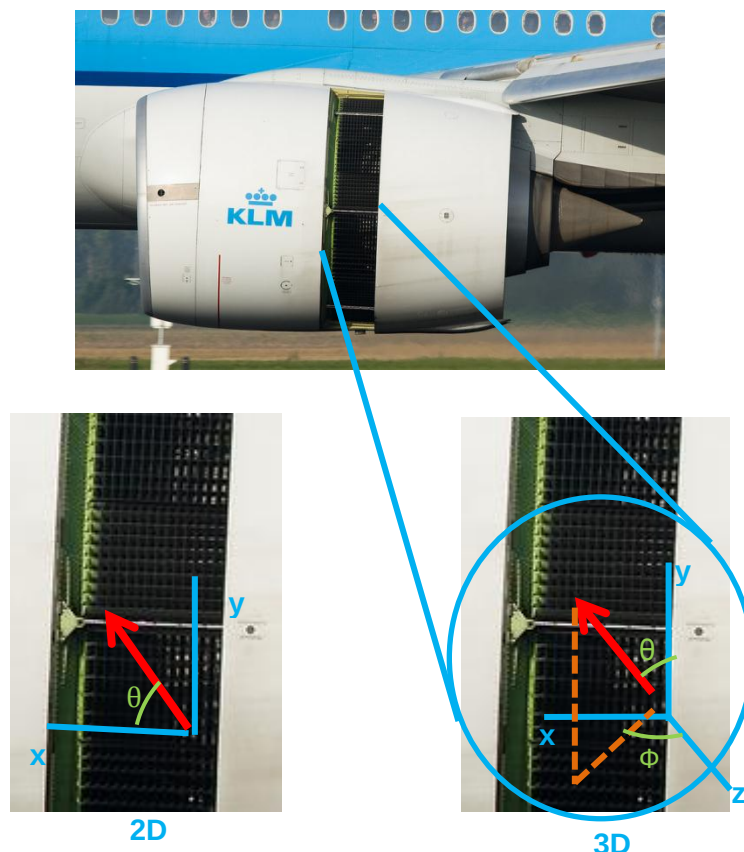


Figure 5.13: Shows the reverse thrust force components. Images adopted from [Ref. 57].

The most important force component from all the force components is the reverse thrust i.e. the axial force component, F_x . The axial force component should be the maximum as only then it can contribute as an efficient reverse force to decelerate the aircraft. The pivoting doors are normally designed and installed in a nacelle at an angle that will maximize this force and will cause the minimum interference with the wing surface. Also, it should be such that the reverse flow will not be re-ingested in the engine as it will induce pressure and temperature distortions along with the FOD. It should also be noted that the vertical force and the side force magnitudes will be minimum as they will cancel out due to the symmetry of the pivoting doors. The side force component will always be the minimum among the three force component, and will cancel out due to symmetry, however, in a cross wind condition its effects need to be taken into account.

The reverse thrust force is expressed as [Ref. 58]:

$$F_{Resultant} = \sqrt{F_x^2 + F_y^2 + F_z^2} \quad [\text{Equation 5.1}]$$

In the above equation, $F_{Resultant}$, is the resultant force, F_x , is the horizontal component of the reverse thrust, F_y , is the vertical component of the reverse thrust and F_z , is the side component of the reverse thrust. The individual forces will be calculated as follows:

$$F_x = F_{reverse} = F_{resultant} \times \sin \theta \times \sin \phi \quad [\text{Equation 5.2}]$$

$$F_y = F_{resultant} \times \sin \theta \times \cos \phi \quad [\text{Equation 5.3}]$$

In the calculation of this paper, the above equations will be simplified to:

$$F_{Resultant} = \sqrt{F_x^2 + F_y^2} \quad [\text{Equation 5.4}]$$

$$F_x = F_{resultant} \times \cos \theta \quad [\text{Equation 5.5}]$$

$$F_y = F_{resultant} \times \sin \theta \quad [\text{Equation 5.6}]$$

In the calculations performed here, the reverser thrust will be calculated as a 2D force, as the angle ϕ will only be provided by the manufacturer or calculated from the aerodynamic and/or CFD model. The force, $F_{resultant}$, is the fan gross thrust, however, for reverser thrust calculation this value is reduced by 5% ; this is to take the blocker door leakage flow into account.

No calculations are shown in this chapter for reverse thrust calculations; also aircraft deceleration time and landing distances calculations are not performed as these are accomplished in Chapter 6. The same procedure applies would be applicable here.

5.10 Conclusion

Two cases were studied; first, the reverser exit effective area was assumed to be the same as the bypass nozzle exit effective area; in the second case the reverser area was increased by 5%. It was observed, increasing the reverser area by 5% could be beneficial in increasing the fan and booster surge margin. Also, the reverser with an exit area of 5% greater than the bypass nozzle area will be beneficial as it will produce more reverse thrust. The best reverser angle is theoretically the smallest angle relative to the axial direction. However, practical problems limit the value to about 35 – 50 degrees.

Chapter 6. Thrust Reverser Performance at Integrated Aircraft-Engine Level- Mixed Exhaust Turbofan

This section discusses thrust reverser techniques for a mixed exhaust high bypass ratio turbofan engine and its effect on aircraft and engine performance. The turbofan engine chosen for this study was CUTS_TF (Cranfield University Three Spool Turbofan) which is similar to Rolls-Royce TRENT 772 engine and the information available for this engine in the public domain is used for the engine performance analysis along with the Gas Turbine Performance Software, GasTurb 10. The CUTEA (Cranfield University Twin Engine Aircraft) which is similar to the Airbus A330 is used alongside with the engine model for the thrust reverser performance calculations. The aim of this research paper is to investigate the effects on mixed exhaust engine performance due to the pivoting door type thrust reverser deployment. The study looks into the engine off-design performance characteristics and how the engine components get affected when the thrust reverser come into operation. This includes the changes into the operating point of fan, IP compressor, HP compressor, HP turbine, IP turbine, LP turbine and the engine exhaust nozzle. CFD analyses were also performed to investigate the thrust reverser flow analysis at landing conditions i.e. forward idle thrust, reverse idle thrust, maximum reverse thrust at 0.211M (140 knot) and maximum reverse at 0.09M (60 knot). Also, the reverser deployment effect on aircraft, deceleration time and landing distances are discussed.

6.1 Introduction

The performance study was carried out on a CUTEA aircraft which is similar to the Airbus A330-300 alongside an engine model CUTS_TF which is similar to the TRENT 772 engine and has a mixed exhaust i.e. hot and cold streams mix and depart from a common nozzle. The TRENT 772 makes use of the pivoting door type thrust reverser which reverses only the bypass stream. Interestingly, the engine has a mixed exhaust, but once the thrust reversers are deployed they only make use of the fan stream i.e. during reverse thrust the engine acts as if it is a separate exhaust as shown in (Figure 6.1). An Airbus A340 uses a similar type of thrust reverser with a CFM56-5C engine which is also a mixed exhaust and uses a pivoting door type thrust reverser (Figure 6.2).



Figure 6.1: Deployed thrust reverser on a mixed exhaust engine. Reverser is operating only on fan stream flow. Images adopted from [Ref. 65].

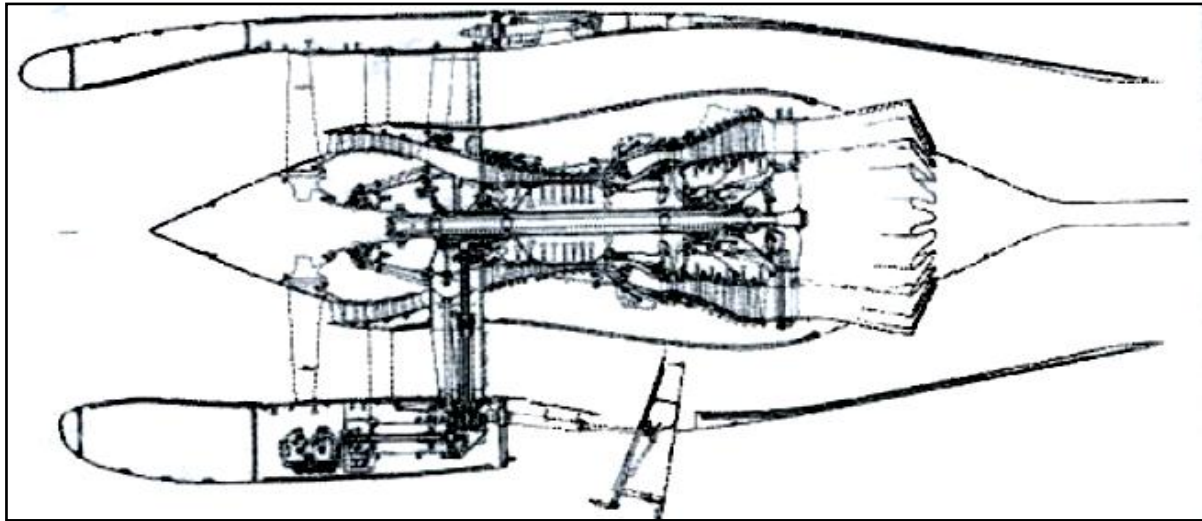


Figure 6.2: Longitudinal section of a mixed exhaust CFM56-5C used on A340. Lower half reverser in operation. Images adopted from [Ref. 69].

On a pivoting door type thrust reverser, the four pivoting doors are movable structures during the reverse thrust. The pivoting doors deflect the exhaust airflow of the engine into the direction enforced by the door angle and sharp edge (kicker plate) at the front end of the door. Pivoting door type thrust reverser has fewer moving parts and simpler kinematics compared with the cascade type thrust reversers. Additionally, the required stiffness of the fixed structure can be achieved at a lower weight. It creates a higher drag in reverse position and actuator loads are higher compared with a cascade type reverser of the same size.

If the total flight time for a civil aircraft is considered, the thrust reversers represent only a small fraction of flight operating time. Even though the thrust reversers operating time is very limited, they are still considered to be a critical component. Their installation on aircraft engines provides safety of aircraft and passengers. However, the installation and use of thrust reversers affects the nacelle design, propulsion weight, aircraft cruise performance, engine maintenance expenses. Also the installation of a thrust reverser system may increase the engine SFC as a result of leakage and pressure drops.

6.2 High Bypass Ratio Mixed Turbofan Engine

In subsonic turbofan engines mixing the hot and cold stream prior to exhausting through a common propelling nozzle can be advantageous, giving a small but significant gain in SFC and specific thrust at cruise. The optimum fan pressure ratio for specific thrust and SFC is significantly lower than separate jet configuration at all flight Mach numbers, and combination of other cycle parameters. The magnitude of this reduction reduces as bypass ratio is increased. This leads to lower weight and cost for both the fan and the fan turbine. The reverse thrust on a mixed exhaust engine increases when a bypass duct blanking style thrust reverser (typical of the design on high bypass ratio turbofans) is deployed. This is because the forward thrust still being produced by the core stream is diminished due to the large dump pressure loss in the mixer chamber, and also due to engine re-matching. In a mixed engine, the core velocity is lower than that of a separate jet engine. Jet noise is proportional to jet velocity to the power of 8 [Ref 78]. The downstream propelling nozzle expansion ratio should approximately be greater than 2.5 for the mixer to be of significant benefit. This is normally achieved during cruise where the nozzle pressure ratio is enhanced at high aircraft forward speed due to lower pressure at high altitudes. Also, the mixer is

designed for the optimal length to diameter ratio so that there is low temperature spread at the mixer exit [Ref. 64].

It is evident from the above, that the engine cycle must be designed for a mixer from the outset, so that, ideally, equal total pressures are achieved at the mixer chute exit plane. The level of fan pressure ratio chosen for a mixed turbofan ensures that total pressure in the hot and cold mixer chute exit plane are equal. The fan outlet pressure should be slightly higher than the LP turbine outlet pressure to keep mixing losses to a minimum; typically this should be about 1.05 – 1.07. The two most common high bypass ratio mixed subsonic turbofan engines are TRENT 772 (Figure 6.3) for Airbus A330 which has a BPR of about 5.0 and the CFM56-5C (Figure 6.2) for Airbus A340 which has a BPR of 6.5. As per [Ref. 64] comparing the mixed exhaust engine with a separate exhaust engine; for a mixed turbofan engine with a BPR of 5:1 and a total temperature ratio of 3, equal total pressures and a lobed mixer with a length to diameter ratio of 2, the actual gain in gross thrust at 0.8 M cruise, is around 2%. Initially, this may not seem like a worthwhile return; however, because momentum drag remains unchanged the gain in net thrust will be around 4%. The improvement in s.f.c is as per net thrust, because the fuel burn for the same core is unchanged since BPR, OPR and TET are held constant [Ref. 63 and 64].

When the mixed engine is throttled back from its design point at high rating, the propelling nozzle expansion ratio falls. Once it is below 2.5 the mixer gross thrust gain falls rapidly. This will occur at higher percentage of thrust when static, than when at high flight Mach number. Furthermore, as described above, the net thrust increase for a given gross thrust gain decreases as flight Mach number is reduced. Therefore, mixer operation must be modelled at all corner points of the operation envelope to ensure satisfactory engine off design performance [Ref. 64]. In off design operation all the parameters affecting the mixer performance vary, such as cold to hot stream temperature and pressure ratios, and propelling nozzle expansion ratio. Hence to model a mixer the complete methodology presented in [Ref. 79] must be used so that the station data is calculated through the mixer, and gross thrust is calculated in the conventional manner using the resulting propelling nozzle conditions [Ref. 79].

The three most common mixer types which, in order of increasing length, are: injection mixer, lobed annular mixer and plain annular mixer. Owing to the high pressure loss of the injection mixer, the lobed or plain annular configurations are the most common [Ref. 64]. They comprise of hot and cold mixer chutes followed by a mixing chamber. When lobes (Figure 6.2) are used at the end of the chutes where mixing is initiated, as opposed to a circular wall, the mixing parameter is increased by up to three times. This has the effect of significantly reducing the required mixing length. The chutes should be designed for an exit Mach number of between 0.35 and 0.55. Gross thrust gain is insensitive to the Mach number levels and their ratio. The static pressure in the exit plane of the mixer chutes will inevitably be equal for hot and cold streams. The mean exit Mach number should be between 0.35 and 0.5 to allow satisfactory mixing and pressure loss. Installation restriction places an upper limit of about 1.25 on the length to diameter ratio [Ref. 64].

6.3 Engine Performance

The CUTS_TF (which is similar to TRENT 772 engine – Figure 6.3) is a three shaft turbofan engine comprising a single stage fan, an eight stage IP compressor fitted with VIGVs and the first two stages are installed with VSVs, six stage HP compressor, single stage HP turbine, single stage IP turbine, four stage LP turbine, common nozzle for combined fan/core flow and a pivoting quadruple door type thrust reverser. In a three spool engine the components interact, producing distinctive trends when any single component's performance changes. Within a three-shaft engine, the

outermost rotor system is the HP rotor. Within the HP rotor there are two more concentric shafts transmitting power – the IP and the LP [Ref. 70]. The arrangement of using multiple compressors driven by their own turbines has a number of advantages. Firstly, the part speed matching and the surge issues are eased. Thus, the same pressure ratio may be achieved in fewer stages, with less variable geometry. Secondly, employing a higher rotational speed for the rear stages allows the HP shaft speed to remain higher at part load than if it were part of a single shaft. Thus, the LP compressor working line remains more acceptable down to lower power or thrust, because the downstream fast running HP compressor can pass more flow. The HP speed remains high because the HP turbine expansion ratio is fixed over a wide power or thrust range, as shown later in the performance calculations. Also, high rotational speeds for the rear stages enable them to have a lower loading, and to be on a lower pitch line, hence alleviating hub tip ratio concerns. However, these advantages of multi-spool compressor must be balanced against the added layout complexity [Ref. 64].

Each individual stage in a multi spool compressor has its own unique performance map. Normally, all these are stacked together to form an overall map which is more convenient for engine performance. The CUTS_TF, IP compressor has eight stages, whereas the HP compressor has six stages. The operating points for the front, mid and rear stages vary on their individual maps. The front stages are pushed towards surge at low speed, due to the flow being restricted by the rear stages, which move towards choke. At high speed the situation is reversed with the front stages in choke and the rear stages moving towards surge. These effects occur because the rear stages referred flow increases strongly as speed increases [Ref. 64]. In order to overcome this problem the IP compressor is fitted with variable IGVs and the first two stages are installed with VSVs. VIGVs and VSVs are mainly required to allow a compressor to have an acceptable low speed surge line with all the stages on a single shaft. Thus, when the engine is throttled back the compressor working line often moves towards the surge, VIGVs provide a mechanism to mitigate this by raising the part speed surge line. The VSVs are partially closed at low speed, reducing the mass flow passing by the front stages for that given speed, which raise the surge line. The working line does not change, being set by downstream components, however the compressor speed increases for a given flow and pressure ratio. The CUTS_TF also incorporates bleed valves at the end of the IP and HP compressors. When bleed valves downstream of a compressor are opened the compressor map is left unaffected, but the working line shows a steep change away from surge, thus maintaining acceptable part speed surge margin [Ref. 64]. The operation of bleed valves, IGVs and VSVs are relevant to the thrust reverser as they allow a smooth transition of engine thrust on landing from forward to reverse thrust. The operating point on the compressor map is primarily dictated by the components surrounding it, as opposed to the compressor itself. The non-dimensional speed lines on the compressor maps close up rapidly beyond, $(N/\sqrt{T})_{relative} = 1$, due to the choking. Beyond choke any further increase in speed will cease to generate any further increase in airflow.

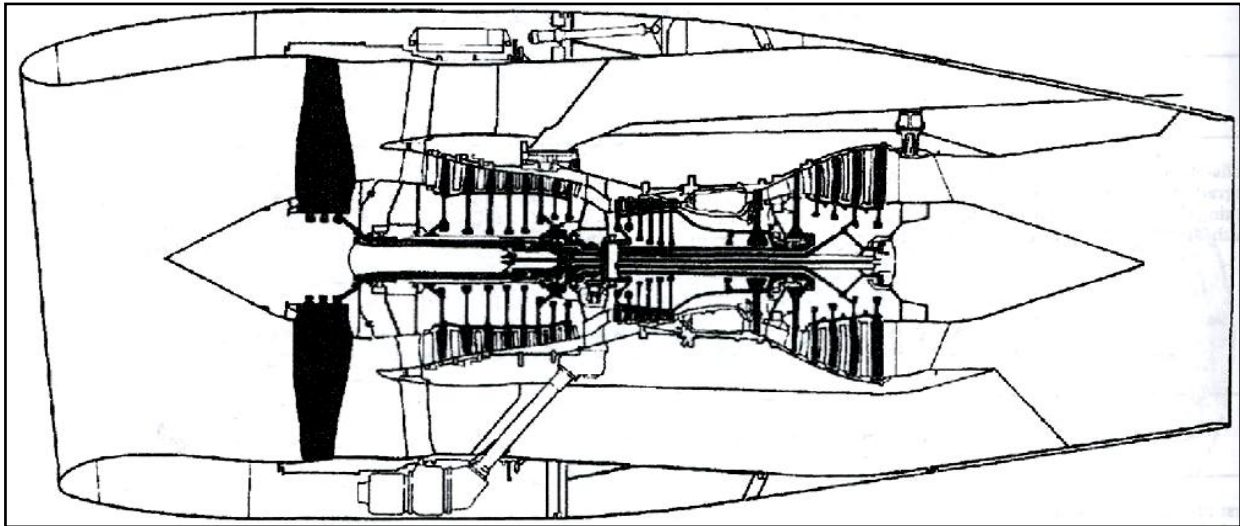


Figure 6.3: Longitudinal cross section of TREN 700 nacelle. Image adopted from [Ref. 69].

6.3.1 Engine Design Point and Off-Design Study

Initially, an engine design point study was carried out for the CUTS_TF engine at SLS condition i.e. maximum power; operating at a particular speed, TET, P.R and mass flow for which the components were designed (Table 6.1).

Table 6.1: Engine design point at SLS condition and off-design at take-off, cruise, landing, idle-reverse, and maximum reverse conditions.

Engine Parameters	Design Point	Off-Design				
	DP SLS Max Power	Take-off M=0.24	Cruise Alt=12,500m M=0.82	Forward Idle Thrust M=0.211	Idle Rev/Thrust (M=0.211)	Max Rev/Thrust (M=0.211)
Engine Mass Flow (kg/s)	910	939	276.8	527.36	587.77	837.65
Net Forward Thrust (kN)	316.3	258	53.51	65.61	-	-
Net Reverse Thrust (kN)	-	-	-	-	-123.11	-209.10
BPR	5.0	5.07	5.05	6.23	6.0	5.44
OPR	35.5	34.8	36.8	13.51	15.96	27.4
TET (K)	1649	1649	1610	1100	1200	1468
P_{fan} / P_{core}	1.0	1.0	0.998	1.02	-	-
Thermal Efficiency	0.48	0.49	0.52	0.45	0.36	0.45
Propulsive Efficiency	0	0.37	0.71	0.4	0.52	0.4
Nozzle Pressure Ratio	1.69	1.74	2.69	1.22	-	-
Common Nozzle Area (m ²)	2.96	2.96	2.96	2.96	2.96	2.96
Core Nozzle Area (m ²)	-	-	-	-	1.305	1.305
Bypass Reverser Area (m ²)	-	-	-	-	2.038	2.038

Table 6.1 shows the variation of performance of the gas turbine over the complete operating speed range and power output, normally referred to as the off-design engine performance, was also performed at take-off, cruise, landing, idle and thrust reverser mode. Here the geometry is fixed (except during reverse thrust) and operating conditions are changeable. The data available in the public domain was used for this study, together with the performance software 'GasTurb 10'. Performance graphs for the fan, IP compressor, HP compressor, HP turbine, IP turbine, LP turbine and nozzle were then plotted along with the thermal and propulsive efficiency variation during reverse thrust operation.

The design and off design studies are beneficial as they allow a comparison of thrust reverser operation with other operating conditions. The compressor, turbine and nozzle design and off-design studies are described below in section 6.3.2, 6.3.3, and 6.3.4. The off-design operating conditions such as take-off, cruise, landing etc. are abbreviated by suffix 6.3.2.1, 6.3.2.2, and so on.

6.3.2 Compressor Performance

In this section the performance of fan, IP and HP compressors are discussed. Figure 6.4, 6.5 and 6.6 show the compressor maps for the fan, IP and HP compressors. The equilibrium running points for a series of speeds at SLS and cruise condition (0.82 M) are plotted and joined up to form an equilibrium running line (Figure 6.4, 6.5 and 6.6). The figures also show the proximity of the operating line, or zone, to the compressor surge line. The CUTS_TF design point calculations were performed at the SLS condition at maximum power. The compressor performance parameters were calculated at the design point and various off-design conditions. Table 6.2 shows the value of pressure ratios at design point and off-design conditions. Table 6.3, shows the values of assumed isentropic efficiencies, specific work and r.p.m at the design point condition.

Table 6. 2: Compressor pressure ratios at different operating conditions

Engine Operating Conditions	Fan P.R	IP compressor P.R	HP compressor P.R
Sea level static (maximum power)	1.77	4.89	4.64
Take-off (M=0.24, 160 knots)	1.74	4.88	4.62
Typical Cruise (Alt =12,500m, M=0.82)	1.8	4.91	4.73
Landing (at M=0.211)	1.22	3.14	3.72
Idle Revers Thrust (at M=0.211)	1.31	3.34	3.86
Reverse Thrust Maximum (at M=0.211)	1.65	4.29	4.25

Table 6.3: SLS design point values of assumed isentropic efficiencies, specific work and r.p.m

Compressor components	Assumed isentropic efficiencies	Specific work (kW/(kg/s))	r.p.m
Fan	0.92	99.4	3,755
IP compressor	0.9	212.7	6,700
HP compressor	0.88	335.3	10,130

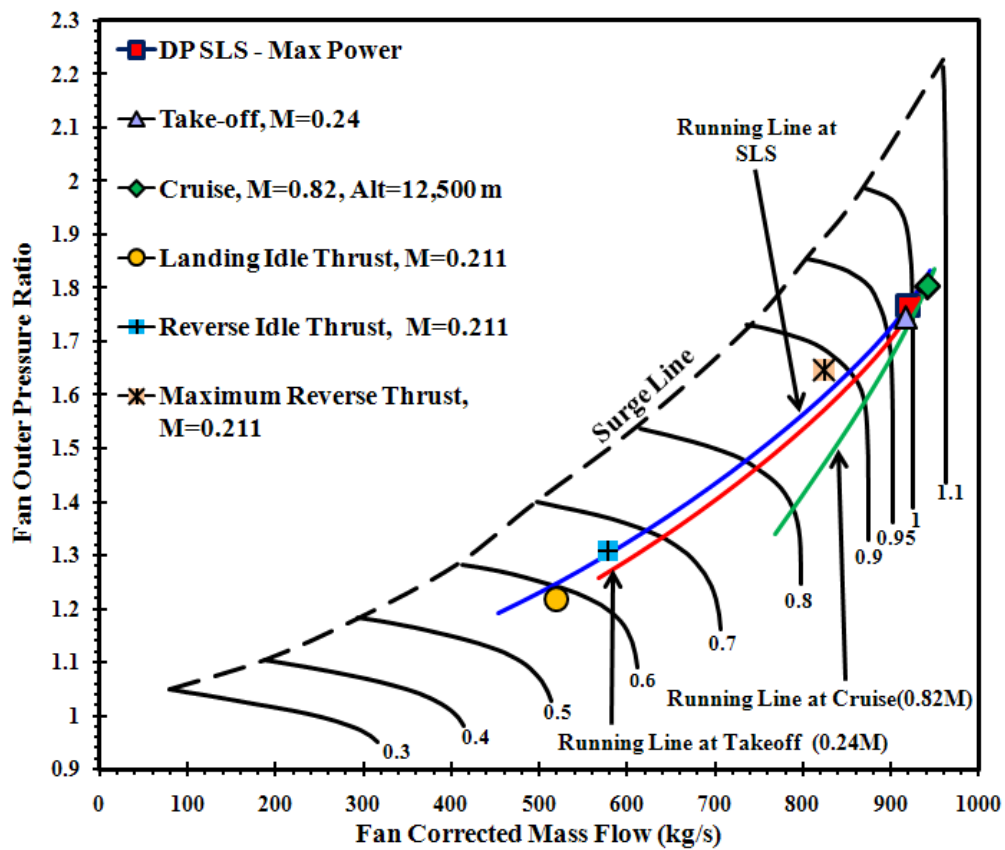


Figure 6.4: Fan P.R against the fan corrected mass flow for different operating conditions.

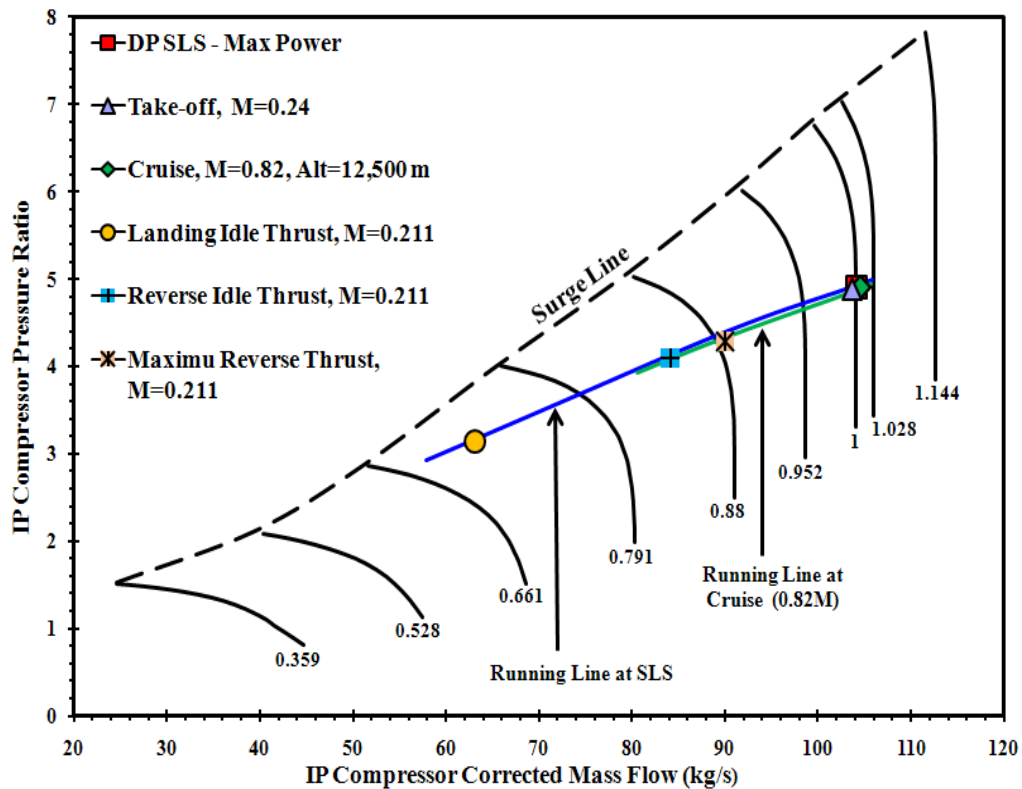


Figure 6.5: IP compressor P.R against the IP compressor corrected mass flow for different operating conditions.

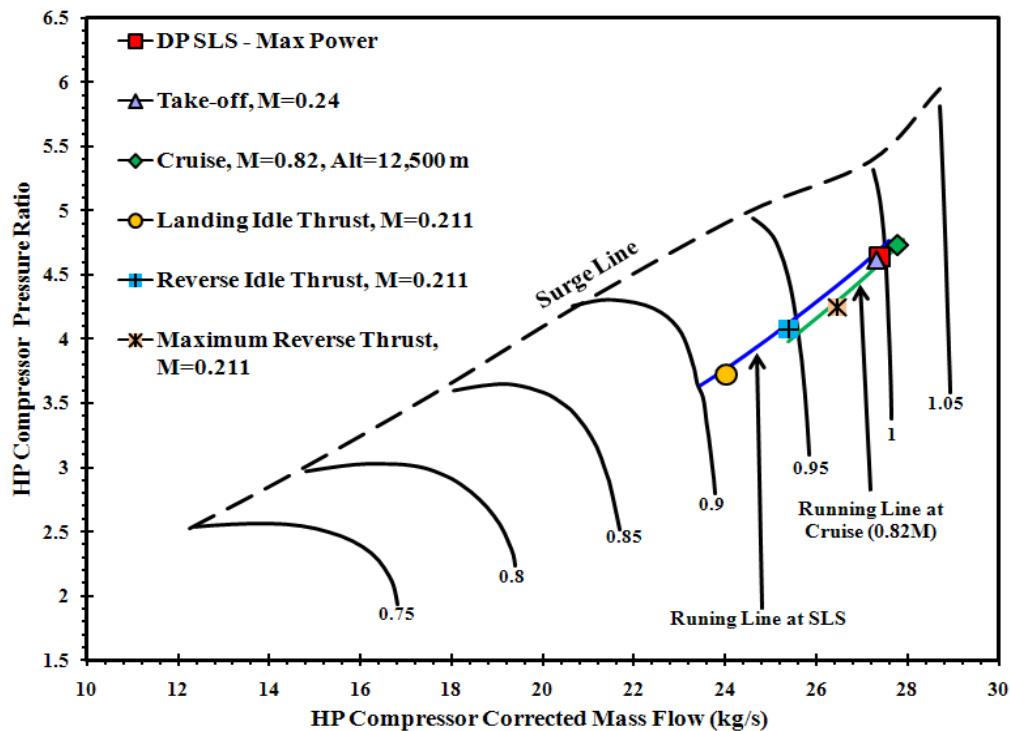


Figure 6.6: HP compressor P.R against the HP compressor corrected mass flow for different operating conditions.

6.3.2.1 Take-off

In order to take-off the pilot releases the brakes and increases engine power. The pilot applies power in two stages from idle to 1.15 EPR. On the A330, there is a protection between 1.16 – 1.28 EPR to protect the engine from blade flutter. The FADEC system will not allow fan speed acceleration above 1.16 EPR until the demanded EPR exceeds 1.28 EPR. When the engine parameters have stabilized, the thrust levers should be advanced without delay to the TOGA detent as appropriate. The FADEC system for the Trent 772 engine uses a MEASTO (Modified Engine Acceleration Schedule for Take-off); it automatically controls the engine acceleration by preventing high N1 at low speed during the take-off roll to avoid fan stall. The take-off thrust is reached at around IAS 60 knots [Ref. 67].

The take-off condition was considered at 0.24M (160 knots), with the nozzle being unchoked (Figure 6.12). Hence, the engine has a unique running line (Figure 6.4). This running line is plotted only for the fan; the running line for the IP and HP compressors will be approximately the same as the SLS running line. Thus, it should be noted that increasing the Mach number from 0 to 0.24 M pushes the running line away from the surge line at low compressor speeds. Fundamentally, this increasing ram pressure means the compressor utilizes a lower pressure ratio for pushing the required flow through the nozzle [Ref. 64]. Increase of ram pressure increase the engine mass flow relative to the design point. The increase of ram pressure means the engine utilizes a lower pressure ratio to push the required flow, thus reducing the fan pressure ratio.

6.3.2.2 Cruise

At cruise condition (Alt=12,500m and 0.82 M), there will be an increase in ram pressure due to high forward speed. The value of TET/T_1 will be higher at cruise due to the very low T_1 , thus, there will be a higher pressure ratio across the fan, IP and HP compressors (Table 6.2). The cruise

running lines at 0.82 M are also shown for comparison with the SLS running line (Figure 6.4, 6.5, and 6.6). The flight Mach number affects the degree of choking of the propelling nozzle; in our case at 0.82 M the propelling nozzle is choked [Table 6.2] and (Figure 6.11). At cruise, the propelling nozzle expansion ratio for a mixed engine should normally be greater than about 2.5 because as the pressure ratio falls below 2.5 the mixer gross thrust gain decreases rapidly. At pressure ratios below 2 the gross thrust gain becomes insignificant [Ref. 64]. The cruise calculations do take into account the customer over board bleed. The corrected mass flow for the fan, IP and HP compressor will increase relative to the design point values.

6.3.2.3 Landing

Alighting of the aircraft takes place at about 0.211 M (140 knots). Once the aircraft is below 9.144m (30ft.) the engine thrust will be set to forward idle. The 'idle thrust' reflects several engine issues including combustor stability, engine temperatures, surge margin levels and the achievable acceleration times to higher power or thrust. In our case, the CUTEA aircraft will touchdown in idle thrust. Figure 6.4, 6.5, and 6.6 shows the landing idle thrust point; for the fan, IP and HP compressors. The landing idle thrust point is closed to the SLS running line but at lower power.

CFD analyses were also performed at landing conditions and the results are presented in the '2D analysis for a mixed exhaust thrust reverser' section.

6.3.2.4 Thrust reverser deployment condition

After landing, the pilot changes the thrust to reverse IDLE at main landing gear touchdown (not before). When REV is indicated in green on ECAM (electronic centralized aircraft monitor), MAX reverser may be applied. The maximum reverse thrust is obtained at N1 between 70% and 85% and is controlled by the FADEC [Ref. 67]. There is no benefit in utilizing higher power because no additional drag is obtained [Ref. 68]. In our case the value of N1 is assumed to be 85% and the reverse thrust calculations were performed at this condition.

Table 6.4: Typical times required for lift dumpers and brakes to be effective and to reduce the engine thrust to reverse idle [13].

Procedure	Time (s)
From main gear touchdown to lift dumpers effective	1.8
From main gear touchdown to brakes effective	2
From main gear touchdown to ground idle	3

On CUTS_TF engine, the thrust reverser will only operate on the fan stream. Four pivoting doors are deployed through which the fan flow is deflected. The blocker door leakage during reverse thrust is approximately 5%. The thrust reverser is deployed approximately 3 seconds after the aircraft alighting. During this time the lift spoilers and aircraft brakes become effective. The thrust reverser efficiency is proportional to the square of the aircraft speed. So, it is recommended to use the thrust reverser at high speeds. Below 70 knots, reverser efficiency decreases rapidly. Below 60 knots, with maximum reverser selected, there is a risk that the engine will stall due to ingestion of disturbed air. Therefore, it is recommended to reduce, smoothly, the reverse thrust to idle at 70 knots. However, the use of maximum reverse thrust is allowed until the aircraft stops, in case of emergency. If airport regulations restrict the use of reverse thrust, the pilot then select and maintain the thrust to reverse idle until taxi speed is reached.

The CUTS_TF is a mixed exhaust engine, and the thrust reverser will only operate on the fan stream (Figure 6.1 and 6.2). Therefore, once the thrust reversers are deployed the engine configuration changes from mixed to separate exhaust. This is because the engine flow exits from two nozzles i.e. the core flow through the common nozzle and the fan flow through the reverser nozzle i.e. deployed pivoting doors.

A new set of performance calculations were performed, this time considering the engine as a separate exhaust configuration. The calculations for the separate exhaust were performed at SLS maximum power conditions by keeping the major engine performance variables the same, as for the mixed exhaust. Two new nozzle areas were calculated i.e. for the fan and the core. The separate exhaust performance calculations were then performed by keeping this fan nozzle area unchanged i.e. 2.04 m^2 (Table 6.1) and this would be approximated as the optimum reverser exit area, and is used for the reverser performance calculations. The value of the core nozzle area uses the initial settings for the mixed exhaust i.e. 1.3 m^2 (Table 6.1). The reverser can be approximated to be operating at the optimum reverse area; however, the core flow will discharge through an excess core area nozzle. The excess core nozzle area is likely to increase the pressure ratio across the LP turbine and this will increase the LP shaft speed. Thus, to avoid the LP shaft from over speeding the fan r.p.m needs to be controlled. It is due to this reasoning that the fan speed during reverse thrust is maintained between 75 – 85%.

According to [Ref. 68] the fan rpm, during maximum reverse thrust, should be maintained between 80 – 85%, however, the fan mechanical speed can only be controlled by the decrease in TET. Thus, the maximum value for the reverse thrust is obtained at a TET value of approximately 1468 K (Table 6.1). The core flow exiting from the core nozzle at maximum reverse thrust condition is subsonic, and therefore expands between the core and the common nozzle. The core flow expansion from the small core nozzle area, to a large common nozzle area will diminish the forward thrust produced by the core stream. The main reason for core thrust reduction is that the LP turbine expansion ratio is increased (Table 6.4); therefore, LP turbine outlet pressure falls due to the large dump pressure loss in the mixer chamber [Ref. 62].

6.3.2.5 Reverse Idle

At landing the thrust lever will be at forward idle. The pilot deploys the thrust reversers by disengaging the forward thrust lever and engaging the reverser lever. This changes the engine thrust from forward idle to reverse idle. This condition is important because sometimes the pilot prefers to decelerate the aircraft by setting the thrust to reverse idle. However, it's also important to note, that during reverse idle condition the engine will be at a higher power than it was at forward idle. This ensures that, if the need arises, the engine responds faster i.e. in case the pilot needs to perform emergency take-off after landing. The operating point for 'reverse idle thrust condition' is shown in (Figure 6.4, 6.5 and 6.6). The reverser thrust was calculated as a 2D force, the explanation of which is given in (Section 6.4).

CFD analyses were also performed at reverse idle condition and the results are presented in (Section 6.5).

6.3.2.6 Maximum Reverse Thrust between 140 – 60 knots ($M=0.211 - 0.09$)

During the thrust reverser operation the TET will remain constant. The 'maximum reverse thrust' operating points are shown on the fan, IP and HP compressor maps (Figure 6.4, 6.5 and 6.6). The maximum reverse thrust operating point for the fan will be slightly above the SLS running line,

however, for the IP and HP compressors the maximum reverse thrust symbols are on the cruise running line and shows sufficient surge margin.

CFD analyses were performed at 0.211M and 0.09M 'maximum reverse thrust' condition and the results are presented in the (Section 6.5).

6.3.2.7 Core/Thermal and Propulsive Efficiency between 140 – 60 knots ($M=0.211 - 0.09$)

The propulsive efficiency after landing will be about 0.54 i.e. about 76% of that at cruise. The higher the propulsive efficiency the greater the reverse thrust. From the engine performance data the values of propulsive and thermal efficiencies at landing are obtained and plotted against the aircraft landing speed (Figure 6.7 and Figure 6.8). It was observed (Figure 6.7) that the value of the propulsive efficiency is greater at high aircraft landing speed and falls significantly as the aircraft speed falls. Therefore, it is due to this effect that pilots are advised to use thrust reversers as soon as the aircraft lands i.e. at high landing speeds. The thermal efficiency on landing, on the other hand, will be about 0.34 i.e. about 70% to what it was at SLS condition (Figure 6.8). The thermal efficiency during the thrust reverser mode increases at reverse idle and at maximum reverse. This increase is also due to the fact that the engine is now operating as a separate exhaust.

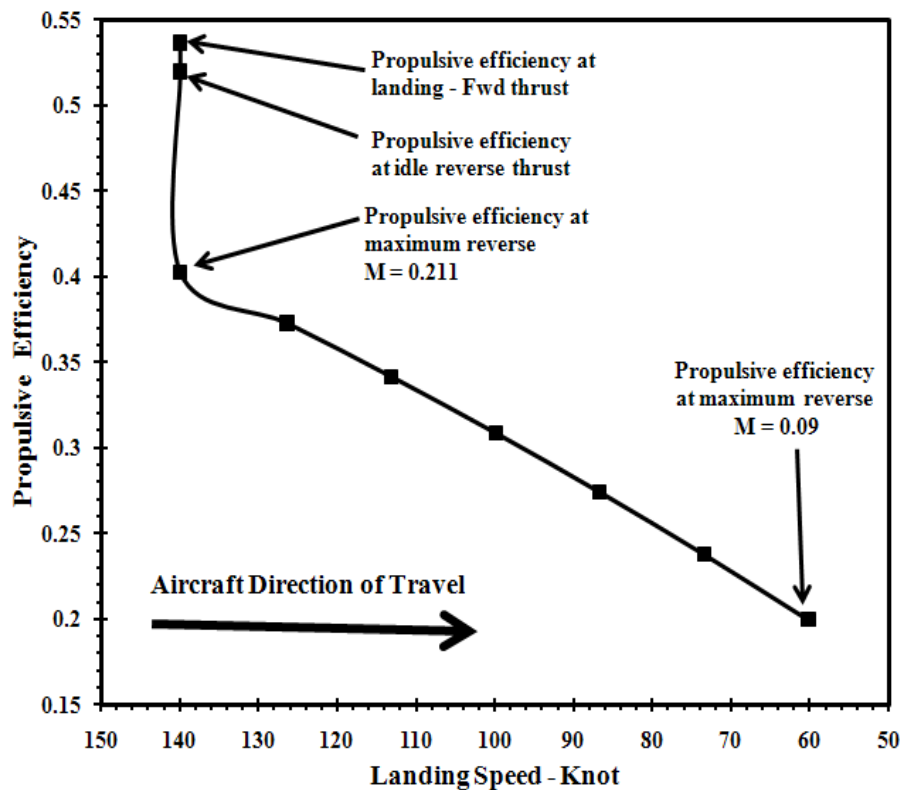


Figure 6.7: Variation of propulsive efficiency with aircraft landing speed (sea level).

Table 6.5: Variation in Fan Performance Parameters Relative to Design Values

Relative to Design Values	SLS-DP	SLS	Take-off	Cruise	Forward Idle Thrust, M=0.211	Idle Reverse @0.211M	Max-Reverse @0.211M	Max-Reverse @0.09M
Mass flow (kg/s)	909.81	1	1.033	0.304	0.58	0.646	0.921	0.901
Corrected mass flow (kg/s)	919	1	0.998	1.024	0.564	0.629	0.897	0.896
Pressure before the fan	100.31	1	1.041	0.274	1.032	1.032	1.032	1.01
Temperature before the fan	287.15	1	1.015	0.856	1.012	1.012	1.012	1.01
Pressure ratio	1.77	1	0.983	1.017	0.689	0.74	0.928	0.932
ΔT	55.21	1	0.986	0.927	0.33	0.471	0.869	0.882
Specific work	99.4	1	0.986	0.924	0.325	0.414	0.902	0.905
R.P.M	3755	1	1.002	0.97	0.592	0.66	0.886	0.885
BPR	5	1	1.014	1.01	1.246	1.214	1.1	1.086
EPR	1.77	1	0.983	1.023	0.671	0.58	0.623	0.637
OPR	35.5	1	0.981	1.038	0.381	0.443	0.762	0.772
Isentropic efficiency	0.92	1	1	0.957	1.011	0.962	0.989	0.990

Table 6.6: Variation in IP compressor Performance Parameters Relative to Design Values

Relative to Design Values	SLS-DP	SLS	Take-off	Cruise	Forward Idle Thrust M=0.211	Idle Reverse @0.211M	Max-Reverse @0.211M	Max-Reverse @0.09M
Mass flow (kg/s)	151.6	1	1.033	0.304	0.58	0.646	0.921	0.901
Corrected mass flow (kg/s)	104.12	1	0.998	1.024	0.564	0.629	0.897	0.896
Pressure before the IP comp	158.26	1	1.041	0.274	1.032	1.032	1.032	1.01
Temp before the IP comp	331.64	1	1.015	0.856	1.012	1.012	1.012	1.01
Pressure ratio	4.899	1	0.983	1.017	0.689	0.74	0.928	0.932
ΔT	208.11	1	0.986	0.927	0.33	0.471	0.869	0.882
Specific work	212.37	1	0.986	0.924	0.325	0.414	0.902	0.905
R.P.M	6700	1	1.002	0.97	0.592	0.66	0.886	0.885
Isentropic efficiency	0.92	1	1	0.957	1.011	0.962	0.989	0.990

Table 6.7: Variation in HP compressor Performance Parameters Relative to Design Values

Relative to Design Values	SLS-DP	SLS	Take-off	Cruise	Forward Idle Thrust M=0.211	Idle Reverse @0.211M	Max-Reverse @0.211M	Max-Reverse @0.09M
Mass flow (kg/s)	151.6	1	1.021	0.302	0.481	0.55	0.851	0.84
Corrected mass flow (kg/s)	27.39	1	0.97	1.014	0.876	0.91	0.96	0.964
Pressure before the HP comp	767.62	1	1.026	0.279	0.489	0.55	0.863	0.85
Temp before the HP comp	539.75	1	1.004	0.881	0.794	0.84	0.955	0.952
Pressure ratio	4.64	1	0.996	1.019	0.802	0.83	0.91	0.913
ΔT	312.2	1	0.999	0.92	0.683	0.762	0.919	0.919
Specific work	335.37	1	0.999	0.905	0.659	0.747	0.912	0.911
RPM	10130	1	1	0.951	0.815	0.83	0.92	0.919
HP comp exit pressure	3561.1	1	1.021	0.285	0.393	0.457	0.786	0.776
HP comp exit temperature	852	1	1	0.895	0.753	0.812	0.941	0.938
Isentropic efficiency	0.88	1	1	0.988	1	0.97	1.032	0.977

6.3.3 Turbine Performance

If a turbine rotor operates between choked nozzles, then its capacity, expansion ratio, and therefore work parameter, remains substantially constant. The benefit of multi spool on compressor matching occurs because the HP and the IP turbine downstream remain choked for much of the operating range. Thus, the pressure ratios across the HP and IP turbines will remain constant and they will operate at a higher shaft speed; the pressure ratio for the LP turbine will vary, dependent upon whether the common nozzle downstream is choked or unchoked.

Table 6.8: Turbine pressure ratios at different operating conditions

Engine Operating Conditions	HP turbine	IP turbine	L.P turbine
	P.R	P.R	P.R
Sea level static (maximum power)	2.69	1.98	3.51
Take-off (M=0.24, 160 knots)	2.69	1.98	3.50
Typical Cruise (Alt =12,500m, M=0.82)	2.66	1.98	3.62
Landing (at M=0.211)	2.70	1.87	2.09
Idle Reverse Thrust (at M=0.211)	2.74	1.92	2.74
Reverse Thrust Maximum (at M=0.211)	2.73	1.98	4.26

Table 6.9: SLS design point values of assumed isentropic efficiencies, specific work and power

Turbine components	Assumed isentropic efficiencies	Specific work (kW/(kg/s))	Power (kW)
HP turbine	0.87	349.2	50,838
IP turbine	0.9	208.1	32,198
LP turbine	0.92	315.5	48,814

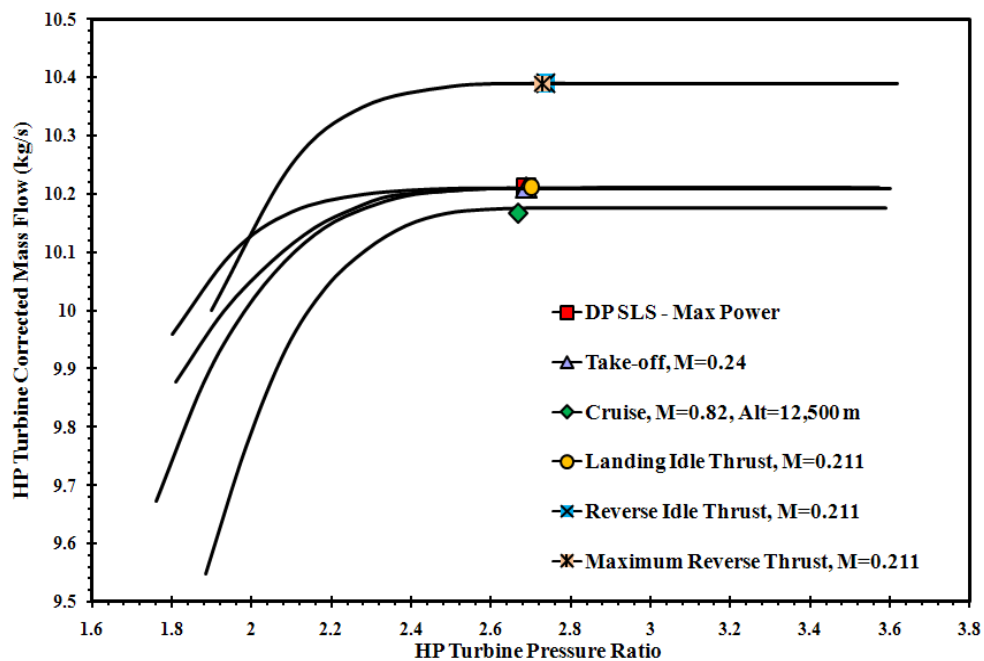


Figure 6.8: HP turbine pressure ratio against the HP turbine corrected mass flow at different operating conditions.

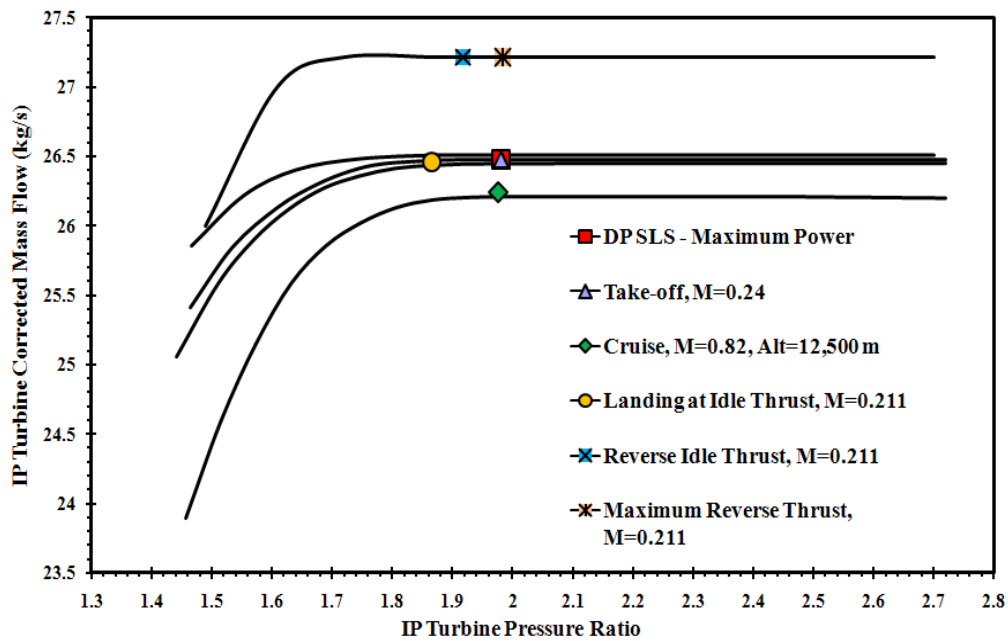


Figure 6.9: IP turbine pressure ratio against the IP turbine corrected mass flow at different operating conditions.

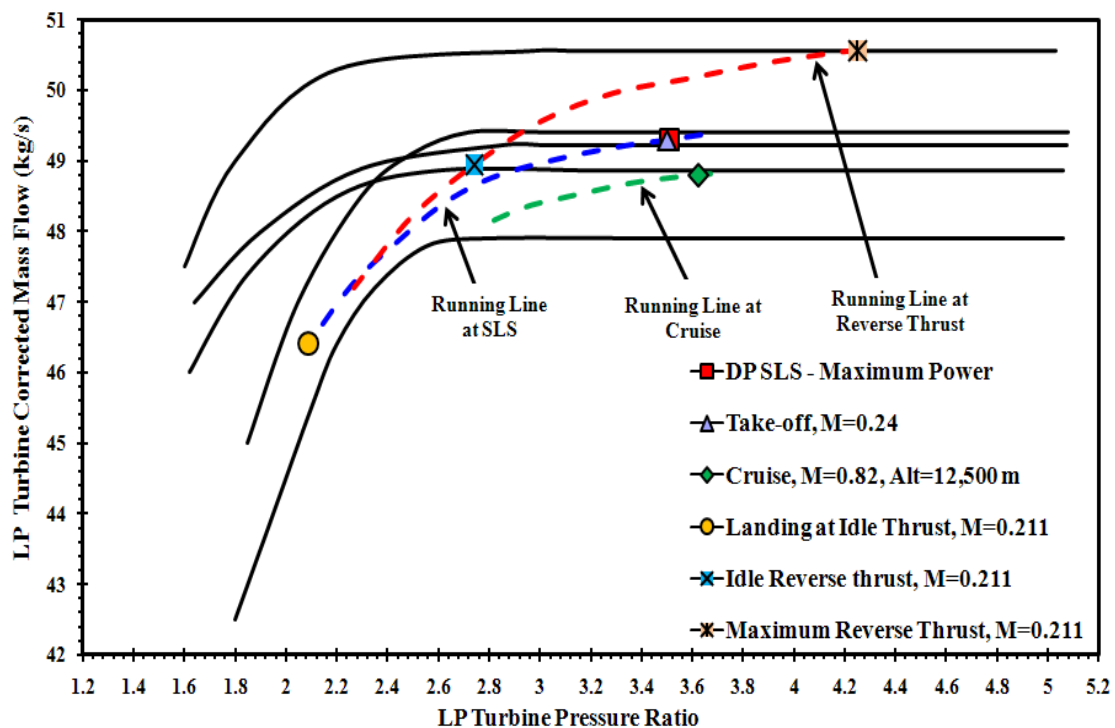


Figure 6.10: LP turbine pressure ratio against the LP turbine corrected mass flow at different operating conditions.

6.3.3.1 Take-off

At take-off (0.24 M) the mass flow relative to the design point increases across the HP, IP and LP turbines. The corrected mass flow, however, remains constant. The pressure ratio across the HP and IP turbines remains unchanged, operating as choked. However, the common nozzle is unchoked (Figure 6.12) which causes the LP turbine pressure ratio to decrease by a very small amount [Table 6.8].

6.3.3.2 Cruise

At cruise (0.82 M) the mass flow and corrected mass flow relative to the design point reduces across the HP, IP and LP turbines (Figure 6.9, 6.10 and 6.11). The decrease in corrected mass flow, by a very small amount, is due to the c_p effect. The pressure ratios across the HP and IP turbines remains at almost the same values as in SLS conditions, however, the LP turbine pressure ratio increases.

6.3.3.3 Landing

At landing (0.211 M), the mass flow relative to the design point reduces across the HP, IP and LP turbines. The corrected mass flow across the LP turbine and pressure ratios across the IP and LP turbines will reduce (Figure 6.10 and 6.11).

6.3.3.4 Reverse Idle

At reverse idle (0.211 M) the mass flow, corrected mass flow and the pressure ratios across the HP, IP and LP turbines will increase as the configuration is changed from forward idle to reverse idle [Table 6.1 and 6.8] and (Figure 6.9, 6.10, and 6.11). The reverser thrust was calculated as a 2D force the explanation of which is given in (Section 4).

6.3.3.5 Maximum Reverse Thrust between 140 – 60 knots ($M=0.211 - 0.09$)

The corrected mass flow across the HP and IP turbines will remain the same as that at reverse idle condition. However, for the LP turbine the corrected mass flow will increase (Figure 6.11). The turbine corrected mass flow for the separate exhaust engines will be higher than that for the mixed exhaust engines; this increase in mass flow is due to the c_p effect (Figure 6.9, 6.10 and 6.11).

Table 6.10: Variation in HP turbine Performance Parameters Relative to Design Values

Relative to Design Values	SLS-DP	SLS	Take-off	Cruise	Forward Idle Thrust, $M=0.211$	Idle Reverse @0.211M	Max-Reverse @0.211M	Max-Reverse @0.09M
Mass flow (kg/s)	145.6	1	1.021	0.289	0.48	0.55	0.85	0.84
Corrected mass flow (kg/s)	10.21	1	1	0.996	1.0	1.02	1.017	1.017
Pressure before the HPT	3383	1	1.021	0.286	0.389	0.46	0.794	0.783
Temp before the HPT	1648	1	1	0.976	0.67	0.73	0.89	0.89
Pressure ratio	2.69	1	1	0.992	1.0	1.02	1.02	1.014
ΔT	372.6	1	0.99	0.99	0.686	0.76	0.915	0.915
HPT cooling air	3561.1	1	1.021	0.284	0.392	0.46	0.796	0.786

pressure								
HPT cooling air temperature	851.9	1	1.003	0.896	0.753	0.82	0.946	0.0.944
Specific work	349.2	1	1.000	0.945	0.67	0.754	0.922	0.922
Power	50838	1	1.021	0.273	0.32	0.413	0.788	0.78
Isentropic efficiency	0.87	1	1	0.98	0.99	1.02	1.02	1.02

Table 6.11: Variation in IP turbine Performance Parameters Relative to Design Values

Relative to Design Values	SLS DP	SLS	Take-off	Cruise	Forward Idle Thrust M=0.211	Idle Reverse @0.211M	Max-Reverse @0.211M	Max-Reverse @0.09M
Mass flow (kg/s)	154.6	1	1.02	0.289	0.477	0.55	0.86	0.844
Corrected mass flow (kg/s)	26.47	1	1	0.991	0.995	1.03	1.028	1.028
Pressure before the HPT	1245.8	1	1.02	0.288	0.388	0.45	0.781	0.772
Temp before the HPT	1275.89	1	1	0.972	0.662	0.72	0.883	0.883
Pressure ratio	1.981	1	1	0.997	0.942	0.97	0.999	1
ΔT	171.5	1	0.999	0.944	0.649	0.74	0.92	0.92
Specific work	208.14	1	0.999	0.941	0.596	0.68	0.894	0.89
Power	32198	1	1.021	0.272	0.284	0.38	0.764	0.75
Isentropic efficiency	0.9	1	0.999	0.972	0.987	1	1.012	1.01

Table 6.12: Variation in LP turbine Performance Parameters Relative to Design Values

Relative to Design Values	SLS-DP	SLS	Take-off	Cruise	Forward Idle Thrust M=0.211	Idle Reverse @0.211M	Max-Reverse @0.211M	Max-Reverse @0.09M
Mass flow (kg/s)	154.69	1	1.021	0.289	0.477	0.549	0.855	0.844
Corrected mass flow (kg/s)	49.29	1	0.999	0.99	0.918	0.992	1.026	1.025
Pressure before the HPT	622.55	1	1.021	0.289	0.412	0.468	0.781	0.771
Temp before the HPT	1104.4	1	1	0.977	0.664	0.716	0.878	0.878
Pressure ratio	3.51	1	0.997	1.031	0.595	0.781	1.211	1.19
ΔT	269.81	1	0.998	0.971	0.432	0.603	0.989	0.984
Specific work	315.54	1	0.998	0.969	0.401	0.564	0.959	0.954
Power	48813	1	1.02	0.281	0.91	0.31	0.819	8.06
Isentropic efficiency	0.92	1	1	0.973	0.977	0.961	0.975	0.974

6.3.4 Nozzle Performance

The CUTS_TF engine employs a mixed nozzle where in normal forward thrust the hot and cold streams are mixed prior to exhausting through a common propelling nozzle. The propelling nozzle expansion ratio should be greater than approximately 2.5 for the mixer to be of significant benefit. Table 6.13, shows that for the CUTS_TF engine the pressure ratio across the nozzle is greater than 2.5 at cruise condition, hence, the maximum benefit from the mixed propelling nozzle is at cruise condition. The static pressure in the exit plane of the mixer chutes will inevitably be equal for the hot and cold streams. The mixer length/diameter ratio is normally around 1.25; it is only in a minority of occasions, such as if the engine is mounted in the fuselage, that higher ratios are used. In off design operation all the parameters affecting mixer performance will vary, such as cold to hot stream temperature and pressure ratios, and propelling nozzle expansion ratio.

Table 6.13: Common nozzle performance parameters – Mixed Exhaust

Engine Operating Conditions	Nozzle e P.R	Nozzle M	P_{cold} / P_{hot}	$T_{mixe d} (K)$	M_{cold}	M_{hot}	M_{mixed}
Sea level static (maximum power)	1.69	0.9	1.0	432	0.28	0.31	0.3
Take-off (M=0.24, 160 knots)	1.74	0.93	1.0	433	0.29	0.31	0.3
Typical Cruise (Alt =12,414m, M=0.8)	2.69	1.0	0.99	387	0.29	0.31	0.31
Landing (at M=0.211)	1.35	0.67	1.01	372	0.26	0.22	0.25

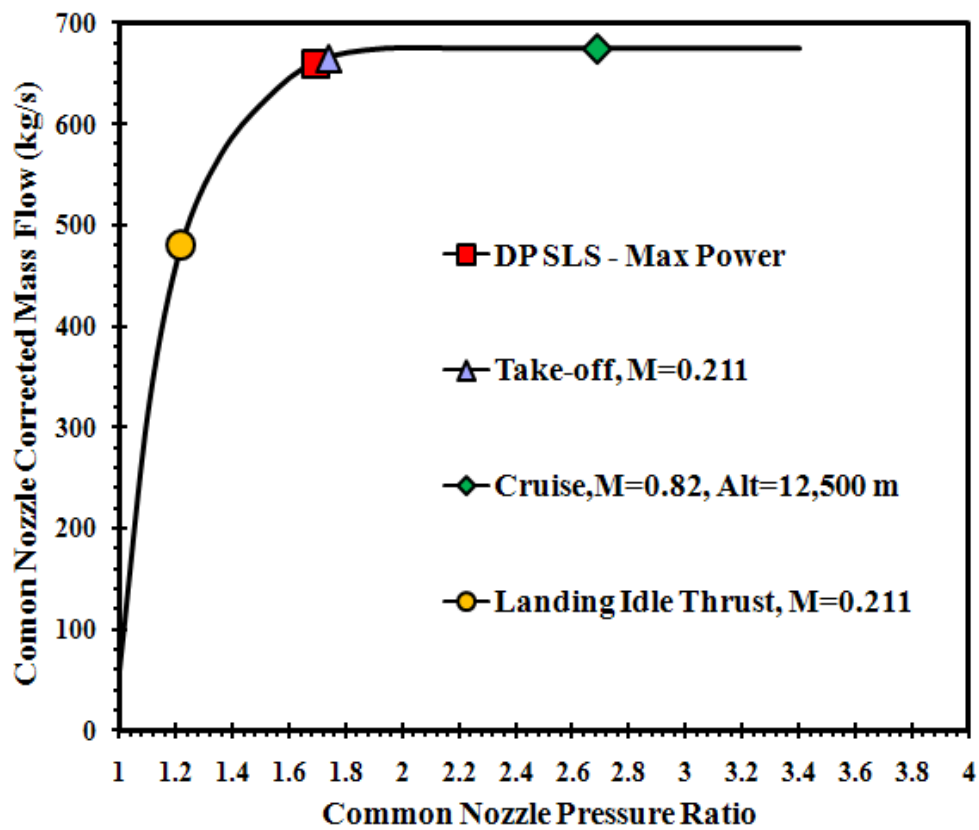


Figure 6.11: Common nozzle pressure ratio against the corrected mass flow at different operating conditions.

Table 6. 14: Core nozzle and reverser exit performance parameters at different operating conditions.

Engine Operation Conditions	Pressure @ core nozzle exit	M _{core} nozzle exit	P.R core nozzle exit	Pressure @ reverser exit	M reverser exit	P.R @ reverser exit
Idle Reverse Thrust (M=0.211)	105.03	0.23	1.04	133.20	0.64	1.31
Reverse Thrust Maximum (M=0.211)	111.47	0.38	1.1	166.7	0.87	1.65
Reverse Thrust Maximum (M=0.09)	111.24	0.37	1.09	163.36	0.86	1.61

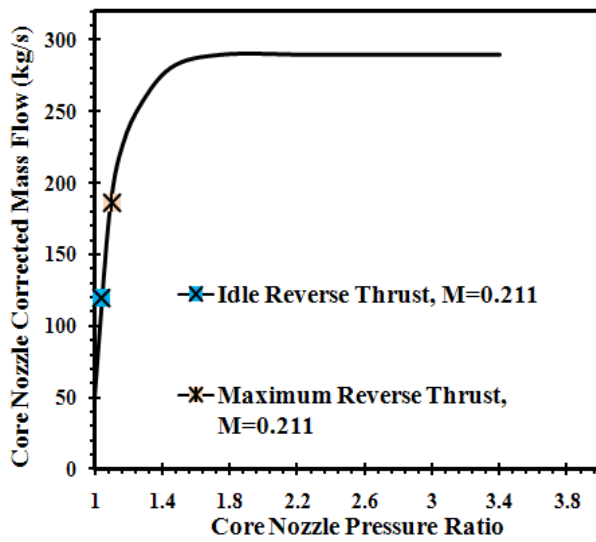


Figure 6.12a

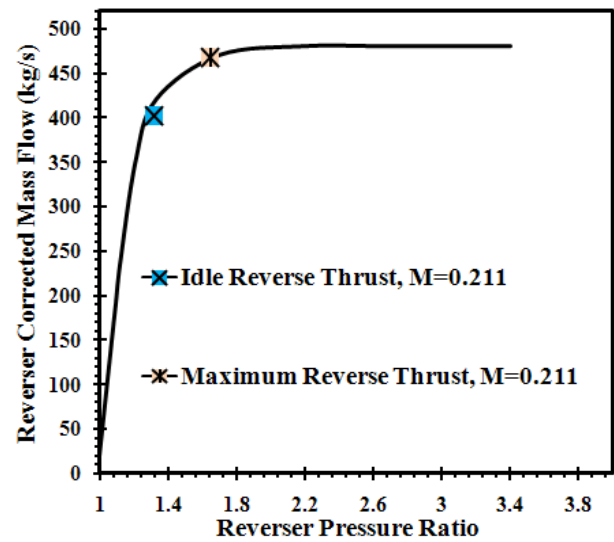


Figure 6.12b

Figure 6.12a: Core nozzle pressure ratio against the core nozzle corrected mass flow during reverse thrust. Figure 6.12b: reverser pressure ratio against the reverser corrected mass flow during reverse thrust.

6.3.4.1 Take-off

At take-off (0.24 M) the common nozzle parameters were compared against the design point. It was found that the nozzle mass flow, corrected mass flow, pressure ratio and throat Mach no will all increase [Table 6.15] and (Figure 6.11).

6.3.4.2 Cruise condition

At cruise (0.82 M) the common nozzle parameters were compared against the design point. The nozzle mass flow, nozzle throat pressure and temperature will decrease. However, the nozzle corrected mass flow, pressure ratio, and the throat Mach number will increase [Table 6.15] and (Figure 6.12). The common nozzle will be choked.

6.3.4.3 Landing condition

At landing (0.211 M) the common nozzle will be unchoked. The nozzle mass flow, corrected mass flow, pressure ratio, Mach number and temperature will all be less than that at design point [Table 6.13] and (Figure 6.12).

6.3.4.4 Reverse Idle

During reverse idle mode (0.211M) the nozzle parameters were compared against the design point. The engine acts as a separate exhaust. The nozzle values were considered for the bypass and the core stream. The bypass stream will produce reverse thrust, whereas the core stream thrust will be deposited in the common nozzle, and diminishes i.e. the core thrust value will be lower than it would have been otherwise [Ref. 62]. Thus, there will now be two nozzle maps as opposed to one common nozzle map. Figure 6.12a and 6.12b along with [Table 6.15] represent the case. Also, the engine power will be slightly higher than that at landing [Table 6.1]. The reverse thrust was calculated as a 2D force the explanation of which is given in (Section 6.4).

6.3.4.5 Maximum Reverse Thrust between 140 – 60 knots ($M=0.211 - 0.09$)

During maximum reverse case the engine was considered to be operating at 85% N1 i.e. fan speed. In comparison to the design point values the engine mass flow and corrected mass flow will reduce.

At $M=0.211$, the thrust reverser and core nozzle mass flows, corrected mass flows, pressure ratios and exit Mach numbers will increase [Table 6.14] and (Figure 6.12a and 6.12b) when compared with the values at reverse idle.

At $M=0.09$, comparison was made with the performance values at $M=0.211$. As the aircraft decelerates, the bypass and core nozzles mass flows and corrected mass flow values will decrease by a small amount. It was due to this negligible difference that the performance values at $M=0.09$ were not plotted on the compressor, turbine and nozzle maps.

Table 6.15: Variation in Common nozzle Performance Parameters Relative to Design Values

Relative to Design Values	SLS-DP	SLS	Take-off	Cruise	Landing	Idle Reverse @0.211M	Max-Reverse @0.211M	Max-Reverse @0.09M
Mass flow (kg/s)	912.91	1	1.033	0.302	0.579	-	-	-
Corrected mass flow (kg/s)	659.34	1	1.01	1.02	0.73	-	-	-
Pressure ratio	1.695	1	1.02	1.587	0.72	-	-	-
Hot stream Mach no	0.306	1	0.997	1.026	0.55	-	-	-
Cold stream Mach no	0.288	1	1.01	1.01	0.77	-	-	-
Mixed stream Mach no	0.3	1	1.01	1.033	0.71	-	-	-
Mixed pressure	171.72	1	1.03	0.279	0.72	-	-	-
Mixed temperature	431.7	1	1	0.895	0.82	-	-	-
Nozzle throat Mach no	0.9	1	1.03	1.111	0.59	-	-	-
Nozzle throat pressure	171.72	1	1.03	0.279	0.72	-	-	-
Nozzle throat temperature	431.7	1	1	0.895	0.82	-	-	-

6.4 Thrust Reverser Performance

At landing the pilot deploys the thrust reversers once the lift dumpers and brakes can be effective. It takes 1.5 seconds for the lift dumpers to be aerodynamically effective for landing configuration, the total time for the brakes and lift dumpers to become effective is about 2 seconds (Table 6.16). In the next 1.5 seconds the pilot reduces the engine thrust to idle.

Table 6.16: The time required for the flaps and brakes to be effective and to reduce the engine thrust to idle.

Procedure	Time (sec)
From main gear touchdown to lift dumper effective	1.8
From main gear touchdown to brakes effective	2
From main gear touchdown to ground idle	3.0

Once the thrust reversers are deployed, the reverser thrust is established on the fan stream (Figure 6.13). This thrust is different from that coming out from a convergent propelling nozzle which, in subsonic civil aircraft, is essentially axial. As shown in (Figure 6.13), the reverse thrust has force components in all three axes; an axial component, F_x , a vertical component F_y , and a side force component, F_z . The pivoting doors are normally designed and installed in a nacelle at an angle that will maximize the reverse thrust and will cause the minimum interference with the wing surface. Also, it should be such that the reverse flow will not be re-ingested in the engine as it will induce pressure and temperature distortions along with the F.O.D. The reverse (gross) thrust force is expressed as [Ref. 69]:

$$F = F_{\text{Resultant}} = \sqrt{F_x^2 + F_y^2 + F_z^2} \quad [\text{Equation 6.1}]$$

In the above equation, $F_{\text{Resultant}} = F$, and is regarded as the resultant force. F_y , is the vertical component of the reverse thrust, F_x , is the horizontal component of the reverse thrust and F_z , is the side component of the reverse thrust. The individual gross thrust forces will be calculated as follows:

$$F_y = F_{\text{resultant}} \times \cos\theta \quad [\text{Equation 6.2}]$$

$$F_x = F_{\text{resultant}} \times \sin\theta \times \sin\phi \quad [\text{Equation 6.3}]$$

$$F_z = F_{\text{resultant}} \times \sin\theta \times \cos\phi \quad [\text{Equation 6.4}]$$

In the calculation of this paper, the above equations will be simplified to 2D (Figure 6.14). The reverse thrust will be calculated as a 2D force, as the angle ϕ can only be provided by the manufacturers or calculated from the aerodynamics and/or 3D CFD model. The axial and vertical force components will be:

$$F = F_{\text{Resultant}} = \sqrt{F_x^2 + F_y^2} \quad [\text{Equation 6.5}]$$

$$F_x = F_{\text{resultant}} \times \cos\theta \quad [\text{Equation 6.6}]$$

$$F_y = F_{\text{resultant}} \times \sin\theta \quad [\text{Equation 6.7}]$$

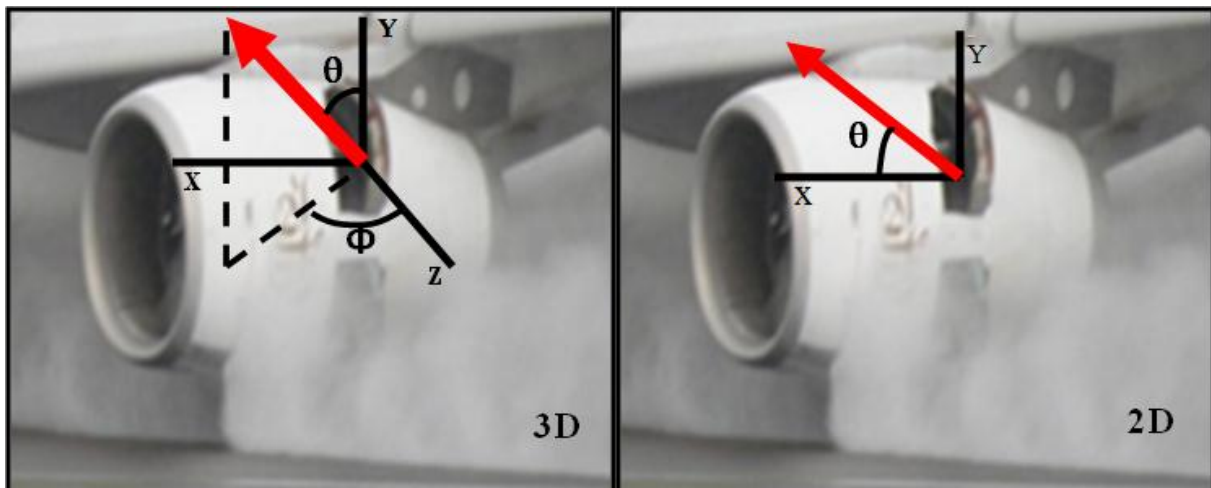


Figure 6.13: Reverse thrust force components in 3D and 2D. Images adopted from [Ref. 65].

Four pivoting doors are deployed through which the fan flow is deflected. The thrust reverser efficiency is proportional to the square of the speed. So, it is recommended to use the thrust reverser at high speeds (Figure 6.14). If the airport authorities restrict the use of reverser thrust the pilot then selects and maintains the engine thrust to reverse idle until taxi speed is reached.

6.5 2D Numerical Analyses for a Mixed Exhaust Thrust Reverser

The performance, design and aerodynamics of thrust reversers for the mixed exhaust high bypass ratio engines are all very complex and challenging. In this section the focus is to shed some light on these areas. The calculations were performed using the information available in the public domain.

The reason for carrying out the CFD analyses was twofold; first to better understand and visualize the thrust reverser flow for a mixed exhaust engine and second to investigate the core flow with the reverser deployed. Without the CFD analyses it would not be possible to study if the core flow will exit as a stable flow through the common nozzle or will expand in the mixer. Although mixed exhaust high bypass ratio engines have been in service for many years no CFD or aerodynamic references were found where such a flow has been investigated. Most of the information is proprietary for the mixed exhaust engines and is not published by the industry experts. Therefore, this work may well be the starting point for anyone interested in the subject.

Two axisymmetric models were built; first was with thrust reverser stowed and the other with the thrust reverser deployed. The former is to investigate the flow at aircraft landing condition and the latter is to investigate the flow at the three reverse thrust conditions i.e. idle reverse thrust, maximum reverse thrust at 0.211 M (140 knots) and maximum reverse thrust at 0.09 M (60 knots). Strictly speaking the engine nacelle may not be axisymmetric and the reversed flow from the pivoting doors installed at the lower part of the nacelle will be different from the reversed flow from the pivoting doors installed at the upper part of the nacelle. This is due to the simple reason that the flow from the lower pivoting doors will be affected by the ground. This type of study would be very time consuming. However, the axisymmetric numerical simulations performed in this paper will still show significant results relating to the reversed flow and will serve the purpose for this study.

The thrust reverser model was built and scaled from that shown in (Figure 6.3). Two structured meshes were built. The CFD simulations were performed on FLUENT. The boundary conditions for

the two models were set as shown in (Figure 6.14). The values for the boundary conditions were set to those obtained from the engine performance model (Table 6.1, 6.2, 6.8, 6.13 and 6.14). The *k-ε* *realizable* turbulence model was used, and the figures and results presented here are of second order converged solution.

The CFD results shows that changing the thrust settings from forward idle to reverse idle at a speed of 0.211M (140 knots) will produce sufficient reverse thrust. Although, the engine is operating at low power the reversed flow will still contribute in slowing the aircraft down. It was also observed that in all three configurations there will be a region of re-circulating flow which sits at the point where the blocker door meets the core casing (Figure 6.19) and will act as a curvature to turn the flow along the pivoting door. The fan flow is in two parts; the upper fan flow which is in contact with the nacelle inner surface and the lower fan flow which is in contact with the core casing. At the reverser exit the lower flow will accelerate along the curvature of the re-circulating flow and the upper fan flow is forced to travel further by the sharp extended nacelle surface. The reverser is designed such that the two flows will merge and accelerate along the pivoting door (Figure 6.19). As the flow leaves the pivoting door surface the increased velocity will allow the reversed flow to continue travelling in the same direction. However, as the reversed flow is not in contact with any surface the flow stream will increase in area hence decelerate the flow. The oncoming free stream air has a high velocity due to high landing speeds. Far ahead it will adjust the streamlines to avoid the pivoting door which for it is an obstruction. Therefore, the higher momentum free stream air will take along with it the reversed flow which has lost most of its momentum, downstream as shown in (Figure 6.16 – 6.19).

As the aircraft decelerates, the oncoming free stream air loses momentum, and at a speed of 0.09M (60 knots) the reverse flow will be at a higher momentum than that of the free stream air. Thus, the reverse flow will push itself forward. The reverse flow not only has a higher momentum but also higher total pressure and total temperature. The reverse flow will try to push itself forward towards the nacelle inlet, however, the oncoming free stream air although at a low velocity will still have some momentum and the two streams will collide. This will create a very high turbulent region above the inlet of the upper section of the nacelle (Figure 6.19 and 6.20). Also, further examination of the total temperature contours reveals (Figure 6.18) that a small stream of reverse flow which has a higher temperature than the oncoming air flow will travel along the outer external surface of the nacelle to the intake and then enters the tip of the fan. This will induce temperature distortions at the inlet of the fan and could affect the surge margin. Also, it is very likely that the flow along the lower nacelle surface will behave similarly despite the proximity of the ground. Thus, at 0.09M (60 knots), there will be a loss in reverse thrust due to reduce propulsive efficiency along with temperature distortion and the likely hood of F.O.D. Thus, it is advisable and is a common practice with airlines to cancel reverse thrust before 0.09M (60 knots).

The flow from the core nozzle to the common nozzle was investigated and it was found that during reverse thrust the core flow will exit as a stable flow i.e. attached to the exhaust plug and will not expand to fill the common nozzle. However, at the common nozzle exit the flow will expand slightly; this expansion of flow will reduce the flow velocity at the exit of the common nozzle and hence forward thrust produced by the core stream will reduce.

6.5.1 Grid and Boundary Conditions

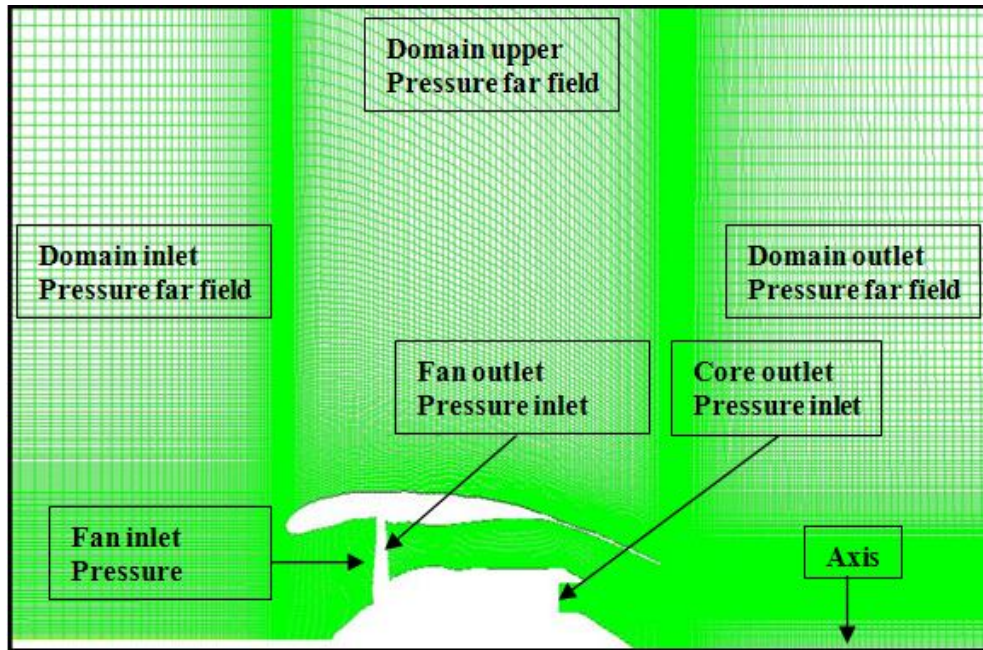


Figure 6.14: Grid and boundary conditions for the stowed reverser (magnified image).

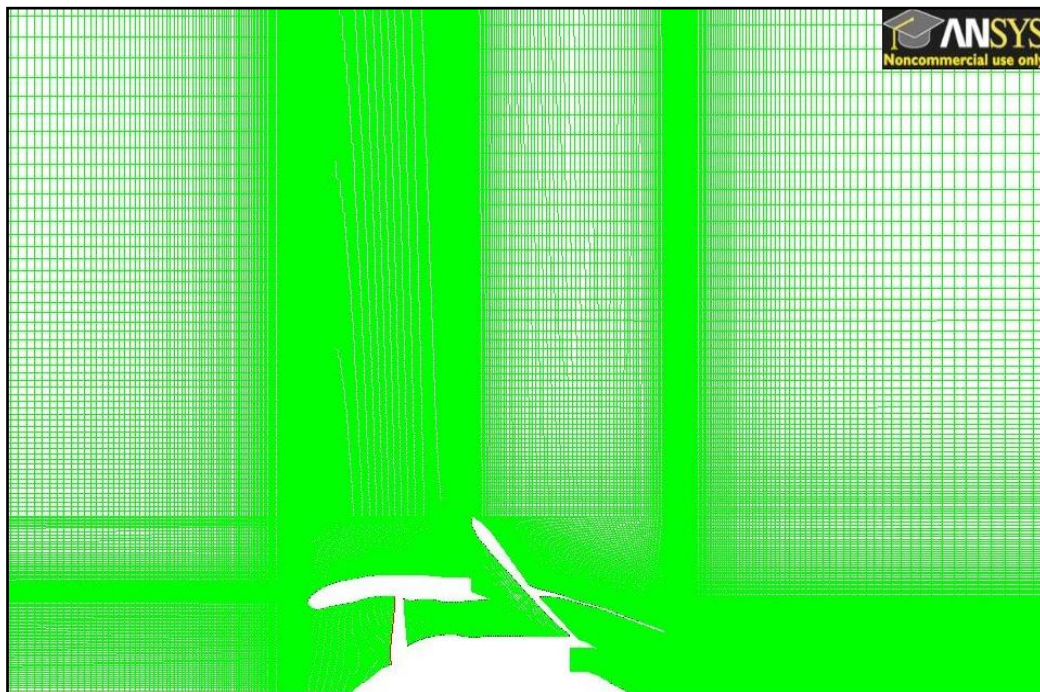


Figure 6.15: Grid for deployed thrust reverser (magnified image).

6.5.2 Static Pressure

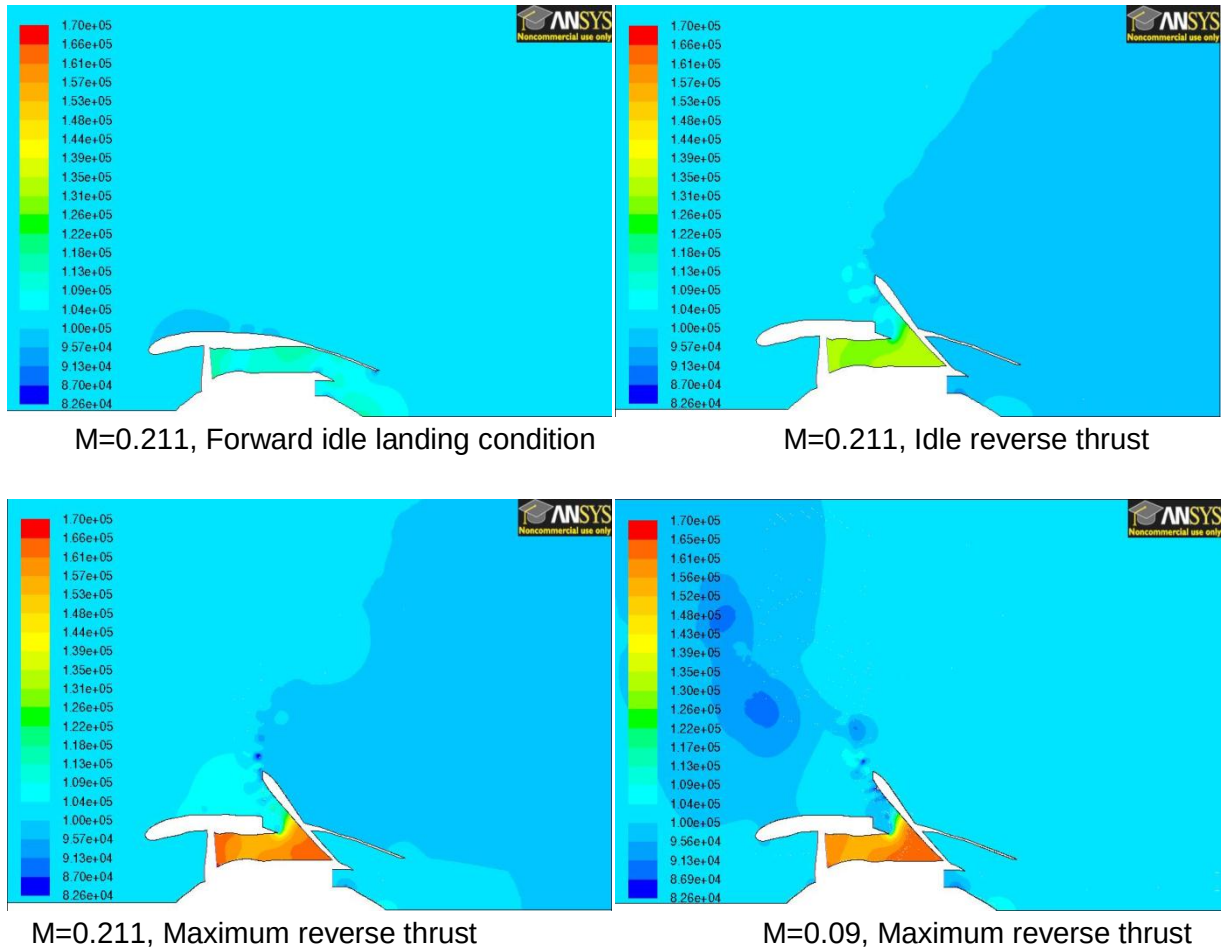
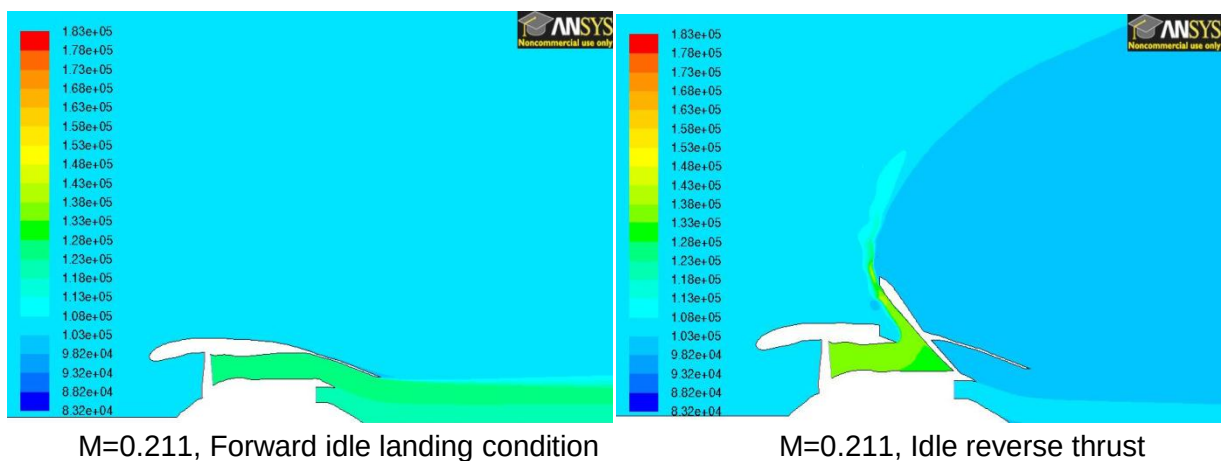


Figure 6.16: Contours of static pressure at forward idle, reverse idle and maximum reverse.

6.5.3 Total Pressure



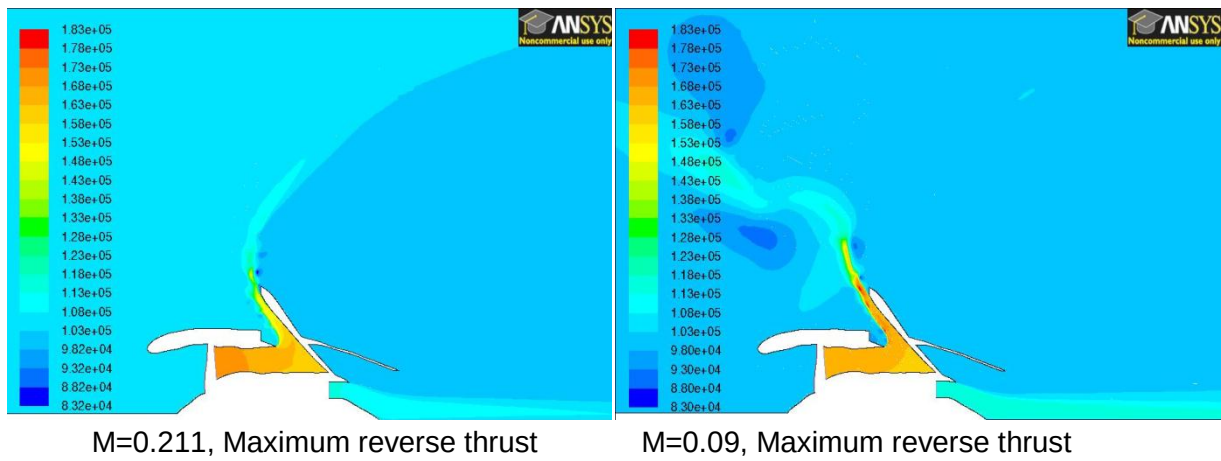


Figure 6.17: Contours of total pressure at forward idle, reverse idle and maximum reverse.

6.5.3 Total Temperature

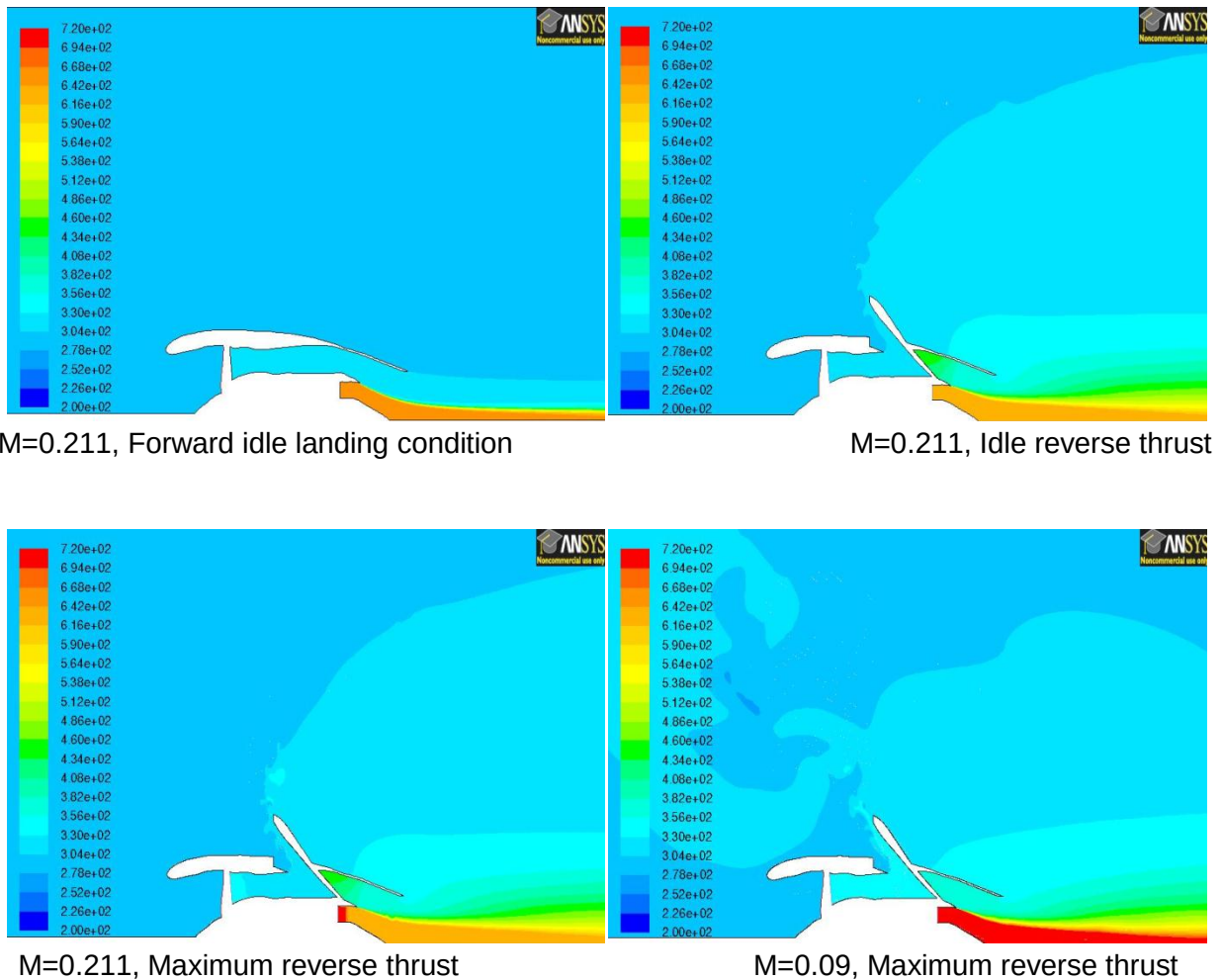
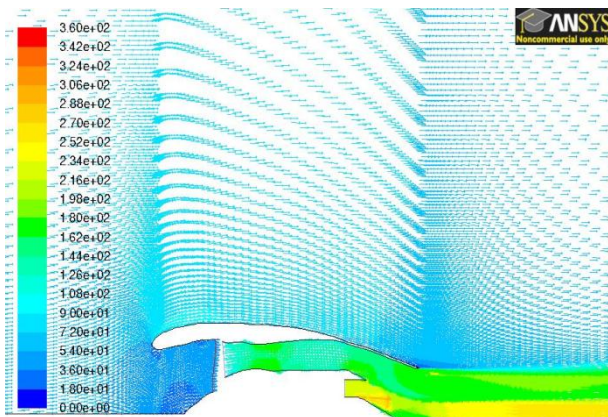
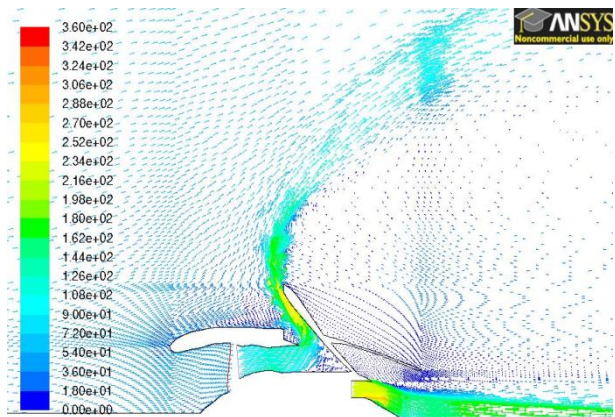


Figure 6.18: Contours of total temperature at forward idle, reverse idle and maximum reverse.

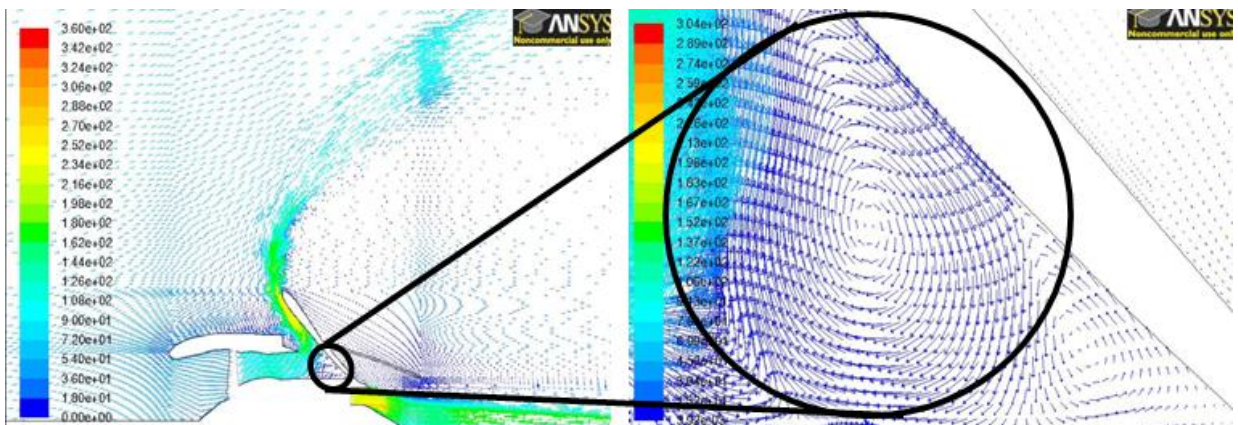
6.5.4 Velocity Vectors



$M=0.211$, Forward idle landing condition



$M=0.211$, Idle reverse thrust



$M=0.211$, Maximum reverse thrust. Re-circulating flow at the corner of blocker door and core casing.

Figure 6.19: Velocity vectors at forward idle, reverse idle, maximum reverse and re-circulating flow.

6.6 Aircraft Performance

Figure 6.19, shows a plot where the aircraft lands at idle power and then engages into reverse idle, then from reverse idle to maximum reverse. The reverse thrust is cancelled at 0.09 M and the aircraft is taxiing at idle thrust. However, the net thrust will increase as the aircraft decelerates from 0.09M to 0.05M; this is because as the aircraft decelerates the inlet momentum drag decreases.

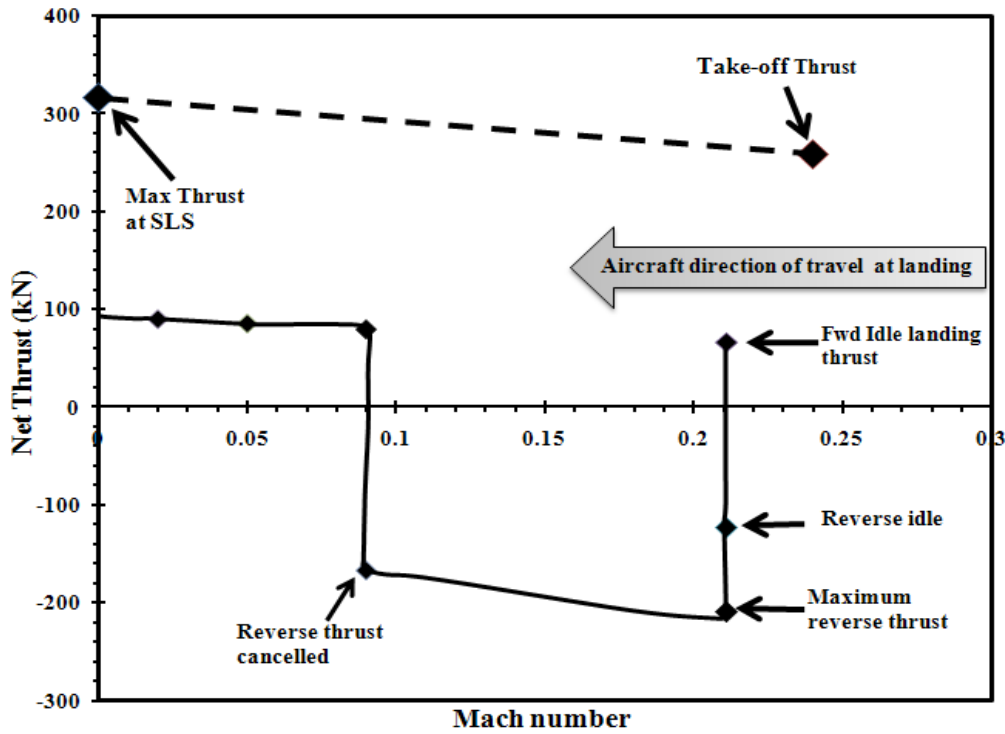


Figure 6.20: Engine thrust profile during aircraft landing.

6.6.1 Aircraft Deceleration Time

During landing the pilot applies reverse thrust to shorten the landing distance. The reverse thrust exhaust is inclined at the pivoting door angle (θ) to the normal flight. If the aircraft is powered by (n) engines, and assuming the average drag on the airplane during landing is, D_{av} , then the time necessary to decelerate the aircraft from touchdown speed (V_{TD}) to any value (V) is given by [Ref. 70]:

$$t = -\frac{m}{nW} \ln \frac{V + V_j \cos \theta + (D_{av}/n\dot{m}_a)}{V_{TD} + V_j \cos \theta + (D_{av}/n\dot{m}_a)} \quad [\text{Equation 6.8}]$$

where

- m : aircraft total mass at landing
- W : mass flow rate of air entering or leaving one engine (negligible fuel mass flow rate)
- V_j : reverse flow exit velocity
- θ : reverser cascade angle, taken as 35°

$$D = D_{av} = \frac{1}{2} \rho V^2 S C_D \quad [\text{Equation 6.9}]$$

Table 6.17: Thrust reverser deployment time

Aircraft maximum landing weight (kg)	V (m/s)	W (kg/s)	Drag (kN)	Rev Thrust(kN)	Time(sec)
180,000	72	837.6	103.104	349.4	1.14
180,000	66.8	833.6	89.014	349.4	1.2
180,000	61.73	829.83	75.714	349.4	1.22
180,000	56.6	826.51	63.715	349.4	1.28
180,000	51.4	823.59	52.545	349.4	1.29
180,000	46.3	821.08	42.635	349.4	1.22
180,000	41.15	818.99	34.418	349.4	1.5
180,000	36.01	815	25.776	349.4	1.41
180,000	30.86	812	18.990	349.4	9.1
				Total deployment time	= 19.36

As mentioned previously, the aircraft configuration used for this calculation is similar to that for an Airbus A330, called CUTEA (Cranfield University Twin Engine Aircraft) and the information available in the public domain was used for the calculations. A reasonable estimated value for the aircraft landing weight was taken as $m=180,000$ kg [Ref. 71], aircraft touchdown speed of 0.211 M (140knots), the average aircraft drag was calculated from (Equation 6.9). The pivoting door angle was taken as 35 degrees. The calculations were performed to find the total time for which the thrust reversers are deployed and the aircraft deceleration rate.

A survey was carried out by British Airways at London Heathrow Airport where they measured the thrust reverser deployment time for various aircraft on a dry runway. In the survey, 3 landings of the Airbus A330 were observed using the reverse thrust greater than idle and average time for use of the reverse thrust was noted to be about 19 second [Ref. 73]. Therefore, the thrust reverser deployment time calculated in this paper [Table 6.17] seems to be well matched with real data.

6.6.2 Calculation of Aircraft Ground Roll Distance

As the aircraft touches down there will be a period of rotation which introduces a slight delay before the wheel brakes can become effective. The typical rate of rotation is about 3 degrees per second; there will be some deceleration during the delay period, even though the brakes have not yet become effective. In a typical touchdown case the speed falls by about 1.5% per second [Ref. 72]. The ground roll time, (t), in which the lift dumpers and brakes become effective is about 3 seconds for large airplane [16]. The next stage is applying the reverse thrust for some 600 to 1000 m. Finally, the thrust reverser is stowed prior to final stop. Thus, the three landing distances will be calculated here. Only the main equations are presented. Detailed derivation is shown in Ref [Ref. 70] and [18]. The landing distance may then be written as:

$$S_{Total} = S_1 + S_2 + S_3 \quad [\text{Equation 6.10}]$$

Where the free roll distance is

$$S_1 = S_{fr} = tV_{TD} \quad [\text{Equation 6.11}]$$

$$S_2 = \frac{m}{2} \frac{V_{TD}^2 - V_{brake}^2}{[T_{rev} + D + \mu_{r1}(W_{force} - L)]_{0.7V_{TD}}} \quad [\text{Equation 6.12}]$$

Here the lift and drag forces are calculated at an average speed equal to seventh-tenth of the touchdown speed. The value for reverse thrust, T_{rev} , are obtained at a reverser cascade angle of 35° .

The third segment is when the brakes are applied and the thrust is again in the axial direction but at idle condition. Here the lift and drag forces are calculated at an average speed equal to thirty five percent of the touchdown speed.

$$S_3 = \frac{m}{2} \frac{V_{brake}^2}{[-T + D + \mu_{r2}(W_{force} - L)]_{0.35V_{TD}}} \quad [\text{Equation 6.13}]$$

Table 6.18: Aircraft landing distance with maximum and idle reverse thrust

V_{TD} (m/s)	V_{TD2} (m/s)	V_B (m/s)	m (k/g)	NetRev/T (kN)	S_1 (m)	S_2 (m)	S_3 (m)
Reverser thrust at MAX power – pivoting door angle 35°							
72	69.8	27.9	185,000	418.2	248	853	67
					S _{Total} = 1190 m (3,904 feet)		
Reverser thrust set at idle power – decelerating with brakes and lift dumpers							
72	69.8	27.9	185,000	246.2	248	1,399	65.7
					S _{Total} = 1712 m (5616 feet)		

The reverse thrust value in the table above is for both engines and the value is taken from the engine performance section (Table 6.1). As shown in (Table 6.18), landing with thrust reverse operating could considerably reduce the landing distance. When the reverse thrust is set to rev-idle and the pilot decelerates the aircraft only with brakes and lift dumpers; the landing distance of 1,712 m (5,616 feet) is similar to that given in [Ref 15] for the Airbus A330 where the distance of 1,722 m is given at maximum landing weight. This shows that the landing distances are given by aircraft manufacturers without taking the effects of thrust reverser into account. Comparison is made between the two cases, one, where the pilot decides to set the thrust to idle, and second when the pilot uses maximum reverse thrust. There is the difference of 545 m (1,788 feet) which is substantial and could be extremely beneficial in case of emergency landing or landing at the airports where the runways could be contaminated due to wet or icy conditions.

6.7 Conclusions

In this study, the thrust reverser for a high bypass ratio mixed exhaust engine operates only on fan stream. Therefore, thrust reverser deployment changes the engine configuration from mixed to separate exhaust. The optimum reverser exit area value was found using the same engine designed as a separate exhaust. The reverser exit area is well designed to give optimum reverser performance. However, the exit area for the core flow will increase the LP turbine pressure ratio, hence; the fan speed should be monitored at high power. CFD analyses shows that during reverse thrust the core stream flow will remain attached to the exhaust plug. Also, at low forward speed i.e. 0.09M the reverse flow may induce temperature distortions at the fan tip. Analyses for time estimation and landing distances were performed using a 35 degree pivoting door angle. It was observed that on a dry runway the use of thrust reversers can reduce the landing distance on average by more than 522 m (1,712 feet).

Chapter 7: CFD Analyses of a Core-Mounted Target Type Thrust Reverser in Stowed and Deployed Conditions

7.1 Introduction

Future high bypass ratio turbofan engines will have higher mass flows and larger nacelle sizes. Increment in mass flow and nacelle size will give rise to momentum drag. An increment in momentum drag provides a room for a less efficient thrust reverser design.

Therefore, for future high bypass ratio turbofan engines there also exists a possibility to adopt a less efficient thrust reverser design as long as it provides sufficient reverse thrust together with momentum drag to decelerate the aircraft within the safe landing distances and in addition can offer thrust reverser weight savings and simplicity in thrust reverser overall design.

One such thrust reverser design that has a potential of reducing overall reverser weight is a core mounted target type thrust reverser concept. The core mounted target type thrust reverser concept was proposed by NASA in the year 1996. However, since the year 2000 no work has been carried out on this concept as per the public domain.

Static wind tunnel tests were performed by NASA, summary of the results is available in the public domain. The results from the wind tunnel tests showed that the core mounted target type thrust reverser is not capable of providing sufficient reverse thrust.

The reason for selecting the core mounted target type thrust reverser concept for this research is its simplicity and a potential to offer weight savings. The author believes that the study carried out by NASA was brief and there is a potential in extending this research further.

The core mounted target thrust reverser concept will mainly be suitable for future high bypass ratio turbofan engines i.e. $9 < \text{BPR} \leq 15$.

Initially, 3D CFD analyses will be carried out on a core mounted target type thrust reverser design. This would allow a direct comparison of the CFD results with the experiments. The CFD study will also provide a greater understanding of the flow physics.

The engine model selected for this study is CUTS_TF, which is similar to GE 90-94B. GE90 is a high bypass ratio turbofan engine, with an approximate bypass ratio of 9.

Wind tunnels tests were performed on a 7.9% scaled model of a GE90 turbofan engine. However, the CFD analyses were carried out on full scale geometry.

In section 7.9, the emphasis is placed upon explaining the aerodynamics with the help of streamlines pattern and static pressure distribution around the engine.

In section 7.10, results from the 3D CFD analyses were compared against the experiments for the static pressure measurements on the fan and core nacelle surfaces and target reverser inner surface.

Section 7.14 – 7.17, discusses the results from the 3D CFD analyses and compares them against the experiments performed by NASA for similar geometries.

Section 7.18, discusses design feasibility for the core mounted target type thrust reverser.

7.2 Structure of the Chapter

This chapter discusses the following areas:

Advantages of performing CFD Analysis

Section 7.3, highlights the importance of performing 2D and 3D CFD analyses for the thrust reverser applications.

CAD Design

The 3D CAD modelling was performed using CATIA V5 design software. Section 7.4, discusses the CAD modelling design and process. The following geometric configurations are studied:

- a) Reverser stowed configuration i.e. forward thrust condition.
- b) 40 degree core mounted target type reverser.
- c) 40 degree core mounted target type reverser with kicker plate.

Once the CAD modelling was completed in CATIA V5, the geometric model were converted into an IGS format and the files were then transferred to ANSYS ICEM software for meshing and geometric cleaning. Due to the complexity of the geometry once the model was transferred into ICEM, the geometry was cleaned i.e. all the points, curves and surfaces needs to be fixed and should be free of errors. This is a necessary process before meshing. See section 7.4 for further details.

Meshing

Unstructured meshes were generated in all cases. The process of 3D meshing is difficult, time consuming, complex, and requires an attention to detail. Surface, prism and volume meshes were generated for the cases.

Before transferring the mesh files into FLUENT, it is important to ensure that the mesh is error free. All the relevant mesh checks need to be completed in ICEM, this process is important as it ensures that the mesh is compatible and free of errors.

Typical mesh for forward thrust geometry has approximately 6 million elements.

Typical mesh for a 40 degree target thrust reverser has approximately 9 million elements.

Typical mesh for a 40 degree target thrust reverser with kicker plate has approximately 10.5 million elements.

See section 7.5 for further details.

Numerical Analyses

ANSYS FLUENT was used as a CFD solver. Section 7.6, discusses the CFD methodologies, which includes discussion on model setup, boundary conditions, selection of turbulence model.

Section 7.8 and 7.9, discusses the 3D CFD analyses for both the static ($M=0.0$) and forward landing ($M=0.211$) conditions.

CFD analyses were performed for the forward thrust configuration and two reverse thrust configurations.

In this section the aerodynamics at static and forward landing conditions are also discussed.

Results were also discussed for the 3D CFD analyses and comparison was made against the experiments.

Design Feasibility

Section 7.18 discusses the design feasibility of the core mounted target type thrust reverser. 30 different reverser designs were tested. The results from the 2D CFD analyses are also presented.

7.3 Advantages of Performing CFD Analysis for Thrust Reverser Study

There are many advantages of performing the 3D CFD analyses, some of which are listed below:

- i) 3D CFD analyses could be helpful in understanding the reverser design.
- ii) 3D CFD analyses could be a useful tool to measure the thrust reverser performance particularly at an initial design phase.
- iii) CFD analyses can be performed at static conditions i.e. $M=0.0$ and at aircraft landing speeds such as $M=0.211$ and at $M=0.09$.
- iv) CFD analyses would be beneficial as they help in flow visualization. This could be useful in understanding the flow physics. Also, it could help to improve the reverser design.
- v) CFD analyses would help to visualize the effect of thrust reverser flow and its interaction with other geometric parts and how their performance would be affected. Mainly reverser deployment can affect the aircraft wing; lift dumpers, runway, fuselage, external nacelle, landing brakes etc.
- vi) CFD analyses are cost effective and calculations can be performed faster in comparison to performing wind tunnel tests.
- vii) Preliminary study of a thrust reverser design can be modeled using CFD. This can be useful as many geometrical design changes can be made relatively easily.
- viii) More measurements are possible with a CFD study, whereas for experiments, probes need to be set up at certain locations.
- ix) CFD analyses can also be used as a validation tool with experiments.

7.4 CAD Design and Modelling

At the start of the project it was decided to perform 3D CFD analysis to model the thrust reverser performance and flow characteristics. Thus, an overall 3D CAD model was required. All the CAD model geometries were built using CATIA V5 software.

NASA performed the wind tunnel experiments, using the GE90 and B777, 7.9% scale models of fan and core exhaust nozzles together with the thrust reverser, wing and pylon geometries. The dimensions and 3D coordinates for most of the geometries were available in the NASA report, [Ref. 33]. However, the 3D CAD models may have small geometrical differences with the experimental setup. One such difference may be because the CAD models were first built as a 7.9% scale model, the geometries were then scaled to approximately represent the real sizes. For most of the cases, the CAD parts were designed with geometric dimensions similar to those available in the public domain, such as Jane's Aircraft of the World, and Jane's Engines.

7.4.1 Building CAD Models

A typical geometry used for the wind tunnel testing is shown below (Figure 7.1). In comparison with the wind tunnel setup the CAD model was designed for the CFD testing. During experimental testing primary and secondary air supply lines were used to provide the fan and core flows. However, for the CFD analysis, complete engine nacelle geometry was built, as shown later. Also, the CFD analyses were performed at landing conditions i.e. at $M=0.211$ and at static conditions as per NASA i.e. $M=0.0$. All of NASA wind tunnel tests were performed at static conditions i.e. $M=0.0$.

Ground effects are important during the landing phase. Therefore, all the CFD analyses were performed on a runway. The external nacelle ground clearance is maintained similar to that for the B777; the values were obtained from Jane's Aircraft of the World.

A large flow domain is important for the CFD analysis. Thus, a rectangular box was built around the geometry. The upstream and downstream dimensions of the far field were set as sixty times the wing span. The height was approximately thirty times the wing span.

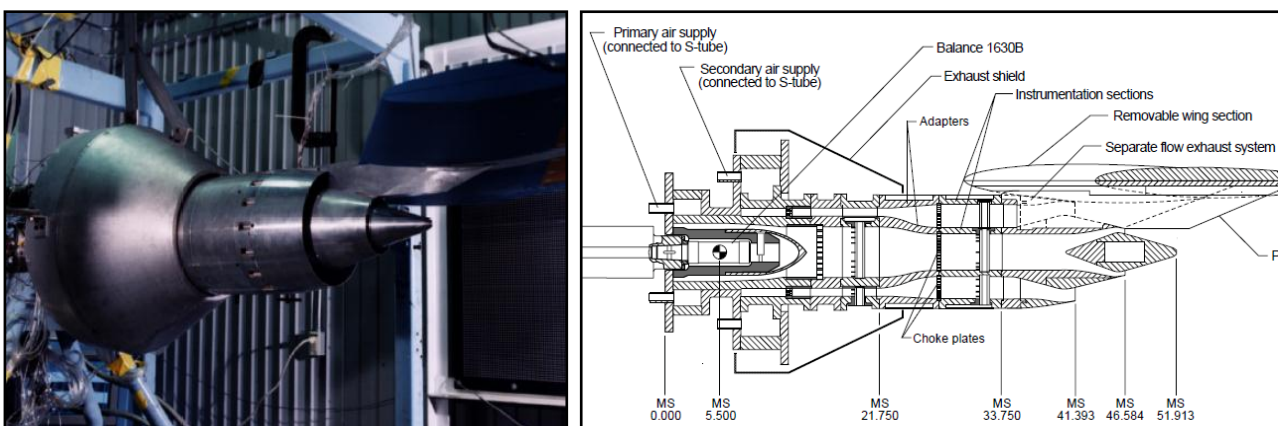


Figure 7.1: (L) A typical geometry used for wind tunnel testing. (R) Geometry schematic [Ref. 33]

The process of building different CAD parts is complex and very time consuming. It involves great attention to detail in processes such as understanding part drawings, drawing part sketches, building model curves and surfaces, scaling parts, assembling parts, as inaccurate dimensions or misleading sizes could affect the end results.

It is also important to ensure that the parts are modelled correctly such that a minimum effort is needed in cleaning the geometry. The geometric dimension and sizing is also important as inaccurate domain sizes may give misleading results.

All CAD parts were designed in CATIA V5, using mechanical part design, geometric shape design, and assembly design workbenches.

7.4.2 Geometric Parts Description

This section shows and discusses the CAD models generated in CATIA V5 for the CFD analyses. Figure 7.2, shows the whole domain. Bigger domains are required for the CFD analyses to model the free stream conditions.

During forward flight fan and core exhaust jets have high speeds and at high power the exhaust flow could travel a long distance. It is important that the downstream far field boundary is set at an appropriate distance such that the domain size will have no effect on the exhaust flows. Similarly, during reverse thrust operation all far field boundaries must be set such as the domain size is sufficient to have minimum possible effect on the overall flow. For these reasons, the pressure far fields boundary condition was set for inlet and outlet with the upstream and downstream zones approximately 60 times the size of the wing span. The pressure far field_1, which is the upper domain, is set to approximately 60 times the wing span sizes (Figure 7.2). From the CFD results these dimensions were sufficient to resolve the flow physics without any disturbances.

The distance between the external fan nacelle surface and the runway was set as per the B777 aircraft configuration mentioned in Jane's Aircraft of the World. As per Jane's, the ground clearance under engine is 16 ft. 10 inches.

A symmetry boundary condition was defined as shown in (Figure 7.2).

A comparison can be made between the overall domain size and the CAD model as shown in (Figure 7.2).

Wing geometry is divided into pressure surfaces, suction surfaces, wing leading edge, wing trailing edge and wing tip. Six wing pressure surfaces and six suction surfaces were built. The geometry is a scaled up model of the wing used by NASA. The wing model matches well with the wing data given in the public domain; the wing chord, wing span, and wing area all were in good approximation with the values given in Jane's Aircraft of the World.

The pylon geometry was a difficult and time consuming task to build. Pylon geometry was built as per NASA. Nine pylon surfaces were built. Pylon was integrated with the wing, engine fan nacelle, and core nacelle surfaces. Well-designed pylon geometry is important for these types of analyses.

The fan nacelle comprises four external and four internal surfaces. The engine forward nacelle was constructed using the data available in the public domain. The size and shape of the nacelle is important. Care should be exercised in designing the nacelle inlet and nozzle areas.

Engine core is comprised of seven surfaces, three external and four internal. Core inlet area and core exhaust nozzle areas are both important.

A CAD model of an exhaust plug was also constructed and placed in the core region. The exhaust plug comprises of three surfaces. The location of the exhaust plug is important, to match the core nozzle area.

Fan cone was also designed as per the data available in the public domain, location and sizing is also important from the analysis point of view. Fan blade geometry was not modelled for this study, instead fan inlet and fan outlet flows were modelled with the help of two disc surfaces as shown. The locations of the surfaces as well as the surface sizes i.e. fan inlet and fan outlet areas are important.

Straight nozzle and two reverser designs were built; this includes, target reverser at 40 degree, target reverser at 40 degree with kicker plate installed. The thrust reversers overall size, installation positions and exhaust areas were built as per the NASA design. Figure 7.2 – 7.8, shows all the reverser geometries.

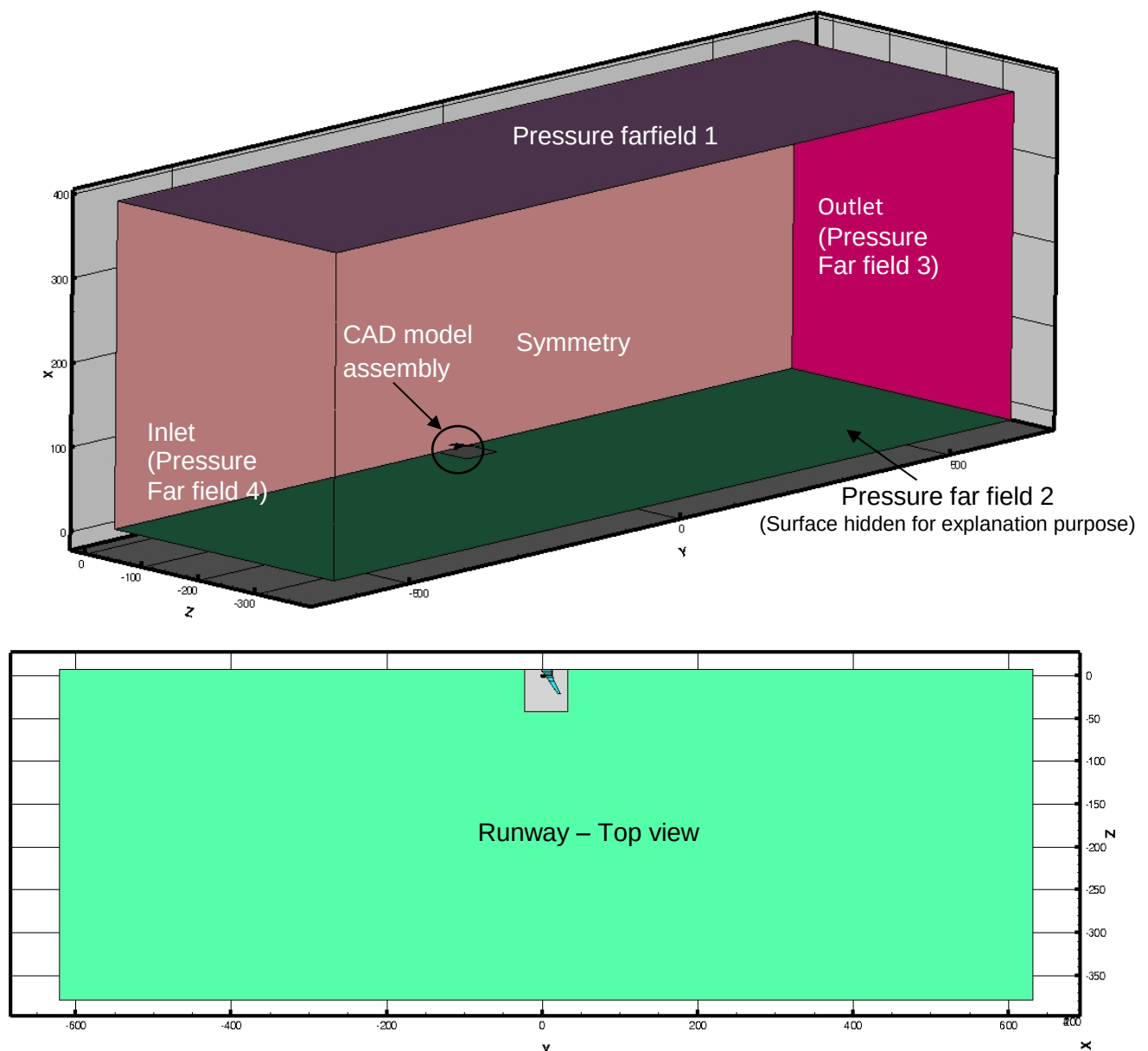


Figure 7.2: (Top) An isometric view of a complete CFD Domain. (Bottom) Top view.

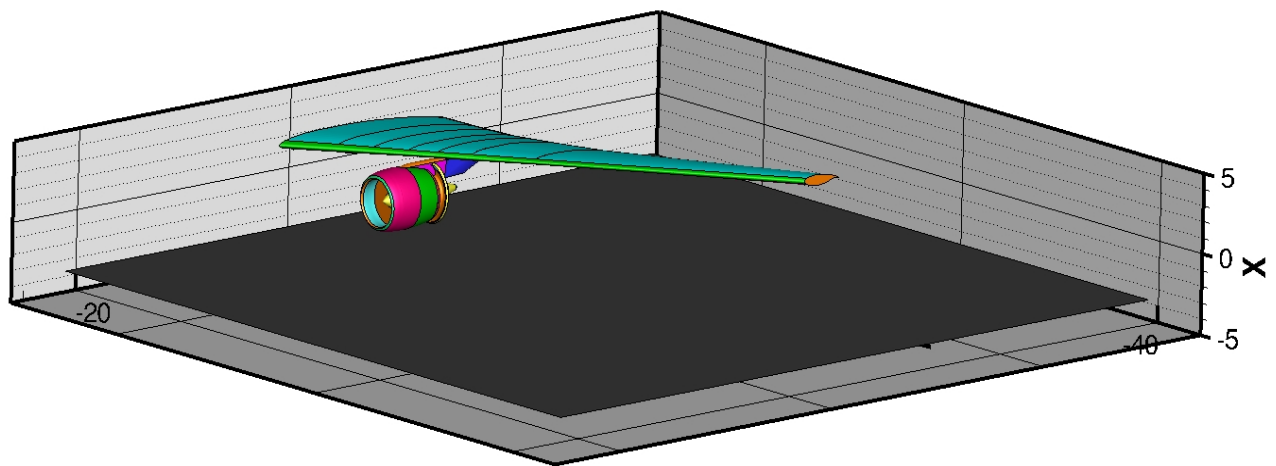


Figure 7.3: (Top) Close view of a typical geometry used.

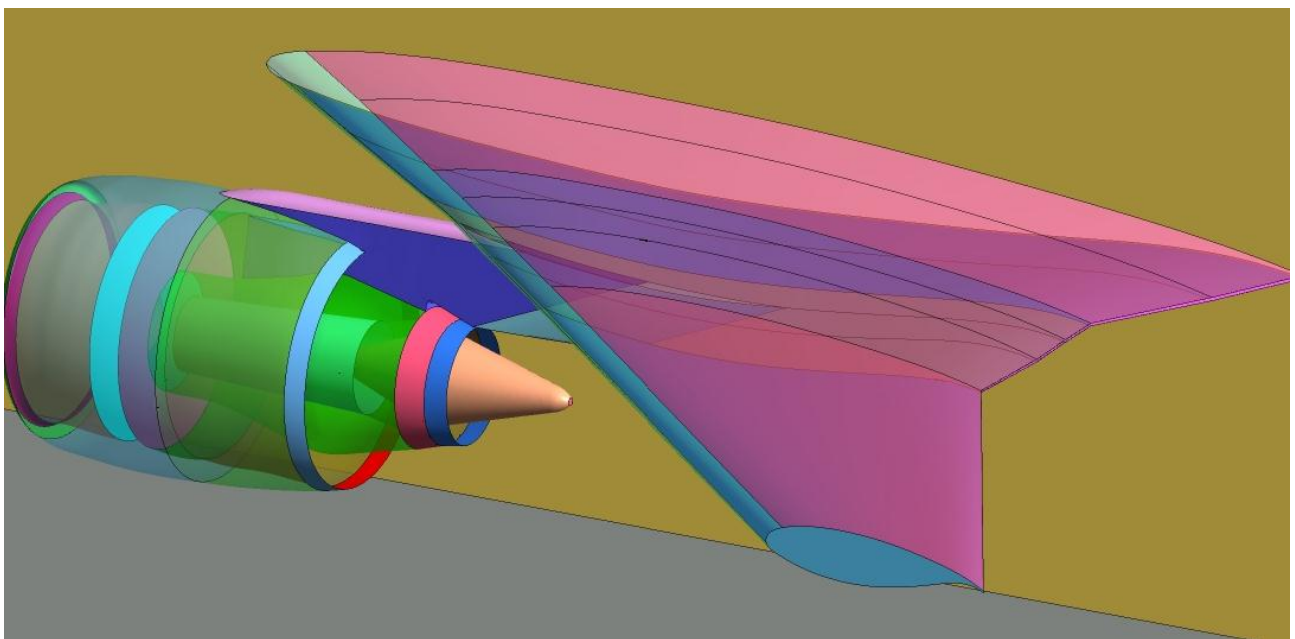


Figure 7.4: A 3D CAD model for a forward thrust configuration with transparency.

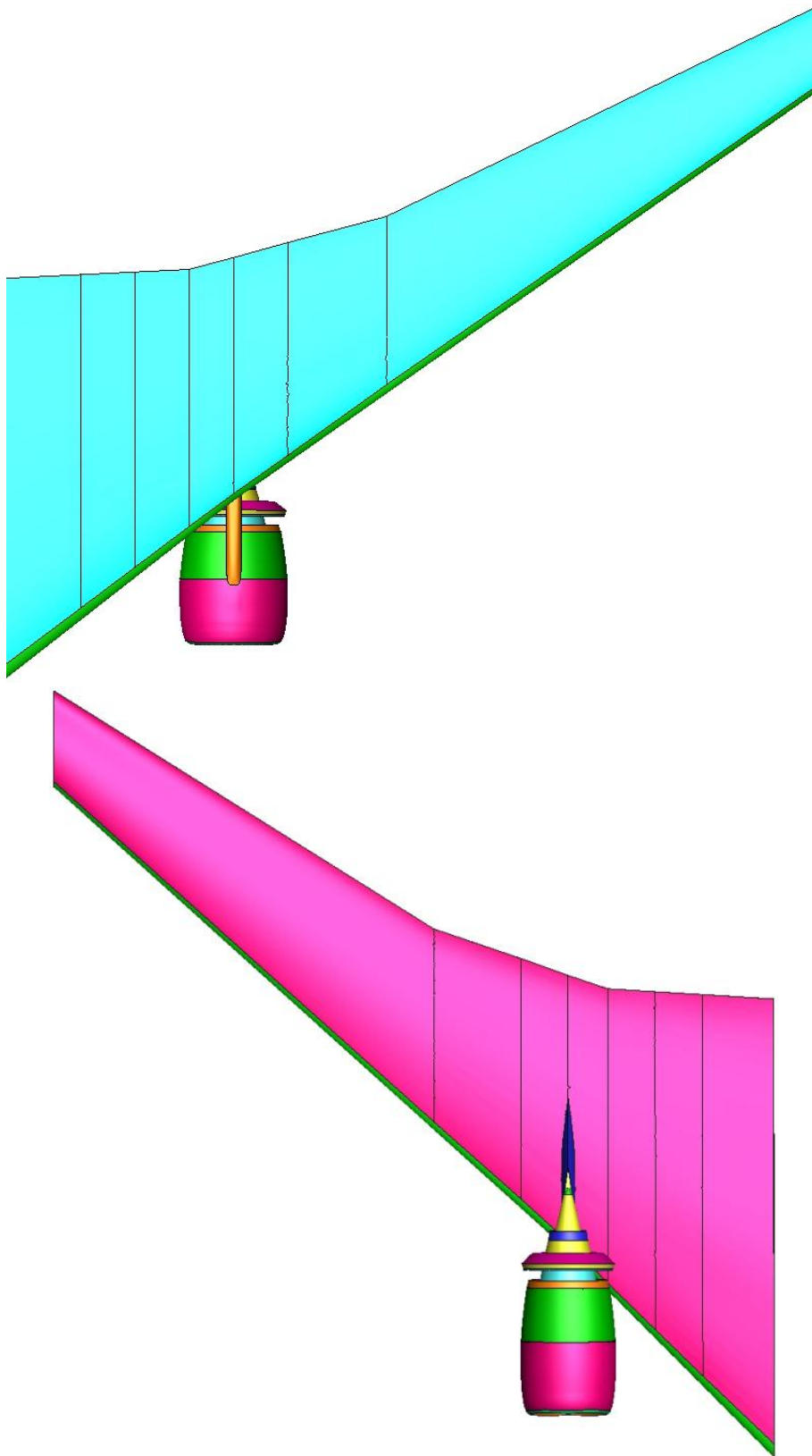
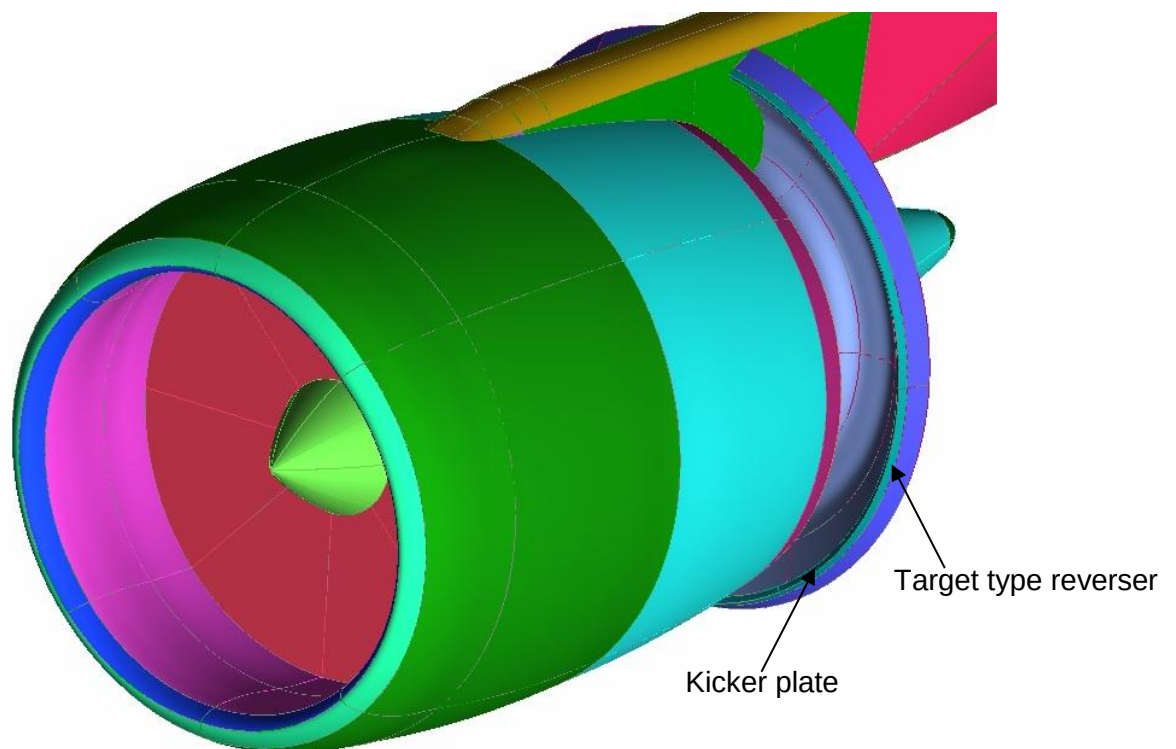
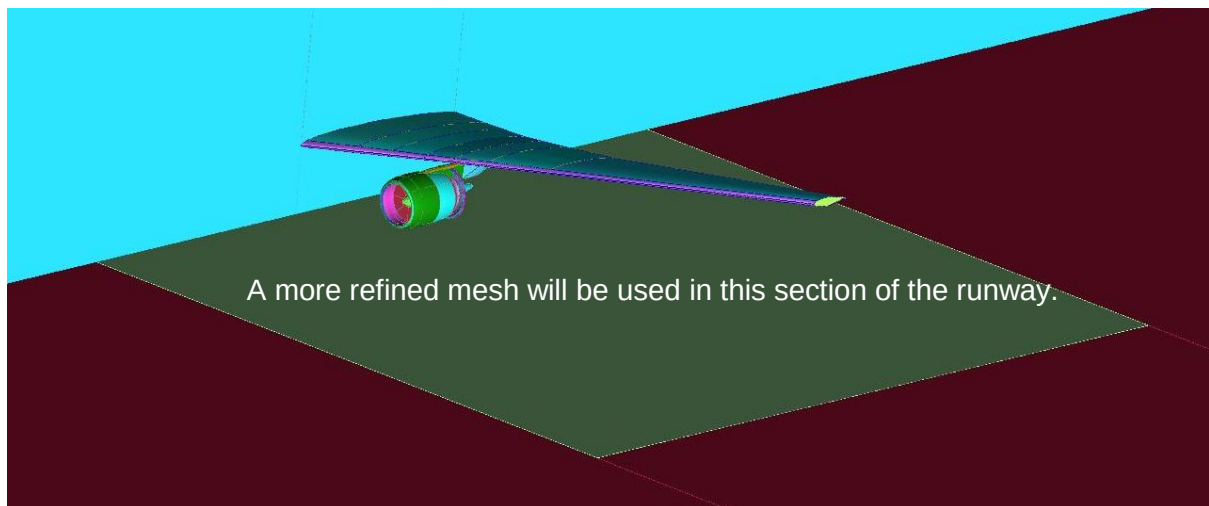


Figure 7.5: Top and bottom view for a core mounted target thrstut reverser installation.



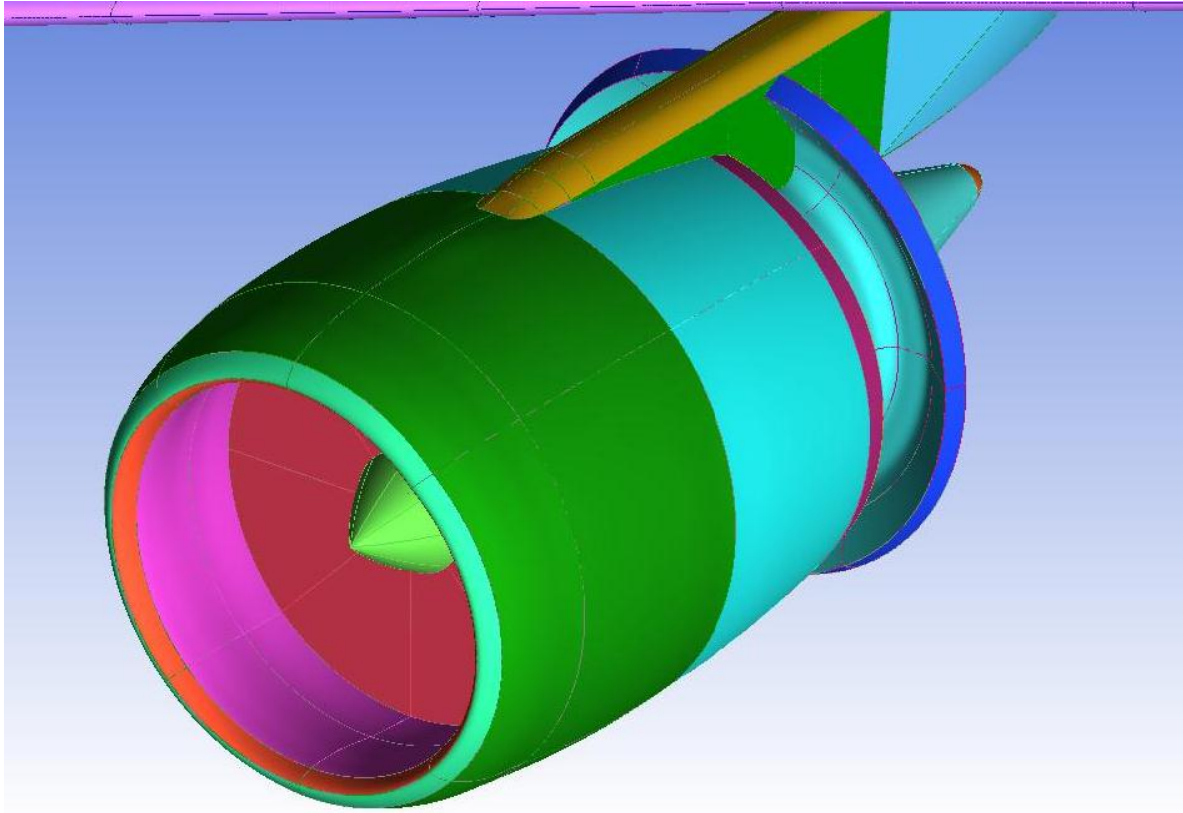


Figure 7.8: A 3D view of a 40 degree target type thrust reverser configuration.

7.5 3D Meshing

During this research, ANSYS ICEM CFD software was used for meshing all the 3D geometries. Unstructured meshing was performed on all the geometries. Initially, a surface mesh was first generated, then the prism mesh i.e. boundary layer mesh was built and finally the volume mesh was generated.

Generation of the surface mesh was challenging and time consuming. The number of mesh elements on geometric surfaces must be refined enough to be able to capture the flow physics. In ICEM CFD, surface mesh can be generated either independently on each geometric part or as a complete surface mesh in which case ICEM solver generates the surface mesh for each part at the same time. The second approach was used. The advantage with the second approach is that the mesh translation from one geometric part to the next will be smooth. Approximately, 10 – 12 million mesh elements were used. Figure 7.9 to 7.15 show surface meshes for complete geometry as well as for the individual components.

Prism elements are important as they represent the boundary layer mesh. In all cases approximately 10 boundary layers were built. Figure 7.15, shows a typical prism mesh for forward thrust configuration. A good prism mesh restricts the wall Y^+ values within the acceptable range. Y^+ of less than 150 was ensured in this study (Figure 7.21). However, the acceptable Y^+ range for k-e turbulence model is 30 to 300 [Ref. 70].

Volume mesh will account for the overall flow physics. Far field mesh is important in order to eliminate the numerical reflections.

Density blocks were used to build refined volume mesh regions in the desired locations. As shown in (Figure 7.15), density blocks were used at the wing leading and trailing edges, fan nacelle inlet and exhaust regions, core exhaust regions, and also density blocks were used with thrust reversers.

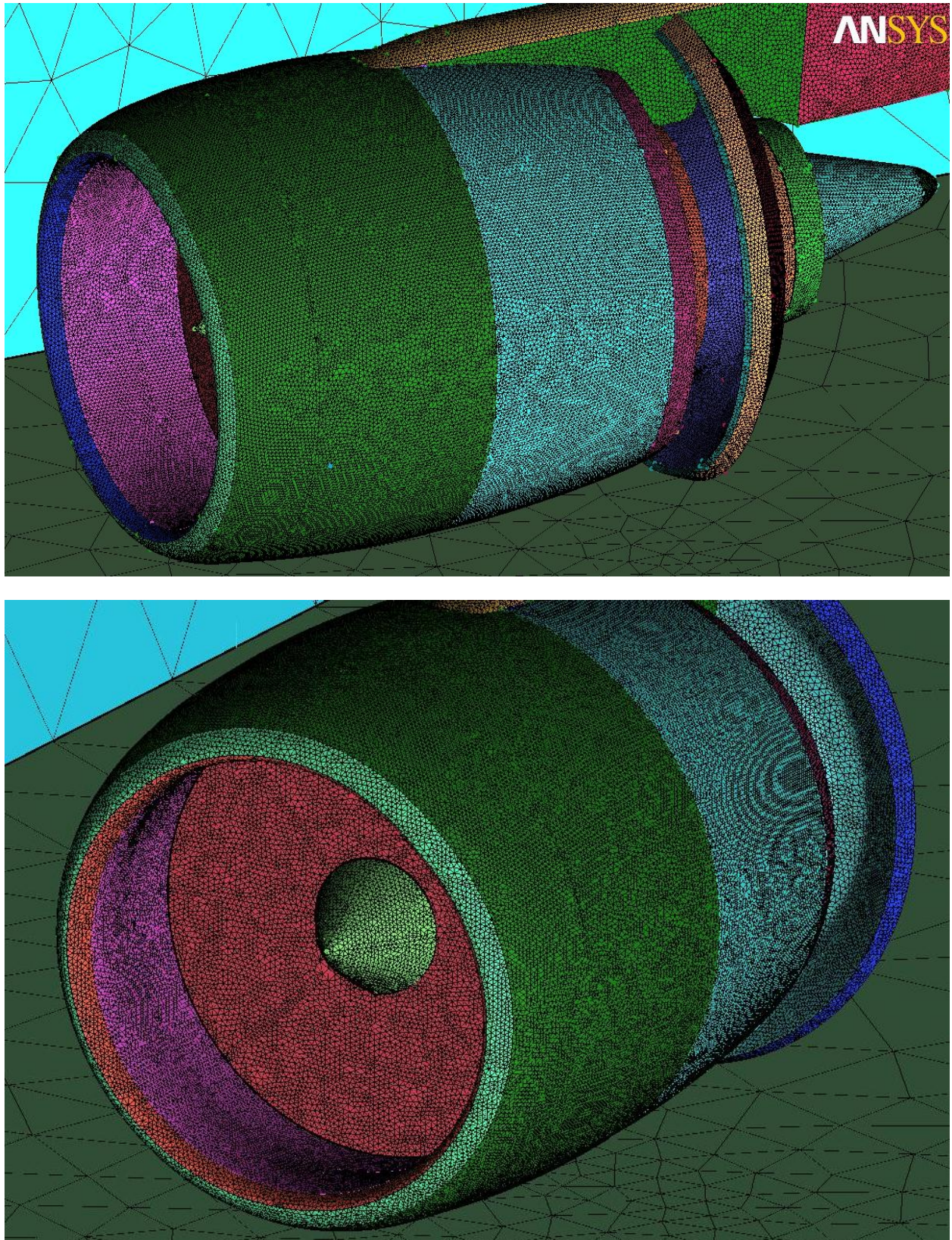


Figure 7.9: Shows a surface mesh for a 40 degree target type thrust reverser. (Top) with kicker plate and (Bottom) without kicker plate.

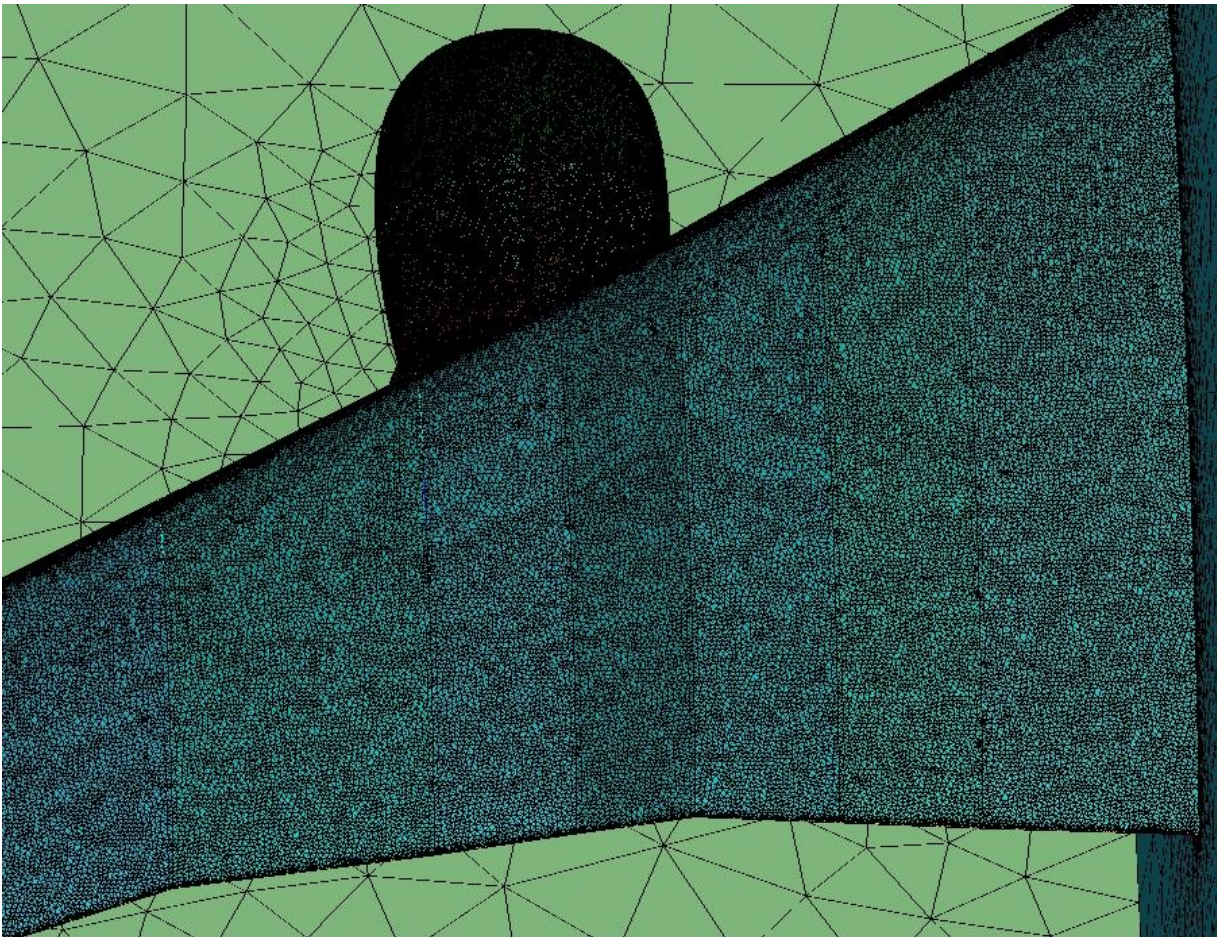


Figure 7.10: Typical surface mesh on wing suction surface.

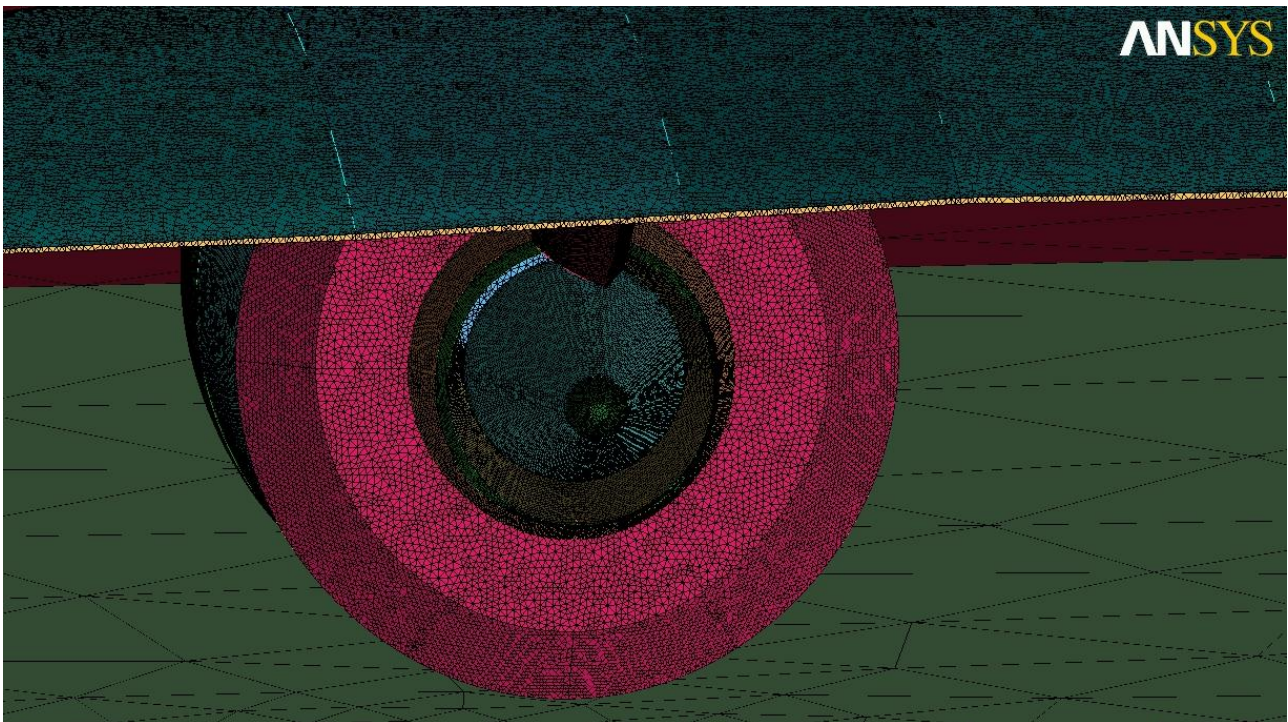


Figure 7.11: Aft view, showing the surface mesh for the wing trailing edge, exhaust plug and rear of the core mounted reverser.

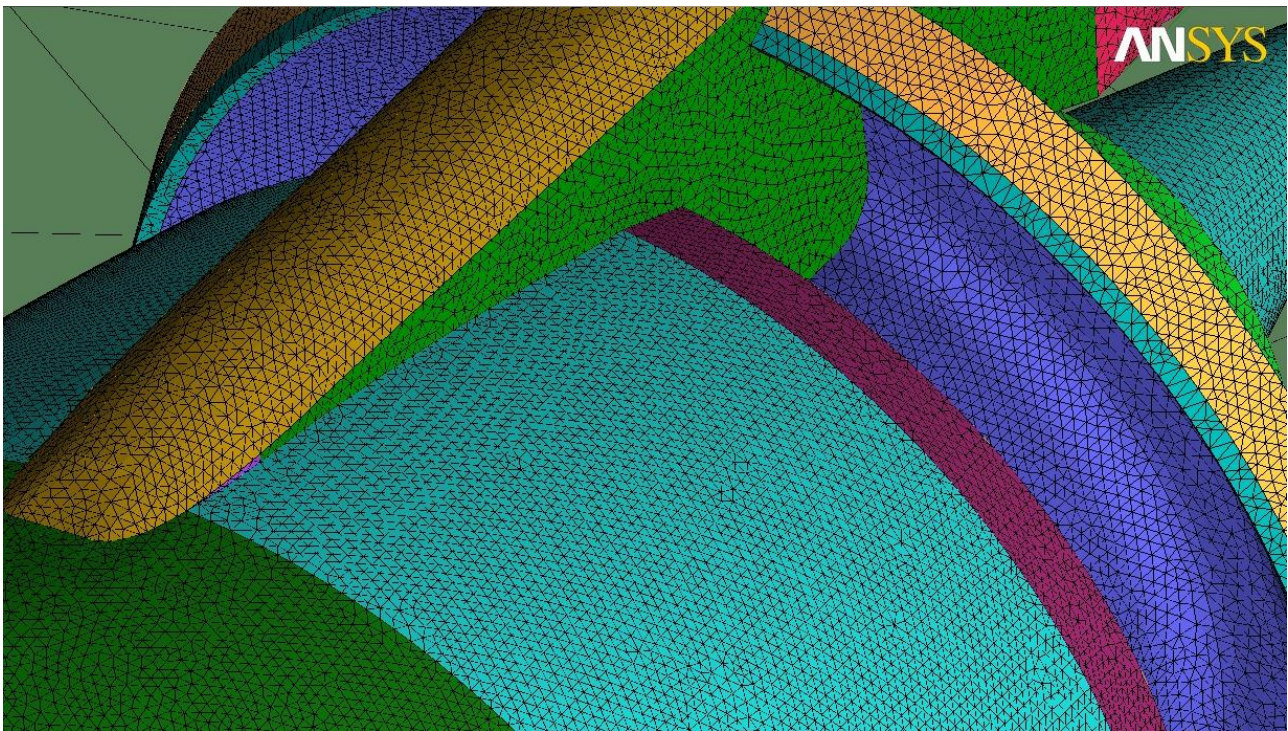
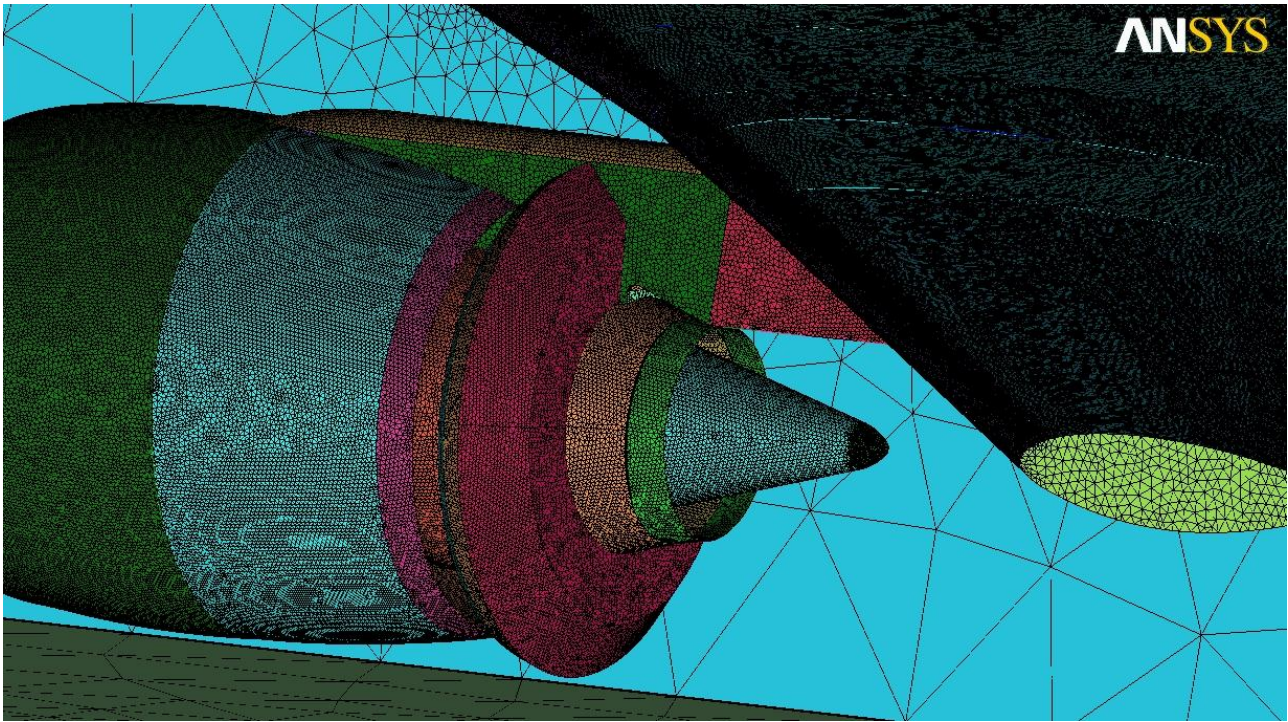


Figure 7.12: (Top) Surface mesh of the reverser, nacelle external surface and pylon are visible. (Bottom) Close view of the nacelle external mesh, pylon and kicker plate.

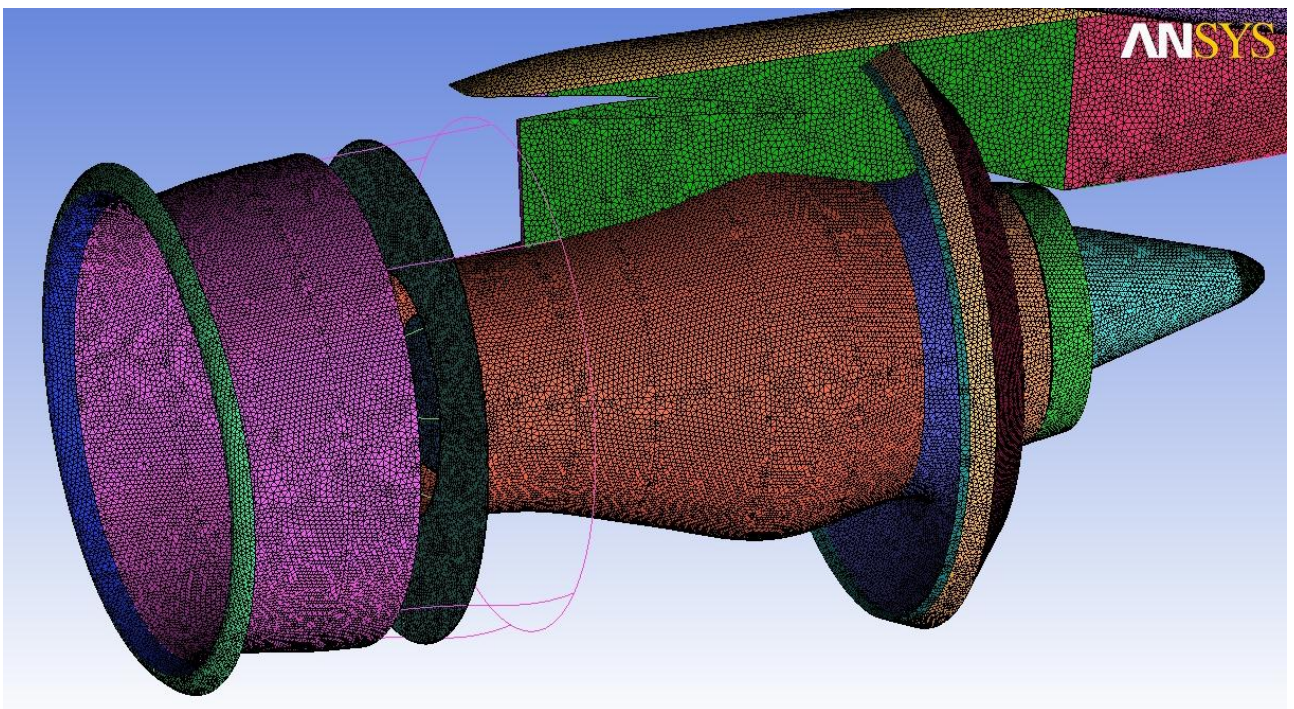
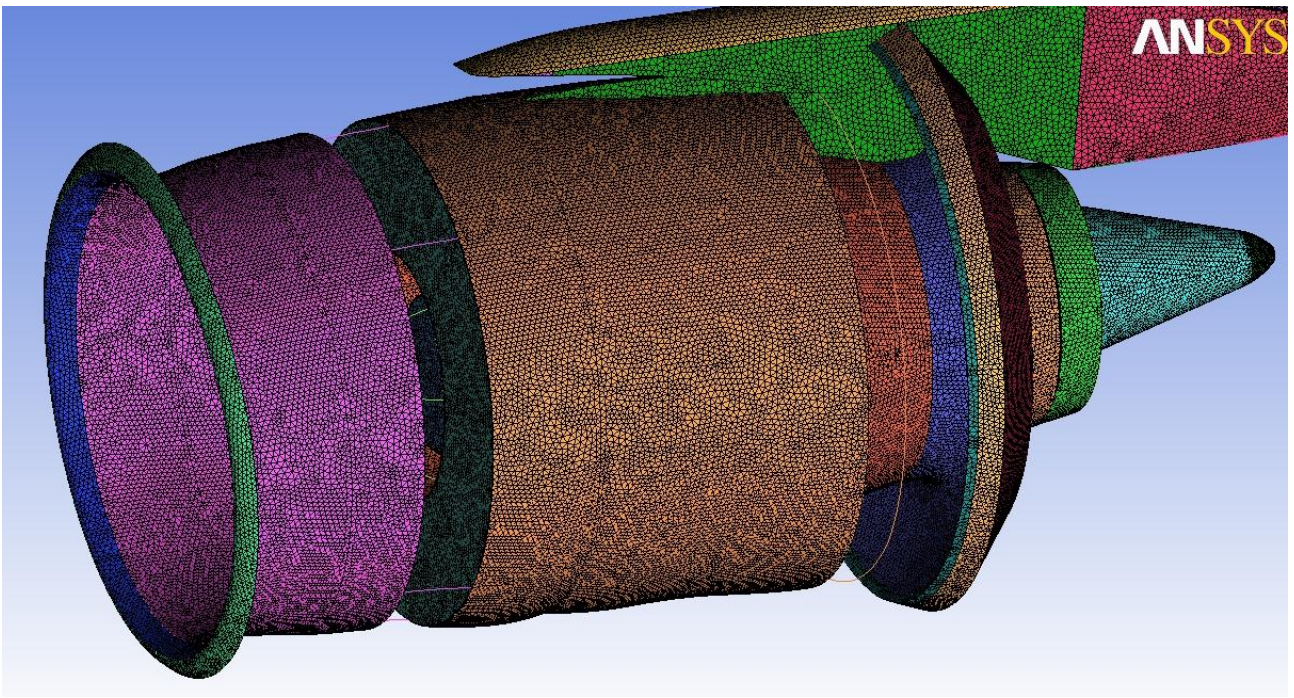


Figure 7.13: Shows the surface mesh on individual components. (Top) shows a surface mesh for fan nacelle internal surface, and for forward nacelle internal surface. (Bottom) shows the mesh on core external surface. Also visible on both figures are the refined mesh on the nacelle inlet regions.

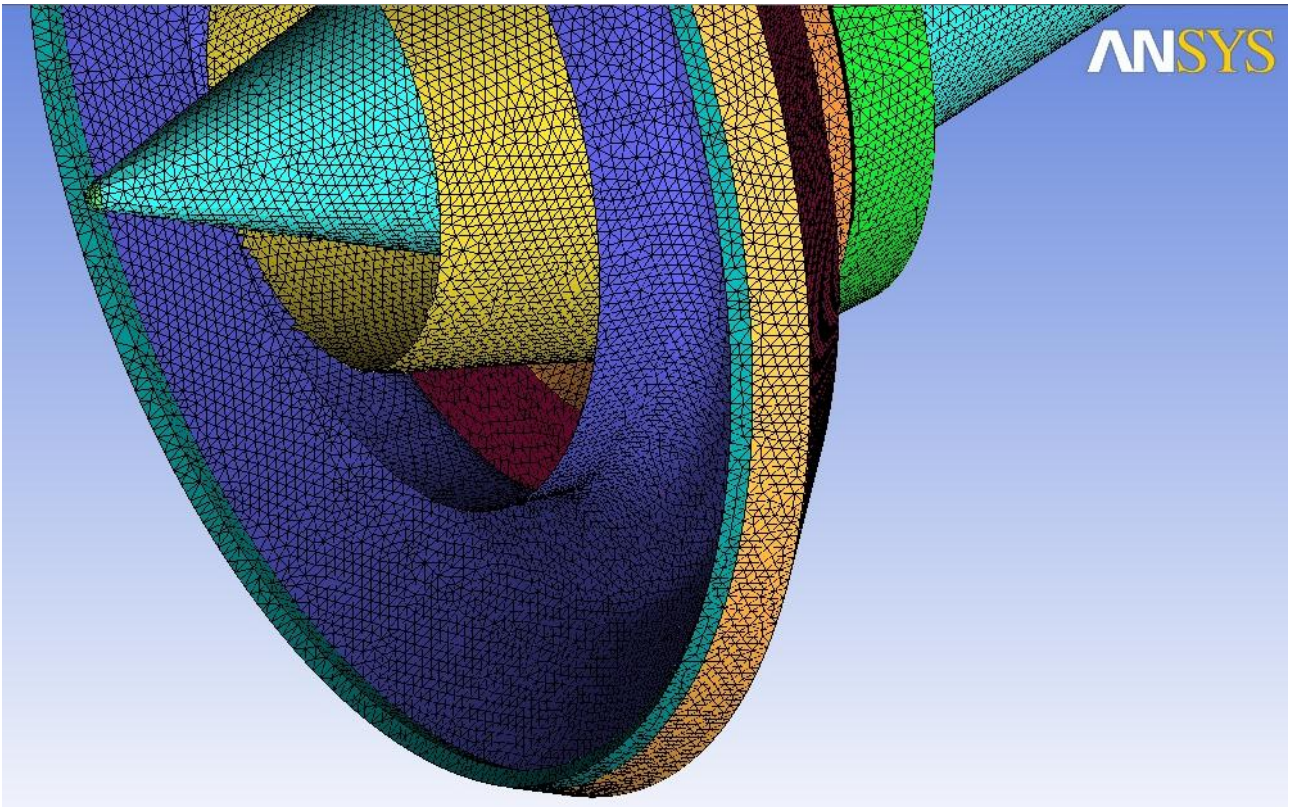
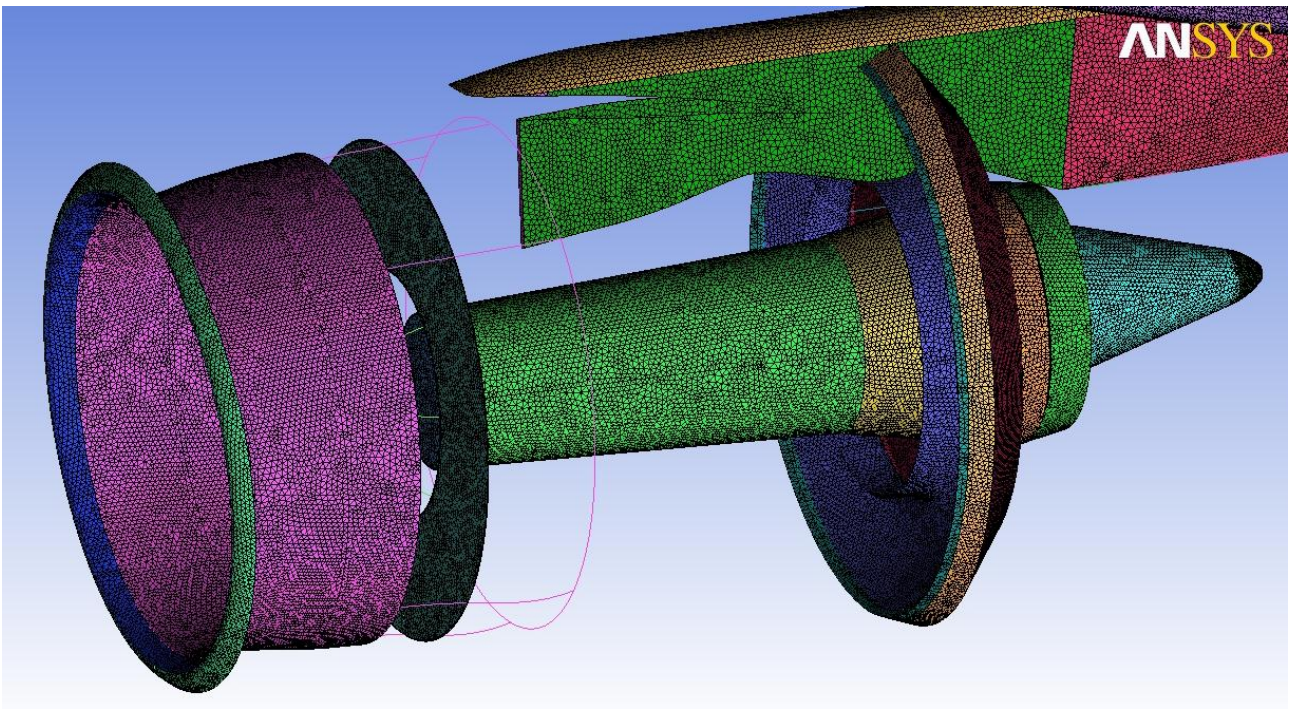


Figure 7.14: (Top) surface mesh on the core internal surface. (Bottom) surface mesh on the core mounted reverser, kicker plate, and exhaust plug.

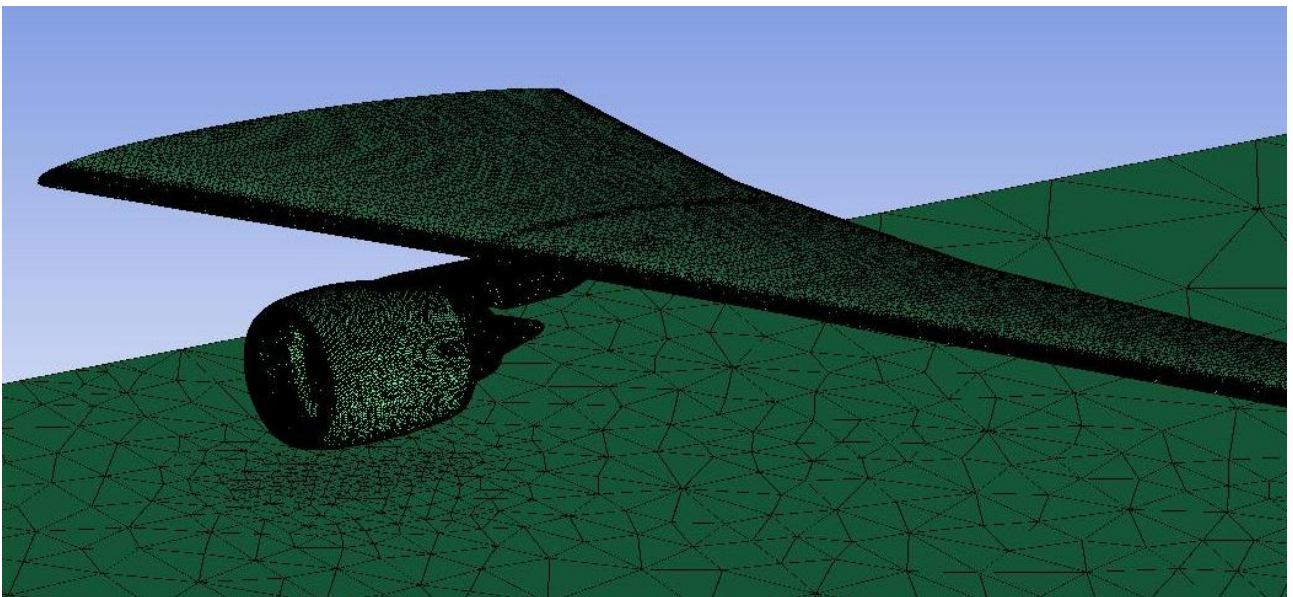
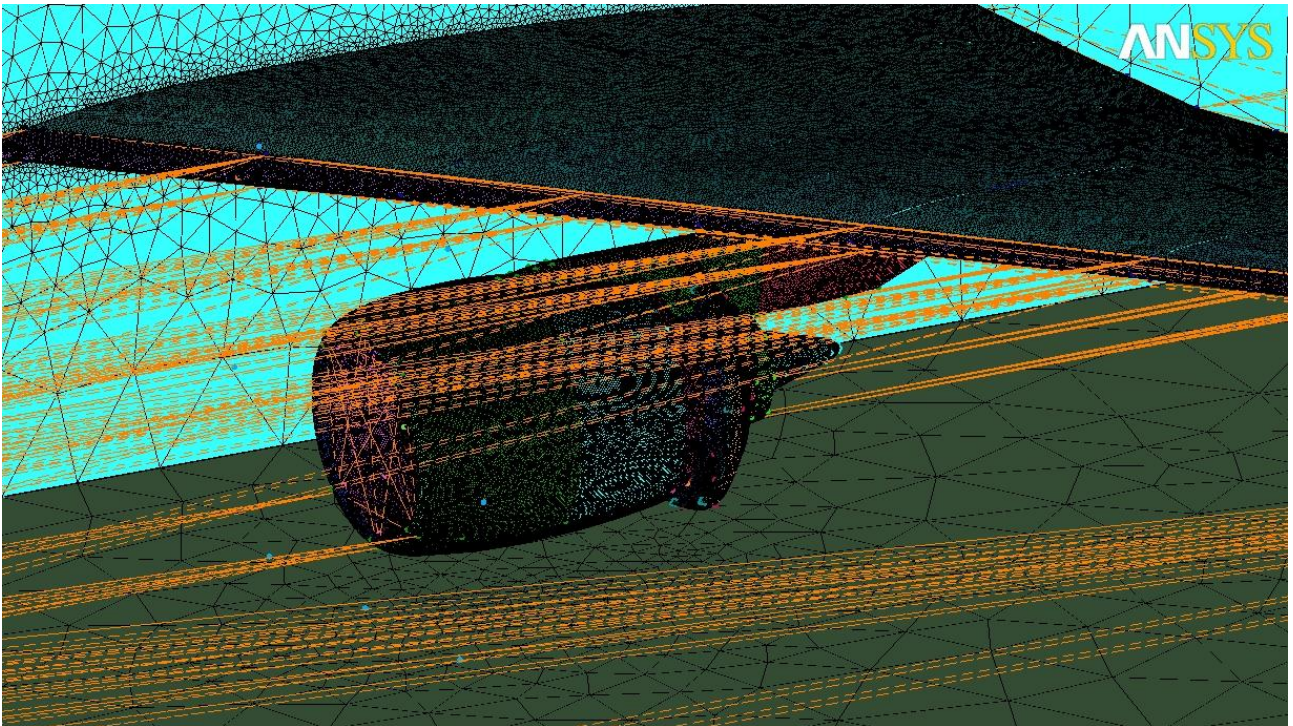
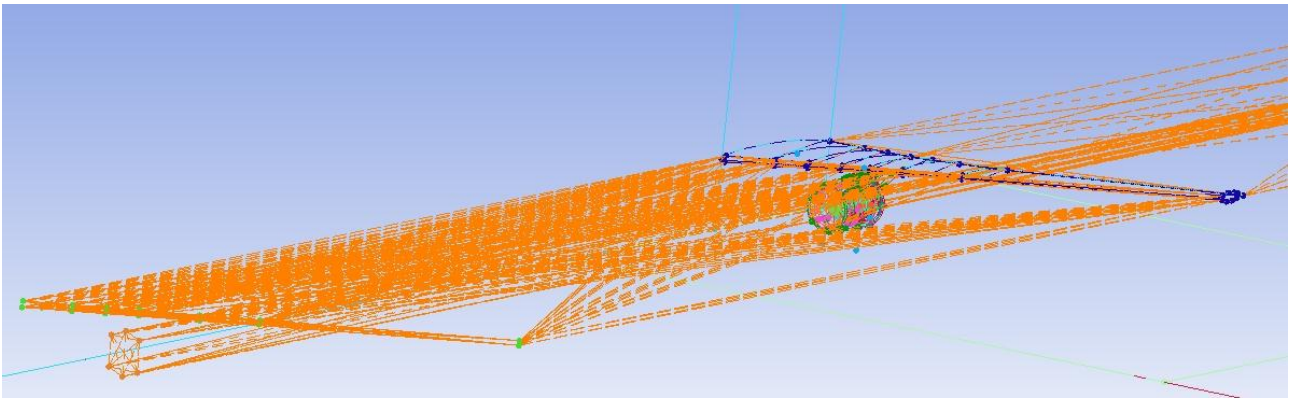


Figure 7.15: (Top) shows typical density mesh regions. (Middle) Close view of the density mesh regions. (Bottom) typical prism mesh for a forward nozzle baseline configuration.

7.6 CFD Methodologies

7.6.1 The CFD methodology involves the following steps

- i) Use CATIA V5 to setup the geometries as per the case requirements. Setup the model characteristics such as inlet, outlet, far field, runway, symmetry.
- ii) Convert the parts to IGS file for mesh generation.
- iii) Generate the mesh for all the forward and reverse thrust design cases. Optimize the mesh size and ensure good quality elements. Refine mesh locally in area where a high resolution of the flow field is essential i.e. aft of the core and fan nozzle exit, wing trailing edge, engine inlet, wing leading edge, reverser exit.
- iv) Ensure that the boundary layer mesh is setup to achieve the correct Y^+ values.
- v) Export the ICEM mesh to ANSYS FLUENT for CFD analysis.

7.6.2 In FLUENT the following needs to be ensured

- i) Setup the model in FLUENT and adjust the scale.
- ii) As for the turbulence, Realizable k - ϵ turbulence was used in all cases.
- iii) Setup the boundary conditions
- iv) Ideal gas should be chosen as the working fluid, with c_p and other fluid properties set accordingly.
- v) Run the CFD simulations and ensure that the second order upwind scheme is used for all the analysis.
- vi) Typically, the steady state computations are well known and established. The convergence was observed, by making sure that with second order scheme the residuals remain unchanged. It was ensured that the mass momentum and energy residuals are less than 10^{-4} . Mass flow balance criterion was performed by calculating the mass flow at the fan outlet and fan nozzle outlet planes.
- vii) Ensure that the Y^+ values are within the appropriate limits for the chosen turbulence model (in the case of Realizable k - ϵ , the values should be between 30 and 300).
- viii) Ensure that the solution is mesh independent.
- ix) Post processes the CFD results.

The theoretical details for the CFD theory and setup are given in (Appendix A2).

7.7 Main Objectives of the CFD Study

One of the main objectives of this research was to perform 3D CFD analyses to study the thrust reverser aerodynamics and its performance at static ($M=0.0$) and aircraft landing speeds ($M=0.211$). This section will discuss the CFD analyses performed during the course of research. The design configurations are similar to that used by NASA. The wind tunnel tests were performed on a 7.9% scale model of a GE 90 engine. The major differences between the experiment and the CFD model are given in [Table 7.1] below.

Table 7.1: shows the major differences between the experiment and the CFD tests.

	Wind Tunnel Experiments	CFD
Dimensions	7.9 % scale model	Full scale
Wing	No	Yes
Runway	No	Yes
Static tests ($M=0.0$)	Yes	Yes
At landing conditions ($M=0.211$)	No	Yes
Front nacelle modeled (engine inlet to fan inlet)	No	Yes

Typical difference between the experimental setup and CFD models are highlighted shown in the [Figure 7.16] below. [Ref. 33]

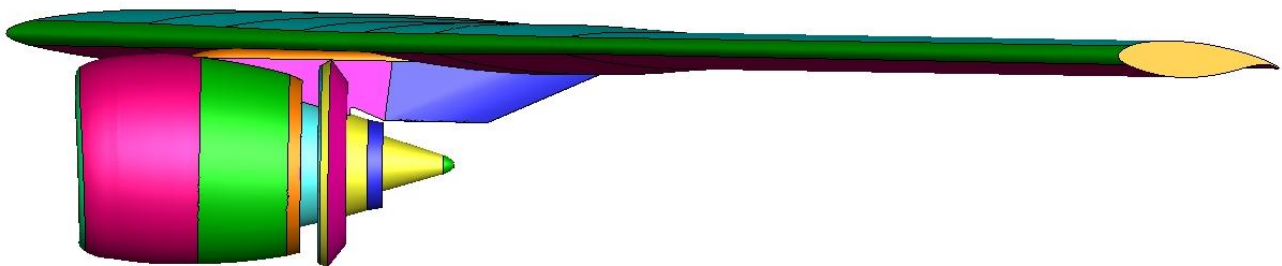


Figure 7.16: (Top) shows a 7.9% scale model of a GE90 engine. (Bottom) shows a full scale 3D CFD model.

The CFD study is divided into the following two parts:

- i) Part 1, covers the 3D CFD analyses at static condition i.e. $M=0.0$.
- ii) Part 2, covers the 3D CFD analyses at forward flight landing conditions, i.e. $M=0.211$.

In both the first and second parts, the 3D CFD analyses were performed for the following three designs:

- i) Reverser Stowed – Forward thrust condition (Baseline case)
- ii) Target reverser deployed at 40 degree
- iii) Target reverser with kicker plate deployed at 40 degree

7.8 Part 1 – CFD Analyses at Static Condition, $M=0.0$

As stated previously, the baseline forward thrust and 40 degree core mounted target thrust reverser configurations were extensively tested by NASA at static conditions. Experimental results for the same configurations are publicly available. The 3D CFD analyses at static conditions would allow a direct comparison with the experimental data. This section discusses the CFD analyses at static conditions ($M=0.0$) for the following three designs:

- i) Forward thrust configuration – Reverser stowed.
- ii) 40 degree core mounted target type thrust reverser – Reverser deployed
- iii) 40 degree core mounted target type thrust reverser with kicker plate – Reverser deployed

7.8.1 CFD Analyses at Reverser Stowed Condition, $M=0.0$ (Baseline)

The baseline design is a 7.9% scale model for a separate exhaust high bypass ratio turbofan engine which is similar to GE90. Static wind tunnel tests were performed at different FNPRs for the forward thrust configuration. A static test for the forward thrust configuration is important, as it would serve as a baseline case against which thrust reverser efficiency and performance can be compared. Figure 7.17, shows a forward thrust model, setup in a wind tunnel for static test.



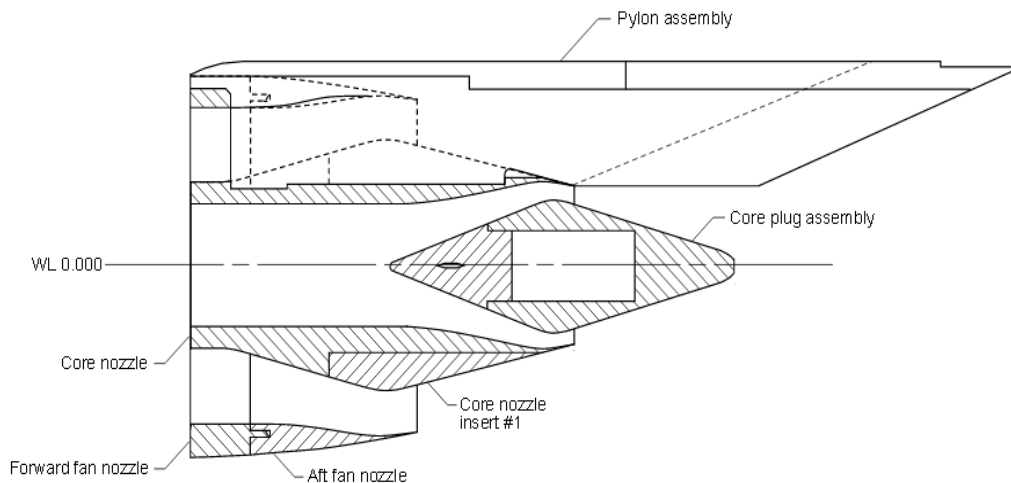


Figure 7.17: (Top) shows a wind tunnel model for a forward thrust configuration. (Bottom) shows a schematic of the vertical cut plane of the model tested [Ref. 8].

Advantages of using CFD are that the 3D CFD analyses would allow a comparison of the thrust reverser performance against that of the forward thrust. Secondly, results from the 3D CFD analyses can be validated against the experiments. Thirdly, CFD analyses can provide an understanding of the flow behaviour.

NASA experiments were carried out for a range of FNPRs. Similarly, 3D CFD analyses were also performed for a same range of fan nozzle pressure ratios that the engine is likely to experience at landing conditions.

The boundary conditions for the CFD analyses were obtained from the GE90-94B performance model at $M=0.0$. GasTurb performance software was used for the performance study.

All CFD analyses were run at static condition, i.e. $M=0.0$ with a pressure based solver, using SIMPLE algorithm. Second order upwind scheme was used for all the analyses. As for the turbulence model, Realizable $k-\epsilon$, was used in all cases (Appendix A2).

Initial case was started with a low value of fan and core outlet pressure, and the case was run at first order. It was then switched to 2nd order convergence scheme with correct pressures. For the subsequent cases, fan and core outlet pressures were then gradually increased from idle to maximum thrust.

The aircraft is considered stationary for the CFD analyses. Far field boundary conditions were set at $M=0.0$, and Pressure=101,325 Pa.

Convergence criteria for the steady state computations are well known and established. Typically, the steady state convergence is measured by monitoring the changes in flow field quantities from iteration to iteration and monitoring a particular value, such as residuals dropping below a certain threshold.

The same can be noted from the (Figure 7.18). The convergence was observed, by making sure that with the second order scheme the residuals remain unchanged. It was ensured that the mass, momentum and energy residuals are less than 10^{-4} . Subsequently, the mass flow rates at fan and core outlets were observed (Figure 7.19 – 7.20). Finally, the mass flow balance criterion was performed by calculating the mass flow rates at the fan outlet and fan nozzle outlet planes. Also, Y^+ values were monitored. For all the CFD cases run, the Y^+ values were within the acceptable range of 30 and 300. Typical contour plot is shown in (Figure 7.21).

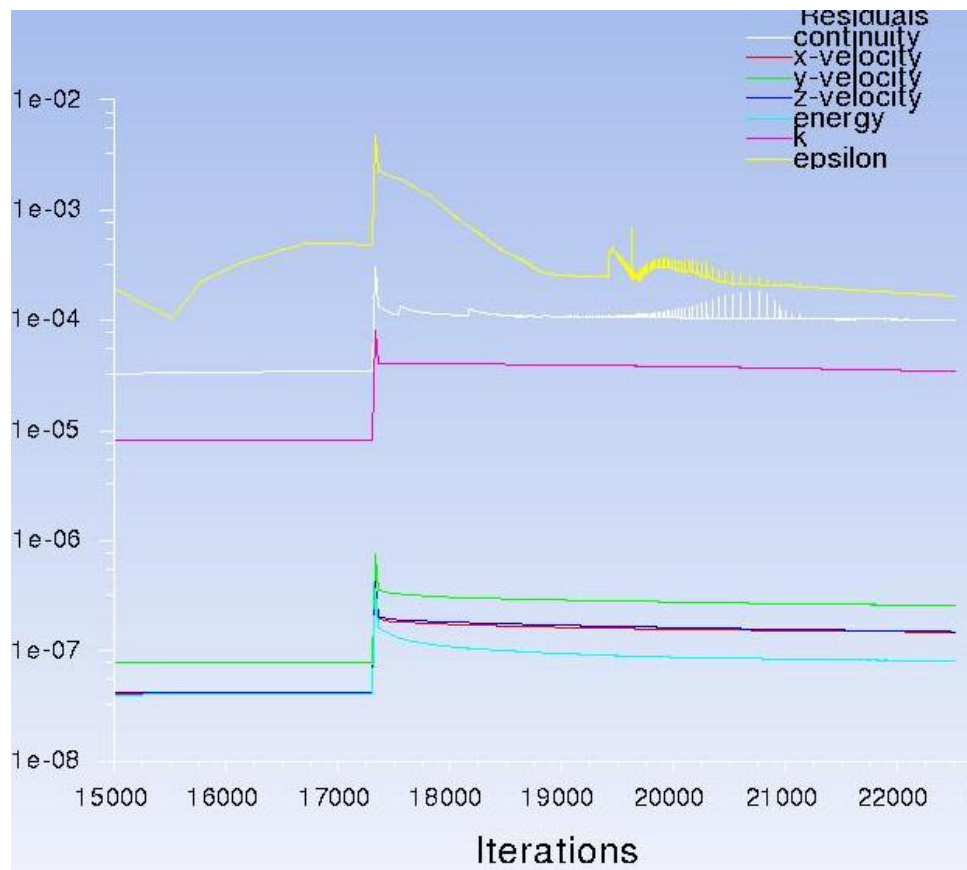


Figure 7.18: Shows the residuals.

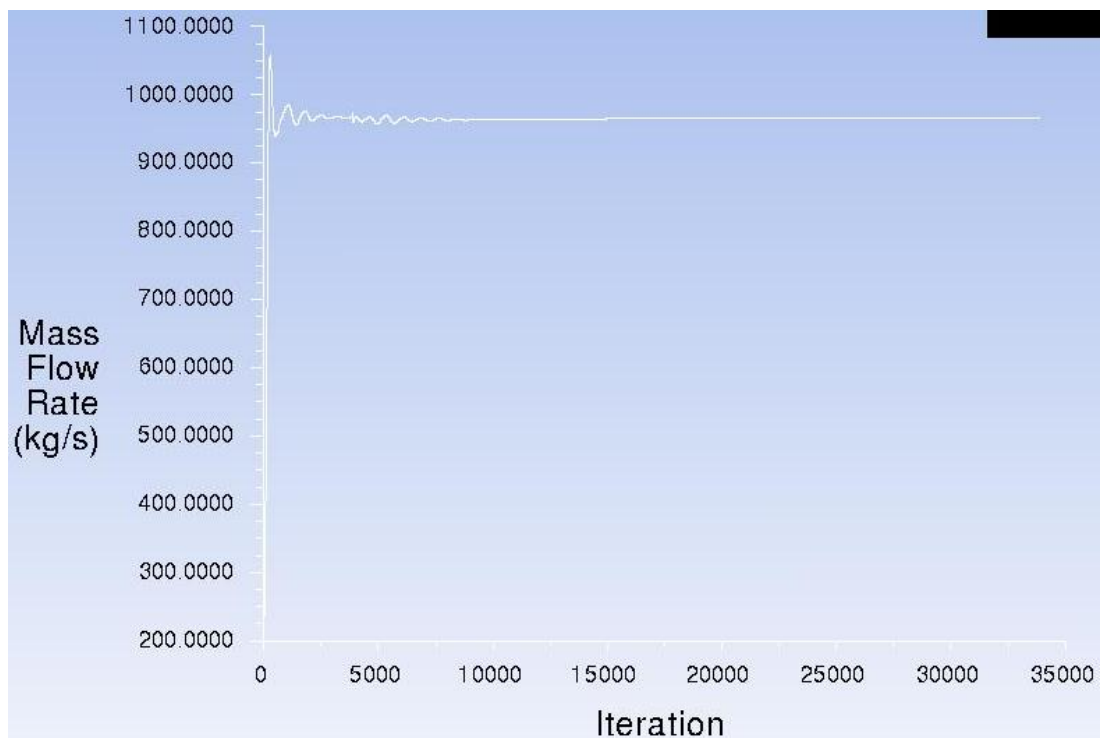


Figure 7.19: Mass flow for the fan outlet.

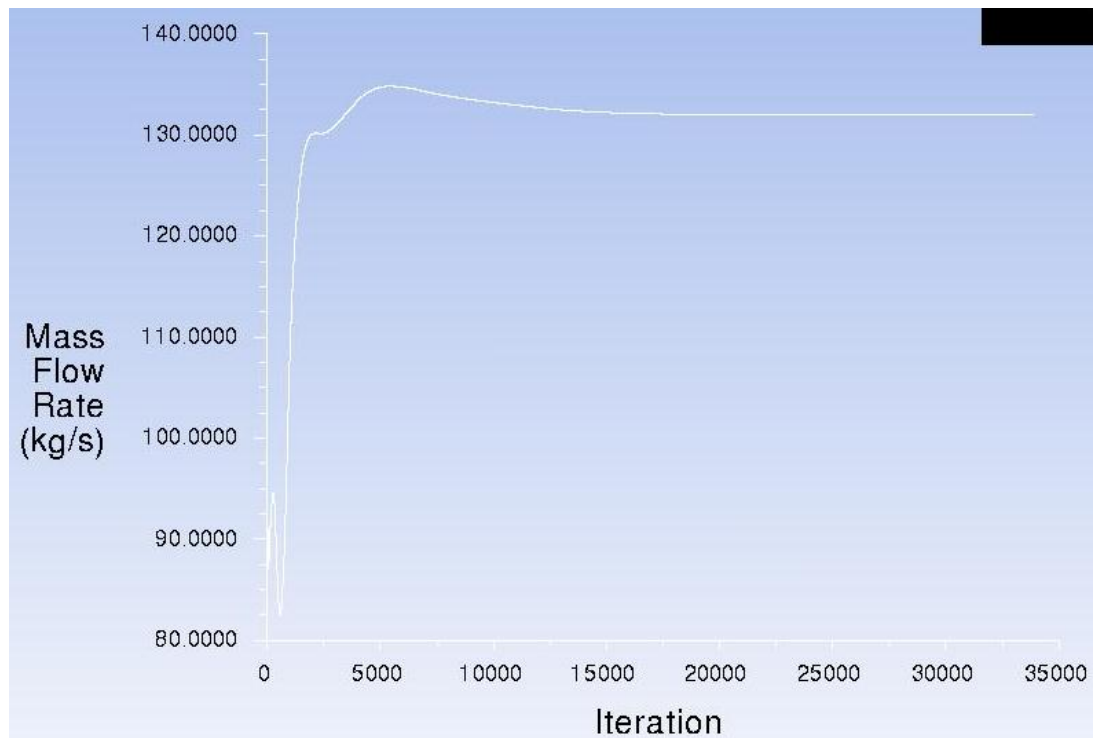


Figure 7.20: Typical examples of residuals and mass flow observations for solution convergence.

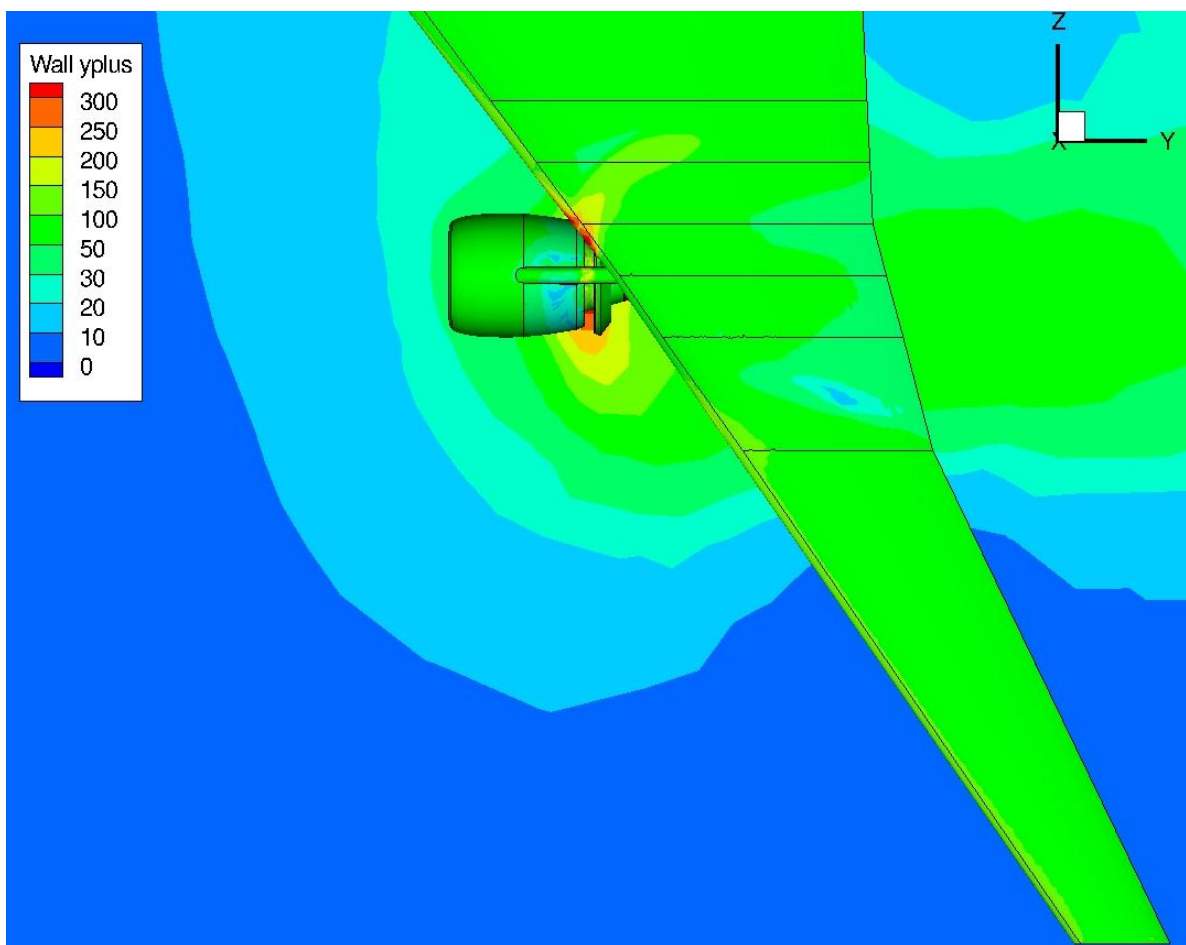


Figure 7.21: Shows a typical Y^+ contours plot. The acceptable range is between 30 and 300. However, in all the CFD cases, the Y^+ values were in the acceptable range.

7.9 Results and Discussion

Streamlines plots for the forward thrust configuration are shown in (Figure. 7.22). The plots are obtained for the 3D geometries by taking horizontal and vertical cut planes from the engine centre line.

In this section, streamlines plots are presented for the $FNPR=1.554$ case. The details of all other contour plots such as static pressure, total pressure and streamline plots are given in (Appendix A3).

For explanation purposes the horizontal and vertical streamline planes are divided into different zones as shown in (Figure 7.22 and 7.23). The formation of zones will allow the author to better explain the flow behaviour in each region.

Zone 1, on the horizontal streamline plane, refers to the flow regime ahead of the engine inlet. The aircraft is stationary, with air sucked into the engine. The streamtube is initially wide spread; however, as the flow accelerates towards the nacelle inlet, the streamlines narrow down (Figure. 7.22). This happens primarily due to the flow being subsonic.

The external flow in zone 2 and zone 3 is not symmetric. In zone 2, majority of the flow travels straight, and meets the fan exhaust flow at approximately 15 meters downstream. The flow is straight in zone 2 because a passage is formed between the two engines on either side of the symmetry. Hence, it can be said that the flow in zone 2 is a guided flow, therefore, streamlines are straight.

Flow in zone 3 approaches the nacelle external surface and the fan exhaust flow at an angle. This is due to suction momentum at engine inlet and high momentum at the engine nozzle exit. Primary source of the streamlines to bend sideways is due to the difference in inlet and exit momentum. As it can be seen from the (Figure. 7.22) that due to high velocity exit flow, suction is created which in turn cause more air to be sucked in from the free stream, as shown in (Figure. 7.22).

In zone 4, the streamlines are straight due to high exit momentum.

It will be shown from the vertical plots that the wing, pylon and runway presence play a significant part in the external flow behaviour.

Zone 5, shows that as the air is sucked into the engine a D-shape streamtube is formed. The streamtube is initially divergent with a height of up to 8 meters above the runway, as the airflow approaches the engine inlet the streamlines converges and enters straight into the engine. The flow in zone 5 is similar to zone 1. The only difference being the line of symmetry is changed.

Zone 6, shows that the flow will come at an angle; this flow will meet the nacelle and pylon top surfaces and will travel along the external surfaces before coming to a halt at the wing leading edge.

Zone 7 shows that the airflow will travel at an angle; with a small portion of the flow in contact with the wing suction surface. The flow will accelerate along the suction surface and would re-join the other major flow. This flow will travel on the outside boundary of the engine exhaust flow.

Flow in zone 6 and zone 7 is similar to that in zone 3.

Zone 8, represents the flow between the nacelle bottom half and the runway. The flow in zone 8 is similar to zone 2. The only difference is instead of the symmetry, this time a passage is formed

between the nacelle bottom surface and the runway, which causes the flow to be uniform and straight.

Zone 9, is the representation of the engine exhaust flow. After the nozzle exits, the flow diverges. The flow in zone 9 is similar to that in zone 4.

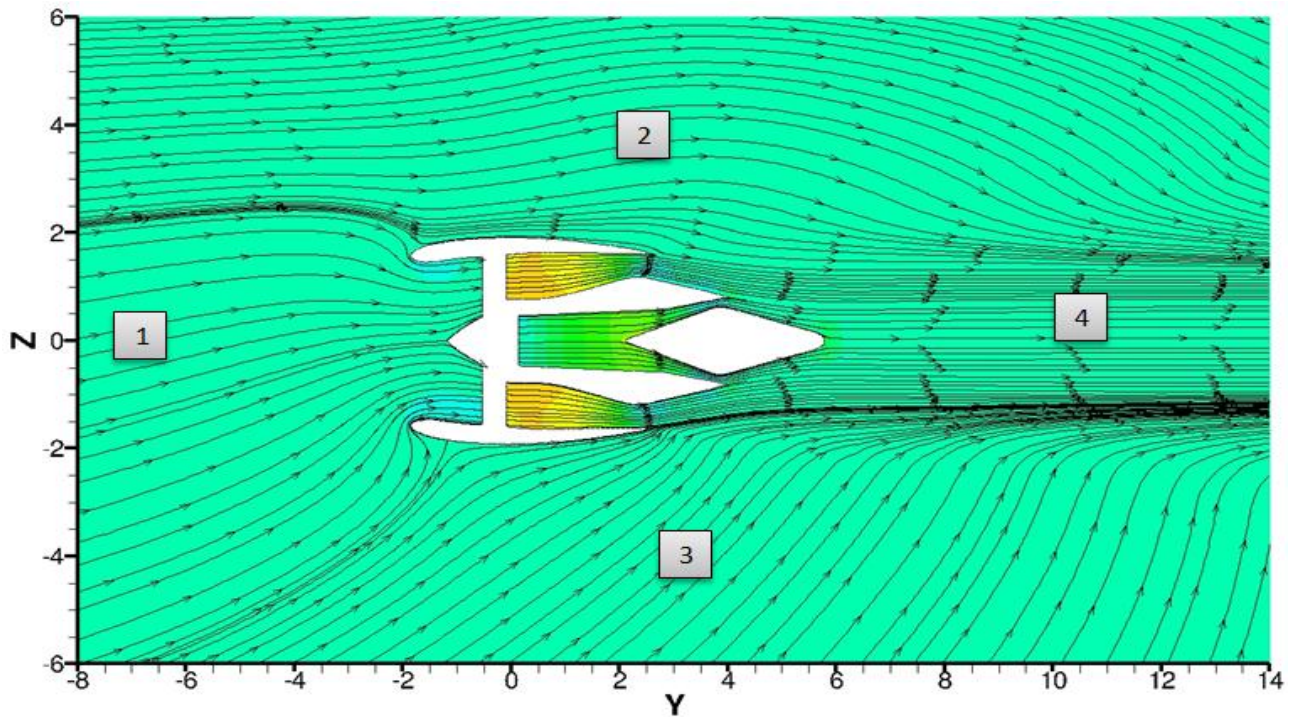


Figure 7.22: Streamline forward thrust, horizontal plane, $M=0.0$.

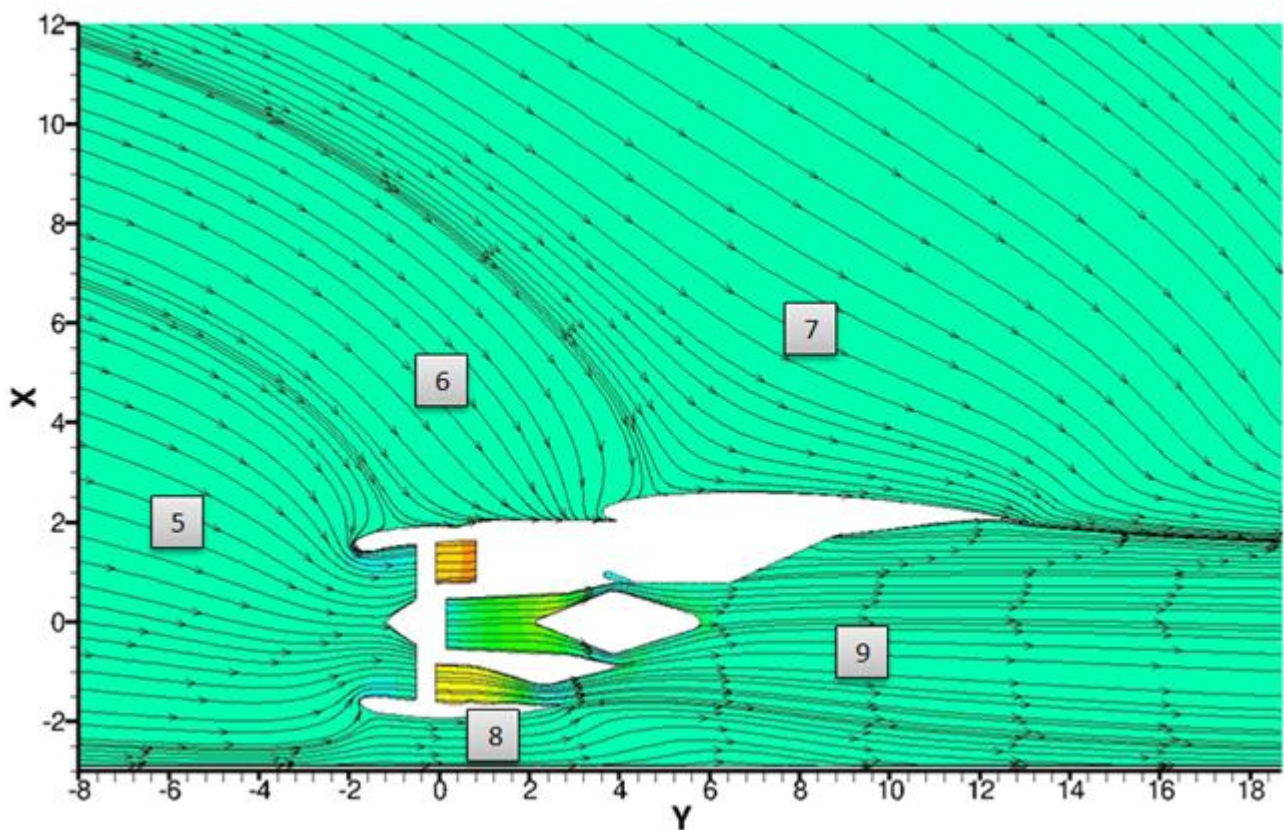


Figure 7.23: Streamline forward thrust, vertical plane, $M=0.0$.

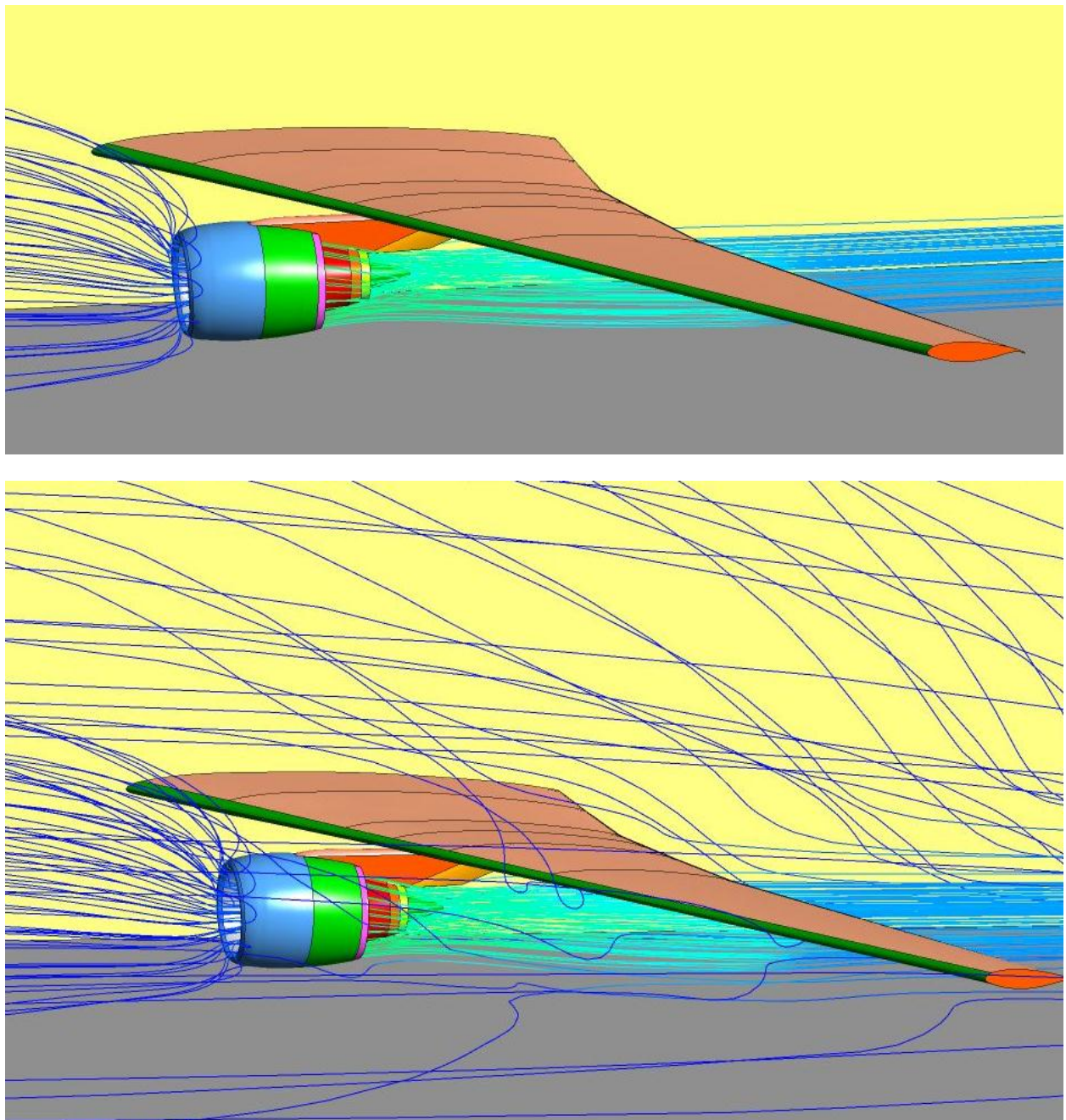


Figure 7.24: 3D Streamlines for the forward thrust configuration at $M=0.0$, $FNPR=1.504$.

7.9.1 40 Degree Core Mounted Target Type Reverser Aerodynamics at $M=0.0$

The wind tunnel tests carried out by NASA were mainly focused on the performance of the core mounted target type thrust reverser at static condition ($M=0.0$). The four thrust reverser designs which were tested by NASA are as follows:

- 20 degree target type thrust reverser
- 20 degree target type thrust reverser with kicker plate
- 40 degree target type thrust reverser, and
- 40 degree target type thrust reverser with kicker plate.

A typical design and the schematic of the design is shown in the (Figure 7.25).

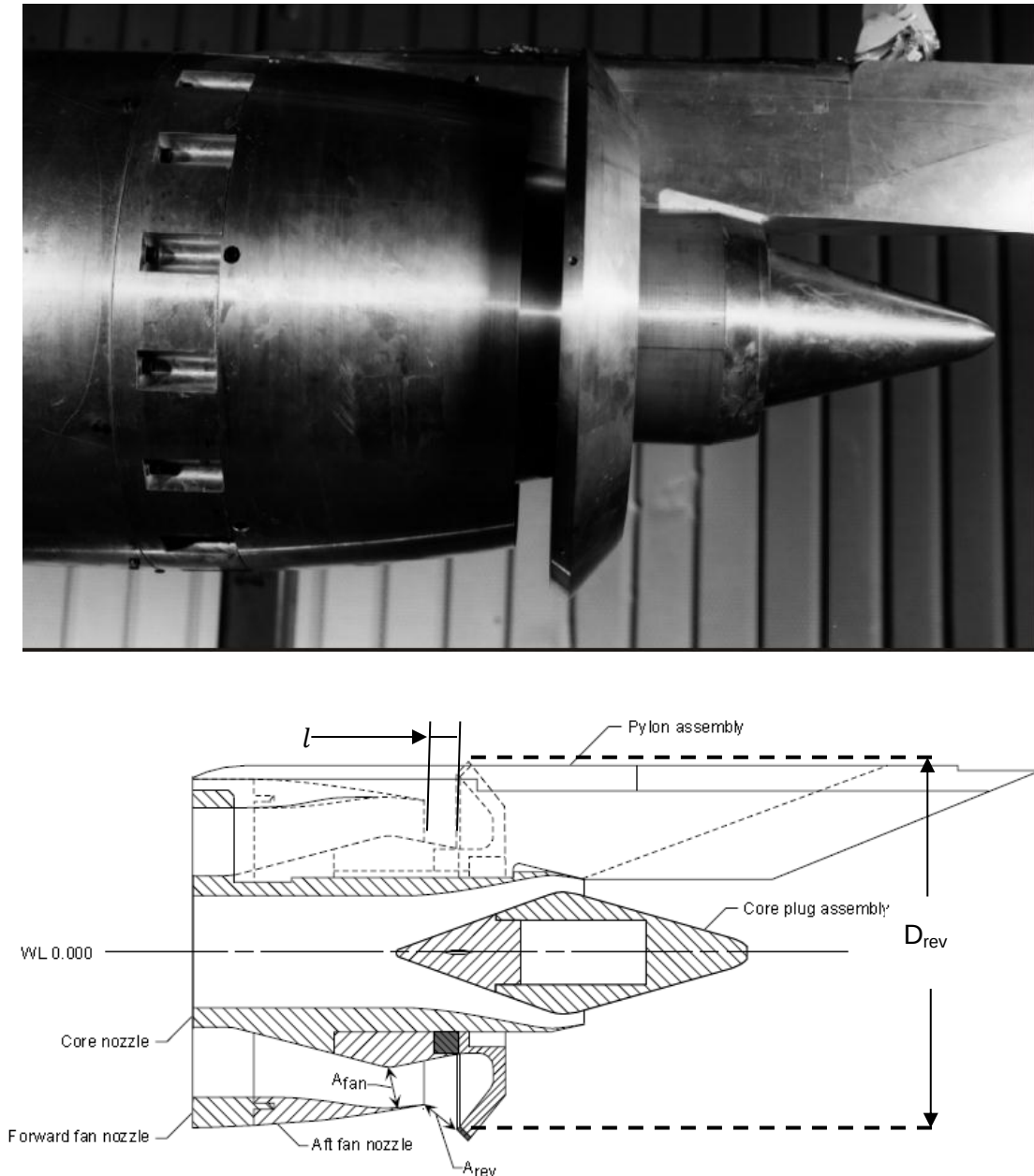


Figure 7.25: (Top) shows a wind tunnel mode for a forward thrust configuration. (Bottom) shows a schematic of a vertical cut plane of the model tested [Ref. 8].

Out of the four thrust reverser designs tested in the wind tunnel, following two designs are selected for the CFD study:

- 40 degree target type thrust reverser
- 40 degree target type thrust reverser with kicker plate.

These designs were selected mainly due to their better performance compare to other ones.

All the wind tunnel thrust reverser static tests were performed on an engine test stand. The engine nacelle front section was ignored, as discussed previously. All the wind tunnel testing was performed without the wing geometry. Also, as the reverser test model was on a stand, no runway

effects were modeled. However, in the CFD study, all three geometric features are taken into account.

Same solver settings as those used previously for the forward thrust configuration were applied. The boundary conditions were set as per the off-design data obtained from the GE90-94B performance model, which was simulated in GasTurb performance software.

In this section, aerodynamics of the engine internal and external flow fields are discussed. Streamlines plots were obtained on the horizontal and vertical planes from the engine center line. All the other contours such as those for the static pressure, total pressure and streamlines are given (Appendix A4)

Thrust reverser aerodynamics involves complex flow fields. An understanding of the external and internal flow fields is important for the thrust reverser design. The CFD simulation could be an effective tool to study and understand the thrust reverser external and internal flow fields.

As per the data available in the public domain the author believes, that this may be first CFD study for the core mounted target type thrust reversers. Both the internal and external flow physics as well as the thrust reverser performance is covered in this study.

In order to simplify the explanation of the flow behavior in different regions, zone numbers are given.

7.9.1.1 Results and Discussion

The target type thrust reverser performance is mainly dependent on the following parameters:

- The target type thrust reverser diameter,
- Location of the thrust reverser aft from the fan nozzle exit and
- Reverser exit area

All the parameters are shown in the (Figure 7.25) above. All these parameters will contribute to the reverser performance, reverser exhaust flow direction and angle.

The reverser exhaust flow will be three dimensional i.e. the flow will have horizontal, vertical and side force component. Ideally, the horizontal thrust component should be the highest. Also, it is important to have a horizontal velocity component in the correct direction i.e. the reverser exhaust flow should exit in the upstream direction i.e. towards the engine inlet.

Figure 7.26, shows a blow up picture of the top half of the thrust reverser in the horizontal plane. As the bypass flow travels downstream towards the reverser exit, a recirculating region (zone 10) will form. The formation of this clockwise re-circulating flow region (zone 10) will have a coanda effect on the bypass stream. This recirculating vortex in the cavity region is the main source of blockage, and will significantly influence the fan exhaust mass flow to reduce, as the effective exit area has decreased.

The deployment of the thrust reverser results in the formation of a vortex (zone 10) which acts as a solid region; just after the vortex the streamlines travel in the vertical upward and downward direction.

The streamline plots show that at static condition the deployment of a thrust reverser could significantly affect the external flow fields (Figure 7.28).

The horizontal streamlines plot shows that the deployment of a thrust reverser will result in the formation of three large re-circulating regions (Zone 7, 8 and 9). These re-circulating regions could be as high as 2.5 times the engine size.

From the current setup, it can be assumed that there is an engine on either side of the symmetry. The gap between the engines is fixed as per the aircraft design and this results in the formation of a flow passage. The size of this flow passage together with the symmetric boundary condition will have an effect on the reverser exhaust flow. When the high momentum flow from the reverser exhausts approach each other, a stagnation point will form; which results in the formation of two contra rotating vortices on either side of the symmetry as shown in zone 7 and 9. There will also be a secondary vortex at the exhaust of the engine as shown in zone 12, the strength of which is dependent on the thrust setting.

The shape, size and behaviour of the vortices in zone 7 and 9 are dependent on the passage size and on the free stream boundary conditions. It is important to note that, if a fuselage was also accounted during this CFD study, it would have still resulted in the formation of two contra rotating vortices in zone 7 and 9.

On the lower half of the horizontal streamline plot there is no obstruction. As the flow leaves zone 10, in the vertical direction it forms a natural clockwise vortex. The formation of this clockwise vortex, as shown in zone 8, is due to the momentum difference between zone 10 and 6.

Part of the flow from the recirculating zones 7 and 8 will travel upstream of the engine, forming zone 5 and 6. It is interesting to note that in the event of thrust reverser deployment at static conditions the flow entering the engine around the horizontal split line will result in inlet distortion. This is mainly due to large variations in pressure and temperature in circumferential plane. Also, the outer part of the flow from zone 7 and 8 will continue travelling upstream and the two flows will merge at approximately 10 meters ahead of the engine; the flow stream will continue to travel straight as shown in zone 1.

Thrust reverser flow in Zone 8, will affect the far field boundary conditions as shown in zone 2 and zone 3. The flow in both these zones will vary considerably at different thrust setting (Appendix A4) so depending on the thrust setting; an approximation of the flow field could be obtained.

The flow field in Zone 4 is also dependent on engine thrust. At higher thrust settings, the exhaust flow will have high momentum and will continue to travel straight. However, at low thrust settings the momentum of the engine exhaust flow is less and will be significantly affected by the disturbance in the external flow field caused due to thrust reverser deployment. Thus, at low thrust settings the engine exhaust flow may end up forming two additional recirculating zones, just downstream of the engine (Appendix A4). It is interesting to note that, the symmetry will have an effect on the core exhaust flow. Figure 7.28 and 7.29, shows that the flow in zone 4 leans toward the symmetry, this means that flow on either side of the symmetry will eventually merge at some distance downstream.

Kicker plate is an important reverser design feature especially for the pivoting door and target type thrust reversers. From (Figure 7.26 and 7.27) the CFD analyses show that the kicker plate helps in enhancing the reverser performance by providing more deflection, compare to no kicker plate. Figure 7.27, is for a target type reverser without a kicker plate, and is included for the comparison purposes between the reverser with and without kicker plate.

Streamline plots in the vertical plane shows that at stationary conditions the deployment of a target type thrust reverser would greatly affect the external flow field which is depicted in (Figure 7.30)

at zones 14 and 15. From the CFD analyses, the flow behaviour in the external flow field is thrust dependent.

In the vertical plane, the air is sucked into the engine from far downstream as shown in Zone 14, (Figure 7.30) and this phenomenon is very much thrust dependent. As shown in (Appendix A4), this can be as far as 150 meters at low thrust setting (Figure 7.30).

The external flow field in zones, 13, 14, 15, and 16 is very much thrust dependent, as shown in (Appendix A4). At low thrust settings, there may be two large recirculating zones downstream of the engine as shown in (Figure 7.30 and Appendix A4). The formation of these recirculating zones is due to both the reverser and the core exhaust flow. Figure 7.32 and Appendix A4, shows that at low thrust settings, the core flow will lose its momentum, this will result in two contra-rotating vortices (Figure 7.32). However, as the engine thrust increases, the front vortex becomes stronger and stronger which is shown in (Figure 7.30 and Appendix A4). The intensity of the second recirculation zone which is due to the core exhaust flow will reduce, and will eventually disappear, leaving either one big recirculation, or no recirculation zone (zone 12 and 13).

It is shown in zone 17 (Figure 7.31) that the top half of the nacelle acts as a favorable surface around which the flow is turned to approximately 180 degrees. This flow is sucked into the engine. It is shown in Zone 19, shows that the flow behind that sucked into the engine (zone 14) will be in contact with the runway. Zone 17 shows that the exhaust flow from the bottom half of the reverser will come in contact with the runway, and will re-enter the engine. It is also shown in zone 17 that the flow comes at an angle at the top of the nacelle, pylon and wing suction surfaces and will travel upstream i.e. into the engine inlet.

Zone 18 shows (Figure 7.31), the formation of z-shape weak streamlines, and they will be similar at almost all thrust settings. This is because, majority of the reverse exhaust flow will re-enter the engine, and the core flow will be at a higher momentum and will continue travelling downstream. Thus, a small region will be formed, which may have less energy flow in the cavity.

3D vortices are shown in Figure 7.33; large engine flow ingestion at static condition is visible.

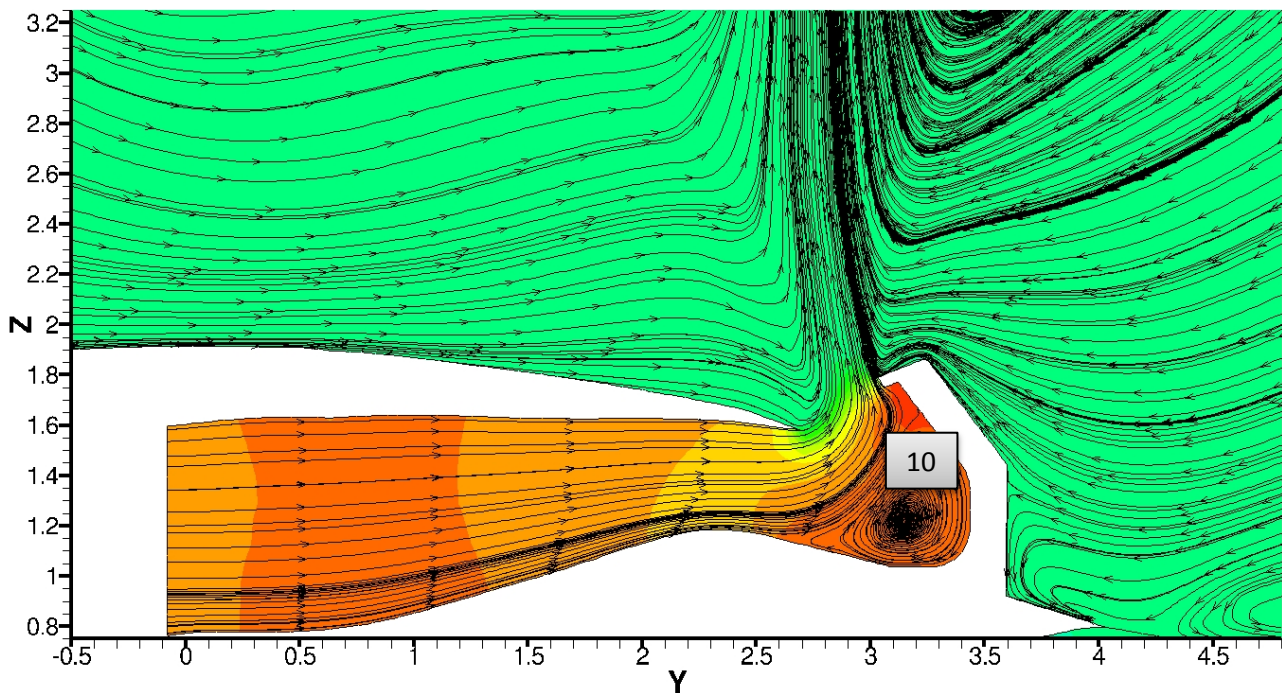


Figure 7.26: Zone 10 shows the recirculating region for a kicker plate configuration, $M=0.0$.

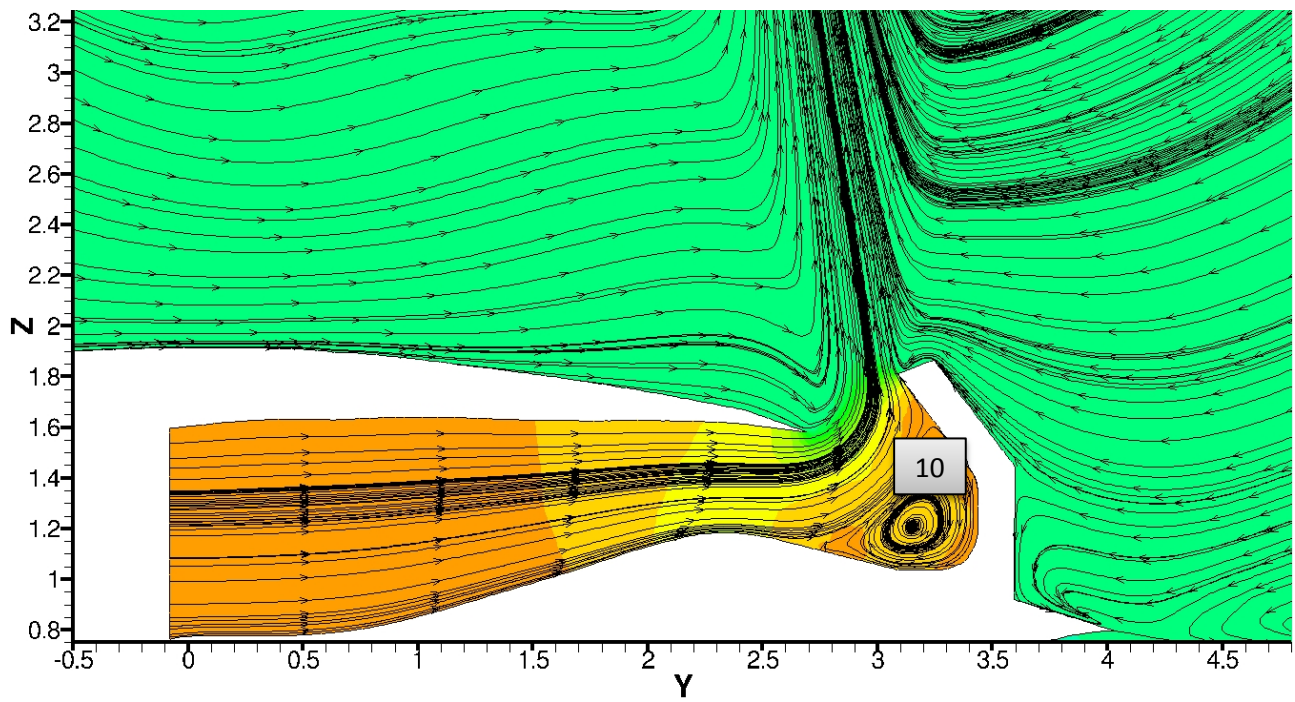


Figure 7.27: Shows the re-circulation zone formed between the core external and the reverser surface and the fan flow turning at the reverser exit, $M=0.0$.

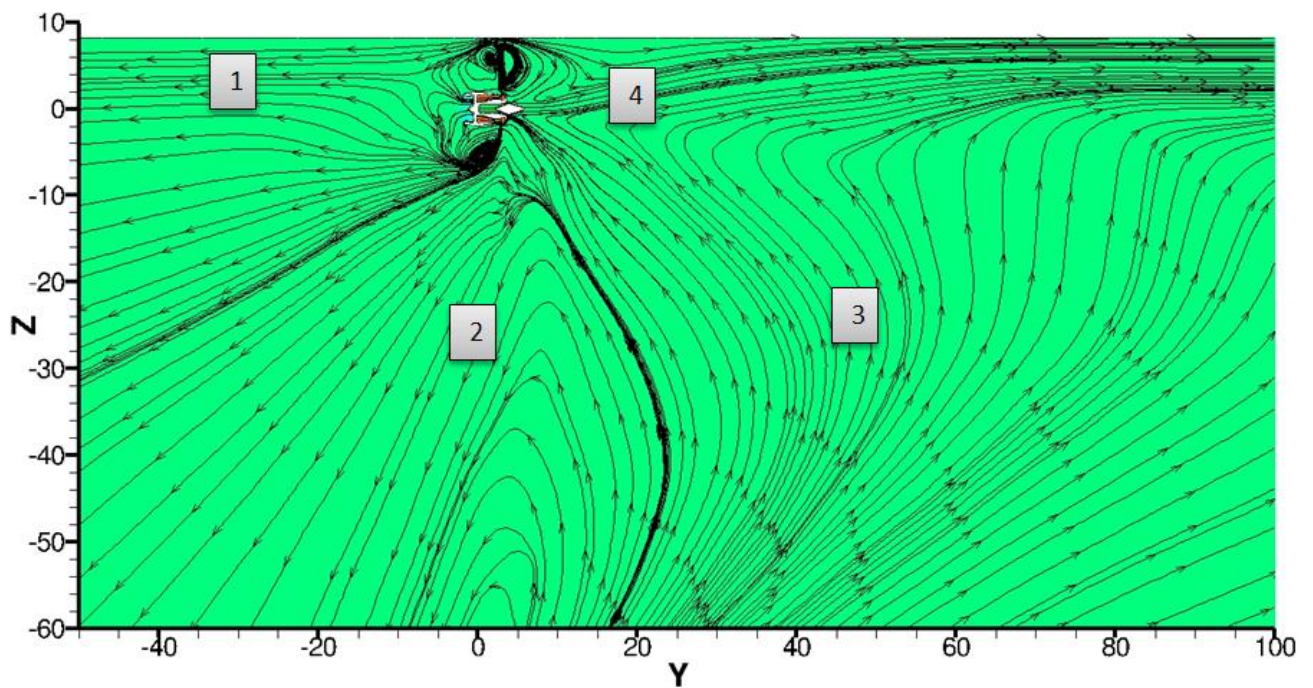


Figure 7.28: Streamlines in the external far field region, horizontal plane, $M=0.0$.

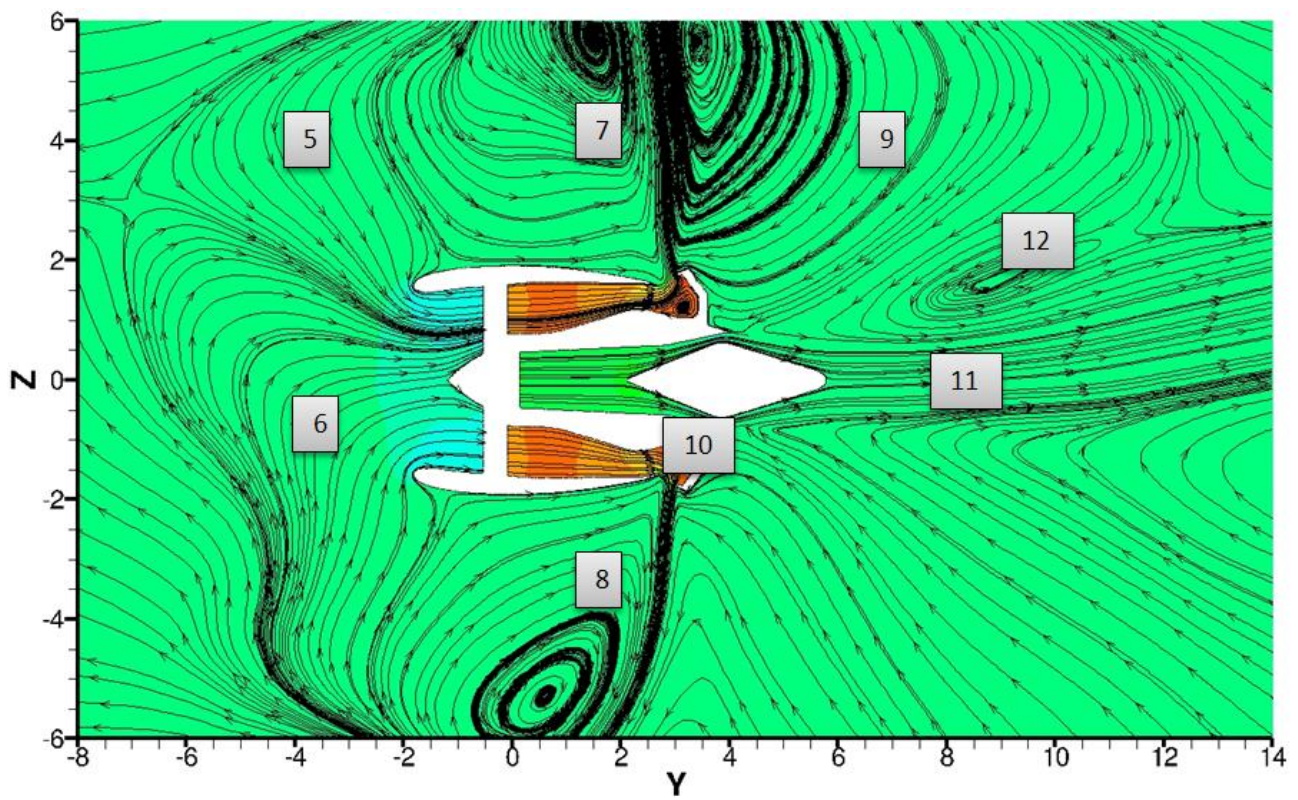


Figure 7.29: Streamlines plot showing the external and internal flow field regions, $M=0.0$.

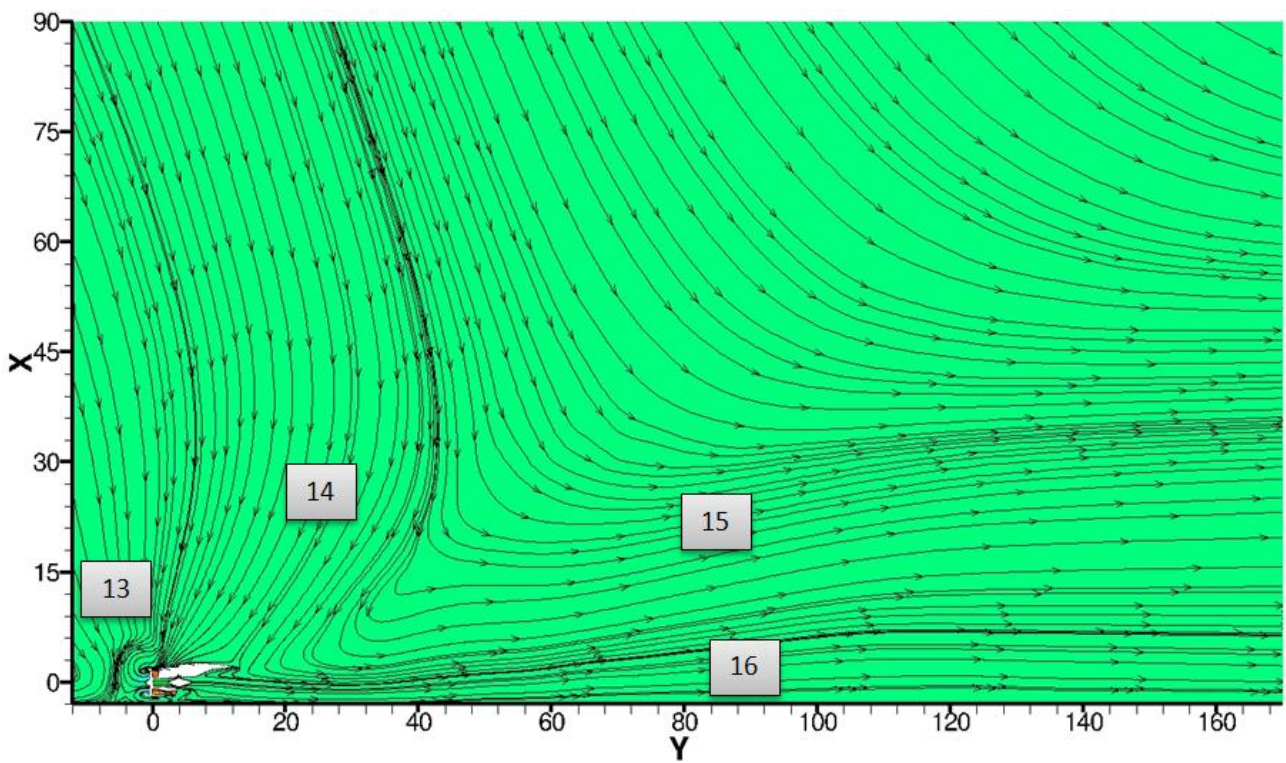


Figure 7.30: Streamlines plot for the external flow field during reverser deployment, vertical plane, $M=0.0$.

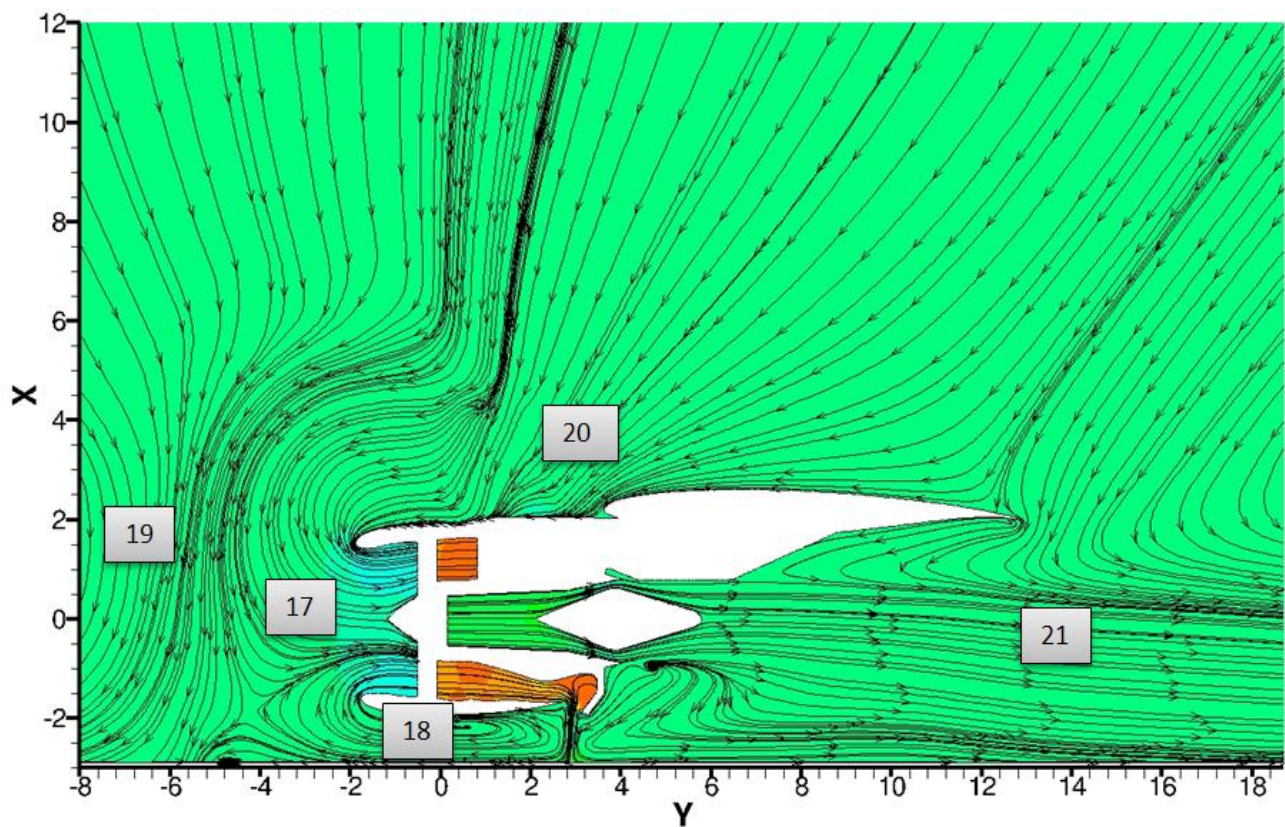


Figure 7.31: Streamlines plot for the external and internal flow fields, vertical plane, $M=0.0$.

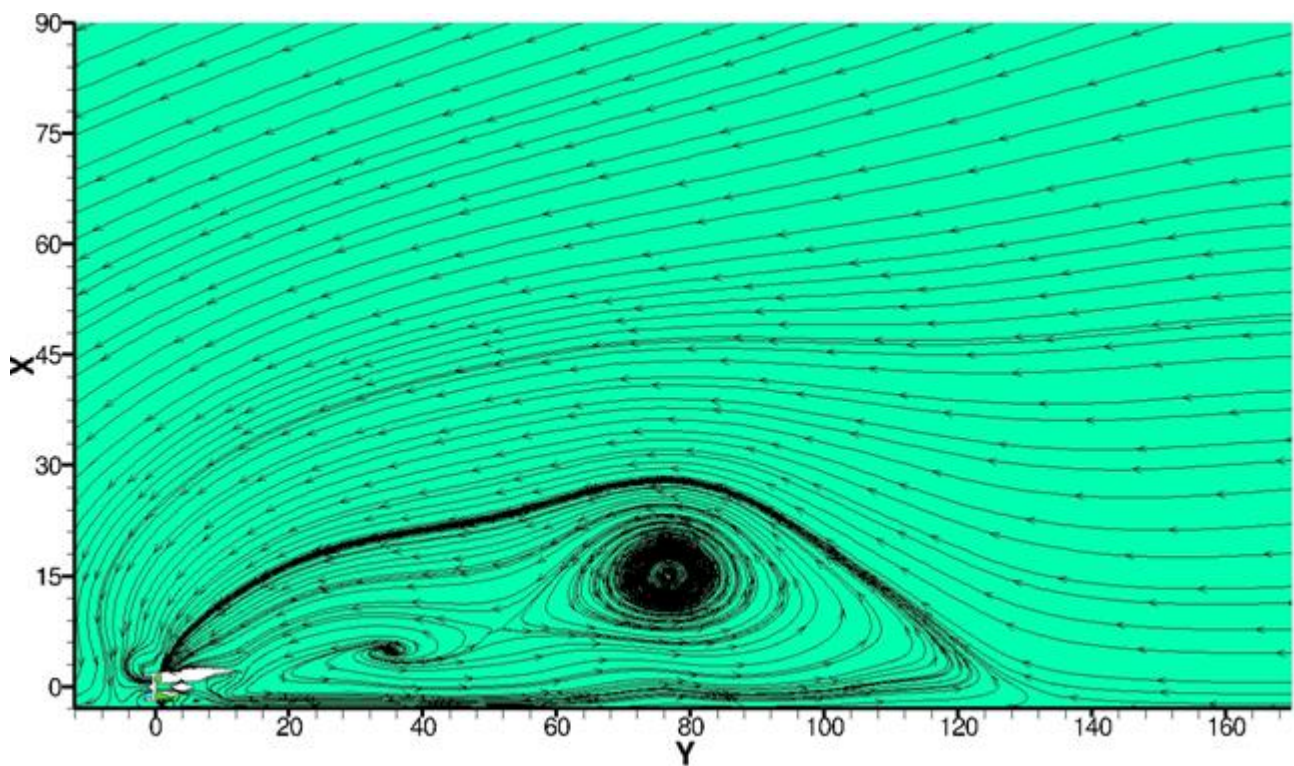


Figure 7. 32: Streamlines plot in the external far field region at low thrust setting during thrust reverser deployment, vertical plane, $M=0.0$.

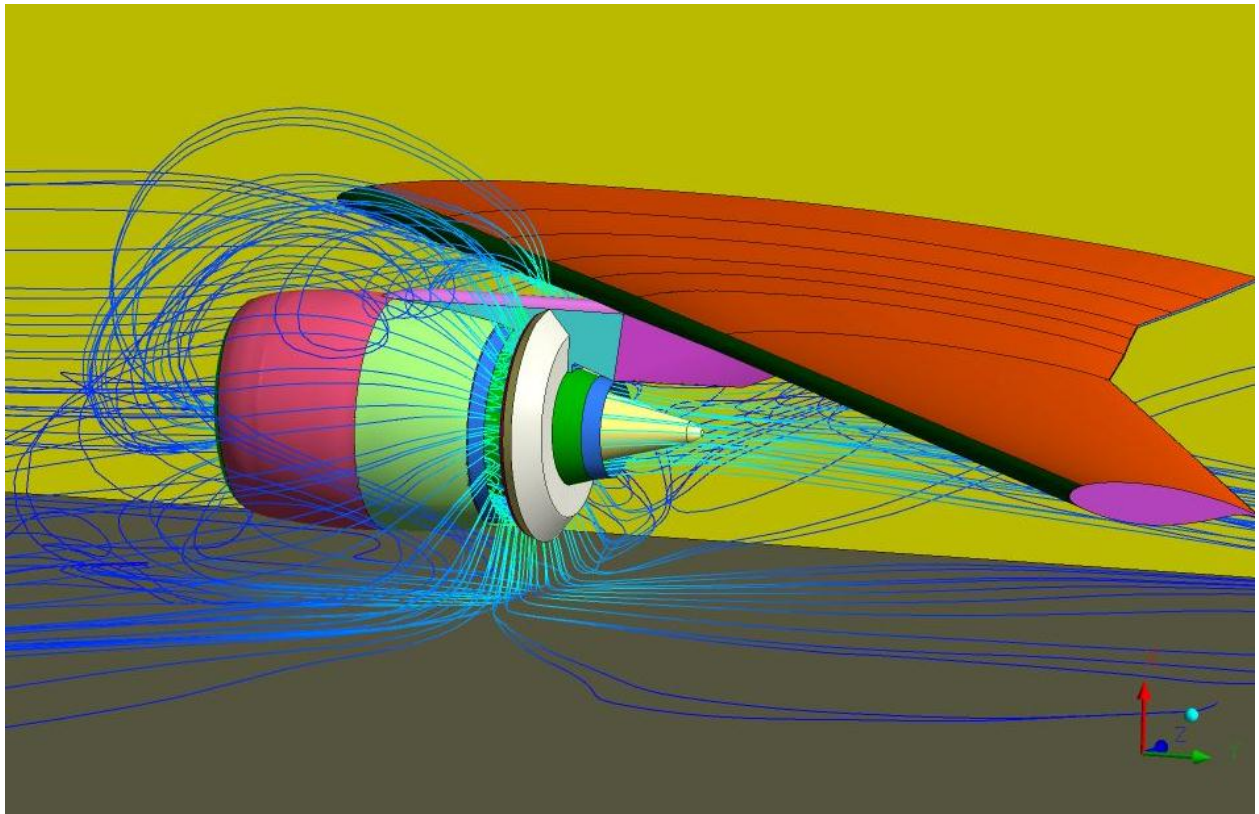
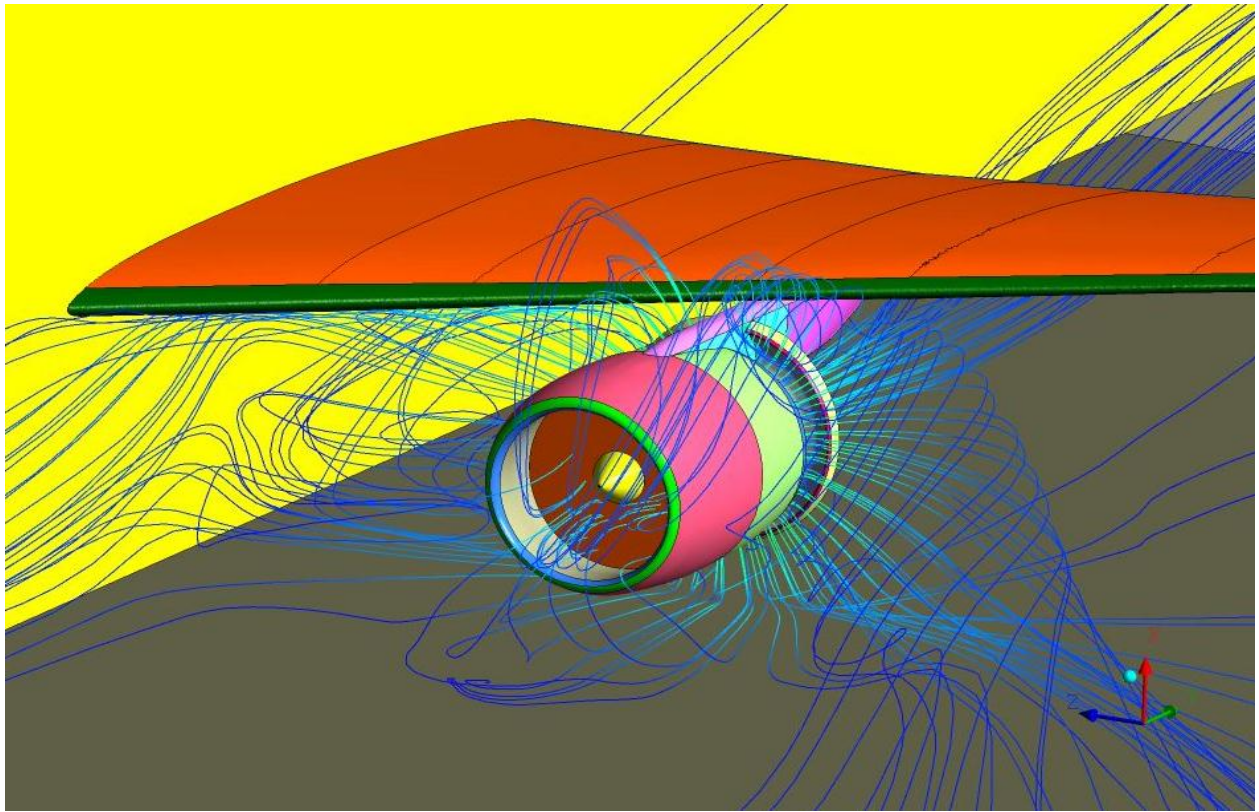


Figure 7. 33: 3D streamline plots for the core mounted target type thrust reverser at $M=0.0$, $FNPR=1.504$.

7.9.2 40 Deg Core Mounted Target Type Thrust Reverser Aerodynamics at M=0.211

The results discussed in this section are for a landing speed of 140 knots ($M=0.211$). In this section the emphasis is placed on the reverser aerodynamics, as well as the variation in reverser performance compared to that at static conditions.

The boundary conditions were set as per the off-design data obtained from the GE90-94B performance model, which was simulated in GasTurb performance software.

7.8.2.1 Results and Discussion

It is shown in (Figure 7.34) that the flow to the engine inlet, exhaust and far field is smooth and steady as shown in zone 1, 2 and 3. Thus, far exterior regions of the external flow fields can be ignored.

As the bypass flow leaves the reverser exit, the free stream air which has a momentum equal to the forward speed of the aircraft pushes the reverser flow in the downstream direction. This results in a clockwise (zone 6) and an anti-clockwise (zone 5) re-circulating flow zones in the top and bottom half of the reverser as shown in (Figure 7.35). These re-circulating flow zones will sit just aft of the thrust reverser. The bottom half of these recirculating zones 5 and 6 will cause part of the core exhaust flow to generate small contra rotating vortices as shown in (Figure 7.35). These contra rotating vortices inherently are unsteady in nature. This may have a large effect on the structural strength of an aircraft system.

The flow pattern behind the reverser and number of re-circulating zones are dependent on thrust settings as shown in (Figure 7.35 and 7.36) and in (Appendix A5).

The outer streamlines of zone 5 and 6 will continue travelling aft along with the oncoming air. However, the gap between the top and bottom streamlines will narrow; eventually the two streams would merge as shown in zone 2.

Zone 8 shows that the vertical plane outer region external aerodynamics can be ignored, as the flow is primarily steady.

Zone 9 shows the flow between the nacelle bottom half and the runway. The exhaust flow from the reverser has a tendency to travel upstream (i.e. in the direction of aircraft), however, the oncoming air has a higher momentum and it travels in an opposite direction to the aircraft. The interaction between the two flows on the runway surface will result in the formation of a re-circulating region. The diameter of this re-circulating flow zone is thrust dependent, as its size is proportional to thrust. This fact is proved from the simulations and the results are attached in (Appendix A5).

Zone 10 is the subject of wing aerodynamics, which is beyond the scope of this study.

Zone 11 shows the core exhaust flow. The recirculation zones under the wing pressure surface will have an effect on the core exhaust flow.

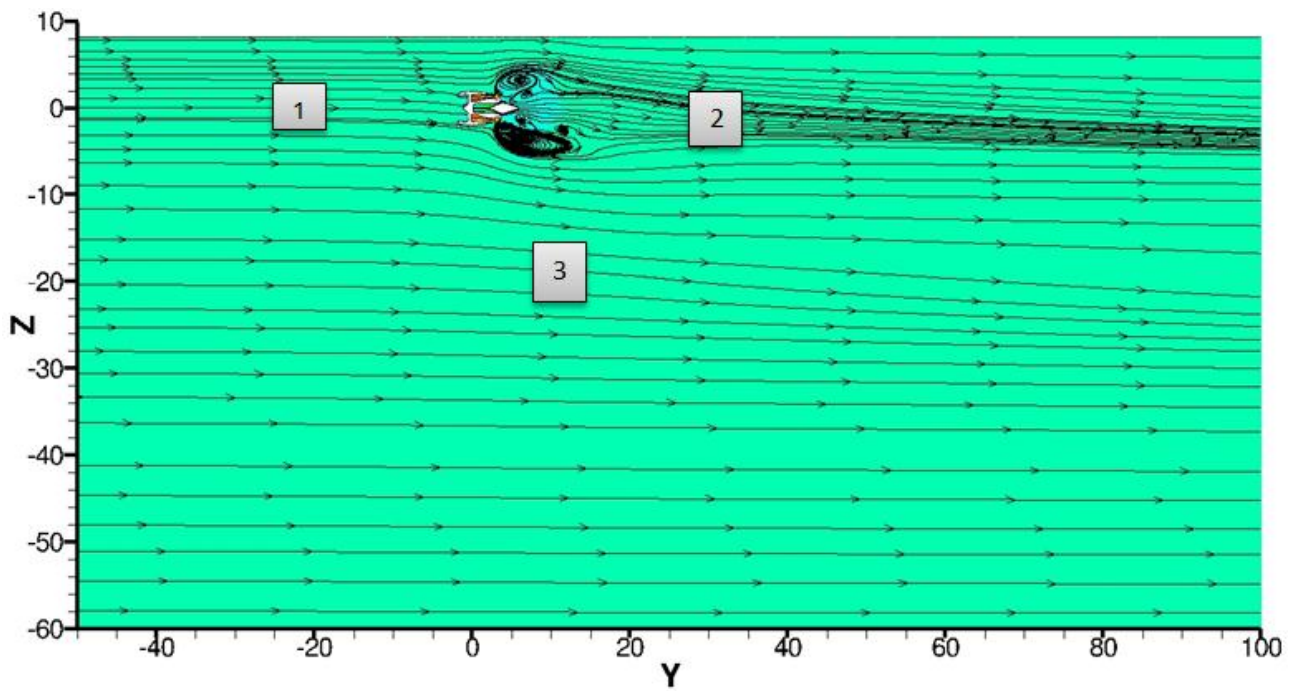


Figure 7.34: Streamlines plot for the external flow field with thrust reverser deployed, horizontal plane, $M=0.211$.

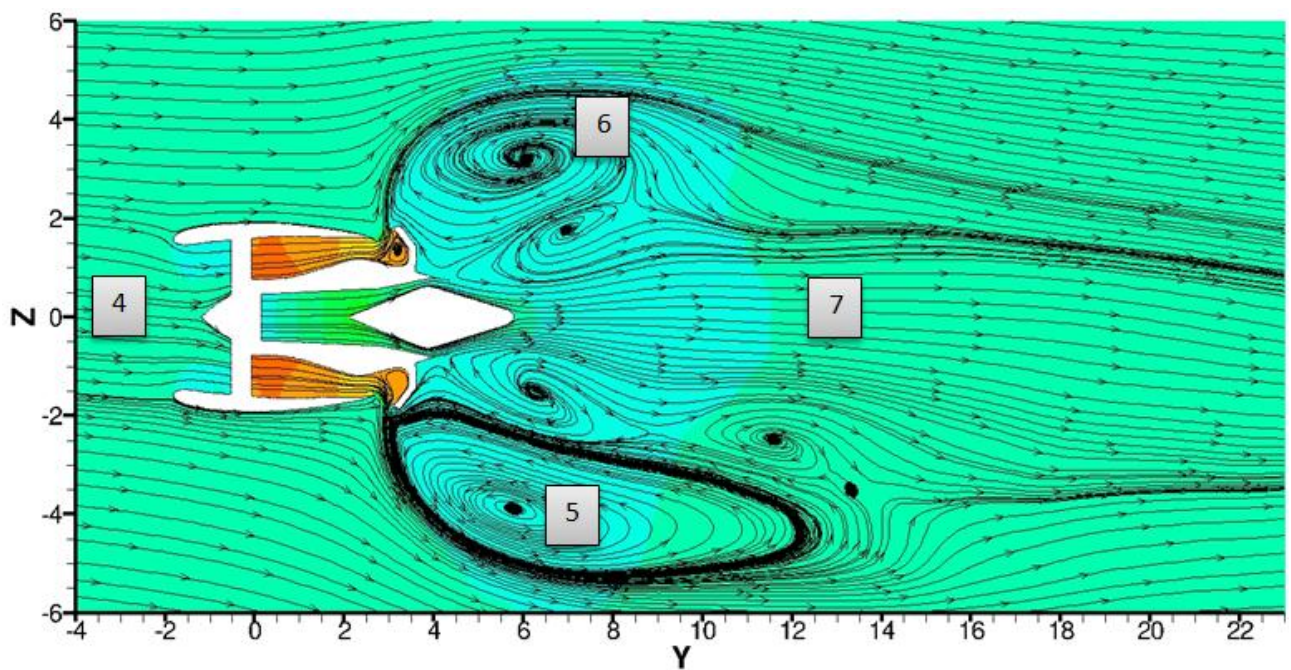


Figure 7. 35: Streamlines plot for the external and internal flow field for the thrust reverser deployed configuration, high thrust settings, horizontal plane, $M=0.211$.

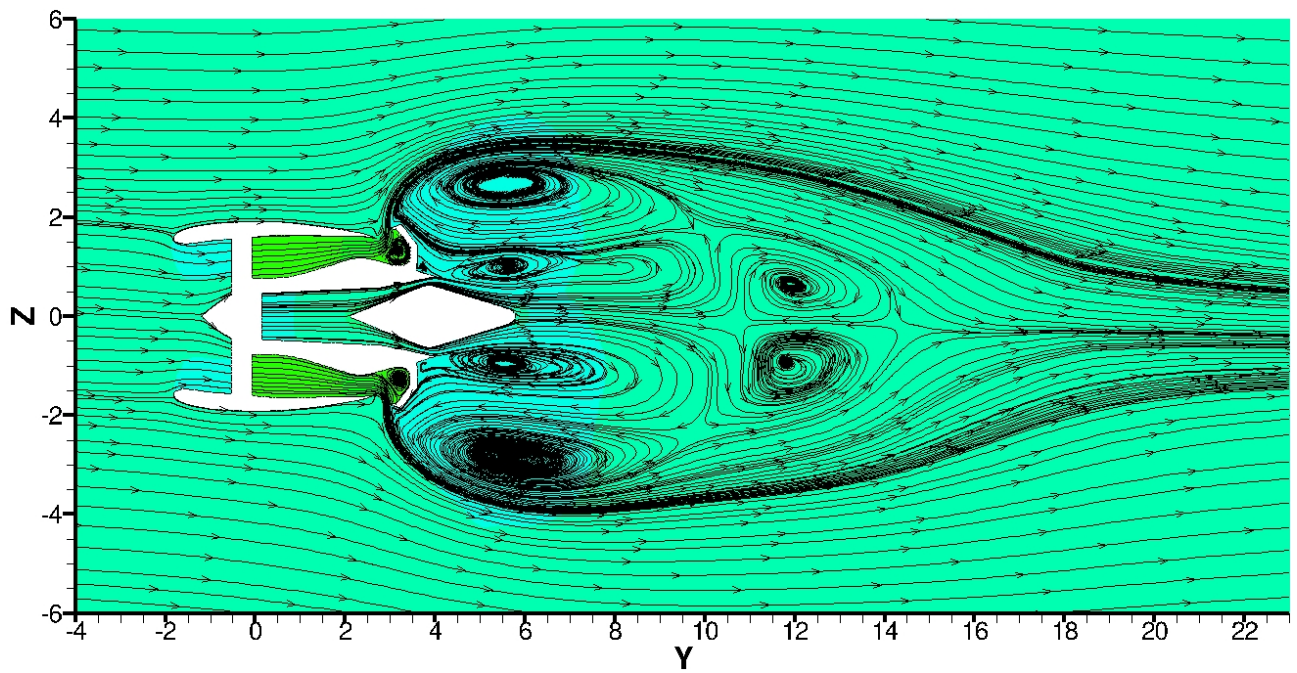


Figure 7.36: Streamlines plot for the external and internal flow field for the thrust reverser deployed configuration, at low thrust setting, horizontal plane, $M=0.211$.

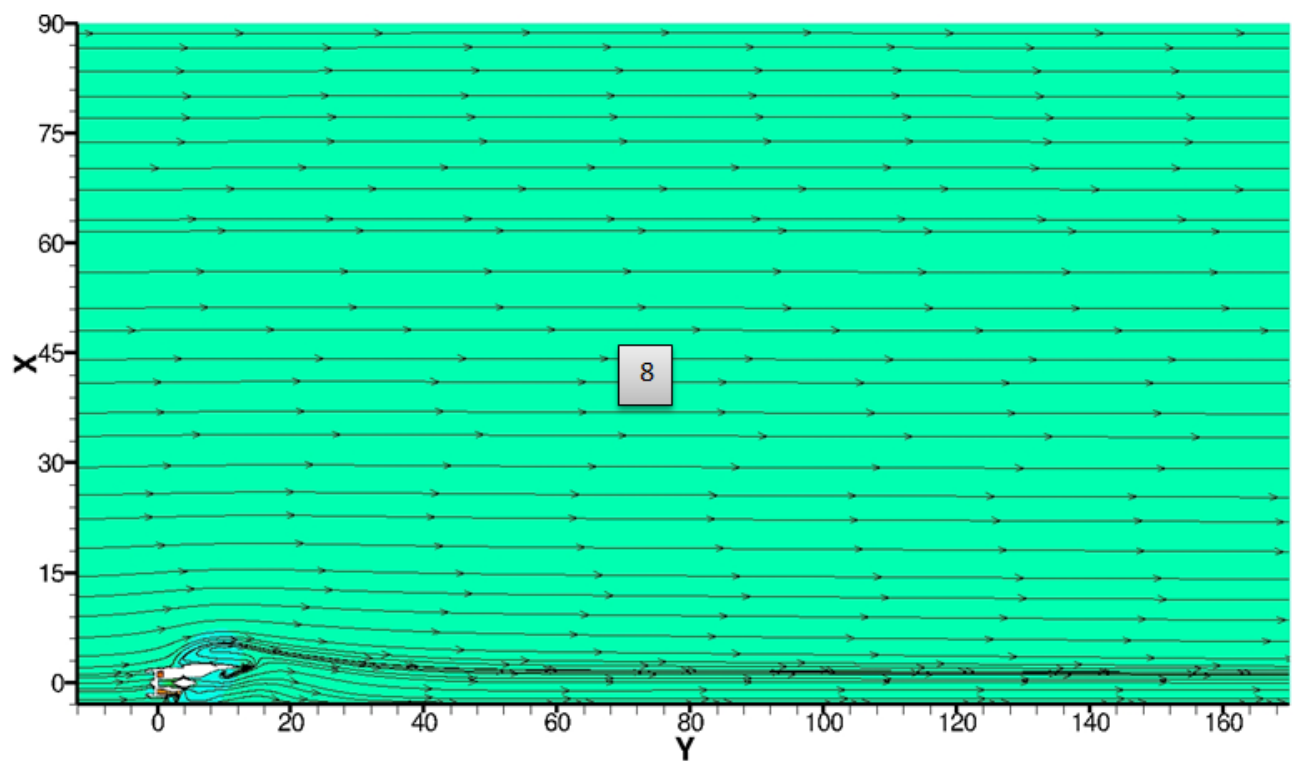


Figure 7.37: Streamlines plot for the external flow field for the thrust reverser deployed configuration, vertical plane, $M=0.211$.

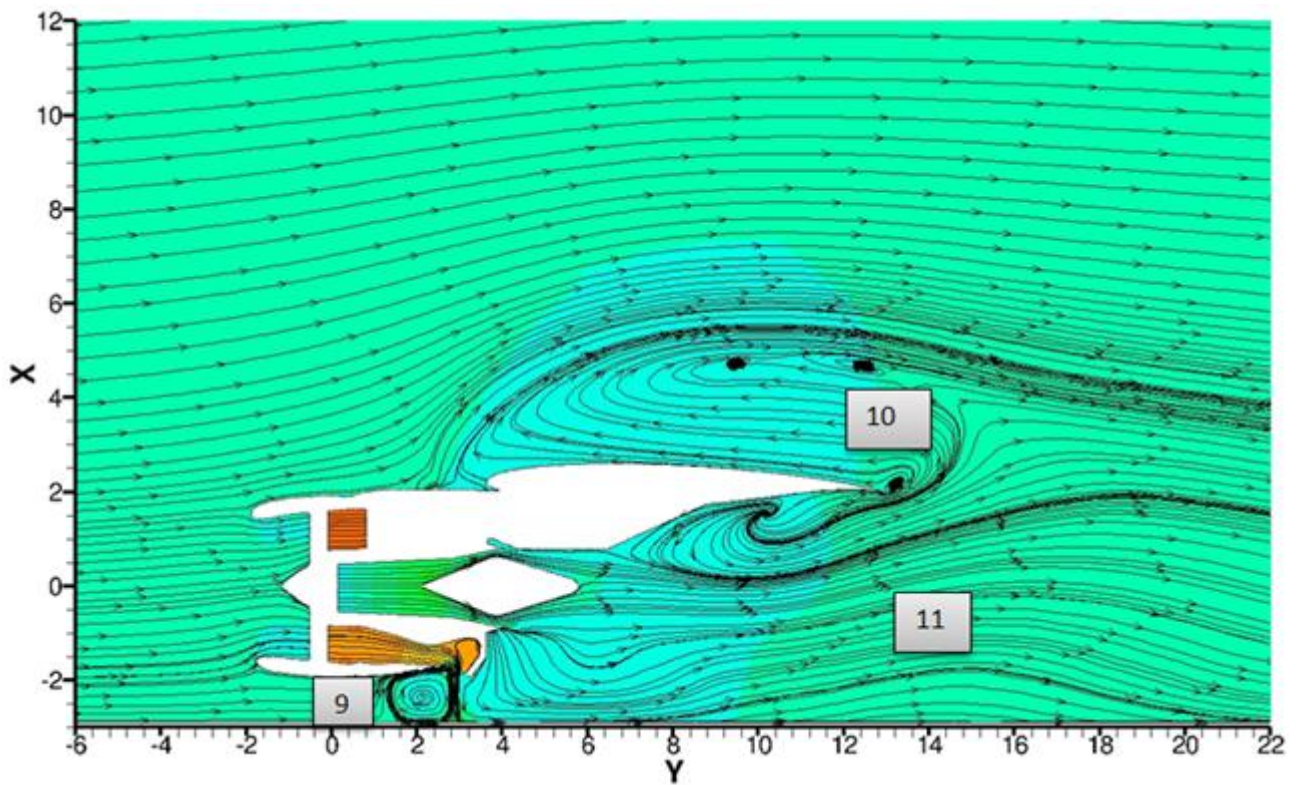


Figure 7.38: Streamlines plot for the external and internal flow field for the thrust reverser deployed configuration, vertical plane, $M=0.211$.

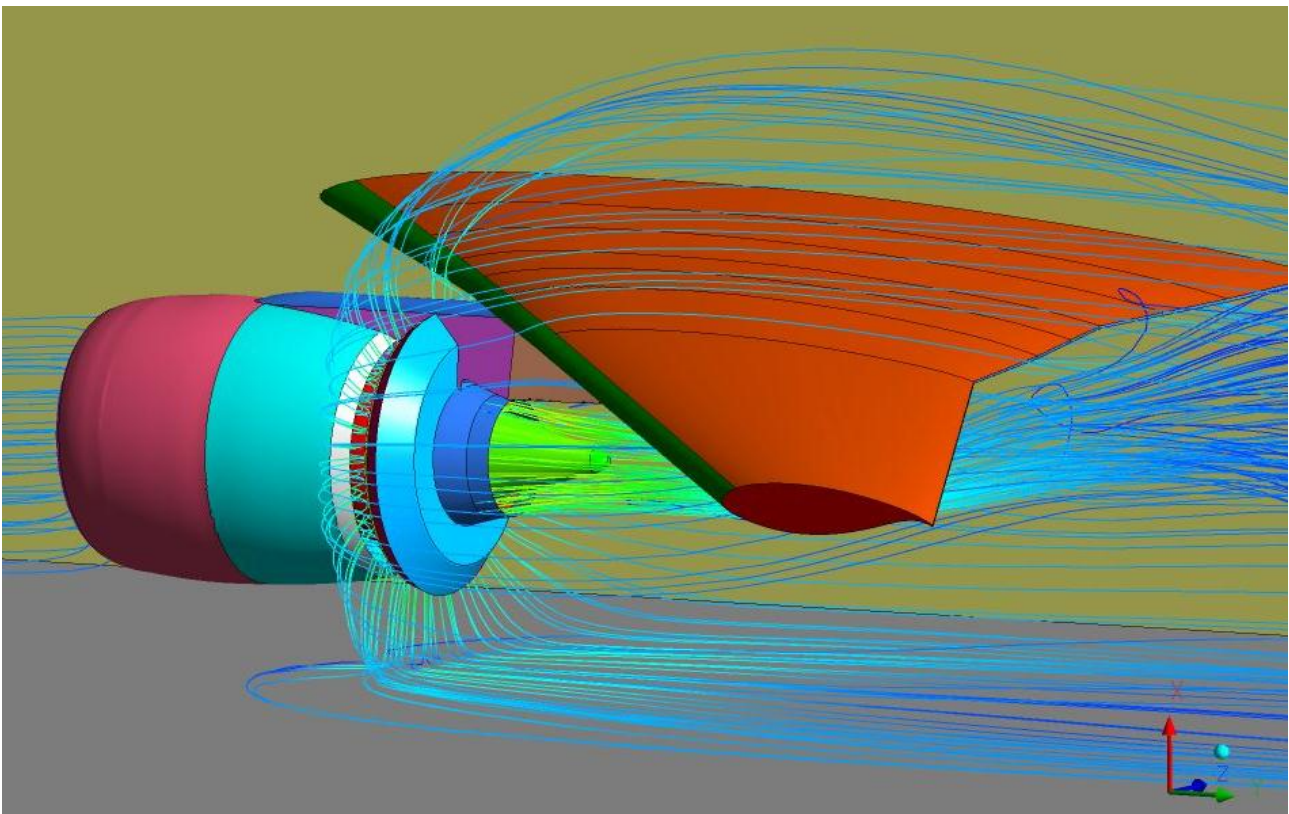
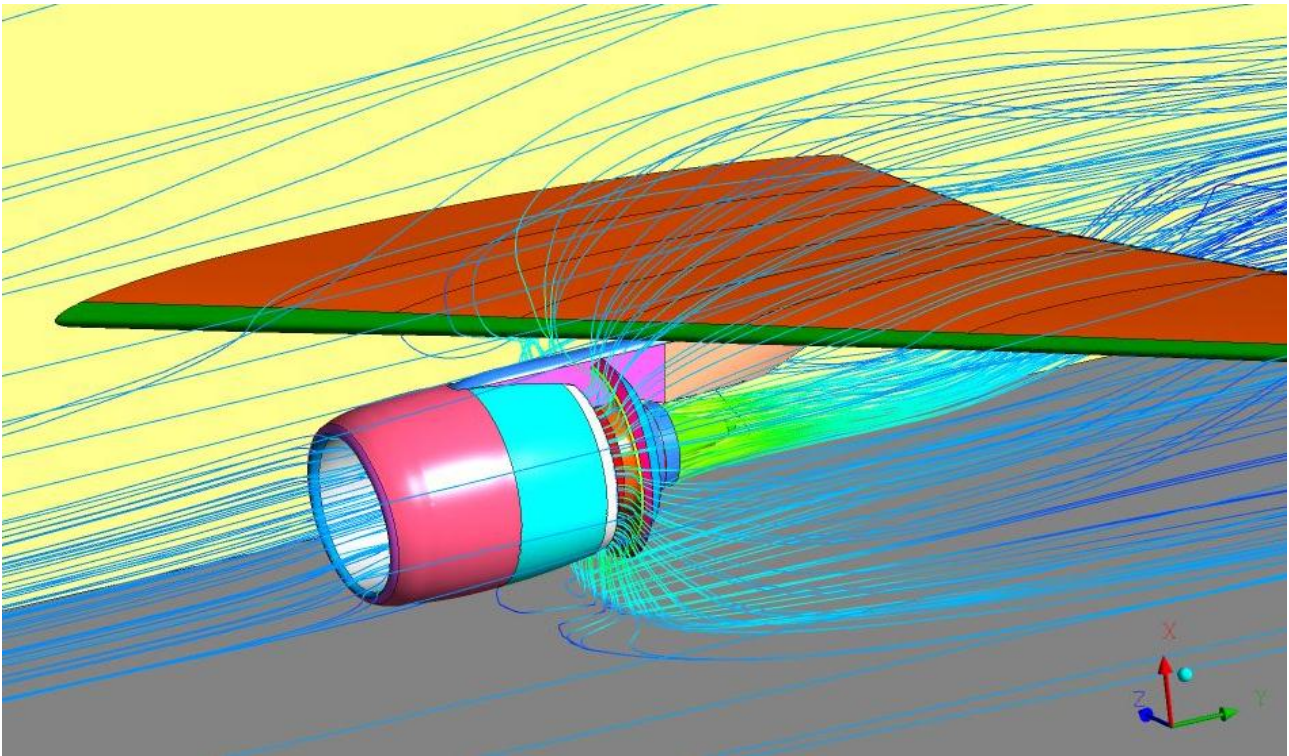


Figure 7.39: 3D streamlines for the core mounted target type thrust reverser with kicker plate at $M=0.211$, $FNPR=1.50$.

7.10 CFD Results Validation against the Experiments

Computational fluid dynamics is today an equal partner with pure theory and experiment in the analysis and solution of fluid dynamic problems. CFD analysis nicely and synergistically complements the other two approaches (as sometimes suggested). There will always be a need for theory and experiment. The future advancement of fluid dynamics will rest upon a proper balance of all three approaches, with computational fluid dynamics helping to interpret and understand the results of theory and experiment, and vice versa [Ref 50].

Accurate wind tunnel testing of thrust reversers is complicated, time consuming and expensive. On the other hand CFD modelling of the thrust reversers can be relatively cheaper and faster. Thrust reversers design feasibility can be easily performed using CFD and the final selected designs can be tested in the wind tunnel.

With CFD modelling, it is imperative that they are checked to give viable and reliable data. In the present work, a direct comparison between the CFD generated data and experimental data is made.

7.10.1 Experimental Testing

The wind tunnel testing was performed on a 3D model. The majority of the data were taken in the dual flow operation mode with both the core and fan nozzles operating over a nominal core/fan nozzle pressure ratio schedule representative of current technology, high bypass ratio turbofan engines.

The mass flow rate of high pressure air supplied to the model was calculated from static-pressure and total temperature measurements taken in two calibrated, multiple-critical venturis (one for the primary air system and one for the secondary air system) located upstream of the dual flow propulsion simulation system. The multiple-critical venturi is the standard high pressure airflow measurement system used in NASA Langley Research Centre 16 Foot Transonic Tunnel and is rated to be 99.9% accurate in mass flow measurements [Ref 8].

Static pressures were measure inside the core and fan nozzles and on model external surfaces (such as the pylon, target, and wing) for each configuration using 0.060-inch diameter static pressure orifices. The location for the pressure orifices for the two target type thrust reverser tested is shown in (Figure 7.40).

Each data point is the average steady-state value computed from 50 frames of data taken at a rate of 10 frames per second. Calibration constants were applied to the data to obtain corrected forces, moments, pressure and temperatures.

The details of the annular (metal) target thrust reverser model showing static pressure orifice locations (denoted by circles) is shown in (Figure 7.41). It is assumed that the same locations were used for the 40 degree annular (metal) target type thrust reverser with kicker plate, as this is not specific in the NASA report.

All the static pressure measurements were taken at a 14 degree clockwise from the engine horizontal split line (Figure 7.41).

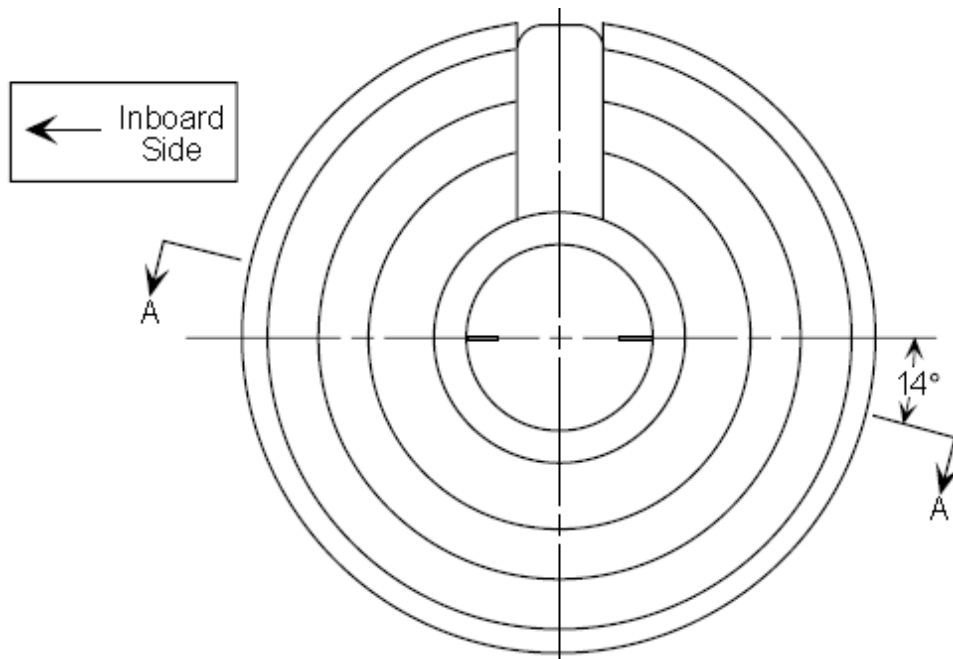


Figure 7.40: Shows a 14 degree clockwise plane which is used for static pressure measurement.

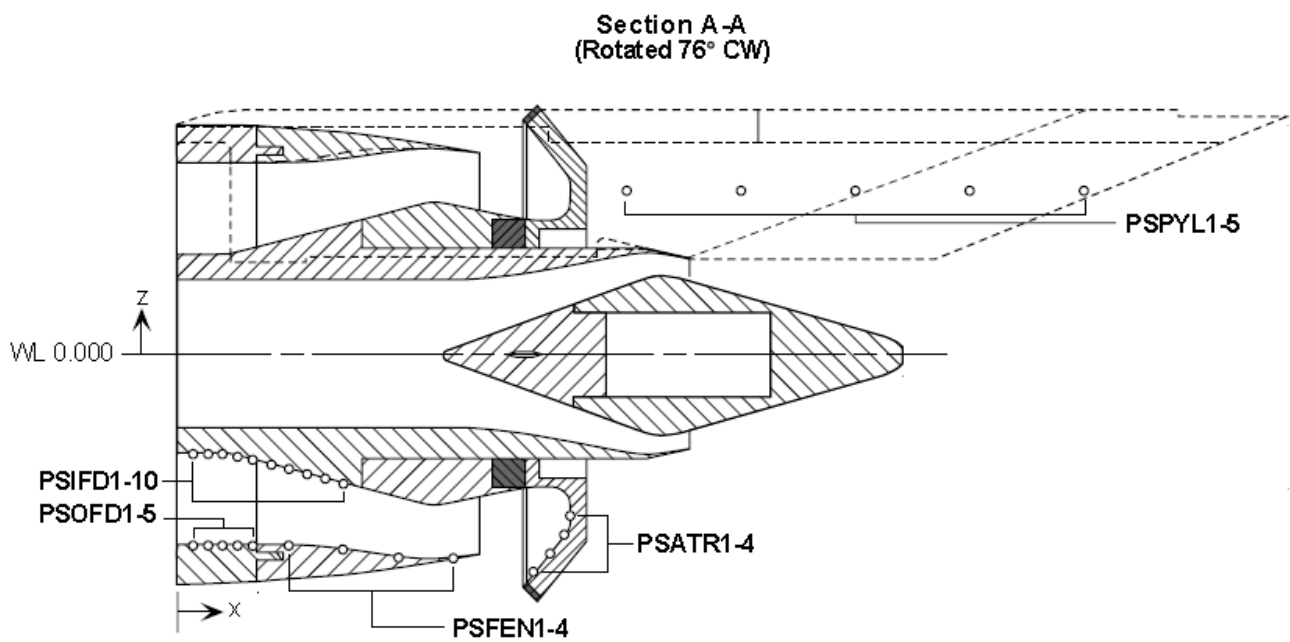


Figure 7.41: Shows a cut-plane and the location of the static pressure orifice for a 40 degree core mounted target type thrust reverser.

7.10.2 CFD Measurements and Data Extraction

Experimental setup allowed for the static pressure measurements at the desired locations. Inbuilt post processing tools within the CFD software (FLUENT) are used for the measurement of static pressure.

A 14 degree clockwise cut-plane similar to that used during the experiments was formed from the engine horizontal split line for the CFD cases. This is important as it would allow for a like for like comparison.

CFD analyses were performed on a full scale model, whereas the experimental testing was conducted on a 7.9% scale model. Thus, it is important to use the same static pressure orifice locations as those used during the experiments.

Static pressure measurements were taken at the core external surface, fan nacelle internal surface and on the inner surface of the target type thrust reverser. For target type thrust reverse with kicker plate, measurements were also taken for the pylon surface.

The comparison of the results was performed for both the target type reverser at 40 degree, and the target type reverser at 40 degree with kicker plate.

For most of the FNPRs, there is a good match found between the CFD analyses and wind tunnel tests performed by NASA. However, at certain conditions differences are observed between the CFD and test cases. These differences could be attributed to the following reasons:

- i) Turbulence model
- ii) Manufacturing tolerances
- iii) Measurement errors
- iv) Numerical Discretization Scheme
- v) Boundary Conditions

As shown in the plots, there is a good agreement; hence it proves that the CFD is capturing the correct flow physics.

The CFD results show good agreement with the experimental data at almost all FNPRs values and for all geometries. The only major difference is for the pylon. During the wind tunnel experiments the runway affect was not accounted as the engine test model was on a stand, and also no wing was installed. The difference in results for the pylon geometry is believed to be due to the inclusion of wing and runway geometries.

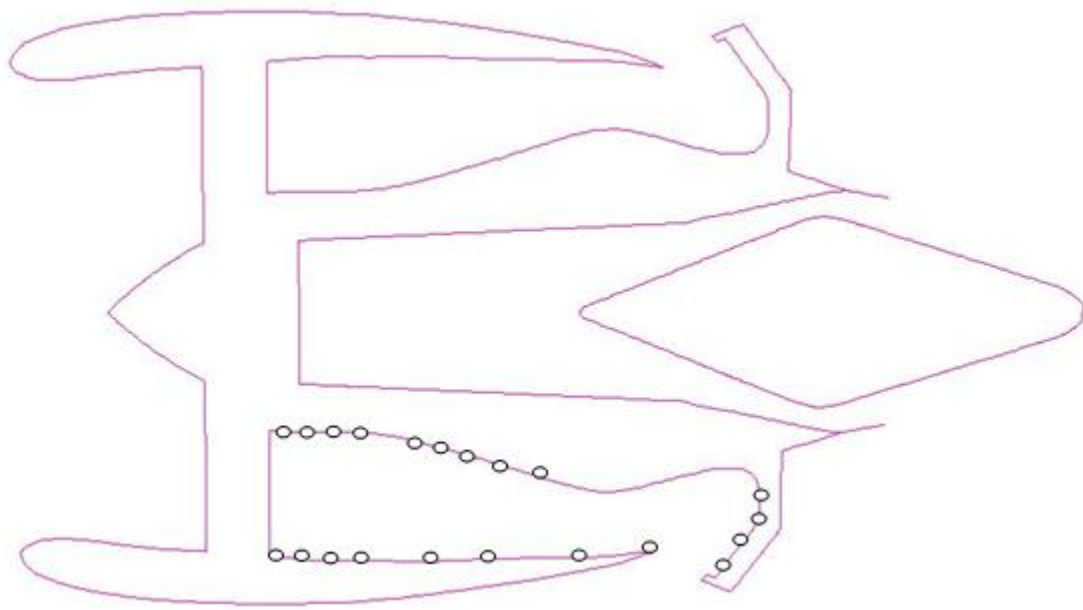


Figure 7.42: A 14 degree cut plane, similar to the experimental tests was taken for the CFD static pressure measurements.

7.11 Target Reverser at 40 Deg – Comparison of Experiment vs. CFD

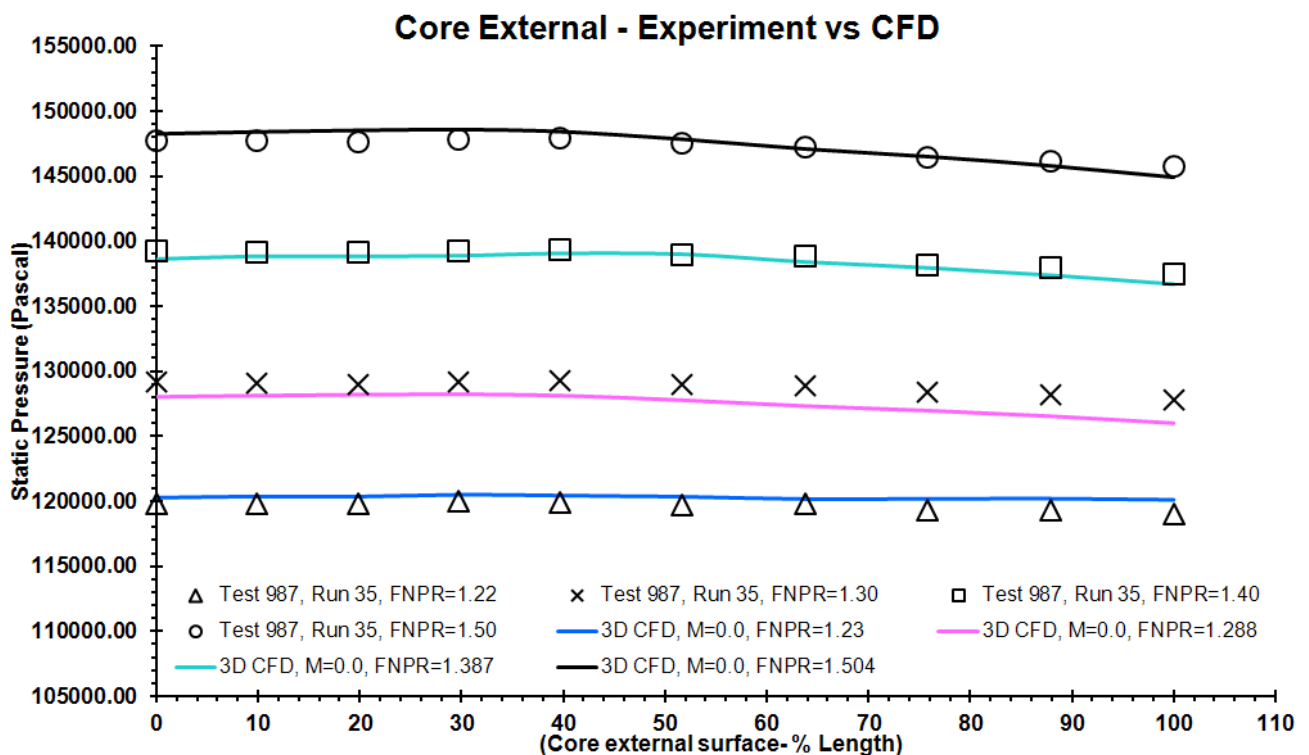


Figure 7.43: CFD and Experimental comparison for the static pressure values at different FNPRs for Core External Surface, for 40 degree target thrust reverser configuration.

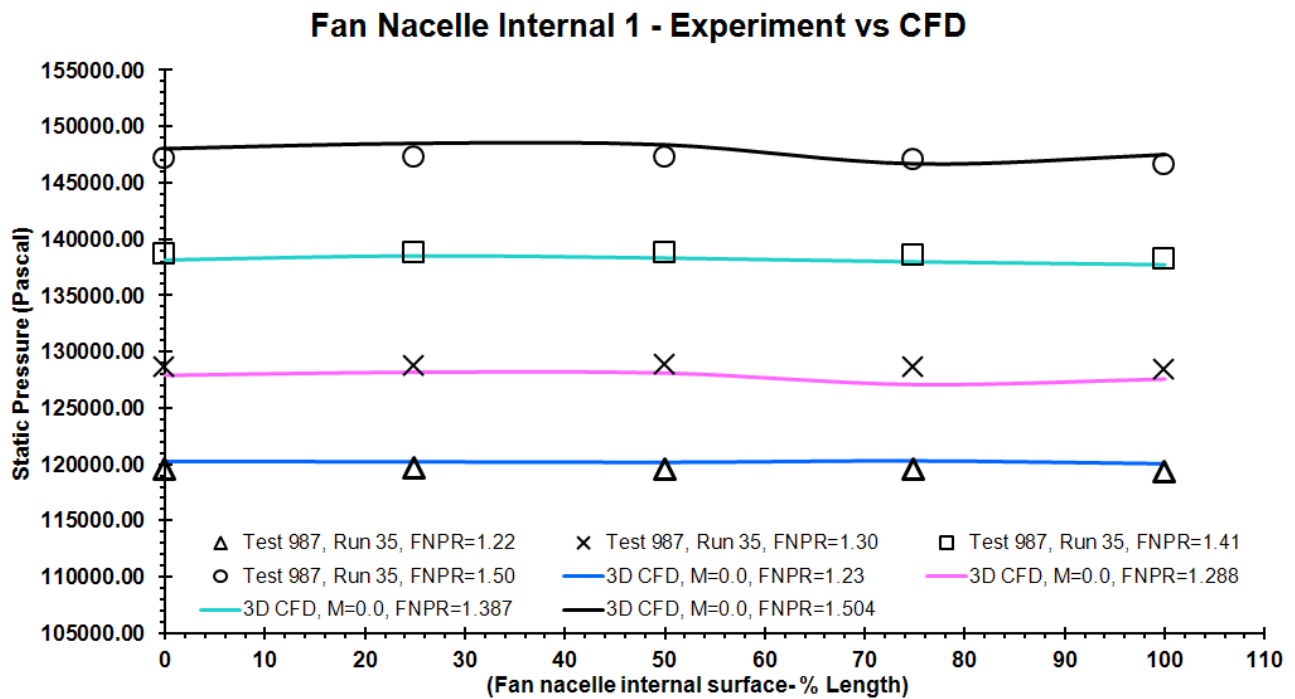


Figure 7.44: CFD and Experimental comparison for the static pressure values at different FNPRs for Fan Nacelle Internal 1, for 40 degree target thrust reverser configuration

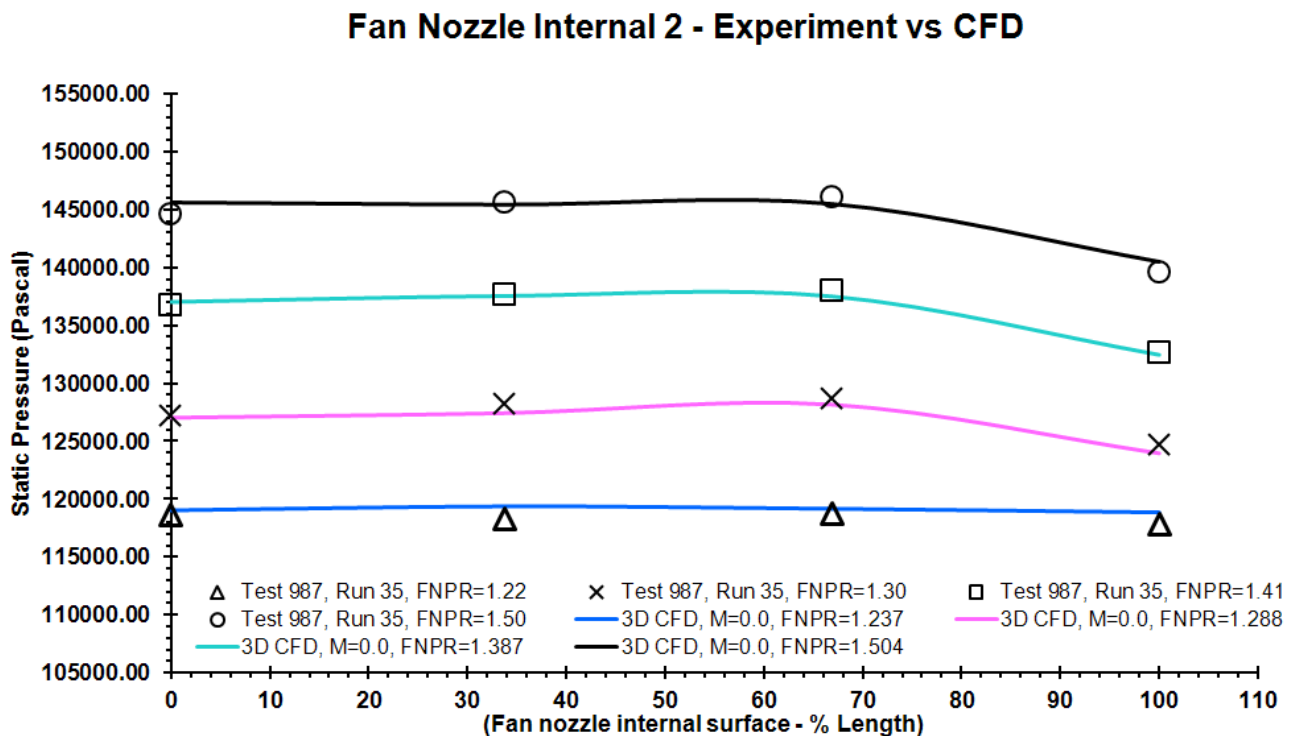


Figure 7.45: CFD and Experimental comparison for the static pressure values at different FNPRs for Fan Nozzle Internal 2, for 40 degree target thrust reverser configuration.

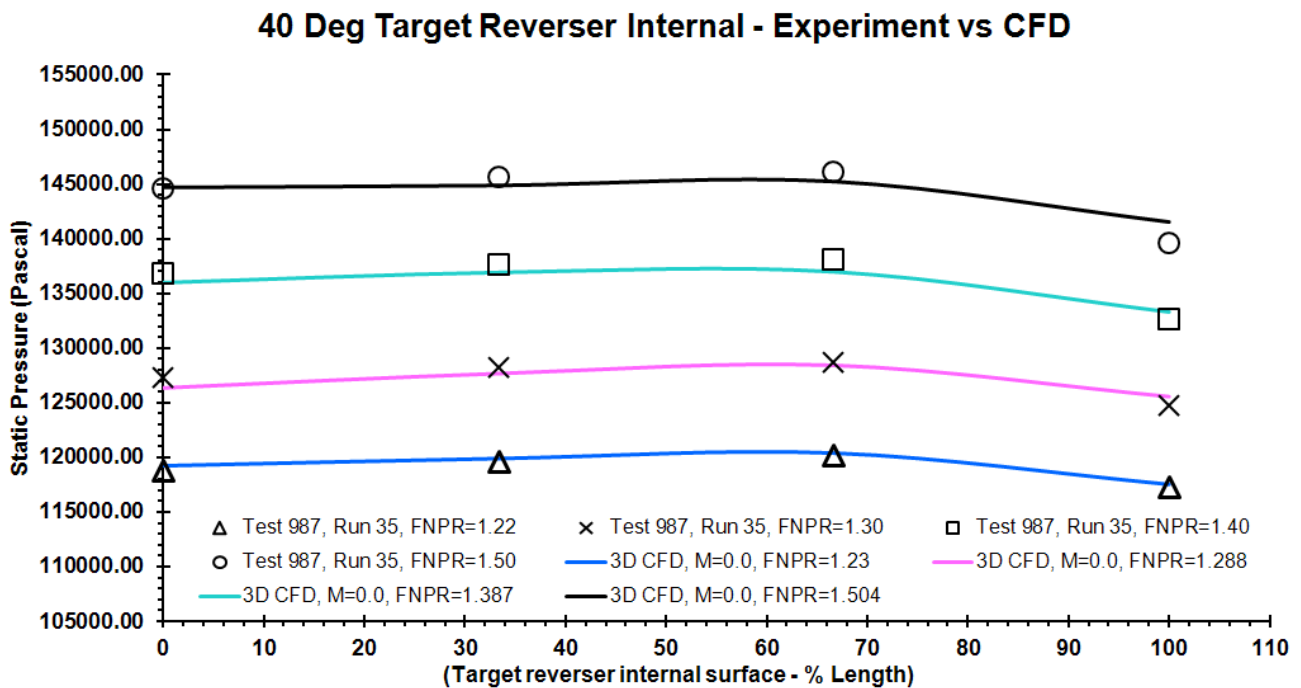


Figure 7.46: CFD and Experimental comparison for the static pressure values at different FNPRs for 40 Deg Target Reverser Internal Surface, for 40 degree target thrust reverser configuration

7.12 Target Reverser at 40 Deg with Kicker Plate – Comparison of Experiment vs. CFD

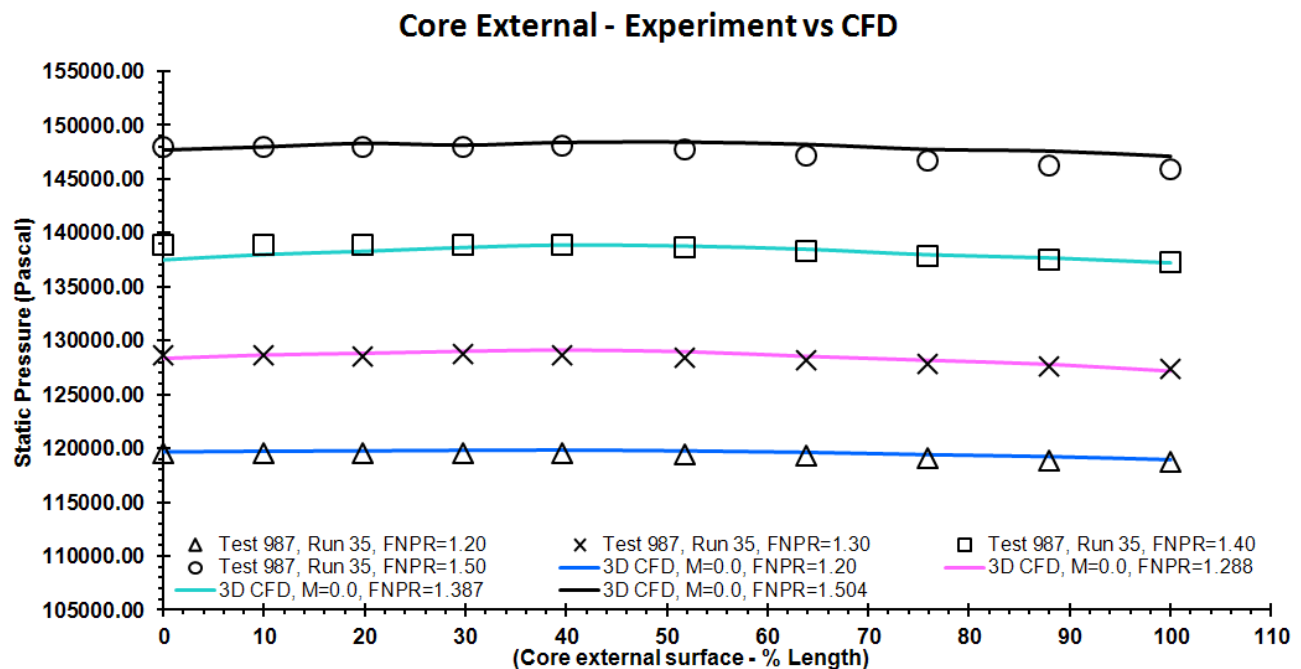


Figure 7.47: CFD and Experimental comparison for the static pressure values at different FNPRs for Core External Surface, for 40 degree target thrust reverser with kicker plate, M=0.0.

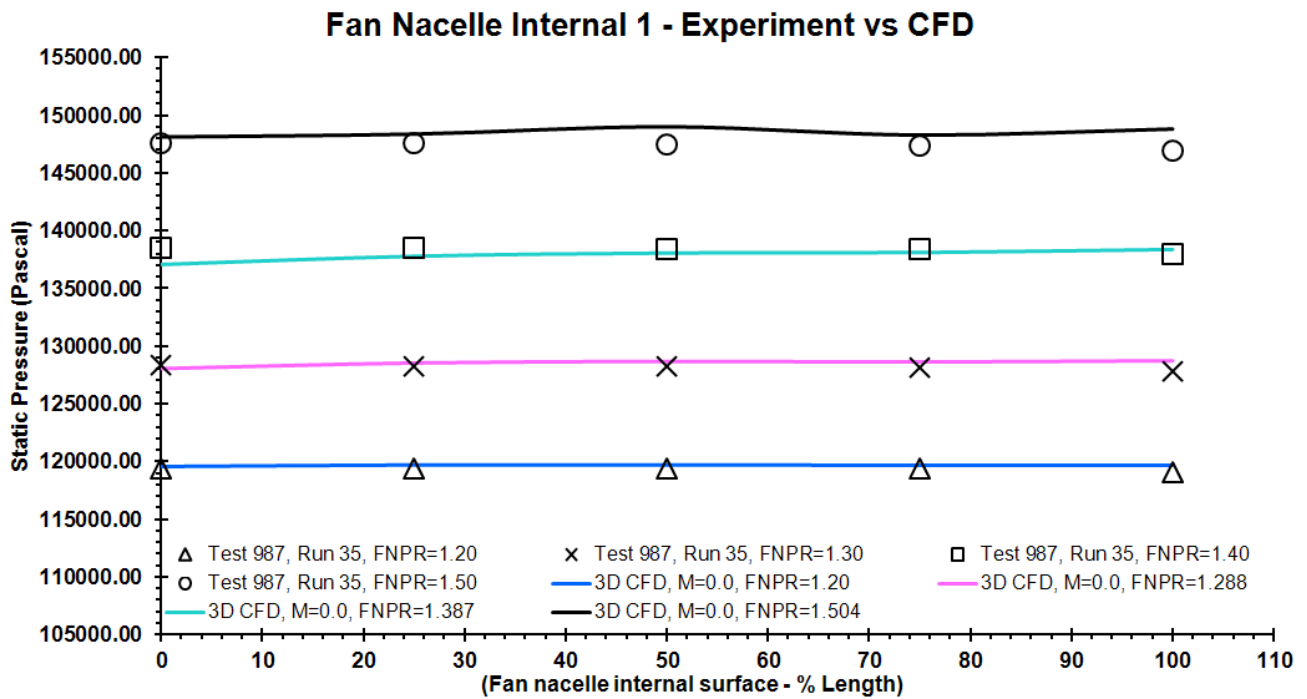


Figure 7.48: CFD and Experimental comparison for the static pressure values at different FNPRs for Fan Nacelle Internal, for 40 degree target thrust reverser with kicker plate, $M=0.0$.

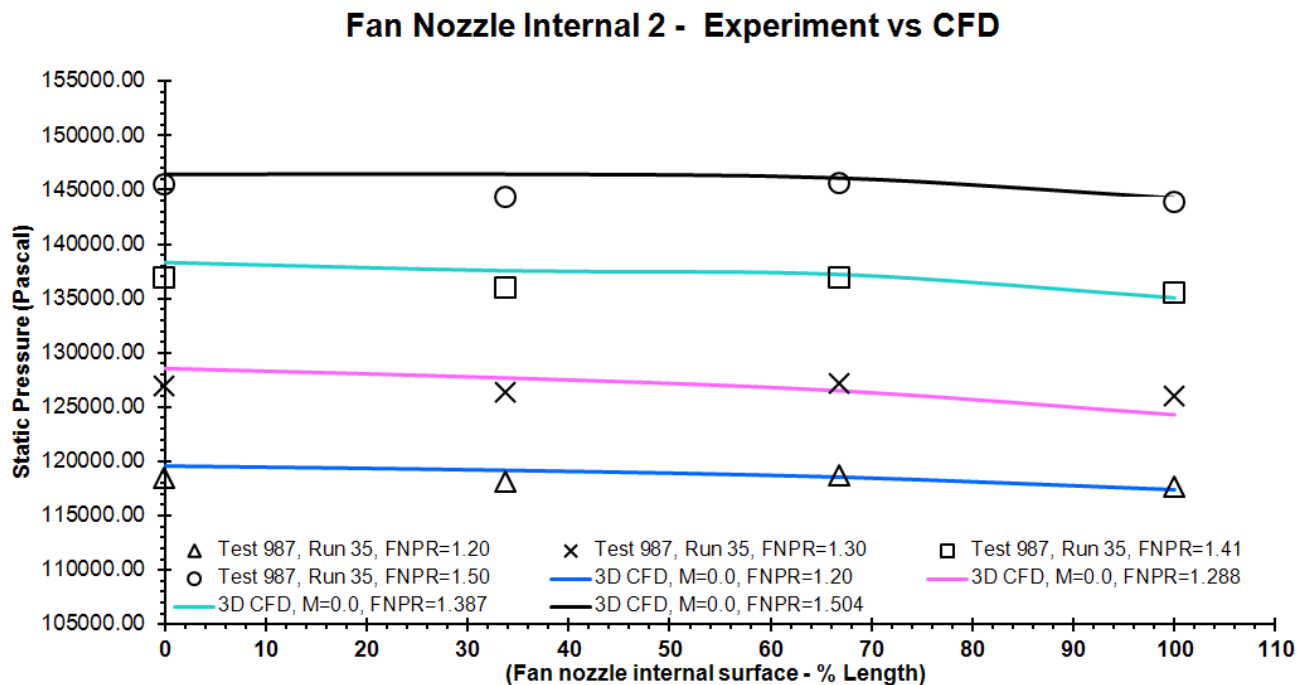


Figure 7.49: CFD and Experimental comparison for the static pressure values at different FNPRs for Fan Nozzle Internal Surface, for 40 degree target thrust reverser with kicker plate, $M=0.0$.

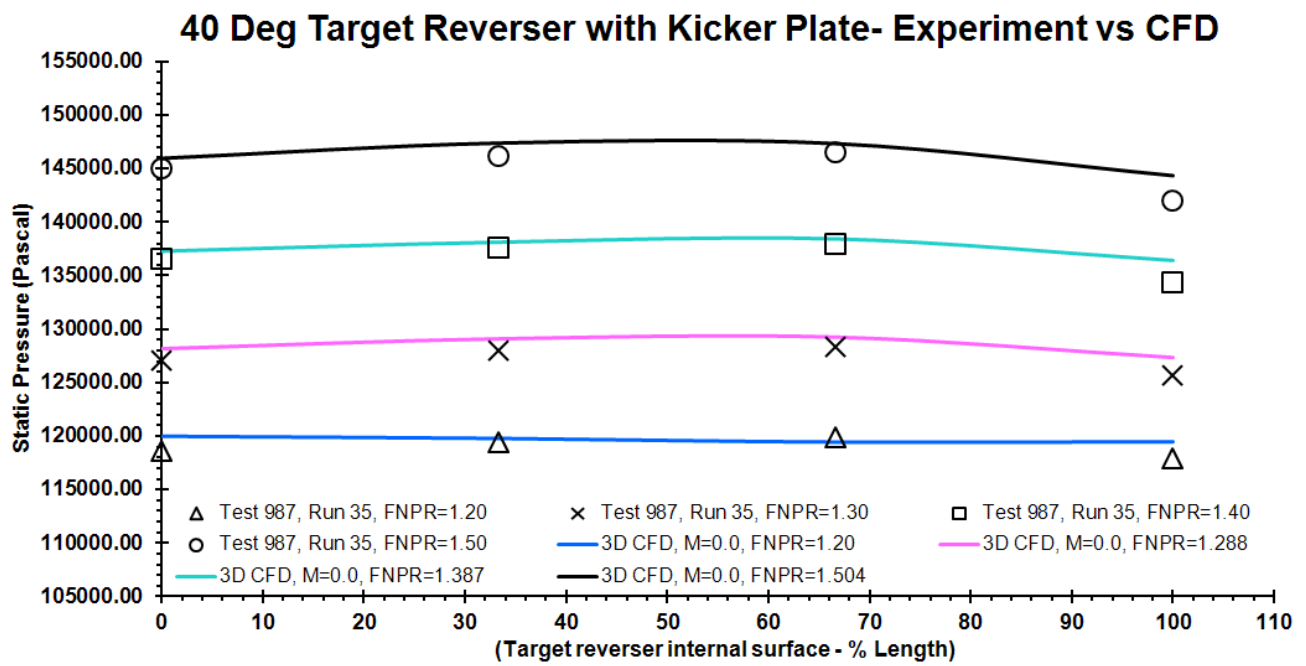


Figure 7.50: CFD and Experimental comparison for the static pressure values at different FNPRs for Target Reverser with Kicker Plate internal surface. M=0.0.

7.13 Results and Discussion for 3D CFD Analyses

7.13.1 Introduction

This section discusses the results obtained from the 3D CFD analyses. The CFD results are presented for both the static ($M=0.0$) and forward landing conditions ($M=0.211$).

First the 3D CFD results for the static tests ($M=0.0$) are discussed for the forward thrust configuration and the two core mounted target type thrust reverser configurations are discussed later. The results for each configuration are compared with the experimental data. The experimental results for the static tests are available in the public domain [Ref 8].

Next, the 3D CFD results for the forward landing configuration ($M=0.211$) are presented. Similar, to the static case, the results are discussed for the forward thrust and the two core mounted target type thrust reverser configurations. No experimental tests were performed by NASA at landing conditions of ($M=0.211$), therefore, only the 3D CFD results are presented.

The results at static condition ($M=0.0$) are discussed and presented in the following sections:

- I. Section 7.14, discusses the CFD results for the forward thrust configuration at static conditions ($M=0.0$).
- II. Section 7.15 discusses the CFD results for the 40 degree core mounted target type thrust reverser configuration with and without kicker plate at static conditions ($M=0.0$)
- III. Section 7.16, discusses the CFD results for the forward thrust configuration at forward landing condition conditions ($M=0.211$).
- IV. Section 7.17 discusses the CFD results for the 40 degree core mounted target type thrust reverser with kicker plate configuration with and without kicker plate at static conditions ($M=0.211$).

7.14 Results and Discussion for the Forward Thrust Configuration at Static Conditions, ($M=0.0$)

The summary of results from the 3D CFD analyses for the forward thrust configurations are given in the table below (Table 7.2). These results for the forward thrust are important as they would allow a comparison with the thrust reverser performance at these same FNPRs.

The boundary conditions of fan and core outlet pressures were set based on the performance calculations.

Figure 7.51, shows the linear variation in fan thrust as the FNPR is increased.

Table 7.2: Shows the Results from the 3D CFD Analyses for the Forward Thrust Configuration at Static Conditions ($M=0.0$).

3D CFD Analysis - Forward Thrust $M=0.0$						
No	$P_{\text{fan Outlet}}$ (KPa)	FNPR	$W_{\text{Fan outlet}}$ (kg/s)	$T_{\text{Fan Gross}}$ (N)	$T_{\text{Core Gross}}$ (N)	T_{Total} (N)
1	121.10	1.19	754.60	131074.02	7670.04	138744.06
2	125.38	1.24	840.60	163328.58	10112.23	173440.81
3	131.23	1.29	909.40	191919.78	12945.77	204865.55
4	136.10	1.34	971.20	219588.32	16230.24	235818.56
5	141.53	1.39	1033.40	249669.44	20517.00	270186.44
6	147.34	1.45	1093.40	280675.78	30928.94	311604.72
7	153.37	1.50	1093.90	311810	30928.94	311733.07
8	158.70	1.55	1202.30	342294.81	52961.91	395256.72

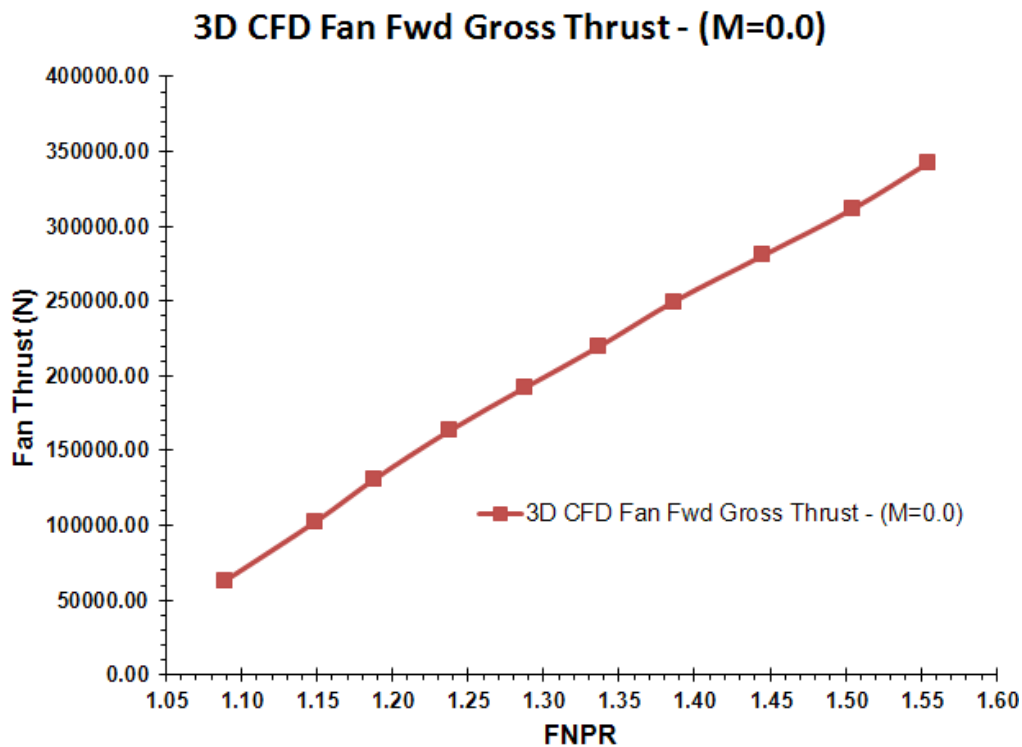


Figure 7.51: Shows the variation in fan gross thrust against the FNPR, $M=0.0$.

7.15 Results and Discussion for the Core Mounted Target Type Thrust Reverser with and without kicker plate at Static Conditions ($M=0.0$)

The target type thrust reverser design and location will cause the flow to bend aggressively, as shown previously in (Section 7.9.1). The reverser exhaust flow will strictly be three dimensional. The high momentum reverser exhaust flow will have thrust components in the axial, radial and side direction, which are named as F_x , F_y and F_z . The resultant of all three thrust components will be the total gross thrust. The core thrust is predominately axial, as explained in (Section 7.9.1).

Aerodynamic results discussed in (Section 7.9.1), showed that the majority of the high momentum reverser exhaust flow would leave the reverser exit plane in a vertical direction. Therefore the majority of the thrust will be in the vertical direction, hence, F_Y , will be the highest and this will be true for all FNPRs. This fact was also verified from the calculations of thrust components for all the CFD cases, and the results are shown in [Table 7.3].

The thrust reverser design used in the CFD analyses was similar to that tested by NASA (Test 987, Run 35, and Configuration 307) and has a reverser exit area ratio of 1.25. Although, the exit area of the reverser is greater than that for the forward thrust configuration; the effective reverser exit area has still significantly reduced. This reduction in reverser effective exit area will significantly affect the fan outlet mass flow. It was observed from the CFD analyses that the mass flow will reduce by up to 40% in comparison to what it was at the same FNPRs for the forward thrust configuration, the results are shown in [Table 7.2 and Table 7.3].

The reduction in effective exit area is caused by the streamline curvature, and also because of the blockage due to the formation of recirculating vortex in the cavity region (zone 10) (Figures 7.26 and 7.27). This re-circulating region (zone 10) will have a coanda effect on the bypass stream, as discussed in the previous section.

The horizontal reverse thrust component for the reverser exhaust flow is referred as, $(-F_x)$; the negative implying the reverse thrust. An important reverser design consideration is that this horizontal component should be as high as possible in magnitude. Also, this should be in the negative direction.

Results from all the 3D CFD cases show that this particular thrust reverser configuration is not producing any reverse thrust. Therefore, the horizontal thrust component, F_x , is in fact in the direction of forward thrust [Table 7.3].

Table 7.3, also shows that the side thrust component, F_z , is significantly less in magnitude in comparison to the horizontal and vertical thrust components, F_x and F_y . Further, due to the symmetry in the reverser design, the side force component, F_z , will almost be equal in magnitude on either side (left and right) of the engine, and therefore cancels out. The same will also be true for the, F_y , component, provided that there is no pylon present. However, there will still be some vertical thrust component resulting from the bottom half of the reverser. This is because the geometry on the top half of the thrust reverser has a restriction i.e. pylon, which restricts its area. Whereas, the bottom half of the reverser will have a larger area, which will result in some addition of vertical thrust in the upward direction. However, with careful thrust reverser design, this phenomenon can be eliminated, or reduced to minimum.

3D CFD results show that in addition to the reverse thrust produced by the exhaust flows, there will be some additional thrust, and this additional thrust is produced by the structure of the target type reverser. This thrust is produced primarily due to the pressure difference on either side of the reverser. Results in [Table 7.3], shows that the deployment of target type thrust reverser will produce a significantly high pressure thrust force, $T_{\text{Pressure Thrust}}$, this pressure thrust force can be accounted as a source of reverser thrust as it will decelerate the aircraft. The values of the pressure thrust for every case was calculated in FLUENT in the horizontal plane.

In [Table 7.3], the axial thrust component is, T_{Axial} . Where the, T_{Axial} , is the corrected balance axial force. For the static tests it is defined as:

$$T_{\text{Axial}} = F_x - T_{\text{core}} \quad \text{[Equation 7.1]}$$

However, from [Table 7.3], the CFD results show that this horizontal thrust component, F_x , is positive i.e. it is acting as a forward thrust, therefore, it will be added to the core thrust, T_{core} . Thus, T_{Axial} , in this case is a combination of F_x and T_{core} .

Four different types of efficiencies are defined in [Table 7.3]. The explanation and calculation methods are defined below:

$$\eta_{eff1} = T_{Pressure} \text{ (Pressure thrust) } / \text{ Fan Forward Thrust} \quad [\text{Equation 7.2}]$$

$$\eta_{eff2} = F_x \text{ (Fan Reverser Thrust Component) } / \text{ Fan Forward Thrust} \quad [\text{Equation 7.3}]$$

$$\eta_{eff3} = (T_{Core} - (F_x)) / \text{ Total Forward Flight Thrust} \quad [\text{Equation 7.4}]$$

$$\eta_{eff4} = ((T_{Pressure} + F_x) - T_{Core}) / \text{ Total Forward Flight Thrust} \quad [\text{Equation 7.5}]$$

As discussed, the two main forces that will affect the reverser thrust are the following:

- The horizontal component of the main reverser exhaust flow, F_x , and
- The resultant pressure thrust component, $T_{Pressure}$

F_x and the resultant pressure thrust, $T_{Pressure \text{ Thrust}}$ are produced due the fan stream; therefore, their performance is checked against the fan thrust in the forward static thrust condition at the same FNPR. Both the reverse thrust forces are represented by [Equation 7.2] and [Equation 7.3].

The net axial thrust force is considered in [Equation 7.4]. F_{Axial} , is the difference between the horizontal component of the reverser exhaust flow, F_x , and the core thrust T_{Core} . This is represented in [Equation 7.4]. The overall net reverse force is represented by [Equation 7.5], which takes pressure thrust into account along with the other axial forces such as T_{Core} and F_x . This is represented in [Equation 7.5].

The results obtained from the 3D CFD analyses for the 40 degree core mounted target type thrust reverser are compared for the reverser efficiency, against the experimental test results for the same configuration tested by NASA (Test 987, Run 35, and Configuration 307).

Also, the above discussion for the 40 degree core mounted target type thrust reverser is equally valid for the 40 core mounted target type thrust reverser with the kicker plate. The 3D CFD results for the core mounted target type thrust reverser with kicker plate are given in [Table 7.4].

The comparisons of the CFD results for the thrust reverser performance against the experiments performed by NASA are shown in (Figure 7.52).

Figure 7.52, also shows the comparison of the core mounted target thrust reverser with and without kicker plate. Although, the kicker plate installation on a target type reverser is useful in deflecting the flow and improving the reverser performance, it was also observed from the 3D CFD analyses that the installation of kicker plate, significantly helps in improving the pressure thrust. The results from the 3D CFD analysis show that the installation of a kicker plate improves the overall pressure thrust by up to 25%. Thus, it can be concluded that the installation of a kicker plate is important, and due to these advantages it is generally found on many target and pivoting door type reversers.

It can be concluded from the 3D CFD analyses at static conditions that the current reverser design is not compatible to satisfy the mass flow compatibility criteria, as the mass flow is reduced by up to 40 % of the forward thrust value. Also, the reverser design is not very effective, as only negligible reverse thrust is obtained, which is not satisfactory.

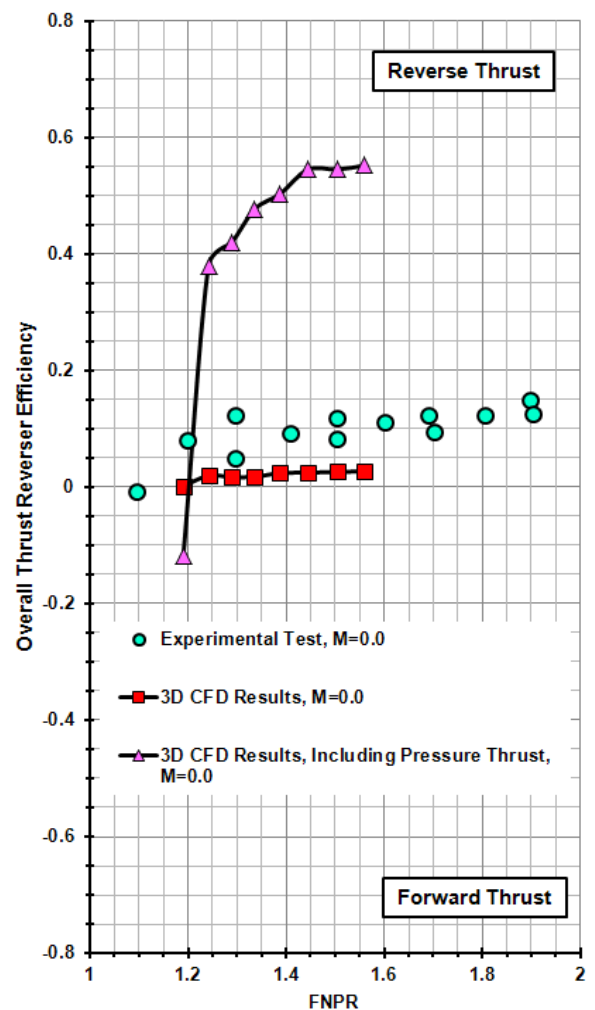
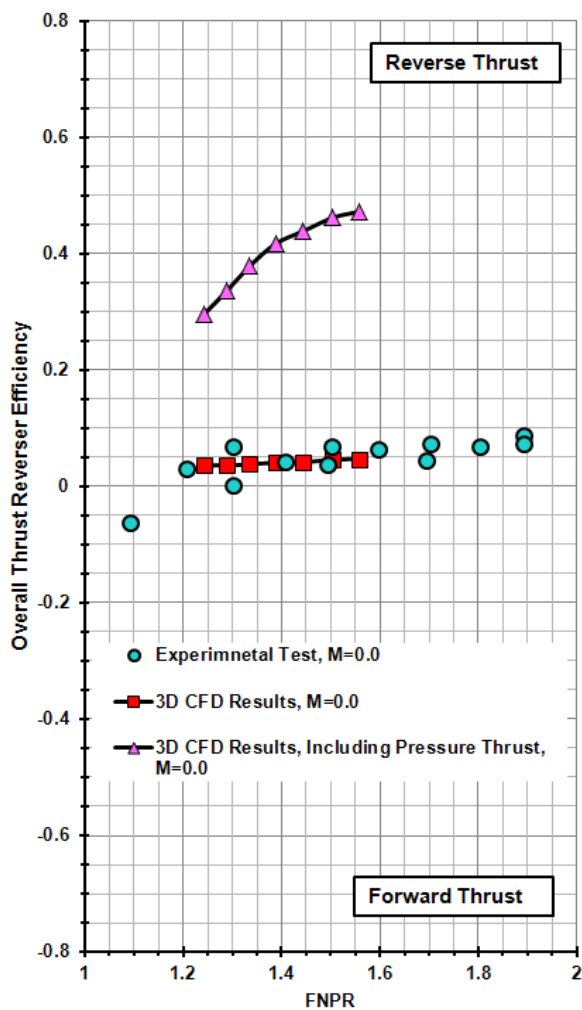


Figure 7.52: Comparison between the results obtained from the 3D CFD analyses against those performed by NASA in the wind tunnel. Also, shown in the figure is the variation in reverse thrust if the pressure thrust is also accounted. (L) 40 degree core mounted target thrust reverser. (R) 40 degree core mounted target thrust reverser with Kicker Plate.

Table 7.3 :3D CFD Results for the Core Mounted Target Type Thrust Reverser at Static Conditions (M=0.0)

3D CFD Analysis - 40 Degree Core Mounted Target Type Reverser - Static Condition, M=0.0														
No	P _{fan} (KPa)	FNPR	W _{Fan} (kg/s)	F _x (kN)	F _y , (kN)	F _z , (kN)	T _{Core Gross} (N)	T _{Axial} (N)	T _{Pressure Thrust} (N)	T _{Viscous Thrust} (N)	η _{eff 1}	η _{eff 2}	η _{eff 3}	η _{eff 4}
1	125.8	1.237	481.1	1129.8	33474.0	16.9	5211.8	6341.6	57717.8	-55.3	0.296	0.007	0.037	0.296
2	130.5	1.287	523.8	973.1	39278.5	9.5	6402.2	7375.3	76318.9	-61.8	0.336	0.005	0.036	0.336
3	135.2	1.337	567.4	1277.7	45526.3	5.8	7688.3	8966.0	98473.9	-70.3	0.379	0.006	0.038	0.379
4	140.5	1.386	613.0	1644.9	52316.4	11.7	9383.8	11028.7	123772.5	-80.6	0.417	0.007	0.041	0.417
5	146.2	1.446	659.0	1538.9	60245.5	26.7	11297.4	12836.4	149695.7	-89.4	0.439	0.005	0.041	0.439
6	152.3	1.505	707.4	2884.6	65886.0	64.5	13372.5	16257.2	178431.7	-100.2	0.462	0.009	0.046	0.462
7	157.9	1.554	749.6	2649.0	73752.1	91.5	15792.2	18441.3	205237.2	-111.5	0.472	0.008	0.047	0.472

Table 7.4: 3D CFD Results for the Core Mounted Target Type Thrust Reverser with Kicker Plate at Static Conditions (M=0.0)

3D CFD Analysis - 40 Degree Core Mounted Target Type Reverser with Kicker Plate- Static Condition, M=0.0														
No	P _{fan} (KPa)	FNPR	W _{Fan} (kg/s)	F _x (kN)	F _y , (kN)	F _z , (kN)	T _{Core Gross} (N)	T _{Axial} (N)	T _{Pressure Thrust} (N)	T _{Viscous Thrust} (N)	η _{eff 1}	η _{eff 2}	η _{eff 3}	η _{eff 4}
1	120.57	1.188	306.40	622.51	14337.72	0.52	857.36	867.32	-14869.30	-31.40	0.005	0.002	-0.118	-0.114
2	125.80	1.237	458.96	1851.17	33552.74	4.10	5273.34	5290.98	73079.00	-16.16	0.011	0.020	0.380	0.447
3	130.54	1.287	502.50	2912.26	36459.08	2.63	6433.02	6454.33	95249.80	-20.80	0.015	0.017	0.419	0.496
4	135.29	1.336	511.99	2745.75	37767.08	0.35	6903.36	6923.96	98532.90	-33.90	0.013	0.018	0.377	0.449
5	140.58	1.386	612.20	2855.71	56687.42	0.10	9360.54	9381.84	148265.10	-19.10	0.011	0.024	0.503	0.594
6	146.26	1.446	668.10	3613.84	65762.02	0.28	11304.00	11327.70	184808.30	-33.60	0.013	0.025	0.545	0.658
7	152.37	1.505	711.50	4165.53	73008.67	1.45	13392.10	13417.30	208869.60	-44.60	0.013	0.026	0.545	0.667
8	157.94	1.554	728.1	5513.58	69704.08	2.37	16043.83	16071.80	239707.80	-53.97	0.016	0.027	0.552	0.700

7.16 Results and Discussion for the Forward Thrust Configuration at Landing Conditions, (M=0.211)

This section discusses the results from the 3D CFD analysis for the forward thrust configuration at landing conditions (M=0.211). The reason for performing the CFD analyses at landing conditions is because it represents a realistic scenario and provides an insight into the reverser performance and aerodynamics at actual landing speed of 140 knots.

The results for the forward thrust configuration at (M=0.211) are important because the reverser performance for the same FNPRs can be compared against it. The results from the 3D CFD analyses at forward thrust conditions are shown in the [Table 7.5] below. An important feature that is taken into account for the analyses at landing conditions is the momentum drag, which is dependent on the engine mass flow.

Table 7.5: Shows the Results from the 3D CFD Analyses for the Forward Thrust Configuration at Landing Conditions (M=0.211)

3D CFD Analysis – Forward Thrust - M=0.211								
No	P _{fan Outlet} (KPa)	FNPR	W _{Fan outlet} (kg/s)	T _{Fan Gross} (N)	T _{Core Gross} (N)	T _{Gross Total} (N)	D _{Momentum} (N)	T _{Net Thrust} (N)
1	129.40	1.28	865.40	177233.92	10188.33	187422.25	66978.20	120444.06
2	134.42	1.33	928.80	205171.92	13008.80	218180.72	72085.44	146095.28
3	139.36	1.38	986.70	232269.18	15830.34	248099.52	76719.30	171380.22
4	144.81	1.43	1045.10	261065.98	18980.00	280045.98	81396.00	198649.98
5	150.70	1.49	1103.00	290971.40	22766.94	313738.34	86079.84	227658.50
6	157.12	1.55	1163.00	322965.10	27083.55	350048.65	90927.90	259120.75
7	163.55	1.61	1219.70	354444.82	31633.42	386078.24	95533.20	290545.04
8	169.53	1.67	1268.40	382803.12	36100.00	418903.12	99488.76	319414.36

7.17 Results and Discussion for the Core Mounted Target Type Thrust Reverser with and without kicker plate at Landing Conditions (M=0.211)

The discussion from (Section 7.15) for the core mounted target type reverser is relevant to this section as well. The major difference is that at landing conditions there will an additional term for momentum drag.

The other observation for the target type reverser without kicker plate at M=0.211, is that the pressure thrust and viscous thrust will increase considerably to what it previously was at static condition. This will have a desirable effect on the landing distance. Therefore, it can be said, that the CFD analyses at landing condition are useful to get realistic values of pressure thrust. This realistic value of pressure thrust may be important to the structural engineer from the strength and structural point of view, as well as to the performance engineer, who would more accurately predict the landing distance with an increase in the pressure thrust.

It was noted in (Section 7.15) that installation of a kicker plate improves the pressure thrust. The same was observed from the CFD results at the landing conditions (M=0.211). Comparing the target type reverser without a kicker plate at landing conditions against the reverser with kicker

plate shows that the configuration with kicker plate will be much more efficient, the results are presented in [Table 7.6 and 7.7].

Also, at the landing conditions ($M=0.211$), it is observed that the reverser exhaust for the current design do not produce any reverser thrust, instead it produces a small forward thrust. Thus, this value of F_x will be added to the core thrust.

In [Table 7.6 and 7.7] different thrust efficiencies are given. The first four are the same as previously described in (Section 7.10.2), the last efficiency, η_5 , is defined as follows:

$$\eta_5 = [\text{Pressure Thrust} + \text{Momentum Drag} + \text{Reverse Thrust}] - (\text{Core Thrust}) / (\text{Net Forward Thrust})$$

A comparison was made between the overall thrust reverser efficiency at static condition ($M=0.0$) against that at landing conditions ($M=0.211$), as shown in (Figure 7.53) for the target type reverse with kicker plate. From (Figure 7.53), there's an increase in reverser efficiency as the forward speed is increased. This is true for both the horizontal component of the reverser thrust, F_x , and for the pressure thrust. The reason for this improvement in reverser efficiency is due to the increase in propulsive efficiency, which was zero at static conditions ($M=0.0$).

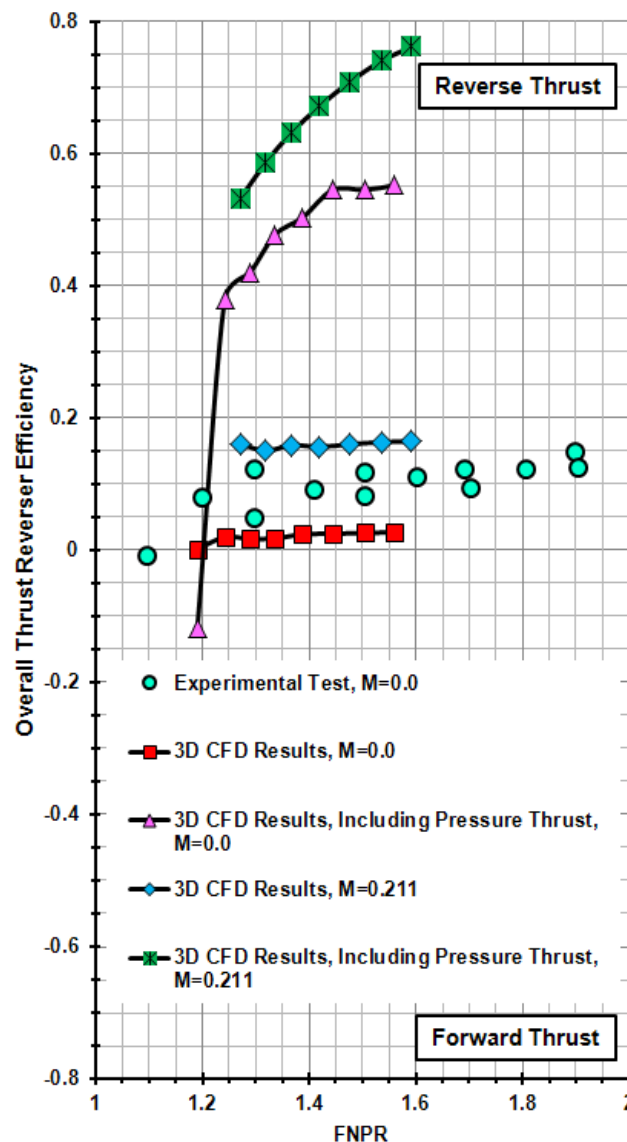


Figure 7.53: Shows a comparison of overall reverser efficiency against the FNPRs at static and forward landing conditions.

Table 7.6: 3D CFD Results for the Core Mounted Target Type Thrust Reverser at landing Conditions (M=0.211)

3D CFD Analysis - 40 Degree Core Mounted Target Type Reverser - Landing Conditions, M=0.211														
No	P _{fan} (KPa)	FNPR	W _{Fan} (kg/s)	F _x (kN)	F _y (kN)	F _z (kN)	T _{Core Gross} (N)	T _{Axial} (N)	T _{Pressure Thrust} (N)	T _{Viscous Thrust} (N)	η _{eff 1}	η _{eff 2}	η _{eff 3}	η _{eff 4}
1	128.75	1.267	498.90	408.45	39473.53	0.58	21371.92	20741.18	102471.00	-108.90	1.02	0.00	0.18	0.43
2	133.61	1.317	553.60	786.18	45784.24	0.24	25484.80	20576.77	130613.00	-124.96	1.03	0.00	0.18	0.48
3	138.43	1.366	596.30	905.27	53693.29	0.02	28845.04	20464.64	156882.00	-119.60	1.03	0.00	0.17	0.51
4	143.74	1.416	640.70	1950.48	61177.06	6.61	34710.47	17177.01	185182.40	-130.60	1.02	0.01	0.18	0.53
5	149.44	1.475	705.00	1099.21	71714.24	1.51	39794.44	17975.10	221474.80	-165.50	1.05	0.00	0.18	0.58
6	155.63	1.535	766.10	4972.48	79886.25	42.86	45373.02	13554.04	268530.10	-187.40	1.09	0.02	0.19	0.62
7	161.31	1.594	793.30	3147.89	84513.30	0.40	46319.00	16512.13	285809.80	-194.50	1.04	0.01	0.17	0.61

Table 7.7: 3D CFD Results for the Core Mounted Target Type Thrust Reverser with Kicker Plate at landing Conditions (M=0.211)

3D CFD Analysis - 40 Degree Core Mounted Target Type Reverser with Kicker Plate - Landing Conditions, M=0.211														
No	P _{fan} (KPa)	FNPR	W _{Fan} (kg/s)	F _x (kN)	F _y (kN)	F _z (kN)	T _{Core Gross} (N)	T _{Axial} (N)	T _{Pressure Thrust} (N)	T _{Viscous Thrust} (N)	η _{eff 1}	η _{eff 2}	η _{eff 3}	η _{eff 4}
1	128.75	1.267	444.40	944.35	32346.98	15.47	18399.21	94396.30	-57.47	0.94	0.005	0.161	0.400	0.532
2	133.61	1.317	490.40	1867.99	38446.77	19.32	20093.92	120434.60	-68.80	0.96	0.009	0.150	0.451	0.587
3	138.43	1.366	532.70	3279.24	43296.47	0.91	23950.08	146770.40	-74.40	0.96	0.014	0.159	0.482	0.632
4	143.74	1.416	576.80	2697.86	51100.88	68.28	28353.28	175364.70	-87.90	0.97	0.010	0.156	0.515	0.671
5	149.44	1.475	621.99	3349.55	57748.08	1.63	33129.46	206102.10	-95.60	0.98	0.012	0.160	0.540	0.708
6	155.63	1.535	668.40	4209.95	65256.85	25.54	38163.50	239316.70	-98.10	0.98	0.013	0.164	0.562	0.741
7	161.31	1.594	705.20	4838.13	70922.98	7.03	42954.92	269938.70	-107.40	0.97	0.014	0.164	0.575	0.761

7.18 Design Feasibility Study for the Core Mounted Target Type Thrust Reverser

Core mounted target type thrust reverser is an interesting concept. However, the wind tunnel tests performed by NASA showed that the current core mounted target type thrust reverser designs are not efficient.

The 3D CFD analyses performed during this research were similar designs that were tested by NASA. The CFD analyses shows similar results to experiments and it can be concluded that the core mounted target type reverser designs tested were not very efficient. In fact, it would be correct to say, that no noticeable reverser thrust was observed at all from any of the reverser designs.

Now the challenge is to improve the core mounted target type reverser design such that the reverser performance can be improved along with satisfying the mass flow compatibility criteria.

It was decided to study the core mounted target type reverser designs in greater detail.

There are certain constraints with the current core mounted reverser design. It would be wise to look at the geometry at this stage. Figure, shows the current thrust reverser design. The main challenge with the current reverser design is that there is a limited space available on the core external surface, this is shown in (Figure 7.44) below. Therefore, the amount of the effective reverser flow area that can be set for a given target angle is limited by the length of the core cowl downstream of the fan exit.

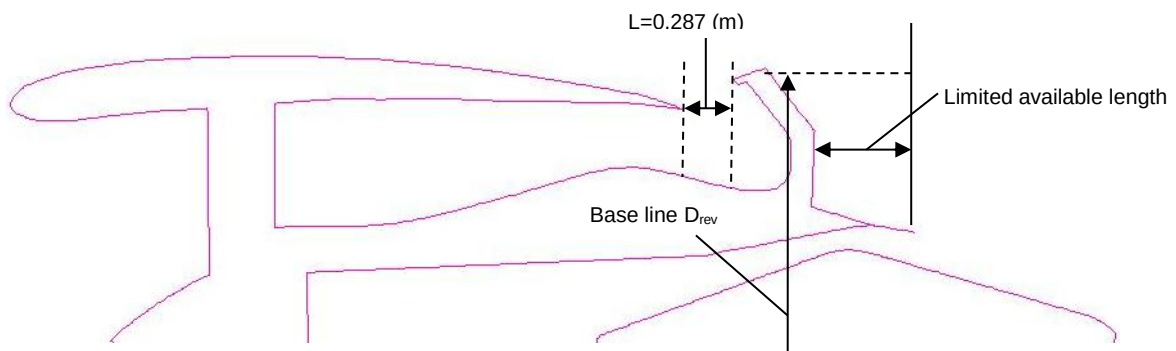


Figure 7.54: Shows a 2D axisymmetric design of a core mounted target type thrust reverser.

The two parameters that can be varied in the core mounted target type thrust reverser design are the reverser length, L , which is the distance between the fan nozzle exit and the reverser exit plane, as shown in the (Figure7.55). The other is reverser diameter, D_{rev} . These two parameters will be varied in this study; the variation in these two parameters will affect the reverser exit area.

It was decided to configure different designs for the core mounted target type thrust reversers. In light of this approximately 30 different reverser designs were generated for the 2D CFD study. The initial reverser diameter for the base line case was, $D_{rev} = 1.869$ (m). The other reverser diameters tested during this study were, 1.954 (m), 2.117 (m), 2.280 (m) and 2.443 (m). For every reverser diameter, the reverser aft length, L , was also varied from the initial length of 0.287 (m) to 0.437 (m), 0.587 (m), 0.737 (m), 0.887 (m) and 1.037 (m). Table 7.7, shows all the results.

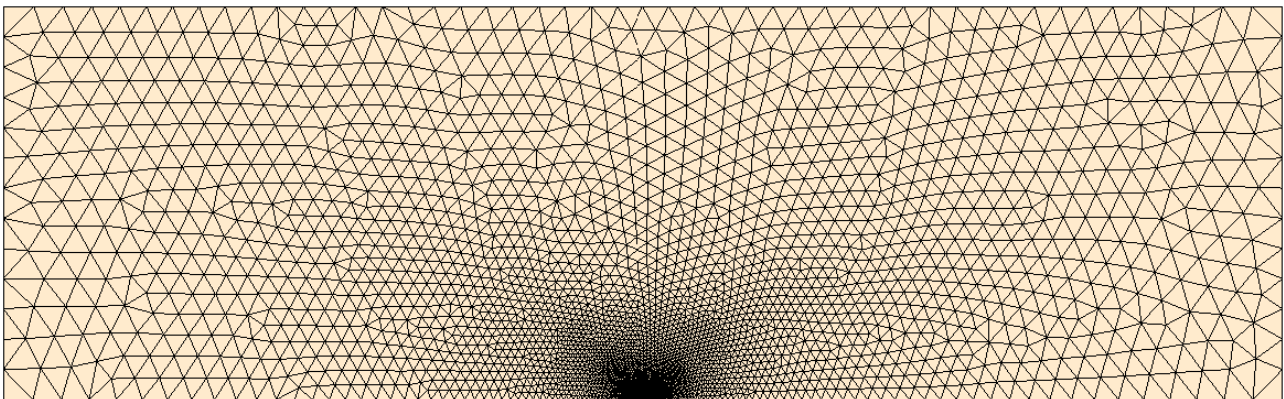
7.18.1 A 2D CFD Study for Forward Thrust at (M=0.211)

To obtain the reverser performance for the various thrust reverser designs a base line case for the forward flight condition is necessary. It is against this baseline case that the performance of all the reverser designs will be assessed.

A 2D CFD study was conducted for the forward flight conditions. The results of which are presented in [Table 7.8]. The baseline case selected for this study is the forward thrust configuration at fan outlet pressure of 159KPa. The 2D mesh for the forward thrust configuration is shown in (Figure 7.55). The baseline case is highlighted in green.

Table 7.8:Shows the 2D CFD results for the forward flight condition (M=0.211) at different FNPRs.

NO	Fan Pressure (KPa)	Fan Mass flow (kg/sec)	Fan Gross Thrust (N)	Core Gross Thrust (N)	Total Gross Thrust (N)	Momentum Drag (N)	Total Net Thrust (N)
1	116	699.92	107157.75	3600.22	110757.97	53215.85	57542.12
2	123	832.53	152436.24	5214.79	157651.03	63391.06	94259.97
3	128	977.78	198391.56	6636.74	205028.30	74254.57	130773.73
4	133	982.95	215167.76	8204.46	223372.22	75052.11	148320.11
5	138	1043.7	242973.36	9804.90	252778.26	79768.08	173010.18
6	143	1105.5	272616.30	11992.20	284608.50	84573.30	200035.20
7	149	1166.9	303394.00	15152.83	318546.83	89364.24	229182.59
8	155	1229	335762.80	16100.70	351863.50	94190.88	257672.62
9	159	1264	355816.00	25393.60	381209.60	96989.76	284219.84
10	161	1284	366838.80	18843.12	385681.92	98591.26	287090.66



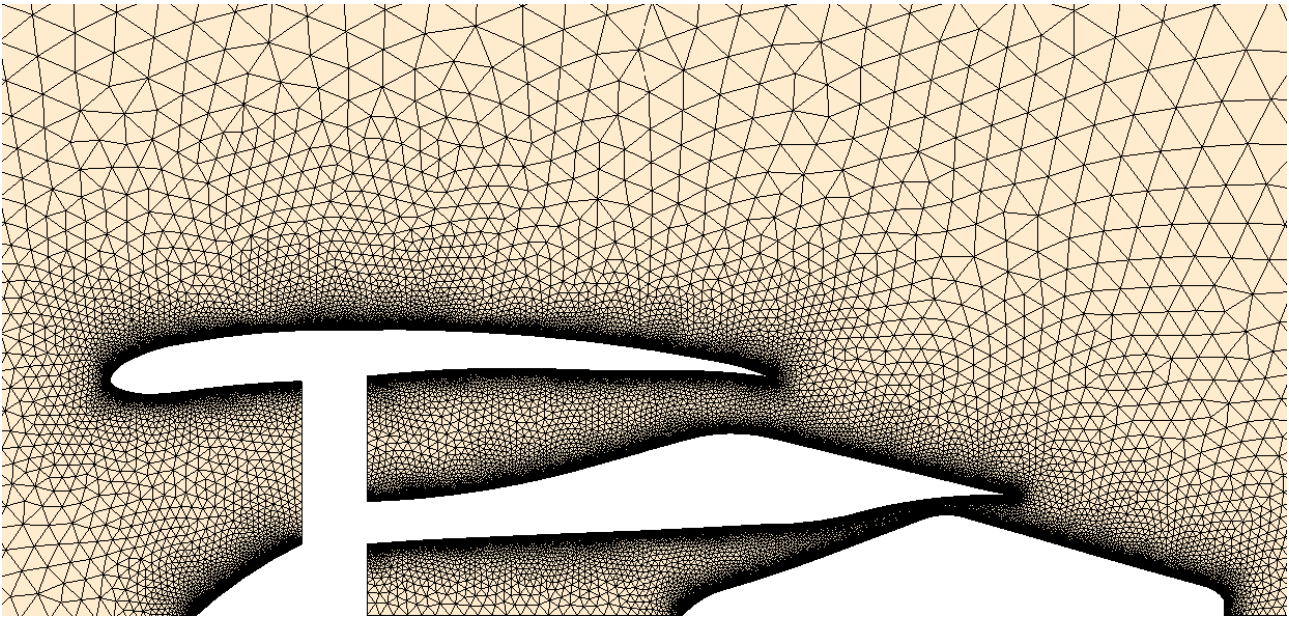


Figure 7.55: Shows the 2D mesh for the forward thrust configuration.

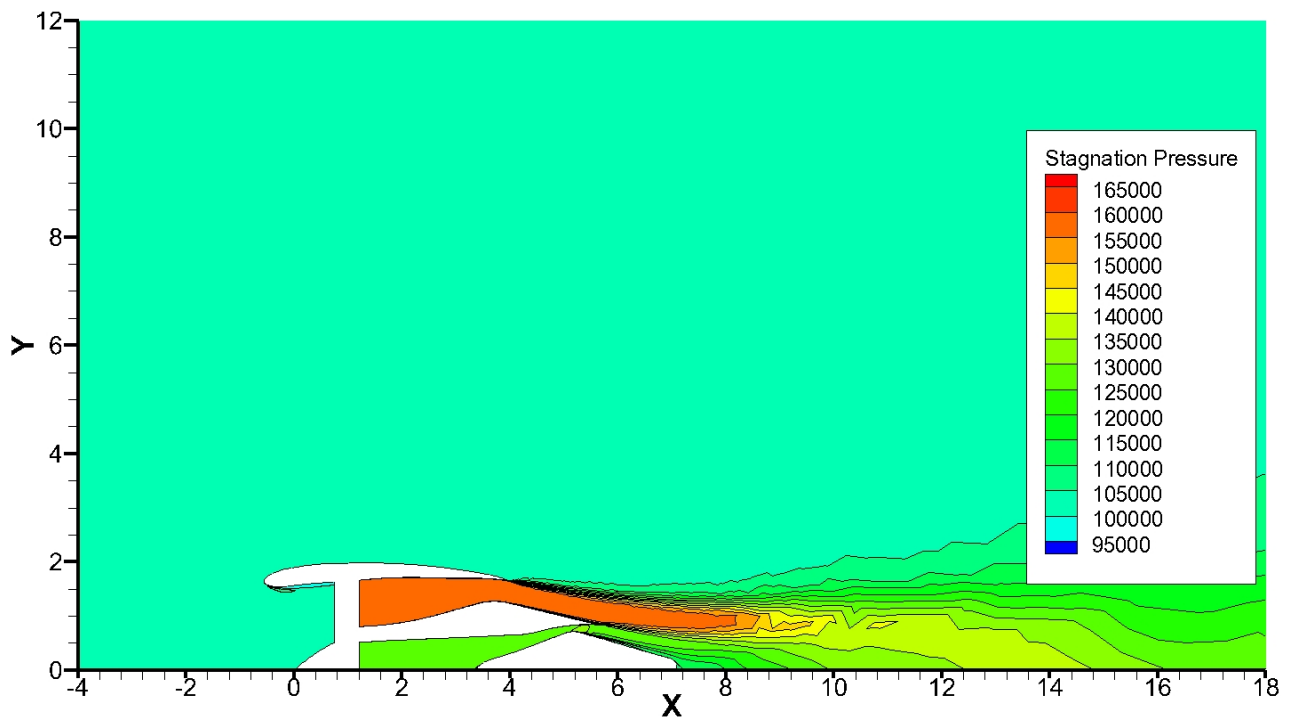


Figure 7.56: Shows total pressure contours for the baseline configuration.

7.18.2 A 2D CFD Study for Core Mounted Target Type Thrust Reverser at ($M=0.211$)

All the reverser designs were built in CATIA V5. The geometries were then meshed using the unstructured grid. Centaur software was used for all the 2D unstructured meshing. The size of the domain i.e. the width and the height were similar to the 3D case. A grid dependency study was also carried out, and it was found that approximately 400,000 elements would be satisfactory to capture the required flow physics. Approximately, 10 boundary layer nodes were used. A typical

2D mesh is shown in (Figure 7.57), streamline plot for baseline reverser design is presented in (Figure 7.58), this reverser design is similar to the one tested during 3D analysis. The detailed mesh and streamline plots for all the other configurations are given in the (Appendix A6).

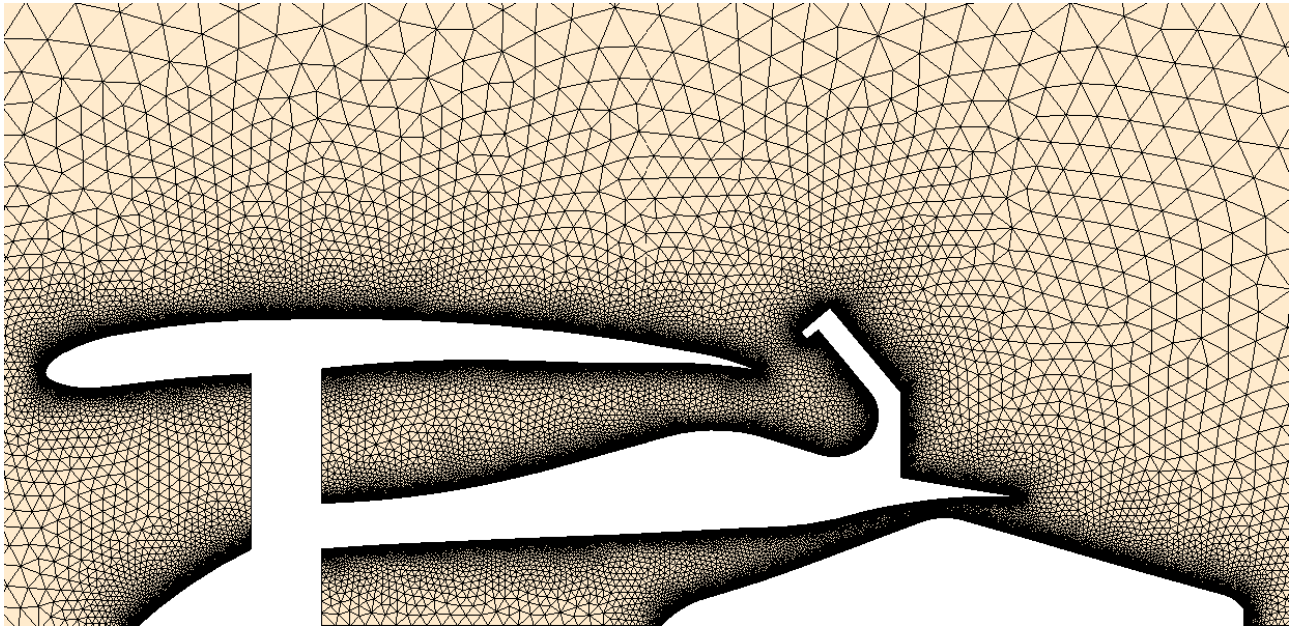


Figure 7.57: Shows a typical 2D unstructured mesh used for the CFD simulations.

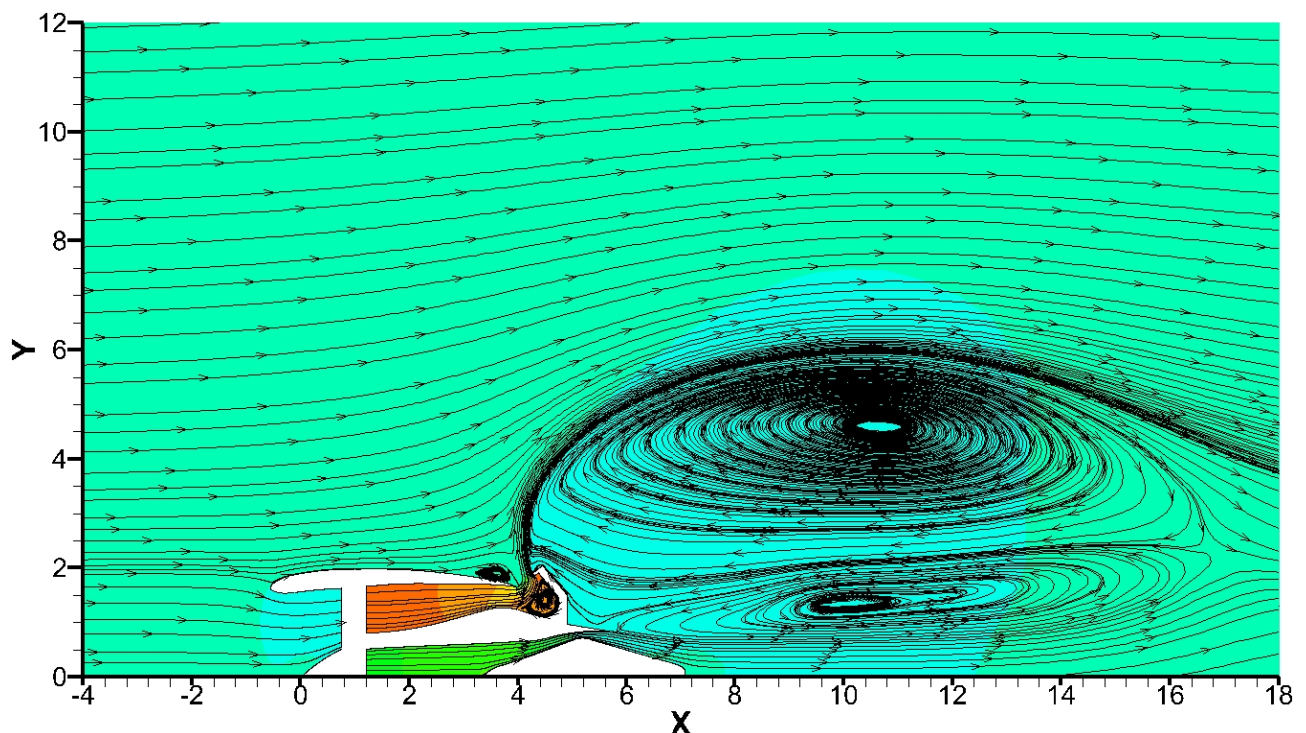


Figure 7.58: Shows a 2D streamline plot for the baseline configuration.

It is important to note that the three key parameters that define the suitability of the core mounted target type thrust reverser are the following:

- Capability to generate sufficient reverser thrust
- Satisfy the mass flow compatibility
- The reverser design should also maintain a satisfactory the runway clearance.

Table 7.9, also shows the suitability criterion for the various thrust reverser designs.

From the 2D CFD results, the designs which achieved reverse thrust are highlighted in green in as shown in [Table 7.9]. It can be observed from [Table 7.9] that although some reverser designs satisfied the mass flow compatibility, they failed to produce reverse thrust. Likewise, some reverser designs that generated reverser thrust failed to satisfy the mass flow compatibility.

Also, the core mounted target type thrust reverser should maintain satisfactory runway clearance. Table 7.9, shows that some thrust reverser configurations satisfy the first two criteria of mass flow and reverse thrust but failed to maintain the necessary runway clearance. In [Table 7.9], all three parameters of suitability criteria are included for comparison. A satisfactory design should satisfy all three.

In Table 7.9, η_1 , η_2 , η_3 are defined as follows:

$$\eta_1 = F_A / F_{\text{Total}},$$

where

$$F_A = (\text{Reverser Thrust, } F_x + \text{Pressure Thrust} + \text{Momentum Drag} - \text{Core thrust})$$

$$F_{\text{Total}} = \text{Net Thrust of the forward thrust configuration.}$$

$$\eta_2 = (\text{Pressure Thrust} + \text{Reverser Thrust, } F_x) / (\text{Fan gross thrust at forward thrust configuration})$$

$$\eta_3 = (\text{Reverser Thrust, } F_x) / (\text{Fan gross thrust at forward thrust configuration})$$

The 2D CFD analyses also proves that the core mounted thrust reverser configuration previously tested by NASA at $D_{rev}=1.869$ failed to produce any reverse thrust.

The results from other configurations show that the fan outlet mass flow is directly proportional to the reverser diameter, D_{rev} , and the axial distance, L , which is defined as the distance between the fan nozzle and the reverser exit.

At $D_{rev}=1.869$, mass flow compatibility was achieved with configuration 5, but, this configuration failed to produce any reverse thrust. Table 7.9, shows that although the reverser design and location for configuration 5 is not generating any reverse thrust; the pressure thrust generated due to the reverser deployment is significant and may be sufficient to decelerate the aircraft. The overall efficiency, η_{overall} , is close to 0.39.

Configuration 6 and 7 produces reverse thrust but failed to meet the criteria for mass flow compatibility.

Configuration 11, do not produce any reverse thrust but similar to configuration 5, therefore, utilisation of pressure thrust may make it suitable.

Configurations 12 to 15, satisfies the reverse thrust criteria, but failed to meet the mass flow compatibility condition.

Configuration 17 is similar to configuration 5 and 11, but may have constraints due to unsatisfactory thrust reverser clearance with the runway.

Configurations 18 to 22 satisfy the reverse thrust conditions but failed to meet the mass flow compatibility. Also, this reverser will be close to the runway surface.

Configuration 23 satisfies both the reverse thrust and mass flow compatibilities but the runway clearance is unsatisfactory.

Configuration 24 to 27 satisfies the reverser thrust criteria, but failed with mass flow compatibility and the requirement for sufficient ground clearance.

Configuration 28 satisfies the reverse thrust and mass flow criteria but failed with on the basis of insufficient runway clearance.

Table 7.9: Compares the performance of various thrust reversers

Design Feasibility Study for Core Mounted Target Thrust Reverser with Kicker Plate											
Config	Drev (m)	L(m)	Rev Area (m ²)	F _x (N)	F _y (N)	η_1	η_2	η_3	Reverse Thrust Achieved	Mass flow Target	Runway Clearance
1	1.869	0.437	5.486	4119.88	116629.16	1.15	0.83	0.01	X	X	X
2	1.869	0.587	6.975	18242.31	115098.54	0.86	0.57	0.05	X	X	X
3	1.869	0.737	8.524	39923.06	107282.26	0.63	0.37	0.11	X	X	X
4	1.869	0.887	10.103	56394.64	96243.62	0.50	0.25	0.16	X	X	X
5	1.869	1.037	11.710	58635.88	87447.72	0.39	0.15	0.16	X	Y	Y
6	1.954	0.287	4.889	10072.98	86626.07	1.42	1.33	0.03	Y	X	Y
7	1.954	0.437	6.144	222.64	107549.36	1.32	1.20	0.00	Y	X	Y
8	1.954	0.587	7.560	2990.39	112905.23	1.14	0.99	0.01	X	X	X
9	1.954	0.737	9.073	13398.55	111394.52	1.02	0.85	0.04	X	X	X
10	1.954	0.887	10.639	13692.45	100469.97	0.90	0.72	0.04	X	X	X
11	1.954	1.037	12.238	30275.58	92724.11	0.72	0.52	0.09	X	Y	Y
12	2.117	0.287	6.695	38005.40	48503.58	1.84	1.38	0.11	Y	X	X
13	2.117	0.437	7.716	15580.76	77699.24	1.61	1.18	0.04	Y	X	X
14	2.117	0.587	8.990	4505.94	89690.72	1.42	1.01	0.01	Y	X	X
15	2.117	0.737	10.408	213.23	95130.98	0.83	0.80	0.00	Y	X	X
16	2.117	0.887	11.922	584.20	93715.78	1.08	0.71	0.00	X	X	X
17	2.117	1.037	13.493	9062.78	91537.77	1.02	0.61	0.03	X	Y	X
18	2.280	0.287	8.743	59706.52	19522.56	2.19	1.64	0.17	Y	X	X
19	2.280	0.437	9.635	39988.98	42804.71	1.94	1.43	0.11	Y	X	X
20	2.280	0.587	10.770	22609.83	56574.47	1.69	1.22	0.06	Y	X	X
21	2.280	0.737	12.081	9823.35	72298.22	1.50	1.06	0.03	Y	X	X
22	2.280	0.887	13.516	3962.74	75295.21	1.31	0.90	0.01	Y	X	X
23	2.280	1.037	15.041	300.04	78562.50	0.55	0.28	0.00	Y	Y	X
24	2.443	0.287	11.046	68958.24	7625.13	2.25	1.67	0.19	Y	X	X
25	2.443	0.437	11.824	58646.37	17284.46	2.26	1.67	0.16	Y	X	X
26	2.443	0.587	12.843	42374.56	33882.07	2.00	1.46	0.12	Y	X	X
27	2.443	0.737	14.052	25451.89	47820.64	1.74	1.24	0.07	Y	X	X
28	2.443	0.887	15.404	14590.99	56422.42	1.49	1.03	0.04	Y	Y	X

Considering the results from the 2D CFD analyses, it can be concluded that the core mounted target type thrust reverser configuration has compatibility issues. The 2D CFD results show that for the shorter diameter reversers designs the reverse thrust is difficult to achieve. The mass flow compatibility can be satisfied for certain configurations but the thrust reverser will be at its maximum aft limit. Also, this installation may have mechanical or installation problems.

Increasing the reverser diameter increases the reverse thrust. When the mass flow compatibility is satisfied with larger reverser diameter, the runway clearance requirement becomes difficult to fulfil.

Thus, in light of the above discussion, it can be concluded that the core mounted target type thrust reverse concept may not be a compatible design and it be said that this design has failed to meet the requirements of thrust reverser.

Chapter 8 A Novel Hybrid Thrust Reverser Design

It was established in the previous chapter that the current core mounted target type thrust reverser designs are not feasible. Therefore, a new approach to the core mounted target type thrust reverser configuration is desired, as a prerequisite the following should be satisfied:

1. Reverse thrust – the thrust reverser must be capable to divert the flow in the direction such that the reverse thrust is created.
2. Mass flow compatibility – the thrust reverser design must be such that on deployment, the engine should pass the same amount of mass flow as it would have in the forward thrust configuration. This ensures that there will be minimal effect on engine performance.
3. Runway clearance – once fully deployed, the thrust reverser diameter must maintain satisfactory runway clearance.

In conjunction with the above requirements, several novel core mounted thrust reverser designs are proposed. A detailed 2D CFD study was performed for the aforementioned novel thrust reverser concepts.

Some of the designs conceived and investigated during the course of this research are highlighted below:

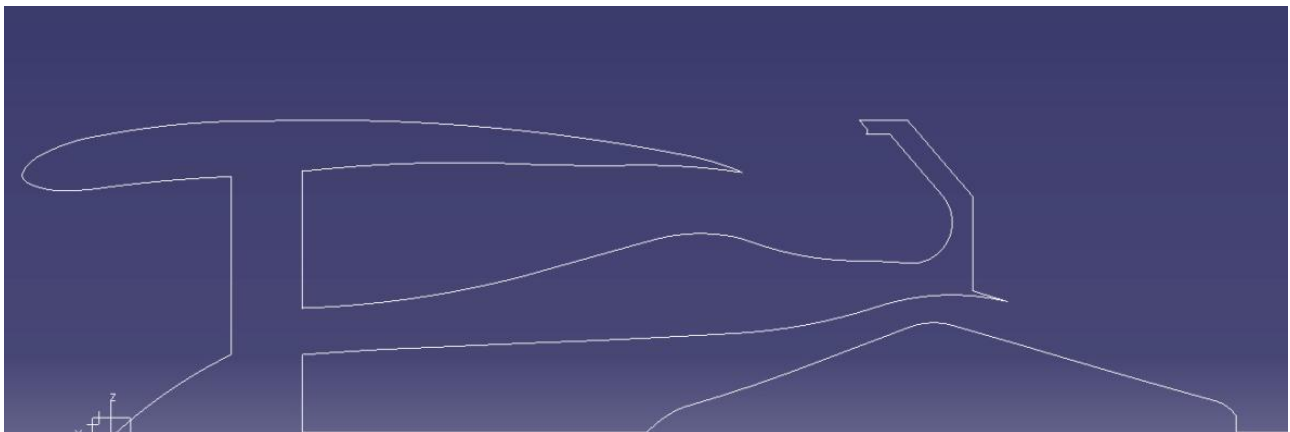


Figure 8.1: An integrated cascade vane on a kicker plate reverser



Figure 8.2: An Integrated cascade on kicker plate and an installed cascade vane reverser.



Figure 8.3: A single vane and a blocker door type reverser configuration.

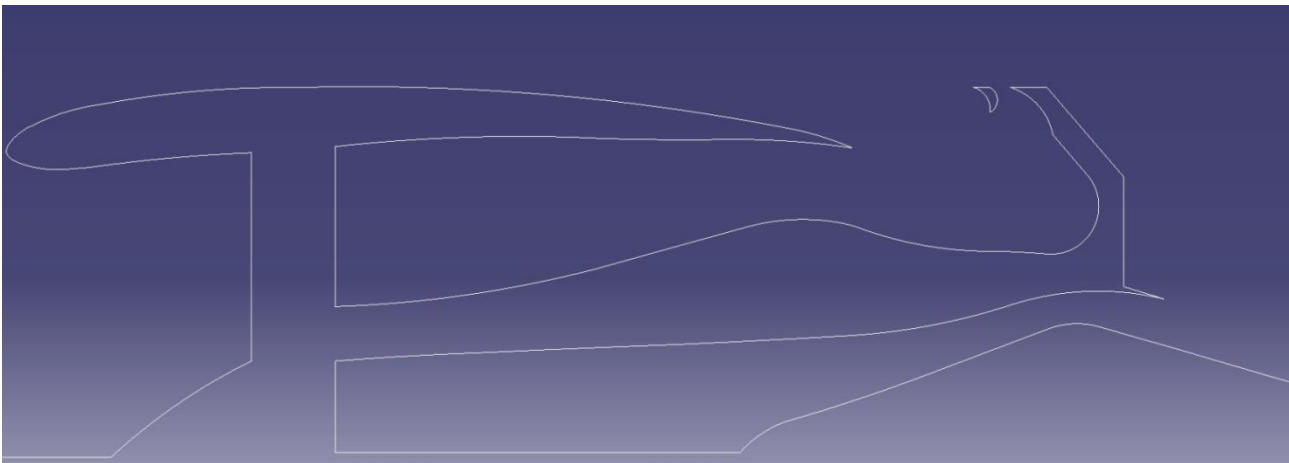


Figure 8.4: A single vane, Target Type Hybrid Reverser.



Figure 8.5: Two vanes Target Type Hybrid Reverser.

2D CFD analyses were performed for all the designs. However, the CFD results are only presented for the last configuration (Figure 8.5).

It was investigated in the previous chapter that when mass flow and reverse thrust criteria is satisfied, the reverser diameter becomes unacceptably high.

Thus, it was decided to look for a completely new reverser design. The new core mounted reverser design should have an acceptable diameter; therefore, the reverser diameter was fixed to an acceptable height of 1.954 m. This height was chosen, as it satisfies the runway clearance requirements.

The other parameter which affects the reverse thrust and mass flow compatibility is the length between the nozzle exit plane and the reverser diameter. A reverser utilising the entire external core surface will not be suitable as it will create mechanical and installation problems. Thus, this distance was fixed at 0.737 m from the fan nozzle exit plane. This distance was arbitrarily chosen based on the CFD study carried out in (Section), however, this can be optimised as mentioned as a future work (Chapter 10).

The steps that follow define how the mass flow and reverse thrust criteria have been satisfied.

Initially it was decided to remove the kicker plate and instead install a cascade vane on the inner side of the reverser as shown in (Figure 8.1). It was thought that removing the kicker plate would increase the reverser exit area and the installation of a vane would help in deflecting the flow. However, an increase in mass flow was observed, but the vane failed to divert the flow, and no reverse thrust was generated.

In the second step an additional cascade vane is installed (Figure 8.2). This cascade vane is similar to that used on a typical conventional cascade type reverser. It was thought, that this will help to guide the flow. From the CFD analyses it was observed that the installation of a cascade vane has provided a favourable flow surface and an increase in mass flow was observed. However, the vane failed to produce any reverse thrust.

In the third step the cascade vane was replaced with a new vane, this vane is thinner at the blade root and thicker at the blade tip. The installation of the vane split the reverser exit domain into two domains of different areas. The vane shape created a divergent convergent passage. From the CFD analyses it was observed that mass flow has increased even further, and for the first time it was observed that the design is generating a reverse thrust along with an increase in mass flow.

However, as the mass flow compatibility was still not fully matched it was decided to increase the reverser area further, and one of the other ways of increasing the reverser area is to make the target door thinner. Thus, a curvature was formed, the formation of the curvature on the inner side of the door helps in flow turning and it also provides an additional effective area. The author believes that this reverse design could be a feasible concept.

Finally, to increase the mass flow further, a second vane was installed. This design helps in achieving the mass flow compatibility target, and it was observed that all the three effective areas produce reverse thrust. This design was named as novel vane target type hybrid reverser (VTTHR).

The rest of the discussion in this chapter elaborates on the VTTHR concept.

8.1 Target Type Hybrid Reverser

The VTTHR fulfils all the required core mounted reverser design criteria which the other designs failed to satisfy. These include the following:

- I. It can be easily stowed and deployed.
- II. This concept will work with both the single cascade and the double cascade vanes. However, the double cascade design will be more effective, in terms of meeting the mass flow compatibility, and achieving the required reverser thrust.
- III. This concept satisfies the compatibility of mass flow.
- IV. This concept satisfies the reverse thrust requirement.
- V. This concept will also have a very high value for pressure thrust, which will be beneficial to decelerate the aircraft.
- VI. The diameter of this reverser concept is compatible, and thus will not cause any issues with the runway clearance.

As per the data available in the public domain, the author believes, that no such reverser design exists, where the target thrust reverser takes advantages of the cascade vanes. At present all the target and pivoting door type thrust reversers are installed mainly with kicker plates.

The VTTHR concept can be a contender for future high bypass ratio turbofan engines. Especially, if the future thrust reverser designs look for new reverser concepts such as the core mounted thrust reverser.

It was investigated from the CFD study that the installation of cascade vanes can help to reduce the required reverser diameter. Therefore, this concept can also benefit both the core mounted as well as other target and pivoting door type thrust reversers. A smaller reverser diameter means less weight, also a lighter reverser will require less stringent power requirements from the actuation and control systems.

Also, from the 3D CFD analyses and the design feasibility study carried out in the previous chapters, it can be concluded that the VTTHR seems to be the only design that can work as a core mounted target type thrust reverser.

At present only a preliminary study has been performed. This design requires further research. The author believes that this design can further be improved by finding the optimum position along the available space on the core external surface. Also, the performance of the cascade vanes can be improved by finding the optimum blade geometries.

The advantages of using the VTTHR concepts are as follows:

- The VTTHR concept utilises the pre-installed external core surfaces together with one or two cascade vanes. Therefore, with this concept there is a potential of weight savings.
- The VTTHR generates both reverser thrust as well as the pressure thrust. The reverser efficiency is approximately 0.22, but together with the pressure thrust the combined

efficiency of this concept is more than twice that of a conventional cascade type reverser. The current cascade type thrust reversers on large high bypass ratio turbofan engines have a reverser efficiency of approximately 0.4. Therefore, the VTTHR offers far superior reverser efficiency.

- High aircraft deceleration could be achieved with VTTHR concepts; this would benefit the aircraft auto brake system (ABS) as less brake pressure would be required. Therefore, VTTHR offers a potential that aircraft brakes life may be extended as low brake pressure would be required.
- The VTTHR concept offers very high reverser efficiency; this means a decrease in aircraft landing distances. This would be beneficial to air traffic controllers and/or airport management as larger volume of flights could be catered for.

The results from the 2D CFD analyses are presented below in [Table 8.1] for the two vane target type hybrid reverser.

Table 8.1: Results for the Two Vane Target Type Hybrid Reverser

Two Vane Target Type Hybrid Reverser												
No	Drev (m)	L(m)	R Area (m ²)	F _x (N)	F _y (N)	η ₁	η ₂	η ₃	η ₄	Reverser thrust achieved	Mass flow Target	Runway Clearance
5	1.954	0.737	11.05	61471.1	112602.4	1.95	0.22	1.22	1.63	Y	Y	Y

Where;

$$\eta_1 = (\text{Reverser Thrust} + \text{Pressure Thrust} + \text{Momentum Drag} - \text{Core Thrust}) / (F_{\text{Total, fwd flight, Net Thrust}})$$

$$\eta_2 = (\text{Fan Reverser Thrust Only}) / (F_{\text{Total, fwd flight, Net Thrust}})$$

$$\eta_3 = (\text{Pressure thrust} + \text{Reverser Axial}) / (F_{\text{Total, fwd flight, Gross Thrust}})$$

$$\eta_4 = (\text{Pressure thrust} + \text{Reverser Axial}) / (\text{Fan}_{\text{fwd flight, Net Thrust}})$$

Streamline plots for the VTTHR concept is presented in (Figure 8.6 and 8.7). The contours of total pressure, static pressure and Mach number are presented in (Figure 8.8 – 8.10). Figure 8.11, shows the unstructured mesh constructed for the VTTHR concept, approximately 12 boundary layers were used.

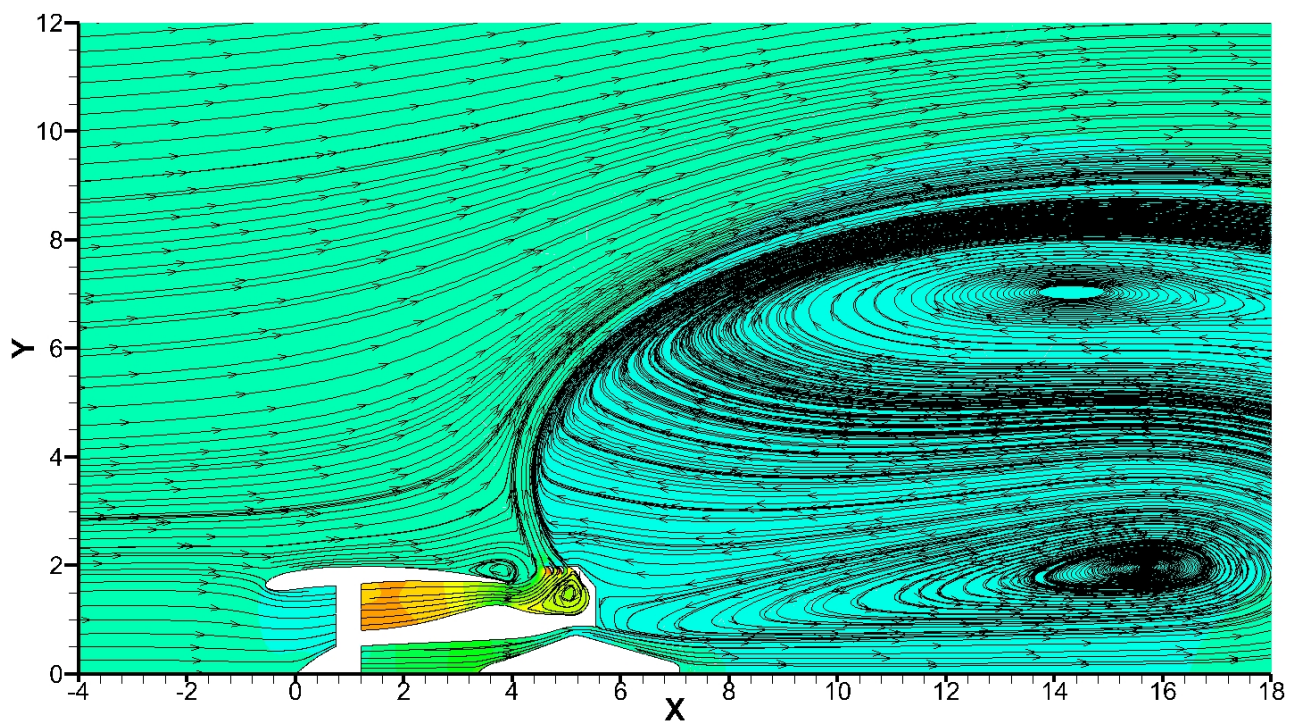


Figure 8.6: Shows the streamlines for the two vanes target type hybrid reverser.

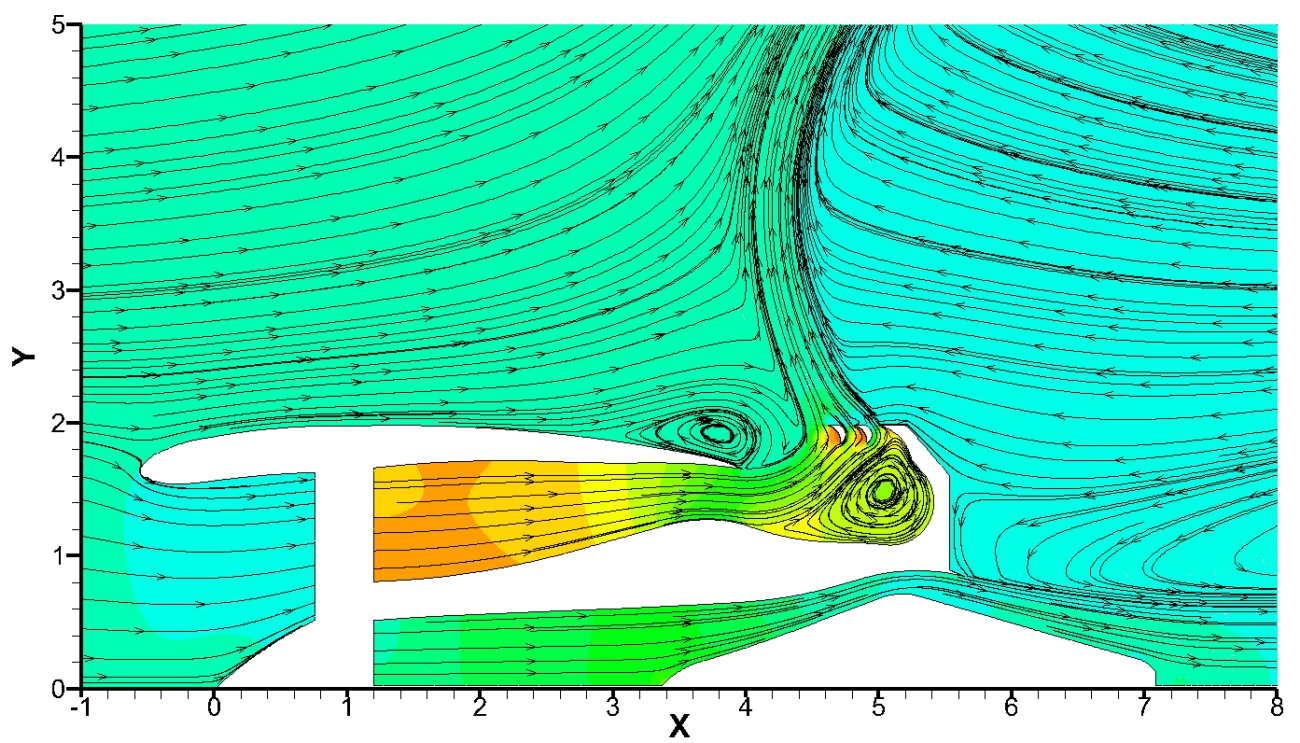


Figure 8.7: A close view of the two vanes target type hybrid reverser.

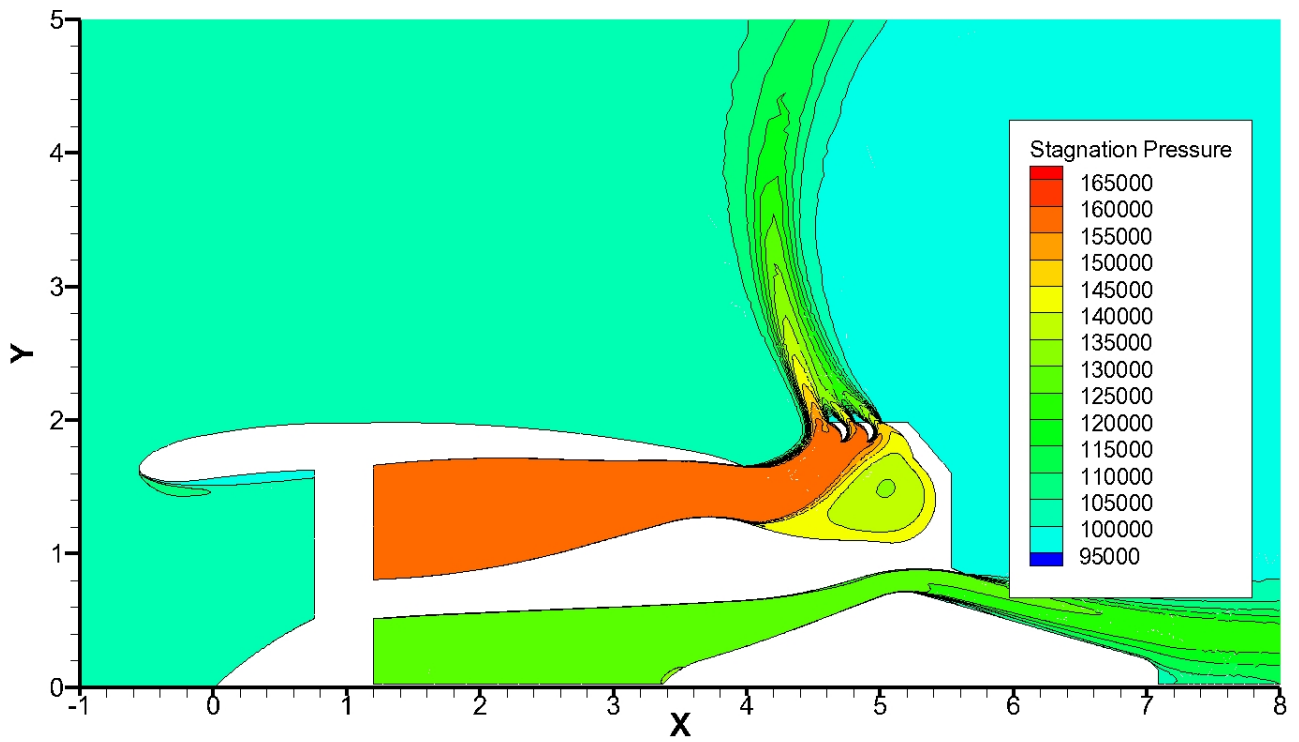


Figure 8.8: Contour plot of total pressure for the two vane hybrid reverser.

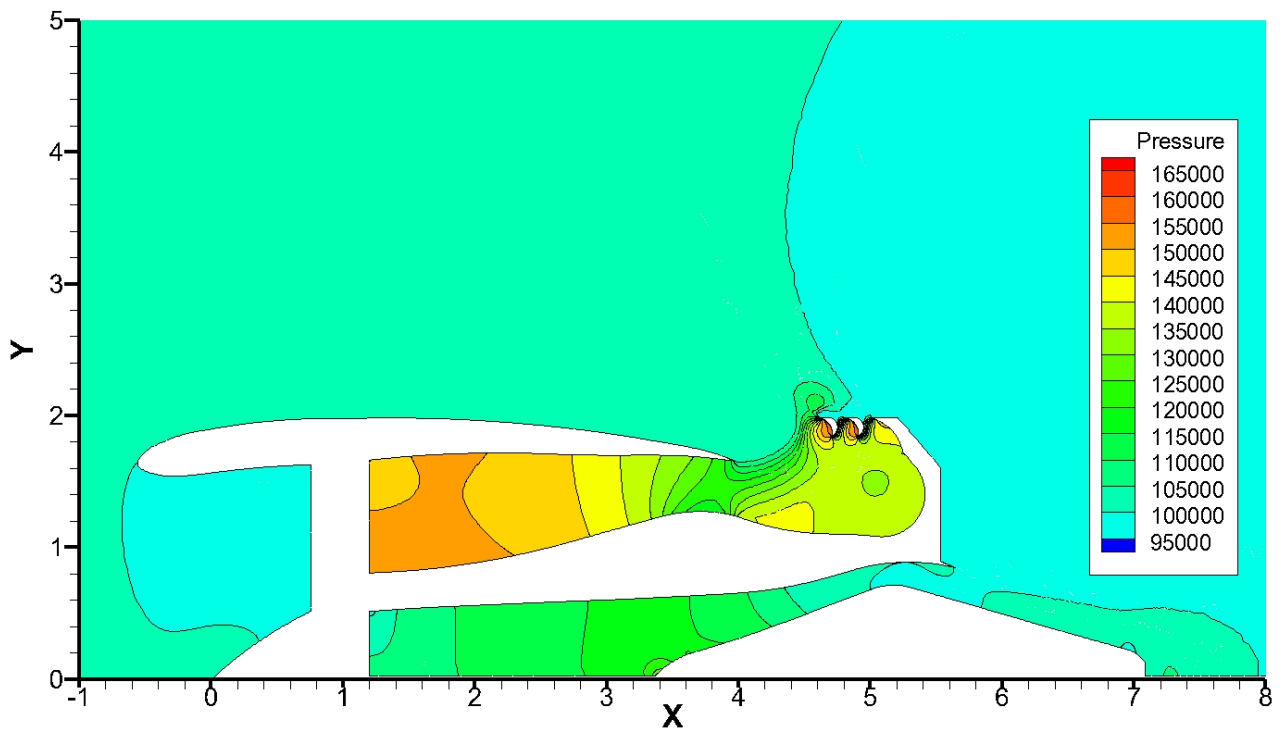


Figure 8.9: Contour plot of static pressure for the two vane hybrid reverser.

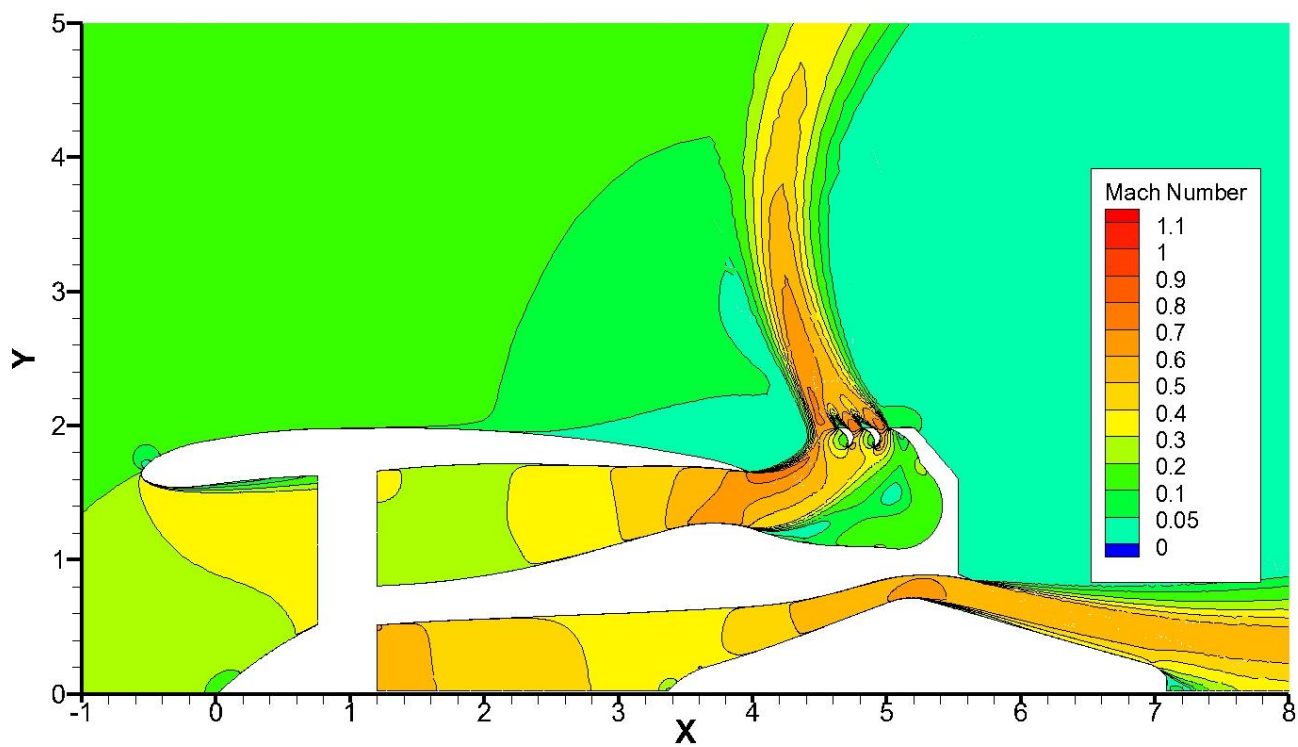


Figure 8.10: Contour plot of Mach no for a two vane hybrid reverser.

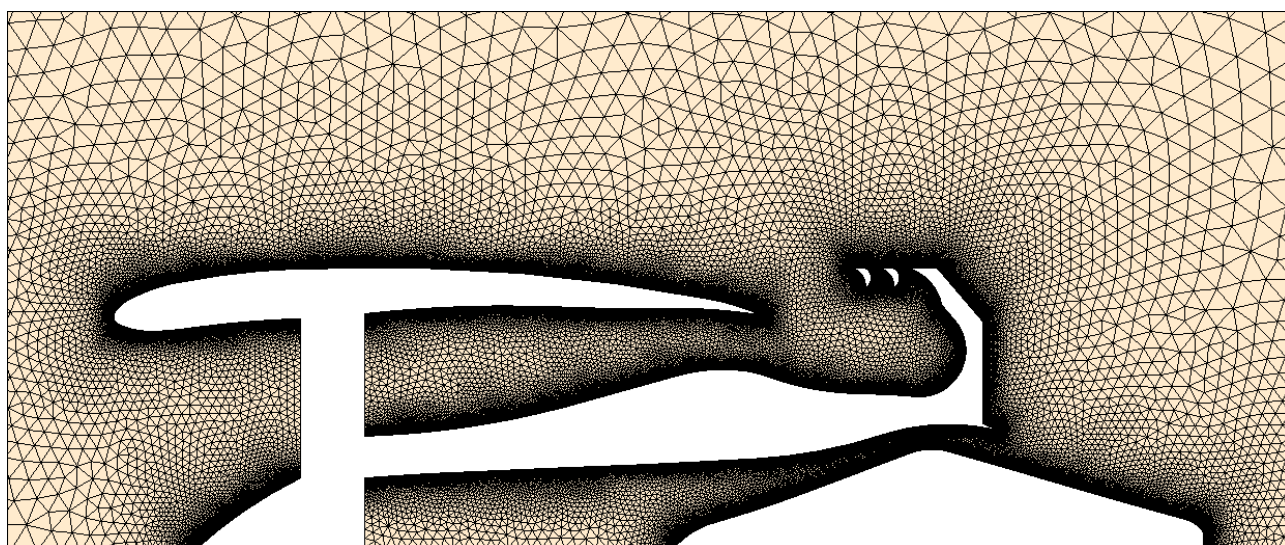


Figure 8.11: An unstructured mesh for the two vane hybrid thrust reverser.

Chapter 9 Conclusions

In order, for the core mounted target type thrust reverser configuration to work efficiently a thoroughly new approach to the reverser design was required as from the 3D and 2D CFD analyses it was concluded that conceptual designs proposed in the public domain are not feasible. In light of this a novel vane target type hybrid thrust reverser (VTTHR) concept was proposed.

The preliminary design feasibility studies for the VTTHR were performed using 2D CFD. It was established that this new thrust reverser design may offer benefits in terms of greater reverser efficiency, weight and ease of storage, relative to conventional designs. Additionally, it was demonstrated from a large number of CFD investigations that this may be the only feasible “core mounted” thrust reverser design concept for future high bypass ratio engines. However, to mature this technology further research is required.

The advantage of using the VTTHR concept is that it utilises the pre-installed external core surfaces together with one or two cascade vanes. Therefore, with this concept there is a potential of weight savings.

From the CFD analyses it was noted that the VTTHR generates both the reverse thrust as well the pressure thrust. The large diameter of the reverser design offers a very high pressure thrust value. The reverser efficiency only on the fan stream is approximately 0.22, but together with the pressure thrust, the combined efficiency of this concept is about 1.22. The current cascade type thrust reversers on large high bypass ratio turbofan engines have an efficiency of approximately 0.4. Therefore, the VTTHR offers far superior reverser efficiency. This would be beneficial in terms of providing quicker and shorter landing distances. This will be beneficial to airlines as high reverser efficiency would also benefit the aircraft auto brake system (ABS), as less brake pressure would be required. Therefore, aircraft brakes life may be extended as low brake pressure would be required, thus offering economic i.e. cost saving benefits to airlines.

Also, on busy airports the VTTHR could be advantageous from an operational prospective as the high reverser efficiency would shorten the landing distances; this would be a beneficial to air transport flight controllers and/or airport management as a larger volume of flights could be catered.

The use of a VTTHR reverser concept relocate reverser hardware to the core cowl, offering potential reductions in reverser and nacelle weight while allowing the nacelle lines to be optimized. Also, installation of VTTHR would benefit aircraft cruise performance, as during cruise flight there will be no losses due to flow leakage and pressure drops that normally occur across the stowed reverser hardware, thus, an improvement in s.f.c is expected.

The feasibility of the VTTHR has been demonstrated but further work is required to quantify the benefit of weight savings and efficiency relative to conventional reverser in service.

3D CFD analyses were performed on the core mounted target type reverser design at static conditions ($M=0.0$). The reverser design was similar to that tested by NASA in the wind tunnel. 3D CFD analyses showed reasonable agreement with the experiments. The CFD methods were therefore deemed to be verified. After the detailed and careful examination of the reverser internal flow it was concluded the respective reverser design lacks the required mass flow compatibility criterion and therefore was considered as non-feasible solution under simulated conditions; in addition the respective design also lacked the ability to generate sufficient reverse thrust.

3D CFD analyses were also performed at forward landing conditions ($M=0.211$). These analyses are important as they represent a more realistic scenario of aircraft landing. No wind tunnel test data was available at this condition. CFD analyses showed an improvement in reverse thrust of about 10% in comparison to static conditions; this gain is obtained mainly due to the increase in propulsive efficiency. Also, flow physics at landing conditions ($M=0.211$) were discussed, once again the flow was strictly three dimensional, however, a less disturbance to external flow field was observed at this condition.

CFD analyses also allowed an estimation of pressure thrust, which was generated mainly due to the pressure difference across the target type reverser surface. This pressure thrust will provide an additional reverse thrust; the value of the pressure thrust will be approximately 80% higher than the reverse thrust. Therefore, it was observed from the CFD study that the pressure thrust is a major contributor in this core mounted target type thrust reverser design. It was also noted from the CFD analyses that the kicker plate not only helps in guiding the flow in the reverse direction but also helps in improving the pressure thrust by approximately 25%.

Following the 3D CFD analyses, a comprehensive reverser design feasibility study was initiated to examine the optimum location for the corresponding core mounted target type thrust reverser using 2D CFD analyses. These analyses were tested against the following three criteria's i) achieve sufficient reverse thrust, ii) satisfy the mass flow compatibility and iii) maintain the satisfactory runway clearance. About 30 different designs were studied, and upon completion of the 2D CFD analyses it was established that the core mounted target type thrust reverser is not compatible with the aforementioned set criteria, and therefore is not a feasible solution.

As per the data available in the public domain, no study was available that investigated the effect of thrust reverser deployment on engine performance. Therefore, two performance studies were conducted during this research; the first study was for the separate exhaust engine and the second one was for the mixed exhaust engine.

The performance analyses were initially carried out on a separate exhaust high bypass ratio turbofan engine, an engine model similar to GE-90 94B was selected. The study highlighted the advantage of increasing the reverser effective area by 5%; it was observed that increasing the reverser exit area will be useful in obtaining additional reverse thrust and would also boost the engine surge margin, this would be advantageous at low speeds and at cross wind conditions.

A performance study was also carried out to investigate the effect of thrust reverser deployment on the performance of mixed exhaust engines. The mixed exhaust engine selected for this study was similar to RR Trent 772. It was interesting to note that during thrust reverser deployment the engine configuration changes from mixed to separate exhaust. Therefore, reverse thrust is obtained only from the fan stream. During thrust reverser deployment the core thrust will diminish due to the large area of the common nozzle. For performance analyses to be performed correctly, it was important to understand the behaviour of the core flow in the common exhaust nozzle. No information was available in the public domain, which highlights the flow behaviour in such a scenario, therefore 2D CFD analyses were performed to investigate if the core exhaust flow during the thrust reverser deployment will be attached to the exhaust plug or will expand in the common nozzle. It was established the core exhaust flow will remain attached to the exhaust plug at maximum reverser thrust condition. The results from the CFD analyses were subsequently used to set up the new engine performance model, this time as a separate exhaust engine. The separate exhaust engine off-design analyses were performed at reverse idle-thrust and maximum reverser thrust conditions. There will be two additional nozzle maps in this case, one for the reverser exhaust and the other for the core. Aircraft deceleration time of 19 seconds was calculated. It was

observed that the difference between landing at reverser idle condition and landing at maximum reverse thrust condition was approximately 522 meters.

In summary this research offers the following:

- A study of a novel vane target type hybrid reverser, it was concluded that this concept may be the only feasible 'core mounted' thrust reverse design.
- A 3D CFD analyses were performed for a core mounted target type thrust reverser at static and forward landing conditions. The reverser design was similar to that tested by NASA in the wind tunnel. CFD results showed reasonable agreement with the experiments. It was concluded that the respected reverser design lacks the requirement of mass flow compatibility and failed to produce any noticeable reverser thrust and therefore was considered as non-feasible under simulated conditions.
- A comprehensive 2D CFD study was performed to examine the optimum location for the corresponding core mounted target type thrust reverser. About 30 different designs were studied, and it was established that core mounted target type thrust reverser design may not be compatible and is therefore not a feasible solution.
- Thrust reverser deployment and its effect on aircraft and engine performance were looked at for the separate and mixed exhaust engines. For the separate exhaust engine it was observed that increase in reverser area would be beneficial to generate additional reverse thrust and also it would be helpful for landings under crosswind or where engine experience surge. For mixed exhaust engine it was observed that the during reverser deployment the engine configuration changes from mixed to separate exhaust as the reverser thrust is only on the bypass stream. Also, 2D CFD analyses were performed and it was concluded that during thrust reverser deployment the core flow will remain attached to the exhaust plug at maximum reverse thrust condition.

Chapter 10 Proposals for Future Work

The following are the proposals for future work

1. Perform transient performance calculations. Strictly speaking, thrust reverser deployment is a transient performance study. This thesis can provide a good start as the design and off-design studies are well established. The same engine performance models for separate and mixed exhaust engines can be used for the transient performance study.
2. A novel vane target type hybrid reverser (VTTHR) concept was proposed in this research. VTTHR design has a great potential as it reduces the reverser diameter, D_{rev} . Also, this is the only reverser design which has a potential to be used as a core mounted target type thrust reverser. The concept of hybrid reverser will also be applicable for both the pivoting door and target types thrust reversers. The author believes that with careful design the performance of this reverser can be improved even further, by optimizing the axial distance between the fan nozzle exit and the reverser. Also, the design of the cascade blade geometries can be further improved. Aerodynamics and finite element-stress analysis will be useful for such a study.
3. NASA performed experimental research on thrust reversers between the year 1996 and 2000, and proposed six innovative thrust reverser concepts. Core mounted target type thrust reverser (CMTTTR) design and aerodynamics studies were conducted during this research. Likewise, other thrust reverser concepts can also be looked at in the future.

From author's point of view, the thrust reverser concepts which have potential for further research are:

- I) fabric target thrust reverser
- II) multi door crocodile thrust reverser and
- III) conventional cascade type thrust reverser with porous blocker door

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APPENDICES

Appendix A1: Thrust Reverser Actuation and Control Systems

A.1 Types of Thrust Reverser Actuation Systems

Three types of thrust reverser actuation systems are in use on turbofan engines. Two of the more common ones are the hydraulic and pneumatic actuation systems. However, new turbofan engines are adapting more to electric actuation systems.

A.2 Hydraulic Actuation System

A hydraulic actuation system consists of several actuators, a control valve module and the locking devices. The actuators move the translating sleeves of the pivoting doors and are installed in the reverser structure. The hydraulic valves of the hydraulic control valve module are controlled by the reverser control system. Figure 3.1, shows components of the hydraulic actuation system of the RR IAE-V2500 reverser. The control valve module of this system is installed on the underside of the engine pylon in front of the reverser structure. The control valves are controlled by the FADEC computer. In the stowed position during the operation for the forward thrust the reverser system is depressurized. The movable parts are held in this position by mechanical locks. These locks are also components of the actuation system. They can either be separately installed or integrated into the hydraulic actuators; both designs are used in the same system.

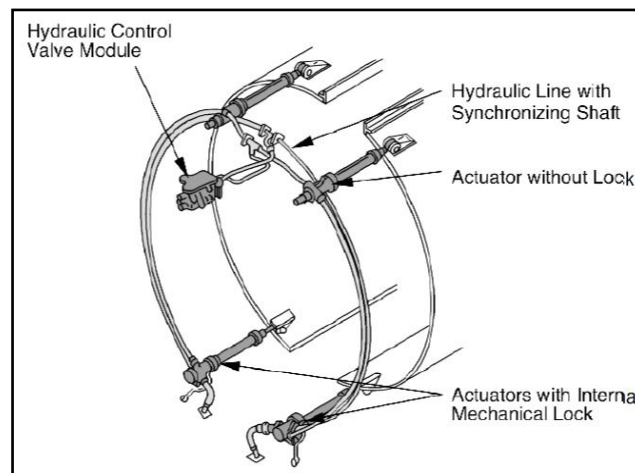
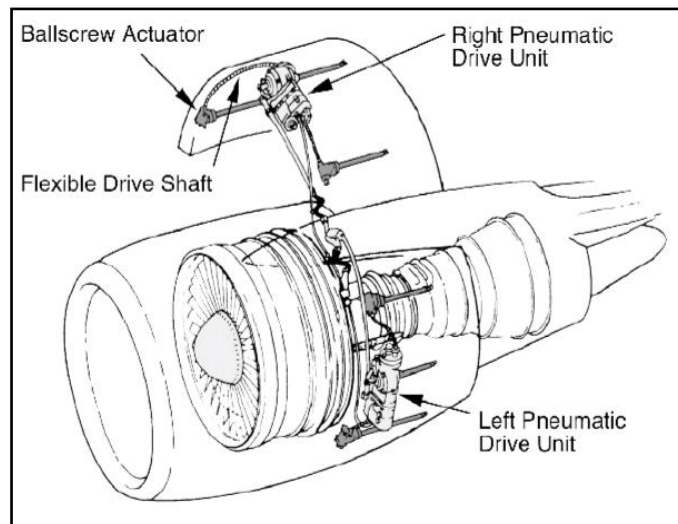


Figure A1: Shows a hydraulic actuation system for the V2500-A5 thrust reverser.

A.3 Pneumatic Actuation System

The pneumatic actuation system consists of one or two air motors driving ball screw actuators via flexible shafts. The air motors are supplied with air from the high pressure compressor of the engine. The ball screw actuators move the translating sleeves. This type of actuation system is used on cascade type thrust reversers only. For the control of this actuation system the control system operates the installed air valves for air supply and directional control. The locking function in the stowed position is achieved by a brake installed on the air motor. In most designs the air motor is integrated into one housing together with a gear, the brake and the directional control valve. Thus, these components form the pneumatic drive unit of a reverser system. Figure 3.2, shows such a system on the Airbus A300-600.



A2: Shows the components of the pneumatically operated thrust reverser for the CF6-80C2 turbofan used on the A300-600.

A4 Thrust Reverser Lever

The thrust reverser lever can be raised only when the forward thrust lever is in the idle position. An interlock stop limits thrust to idle reverse while the reverser is in transit. The interlock system also restricts the forward thrust levers from moving forward, until thrust reverser levers are fully down and the reverse sleeves are no longer in transit. The EECs control thrust limits during reverser operation. When the reverse thrust levers are pulled aft to the interlock position the auto-throttle disengages the auto-speed brakes deploy. Typical examples of the thrust reverser lever are shown in Figure 3.3.

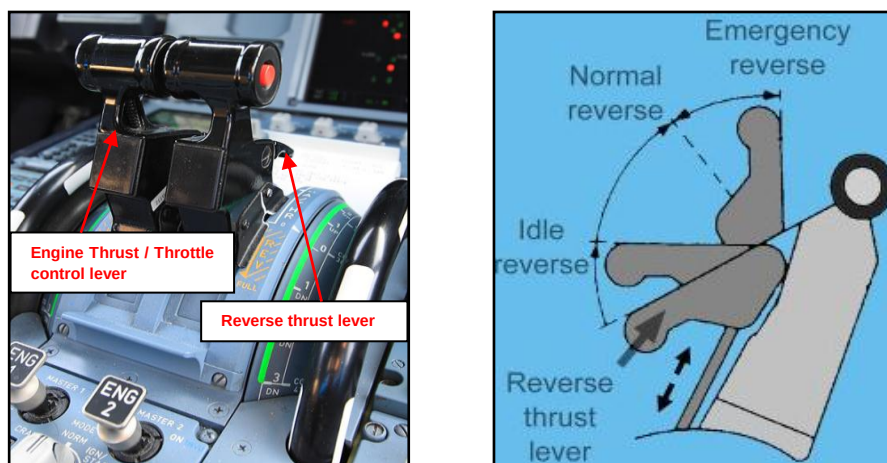


Figure A3: (L) shows the thrust lever for an A320 aircraft, the reverse thrust lever is connected at the front of the main lever. (R) Shows a side view of a thrust lever, reverse thrust lever in detail is shown.

In an aircraft cockpit the reverser indication REV is displayed above each digital EPR indication. REV is displayed in amber whilst the reverser is in transit. When the interlock releases the thrust reverser its position and movement is monitored. Once the reverser is fully deployed the REV indication light changes from amber to green. All forward thrust reference displays are inhibited. When reverse thrust is no longer required the thrust reverser levers are moved forward and down to the reverse idle position, this schedules the fuel flow for minimum idle operation. Moving the thrust reverser levers to the full down position retracts the reverser translating sleeves; once the translating sleeves are fully stowed the reverser is locked. While the reverser is in transit the REV indication light once again changes the colour to amber. The thrust levers cannot be moved forward until the reverse thrust levers are fully down. When the reverser reaches the stowed position, the REV annunciation disappears. During reverser deployment if the REV ISLN light illuminates and the L/R REV ISLN VAL advisory message is displayed in the cockpit than a fault exists in the reverser system. The affected reverser should deploy normally after landing but may not stow when commanded.

A5 Control System for a Pivoting Door Type Thrust Reverser – A320

The Airbus A320 employs the CFM56-5A/5B engine with pivoting door thrust reversers. In forward thrust configuration the cowling masks the blocker doors, thus providing fan flow ducting with minimized thrust loss. However, in the reverse thrust configuration the blocker doors are deployed in order to obstruct the fan duct; the fan flow is rejected laterally through the reverser with a forward velocity component which provides the reverse thrust. The reverse thrust mode is controlled and indicated in the cockpit and is hydraulically actuated after cockpit command and only operative on ground. The reverse thrust consist of two half-fan ducts cowls (D-ducts) hinged at pylon and latched at the bottom. The cowl opening system is used for maintenance purpose only. It is hydraulically actuated and composed of an actuator on each cowl, a hydraulic junction box and the associated piping [Ref 23]. The thrust reversers for the A-320 family aircraft are controlled by the EEC of the respective engine. Figure 3.4, below shows this in a simplified schematic. The same basic design principle is used on all Airbus aircrafts with FADEC-controlled engines.

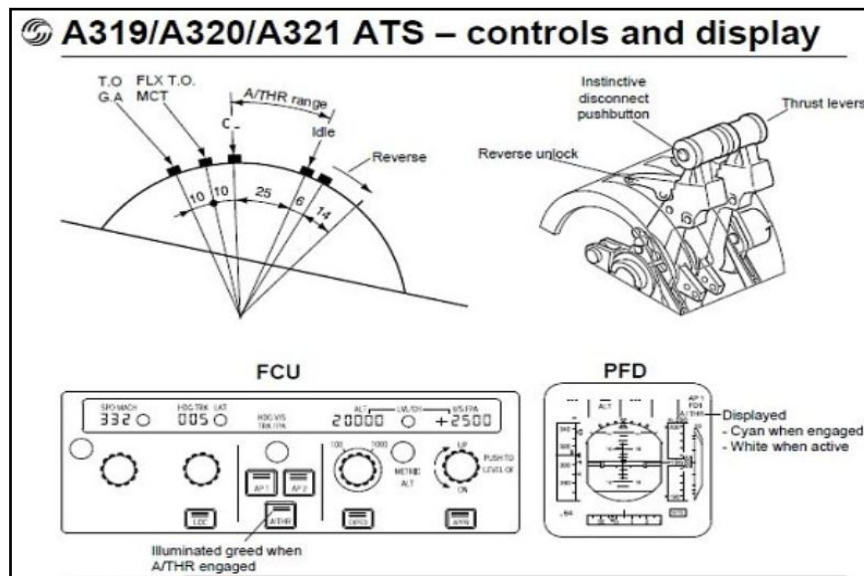


Figure A4: (L) Airbus A-319, A-320, A-321 controls and display

The reverser has four door actuators and four mechanical locks that are released with hydraulic pressure. The EEC controls directly the hydraulic valves of the hydraulic valve module. It is also connected to deploy and stow switches of the four pivoting doors. The hydraulic pressure for the reverser systems is shut off upstream of the hydraulic valve module by an isolation valve. It opens only if the respective aircraft computer detects the thrust lever angle in the reverser range and the thrust lever of other engine in the idle range. For the deployment the following conditions must be complied with:

- Thrust lever angle in the reverser range
- Thrust lever of the other engine near idle
- Engine running
- Hydraulic pressure available
- Ground signal from airframe systems

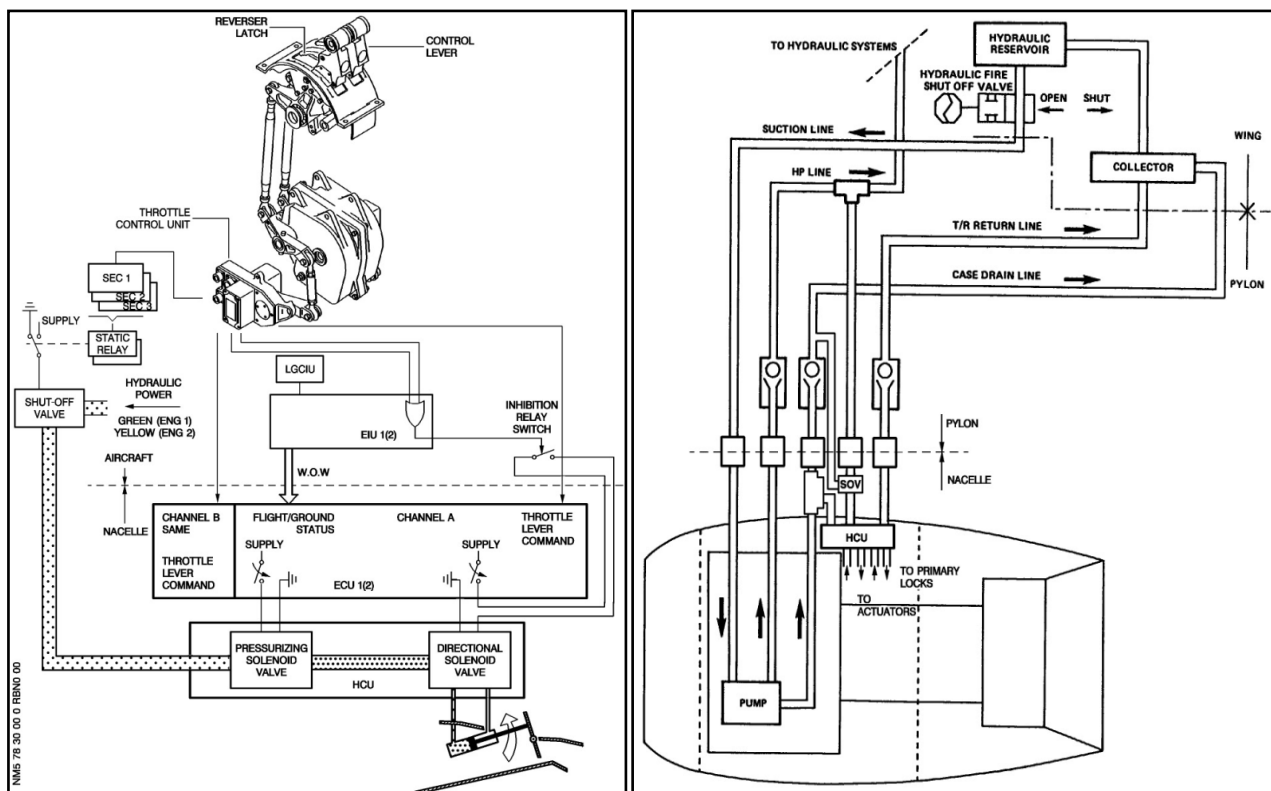


Figure A5: (L) The thrust lever command control for the Airbus, A-320 employing the CFM-56-5B engine. (R) Shows the hydraulic supply for a typical turbofan engine.

The reverser can only be operated with a running engine and the aircraft on the ground. After the thrust lever is placed in the reverse range, the EEC switches the hydraulic valves for the deploy operation. The hydraulic pressure releases the door latches first and then it enters each actuator (Figure 3.4). When the pivoting doors reached the deployed position, the EEC closes the isolation valve within hydraulic valve module to depressurize the system. The airflow keeps the pivoting doors open. During the deployment of pivoting doors the EEC keeps the engine at idle. After the EEC has detected all doors fully deployed, it accelerates the engine to the selected reverse thrust. During reverse thrust selection the thrust lever can be moved directly to the desired power setting, because it has no interlock stop. The interlock function for the delay of the engine acceleration is established in the software of the EEC. Thus, no interlock stop for the thrust lever is necessary. This design keeps the thrust lever kinematics simple.

After the thrust lever has been moved into the forward thrust region, the EEC stows the pivoting doors completely i.e. close the reverser doors completely and neatly, and, switches off the hydraulic pressure. If now all doors are locked correctly, they remain in the stowed position. Otherwise an unlocked door would be lifted a few degrees by the elastic seals and the air pressure. This would change the stow switch into the unlocked stage and the EEC pressurizes the system again for stowing the door. During the time the EEC senses an unlocked door, it sends an unlocked warning to the flight deck. During the reverser operation the EEC sends the reverser position data to the indication system for the flight deck indication. If the EEC detects a system fault in the reverser system, it sends the corresponding fault message to the warning system. The worst system fault will be the latch fault of the primary and secondary latch of a pivoting door during forward thrust operation. In this case the door would be opened by the airflow. The EEC reacts by setting the engine thrust to idle to minimize the drag of the open pivoting door.

A6 Control System for a Cascade Type Thrust Reverser – B777

Messier-Bugatti-Dowty was the sole supplier for the cascade type thrust reversers on all three engines selected to power the Boeing 777. Linear hydraulic actuation system is used to initiate and control the motion of the reverser. Control of the system is by means of a signal input provided by the pilot in combination with signals from the engine control computer system (commonly known as FADEC or EEC).

Dowty is responsible for the design and operation of the entire thrust reverser actuation system (TRAS) on the B777 aircraft. This system provides the muscle to operate and control a reverser of the transcowl design concept. A reverser of this type has a unique requirement. Six actuators, imparting linear motion to two independent transcowl, must be synchronized. The reason for this is to preclude structural damage due to force fight, (i.e. uneven load distribution), positional mismatches at installation, or a jammed transcowl occurring while traversing in its rail track. The designers, as a starting point, had to find a way to achieve synchronization of three actuators per independent transcowl (each half opposite the other on the nacelle). The synchronization problem was solved by mechanically joining three actuators through rotating flexible drive shaft such that all three actuators can be forced to travel at the same velocity. Linear motion of each hydraulic actuator piston is converted to rotary motion of the flexible drive shaft by an internal synchronization drive consisting of a lead screw nut/lead screw set and a worm gear/worm shaft set. Low friction linear drive screws and worm gear sets internal to the hydraulic actuator are employed for this. The two independent transcowl are synchronized through hydraulic flow dividers, thereby ensuring simultaneous movement of both halves. [article]

A second unique characteristic of this system is found in the internal locking feature of the actuators. These locks, in part, are critical to the aircraft safety, and on the Dowty system the locking actuators (two per transcowl) are used as a method of ensuring that the thrust reverser remains stowed in flight. The design of the locking device employed in these actuators features a segmented key design sold under the trademark 'Ram Lock'. Within this, the keys provide a lock mechanism between the piston outside diameter and the inner wall of the cylinder. When the keys are engaged the piston cannot move. Only when the lock mechanism has been triggered to release, will the actuators operate. Lock position indication is provided with a proximity sensor to indicate the lock status. The actuator can be manually unlocked for maintenance purposes. This locking concept has proven to be extremely reliable over many thousands of hour's flight time on many different applications. [article]

In addition to the locking actuators on each transcowl half, a third locking device is used in the 777 system, to obtain the required level of system safety. This is accomplished by a synchronized lock, which engages the synchronization drive of the actuators whenever the TRAS I hydraulically depressurized. A signal from the flight deck provides control over a separate valve to pressurize and unlock the synchronized lock. Additionally, hydraulic pressure to the TRAS is isolated from the aircraft main hydraulic system by an isolation valve. This valve assures isolation of aircraft hydraulic pressure from the actuators in flight. As a final safety feature, a sensor is employed to sense and transmit the position of the transcowl. The B777 TRAS utilizes two rotary variable differential transducers (RVDTs) with dual-channel sensing elements, one each per translating sleeve. These RVDTs provide translating sleeve position signals to the engine control system. The purpose is for limiting engine thrust to idle (low power) whenever the translating sleeves are in a position other than commanded by the pilot. Should this unit sense that the transcowl has deployed un-commanded by a per-determined amount, this signal will cause the engine control computer to

initiate an engine thrust reduction to idle. This in part is to avoid unnecessary stresses in the structures. [article]

In recent years thrust reverser actuation system safety requirements have been elevated to the same level as that of the primary flight control system. This has been strongly influenced by the significant thrust increases incorporated into today's engines, as well as upgraded FAA requirements related to the safety of reverser systems. Present day systems for jet engine reverser systems must be designed such that an un-commanded deployment does not occur in the life of the fleet of such aircraft. Specific FAA/JAA criteria must be satisfied to meet this requirement.

The result of the newly imposed safety standards on the supplier of the TRAS system is that more redundancy must be built into the thrust reverser actuation design. Because of this system architecture has been more complex. The design of a TRAS currently requires a greater knowledge of the inter- workings of the thrust reverser system as a whole, to ensure not only that all the various components of the actuation system perform as specified, but also that every possible system anomaly has been anticipated and safeguards provided to prevent an inadvertent deployment of a reverser.

Although the above factors contribute to making the design of a TRAS system more complex, the bottom line is system safety. The flying public can take comfort not only in the fact that the aircraft has alternate braking system when needed, but that the reverser system is designed and built with the latest technology and the utmost care, with the safety of the aircraft and passengers as the end goal.

A7 Control System for a Target Type Thrust Reverser – B737-100/200

In this section the B737-100/200 aircraft which uses the Pratt and Whitney JT-8D engine is discussed. The PW-JT-8D engine is a low bypass ratio turbofan engine, ($BPR \approx 0.97$) that incorporates low and high pressure spools comprised of multiple compressor and turbine stages.

The original B737-100/200 thrust reversers were pneumatically powered clamshell door type thrust reversers taken straight from the B727 aircraft. On reverser deployment, bleed air is extracted from the 13th stage of a compressor for pneumatic actuator that rotates the deflector doors and clamshell doors into position. Unfortunately, the clamshell thrust reverser design on the B737-100/200 aircraft was relatively ineffective and apparently tended to push the aircraft up off the runway when deployed. This reduced the down force on the main wheels thereby reducing the effectiveness of the wheel brakes.

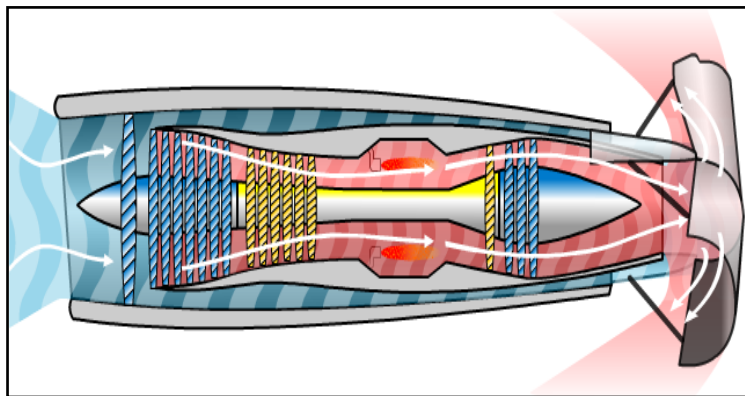


Figure A6: B737-100/200 target type thrust reverser employing a PW JT8D engine [12].

In the year 1969, Boeing and Rohr carried out the design studies to increase the effectiveness of the thrust reverser. The thrust reverser design was changed from a pneumatically powered clamshell type thrust reverser to a hydraulically powered target type thrust reversers (Figure 3.5). This requires a 48 inch extension to the tail pipe to accommodate the two cylindrical deflector doors which were mounted on a four bar linkage system and associated hydraulics. The doors were set at 35 degree away from the vertical to allow the exhaust to be deflected inboard and over the wings and outboard and under the wings. This ensures that exhaust and debris is not blown into the wheel-well, nor is it blown directly downwards which would lift the weight off the wheels or be re-ingested. These thrust reversers are locked against inadvertent deployment by both deflector door locks and the four bar linkage being over centre. To illustrate how poor the original clamshell type thrust reverser system was Boeing own data says that the target type thrust reverses at an engine pressure ratio (EPR) of 1.5 were twice as effective as the clamshells type thrust reverser.

The main components responsible to control the position of the two deflector doors are the hydraulic isolation valve, directional control valve, two locking actuators, and two positioning actuators. During flight, the hydraulic isolation valve is close and the directional control valve is oriented toward the lock port of the locking actuators and the stow port of the positioning actuators.

The thrust reverser operation is initiated by moving the reverse thrust lever mounted on the forward thrust lever at the control stand. Left and right reverse thrust levers are available for independent operation of the thrust reversers installed on the left and right engines. The forward thrust lever must be returned to the idle position before the reverse thrust levers are moved.

As the landing gear is compressed upon touchdown, an air-ground switch is closed, allowing electrical power to be sent to the isolation valve. Subsequently, the isolation valve opens and the hydraulic pressure becomes available for reverse thrust operation. When reverse thrust is selected by moving the thrust reverser lever toward an interlock position the directional control valve is re-oriented through a mechanical link, and hydraulic pressure is applied to the unlock port of the locking actuators and the deploy port of the positioning actuators. As the locking actuators retract, door latches are unlocked allowing the deflector doors to move from the stow position. The deflector doors start translating toward the deploy position as the positioning actuators are retract. As the deflector doors approach the fully deployed position, the mechanical interlock allows the reverse thrust lever to be moved further aft for application of increased reverse thrust.

In the cockpit the REVERSER light shows either control valve or sleeve position disagreement or that the auto re-stow circuit is activated. This light will illuminate every time the reverser is commanded to stow, but extinguishes after the stowed has completed, and will only brig up master caution ENG if a malfunction has occurred. Recycling the reverse thrust will often clear the fault. If this occurs in flight, reverse thrust will be available after landing. The REVERSER UNLOCKED light (EIS panel) is potentially much more serious and will illuminate in-flight if a sleeve gets mechanically unlocked. Only multiple failures will allow the engine to go into reverse thrust.

The B737-100/200 thrust reverser panel has a LOW PRESSURE light which refers to the reverser accumulator pressure when insufficient pressure is available to deploy the reversers. The blue caption between the switches is ISOLATION VALVE and illuminates when the three conditions for reverse thrust are satisfied: Engine running, aircraft on ground and fire switches in normal position. The guarded NORMAL/OVERRIDE switches are installed to enable the reverse thrust to be selected on the ground with engines stopped (for maintenance purposes).

Appendix A2: CFD Theory

A2.1 Setting up CFD Solver

All the 2D and 3D numerical analyses were performed using ANSYS FLUENT software. This section gives the analytical background of the equations used within ANSYS FLUENT software for the numerical analyses. Details are mainly represented of the setup of the thrust reverser model in ANSYS FLEUNT.

A2.2 Pressure Based Solver

Pressure-based solver was used for this study. In the pressure-based approach, the pressure field is extracted by solving a pressure correction equation which is obtained by manipulating continuity and momentum equations. ANSYS FLUENT will solve the governing integral equations for the conservation of mass, momentum and energy and other scalars such as turbulence. A control-volume-based technique is used that consist of:

- Division of domain into discrete control volumes using a computational grid.
- Integration of the governing equations on the individual control volumes to construct algebraic equations for the discrete dependent variables (“unknowns”) such as velocities, pressure, temperature and conserved scalars.
- Linearization of the discretized equations and solution of the resultant linear equation system to yield updated values of the dependent variables.

The pressure-based solver employs an algorithm which belongs to a general class of methods called the projection method. In the projection method, the constraint of mass conservation (continuity) of the velocity field is achieved by solving a pressure (or pressure correction) equation. The pressure equation is derived from the continuity and the momentum equations in such a way that the velocity field, corrected by the pressure, satisfies the continuity. Since the governing equations are nonlinear and coupled to one another, the solution process involves iterations wherein the entire set of governing equations is solved repeatedly until the solution is converges.

Two pressure based solver algorithms are available in ANSYS FLUENT, a segregated algorithm and a coupled algorithm. Both these approached are used during the CFD study. The segregated algorithm was used at static conditions (i.e. $M=0.0$) and coupled algorithm was used at landing conditions i.e. $M=0.211$.

A2.3 Pressure-Based Segregated Algorithm

The pressure-based solver uses a solution algorithm where the governing equations are solved sequentially (that is segregated from one another). Because the governing equations are non-linear and coupled, the solution loop must be carried out iteratively in order to obtain a converged numerical solution.

In the segregated algorithm, the individual governing equations for the solution variables (for example, $u, v, w, p, T, k, \varepsilon$, etc.) are solved one after another. Each governing equation, while being

solved is 'decoupled' or 'segregated' from other equations, hence its name. The segregated algorithm is memory efficient, since the discretized equations only be stored in the memory one at a time. However, the solution convergence is relatively slow, in as much as the equations are solved in a decoupled manner.

With the segregated algorithm, an overview of the steps for each iteration is outlined below:

- i) Update fluid properties (for example, density, viscosity, specific heat) including turbulent viscosity (diffusivity) based on the current solution.
- ii) Solve the momentum equations, one after another, using the recently updated values of pressure and face mass fluxes.
- iii) Solve the pressure correction equation using the recently obtained velocity field and the mass-flux.
- iv) Correct fan mass fluxes, pressure, and the velocity field using the pressure correction obtained from step 3.
- v) Solve the equations for additional scalars, if any, such as turbulent quantities, energy, species, and radiation intensity using the current values of the solution variables.
- vi) Update the source terms arising from the interactions among different phases (for example, source term for the carrier phase due to discrete particles).
- vii) Check for the convergence of the equations.

The SIMPLE algorithm uses a relationship between velocity and pressure corrections to enforce mass conservation and to obtain the pressure field.

The pressure-based segregated algorithm solves the momentum equation and pressure correction equations separately. This semi-implicit solution method results in slow convergence.

A2.4 Pressure-Based Coupled Algorithm

Unlike the segregated algorithm described above, the pressure-based correction algorithm solves a coupled system of equations comprising the momentum equations and the pressure-based continuity equation. Thus, in the coupled algorithm, steps 2 and 3 in the segregated algorithm are replaced by a single step in which the coupled system of equations are solved. The remaining equations are solved in a decoupled fashion as in the segregated algorithm.

Using the coupled approach offers some advantages over the non-coupled or segregated approach. The coupled scheme obtains a robust and efficient single phase implementation for steady-state flows, with superior performance compared to the segregated solution schemes.

Since the momentum and continuity equations are solved in a closely coupled manner, the rate of solution convergence significantly improves when compared to the segregated algorithm. However, the memory requirement increases by 1.5 – 2 times that of the segregated algorithm

since the discrete system of all momentum are pressure based continuity equations must be stored in the memory when solving for the velocity and pressure fields (rather than just a single equation, as is the case with the segregated algorithm).

The pressure-based segregated algorithm solves the momentum equation and pressure correction equations separately. This semi-implicit solution method results in slow convergence.

The coupled algorithm solves the momentum and pressure-based continuity equation together. The full implicit coupling is achieved through an implicit discretization of pressure gradient terms in the momentum equations, and an implicit discretization of the face mass flux, including the Rhie-Chow pressure dissipation terms. The pressure-based coupled algorithm is not compatible with the non-iterative time advancement solver (NITA) and fixed velocity option.

A 2.5 General Scalar Transport Equation: Discretization and Solution

ANSYS FLUENT uses a control-volume-based technique to convert a general scalar transport equation to an algebraic equation that can be solved numerically. This control volume technique consists of integrating the transport equation about each control volume, yielding a discrete equation that express the conservation law on a control-volume basis.

Discretization of the governing equations can be illustrated most easily by considering the unsteady conservation equation for transport of a scalar quantity ϕ . This is demonstrated by the following equation written in integral form for an arbitrary control volume V as follows:

$$\int_V \frac{\partial \rho \phi}{\partial t} dV + \oint \rho \phi \vec{v} \cdot d\vec{A} = \oint \Gamma_\phi \nabla \phi \cdot d\vec{A} + \int_V S_\phi dV$$

Where

ρ = density

$\vec{v}$ = velocity vector ($= u\hat{i} + v\hat{j}$ in 2D)

$\vec{A}$ = surface area vector

Γ_ϕ = diffusion coefficient for ϕ

$\nabla \phi$ = gradient of $\phi = ((\partial \phi / \partial x)\hat{i} + (\partial \phi / \partial y)\hat{j})$ in 2D

S_ϕ = source of ϕ per unit volume

Equation (above) is applied to each control volume, or cell, in the computational domain. Discretization of Equation on a given cell yields

$$\frac{\partial \rho \phi}{\partial t} V + \sum_f^{N_{faces}} \rho_f \vec{v}_f \phi_f \cdot \vec{A}_f = \sum_f^{N_{faces}} \Gamma_\phi \nabla \phi_f \cdot \vec{A}_f + S_\phi V$$

Where

N_{faces} = number of faces enclosing cell

ϕ_f = value of ϕ convected through face f

$\rho_f \vec{v}_f \cdot \vec{A}_f$ = mass flux through the face

$\vec{A}_f$ = area of face f , $|A|$ ($= |A_x \hat{i} + A_y \hat{j}|$ in 2D)

$\nabla \phi_f$ = gradient of ϕ at face f

V = cell volume

Equation above is known as the discretized scalar transport equation. In the equation above ϕ is the unknown scalar variable at the cell centre as well as the unknown values in surrounding neighbour cells. This equation in general, is non-linear with respect to these variables. A linearized form of the above equation can be written as

$$a_p \phi = \sum_{nb} a_{nb} \phi_{nb} + b$$

Where the subscript nb refers to neighbour cells, and a_p and a_{nb} are the linearized coefficients for ϕ and ϕ_{nb} .

The number of neighbours for each cell depends on the mesh topology, but will typically equal the number of faces enclosing the cell (boundary cells being the exception).

Similar equations can be written for each cell in the mesh. This results in a set of algebraic equations with a sparse coefficient matrix. For scalar equations, ANSYS FLUENT solves this linear system using a point implicit (Gauss-Seidel) linear equation solver in conjunction with an algebraic multi-grid (AMG) method.

Where $\frac{\partial \rho \phi}{\partial t} V$ is defined in Temporal Discretization [Ref]. The equations solved by ANSYS FLUENT take the same general form as the one given above and apply readily to multi-dimensional, unstructured meshes composed of arbitrary polyhedral.

Gauss-Seidel is the simplest smoother type and is recommended when using the pressure-based segregated solver.

A2.6 Spatial Discretization

By default, ANSYS FLUENT stores discrete values of the scalar ϕ at the cell centre. However, face values ϕ_f are required for the convection terms and must be interpolated from the cell centre values. This is accomplished using an upwind scheme.

Upwinding means that the face value ϕ_f is derived from quantities in the cell upstream, or 'upwind', relative to the direction of the normal velocity v_n (Equation). ANSYS FLUENT allows you to choose

from several upwind schemes: first-order upwind scheme, second-order upwind scheme, power law and QUICK.

A2.7 First-Order Accuracy vs Second-Order Accuracy

When the flow is aligned to the mesh (e.g., laminar flow in a rectangular duct modeled with a quadrilateral or hexahedral mesh) the first-order upwind discretization may be acceptable. When the flow is not aligned with the mesh (i.e., when it crosses the mesh lines obliquely), however, first order convective discretization increases the numerical discretization error (numerical diffusion). For the triangular and tetrahedral meshes, since the flow is never aligned with the mesh, you will generally obtain more accurate results by using the second-order discretization. For quad/hex meshes, better results are usually obtain using the second-order discretization, especially for complex flows.

In summary, while the first-order discretization generally yields better convergence than the second-order scheme, it generally will yield less accurate results, especially on tri/tetra meshes. Usually, for most of the cases iterations are initially performed with first-order scheme and then turn on the second-order scheme and continue the calculation to convergence.

A2.8 Second-Order Upwind Scheme

When the second-order accuracy is desired, quantities at cell faces are computed using a multidimensional linear reconstruction approach. In this approach, higher-order accuracy is achieved at cell faces through a Taylor series expansion of the cell-centered solution about the cell centroid. Thus when second-order upwinding is selected, the face value ϕ_f is computed using the following expression:

$$\phi_{f,sou} = \phi + \nabla\phi \cdot \vec{r}$$

Where ϕ and $\nabla\phi$ are the cell-centered value and its gradient in the upstream cell, and $\vec{r}$ is the displacement vector from the upstream cell centroid to the face centroid. This formulation required the determination of the gradient $\nabla\phi$ in each cell. Finally, the gradient $\nabla\phi$ is limited so that the new maxima or minima are introduced.

Evaluation of Gradients and Derivatives

Gradients are needed not only for constructing values of a scalar at the cell faces, but also for computing secondary diffusion terms and velocity derivatives. The gradient $\nabla\phi$ of a given variable ϕ is used to discretize the convection and diffusion terms in the flow conservation equations. The gradients are computed in ANSYS FLUENT using the following methods:

- Green-Gauss Cell-Based
- Green-Gauss Node-Based
- Least Squares Cell-Based

A2.9 Green-Gauss Theorem

When the Green-Gauss theorem is used to compute the gradient of the scalar ϕ at the cell centre c_0 , the following discrete form is written as

$$(\nabla\phi)_{c_0} = \frac{1}{v} \sum_f \overline{\phi}_f \vec{A}_f$$

Where $\overline{\phi}_f$ is the value of ϕ at the cell face centroid. The summation is over all the faces enclosing the cell.

A2.10 Green-Gauss Node-Based Gradient Evaluation

In the above equation $\overline{\phi}_f$ can be computed by the arithmetic average of the nodal values on the face.

$$\overline{\phi}_f = \frac{1}{N_f} \sum_n^{N_f} \phi_n$$

Where N_f is the number of nodes on the face.

The nodal values, ϕ_n in the above equation are constructed from the weighted average of the cell values surrounding the nodes. This scheme reconstructs exact values of a linear function at a node from surrounding cell-centered values on arbitrary unstructured meshes by solving a constrained minimization problem, preserving a second-order spatial accuracy.

The node-based gradient is known to be more accurate than the cell-based gradient particularly on irregular (skewed and distorted) unstructured meshes, however, it is relatively more expensive to compute than the cell-based gradient scheme.

A2.13 Steady-State Iterative Algorithm

If you are performing a steady state calculation, the governing equations for the pressure-based solver do not contain time-dependent terms.

A2.14 Setting Under-Relaxation Factors

The pressure-based solver uses under-relaxation of equations to control the update of computed variables at each iteration. This means that all equations solved using the pressure-based solver, including the non-coupled equations solved by the density-based solver will have under-relaxation factors associated with them.

In ANSYS FLEUNT, the default under-relaxation parameters for all variables are set to values that are near optimal for the largest possible number of cases. These values are suitable for many problems, but for some particular nonlinear problems (e.g. some turbulent flows) it is prudent to reduce the under-relaxation factors initially.

A2.15 Under-Relaxation of Variables

The under-relaxation of variables is used in all cases for some material properties, in the pressure-based coupled algorithm where this explicit under-relaxation is used for momentum and pressure.

Because of the nonlinearity of the equation set being solved by ANSYS FLUENT, it is necessary to control the change of ϕ . This is typically achieved by under-relaxation of variables (also referred to as explicit relaxation), which reduces the change of ϕ produced during each iteration. In a simple form, the new value of the variable ϕ within a cell depends upon the old value, ϕ_{old} , the computed change in ϕ , $\Delta\phi$, and the under-relaxation factor, α , as follows:

$$\phi = \phi_{old} + \alpha\Delta\phi$$

A2.16 Under-Relaxation of Equations

The under-relaxation of equations, also known as implicit relaxation, is used in the pressure-based solver to stabilize the convergence behavior of the outer nonlinear iterations by introducing selective amount of ϕ in the system of discretized equations. This equivalent to the location-specific time step.

$$\frac{a_p^\phi}{\alpha} = \sum_{nb} a_{nb} \phi_{nb} + b + \frac{1 - \alpha}{\alpha} a_p \phi_{old}$$

The CFL number if a solution parameter in the pressure-based coupled algorithm and can be written in terms of α :

$$\frac{1 - \alpha}{\alpha} = \frac{1}{CFL}$$

A2.17 Modeling Turbulence

Turbulence is a three-dimensional unsteady random motion observed in fluids at moderate to high Reynolds numbers. As technical flows are typically based on fluids of low viscosity, almost all technical flows are turbulent.

While turbulence is, in principle, described by the Navier-Stokes equations, it is not feasible in most situations to resolve the wide range of scale in time and space by Direct Numerical Simulation (DNS) as the CPU requirements would by far exceed the available computing power for any foreseeable future. For this reason, averaging procedures have to be applied to the Navier-Stokes equation to filter out all, or at least, parts of the turbulent spectrum. The most widely applied averaging procedure in Reynolds-averaging (which, for all practical purposes is time-averaging) of

the equations, resulting in the Reynolds Averaged Navier-Stokes (RANS) equations. By this process, all turbulent structures are eliminated from the flow and a smooth variation of the averaged velocity and pressure fields can be obtained. However, the averaging process introduces additional unknown terms into the transport equations (Reynolds Stresses and Fluxes) which need to be provided by suitable turbulence models (turbulent closure). The quality of the simulation can depend crucially on the selected turbulence model and it is important to make the proper model choice as well as to provide a suitable numerical grid for the selected model. An alternative to RANS are Scale-Resolving Simulation (SRS) models. With SRS methods, at least a portion of the turbulent spectrum is resolved in at least part of the flow domain. The most well-known such method is Large Eddy Simulation (LES), but many new hybrids (models between RANS and LES) are appearing. As all SRS method require time resolved simulations with relatively small time steps, it is important to understand that these methods are substantially more computationally expensive than RANS simulations.

It is an unfortunate fact that no single turbulence model is universally accepted as being superior for all classes of problems. The choice of turbulence model will depend on considerations such as the physics of the flow, the established practice for a specific class of problem, the level of accuracy required, the available computational resources, and the amount of time available for the simulation. To make the most appropriate choice of mode for your application, one needs to understand the capabilities and limitations of the various options.

A2.18 Reynolds Averaged Navier-Stokes (RANS) Turbulence Models

RANS models offer the most economic approach for computing complex turbulent industrial flows. Typical examples of such models are the $k - \varepsilon$ or the $k - \omega$ models in their different forms. These models simplify the problem to the situation of two additional transport equations and introduce an Eddy-Viscosity (turbulent viscosity) to compute the Reynolds Stresses. More complex RANS models are available which solve an individual equation for each of the six independent Reynolds Stresses directly (Reynolds Stress Models – RSM) plus a scale equation (ε -equation or ω -equation). RANS models are suitable for many engineering applications and typically provide the level of accuracy required. Since none of the models are universal, one has to decide which model is the most suitable for a give application.

In Reynolds averaging, the solution variables in the instantaneous (exact) Navier-Stokes equations are decomposed into the mean (ensemble-averaged or time averaged) and fluctuating components. For the velocity components:

$$u_i = \bar{u}_i + u_i'$$

Where $\bar{u}_i$ and u_i' are the mean and fluctuating velocity components ($i=1, 2, 3$).

Likewise, for pressure and other scalar quantities:

$$\phi = \bar{\phi} + \phi'$$

Where ϕ denotes a scalar such as pressure, energy, or species concentration.

Substituting expression of this form for the flow variables into the instantaneous continuity and momentum equations and taking a time (or ensemble) average (and dropping the over bar on the mean velocity, $\bar{u}$) yields the ensemble-averaged momentum equations. They can be written in Cartesian tensor form as:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0$$

$$\frac{\partial \rho}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[\mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \delta_{ij} \frac{\partial u_l}{\partial x_l} \right) \right] + \frac{\partial}{\partial x_j}(-\rho \overline{u'_i u'_j})$$

Equation () and () are called the Reynolds-averaged Navier-Stokes (RANS) equations. They have the same general form as the instantaneous Navier-Stokes equations, with the velocities and other solution variables now representing ensemble-averaged (or time-averaged) values. Additional terms now appear that represent the effects of turbulence. These Reynolds stresses, $-\rho \overline{u'_i u'_j}$, must be modeled in order to close Equation ().

For variable-density flows, Equation () and Equation () can be interpreted as Favre-averaged Navier-Stokes equations, with the velocities representing mass-averaged values. As such Equation () and Equation () can be applied to variable-density flows.

2.19 Bossinesq Approach vs. Reynolds Stress Transport Models

The Reynolds-averaged approach to turbulence modeling requires that the Reynolds stresses in Equation () are appropriately modeled. A common method employs the Bossinesq hypothesis (Ref) to relate the Reynolds stresses to the mean velocity gradients:

$$-\rho \overline{u'_i u'_j} = \mu_t \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} \left(\rho k + \mu_t \frac{\partial u_k}{\partial x_k} \right) \delta_{ij}$$

The Bossinesq hypothesis is used in Spalart-Allmaras model, the k- ϵ models, and the k- ω models. The advantage of this approach is the relatively low computational cost associated with the computation of the turbulent viscosity, μ_t . In the case of the Spalart-Allmaras model, only one additional transport equation (representing turbulent viscosity) is solved. In the case of the k- ϵ and k- ω models, two additional transport equations (for the turbulence kinetic energy, k, and either the turbulence dissipation rate, ϵ , or the specific dissipation rate, ω) are solved, and μ_t is computed as a function of k and ϵ or k and ω . The disadvantage of the Bossinesq hypothesis as presented is that it assumes μ_t is an isotropic scalar quantity, which is strictly not true. However the assumption of an isotropic turbulent viscosity typically works well for shear flows dominated by only one of the turbulent shear stresses. This covers many technical flows, such as wall boundary layers, mixing layers, jets, etc.

The alternative approach, embodied in the RSM, is to solve transport equations for each of the terms in the Reynolds stress tensor. An additional scale-determining equation (normally for ϵ or ω) is also required. This means that five additional transport equations are required in 2D flows and seven additional transport equations must be solved in 3D.

In many cases, models based on the Bossinesq hypothesis perform very well, and the additional computational expense of the Reynolds stress model is not justified. However, the RSM is clearly superior in situations where the anisotropy of turbulence has a dominant effect on the mean flow. Such case includes highly swirling flows and stress-driven secondary flows.

A2.20 k- ϵ Turbulence Models

Two equation models are historically the most widely used turbulence models in industrial CFD. They solve two transport equations and model the Reynolds Stresses based using the Eddy Viscosity approach. Two-equation turbulence models allow the determination of both, a turbulent length and time scale by solving two separate transport equations.

The standard k- ϵ model in ANSYS FLUENT falls within this class of models and has become the workhorse of practical engineering flow calculations in the time since it was proposed by Launder and Spalding (Ref). Robustness, economy, and reasonable accuracy for a wide range of turbulent flows explain its popularity in industrial flow and heat transfer simulations. It is a semi-empirical model, and the derivation of the model equations relies on phenomenological considerations and empiricism.

The standard k- ϵ model is a model based on model transport equations for the turbulence kinetic energy (k) and its dissipation rate (ϵ). The model transport equation for k is derived from the exact equation, while the model transport equation for ϵ was obtained using physical reasoning and bears little resemblance to its mathematically exact counterpart.

In the derivation of the k- ϵ model, the assumption is that the flow is fully turbulent, and the effects of molecular viscosity are negligible. The standard k- ϵ model is therefore valid only for fully turbulent flows.

The draw-back of all k- ϵ models is their insensitivity to adverse pressure gradient and boundary layer separation. They typically predict a delayed and reduced separation relative to observations. This can result in overly optimistic design evaluation for flows which separate from smooth surfaces (aerodynamic bodies, diffusers, etc.). The k- ϵ model is therefore not widely used in external aerodynamics.

As the strengths and weaknesses of the standard k- ϵ model have become known, modifications have been introduced to improve its performance. Two of these variants are available in ANSYS FLUENT: the RNG k- ϵ model and the realizable k- ϵ model.

In ANSYS FLUENT, the use of the Realizable k- ϵ model is recommended relative to other variants of the k- ϵ family. It is recommended to use the k- ϵ model in combination with the Enhanced Wall Treatment (EWT). For cases where the flow separates under adverse pressure gradients from smooth surfaces (airfoils, etc.), k- ϵ models are generally not recommended.

A2.21 Transport Equations for the Standard k-ε Model

The turbulent kinetic energy, k , and its rate of dissipation, ε , are obtained from the following transport equations:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_b - \rho \varepsilon - Y_M + S_k$$

And

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_i}(\rho \varepsilon u_i) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + C_{1\varepsilon} \frac{\varepsilon}{k} (G_k + C_{3\varepsilon} G_b) - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} + S_\varepsilon$$

In these equations, G_k represents the generation of turbulence kinetic energy due to the mean velocity gradients. G_b is the generation of turbulence kinetic energy due to buoyancy; Y_M represents the contribution of the fluctuating dilation in compressible turbulence to the overall dissipation rate. $C_{1\varepsilon}$, $C_{2\varepsilon}$, and $C_{3\varepsilon}$ are constants; σ_k and σ_ε are turbulent Prandtl numbers for k and ε , respectively; S_k and S_ε are user defined source terms.

The turbulent (or eddy) viscosity, μ_t , is computed by combining k and ε as follows:

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon}$$

where C_μ is a constant.

The model constants, $C_{1\varepsilon}$, $C_{2\varepsilon}$, C_μ , σ_k and σ_ε have the following default values:

$$C_{1\varepsilon} = 1.44, C_{2\varepsilon} = 1.92, C_\mu = 0.09, \sigma_k = 1.0, \sigma_\varepsilon = 1.3$$

These default values have been determined from experiments for fundamental turbulent flows including frequently encountered shear flows like boundary layers, mixing layers and jets as well as for decaying isotropic grid turbulence. They have been found to work fairly well for a wide range of wall-bounded and free shear flows.

A2.22 Realizable k-ε Model

The standard k-ε model differs from the standard k-ε model in two important ways:

- The realizable k-ε model contains an alternative formulation for the turbulent viscosity.
- A modified transport equation for the dissipation rate, ε , has been derived from an exact equation for the transport of the mean-square vorticity fluctuation.

The term ‘realizable’ means that the model satisfies certain mathematical constraints on Reynolds stresses, consistent with the physics of turbulent flows. Neither, the standard k-ε model nor the RNG k-ε model is realizable.

One limitation of the realizable k - ε model is that it produces non-physical turbulent viscosities in situations when computational domain contains both rotating and stationary fluid zones (for example, multiple reference frames, rotating sliding meshes). This is due to the fact that the realizable k - ε model includes the effects of mean rotation in the definition of the turbulent viscosity. This extra rotation effect can has been tested on single moving reference frame systems and showed superior behavior over the standard k - ε model. However, due to the nature of this modification, its application to multiple reference frame systems should be taken with some caution.

A2.23 Transport Equations for the Realizable k - ε Model

The modeled transport equations for the k and ε model are

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_j}(\rho k u_j) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_b - \rho \varepsilon - Y_M + S_k$$

and

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_j}(\rho \varepsilon u_j) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + \rho C_1 S \varepsilon - \rho C_2 \frac{\varepsilon^2}{k + \sqrt{\nu \varepsilon}} + C_{1\varepsilon} \frac{\varepsilon}{k} C_{3\varepsilon} G_b + S_\varepsilon$$

where

$$C_1 = \max \left[0.43, \frac{\eta}{\eta + 5} \right], \quad \eta = S \frac{k}{\varepsilon}, \quad S = \sqrt{2 S_{ij} S_{ij}}$$

Note that the k equation is the same as the standard k - ε model and the RNG k - ε model, except for the model constants. However, the form of the ε equation is quite different from those in the standard and RNG-based k - ε models. One of the noteworthy features is that the production term in the ε equation (the second term on the right-hand side) does not involve the production of k ; that is, it does not contain the same G_k term as the other k - ε models. It is believed that the present form better represents the spectral energy transfer. Another desirable feature is that the destruction term (the third term on the right-hand side of Equation) does not have any singularity; that is, its denominator never vanishes, even if k vanishes or becomes smaller than zero. This feature is constant with traditional k - ε models, which have a singularity due to k in the denominator.

The difference between the realizable k - ε model and the standard and RNG k - ε models is that C_μ is no longer constant. It is computed from

$$C_\mu = \frac{1}{A_0 + A_s \frac{k U^*}{\varepsilon}}$$

Where

$$U^* = \sqrt{S_{ij} S_{ij} + \tilde{\Omega}_{ij} \tilde{\Omega}_{ij}}$$

and

$$\tilde{\Omega}_{ij} = \Omega_{ij} - 2\varepsilon_{ijk}\omega_k$$

$$\Omega_{ij} = \overline{\Omega_{ij}} - \varepsilon_{ijk}\omega_k$$

where $\overline{\Omega_{ij}}$ is the mean rate-of-rotation tensor viewed in a moving reference frame with the angular velocity ω_k . The model constant A_0 and A_s are given by

$$A_0 = 4.04, \quad A_s = \sqrt{6} \cos \phi$$

where

$$\phi = \frac{1}{3} \cos^{-1}(\sqrt{6}W), \quad W = \frac{S_{ij}S_{jk}S_{ki}}{\tilde{S}^3}, \quad \tilde{S} = \sqrt{S_{ij}S_{ij}}, \quad S_{ij} = \frac{1}{2} \left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j} \right)$$

It can be seen that C_μ is a function of the mean strain and rotation rates, the angular velocity of the system rotation, and the turbulence fields (k and ε). C_μ in Equation can be shown to recover the standard value of 0.09 for an inertial sub layer in an equilibrium boundary layer.

In ANSYS FLEUNT, the term $-2\varepsilon_{ijk}\omega_k$ is, by default, not included in the calculation of, $\tilde{\Omega}_{ij}$. This is an extra rotation term that is not compatible with cases involving sliding meshes and multiple reference frames. But the term can be included by using a text command.

A2.24 Grid Resolution RANS Models

Grid generation has a strong impact on model accuracy. There are many considerations which have to be followed when generating high quality CFD grids. From a turbulence modeling standpoint, the most important one is that the relevant shear layers should be covered by at least ~10 cells normal to the layer. Below this resolution, the model will not be able to provide its calibrated performance. Especially for free shear flows, whose location is not known during grid generation, this is a requirement which is hard to achieve. Nevertheless, one should be aware that for lower resolution, the model performance can degrade.

For wall bounded flows, a structured mesh in wall-normal direction is highly recommended. The structured portion of the mesh should cover the entire boundary layer and extend beyond the boundary layer thickness to avoid restricting the growth of the boundary layer. One should ensure that the prism layer covers the wall boundary layer entirely. Note that these are not specific requirements of these models, but are general requirements for wall boundary layer simulations.

Both, ε -based and ω -based models offer Enhanced Wall Treatment options, which make the models relatively insensitive to the y^+ value of the wall cell. Generally speaking, it is more important to ensure that the boundary layer is covered with sufficient cells, then to achieve a certain y^+ criterion.

When wall functions are used, it is essential to avoid meshes with y^+ values lower than ~30 as the wall shear stress and the wall heat transfer can and will seriously deteriorate under such conditions. For this reason, the usage of Enhanced Wall Treatments (to be selected for ε -equation and default for ω -equation based models) is recommended.

A2.25 Near-Wall Treatment for Wall-Bounded Turbulent Flows

Turbulent flows are significantly affected by the presence of walls. Obviously, the mean velocity field is affected through the no-slip condition that has to be satisfied at the wall. However, the turbulence is also changed by the presence of the wall in non-trivial ways. Very close to the wall, viscous damping reduces the tangential velocity fluctuations, while kinematic blocking reduces the normal fluctuations. Toward the outer part of the near-wall region, however, the turbulence is rapidly augmented by the production of turbulence kinetic energy due to the large gradients in mean velocity.

The near-wall modeling significantly impacts the fidelity of numerical solutions, in as much as walls are the main source of mean vorticity and turbulence. After all, it is the near wall region that the solution variables have large-gradients, and the momentum and other scalar transports occur most vigorously. Therefore, accurate representation of the flow in the near-wall region determines successful predictions of wall-bounded turbulent flows.

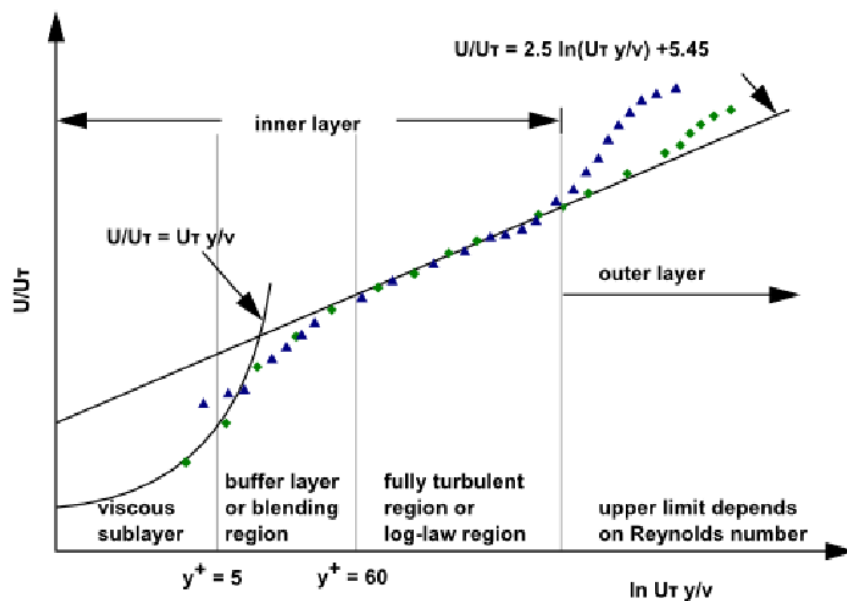
Numerous experiments have shown that the near wall region can be largely subdivided into three layers. In the innermost layer, called the 'viscous sub layer', the flow is almost laminar, and the (molecular) viscosity plays a dominant role in the momentum and heat or mass transfer. In the outer layer, called the fully-turbulent layer, turbulence plays a major role. Finally, there is an interim region between the viscous sub layer and the fully turbulent layer where the effects of molecular viscosity and turbulence are equally important. Figure, illustrates these subdivisions of the near-wall region, plotted in semi-log coordinates.

y^+ is defined as:

$$y^+ = \frac{\rho \mu_\tau y}{\mu}$$

Where μ_τ is the friction velocity, defined as

$$\sqrt{\frac{\tau_w}{\rho}}$$



High quality numerical results for the wall boundary layer will only be obtained if the overall resolution of the boundary layer is sufficient. This requirement is actually more important than achieving certain y^+ values. The minimum number of cells to cover boundary layer accurately is around 10, but values of 20 are desirable. It should also be noted that an improvement of boundary layer resolution can often be achieved with moderate increase in numerical effort, as it requires only a mesh refinement in the wall-normal direction. The associated increase in accuracy is typically well worth the computing costs. For unstructured meshes, it is recommended that you generate prism layers near the wall with 10 – 20 or more layers for an accurate prediction of the wall boundary layers. The thickness of the prism layer should be designed to ensure that around 15 or more nodes are actually covering the boundary layer. This can be checked after a solution is obtained, by looking at the turbulent viscosity, which has a maximum in the middle of the boundary layer – this maximum gives an indication of the thickness of the boundary layer (twice the location of the maximum gives the boundary layer edge). It is essential that the prism layer is thicker than the boundary layer as otherwise there is a danger that the prism layer confines the growth of the boundary layer.

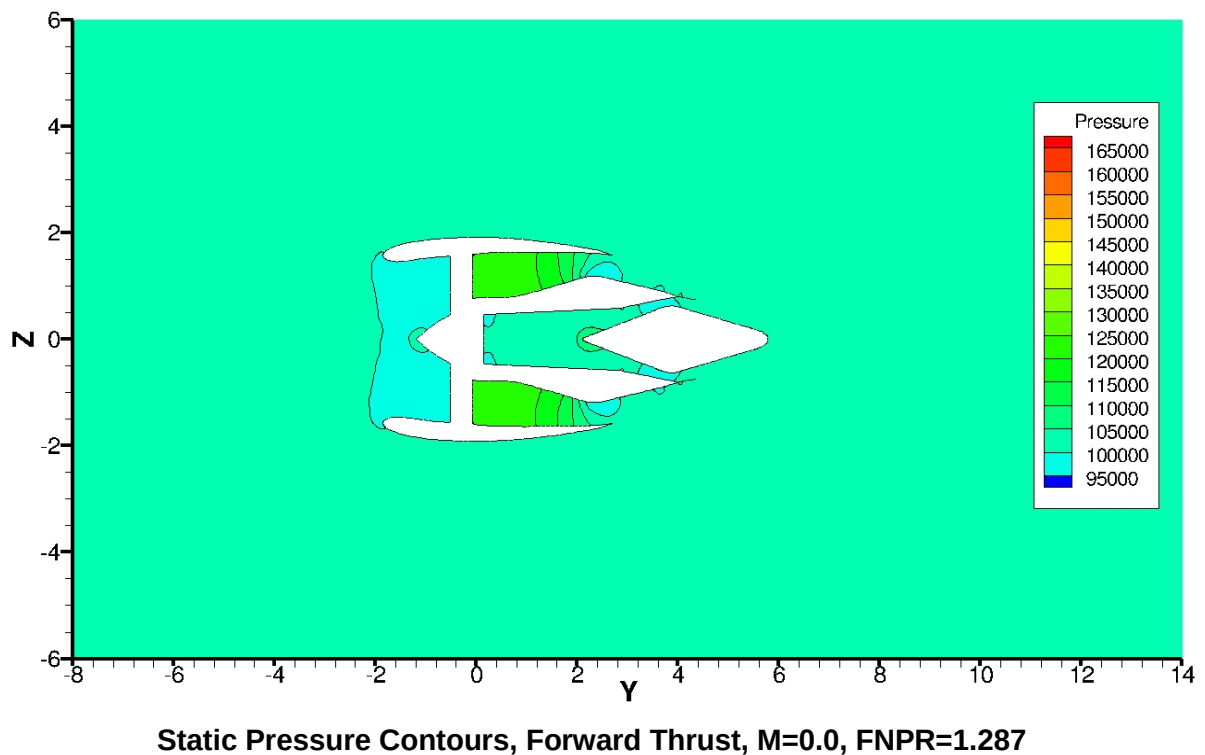
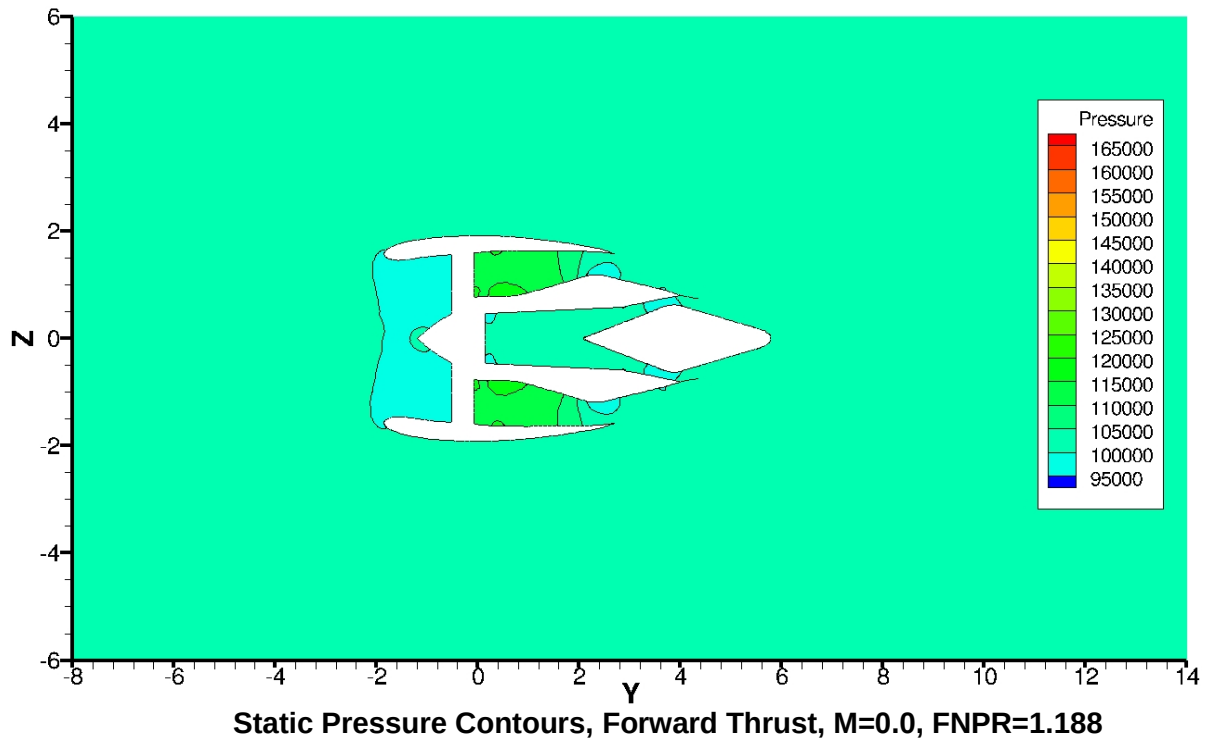
A2.26 Enhanced Wall Treatment for Momentum and Energy Equations

To have a method that can extend its applicability throughout the near-wall region (that is, viscous sub layer, buffer region, and fully-turbulent outer region) it is necessary to formulate the law-of-the-wall as a single wall law for the entire wall region. The enhanced wall functions were developed by smoothly blending the logarithmic layer formulation with the laminar formulation. The enhanced turbulent law-of-the-wall for compressible flow with heat transfer and pressure gradients has been derived by combining the approaches of White and Christoph (Ref) and Huang et al (Ref).

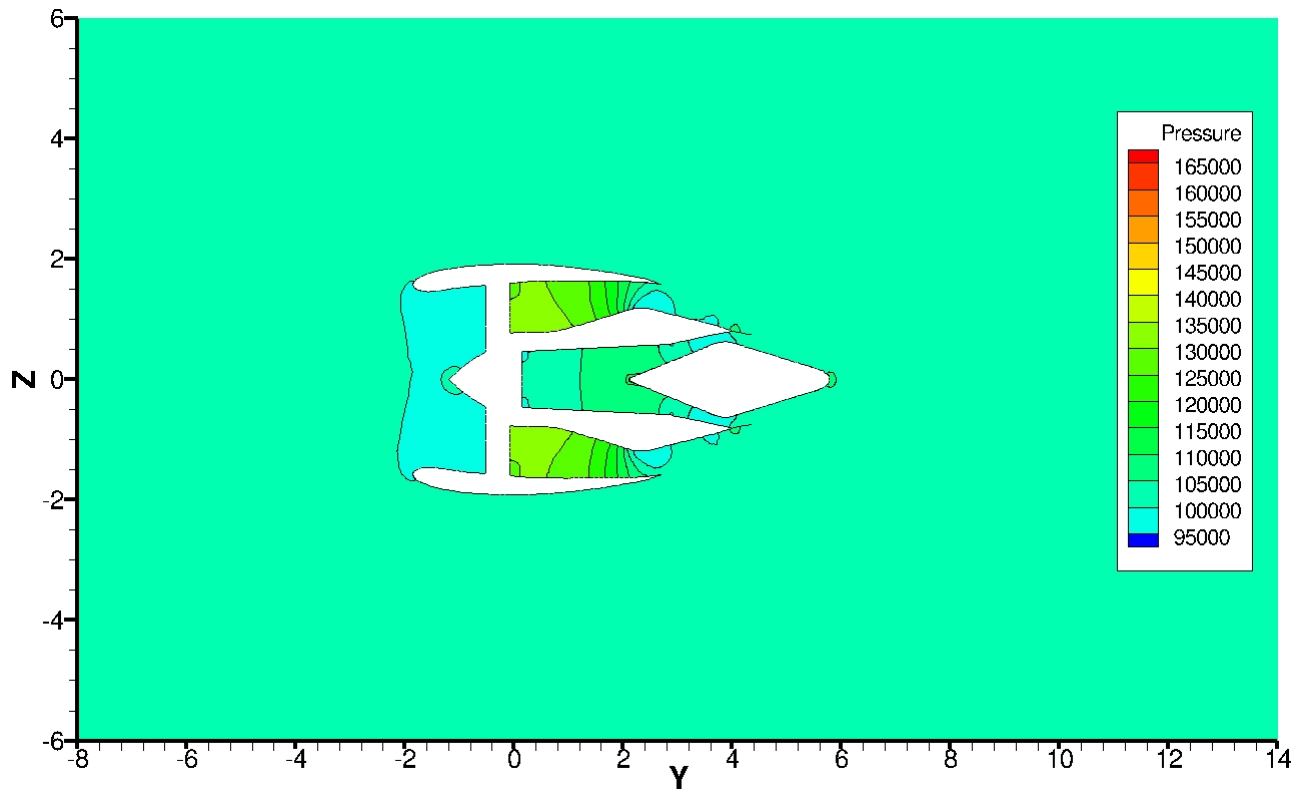
Appendix A3: Forward Thrust Contours of Static and Total Pressure and Streamlines, $M = 0.0$ Static

Appendix A3 – Forward Thrust at $M=0.0$

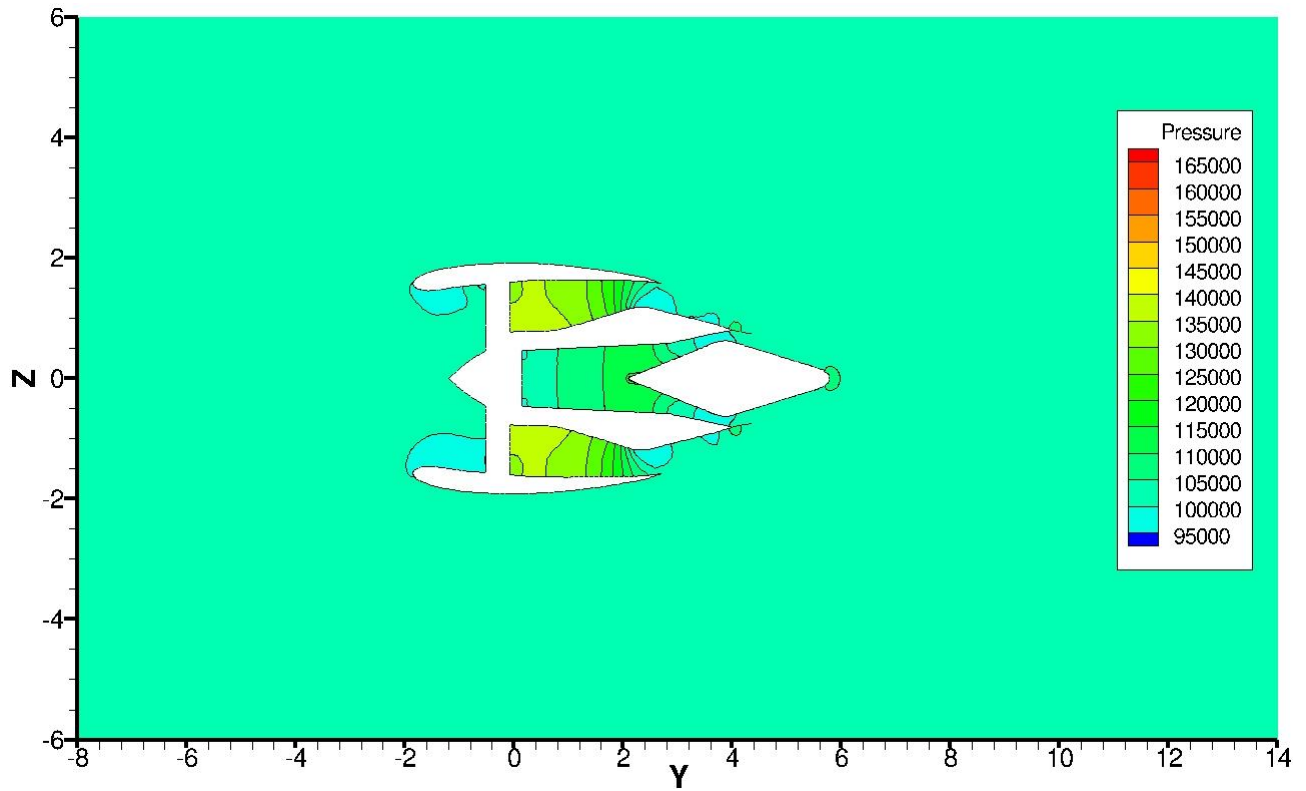
Appendix A3.1 – Static Pressure Contours



Static Pressure Contours, Forward Thrust, $M=0.0$, $FNPR=1.386$

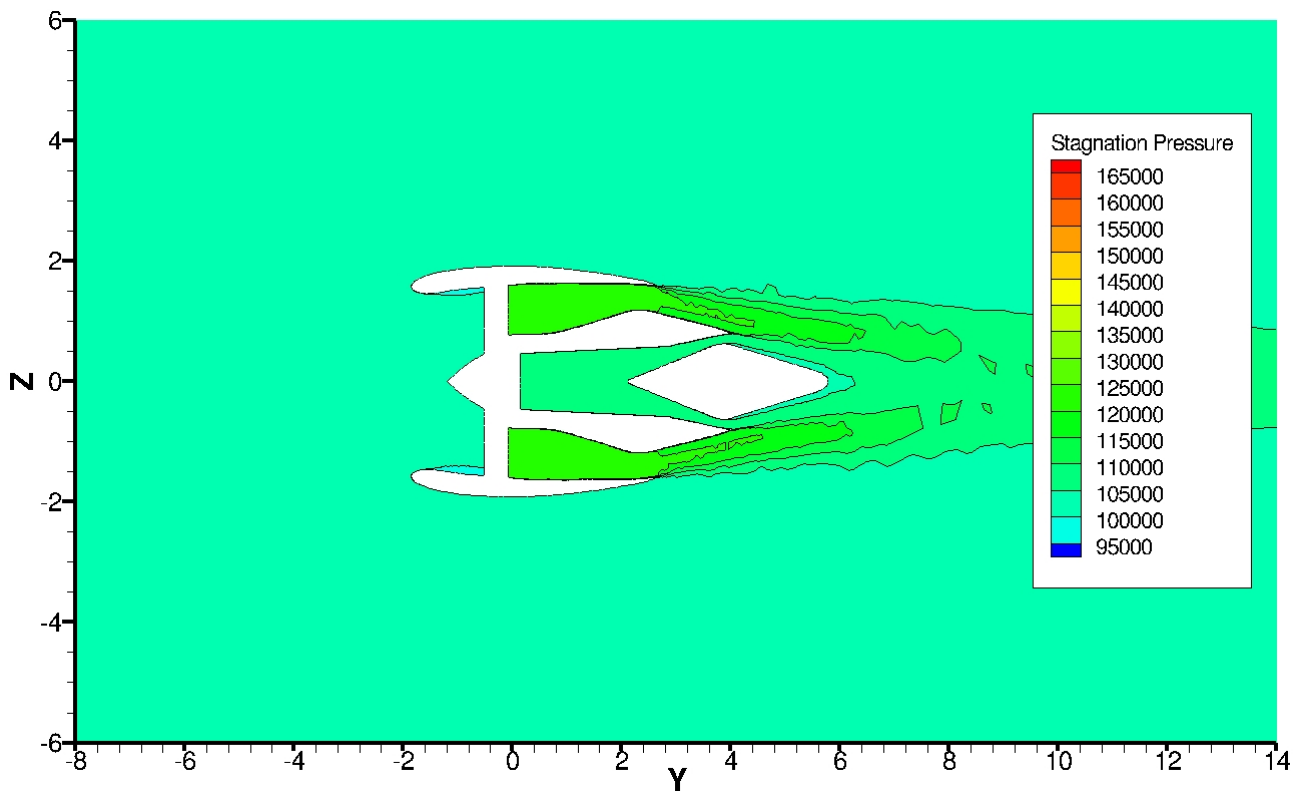


Static Pressure Contours, Forward Thrust, $M=0.0$, $FNPR=1.505$

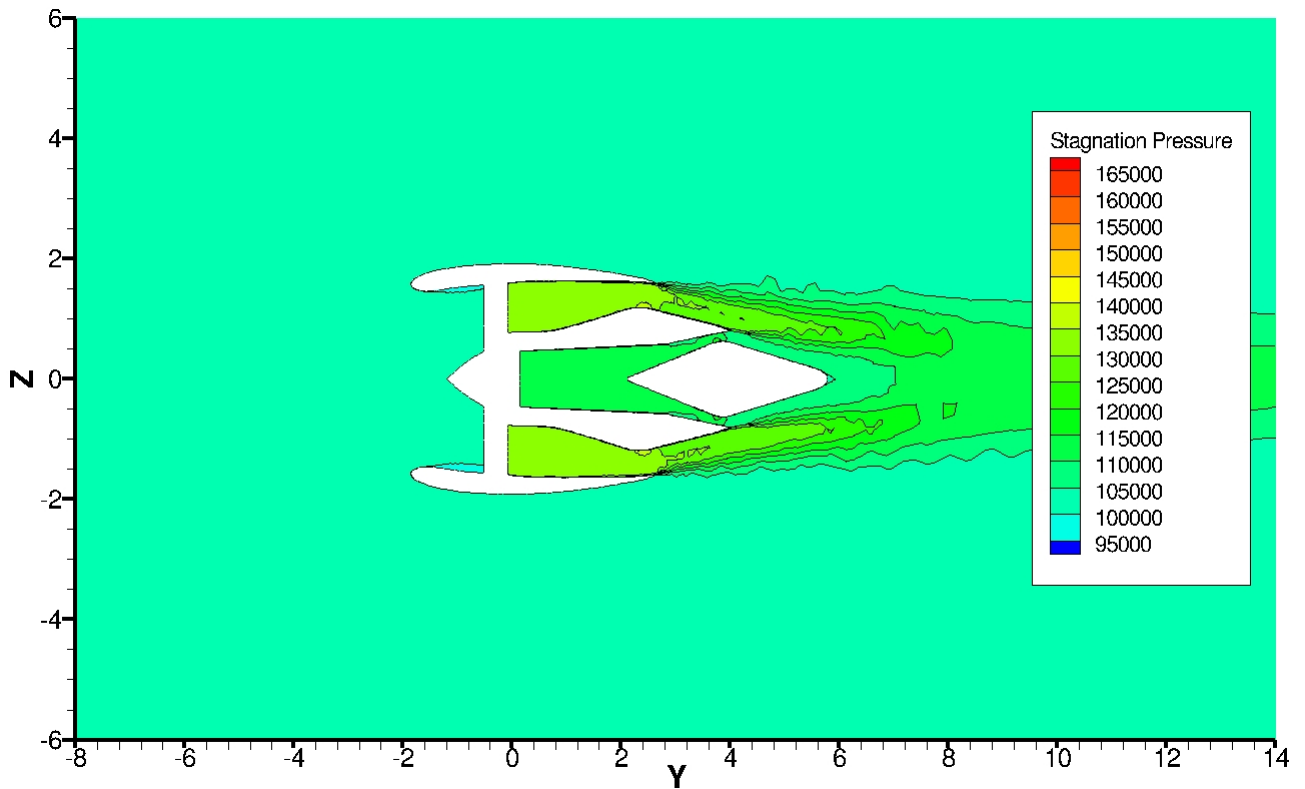


Appendix A3.2 – Total Pressure Contours

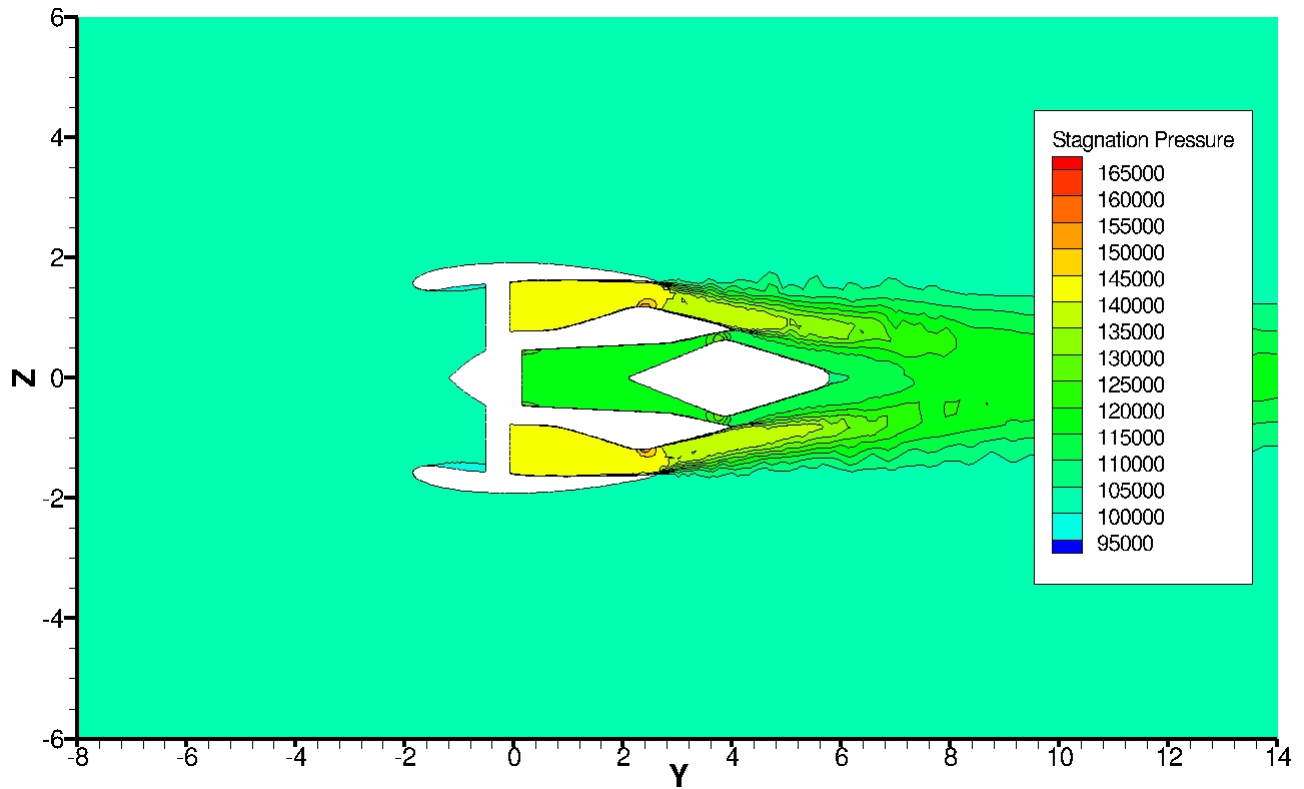
Total Pressure Contours, Forward Thrust, $M=0.0$, $FNPR=1.188$



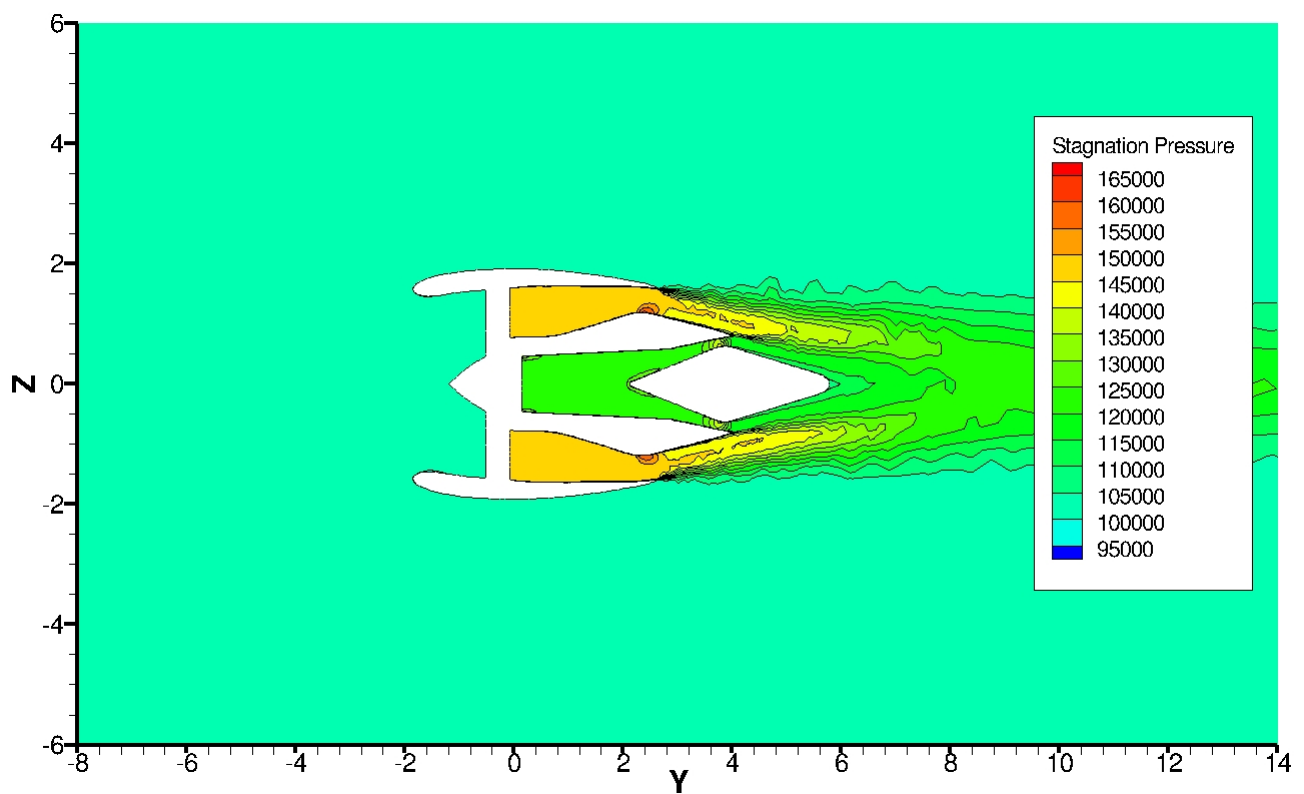
Total Pressure Contours, Forward Thrust, $M=0.0$, $FNPR=1.287$



Total Pressure Contours, Forward Thrust, $M=0.0$, $FNPR=1.386$

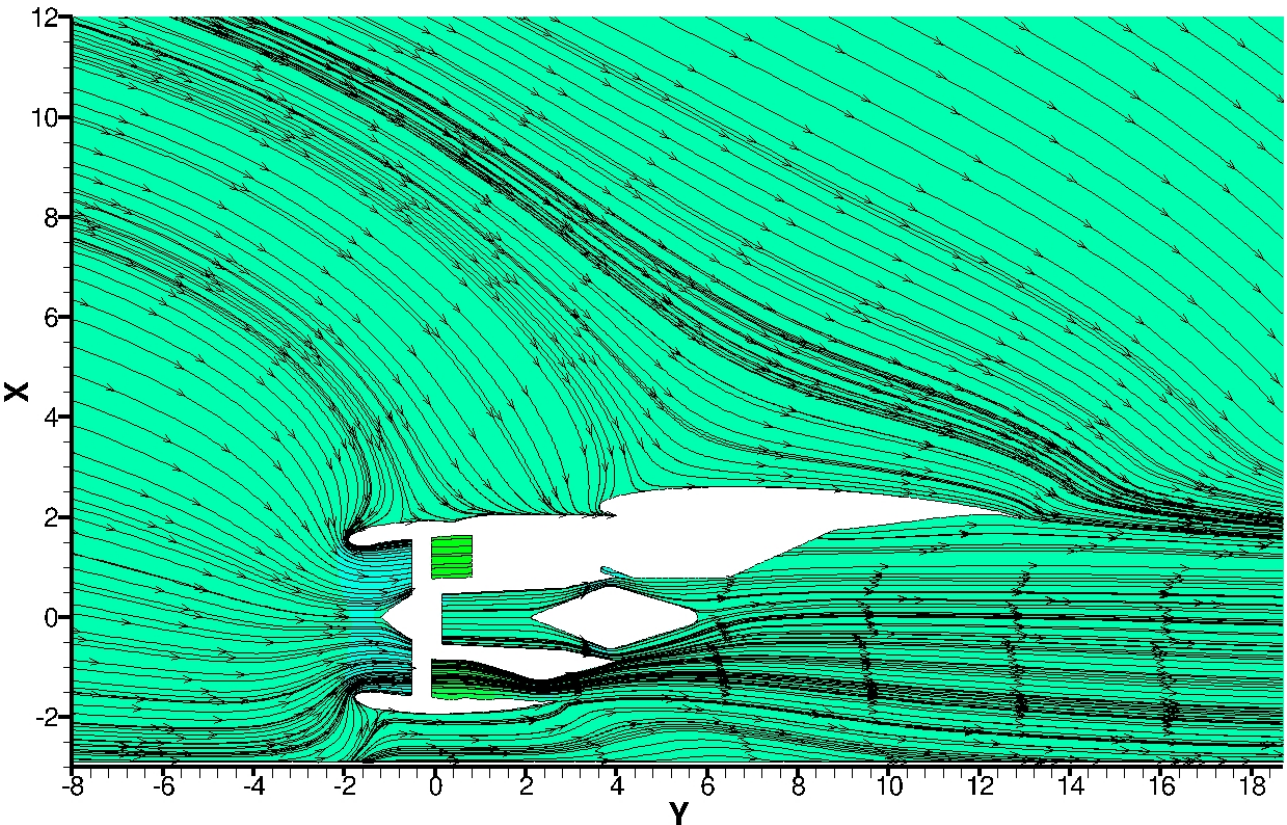
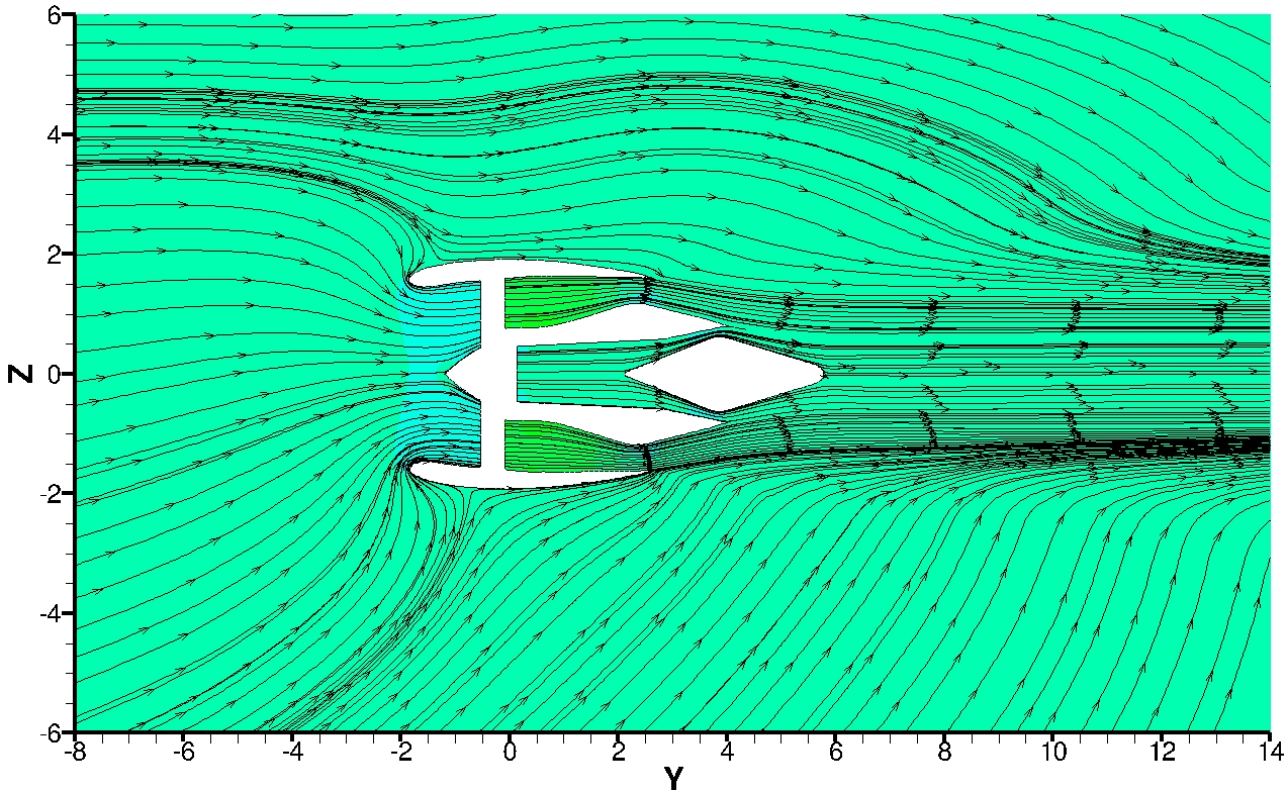


Total Pressure Contours, Forward Thrust, $M=0.0$, $FNPR=1.505$

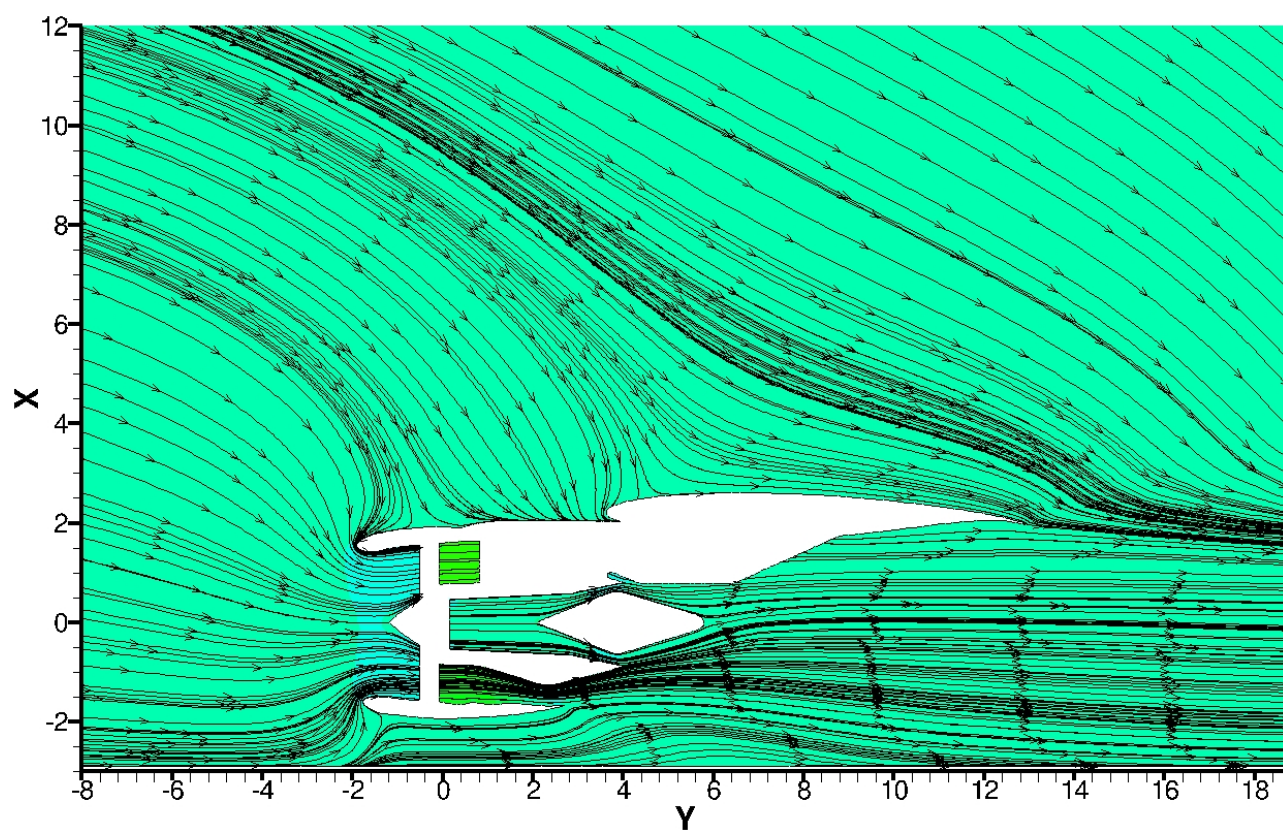
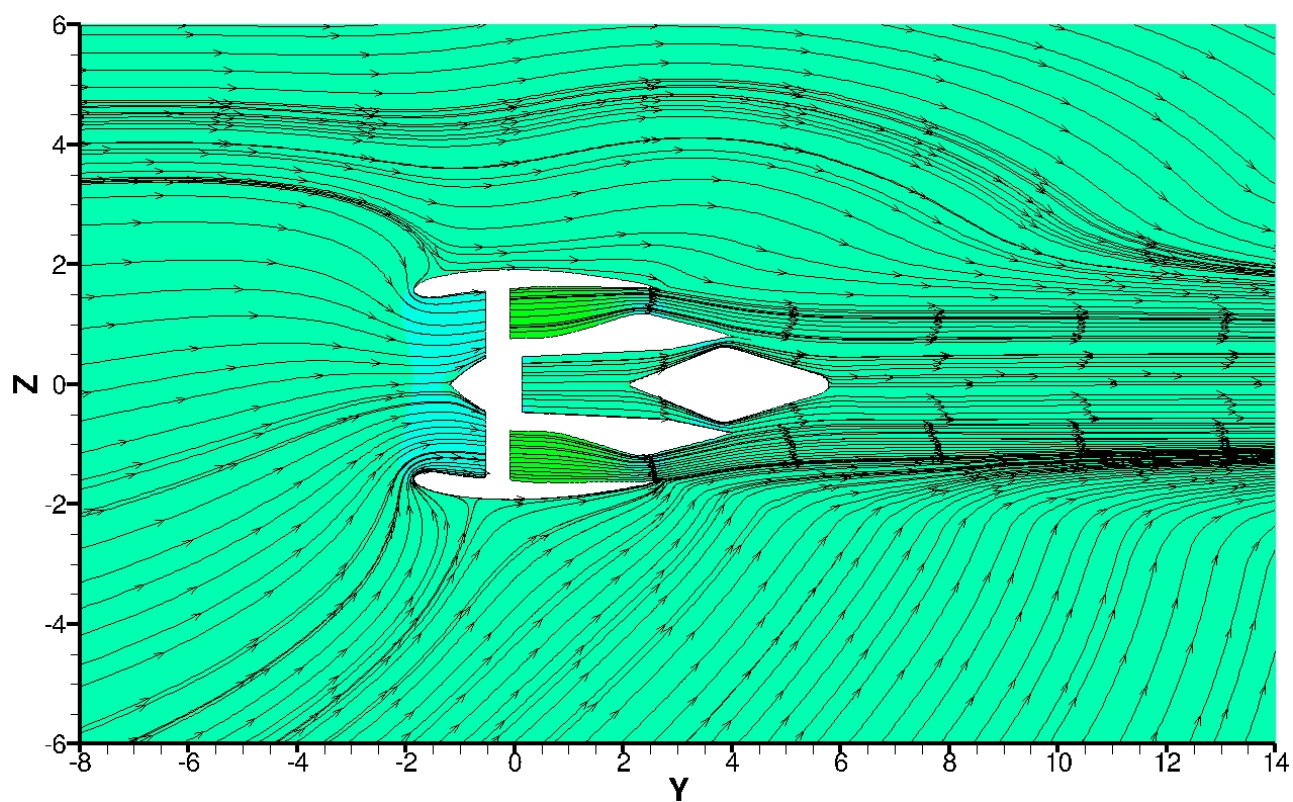


Appendix A3.3 Streamlines Plot

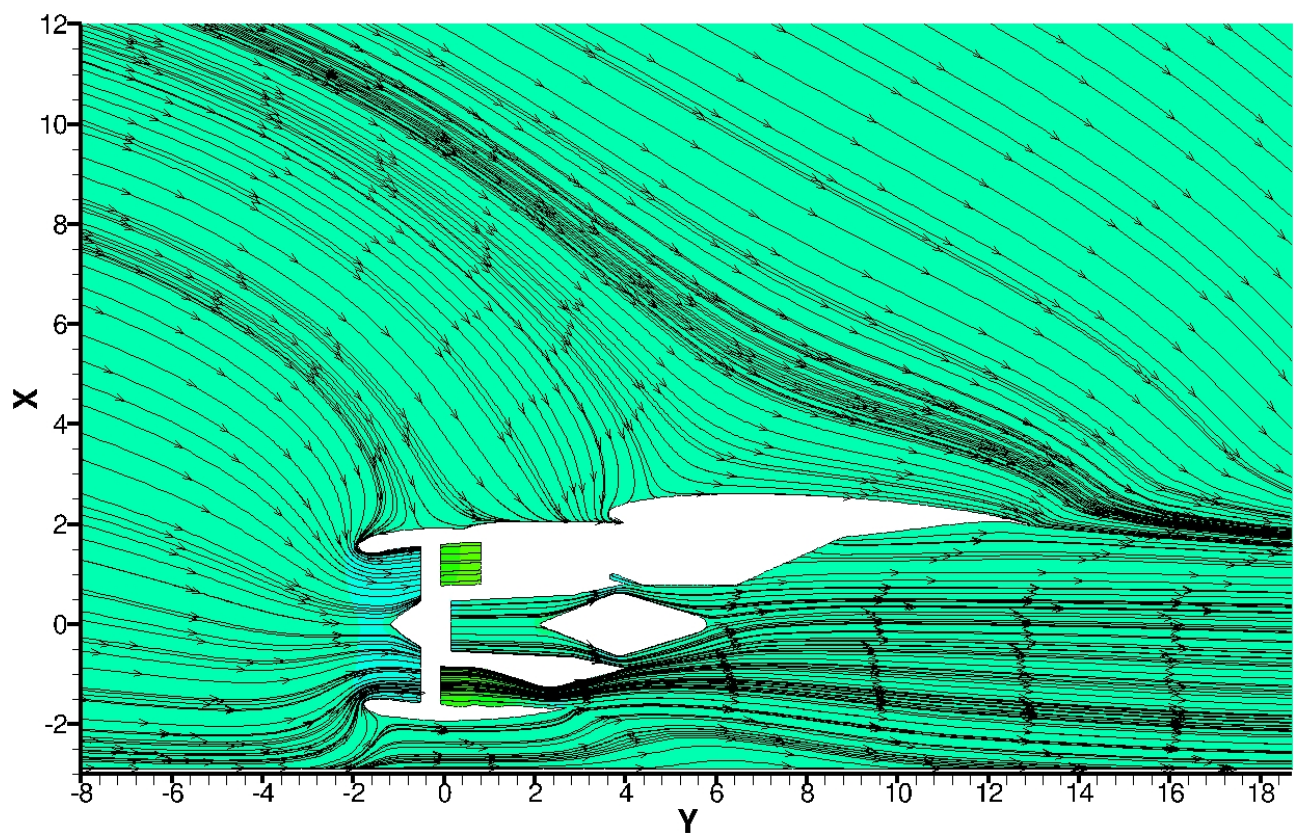
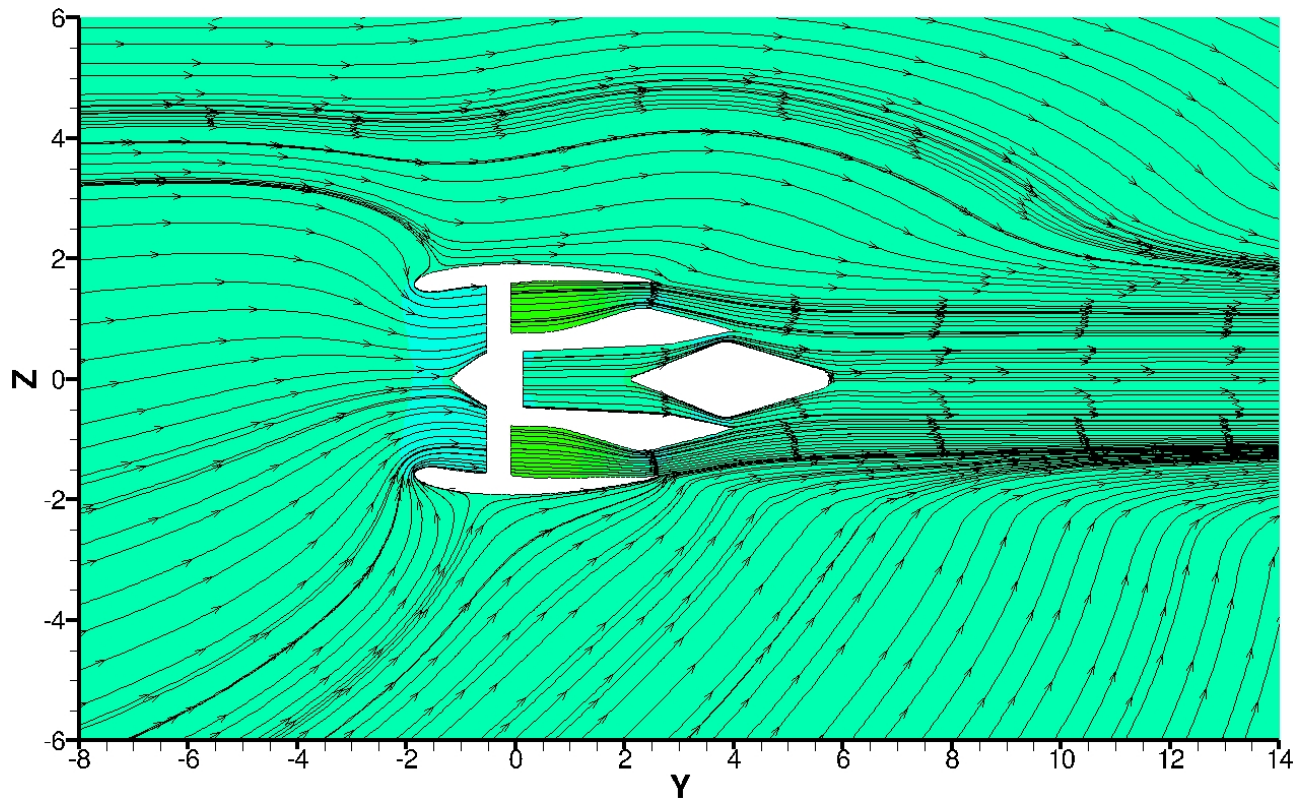
Streamlines, Forward Thrust, $M=0.0$, $FNPR=1.188$



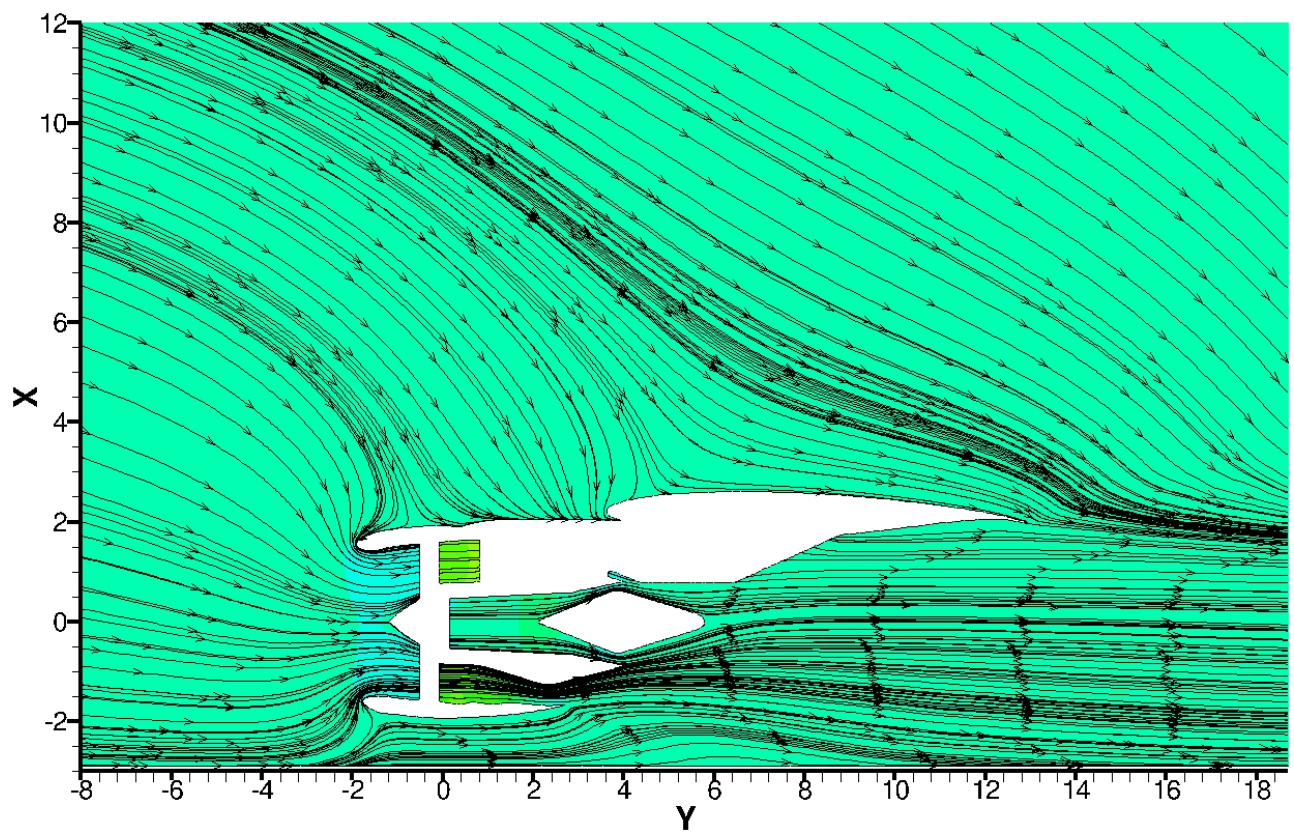
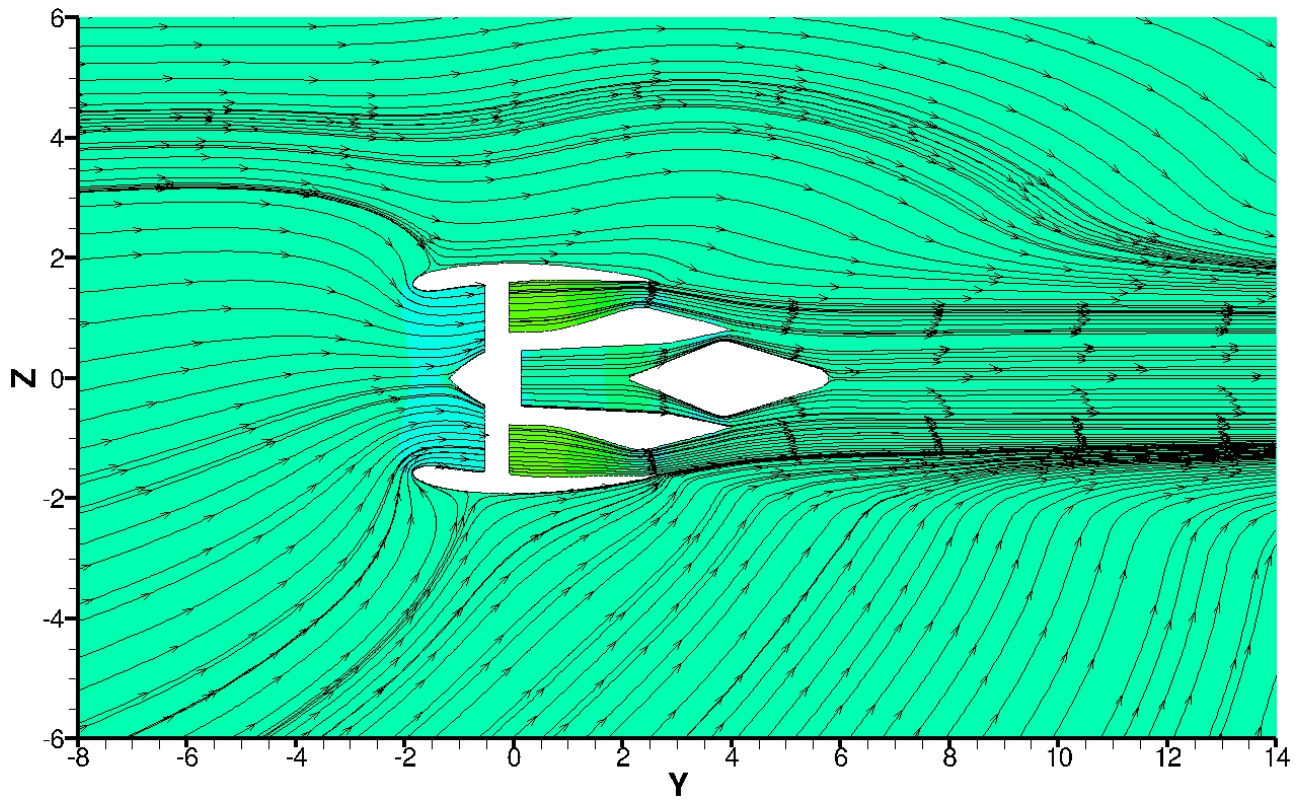
Streamlines, Forward Thrust, $M=0.0$, $FNPR=1.237$



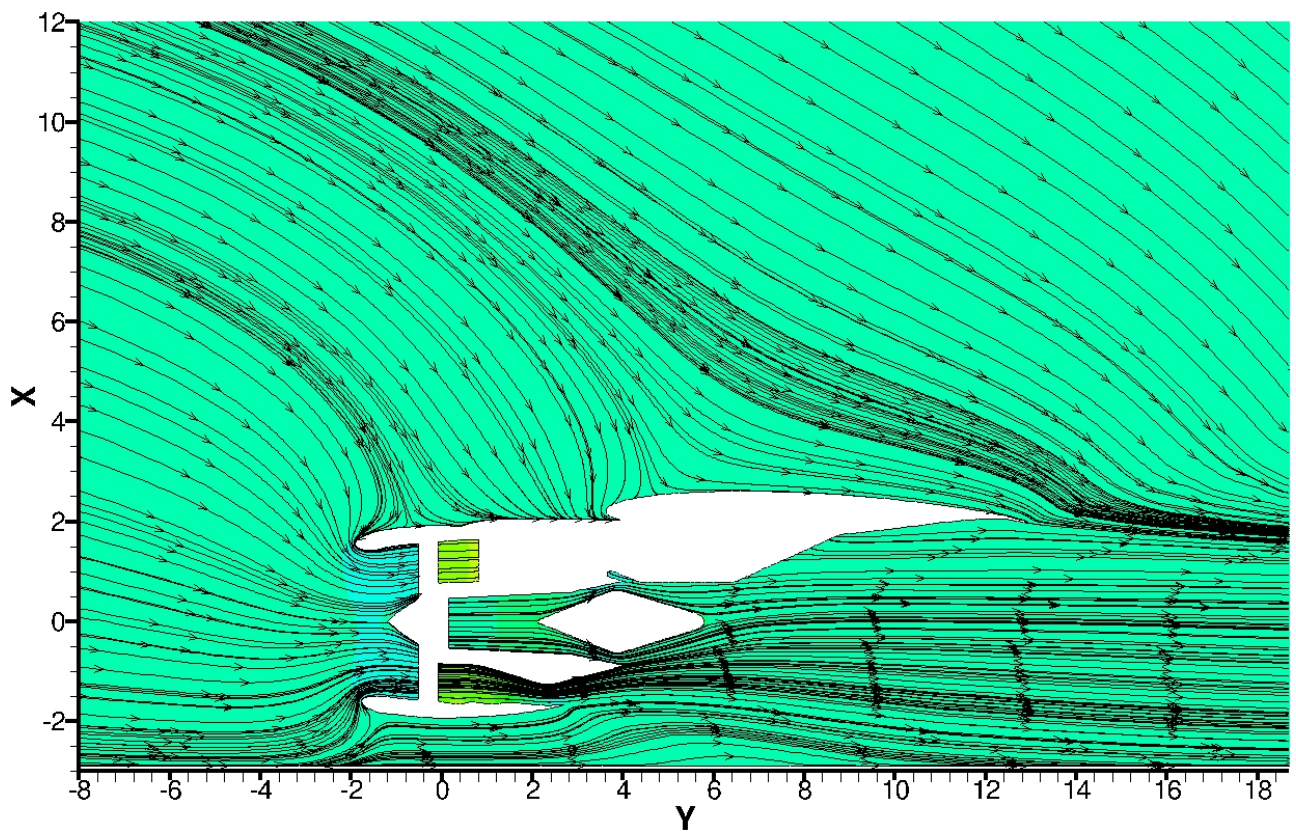
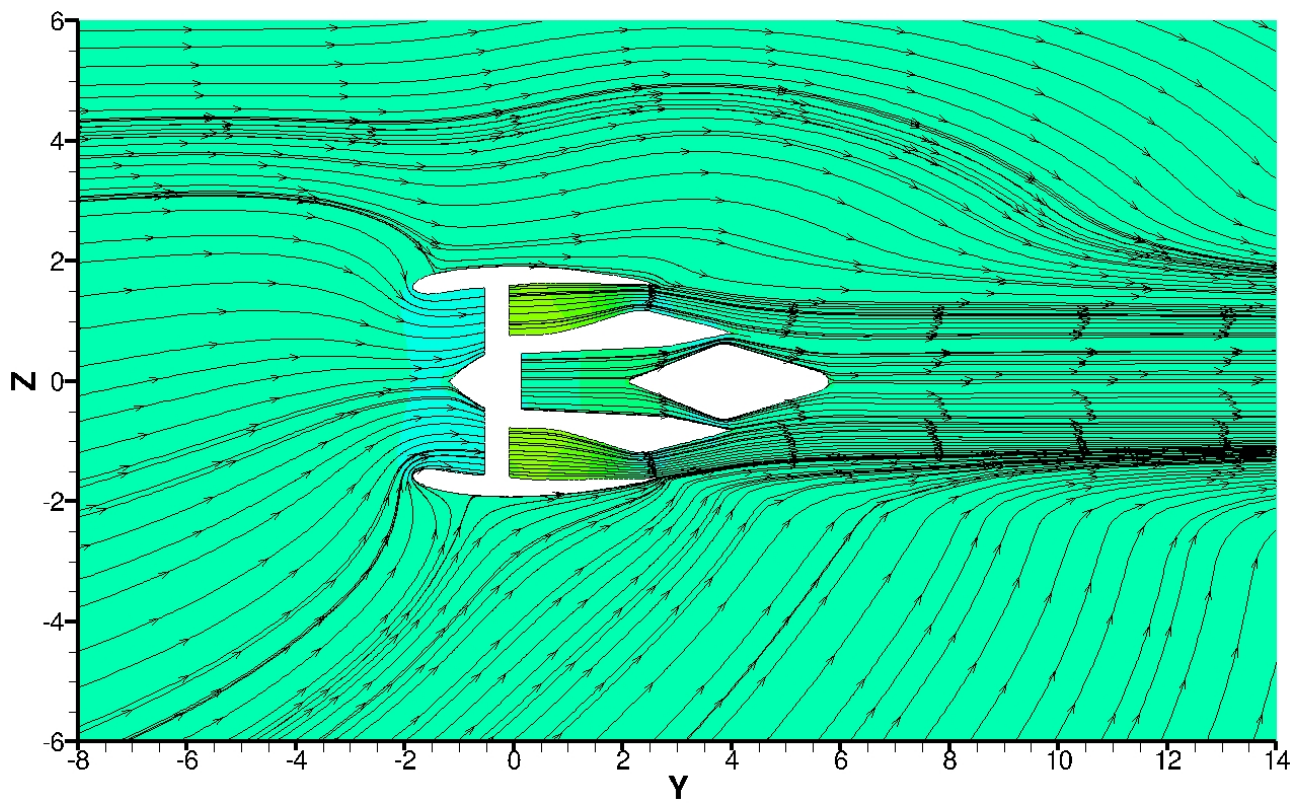
Streamlines, Forward Thrust, $M=0.0$, $FNPR=1.287$



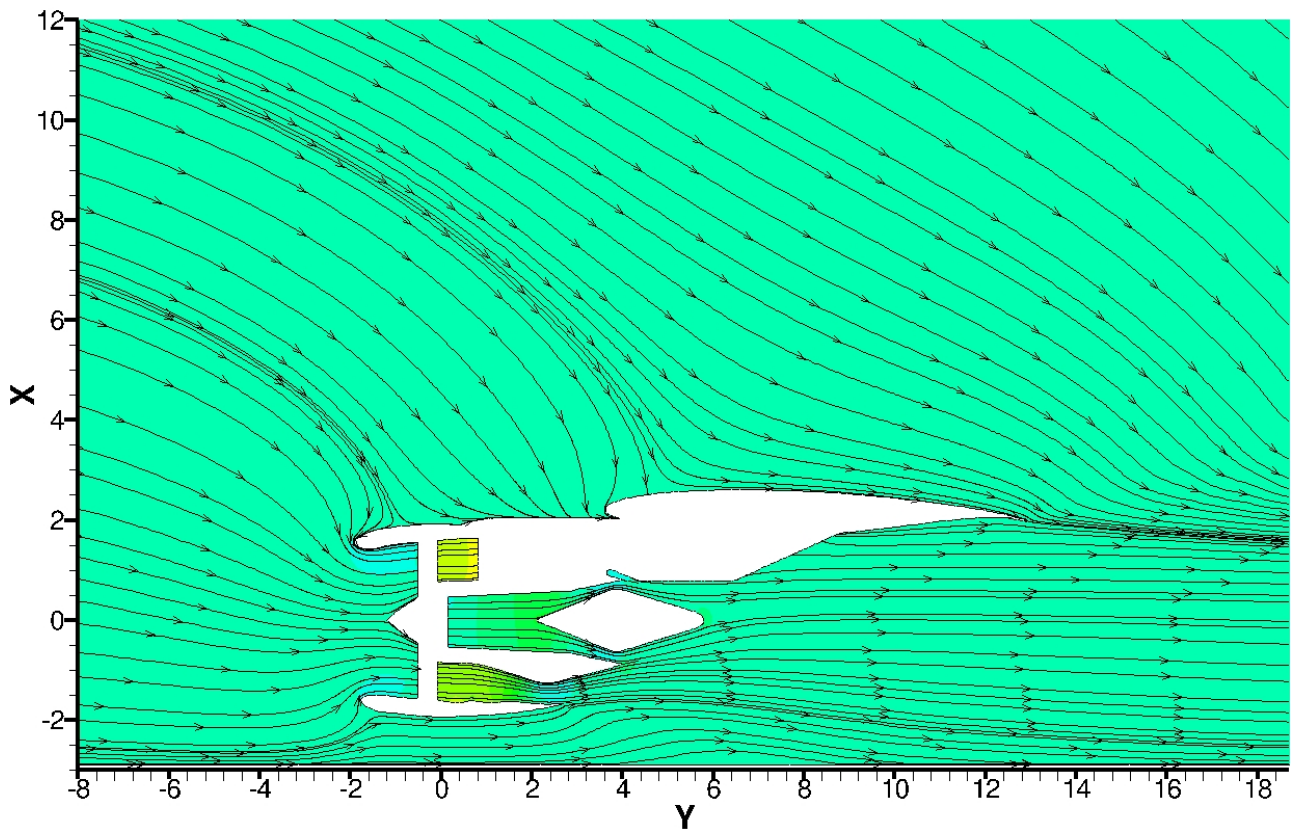
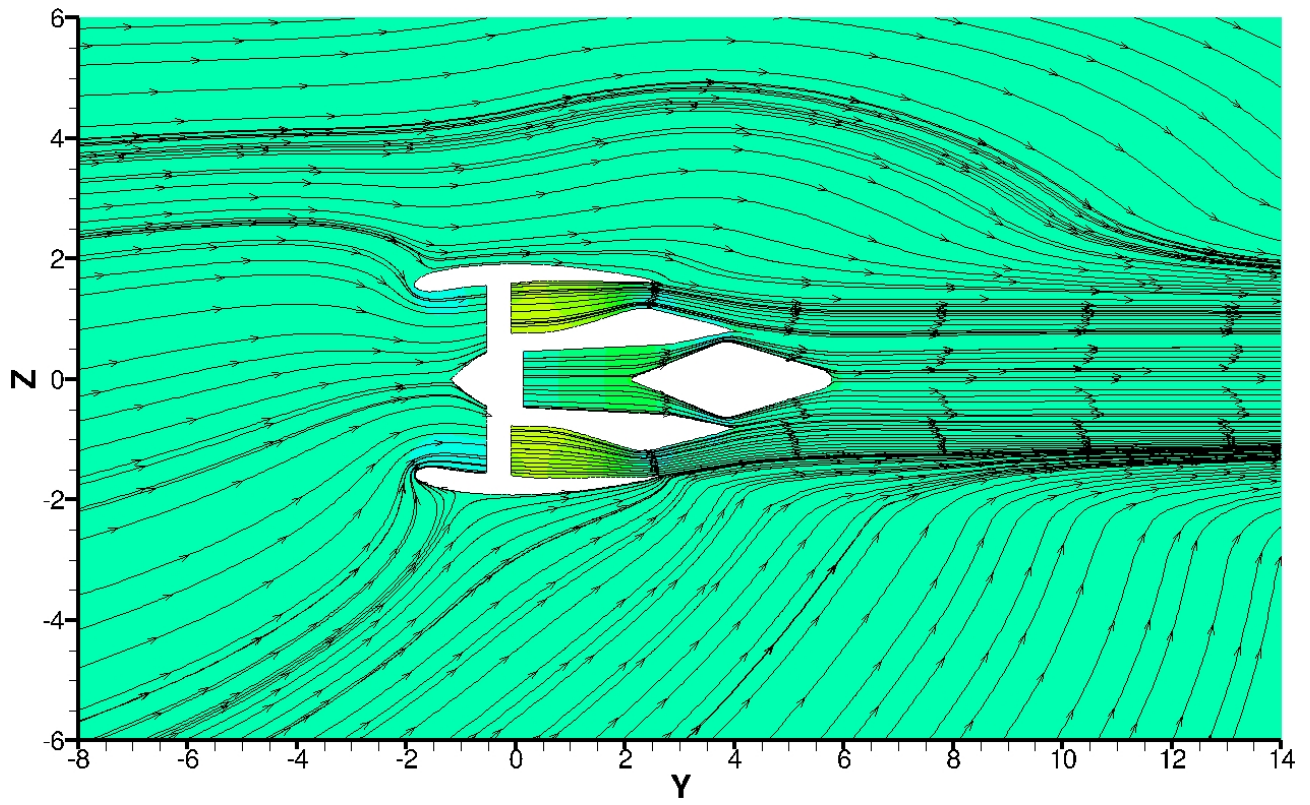
Streamlines, Forward Thrust, $M=0.0$, $FNPR=1.336$



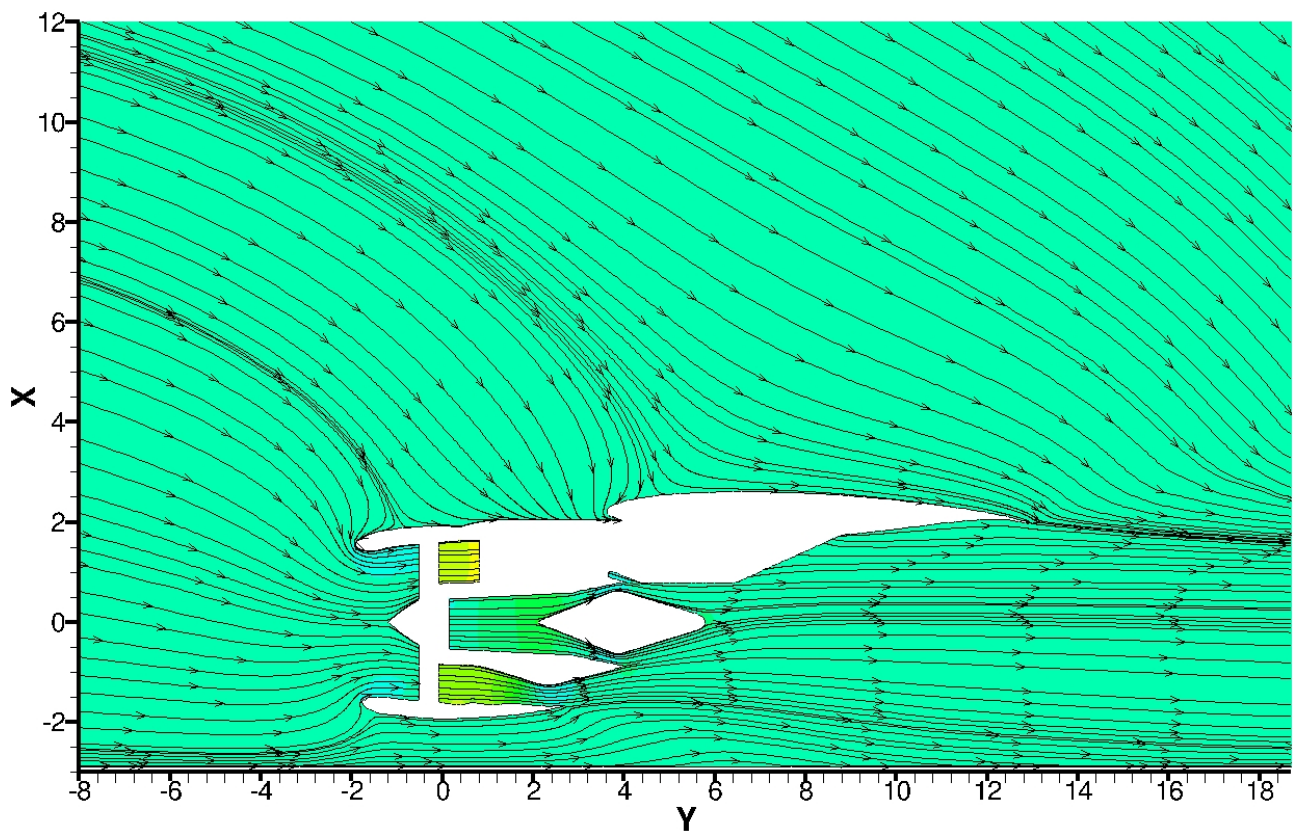
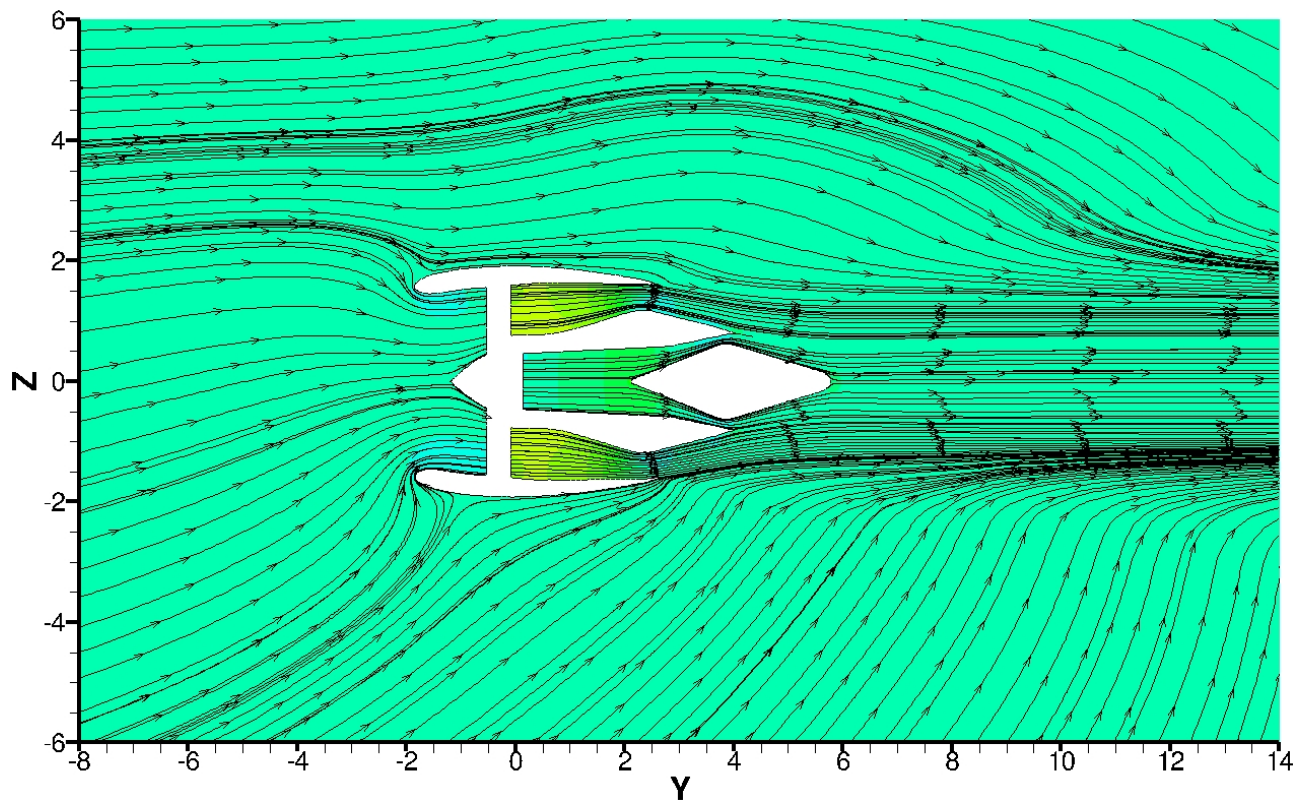
Streamlines, Forward Thrust, $M=0.0$, $FNPR=1.386$



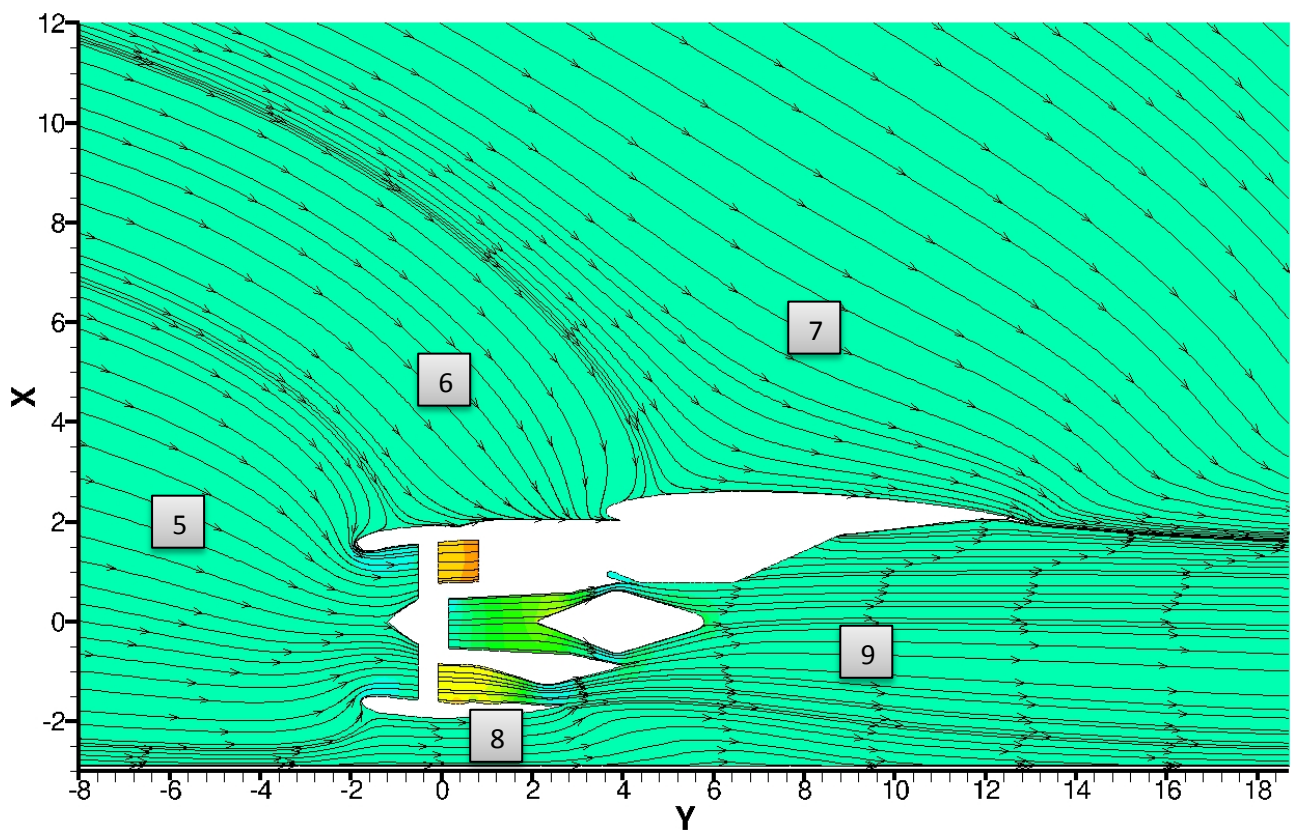
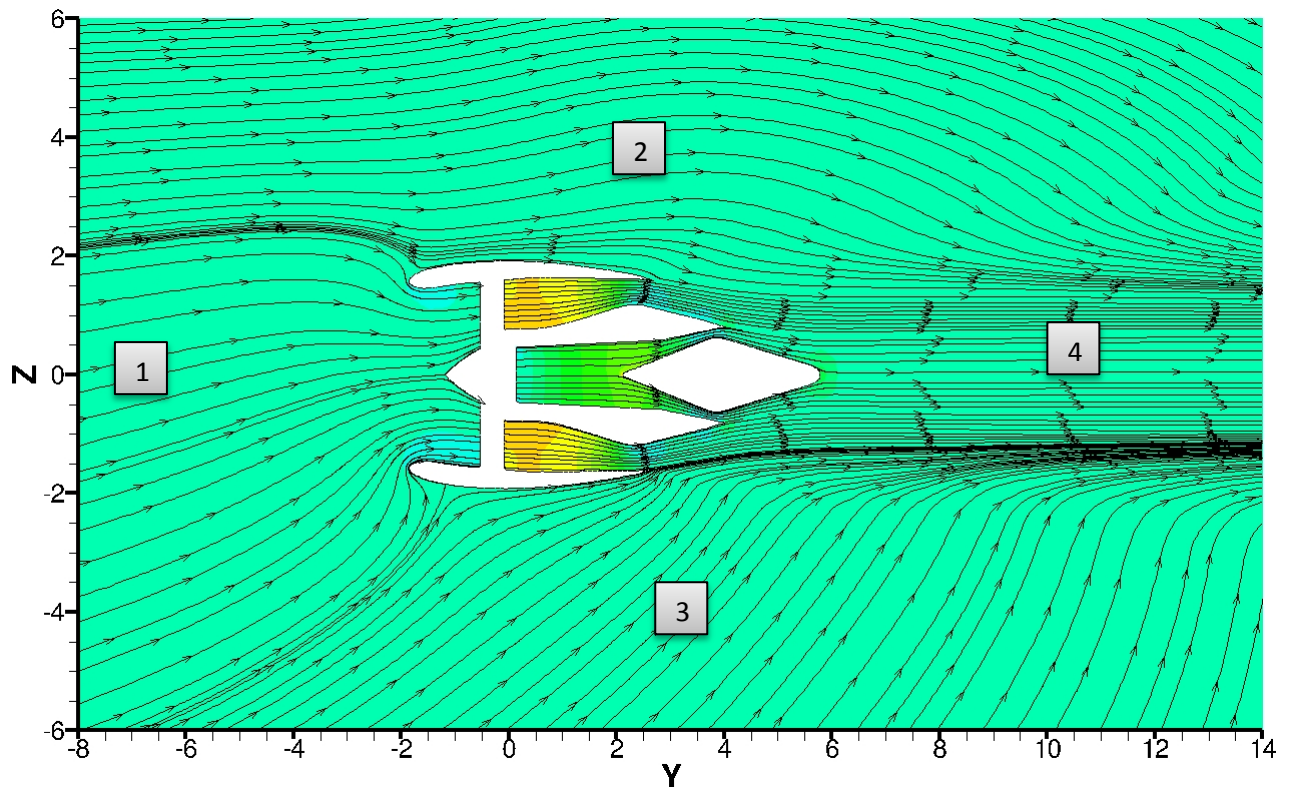
Streamlines, Forward Thrust, $M=0.0$, $FNPR=1.445$



Streamlines, Forward Thrust, $M=0.0$, $FNPR=1.505$



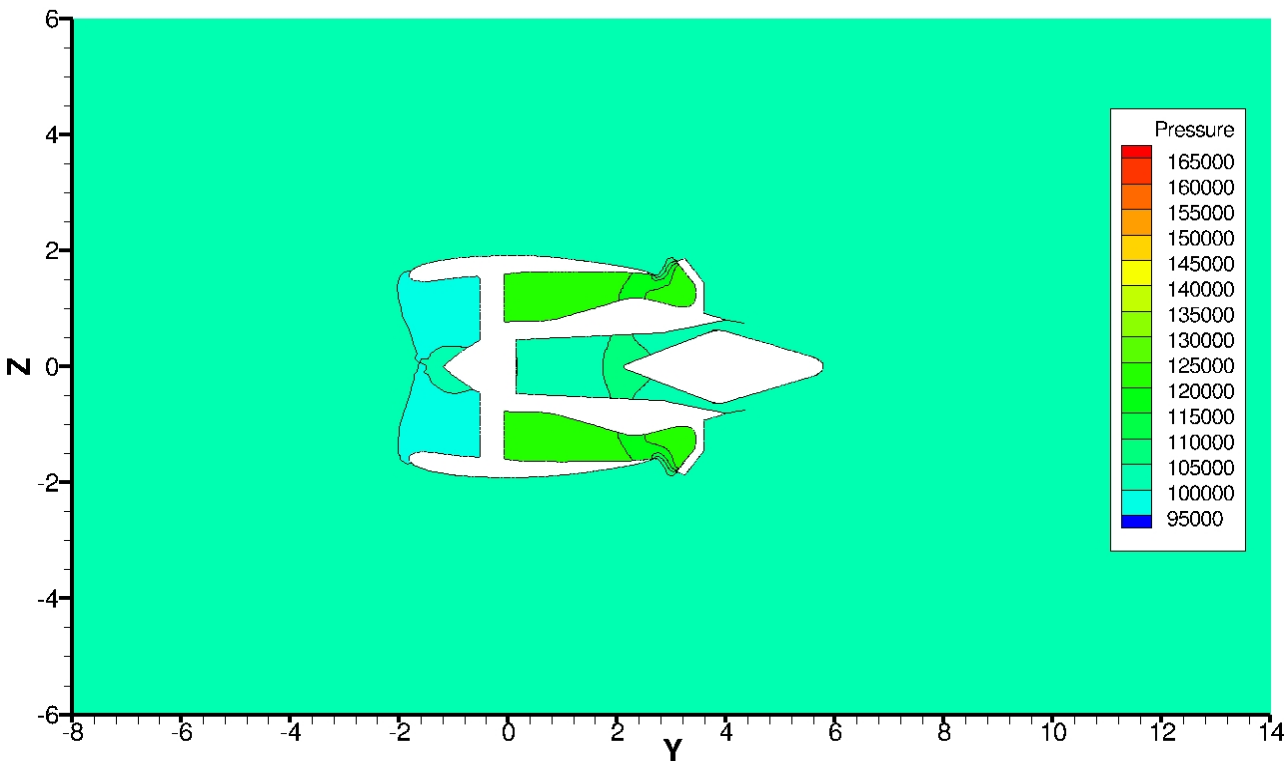
Streamlines, Forward Thrust, $M=0.0$, $FNPR=1.554$



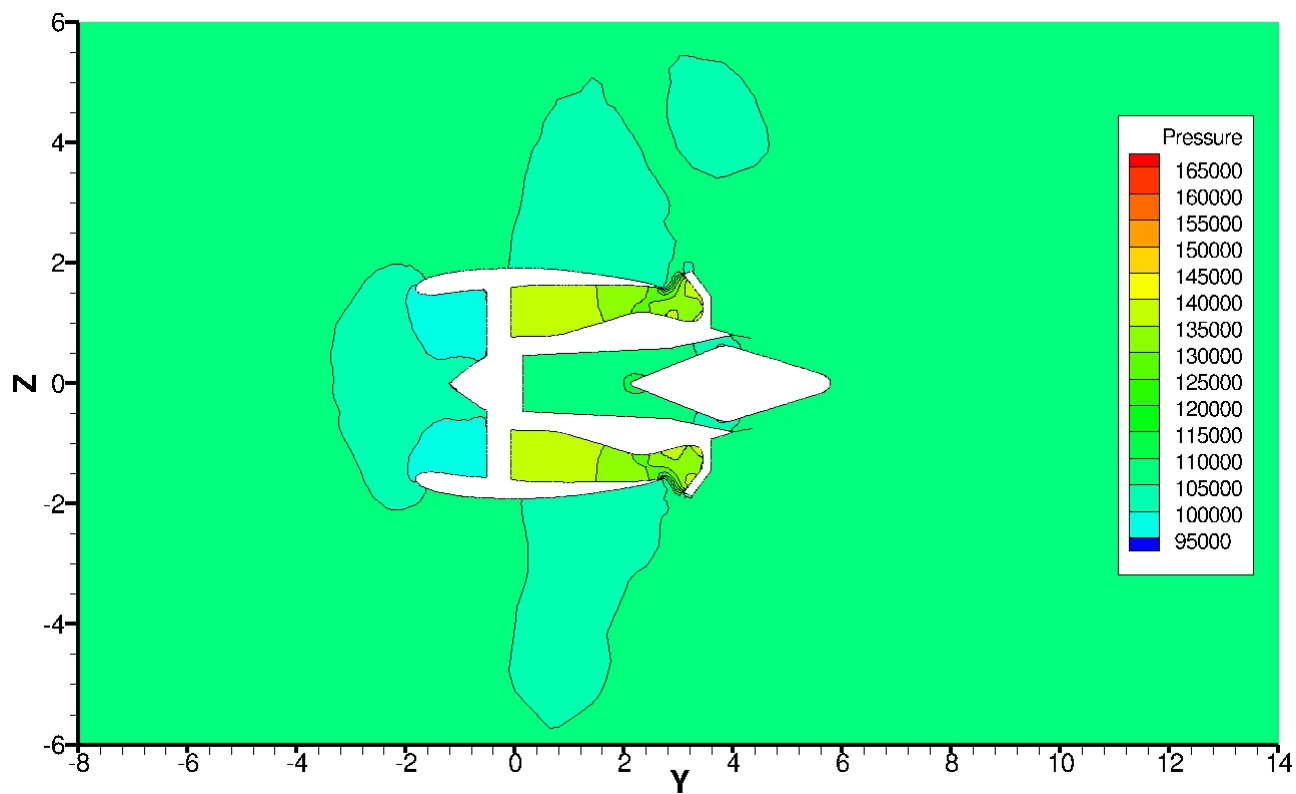
Appendix A4: Reverse Thrust 40 Degree with and without kicker plate at Static Condition, $M=0.0$

Appendix A4.1 –Static Pressure Contours

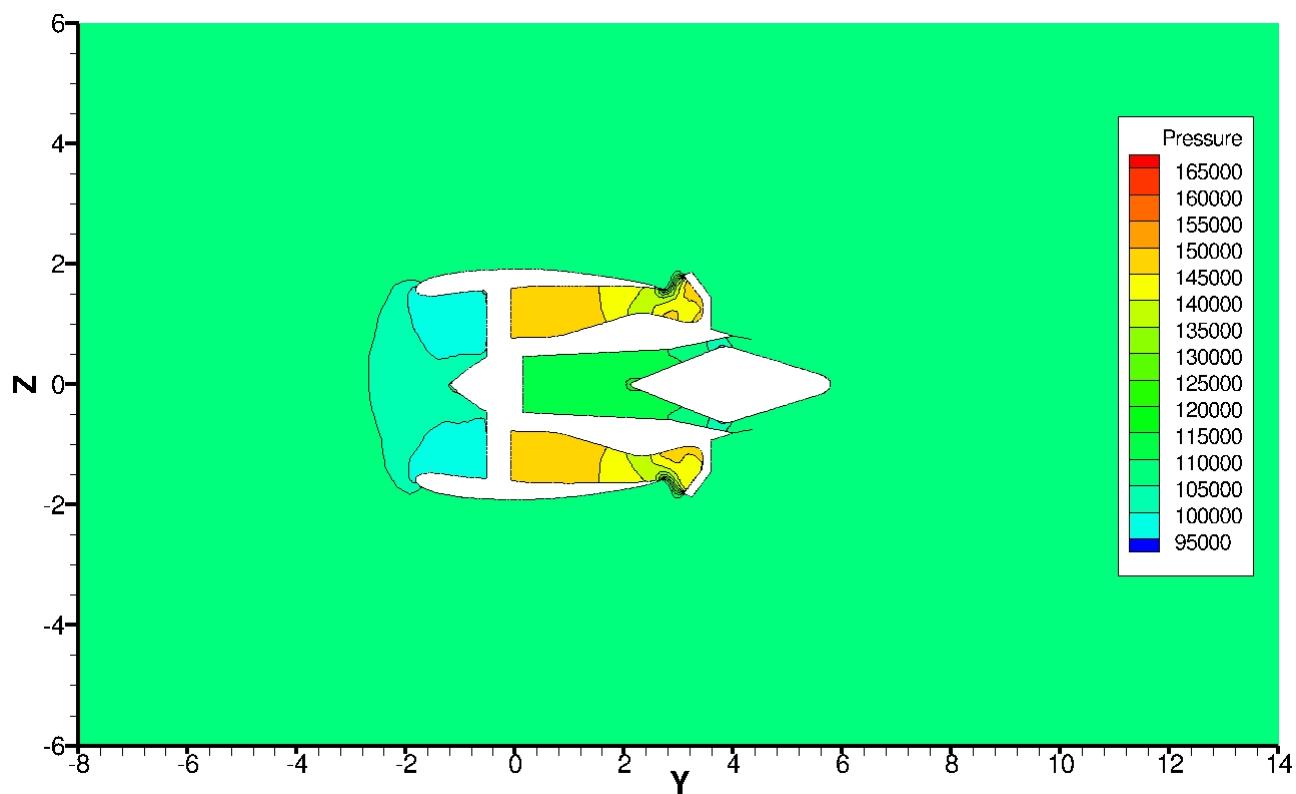
Static Pressure Contours, 40 Deg Core Mounted Target Reverser, $M=0.0$, $FNPR=1.237$



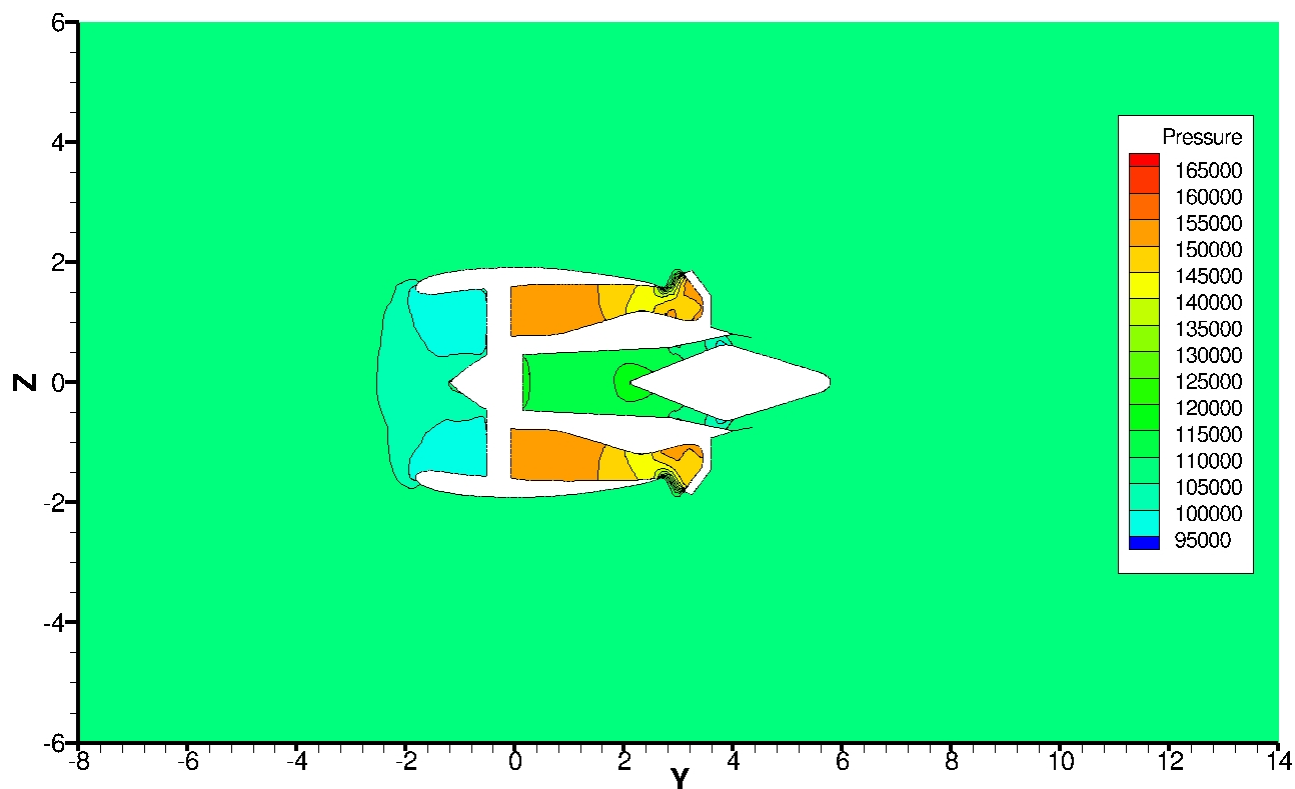
Static Pressure Contours, 40 Deg Core Mounted Target Reverser, $M=0.0$, $FNPR=1.386$



Static Pressure Contours, 40 Deg Core Mounted Target Reverser, $M=0.0$, $FNPR=1.505$

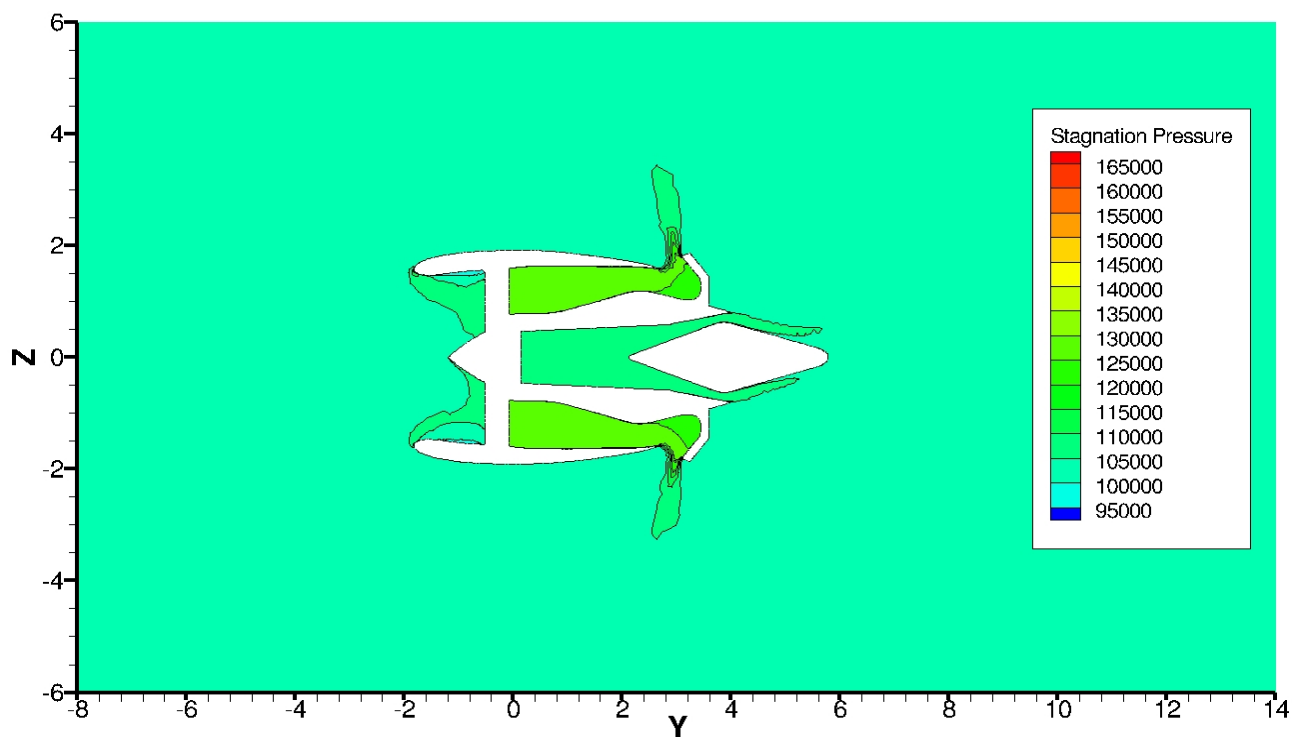


Static Pressure Contours, 40 Deg Core Mounted Target Reverser, $M=0.0$, $FNPR=1.554$

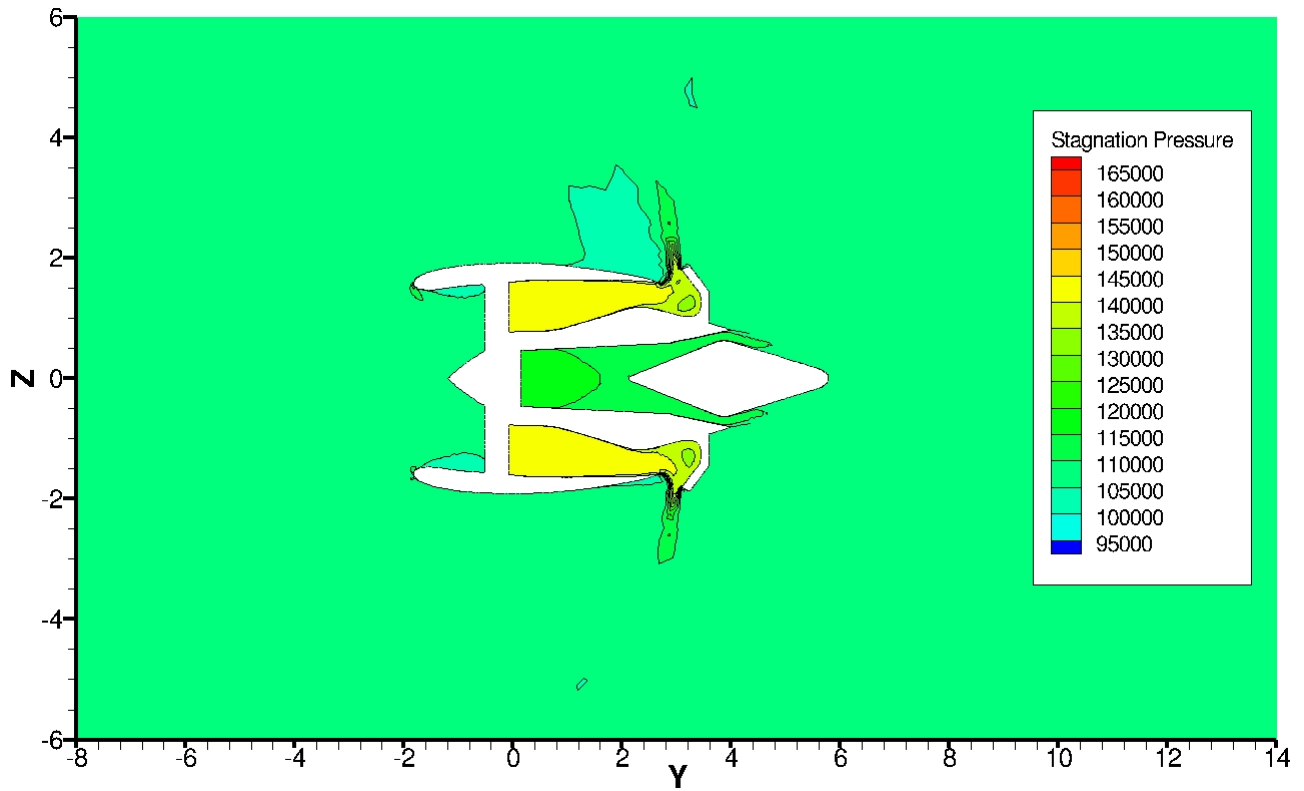


Appendix A4.2 – Total Pressure Contours

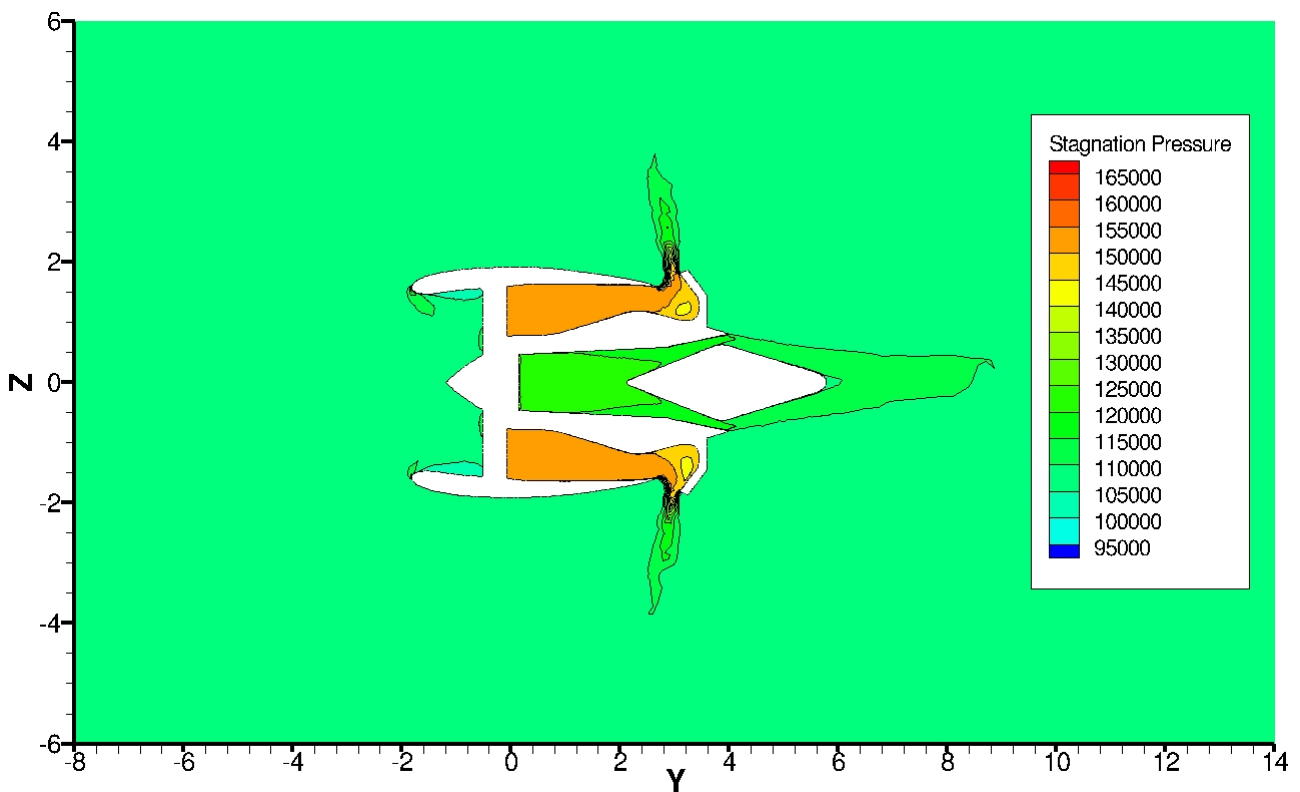
Total Pressure Contours, 40 Deg Core Mounted Target Thrust Reverser, $M=0.0$, $FNPR=1.237$



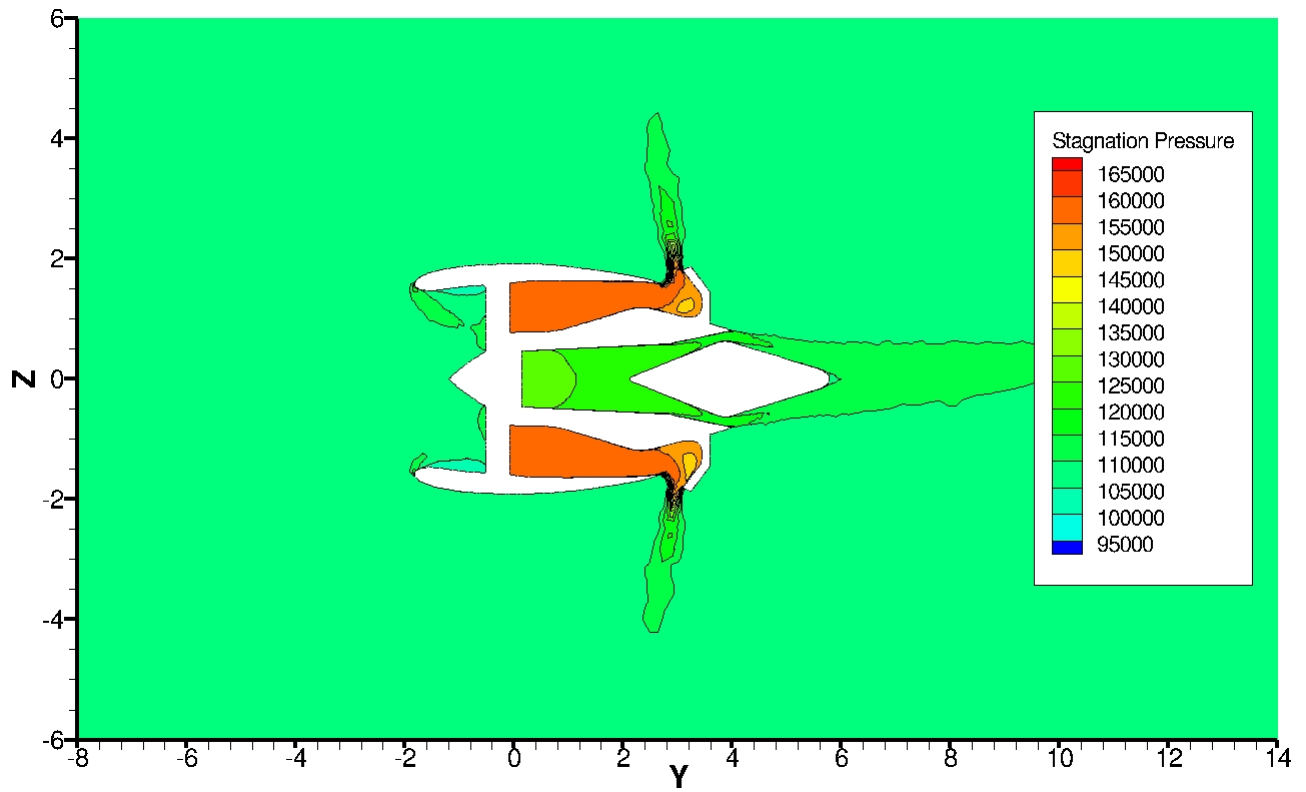
Total Pressure Contours, 40 Deg Core Mounted Target Thrust Reverser, $M=0.0$, $FNPR=1.386$



Total Pressure Contours, 40 Deg Core Mounted Target Thrust Reverser, $M=0.0$, $FNPR=1.505$

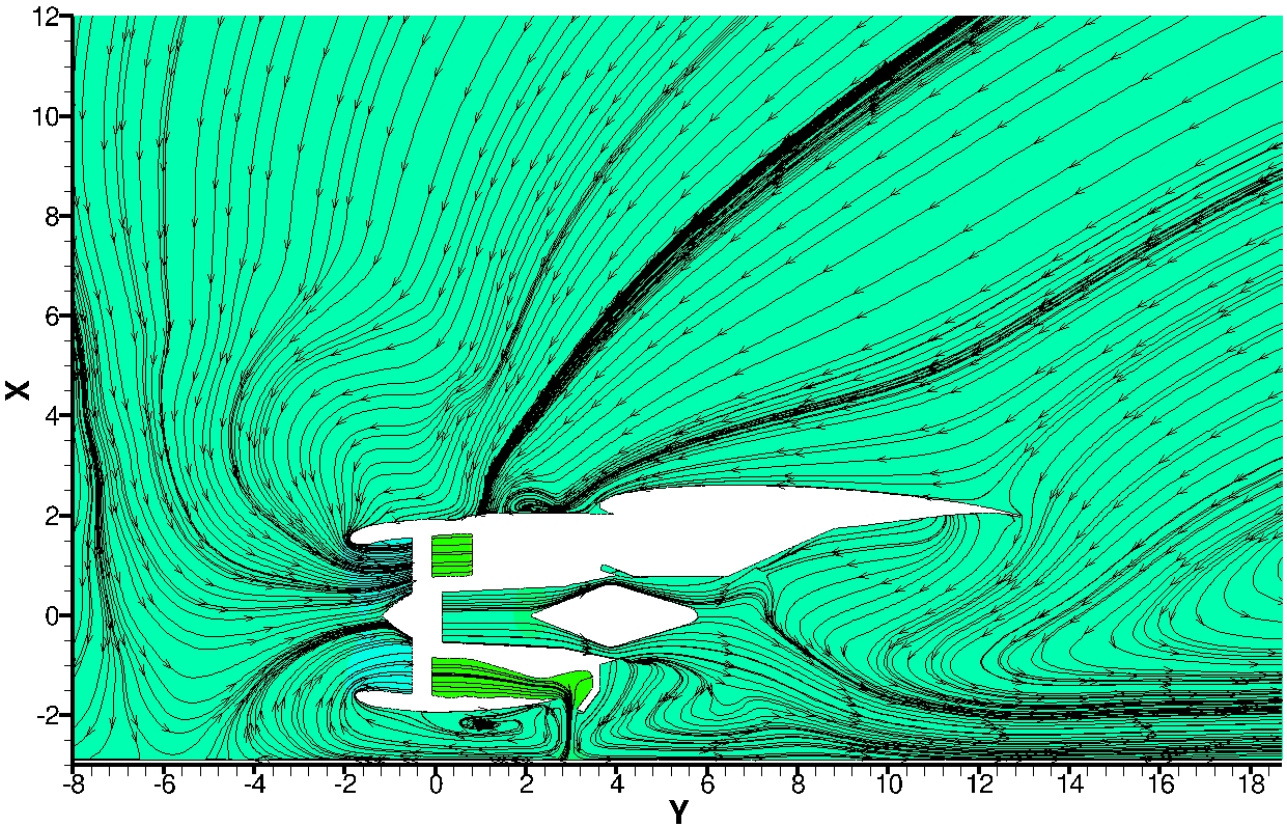
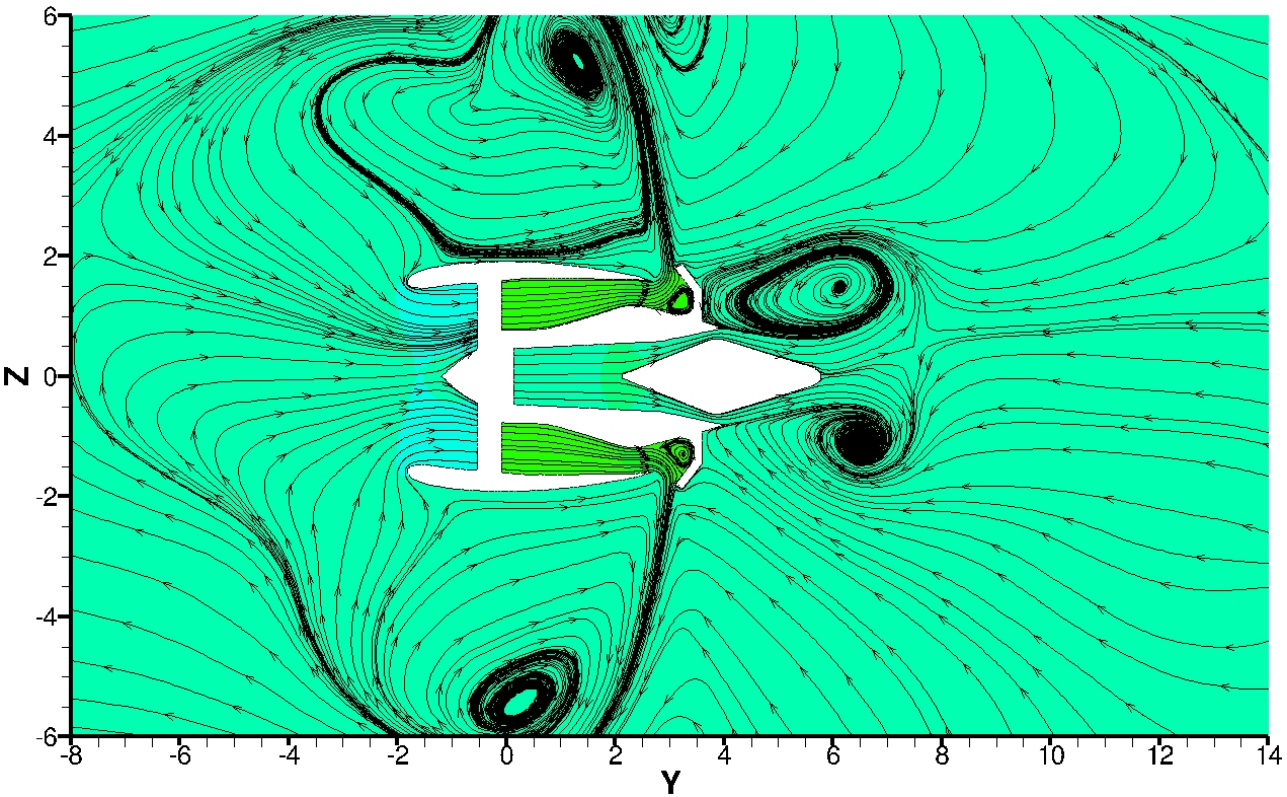


Total Pressure Contours, 40 Deg Core Mounted Target Thrust Reverser, $M=0.0$, $FNPR=1.505$

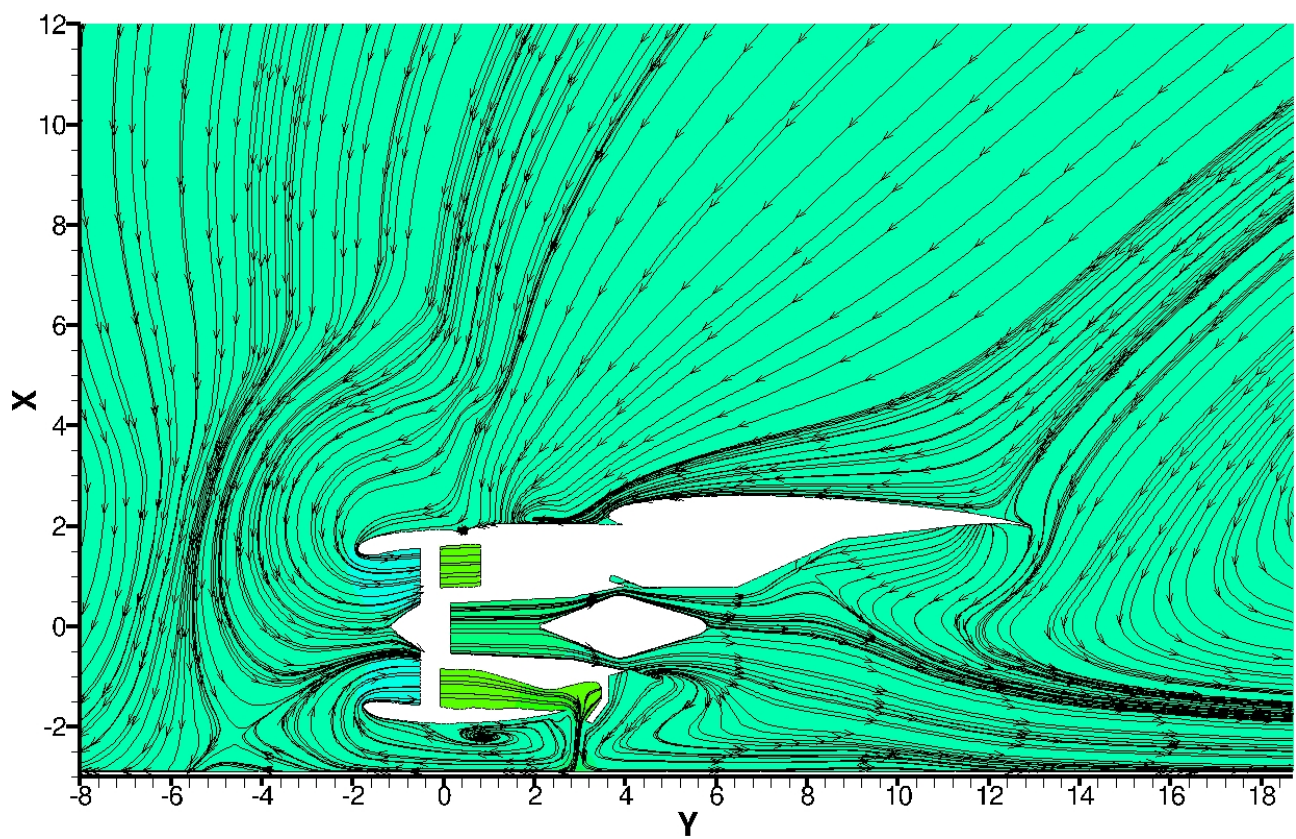
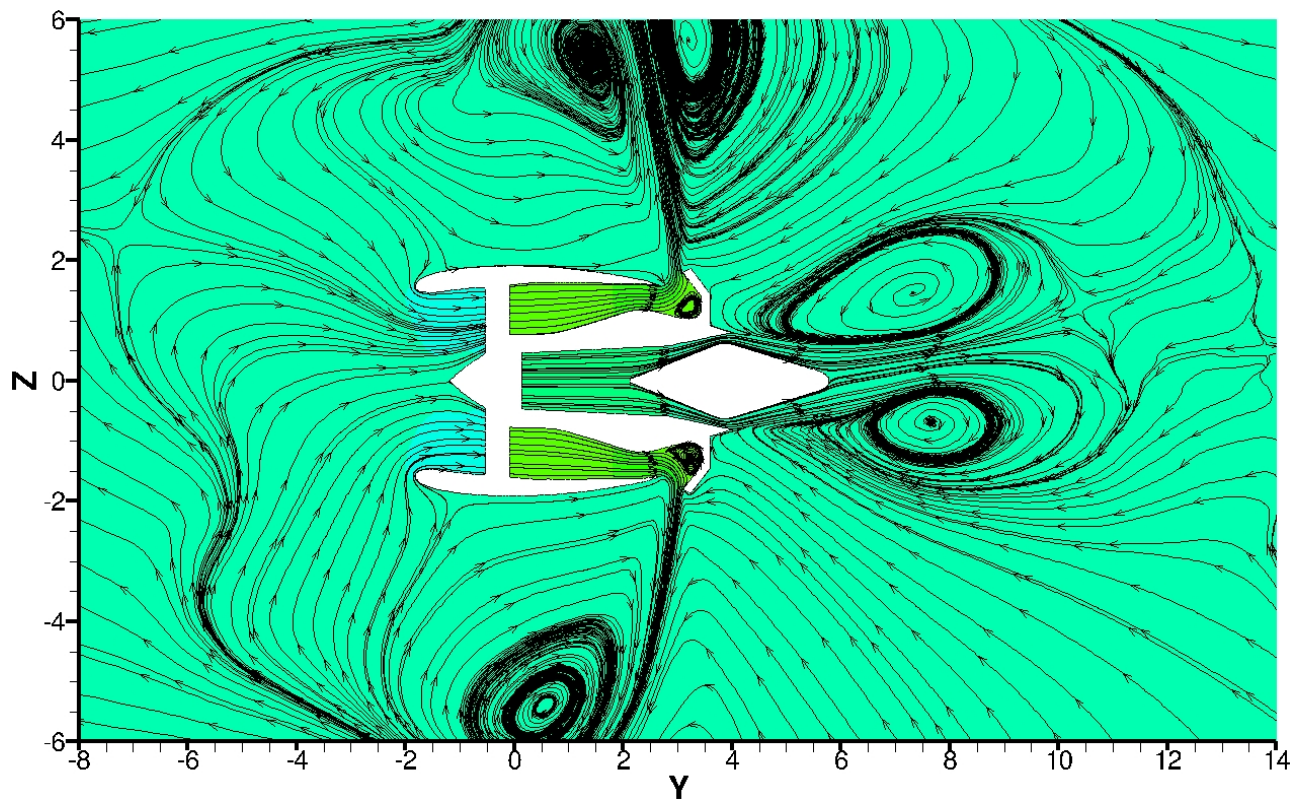


Appendix A4.3 – Streamlines Plot

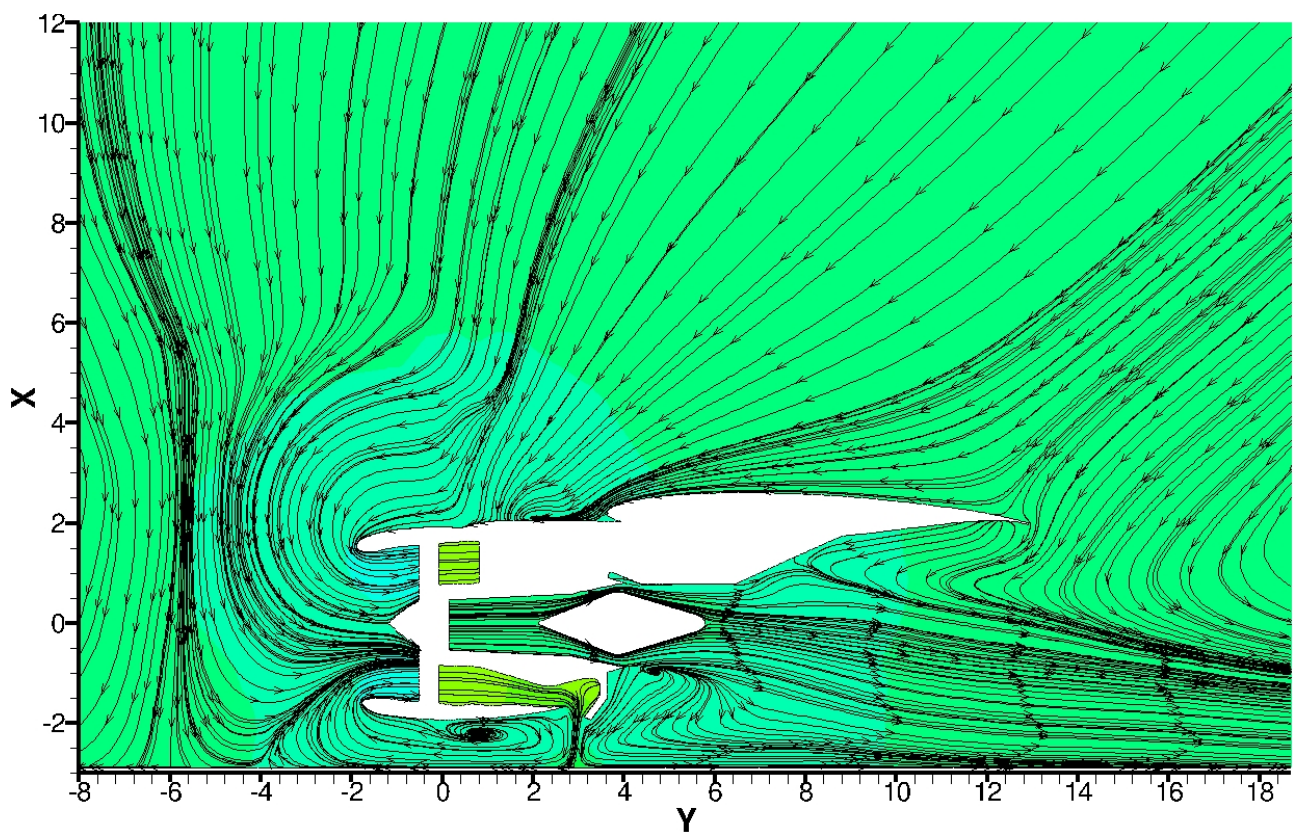
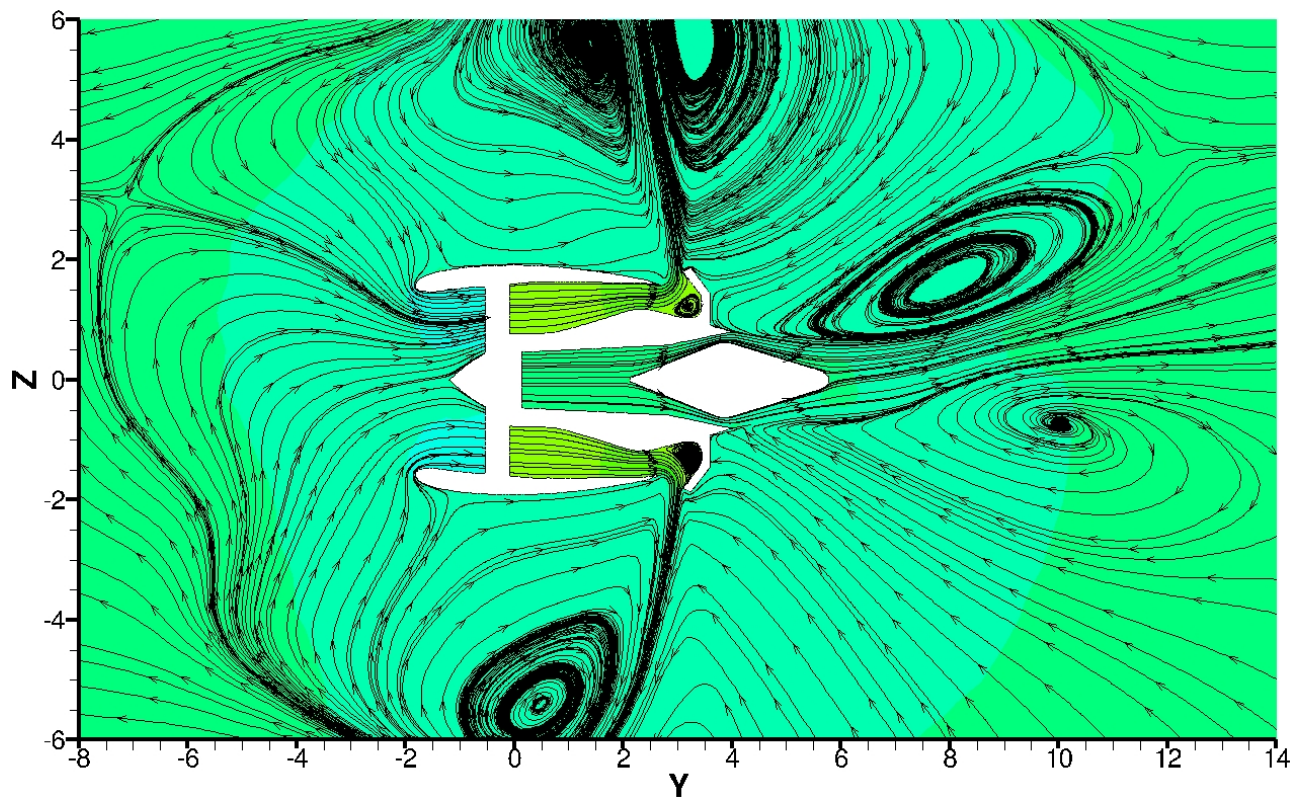
Streamlines Plot, 40 Deg Core Mounted Target Thrust Reverser, $M=0.0$, $FNPR=1.237$



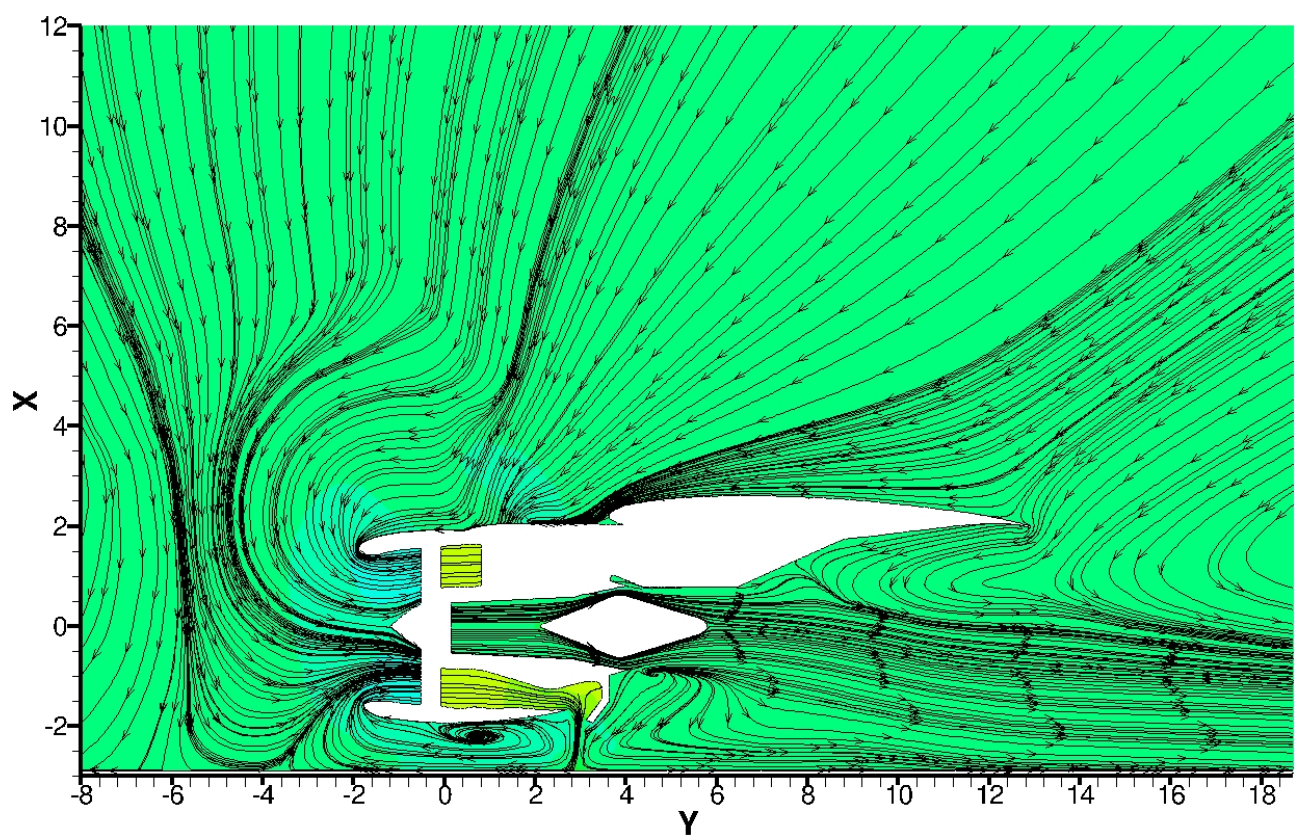
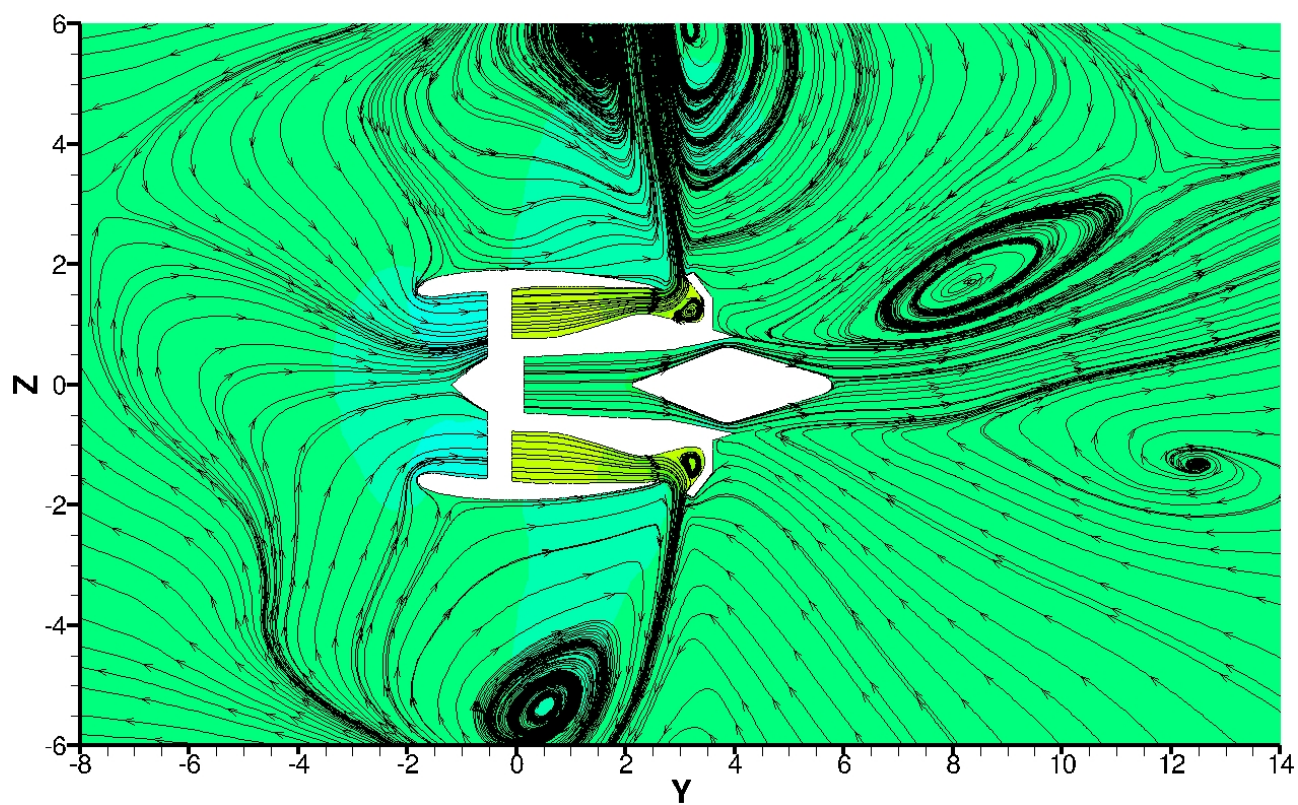
Streamlines Plot, 40 Deg Core Mounted Target Thrust Reverser, $M=0.0$, $FNPR=1.287$



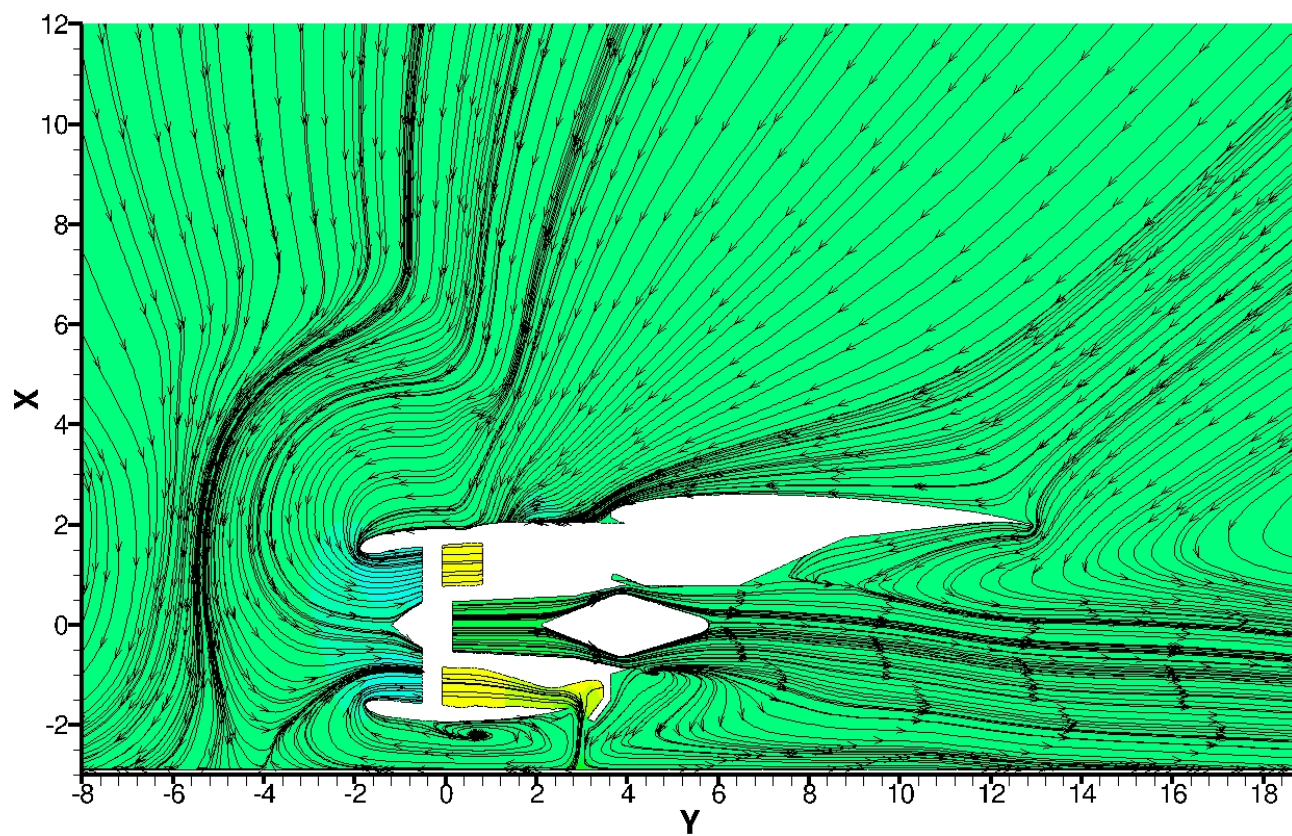
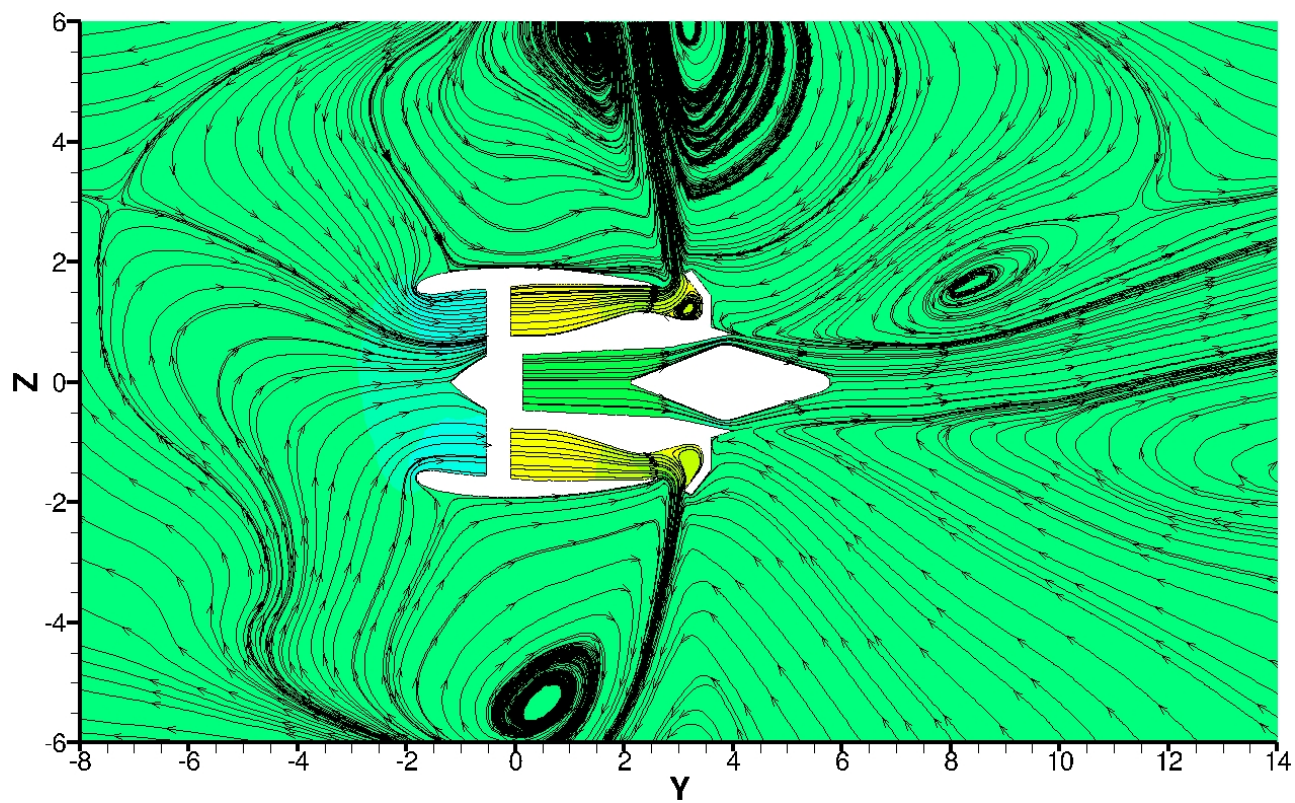
Streamlines Plot, 40 Deg Core Mounted Target Thrust Reverser, $M=0.0$, $FNPR=1.337$



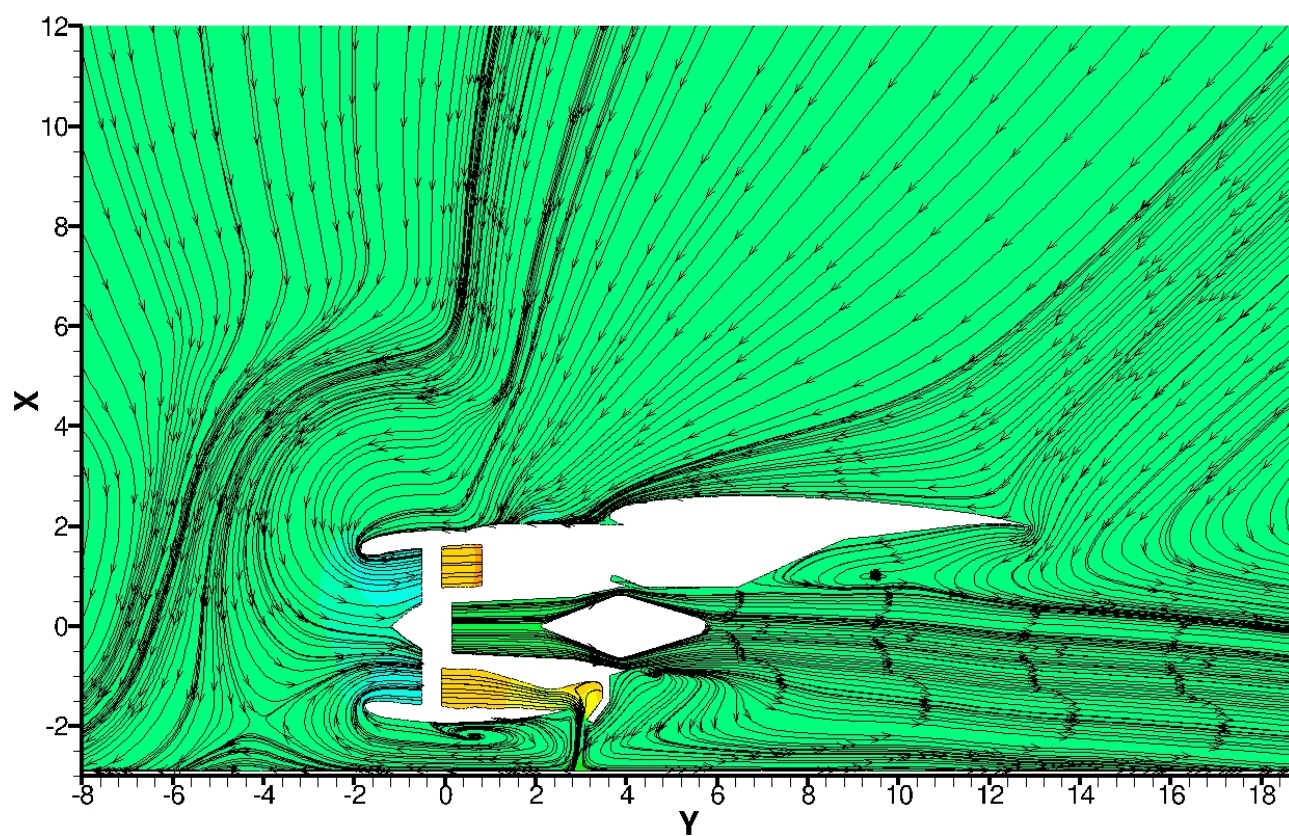
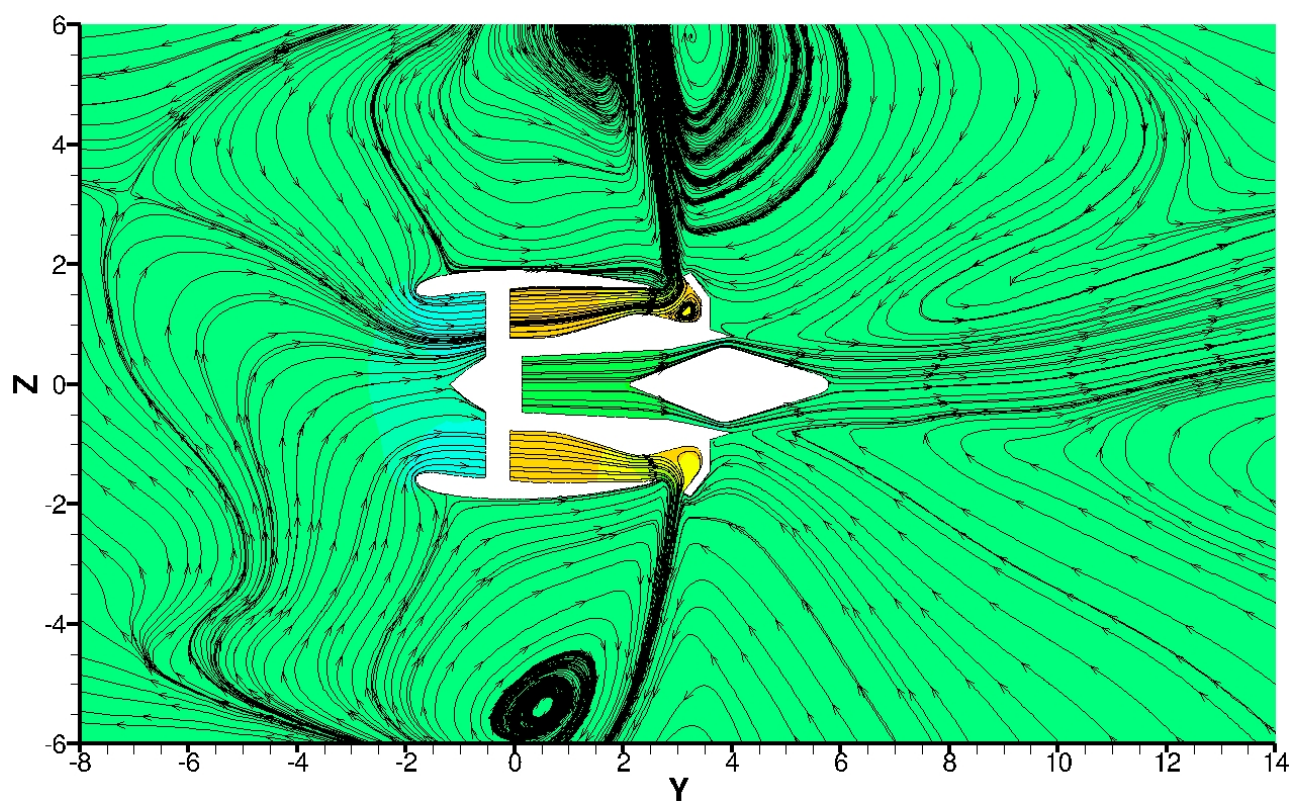
Streamlines Plot, 40 Deg Core Mounted Target Thrust Reverser, $M=0.0$, $FNPR=1.386$



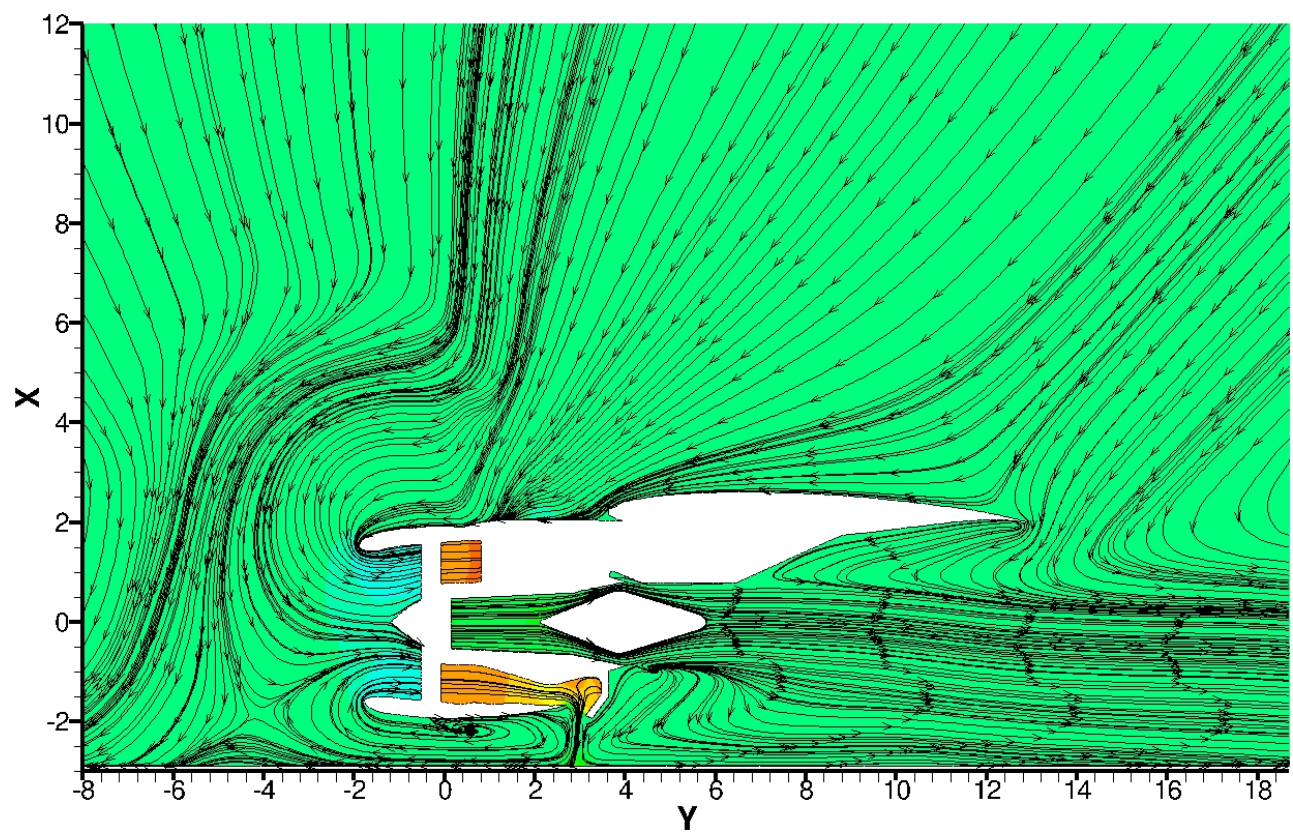
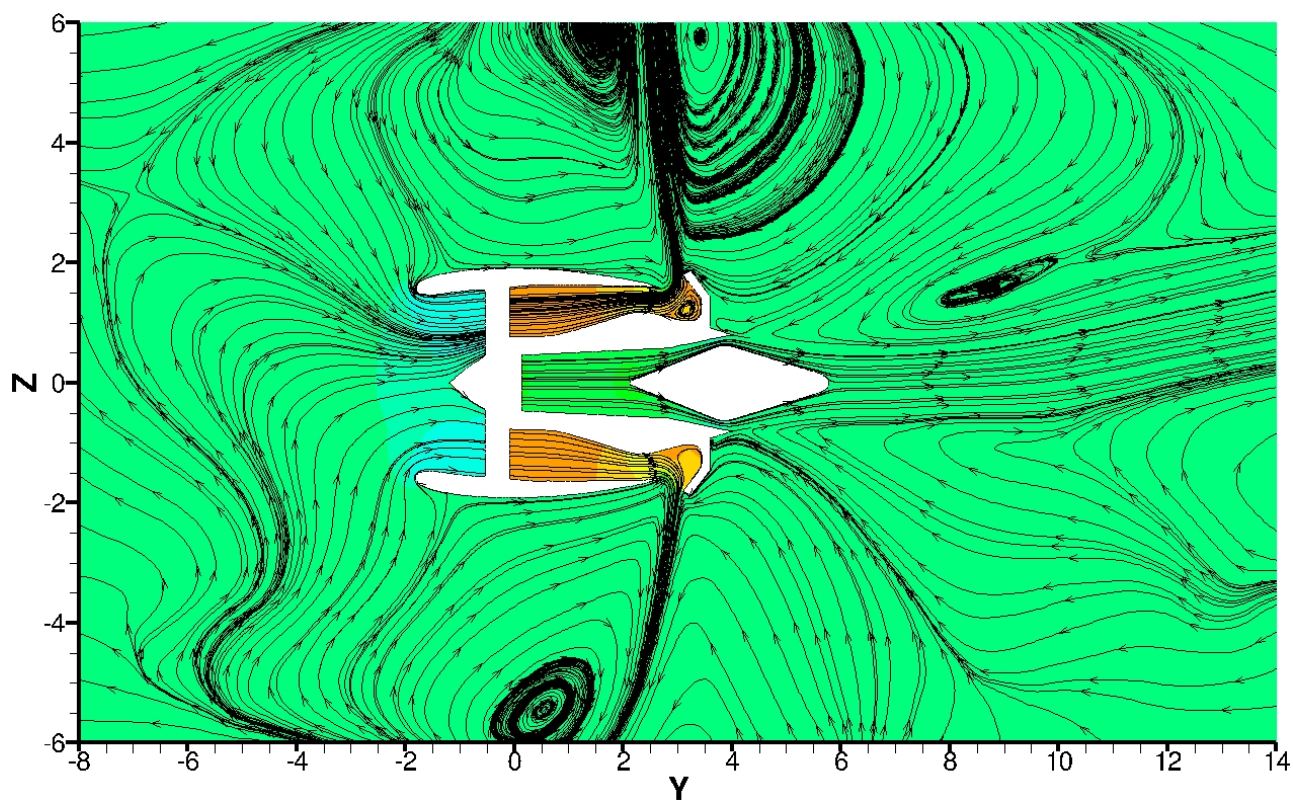
Streamlines Plot, 40 Deg Core Mounted Target Thrust Reverser, $M=0.0$, $FNPR=1.446$



Streamlines Plot, 40 Deg Core Mounted Target Thrust Reverser, $M=0.0$, $FNPR=1.505$

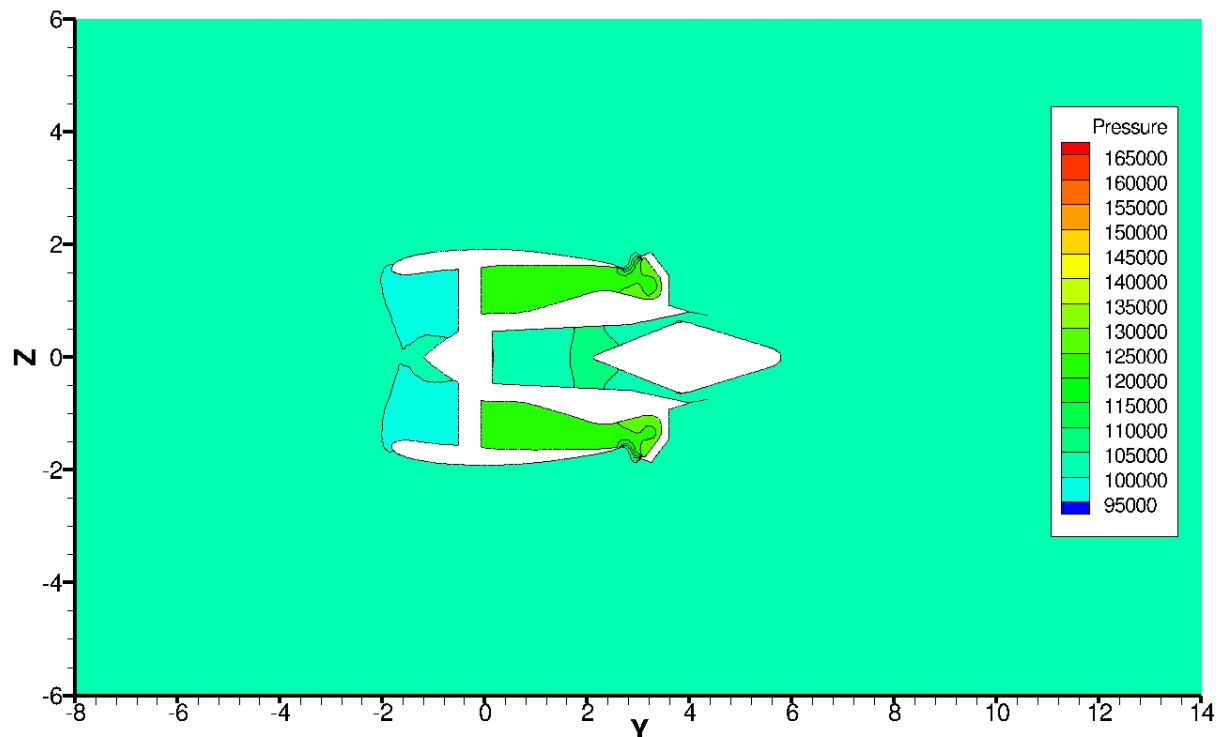


Streamlines Plot, 40 Deg Core Mounted Target Thrust Reverser, $M=0.0$, $FNPR=1.505$

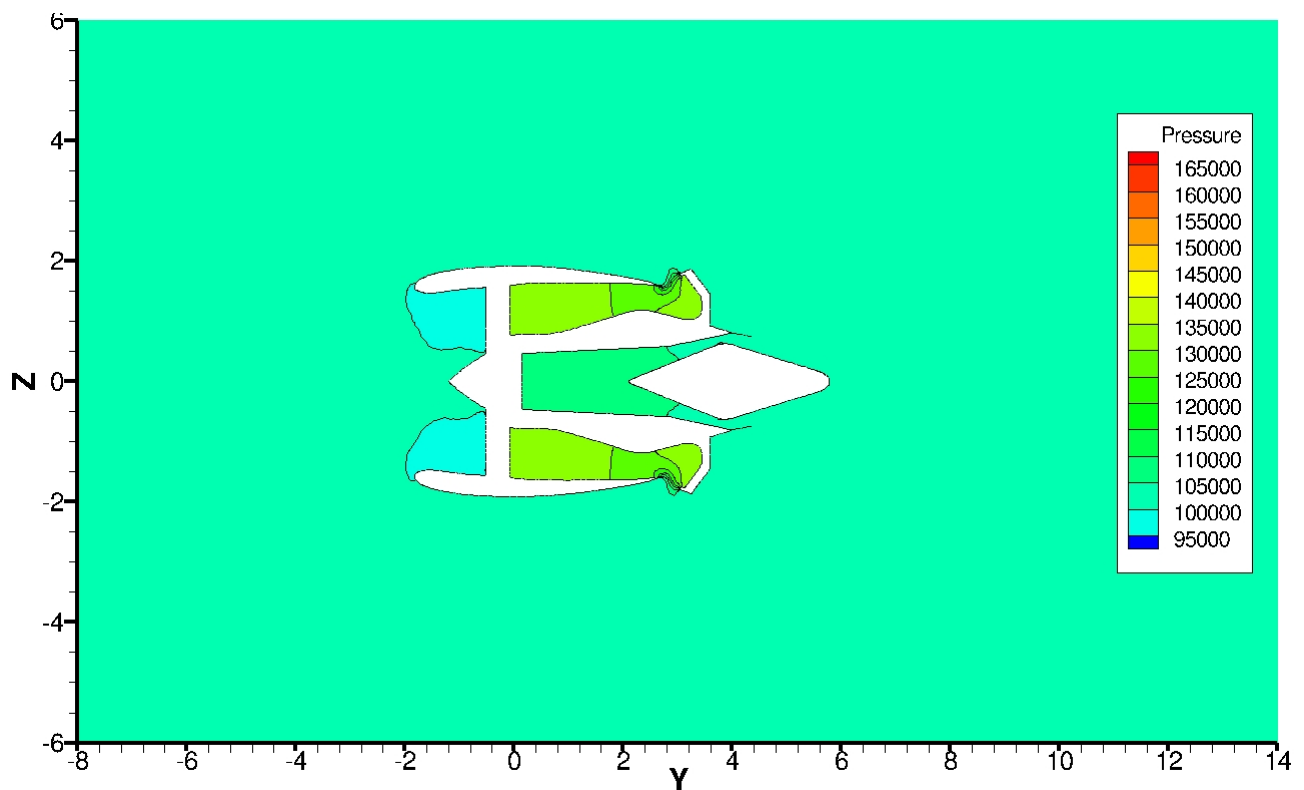


Appendix A4.4 – Static Pressure Contours with Kicker Plate, $M=0.0$

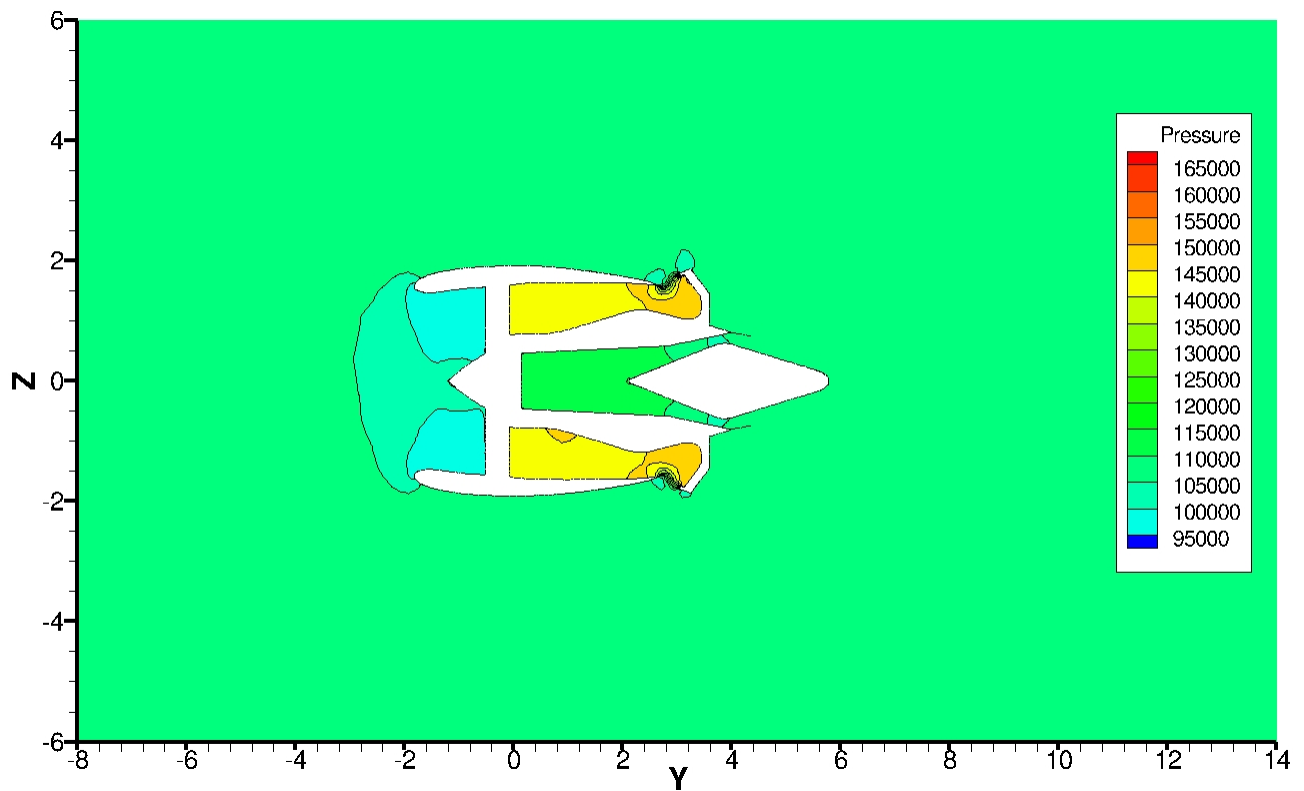
Static Pressure Contours, 40 Deg Core Mounted Target Reverser with Kicker Plate, $M=0.0$,
 $FNPR=1.237$



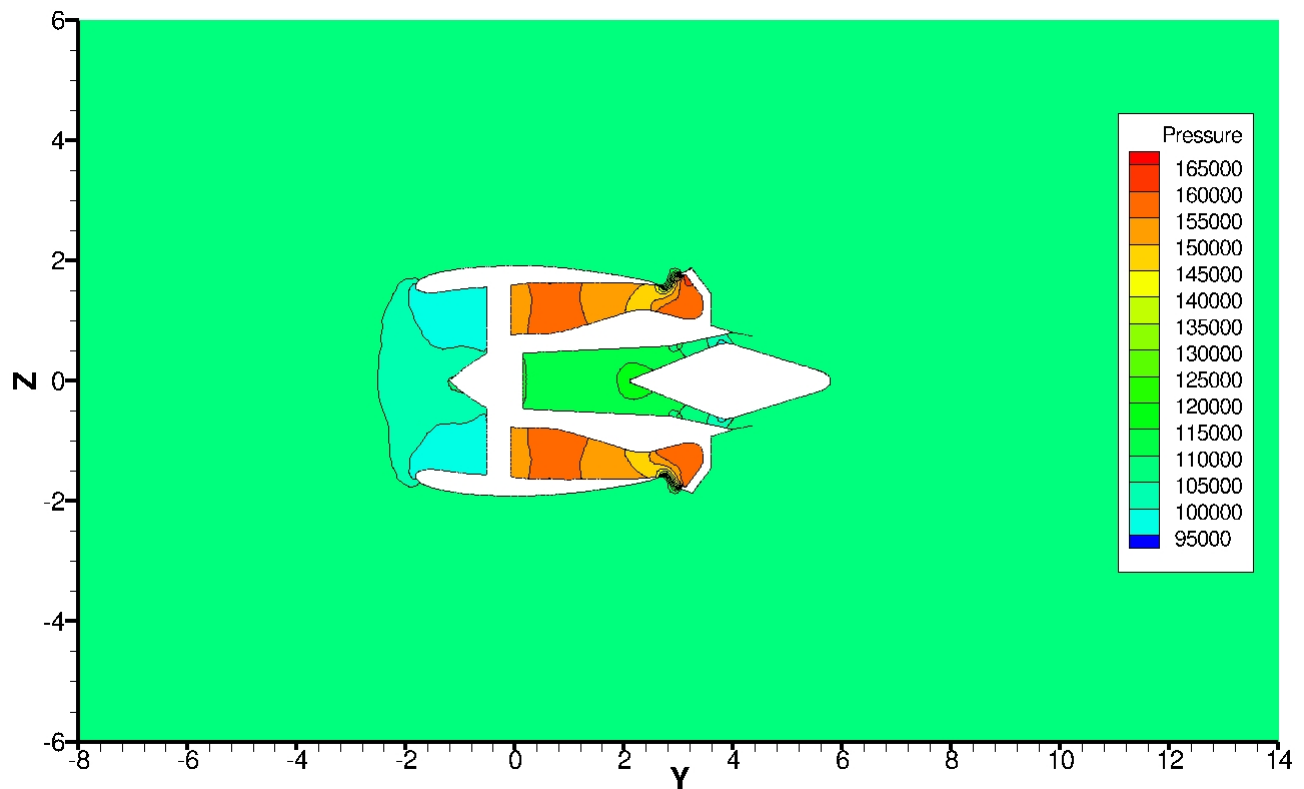
Static Pressure Contours, 40 Deg Core Mounted Target Reverser with Kicker
Plate, $M=0.0$, $FNPR=1.337$



Static Pressure Contours, 40 Deg Core Mounted Target Reverser with Kicker Plate, $M=0.0$,
 $FNPR=1.446$

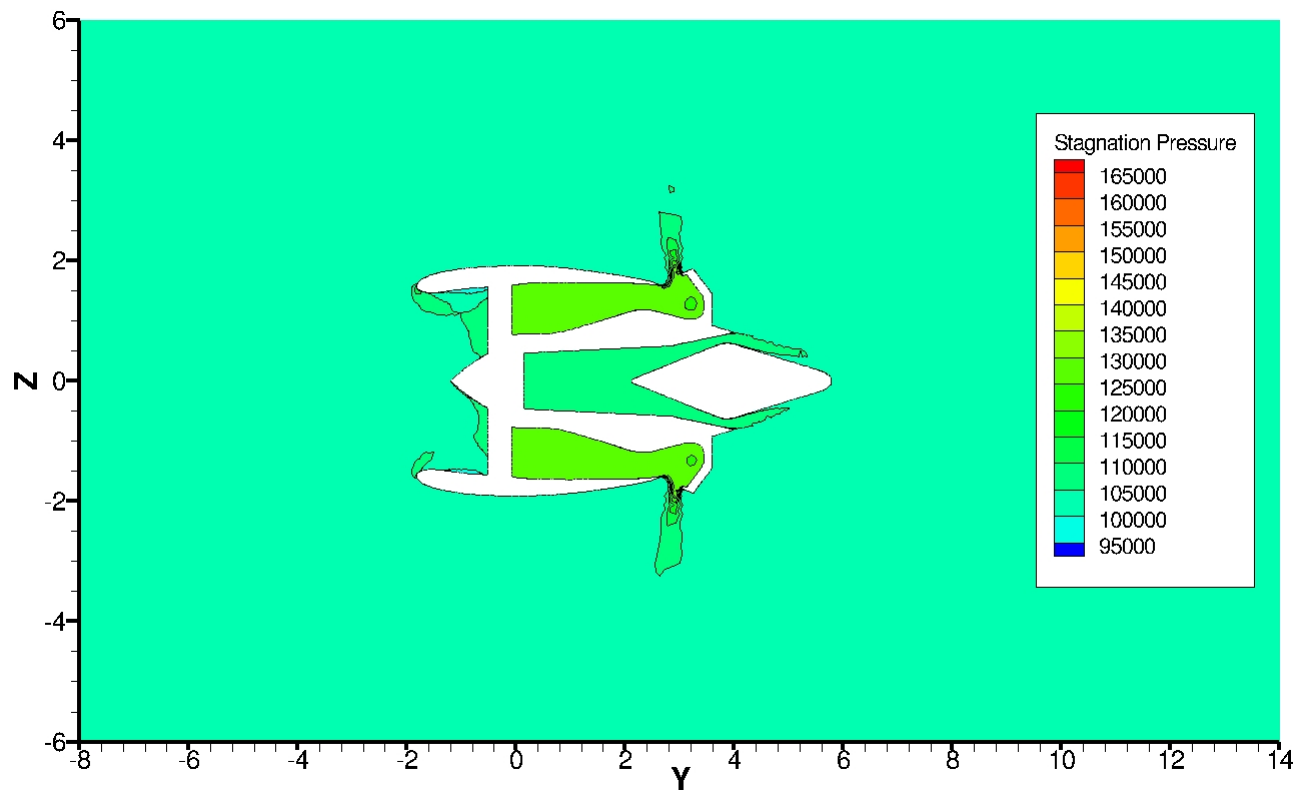


Static Pressure Contours, 40 Deg Core Mounted Target Reverser with Kicker Plate, $M=0.0$,
 $FNPR=1.505$

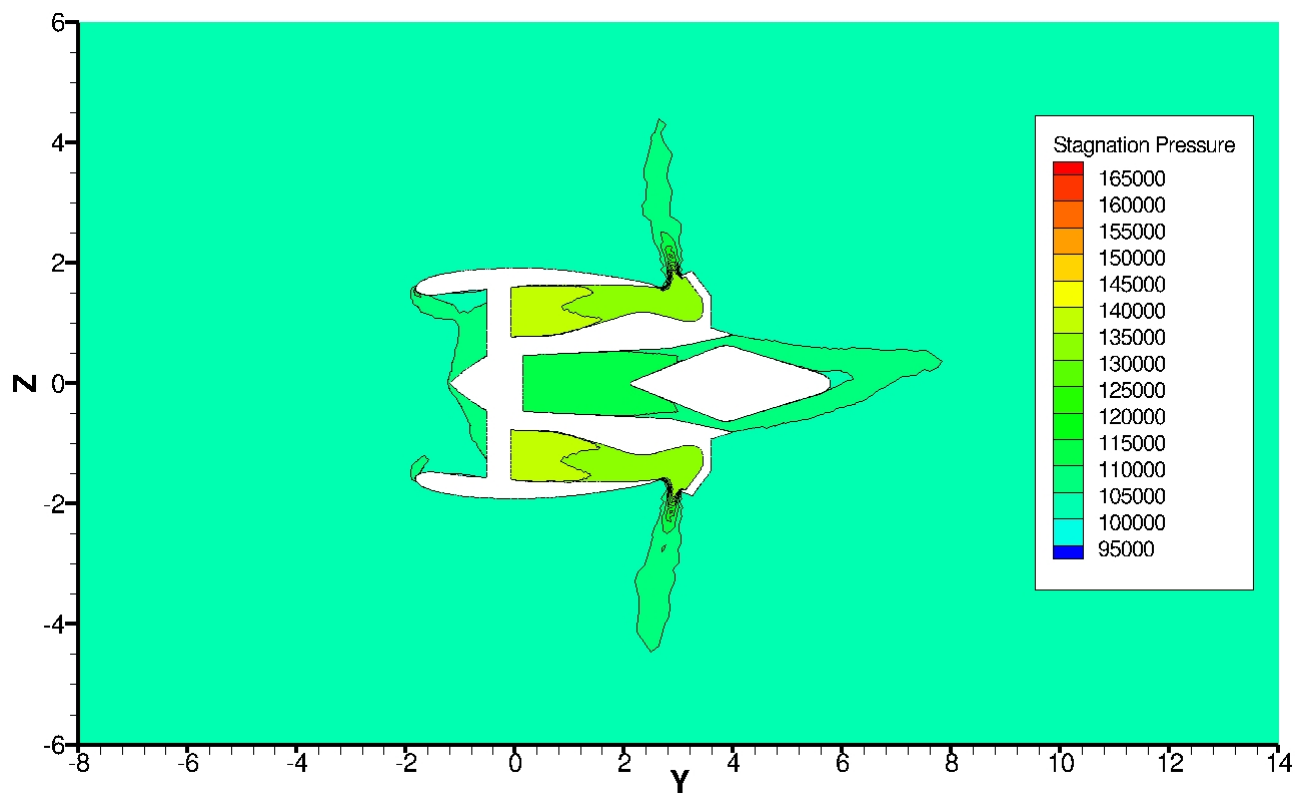


Appendix A4.5 – Total Pressure Contours with Kicker Plate, $M=0.0$

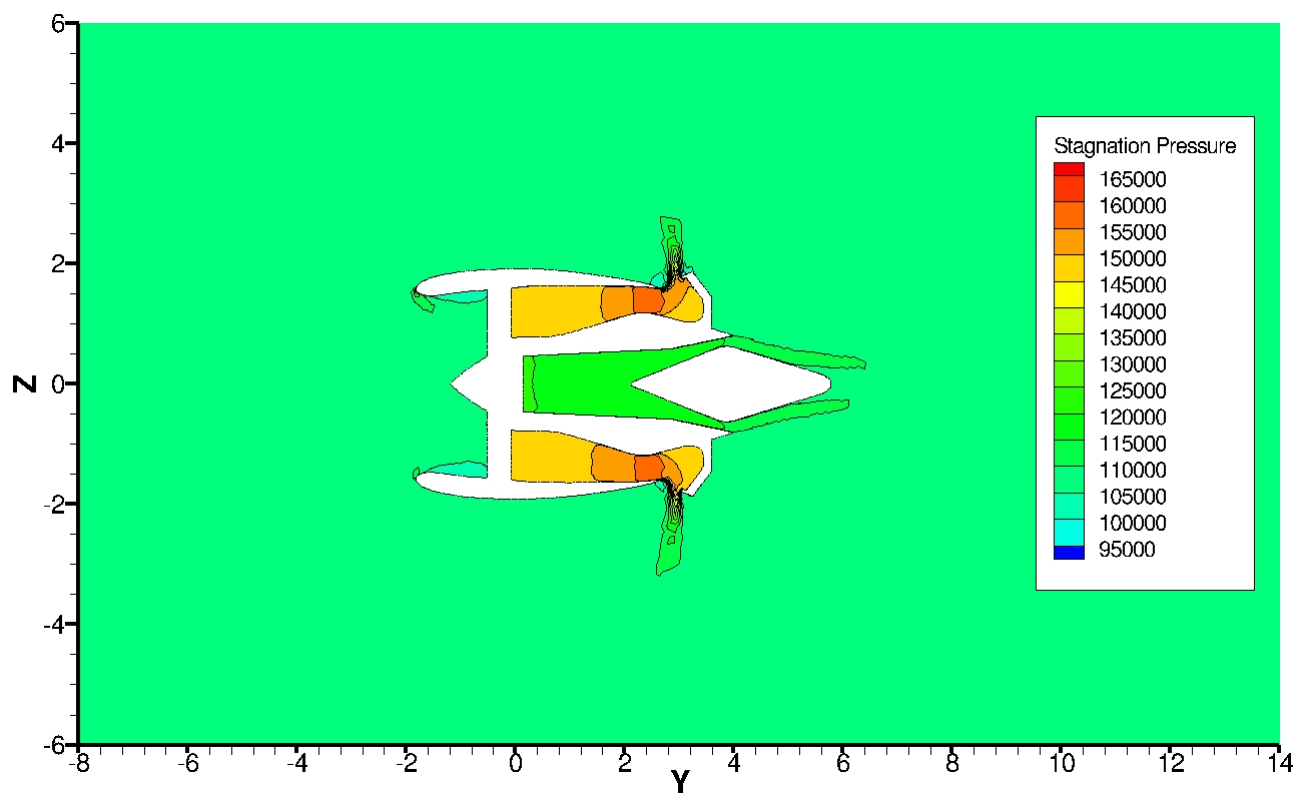
Total Pressure Contours, 40 Deg Core Mounted Target Reverser with Kicker Plate, $M=0.0$,
FNPR=1.237



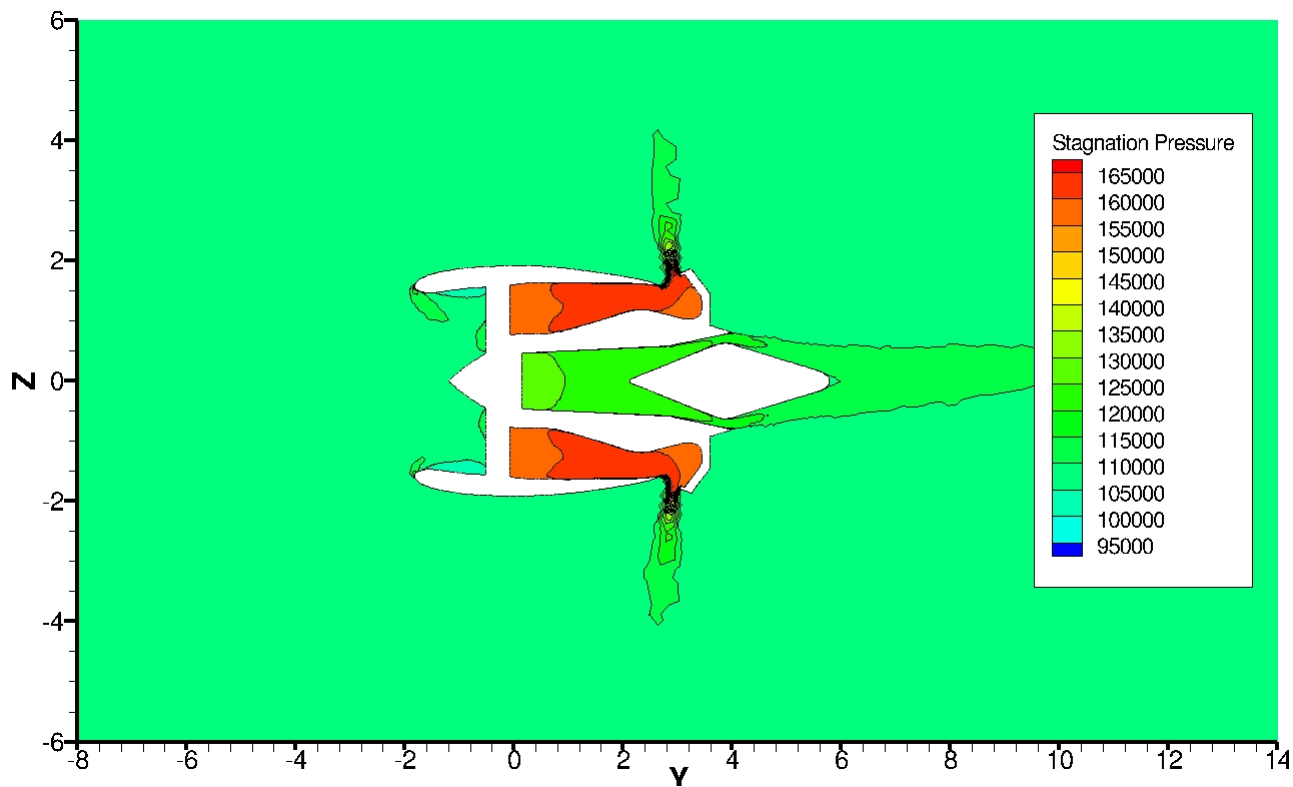
Total Pressure Contours, 40 Deg Core Mounted Target Reverser with Kicker Plate, $M=0.0$,
FNPR=1.336



**Total Pressure Contours, 40 Deg Core Mounted Target Reverser with Kicker Plate, $M=0.0$,
FNPR=1.446**

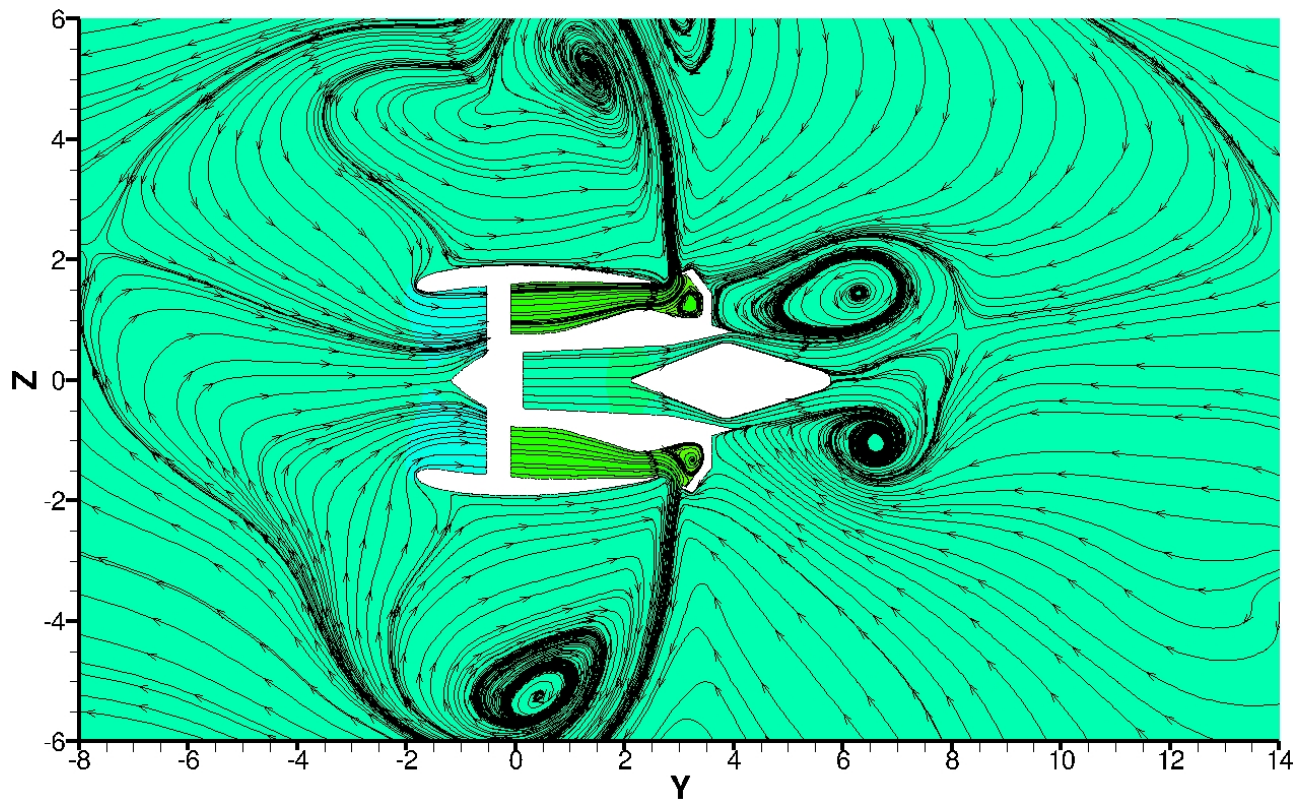
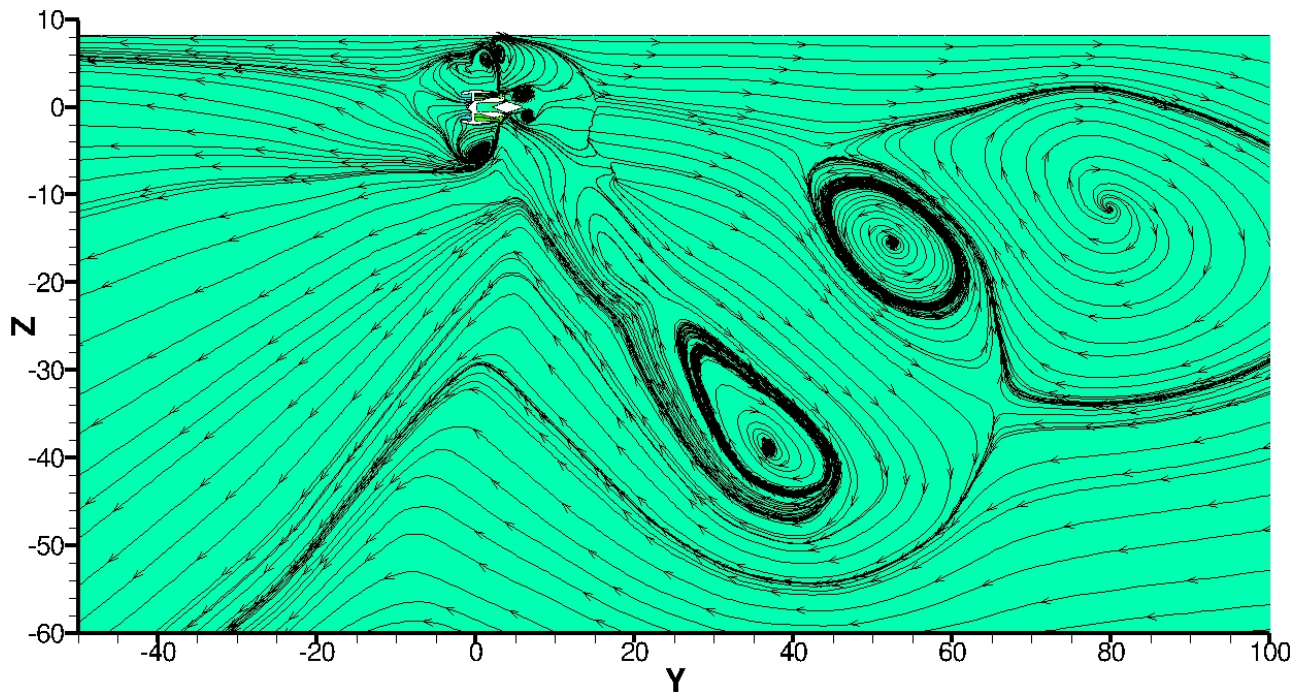


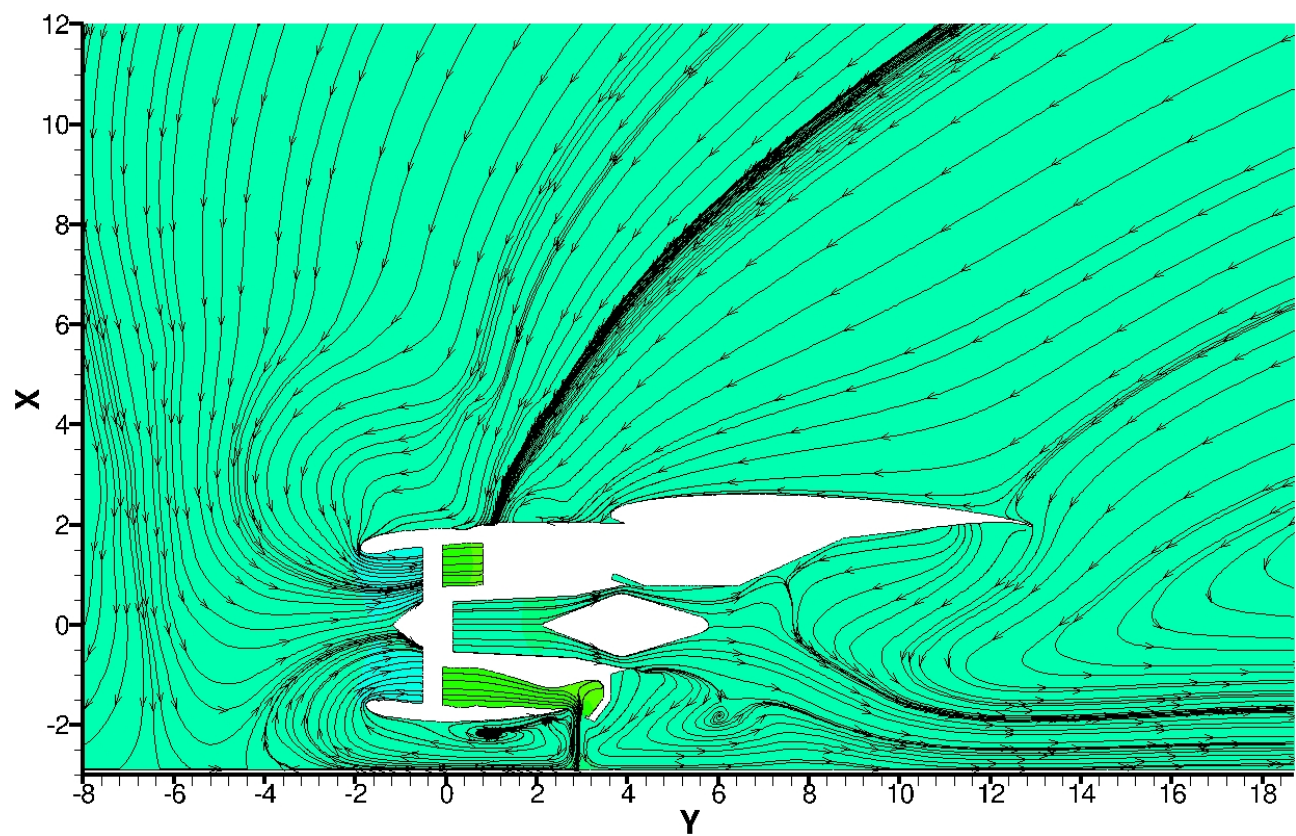
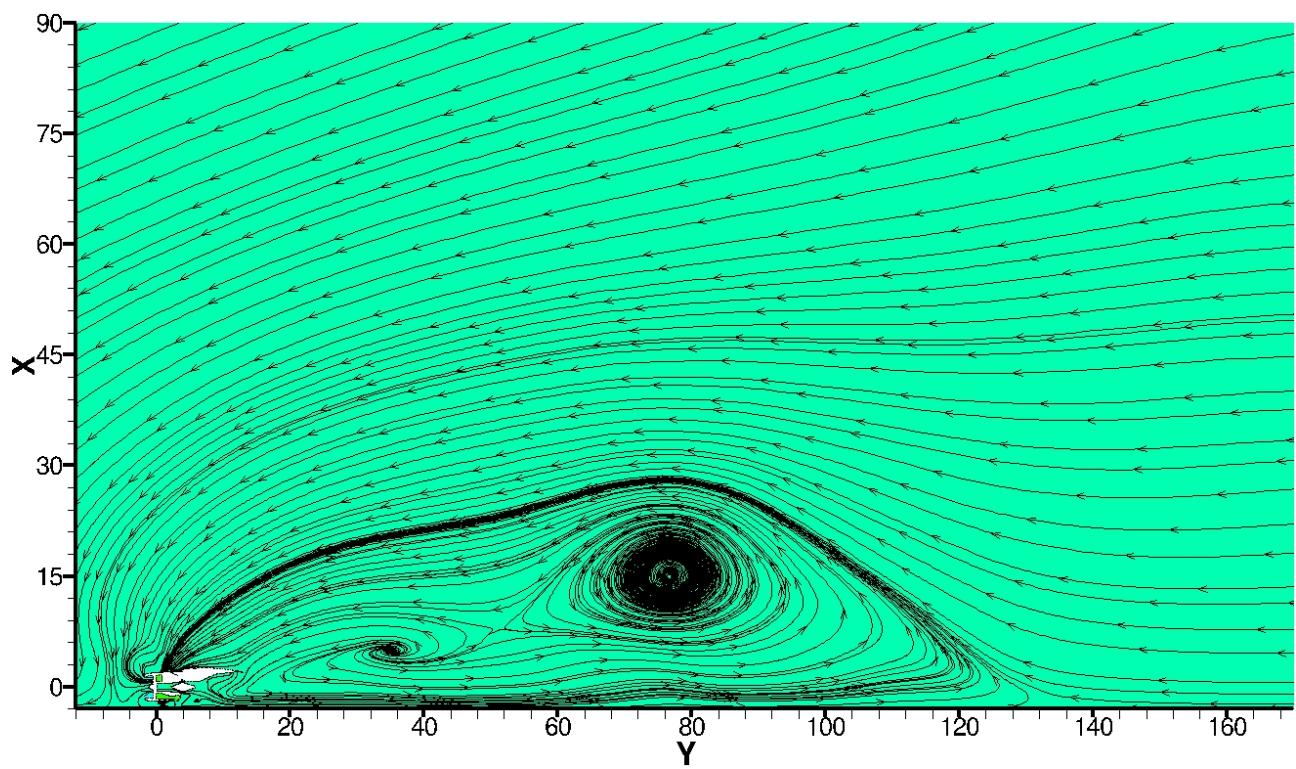
**Total Pressure Contours, 40 Deg Core Mounted Target Reverser with Kicker Plate, $M=0.0$,
FNPR=1.554**



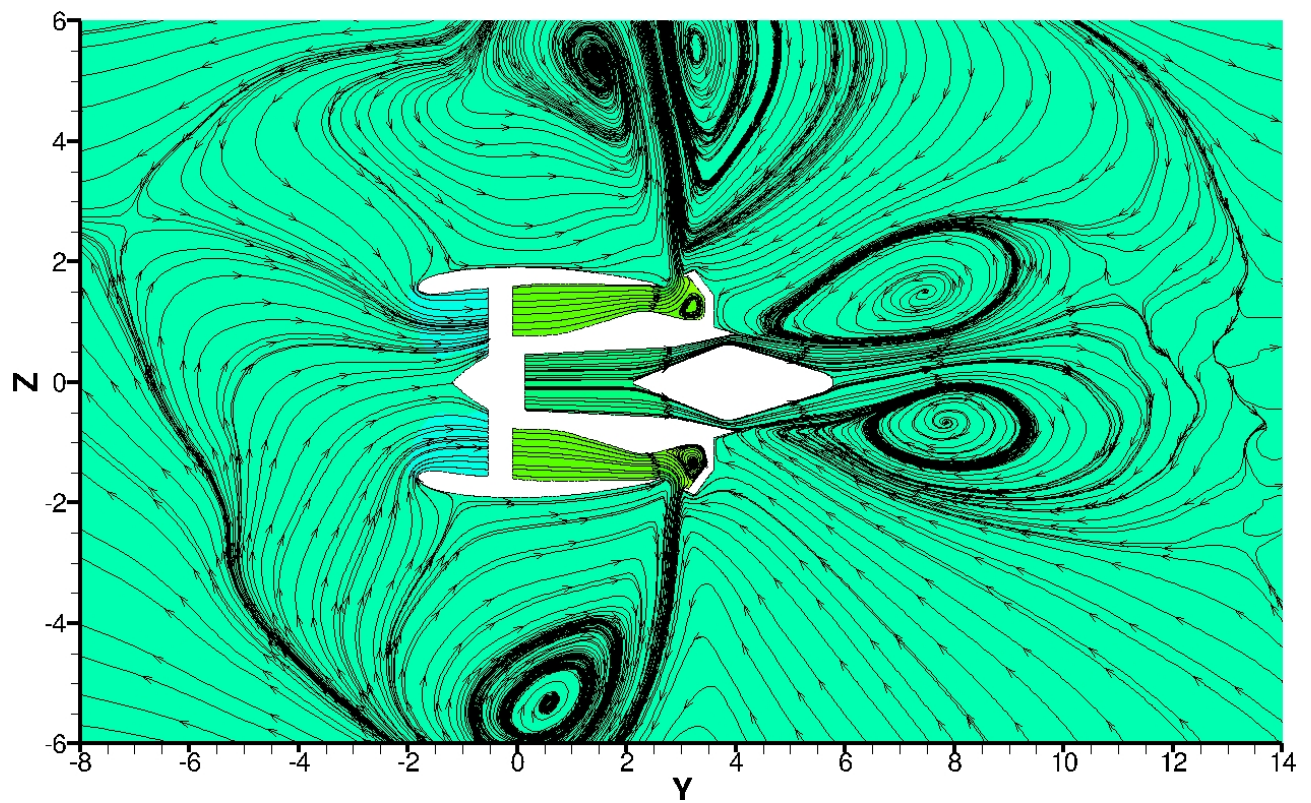
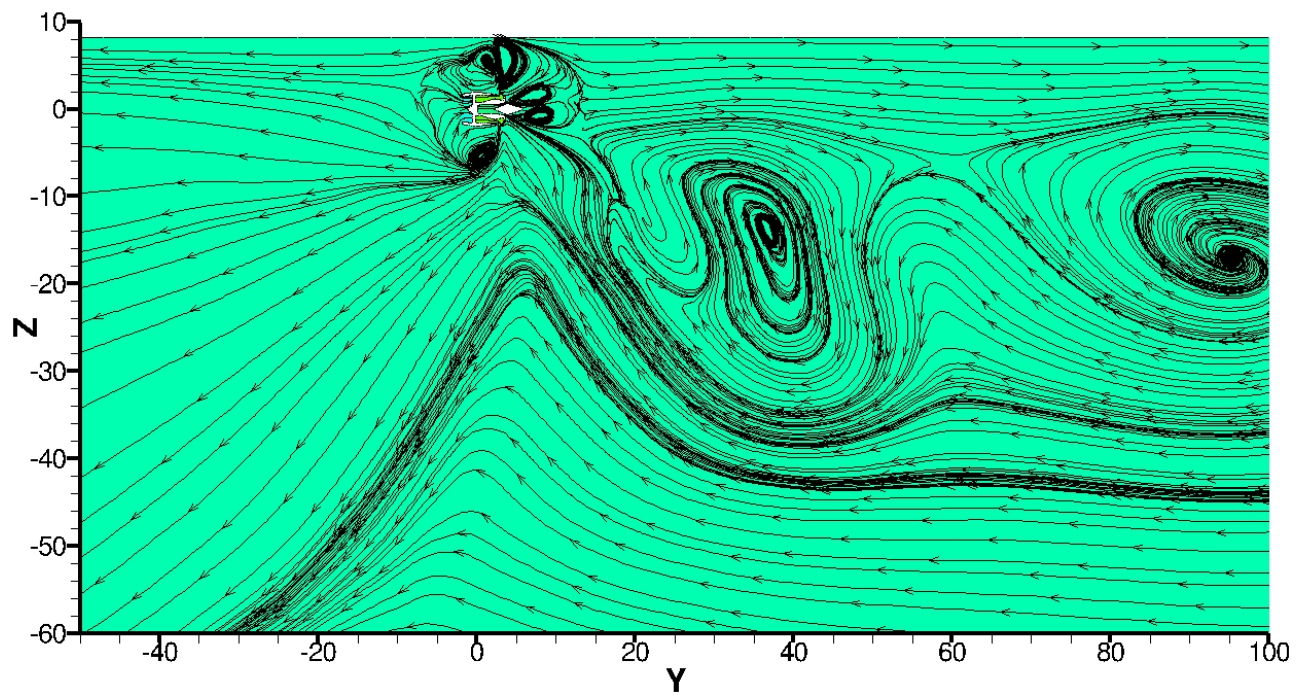
Appendix A4.6 – Streamlines Plot with Kicker Plate, $M=0.0$

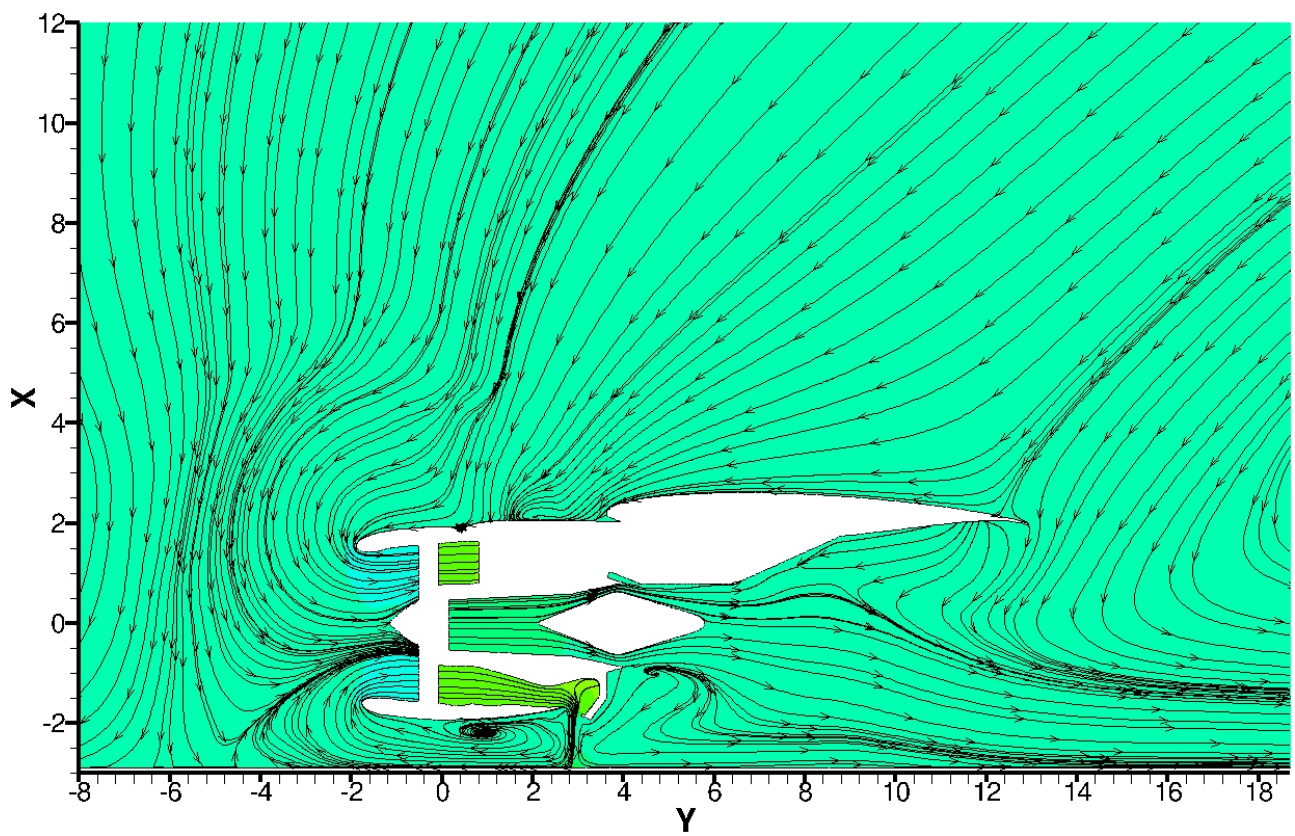
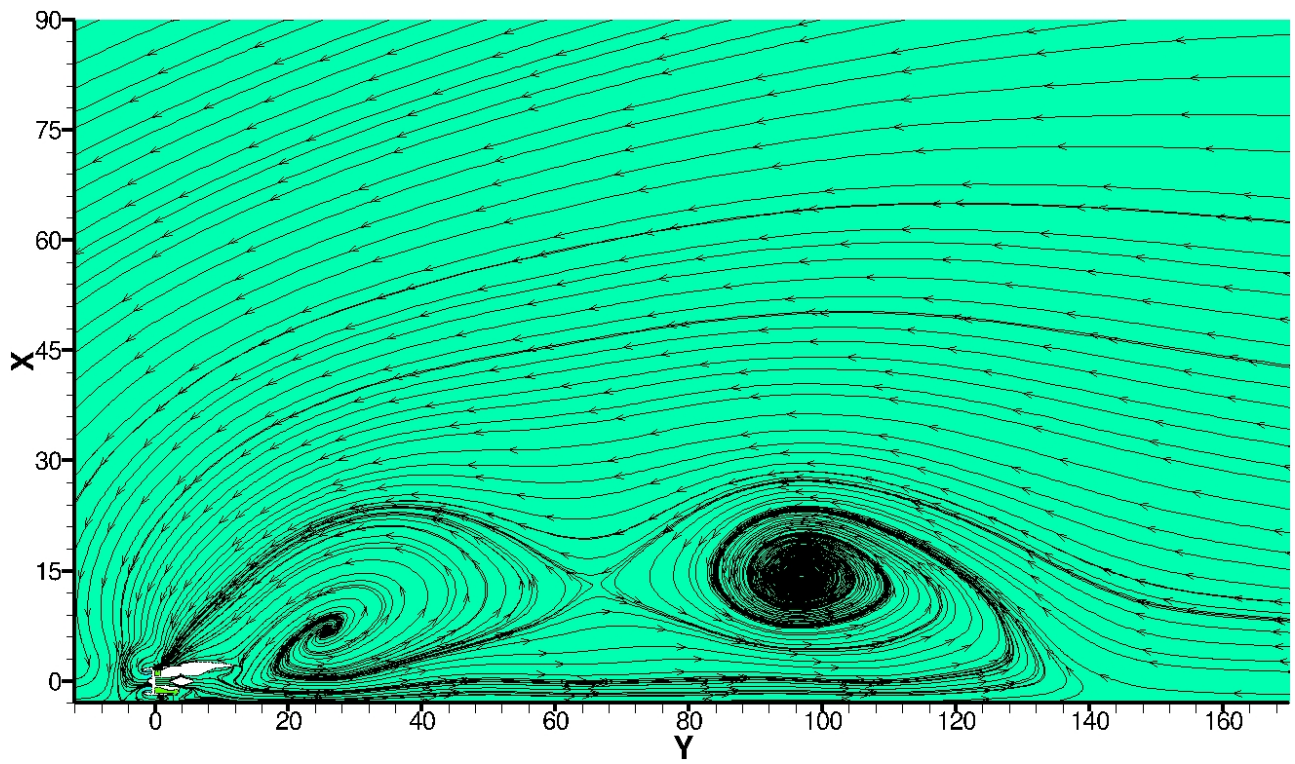
Streamlines Plot, 40 Deg Core Mounted Target Reverser with Kicker Plate, $M=0.0$,
 $FNPR=1.237$



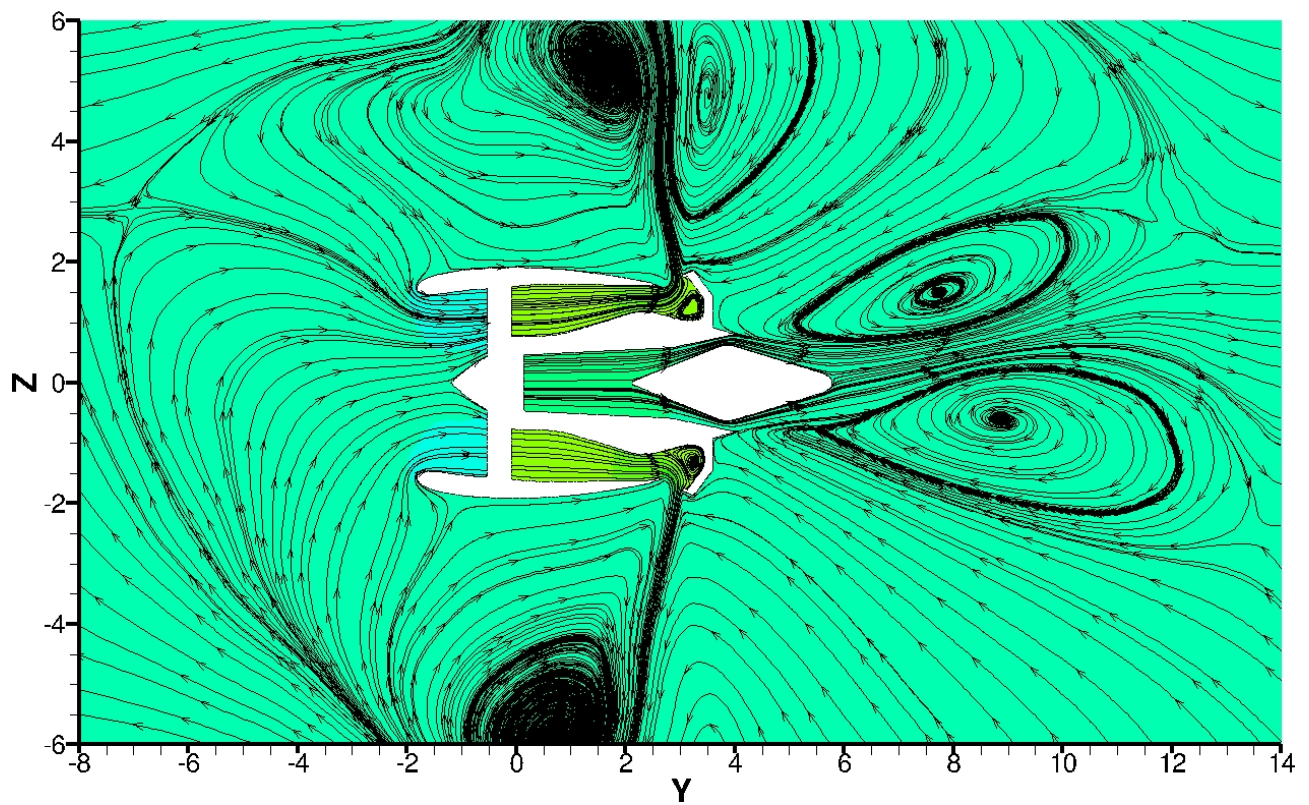
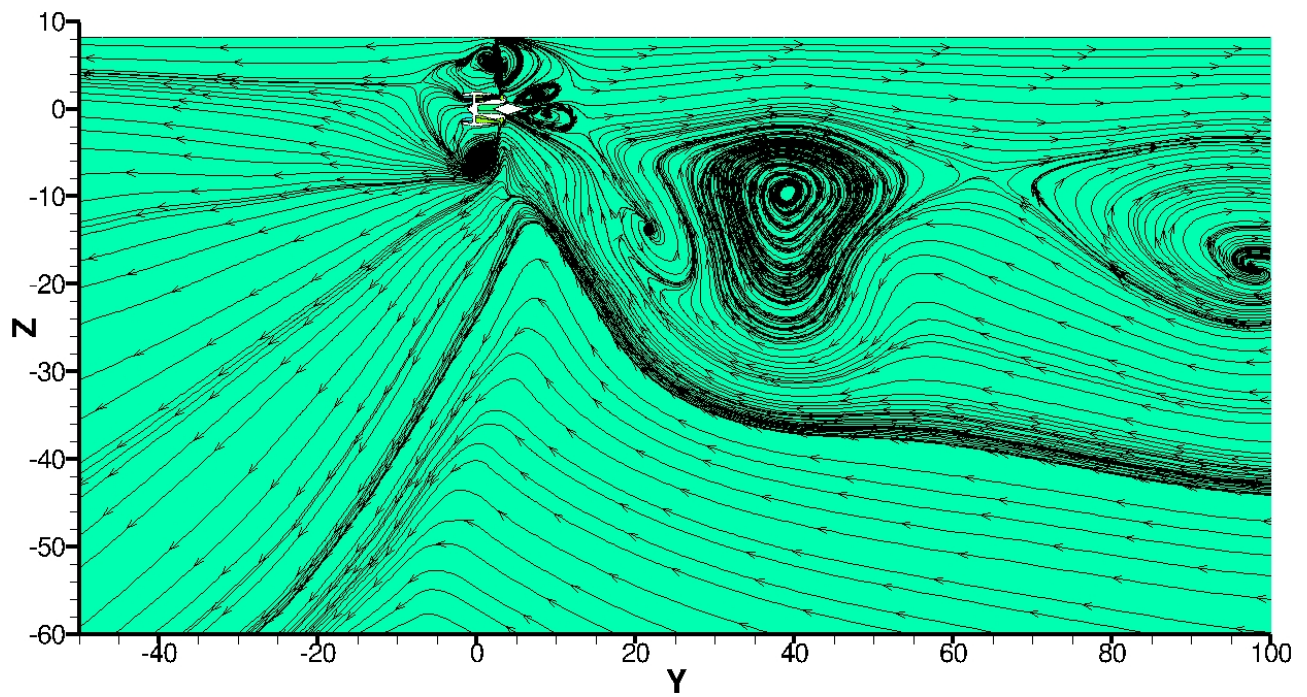


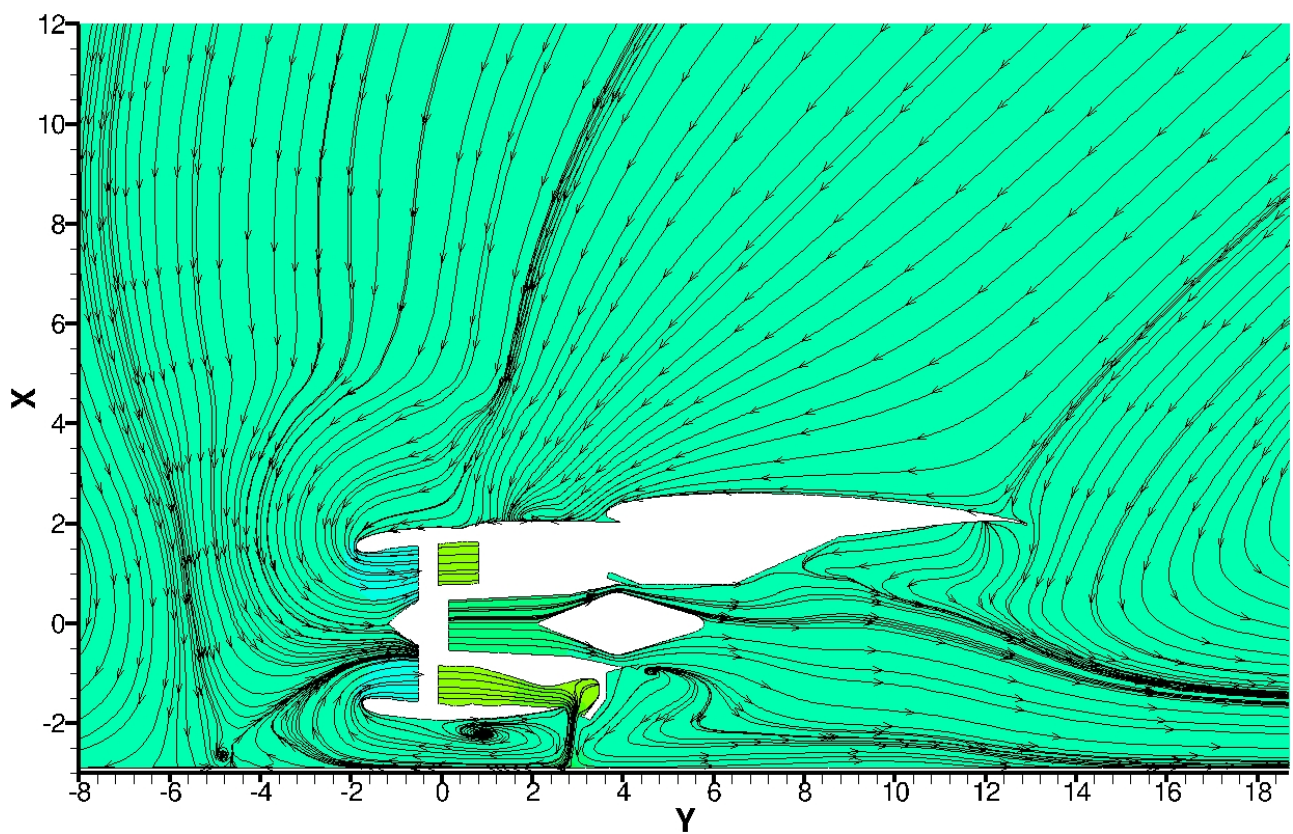
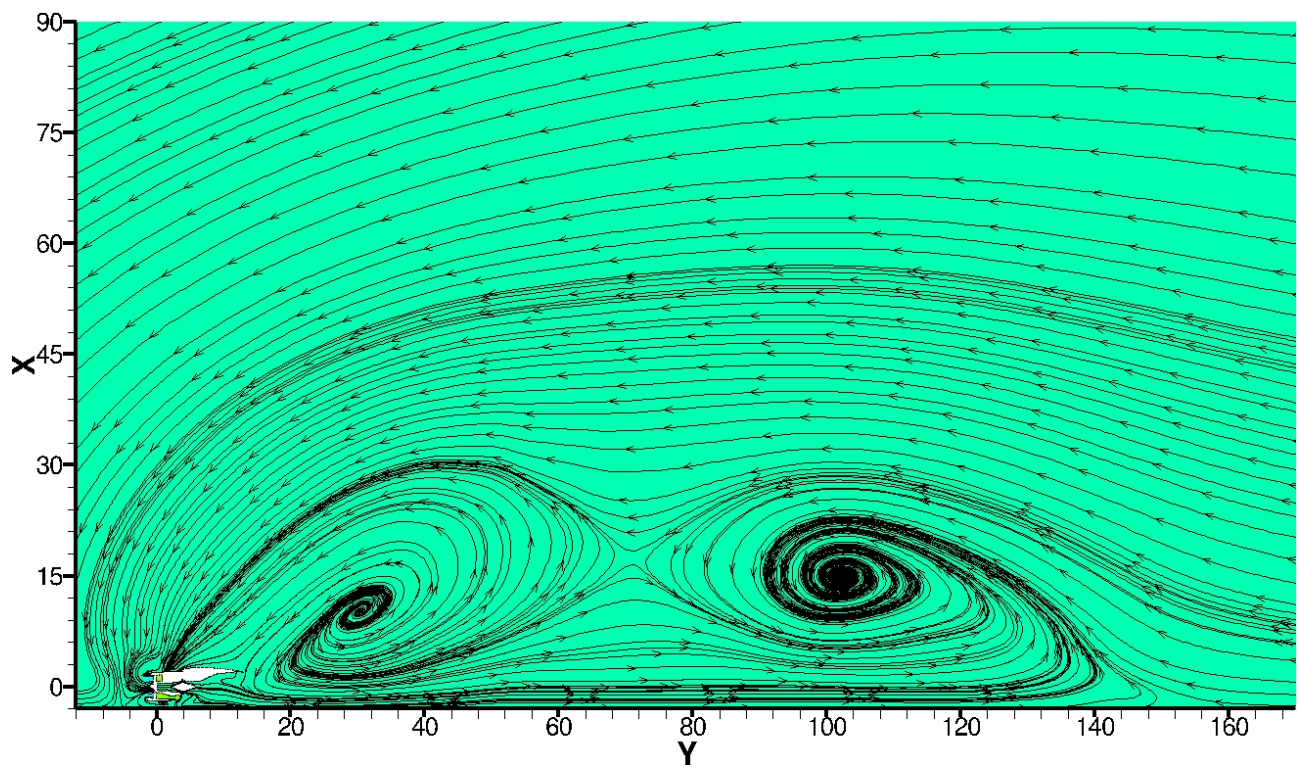
Streamlines Plot, 40 Deg Core Mounted Target Reverser with Kicker Plate, $M=0.0$,
 $FNPR=1.287$



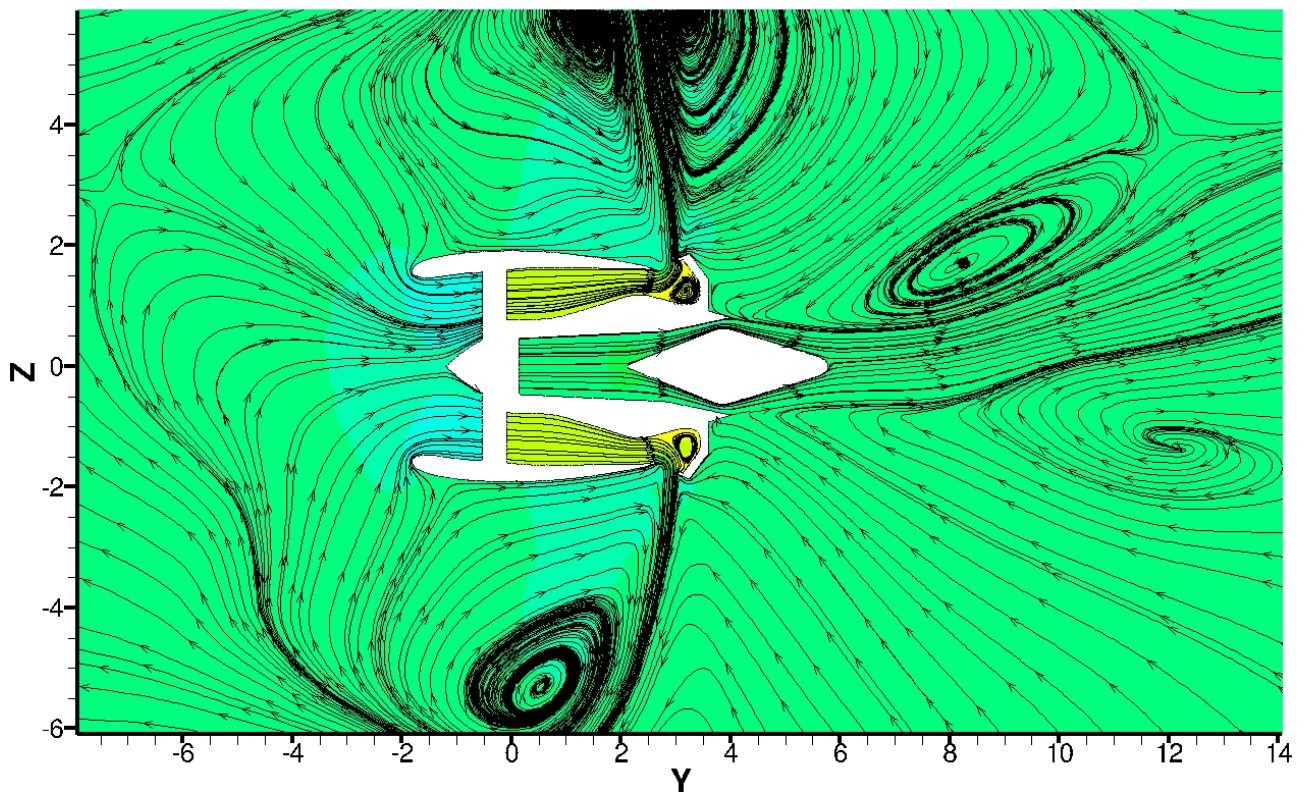
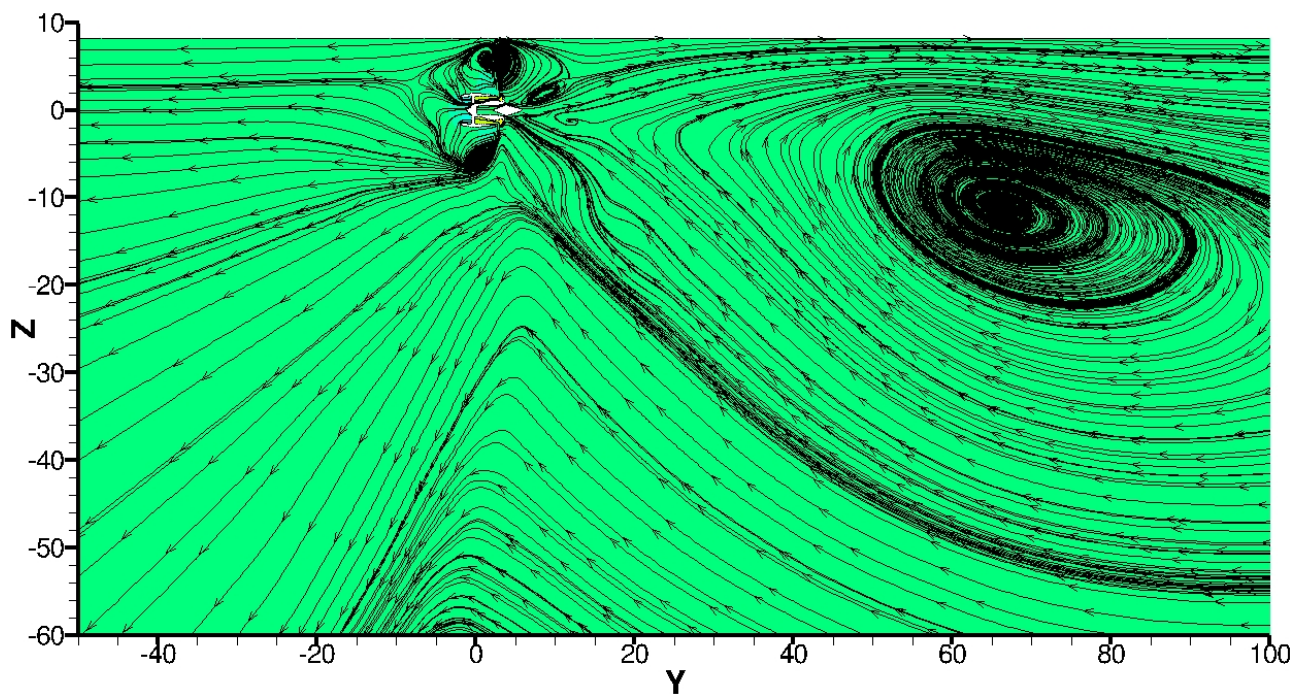


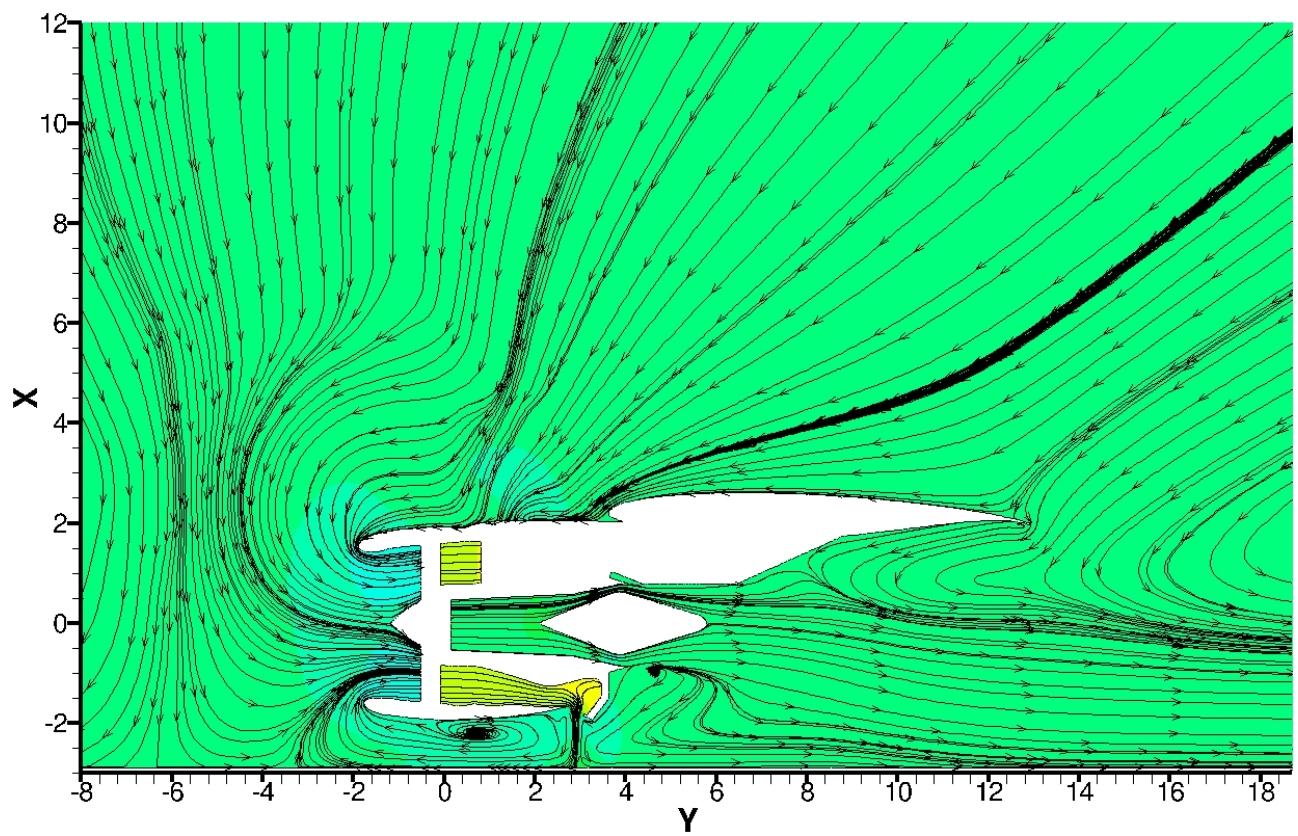
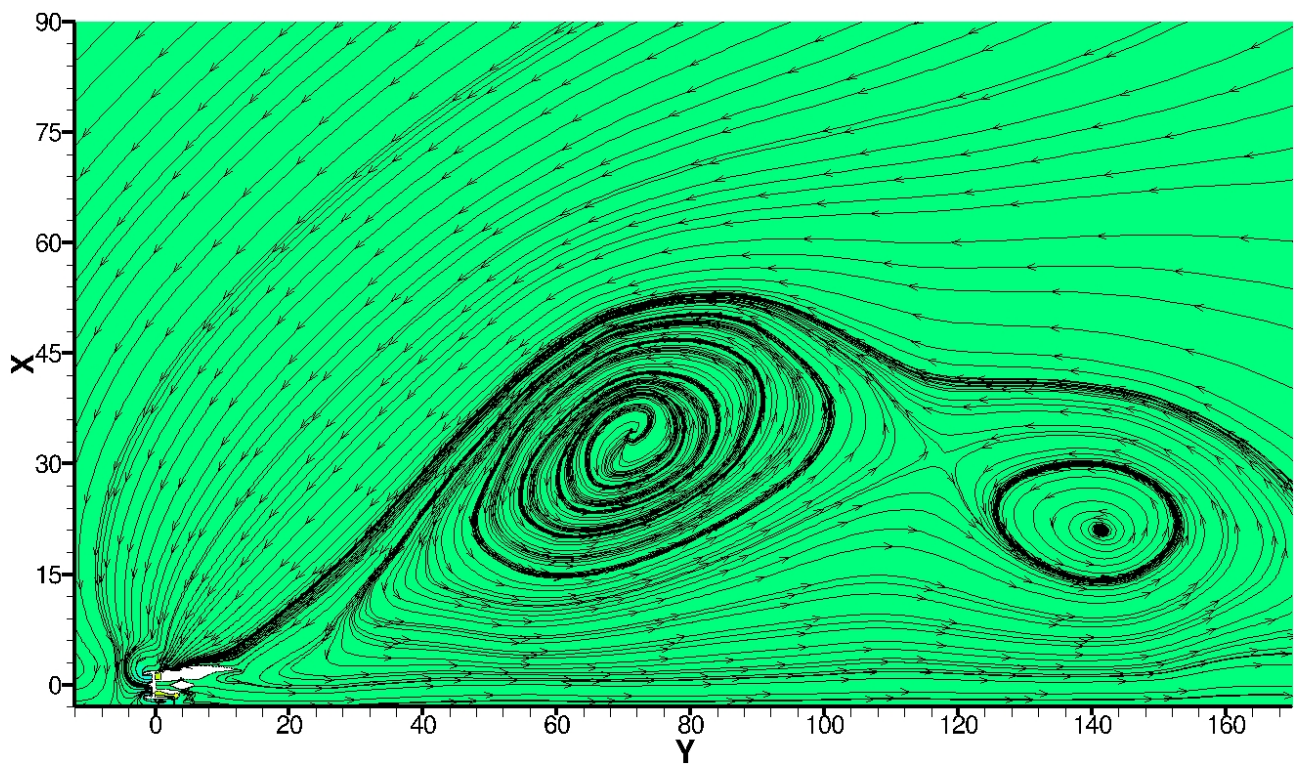
Streamlines Plot, 40 Deg Core Mounted Target Reverser with Kicker Plate, $M=0.0$,
 $FNPR=1.336$



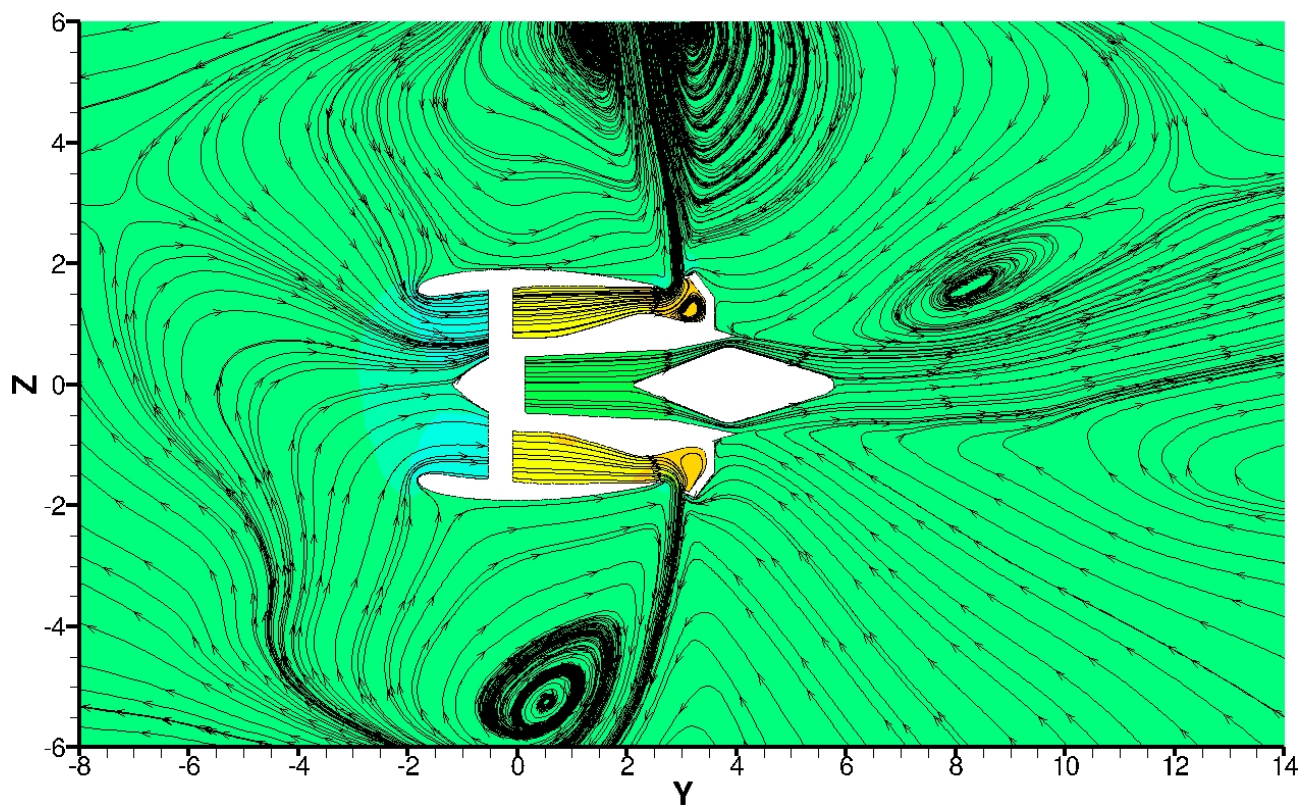
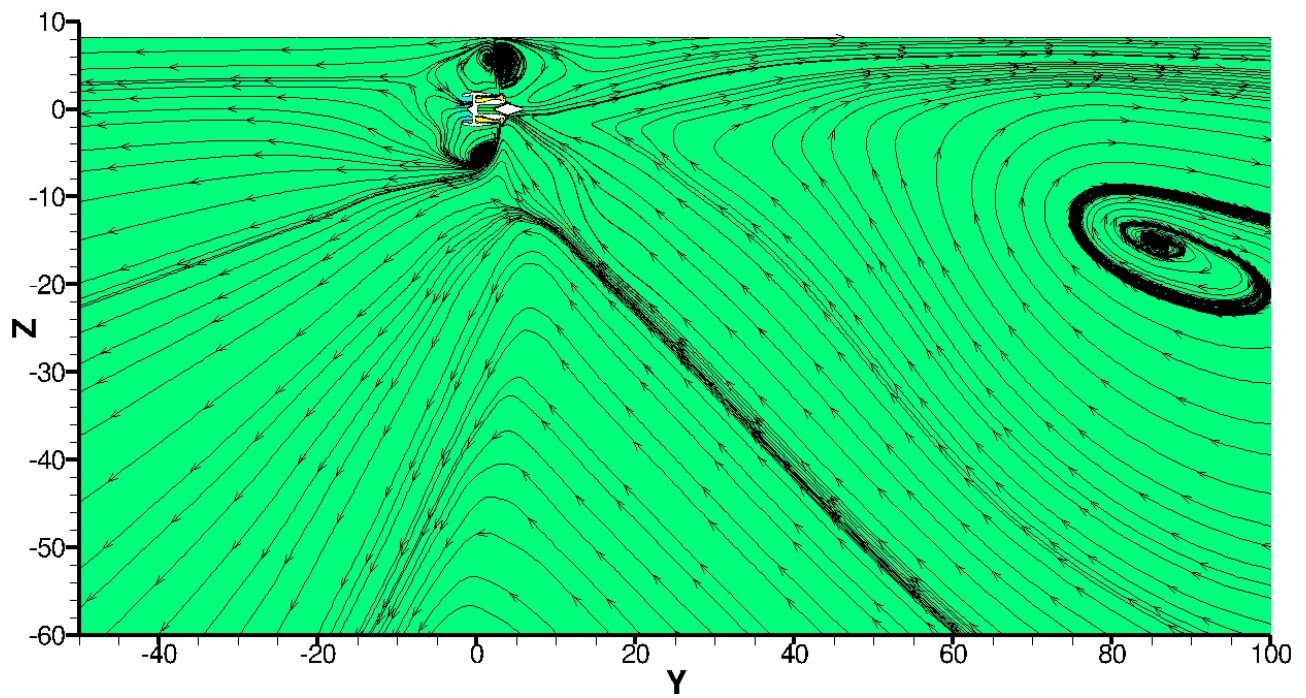


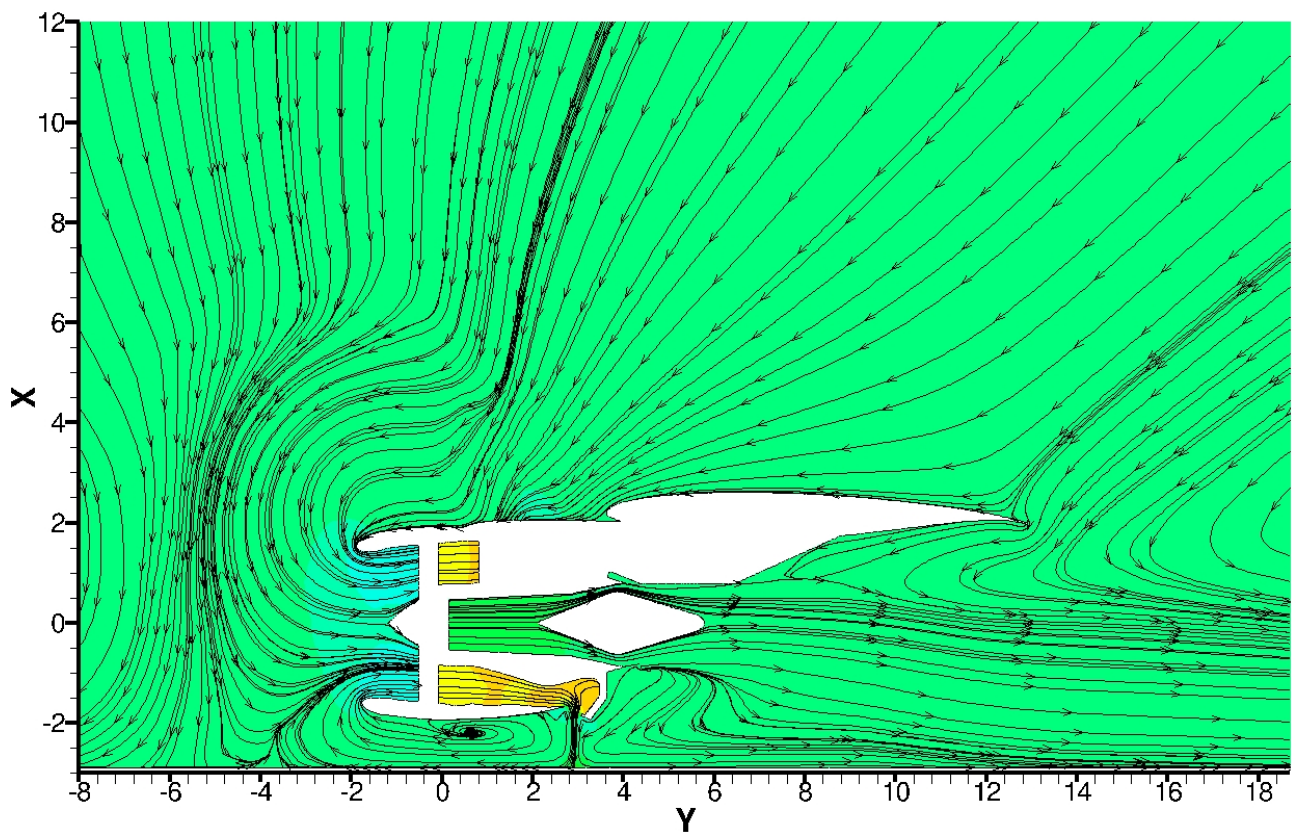
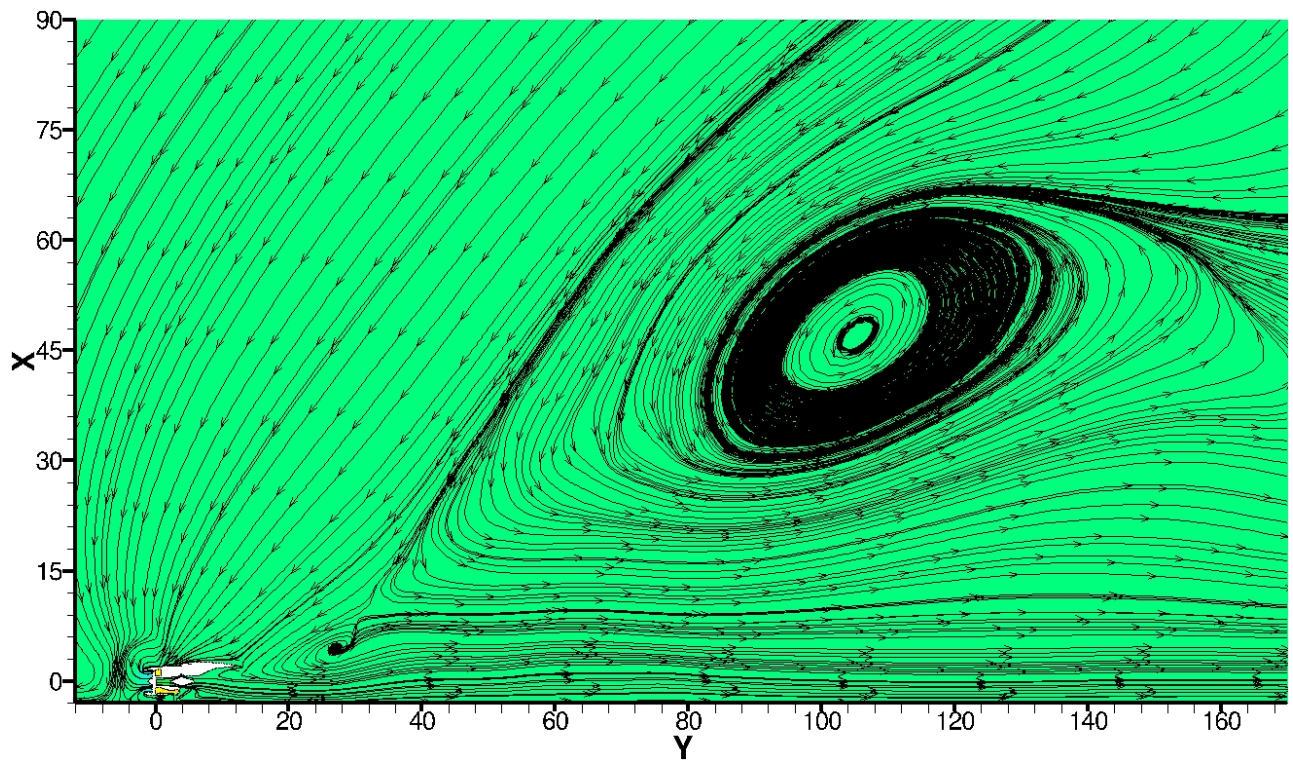
Streamlines Plot, 40 Deg Core Mounted Target Reverser with Kicker Plate, $M=0.0$,
 $FNPR=1.386$



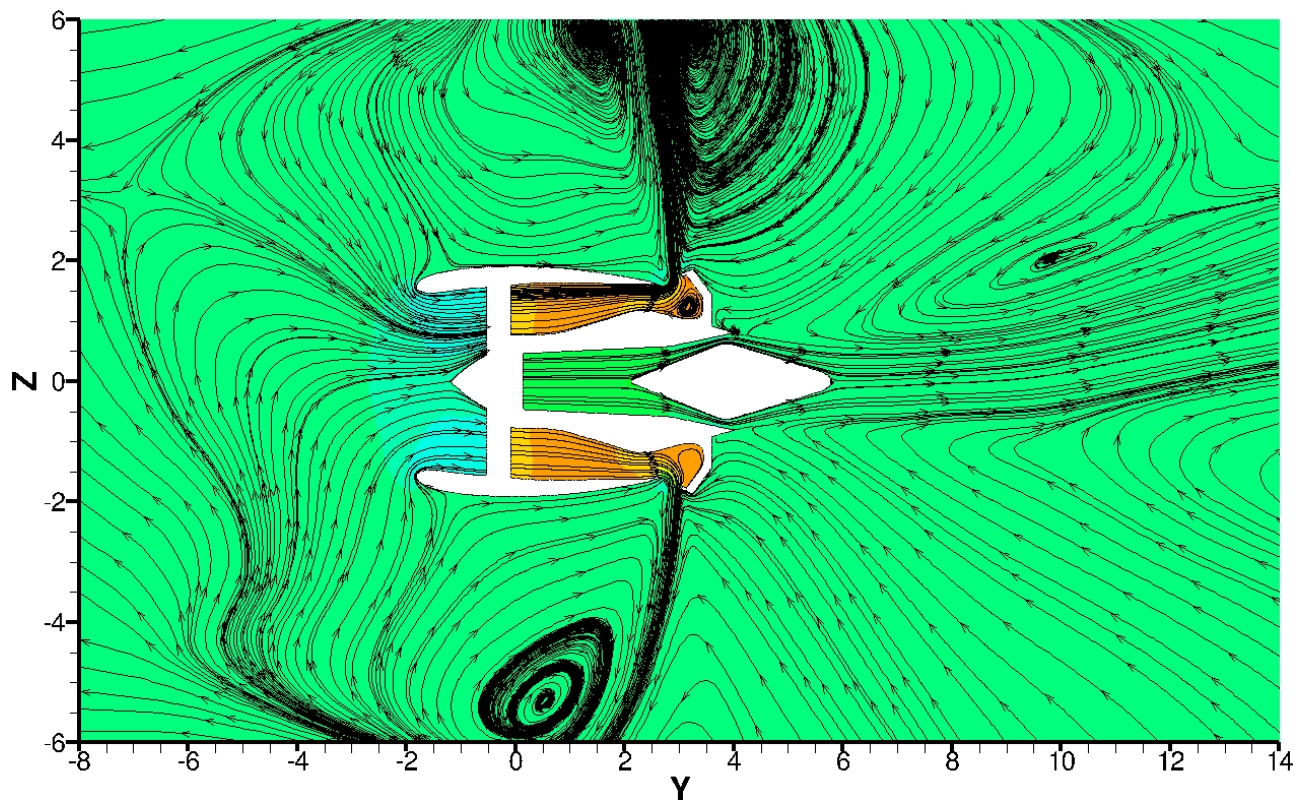
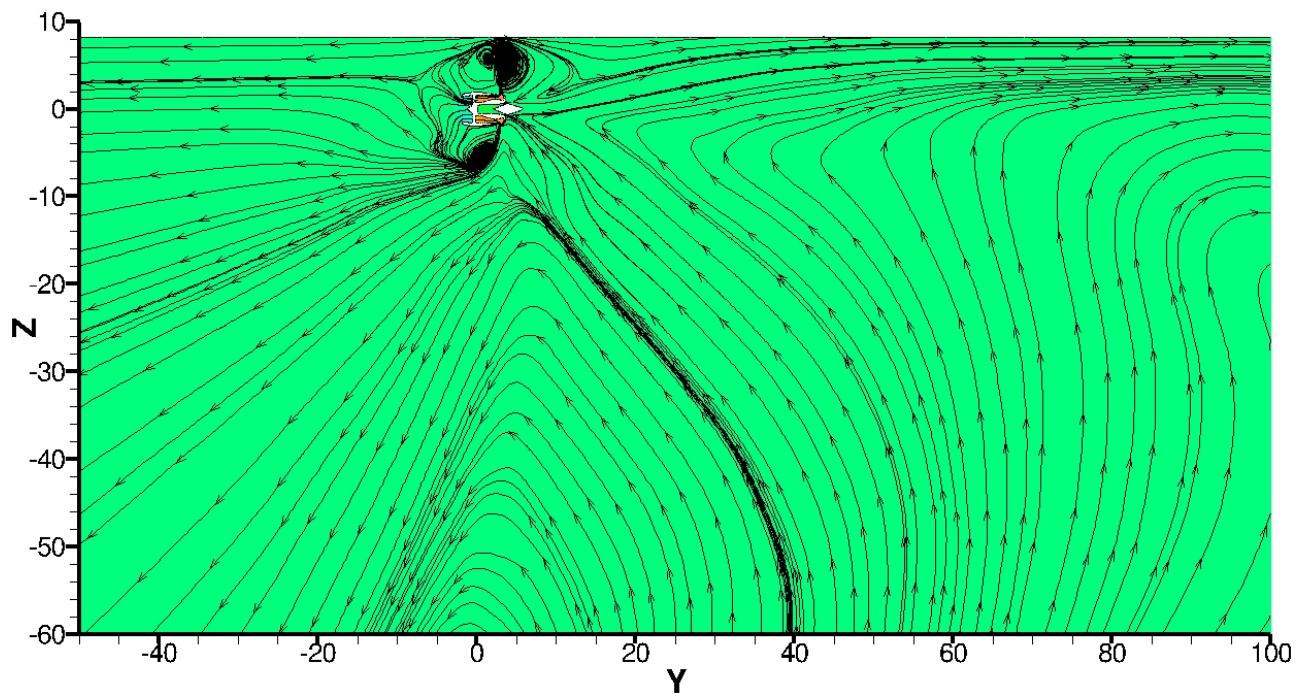


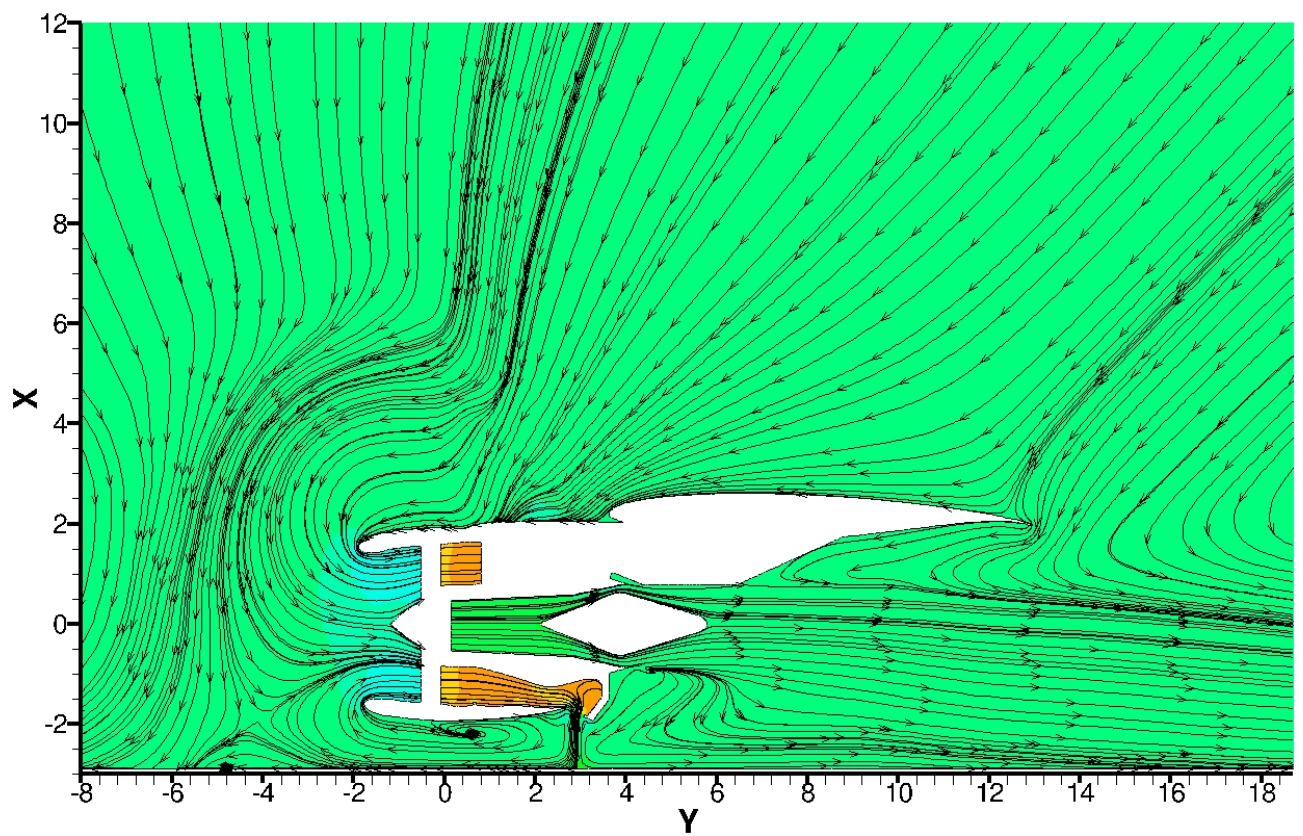
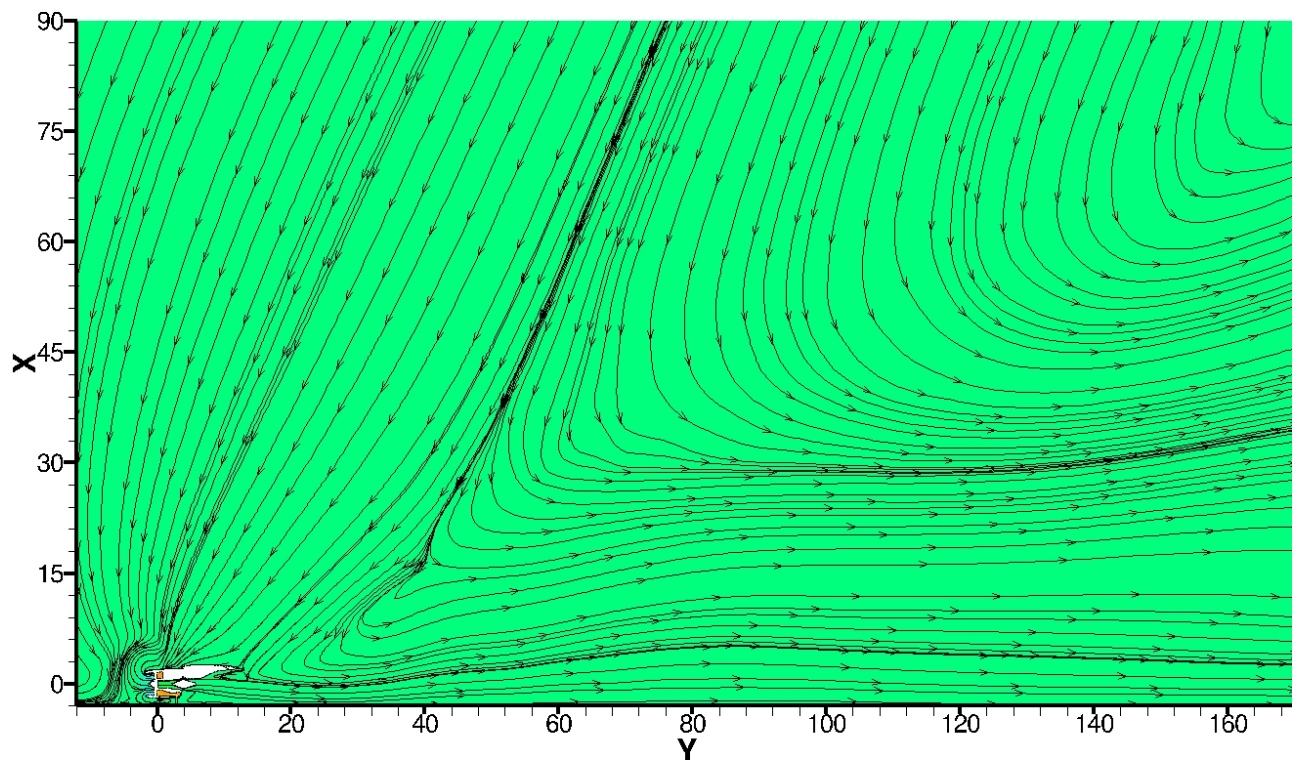
Streamlines Plot, 40 Deg Core Mounted Target Reverser with Kicker Plate, $M=0.0$,
 $FNPR=1.446$



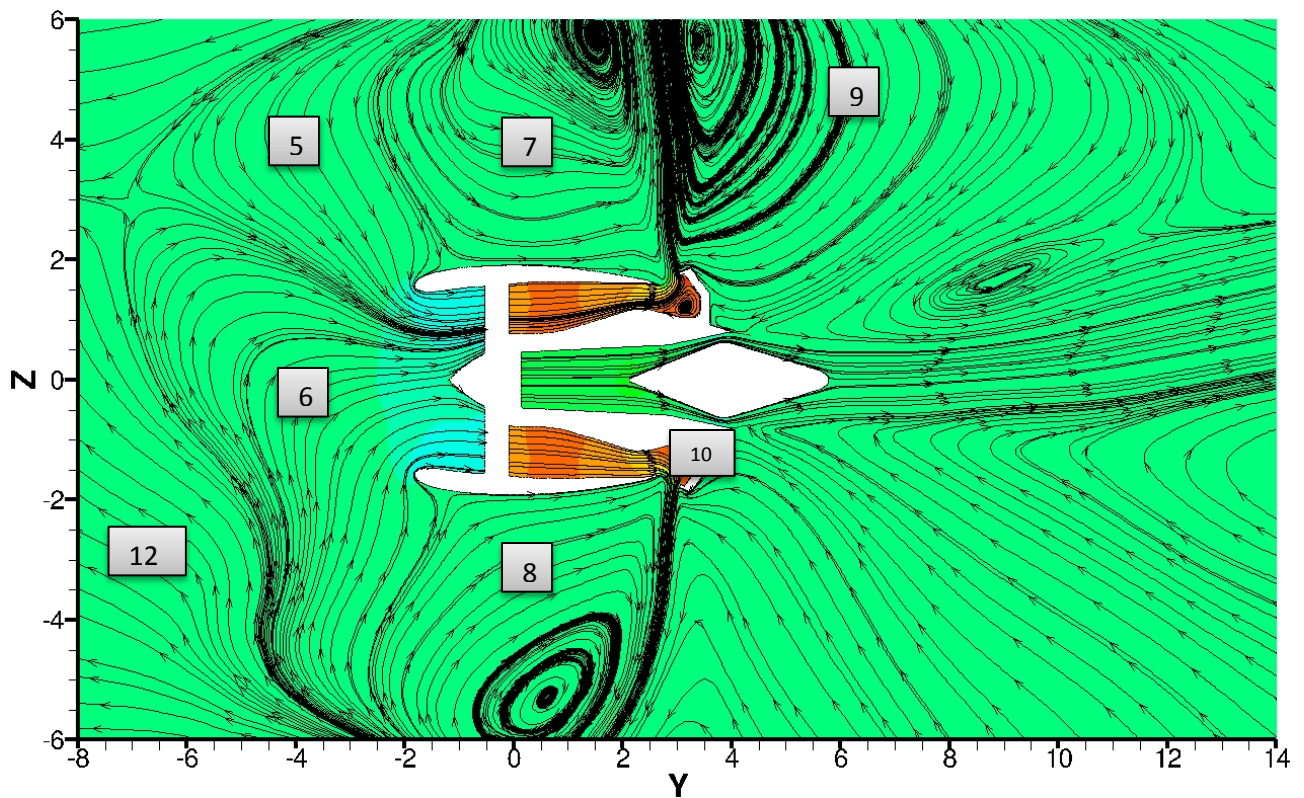
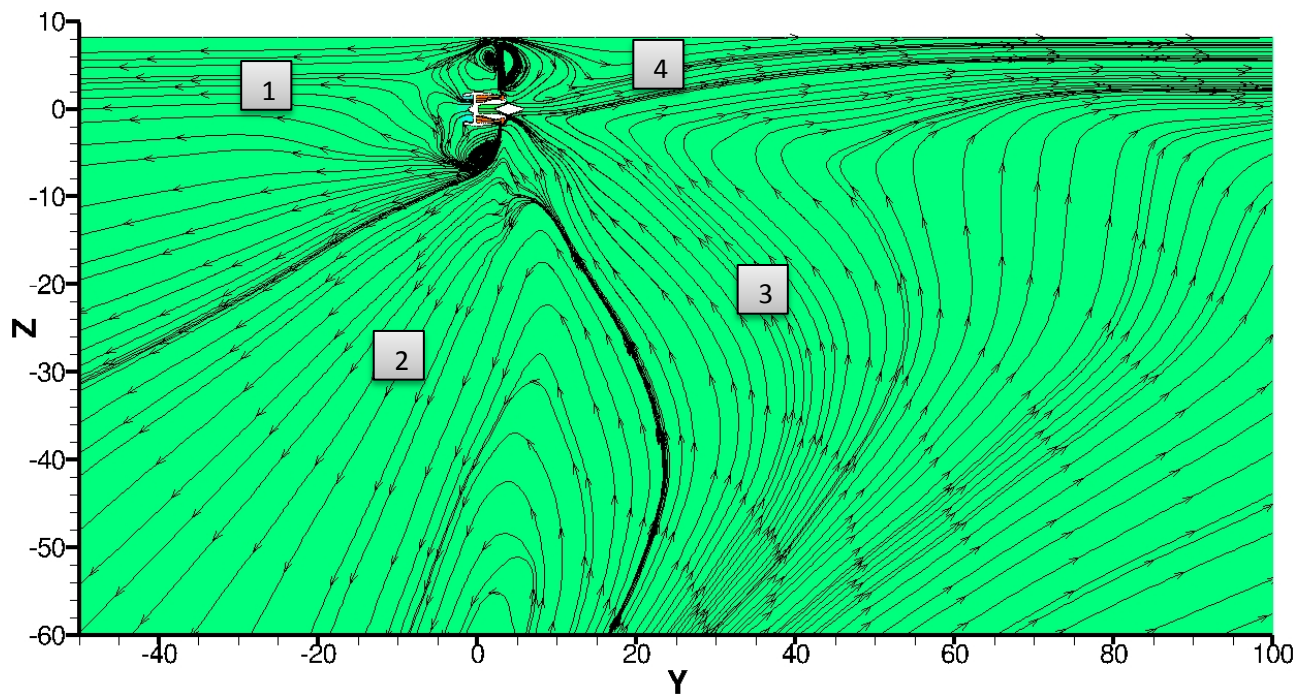


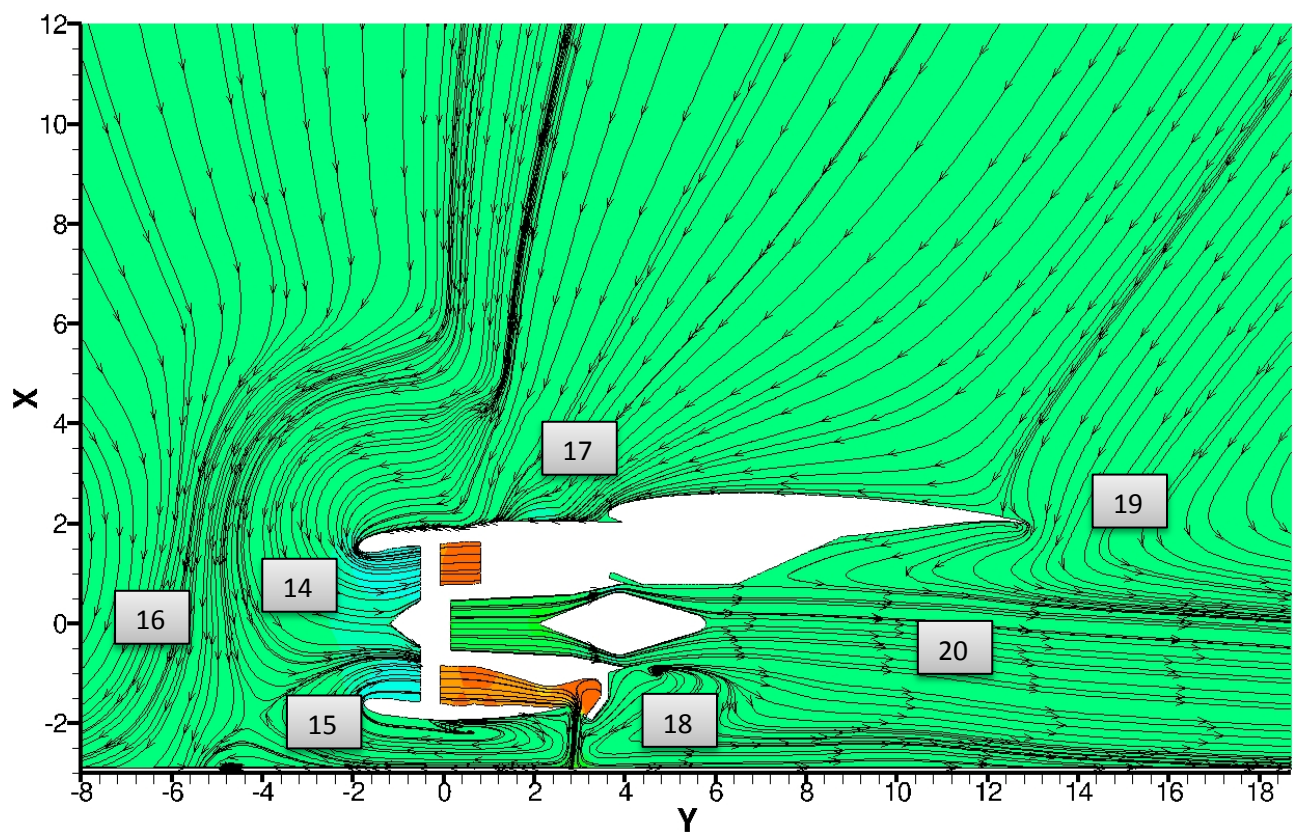
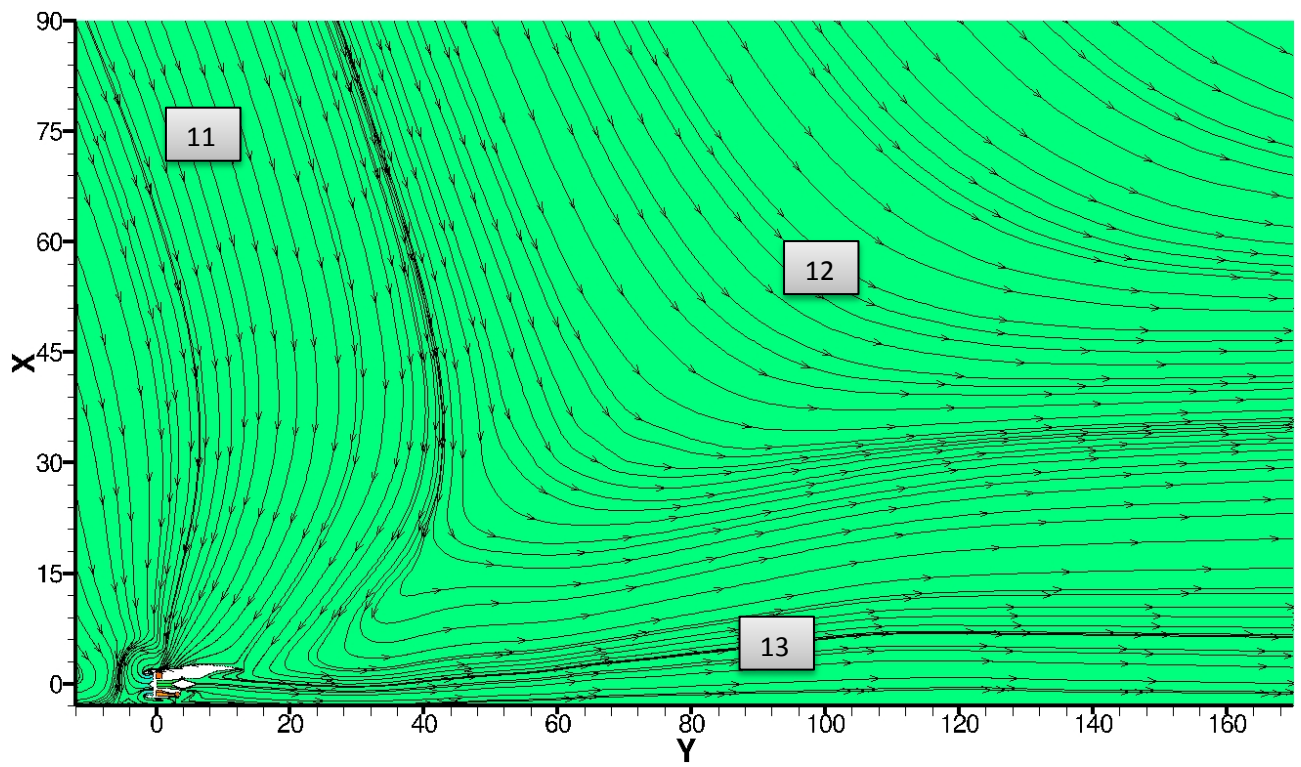
Streamlines Plot, 40 Deg Core Mounted Target Reverser with Kicker Plate, $M=0.0$,
 $FNPR=1.505$





Streamlines Plot, 40 Deg Core Mounted Target Reverser with Kicker Plate, $M=0.0$,
 $FNPR=1.554$

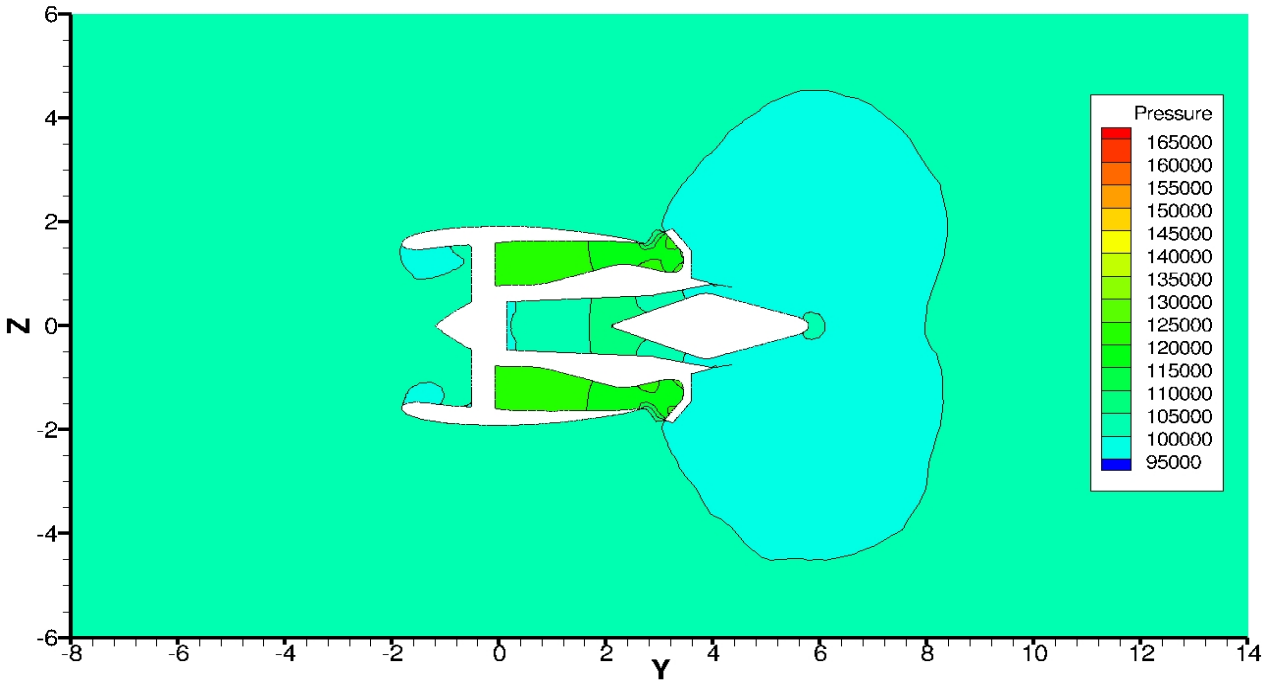




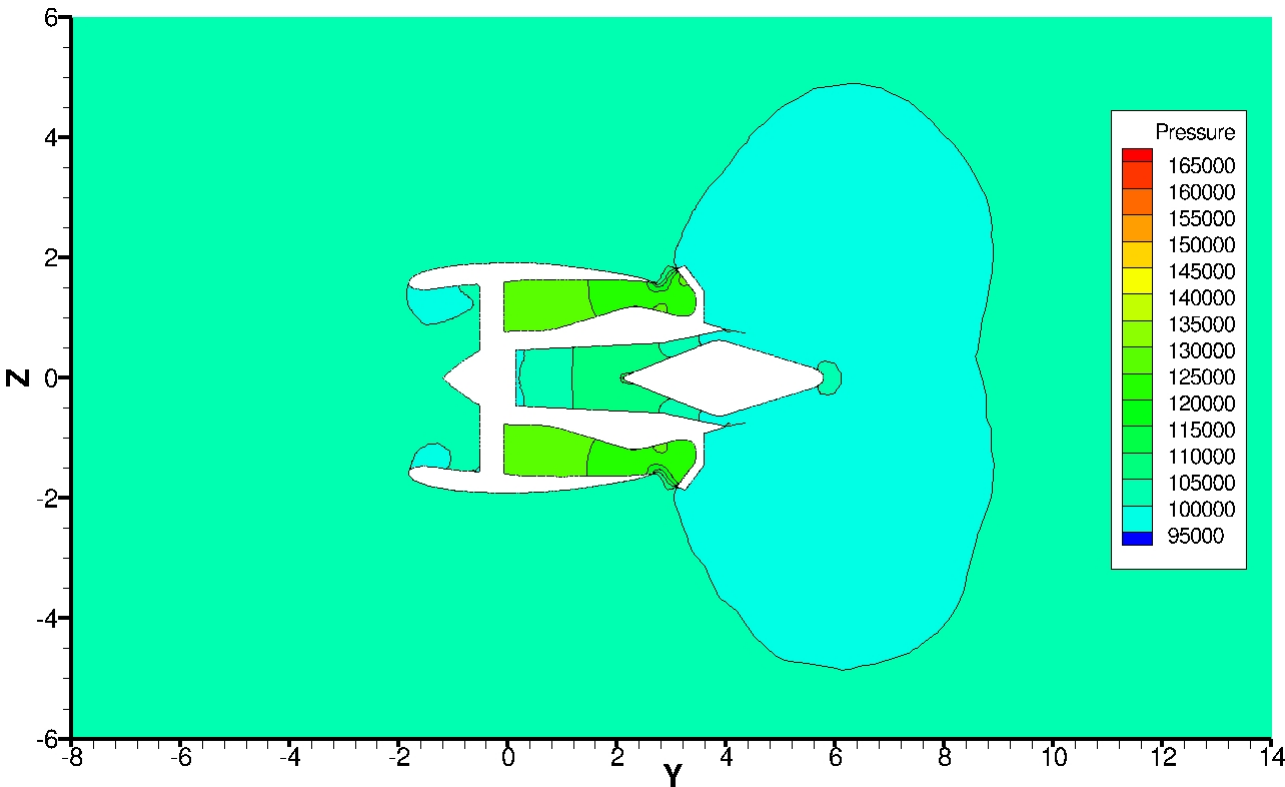
Appendix A5: Reverse Thrust 40 Degree with and without kicker plate at Static Condition, M=0.211

Appendix A5.1 –Static Pressure Contours

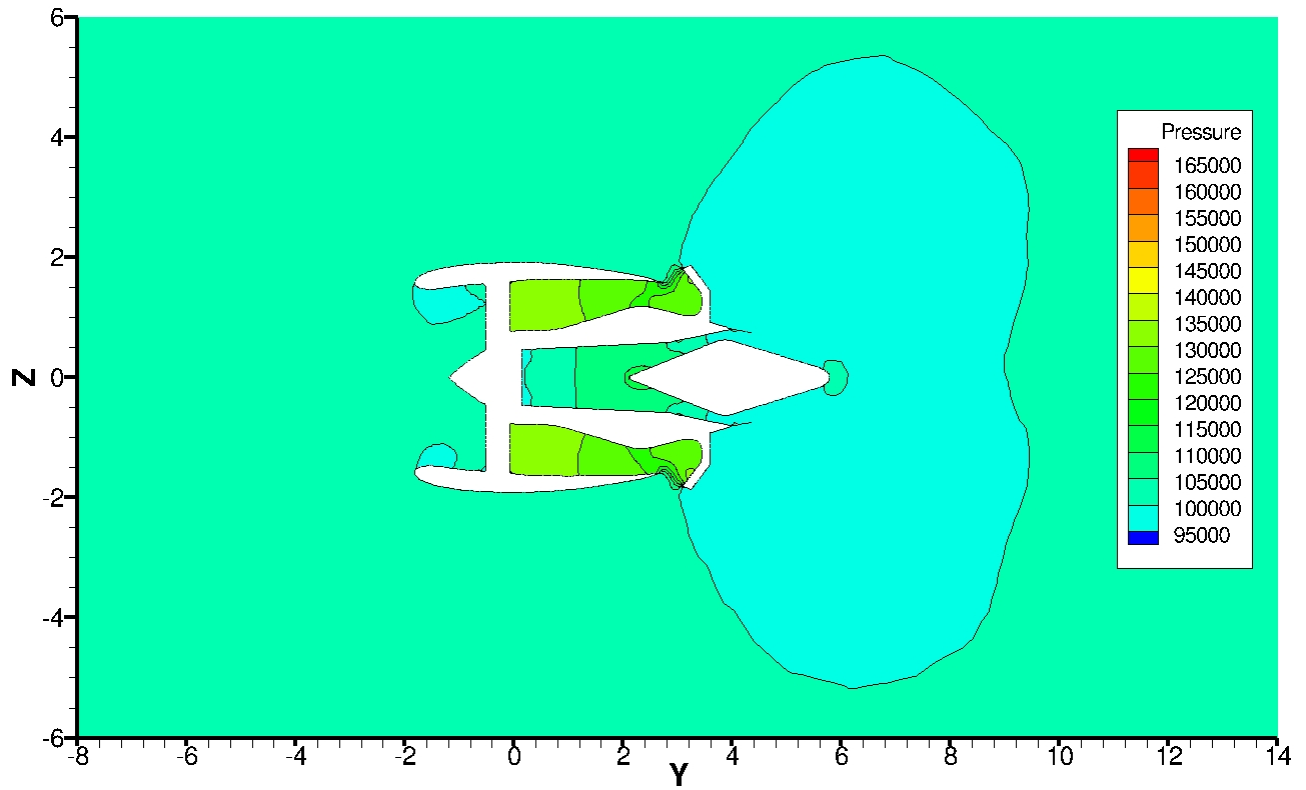
Static Pressure Contours, 40 Deg Core Mounted Target Reverser, M=0.211, FNPR=1.218



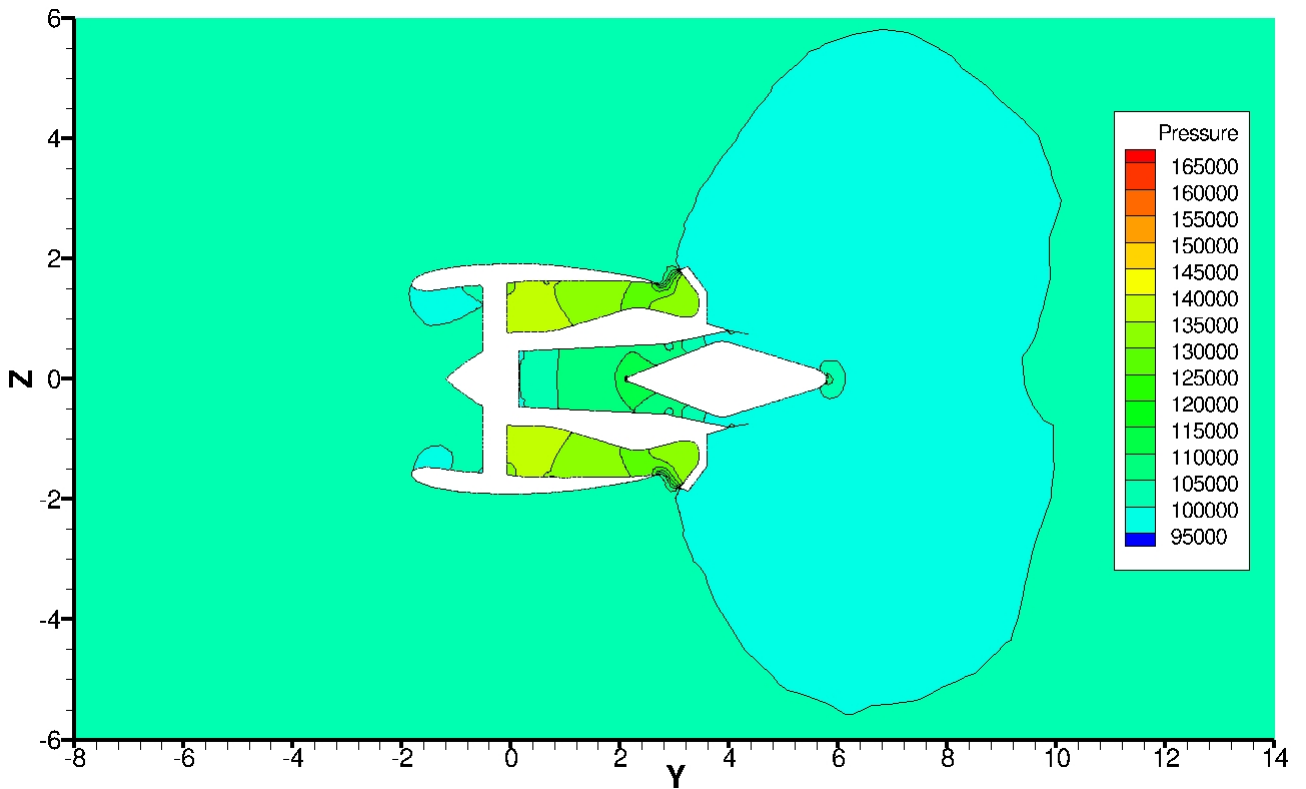
Static Pressure Contours, 40 Deg Core Mounted Target Reverser, M=0.211, FNPR=1.267



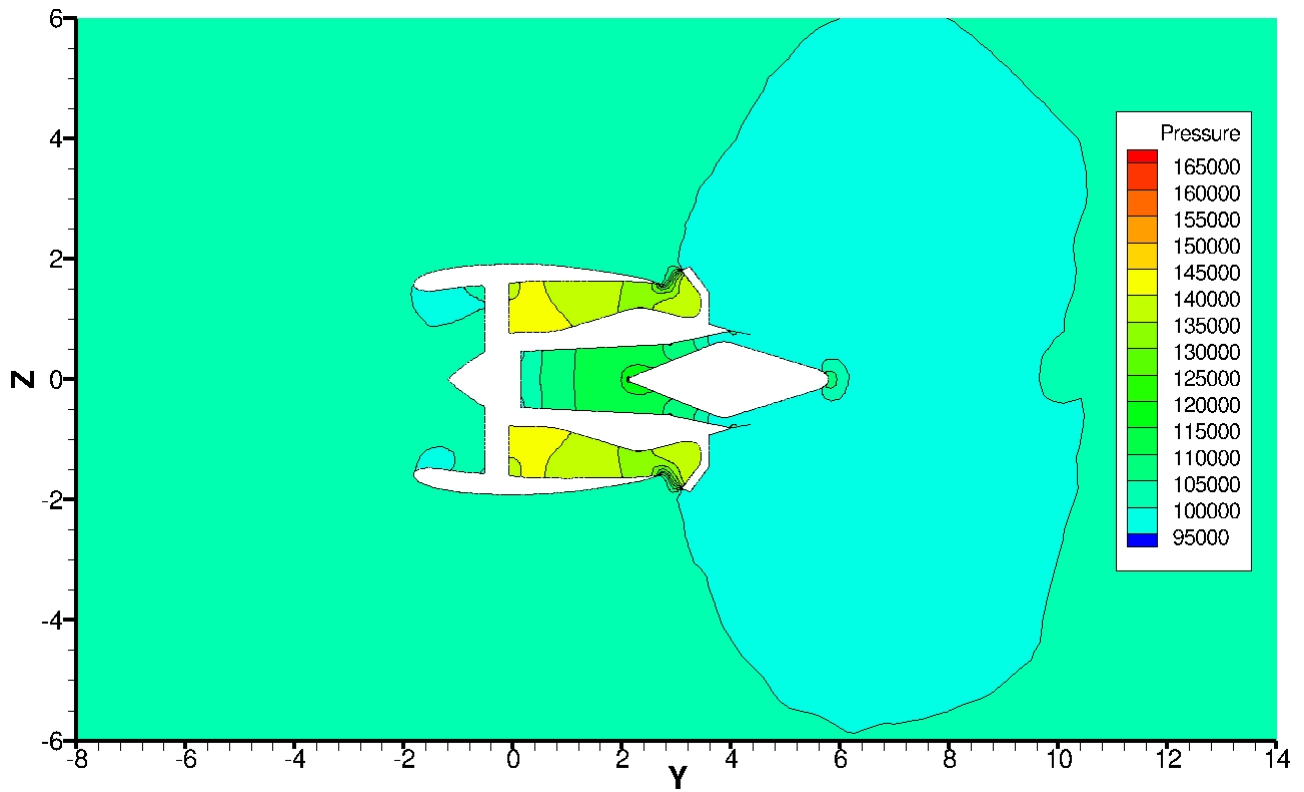
Static Pressure Contours, 40 Deg Core Mounted Target Reverser, $M=0.211$, $FNPR=1.317$



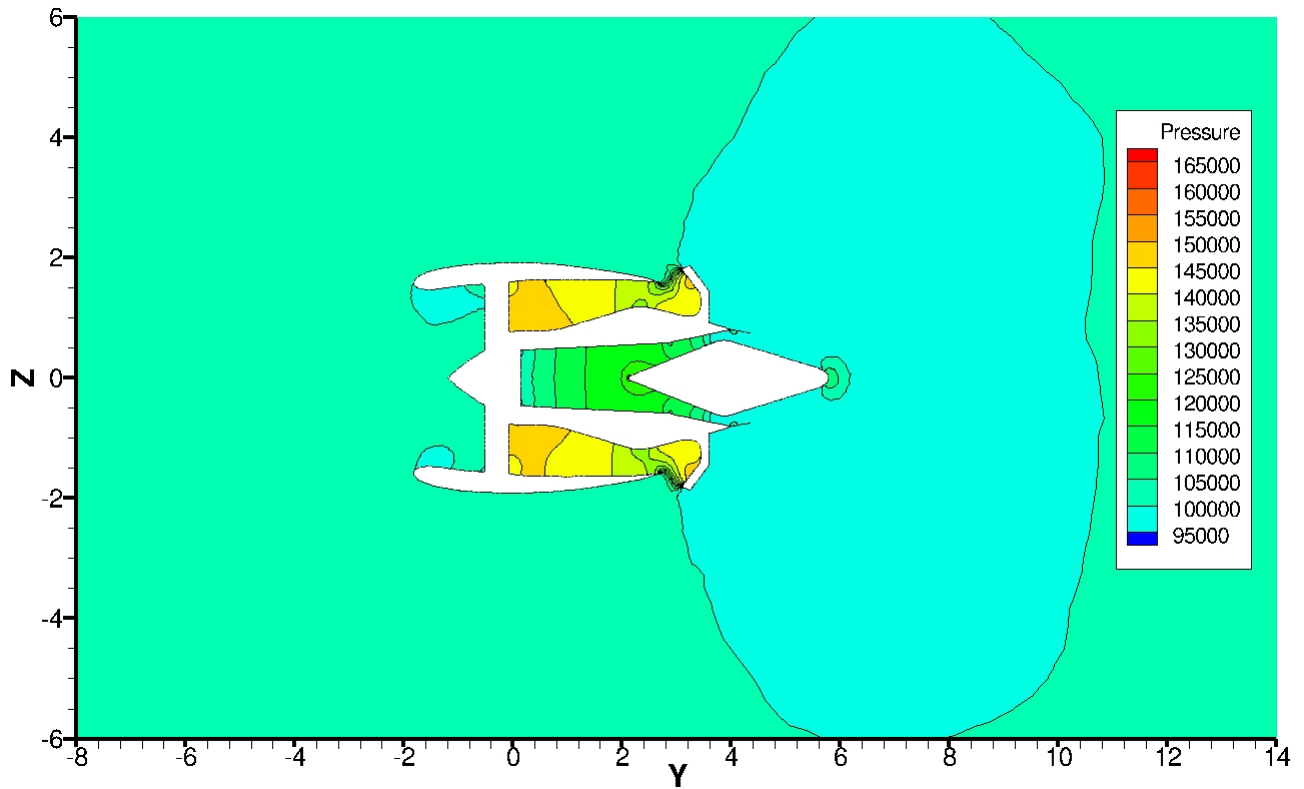
Static Pressure Contours, 40 Deg Core Mounted Target Reverser, $M=0.211$, $FNPR=1.366$



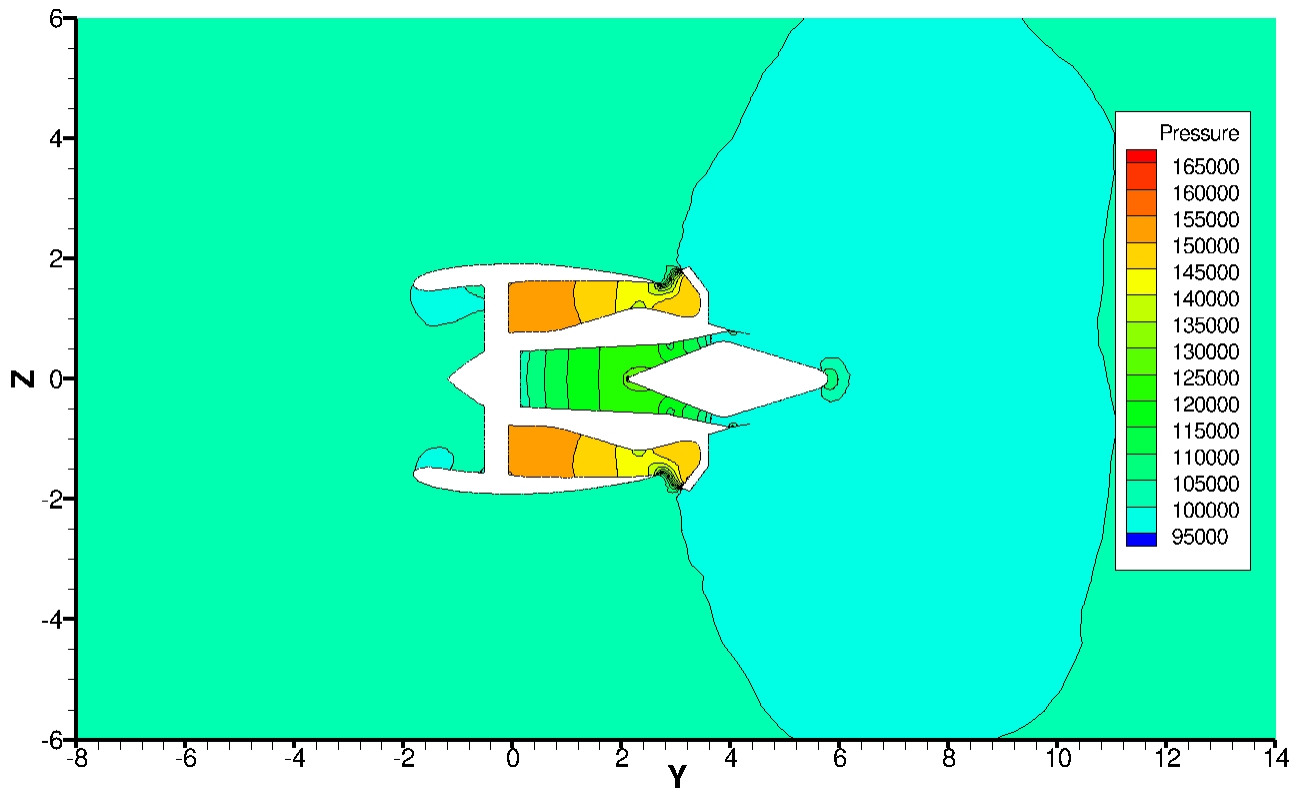
Static Pressure Contours, 40 Deg Core Mounted Target Reverser, $M=0.211$, $FNPR=1.416$



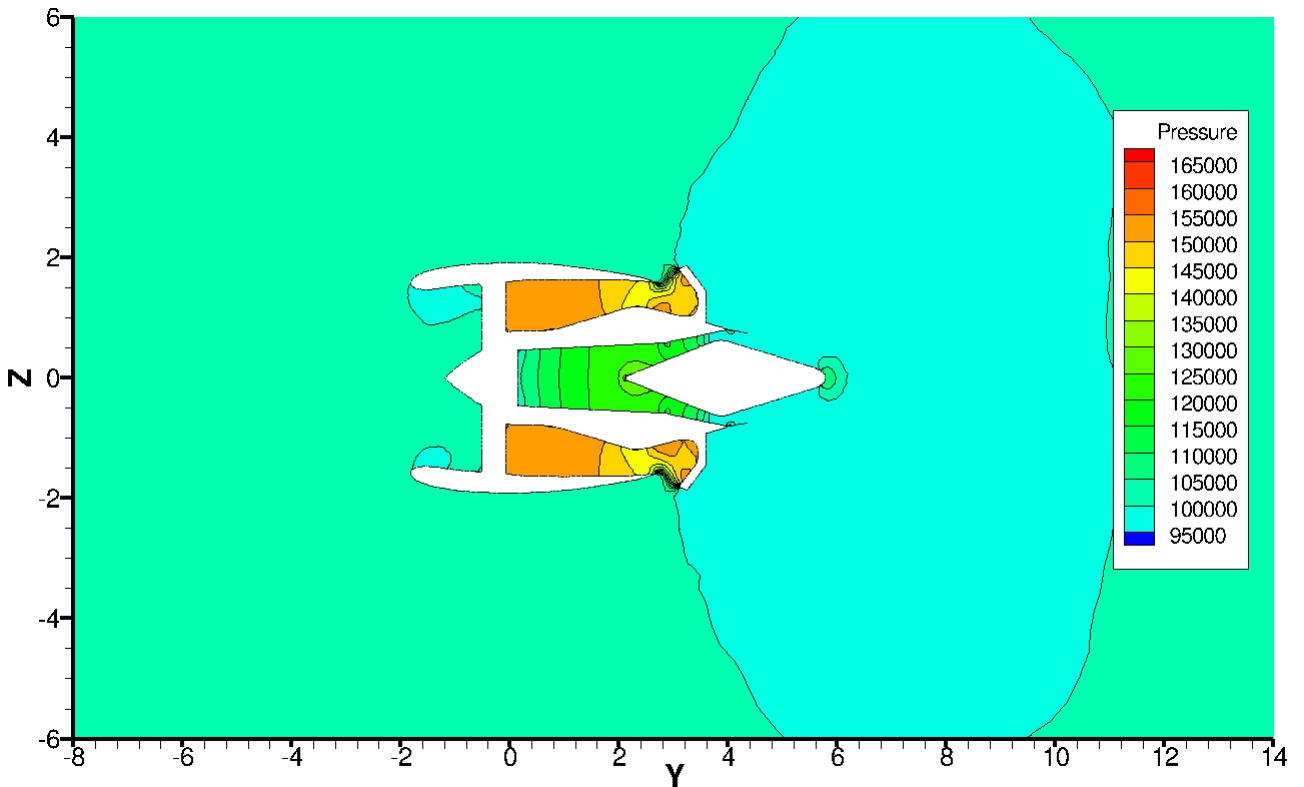
Static Pressure Contours, 40 Deg Core Mounted Target Reverser, $M=0.211$, $FNPR=1.475$



Static Pressure Contours, 40 Deg Core Mounted Target Reverser, $M=0.211$, $FNPR=1.535$

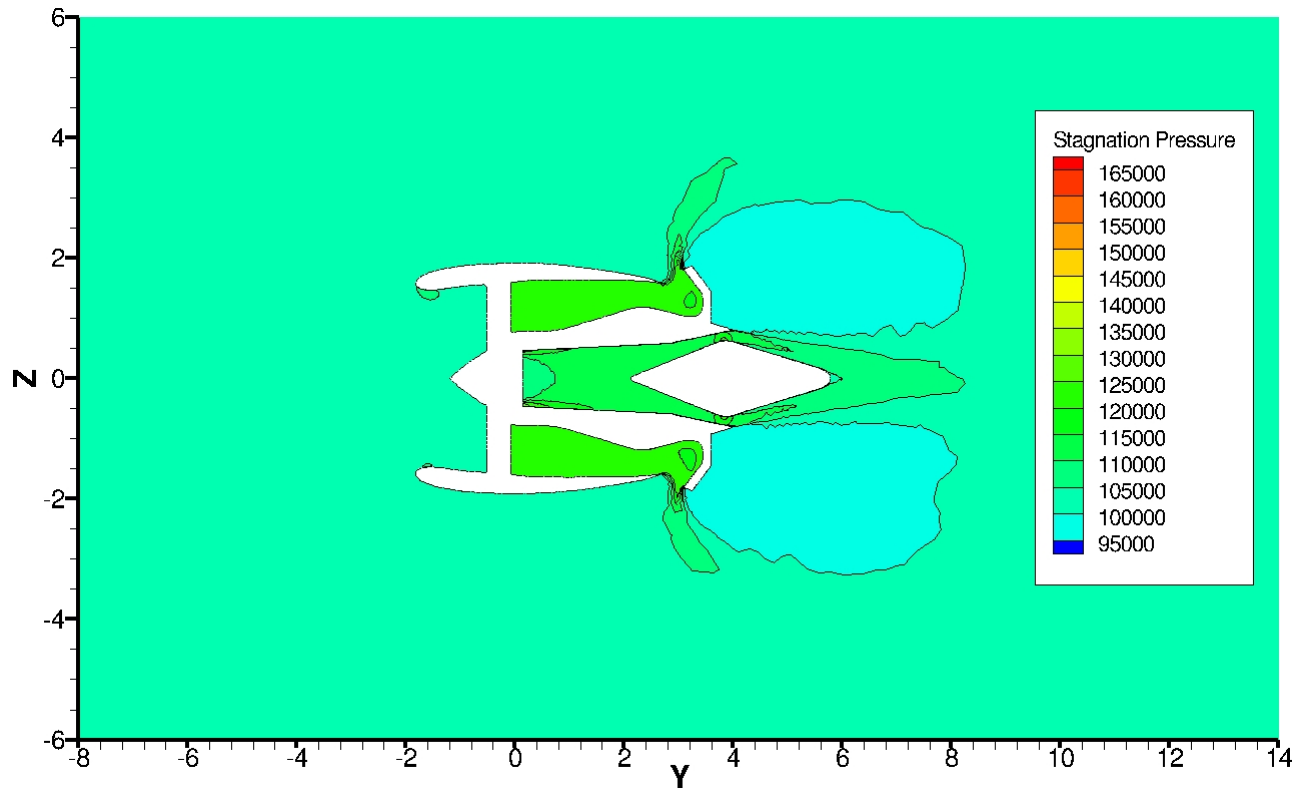


Static Pressure Contours, 40 Deg Core Mounted Target Reverser, $M=0.211$, $FNPR=1.574$

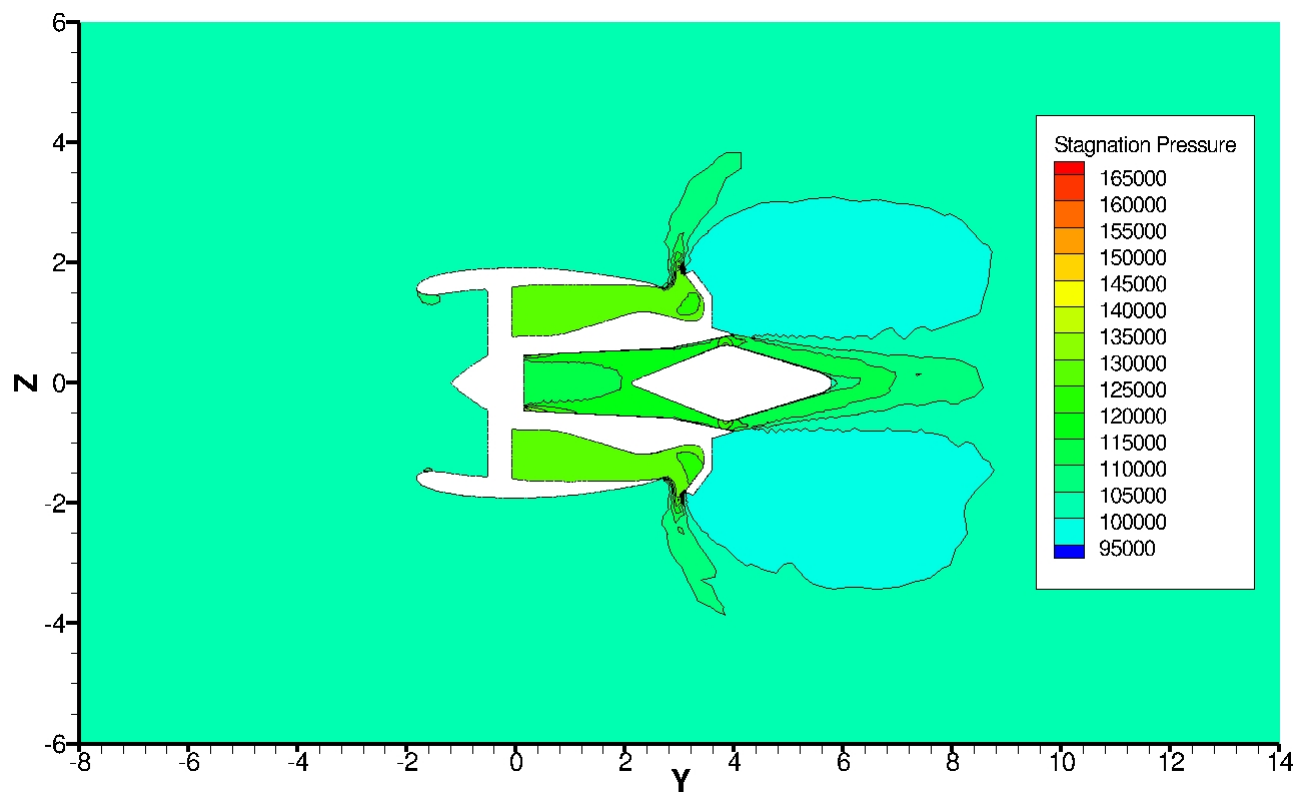


Appendix A5.2 – Total Pressure Contours

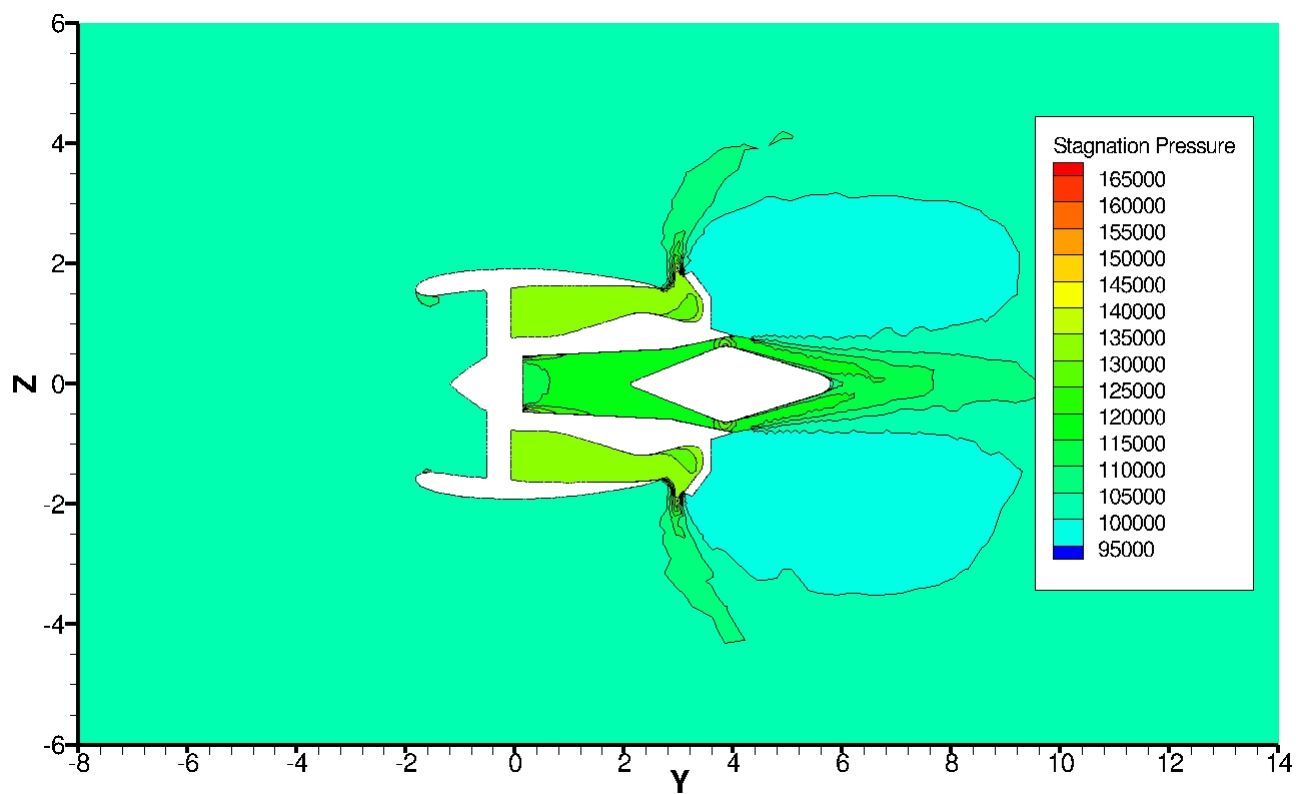
Total Pressure Contours, 40 Deg Core Mounted Target Reverser, $M=0.211$, $FNPR=1.218$



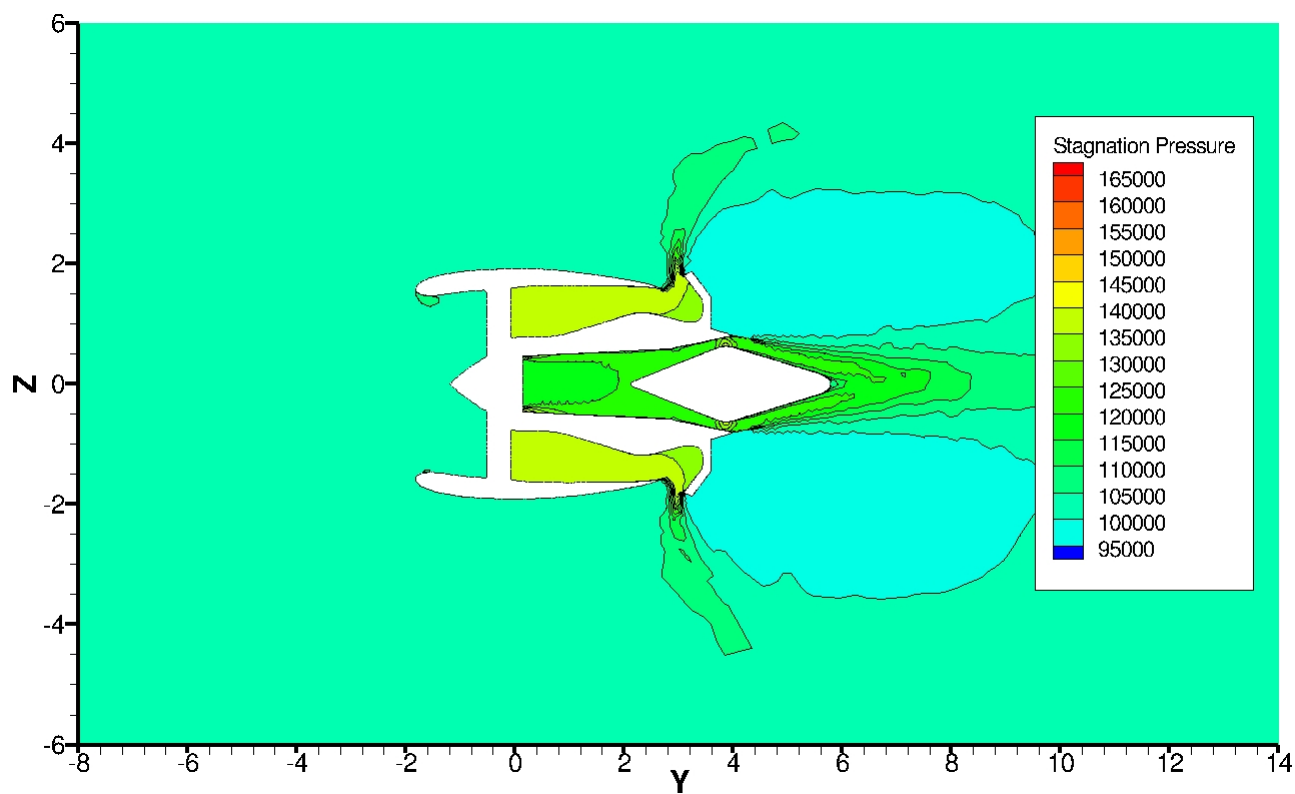
Total Pressure Contours, 40 Deg Core Mounted Target Reverser, $M=0.211$, $FNPR=1.267$



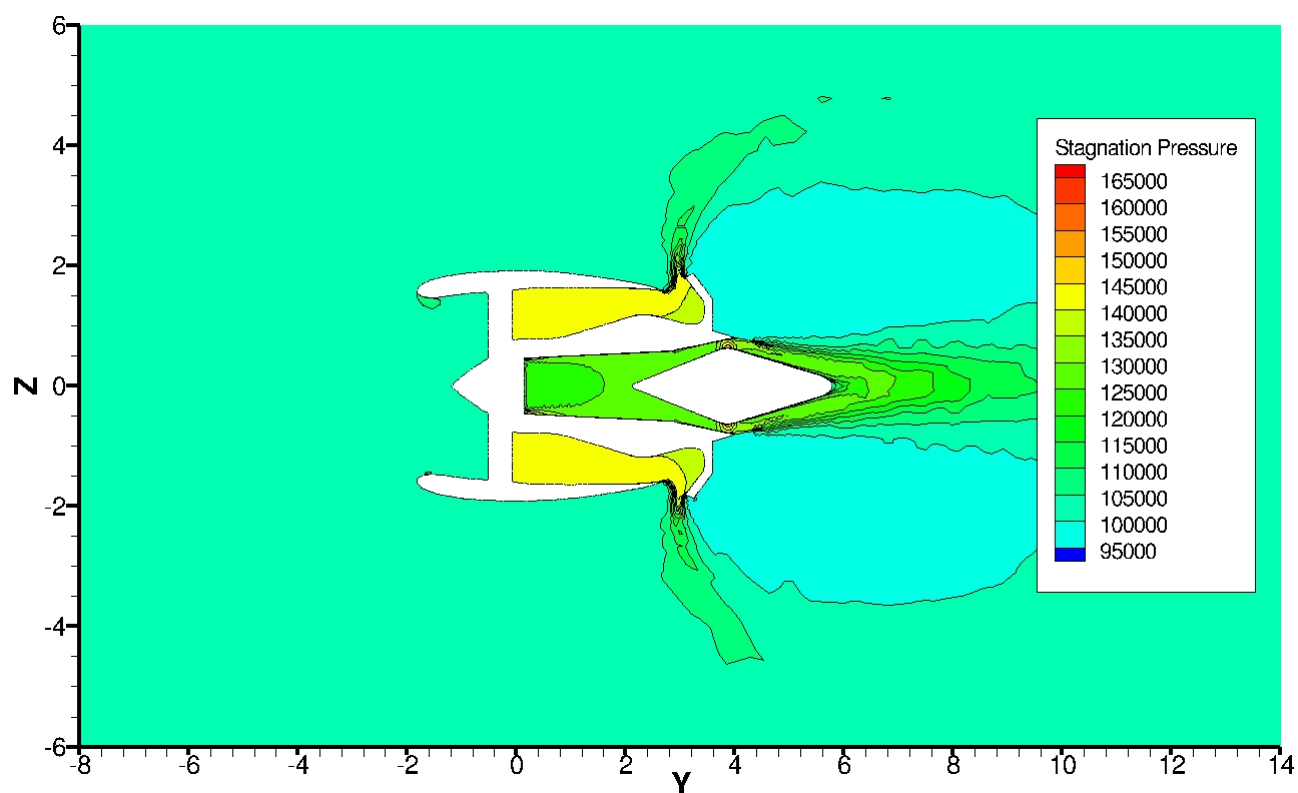
Total Pressure Contours, 40 Deg Core Mounted Target Reverser, $M=0.211$, $FNPR=1.317$



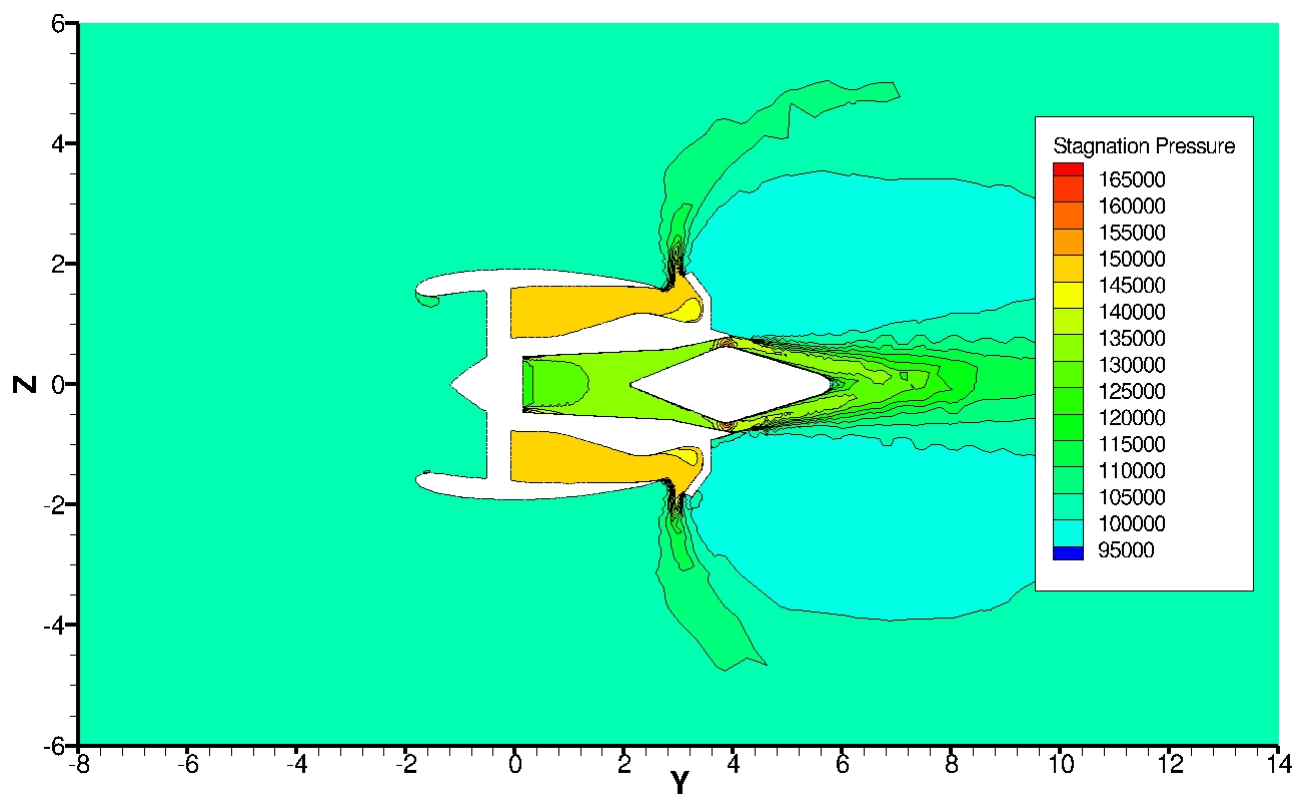
Total Pressure Contours, 40 Deg Core Mounted Target Reverser, $M=0.211$, $FNPR=1.366$



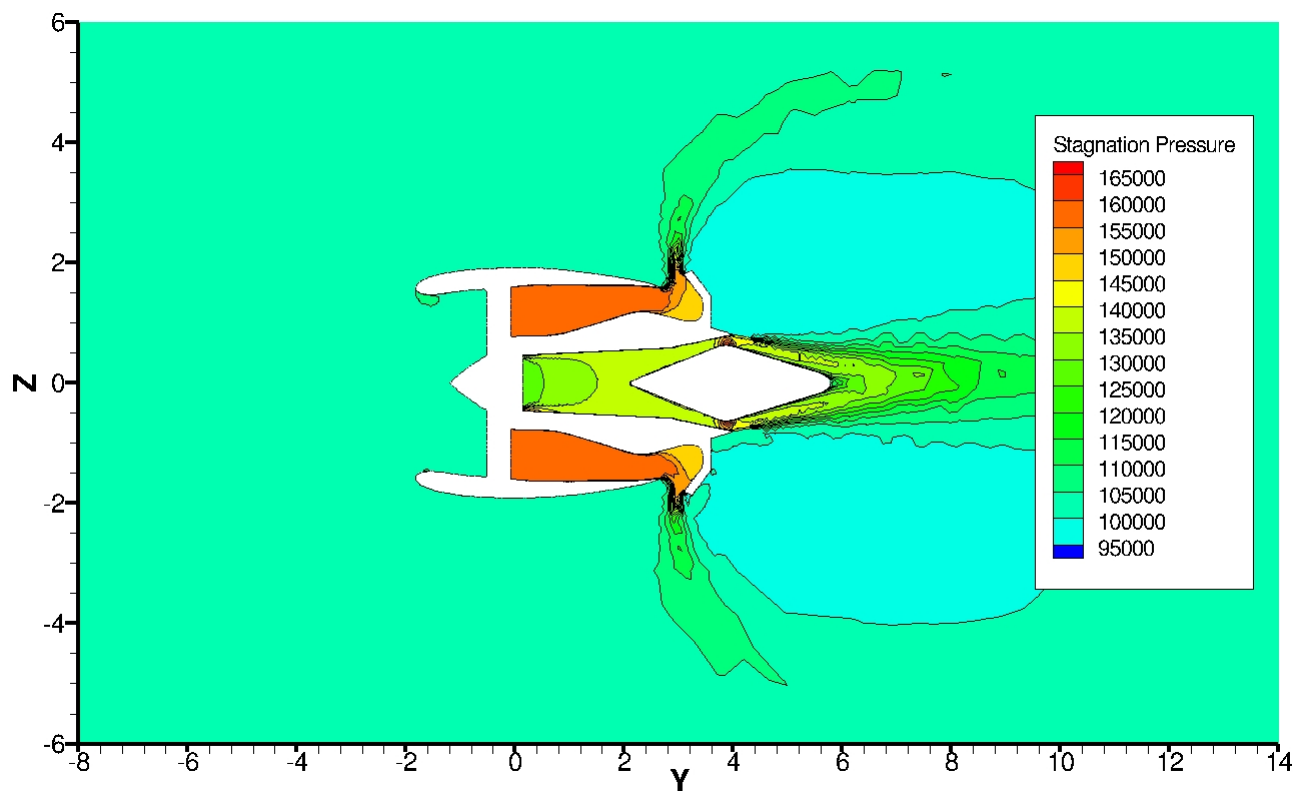
Total Pressure Contours, 40 Deg Core Mounted Target Reverser, $M=0.211$, $FNPR=1.416$



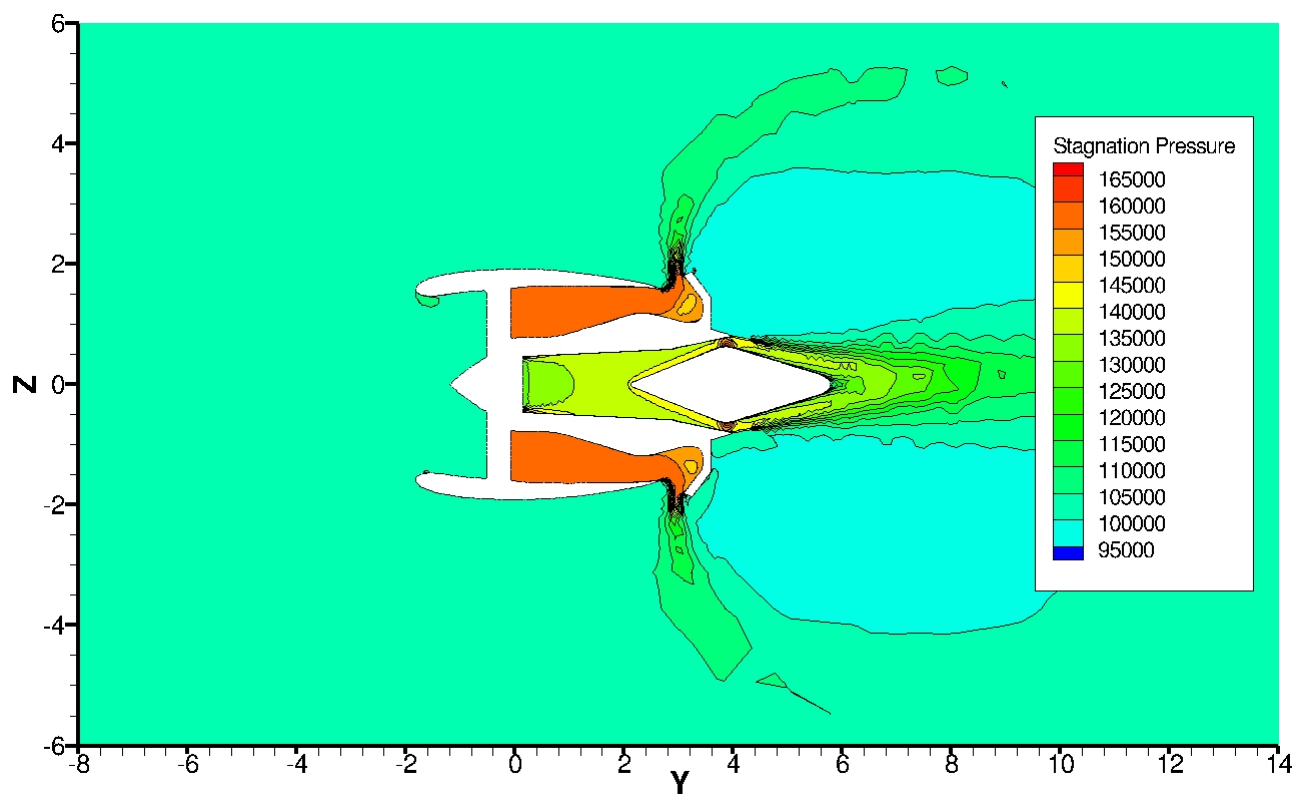
Total Pressure Contours, 40 Deg Core Mounted Target Reverser, $M=0.211$, $FNPR=1.475$



Total Pressure Contours, 40 Deg Core Mounted Target Reverser, $M=0.211$, $FNPR=1.535$

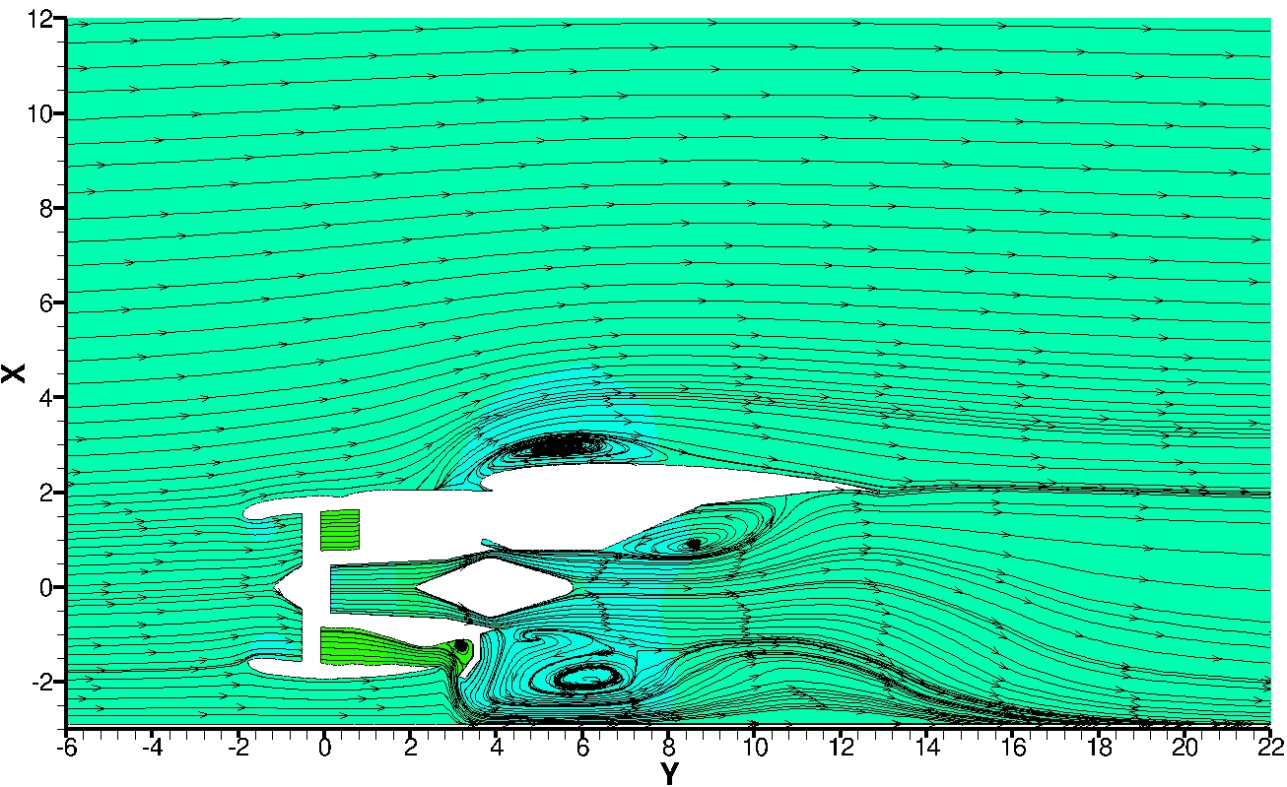
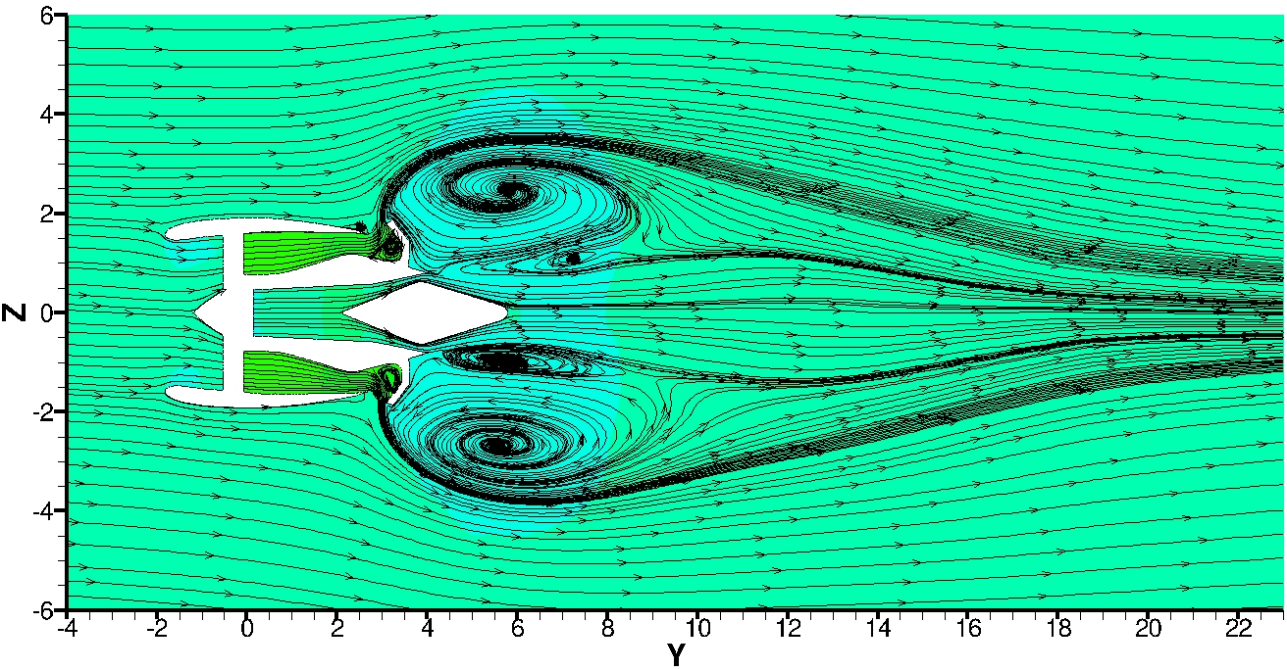


Total Pressure Contours, 40 Deg Core Mounted Target Reverser, $M=0.211$, $FNPR=1.574$

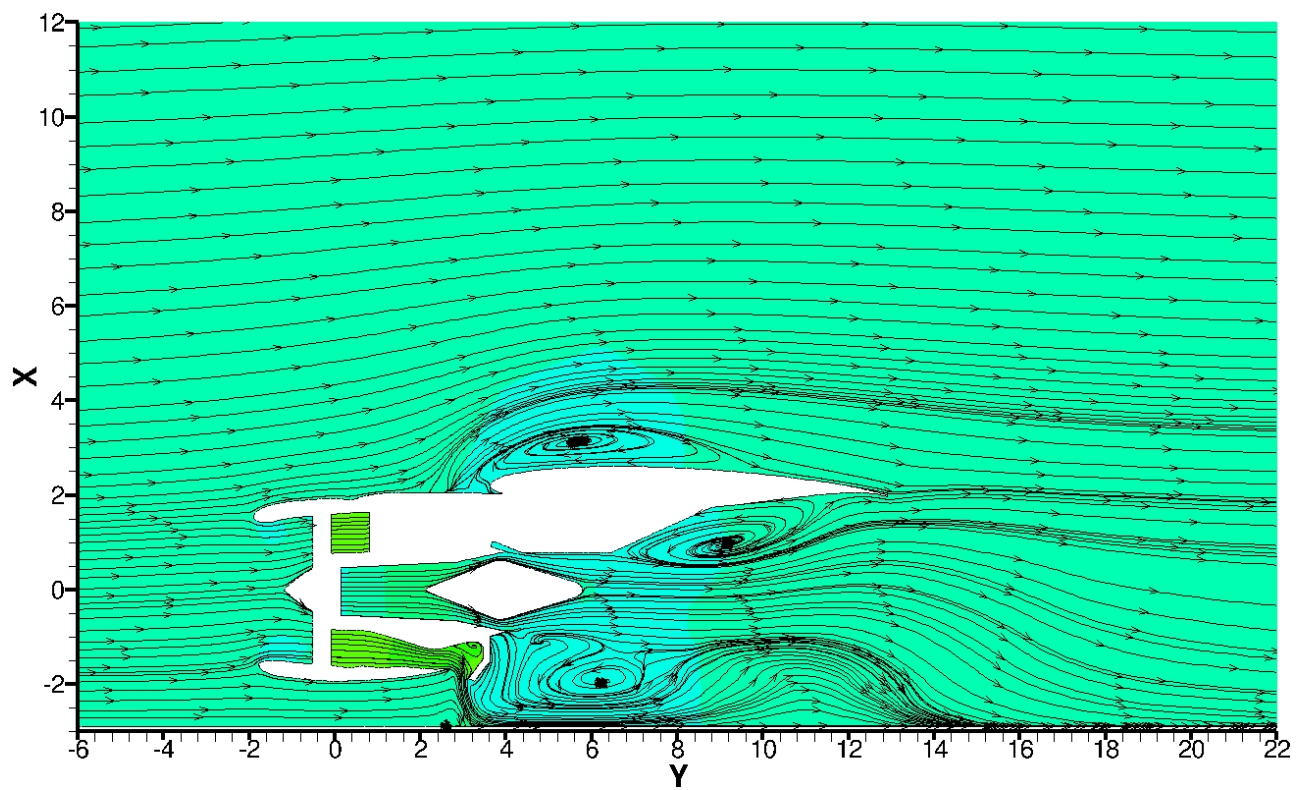
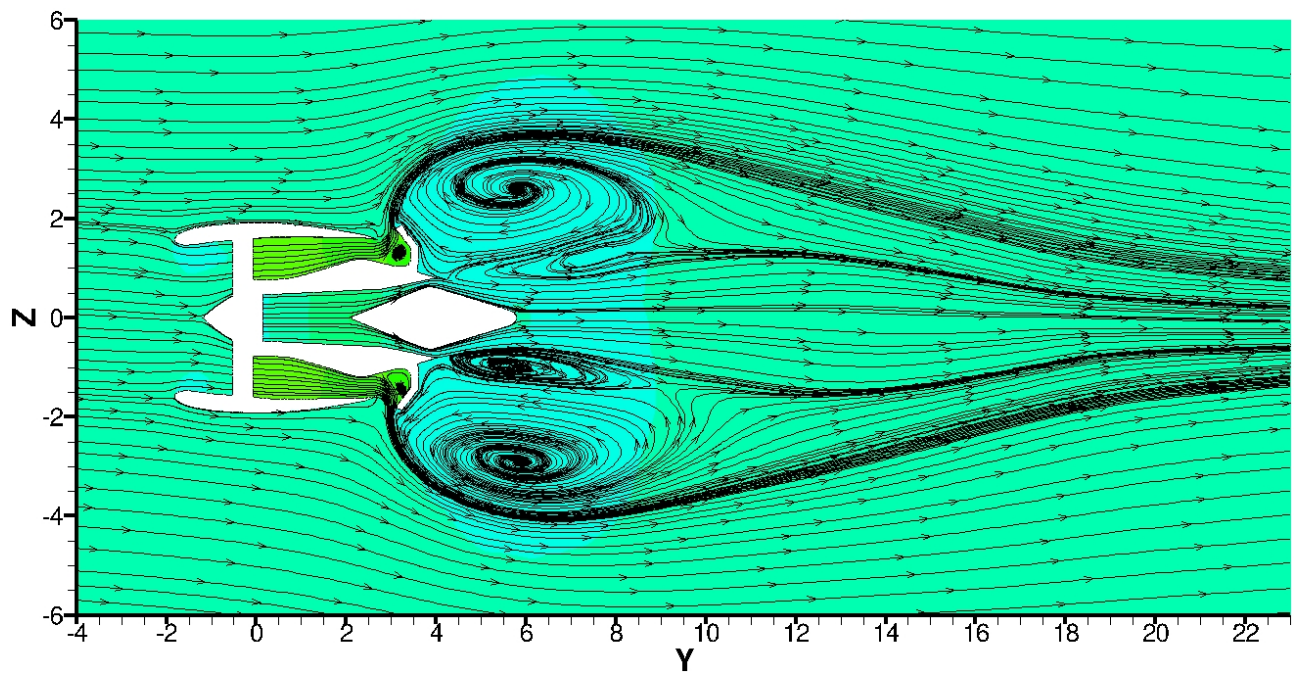


Appendix A5.3 – Streamline Plots

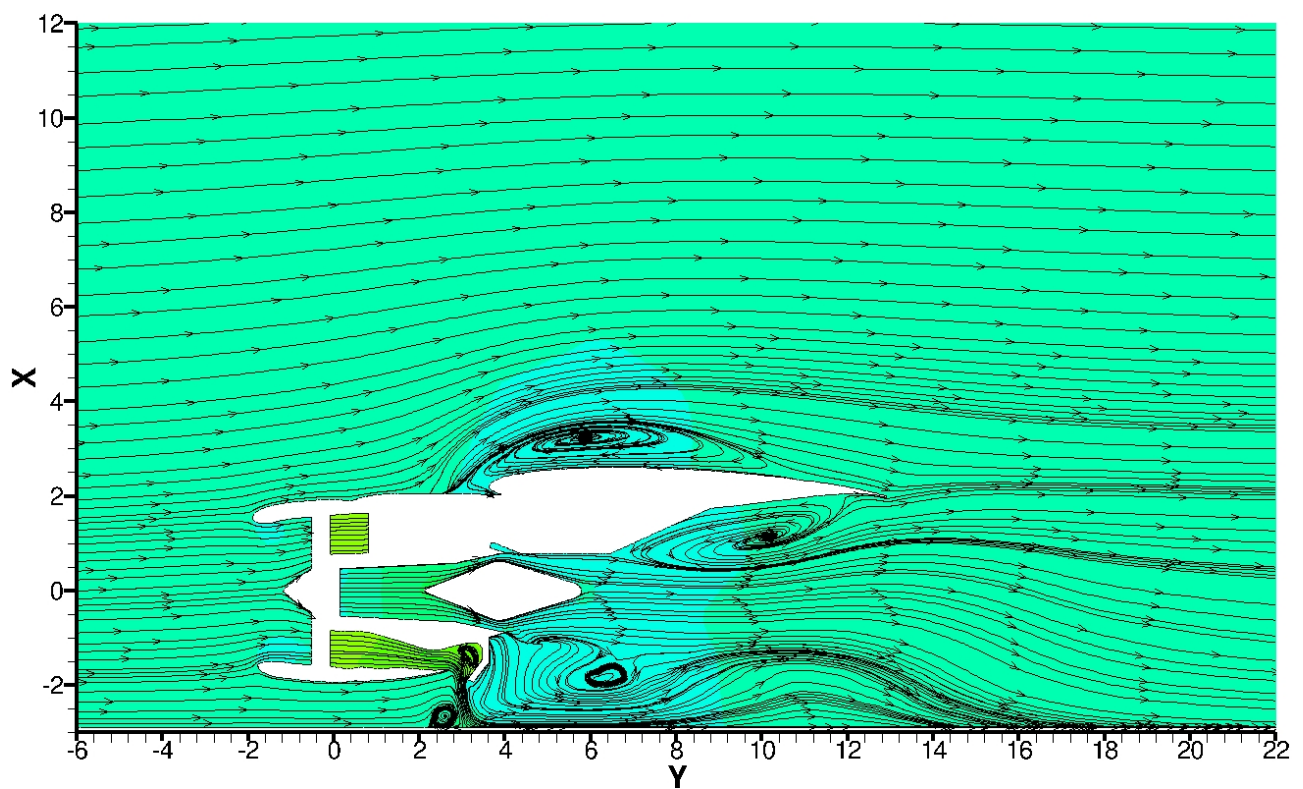
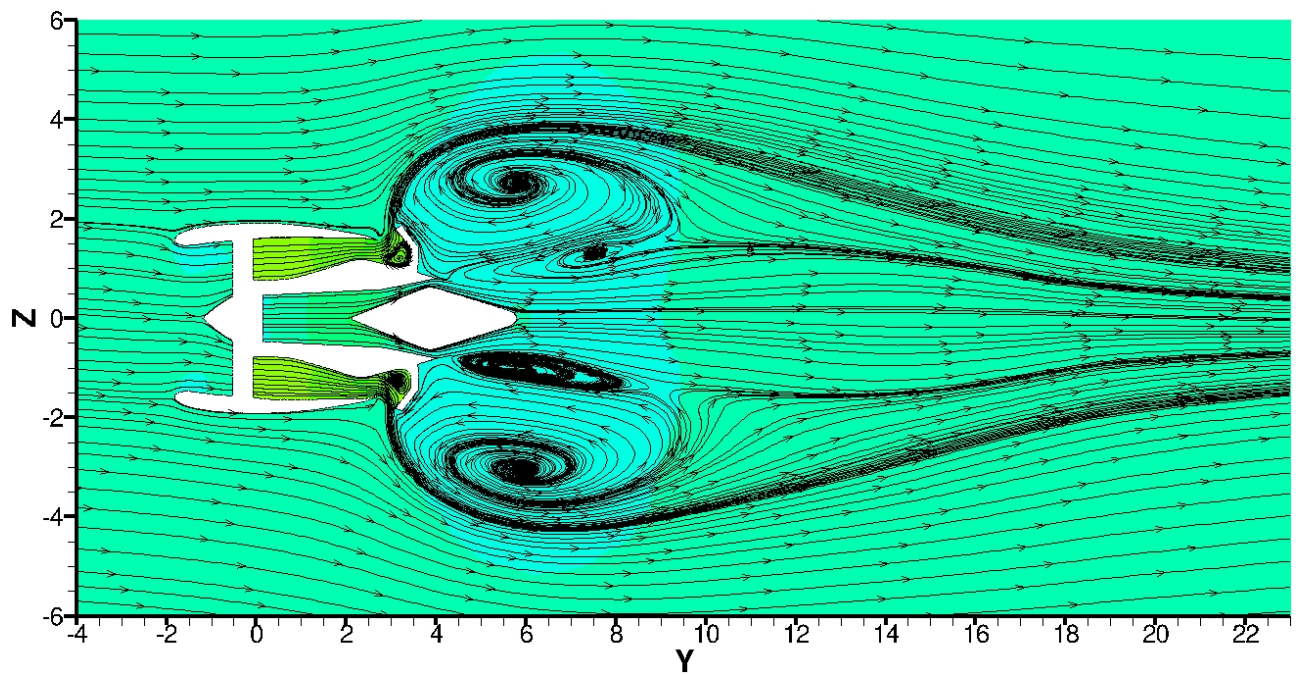
Streamline Plot, 40 Deg Core Mounted Target Reverser, $M=0.211$, $FNPR=1.218$



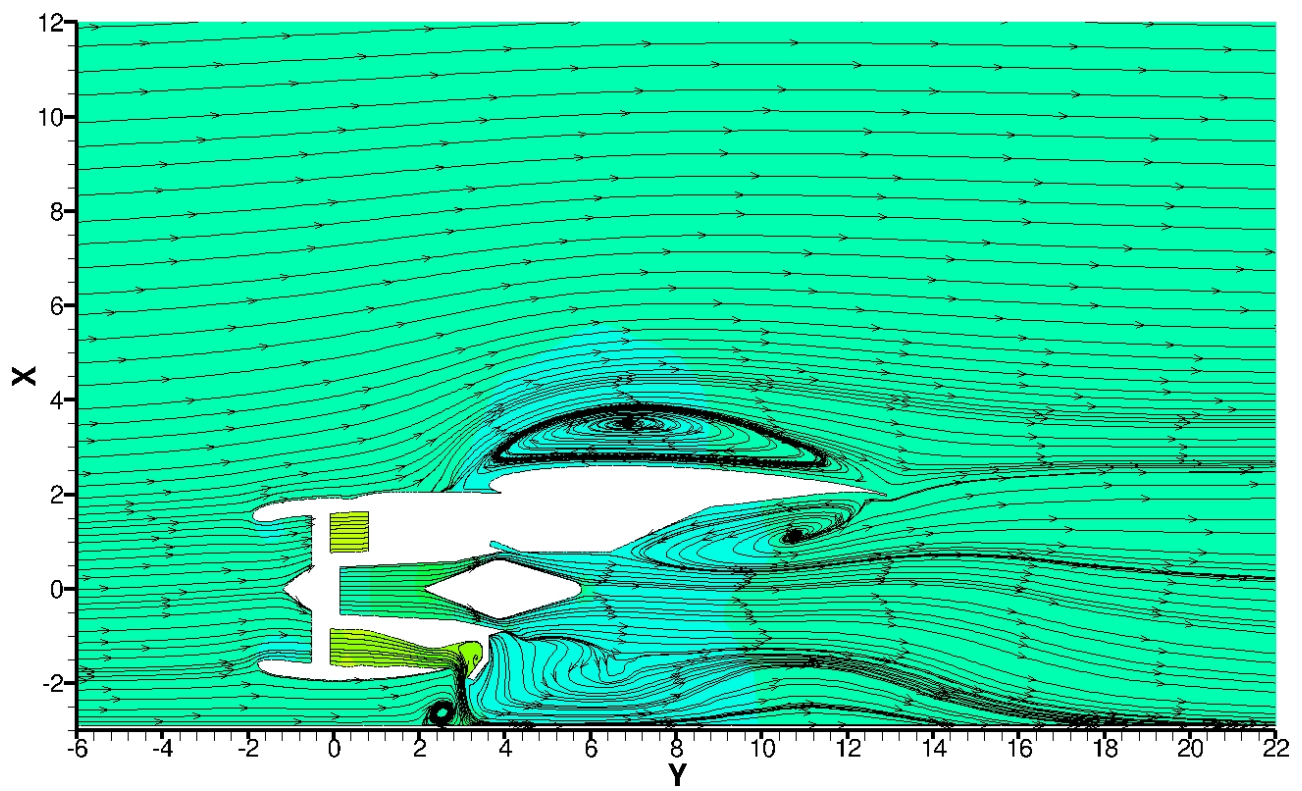
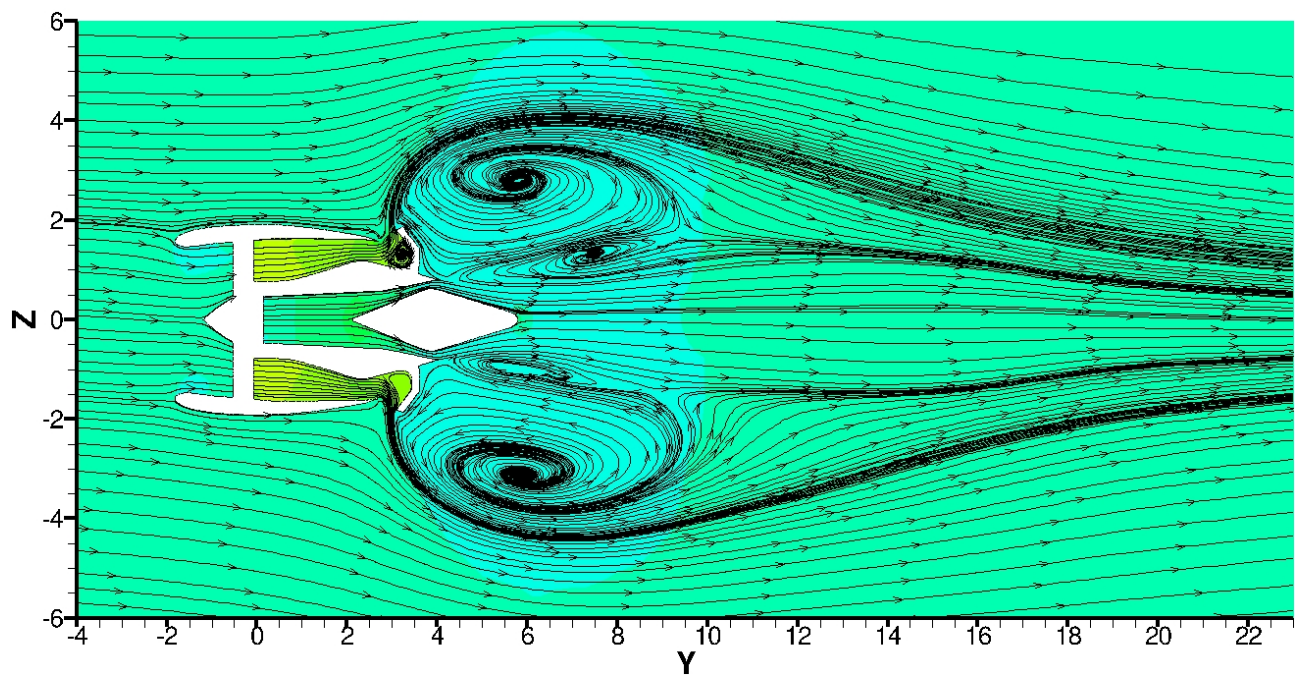
Streamline Plot, 40 Deg Core Mounted Target Reverser, $M=0.211$, $FNPR=1.267$



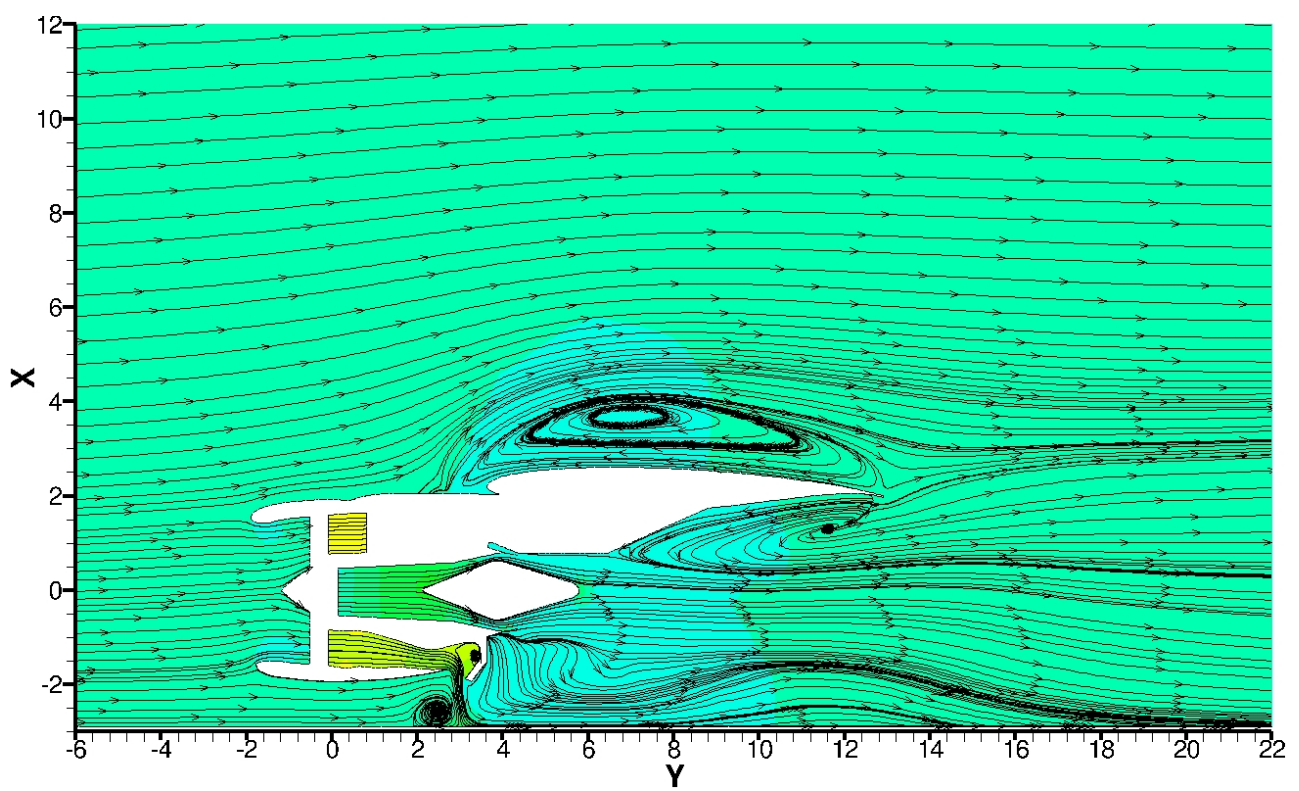
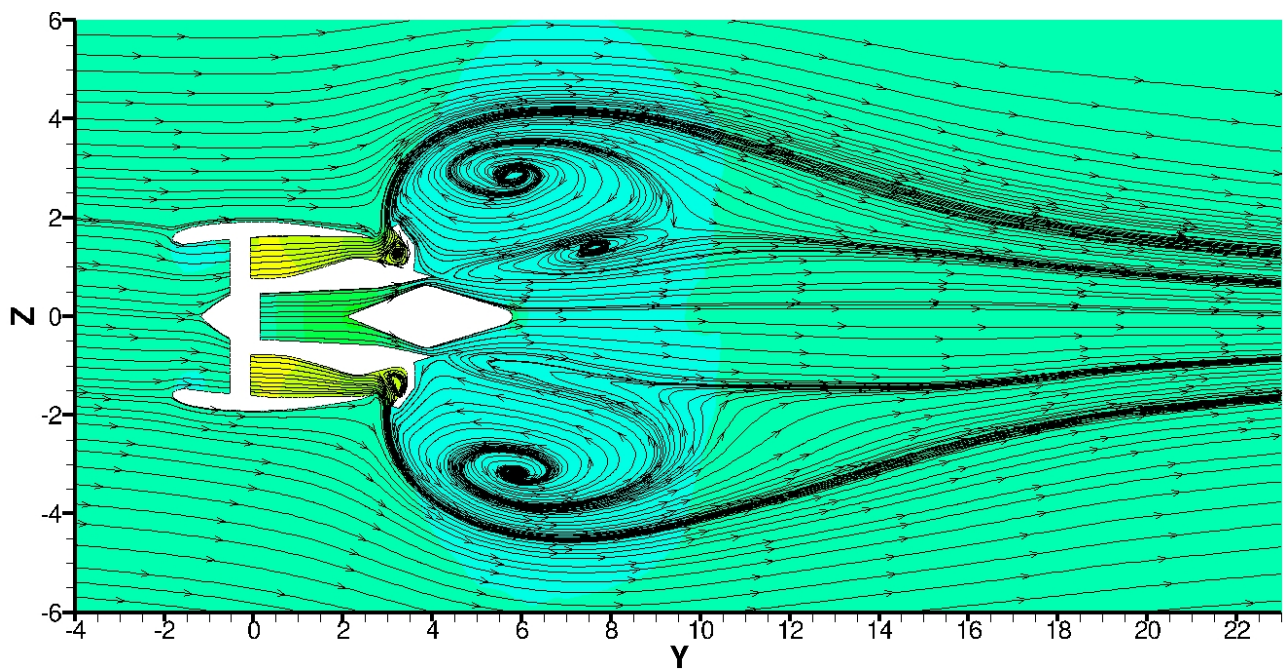
Streamline Plot, 40 Deg Core Mounted Target Reverser, $M=0.211$, $FNPR=1.317$



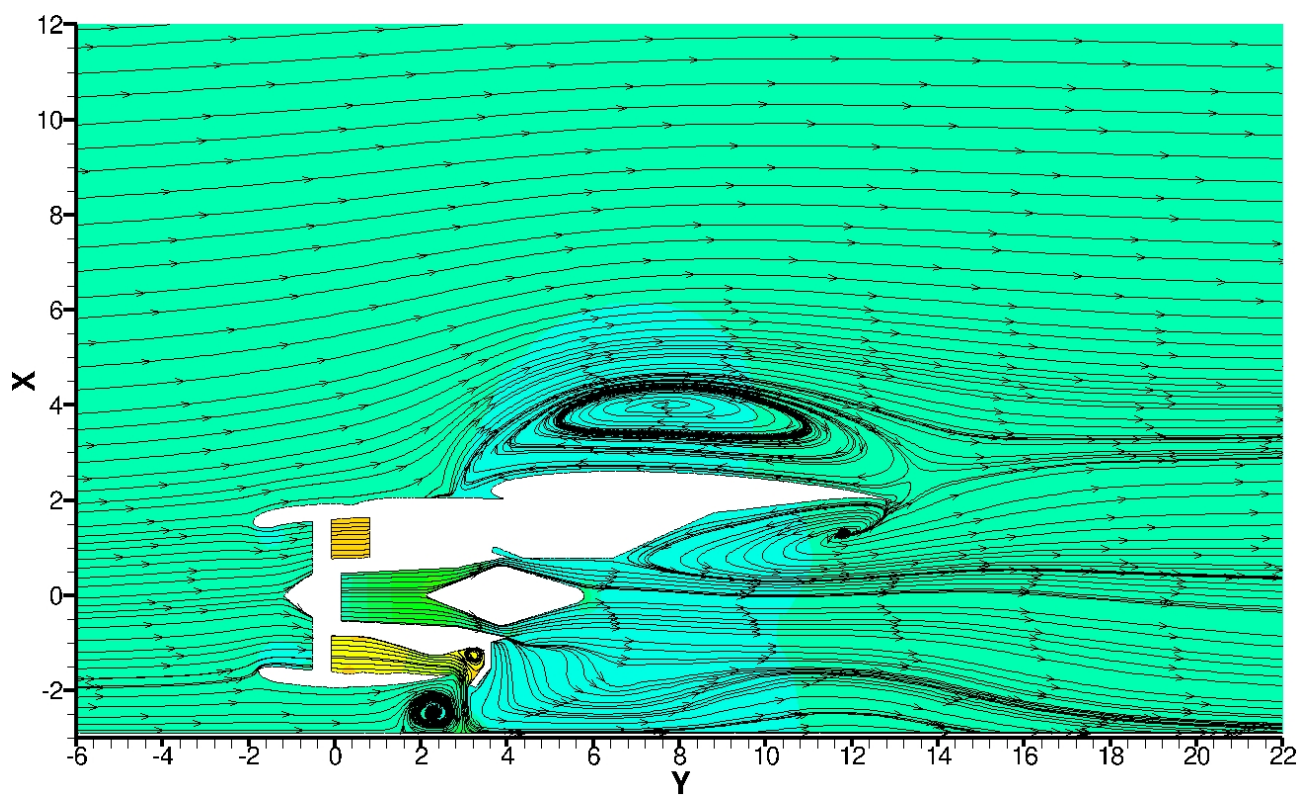
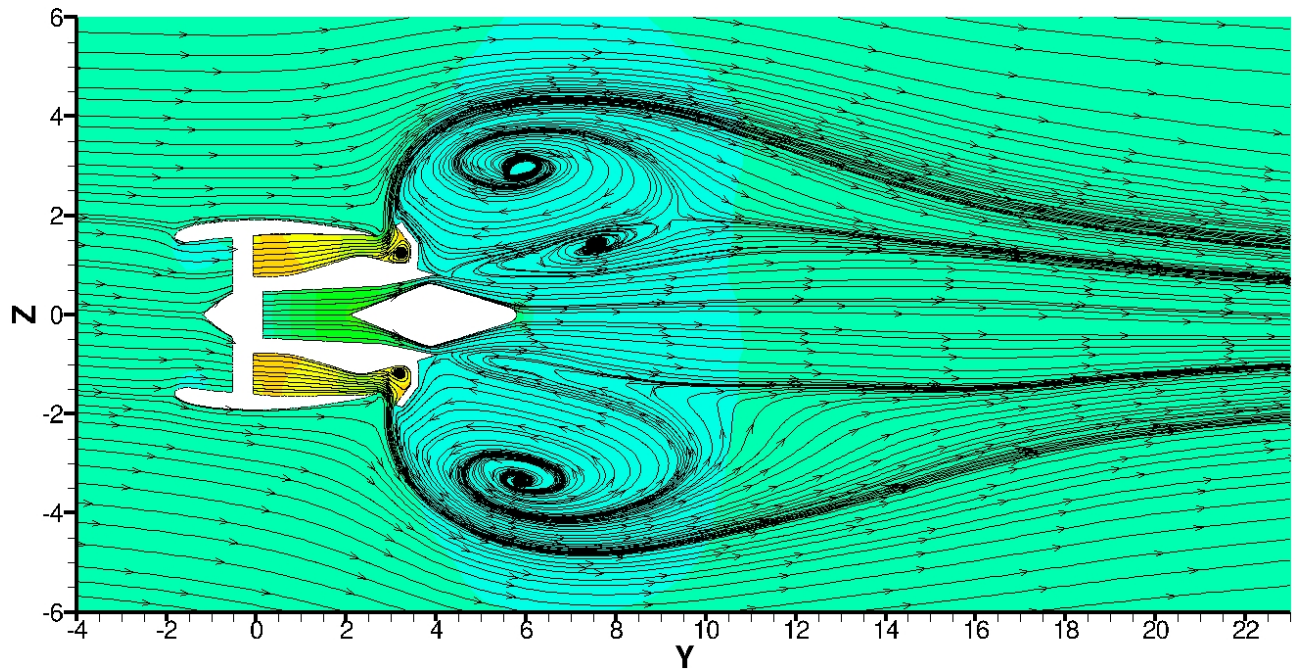
Streamline Plot, 40 Deg Core Mounted Target Reverser, $M=0.211$, $FNPR=1.366$



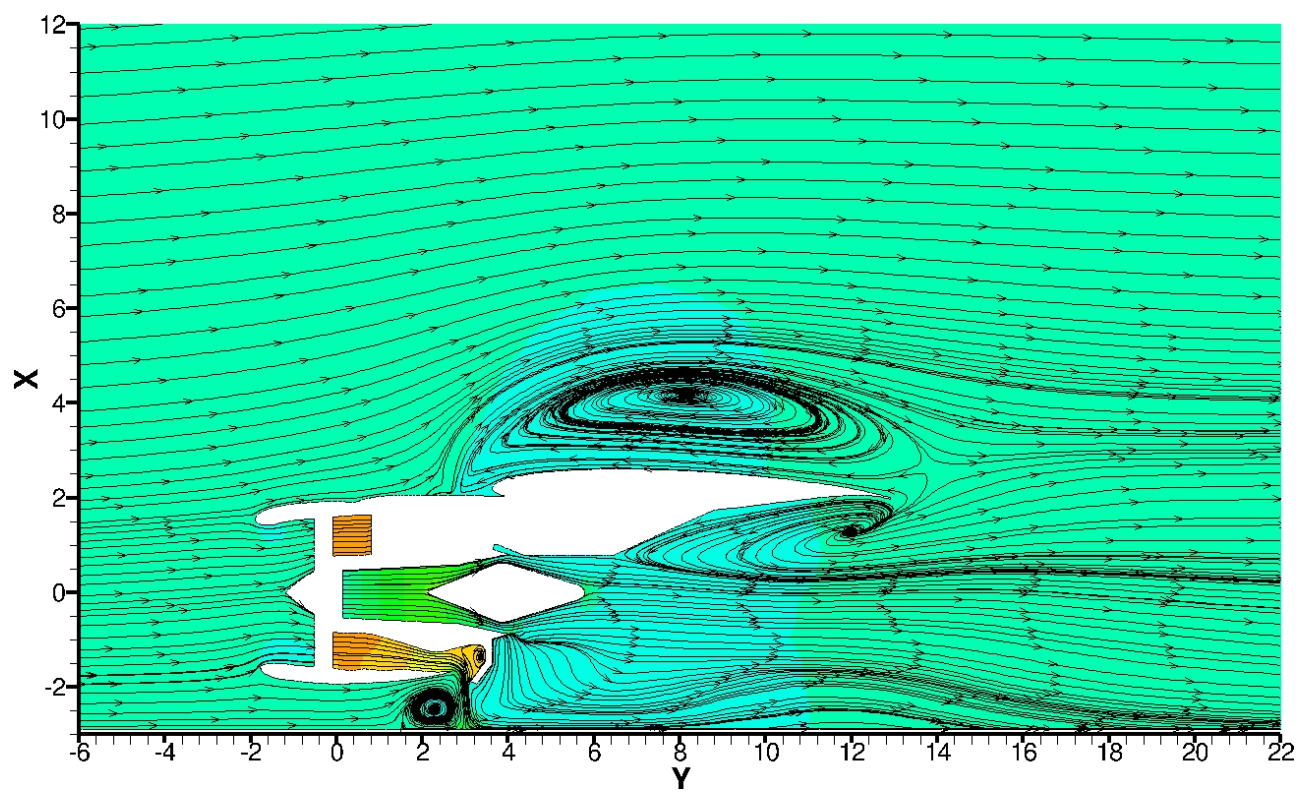
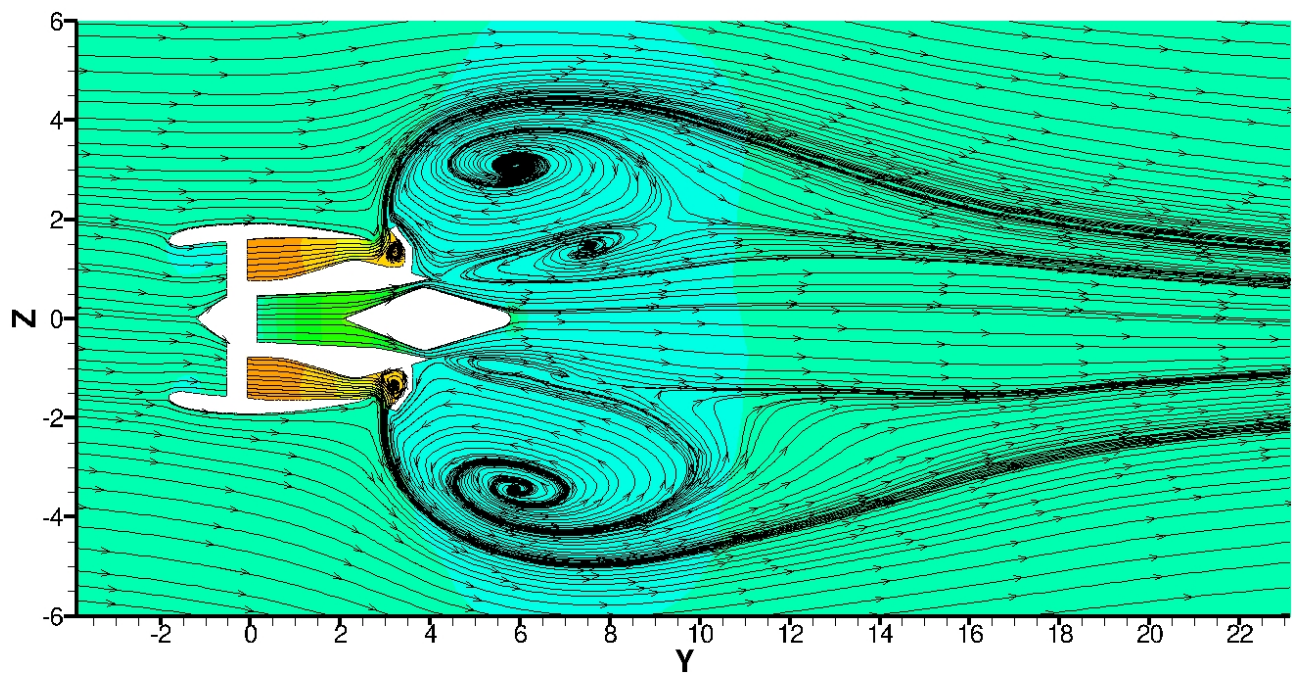
Streamline Plot, 40 Deg Core Mounted Target Reverser, $M=0.211$, $FNPR=1.416$



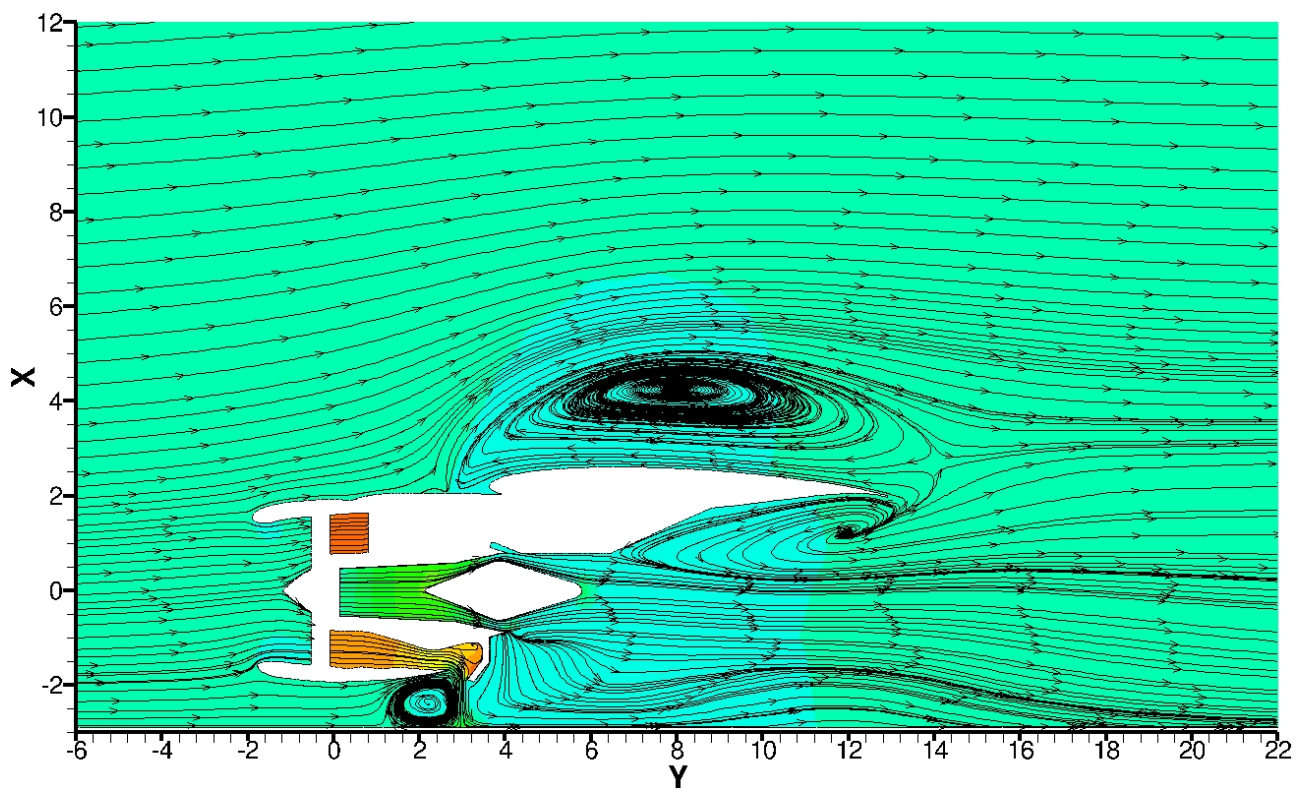
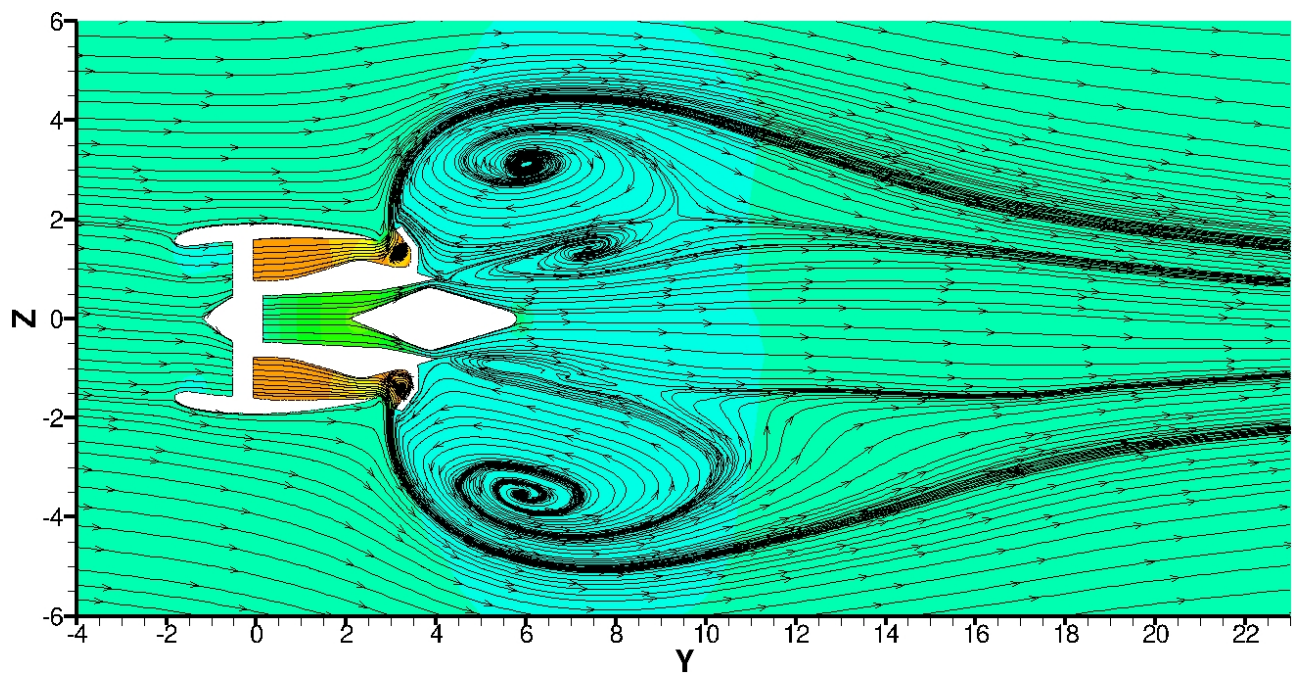
Streamline Plot, 40 Deg Core Mounted Target Reverser, $M=0.211$, $FNPR=1.475$



Streamline Plot, 40 Deg Core Mounted Target Reverser, $M=0.211$, $FNPR=1.535$

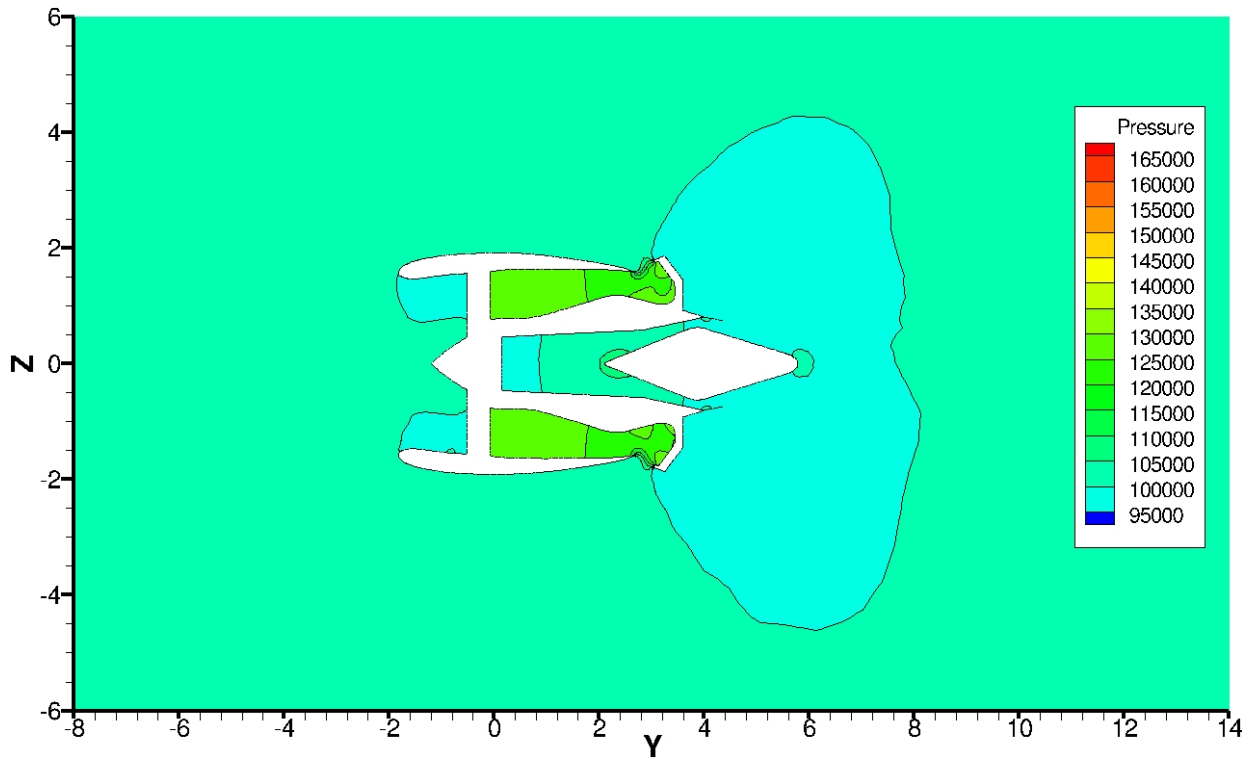


Streamline Plot, 40 Deg Core Mounted Target Reverser, $M=0.211$, $FNPR=1.574$

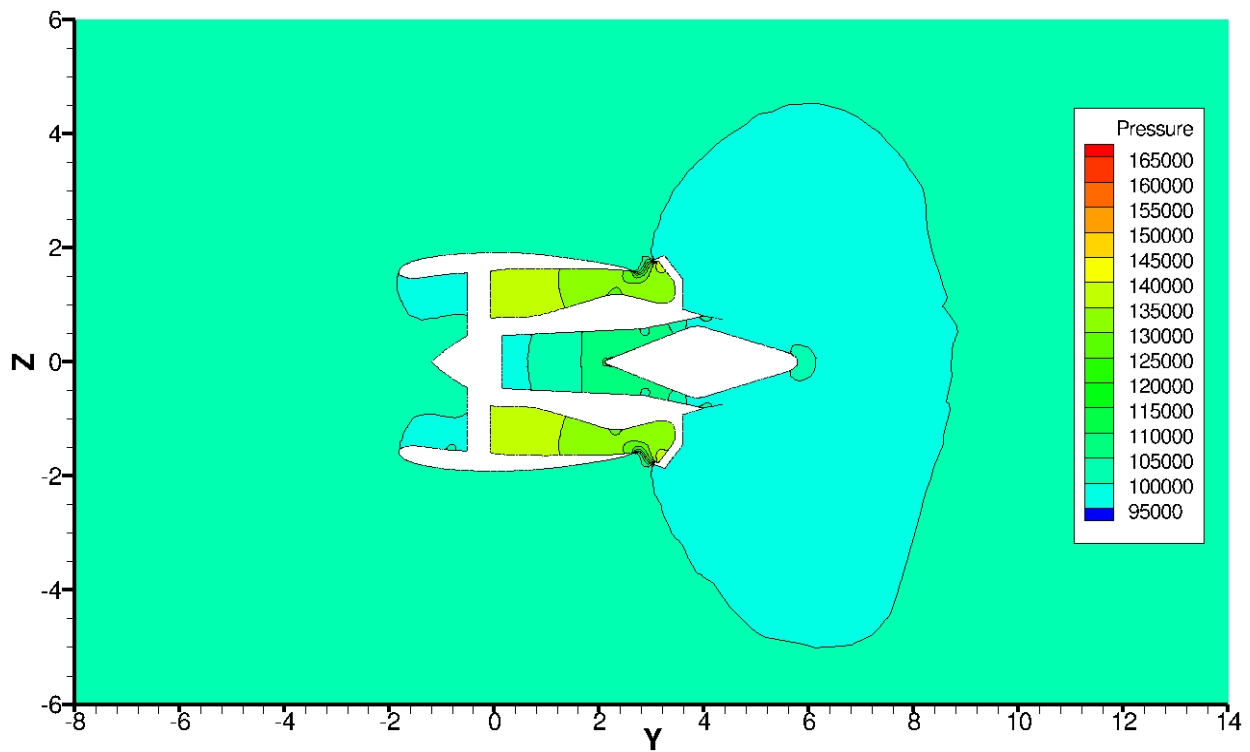


Appendix A5.4 – Static Pressure Contours with Kicker Plate, $M=0.211$

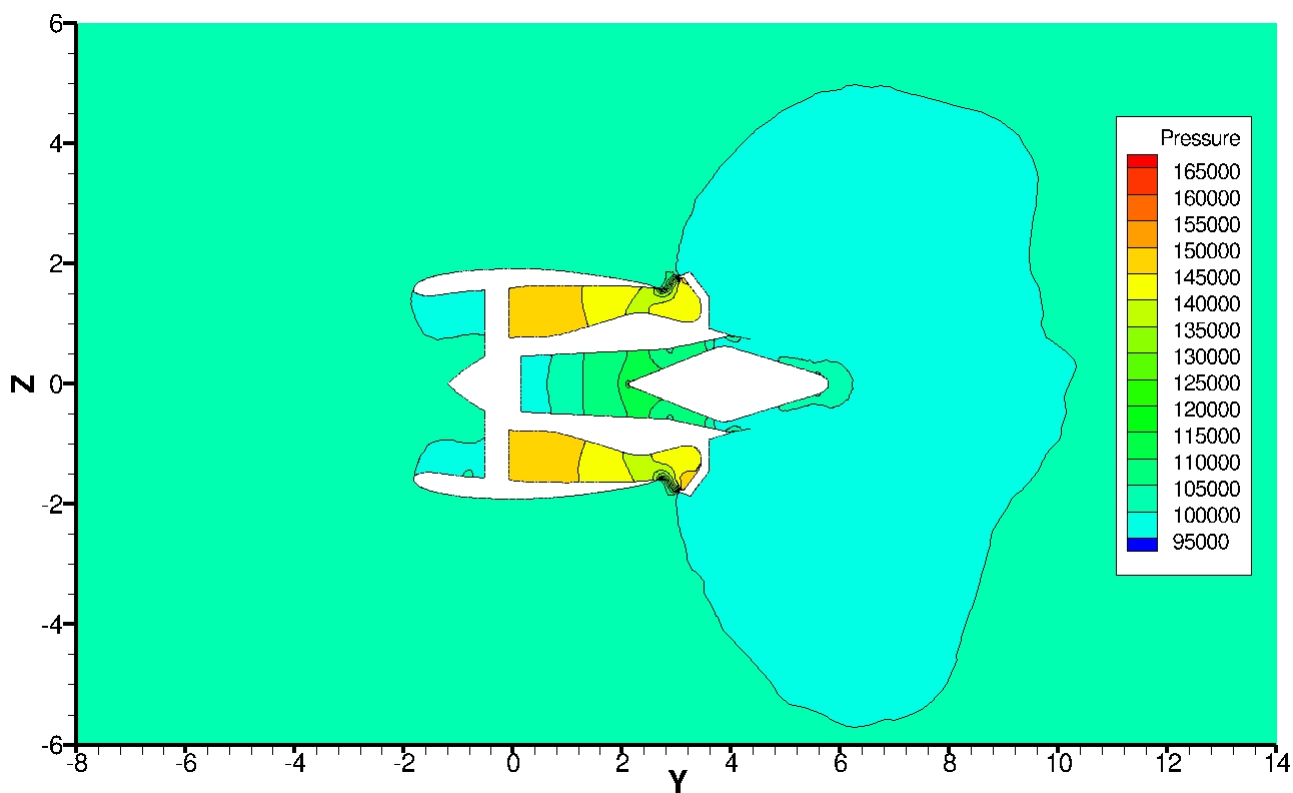
Static Pressure Contours, 40 Deg Core Mounted Target Reverser with Kicker Plate, $M=0.211$,
 $FNPR=1.267$



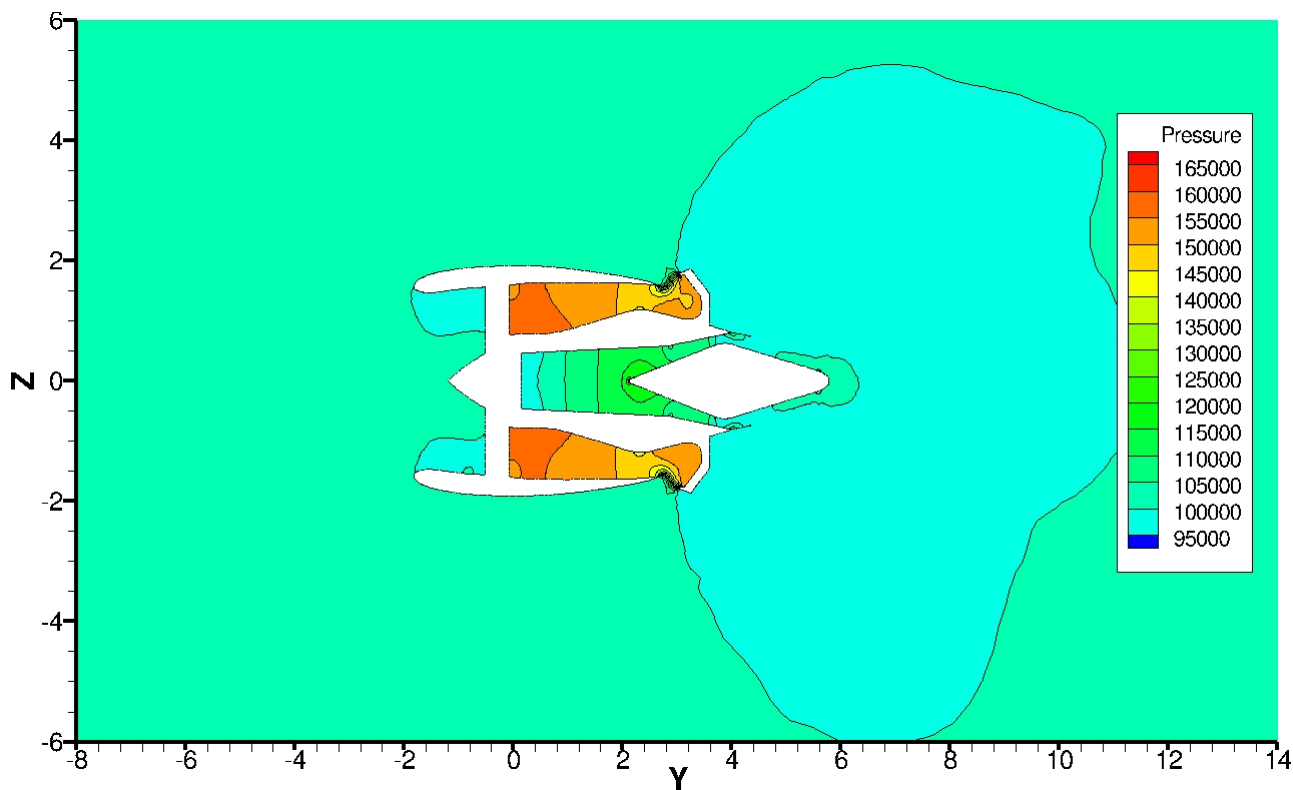
Static Pressure Contours, 40 Deg Core Mounted Target Reverser with Kicker Plate, $M=0.211$,
 $FNPR=1.366$



Static Pressure Contours, 40 Deg Core Mounted Target Reverser with Kicker Plate, $M=0.211$,
 $FNPR=1.475$

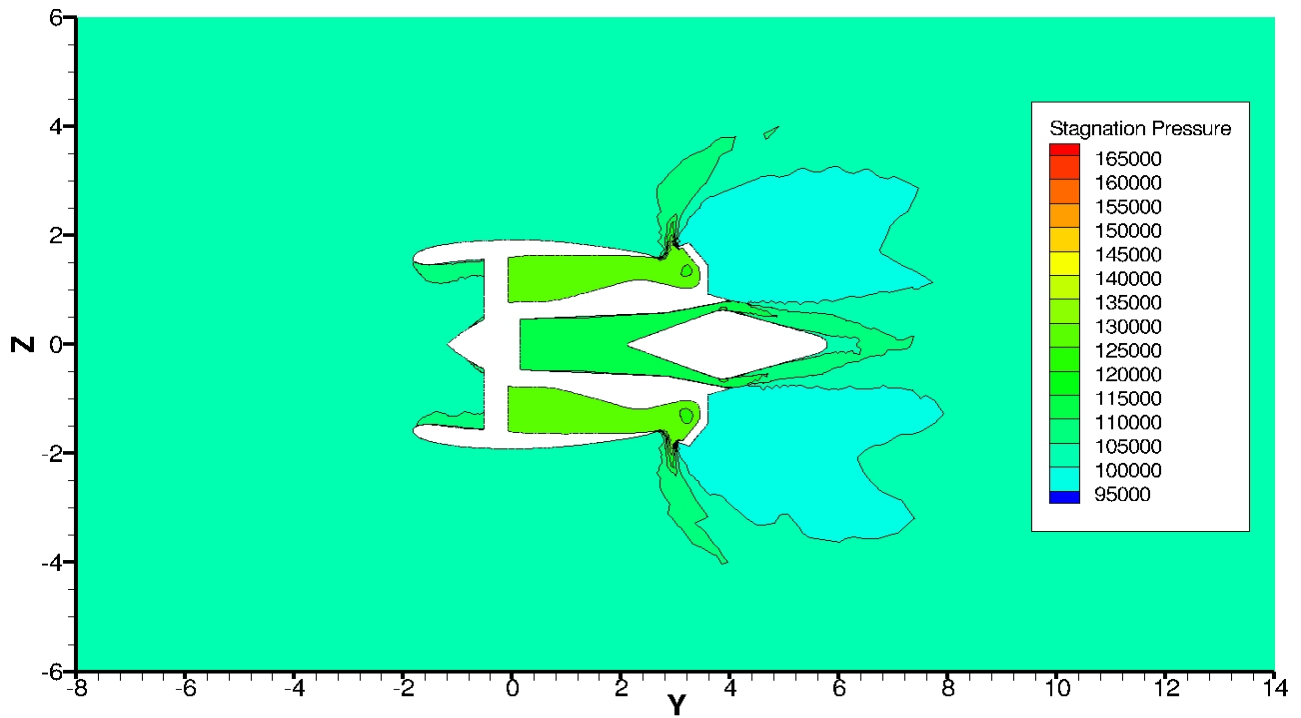


Static Pressure Contours, 40 Deg Core Mounted Target Reverser with Kicker Plate, $M=0.211$,
 $FNPR=1.574$

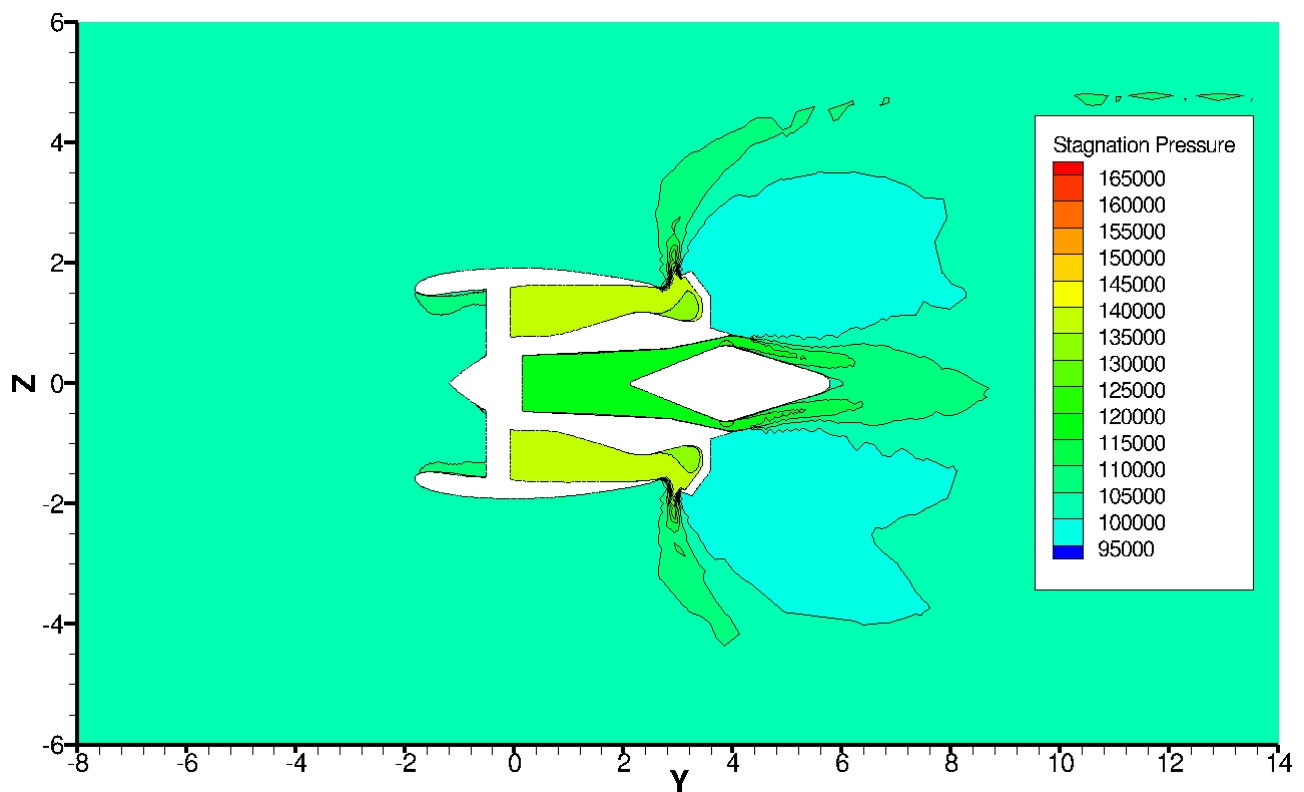


Appendix A5.5 – Total Pressure Contours with Kicker Plate, $M=0.211$

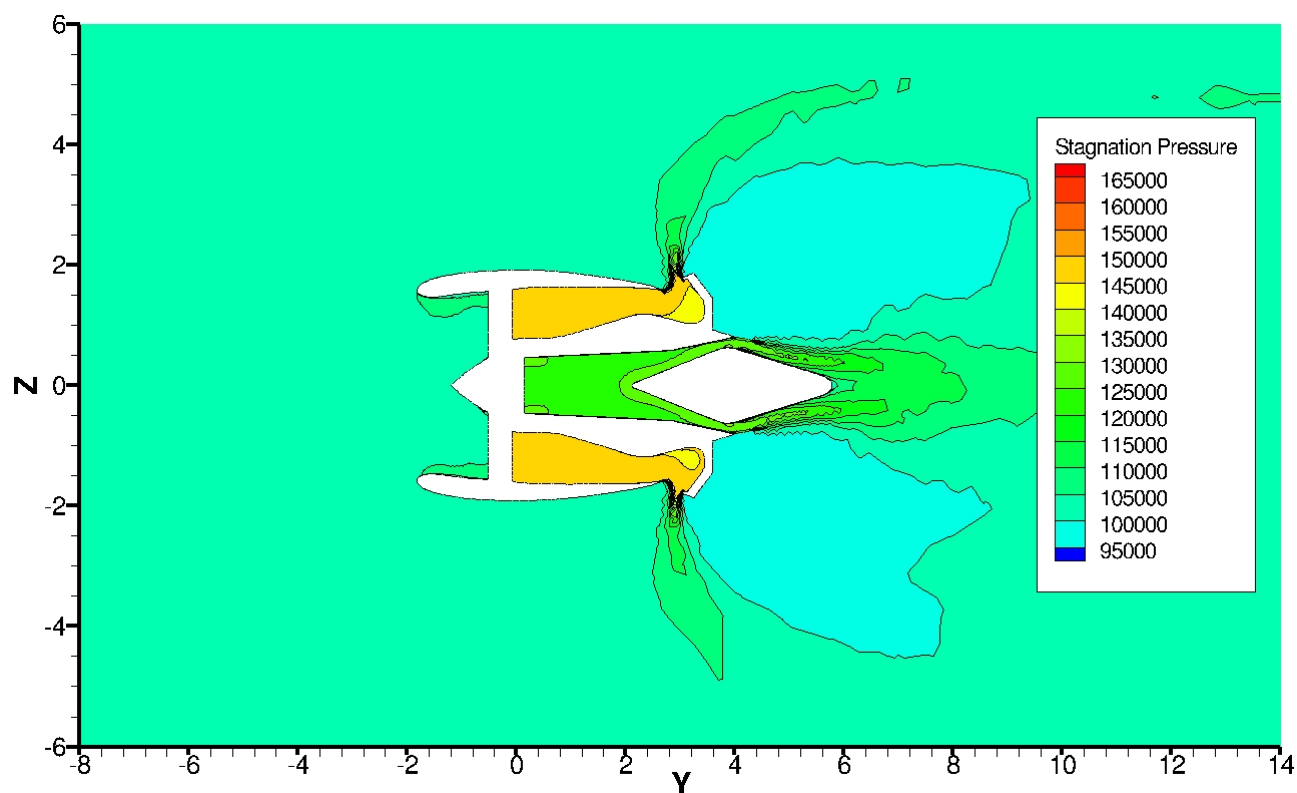
Total Pressure Contours, 40 Deg Core Mounted Target Reverser with Kicker Plate, $M=0.211$,
 $FNPR=1.267$



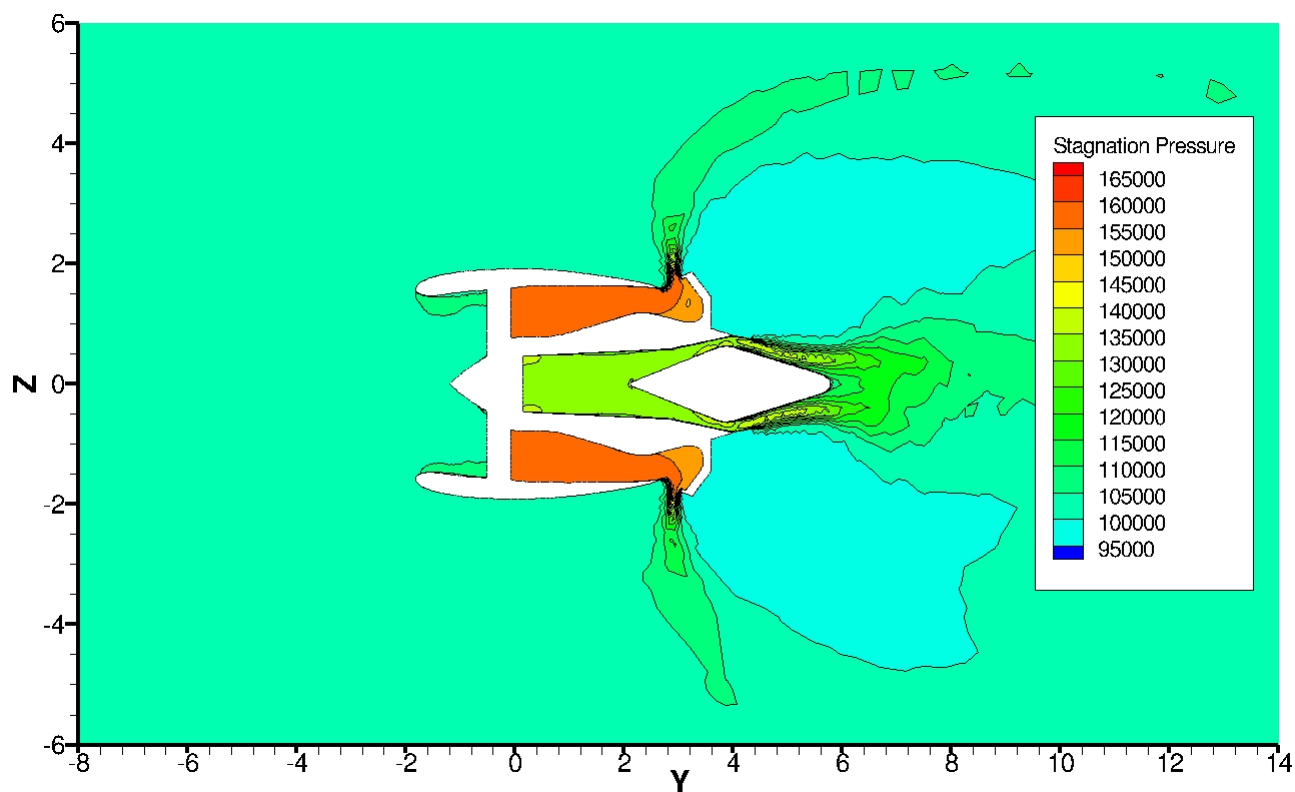
Total Pressure Contours, 40 Deg Core Mounted Target Reverser with Kicker Plate, $M=0.211$,
 $FNPR=1.366$



Total Pressure Contours, 40 Deg Core Mounted Target Reverser with Kicker Plate, $M=0.211$, $FNPR=1.475$

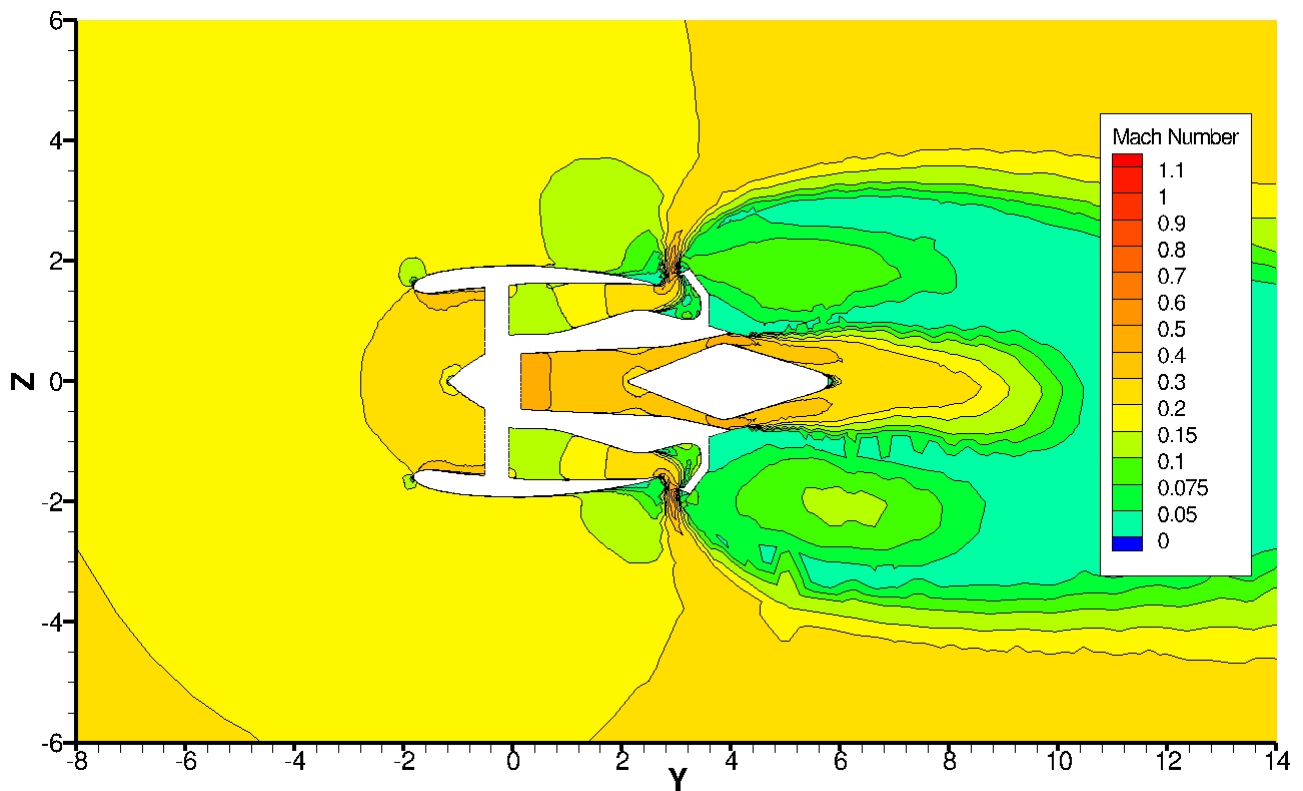


Total Pressure Contours, 40 Deg Core Mounted Target Reverser with Kicker Plate, $M=0.211$, $FNPR=1.574$

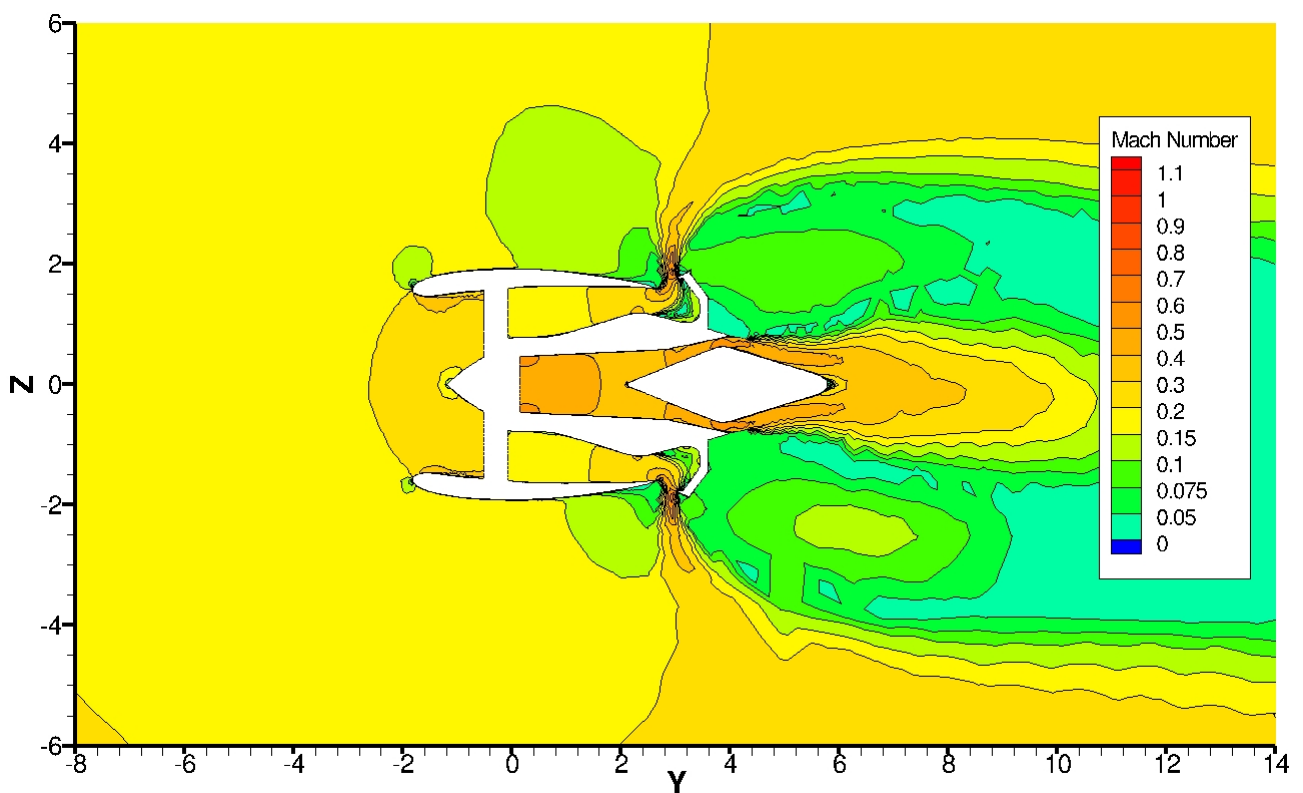


Appendix A5.6 – Mach Number with Kicker Plate, $M=0.211$

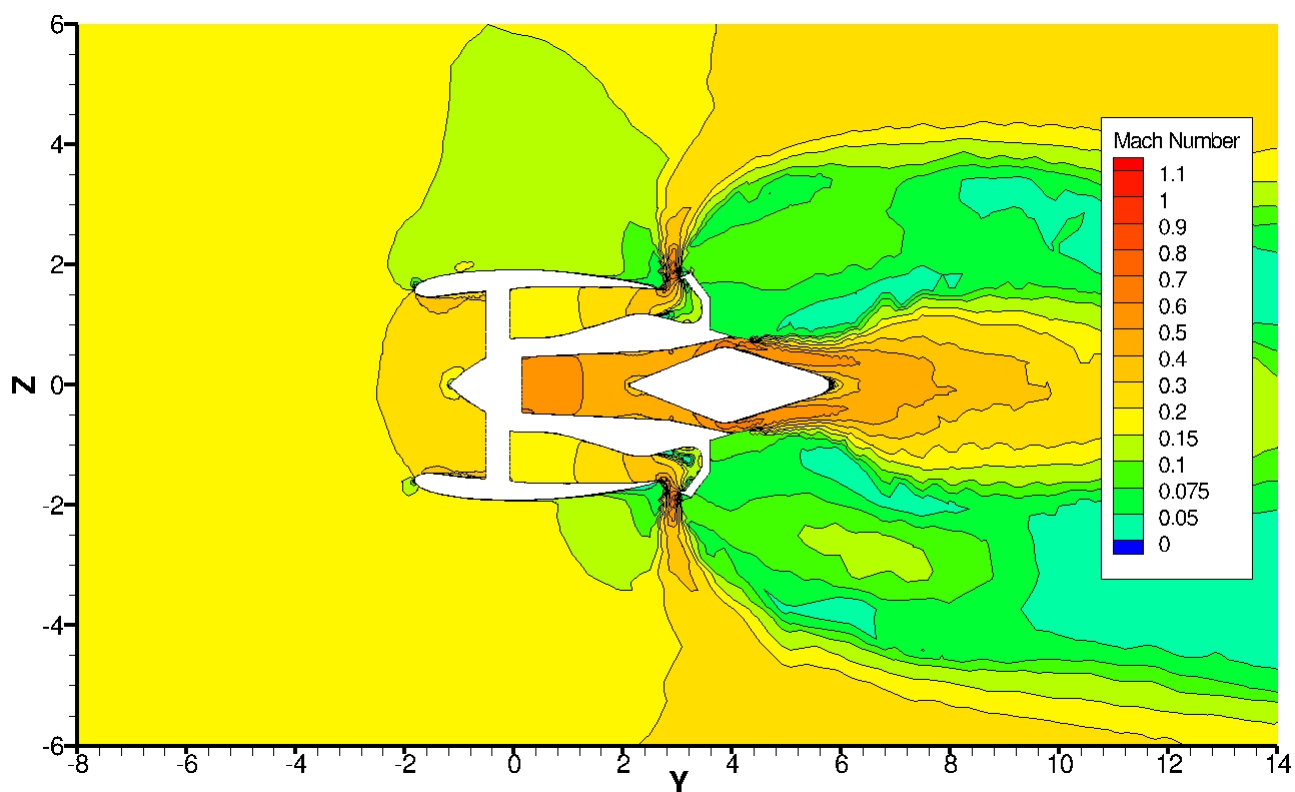
Mach no Contours, 40 Deg Core Mounted Target Reverser with Kicker Plate, $M=0.211$, $FNPR=1.267$



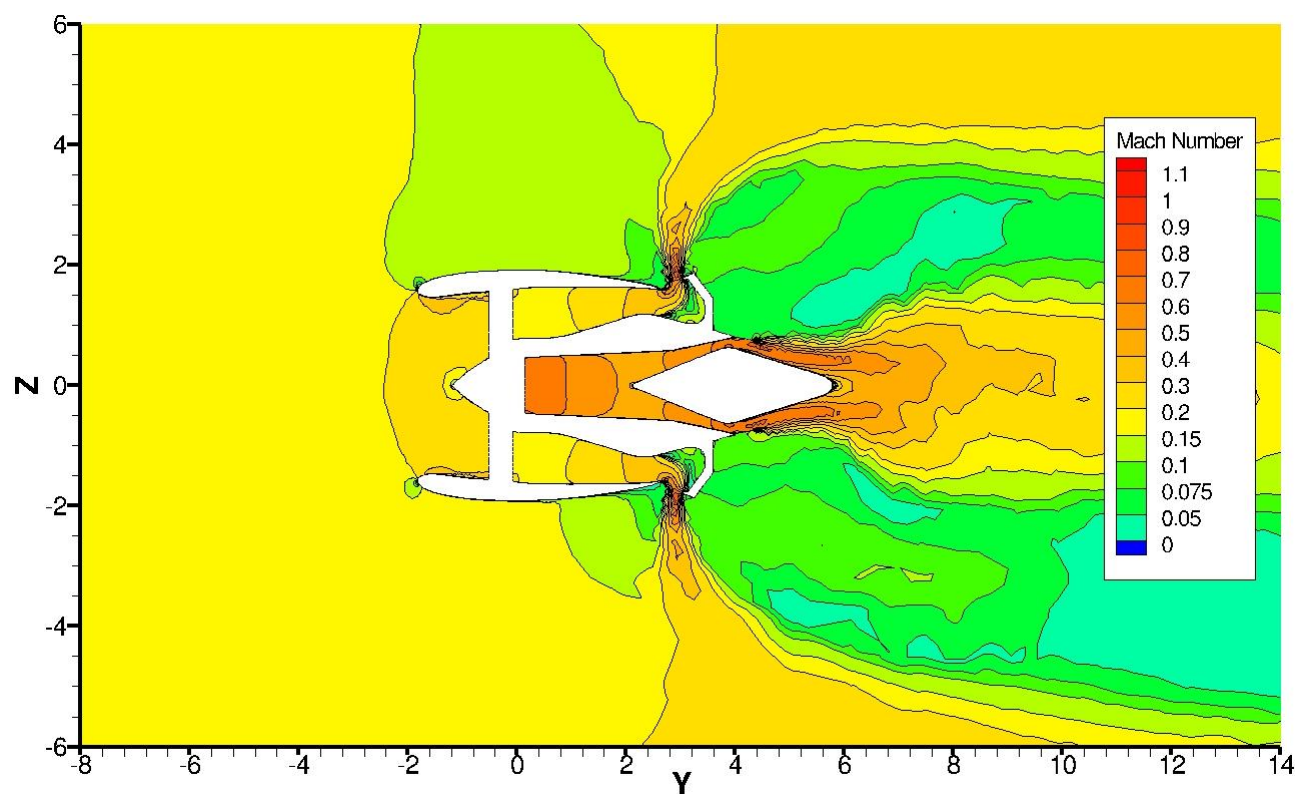
i) Mach no Contours, 40 Deg Core Mounted Target Reverser with Kicker Plate, $M=0.211$, $FNPR=1.366$



ii) Mach no Contours, 40 Deg Core Mounted Target Reverser with Kicker Plate, $M=0.211$, $FNPR=1.475$

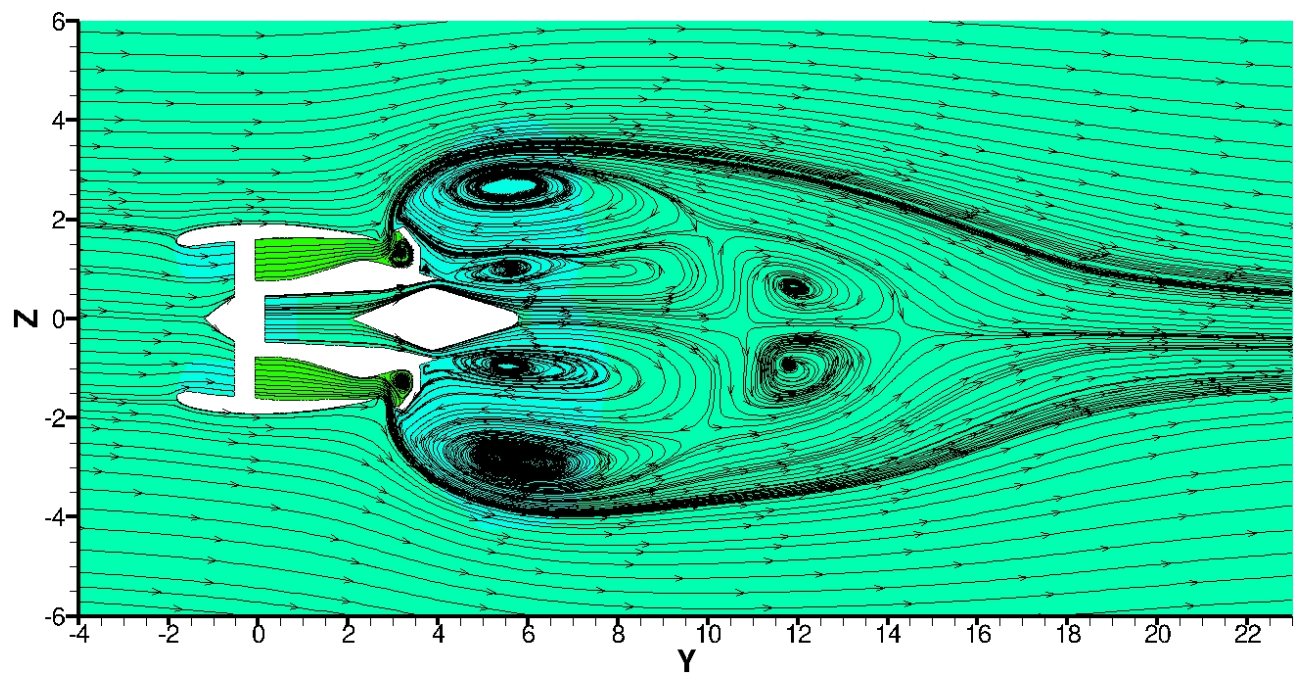
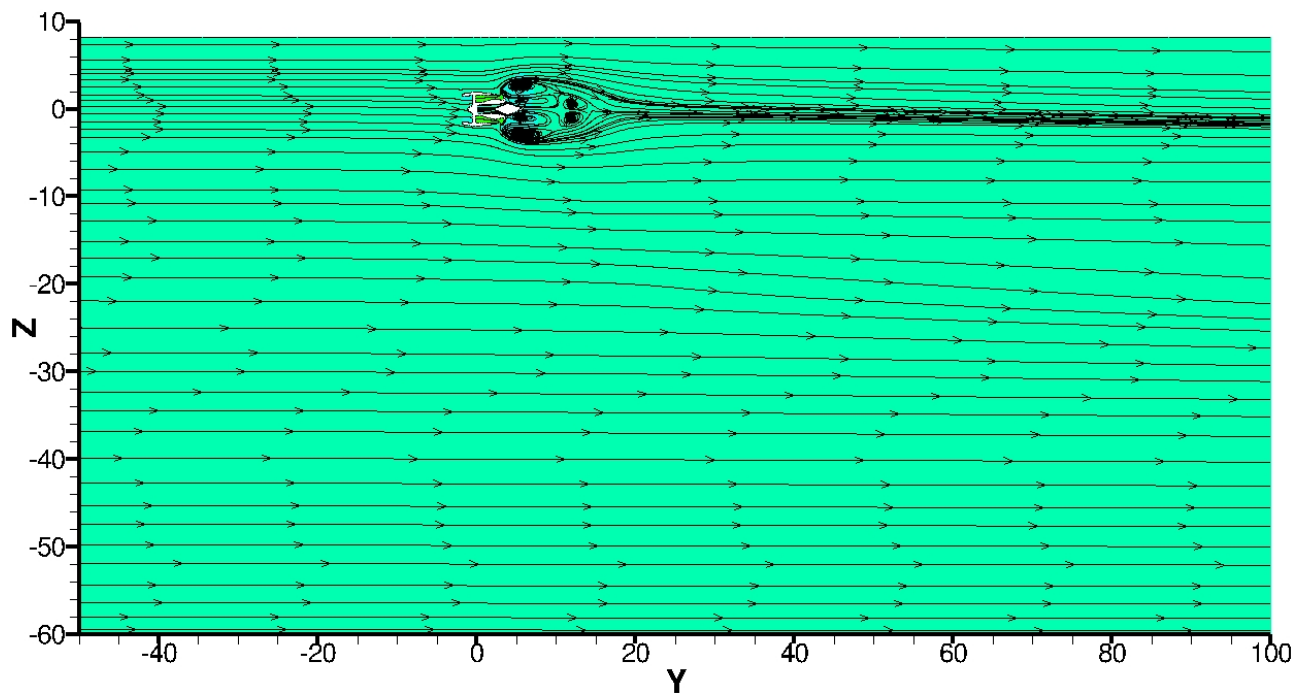


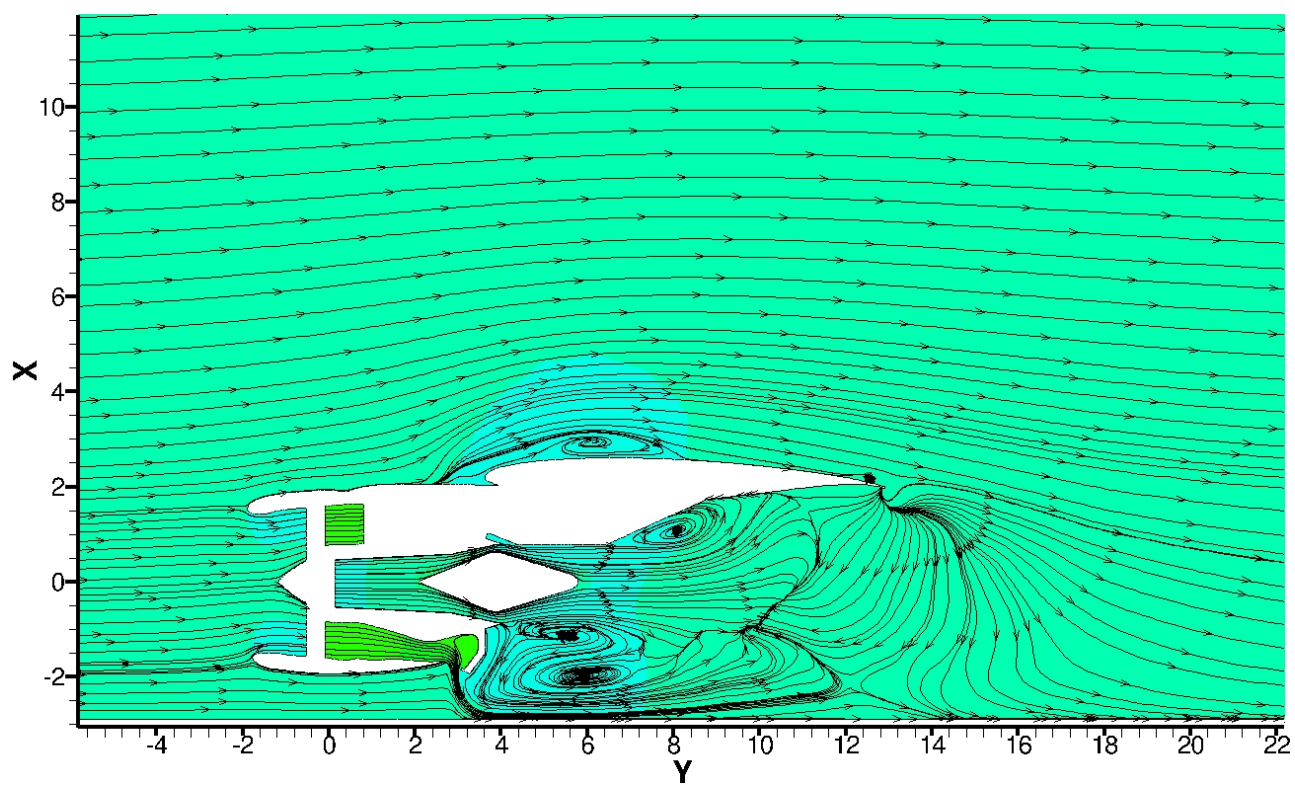
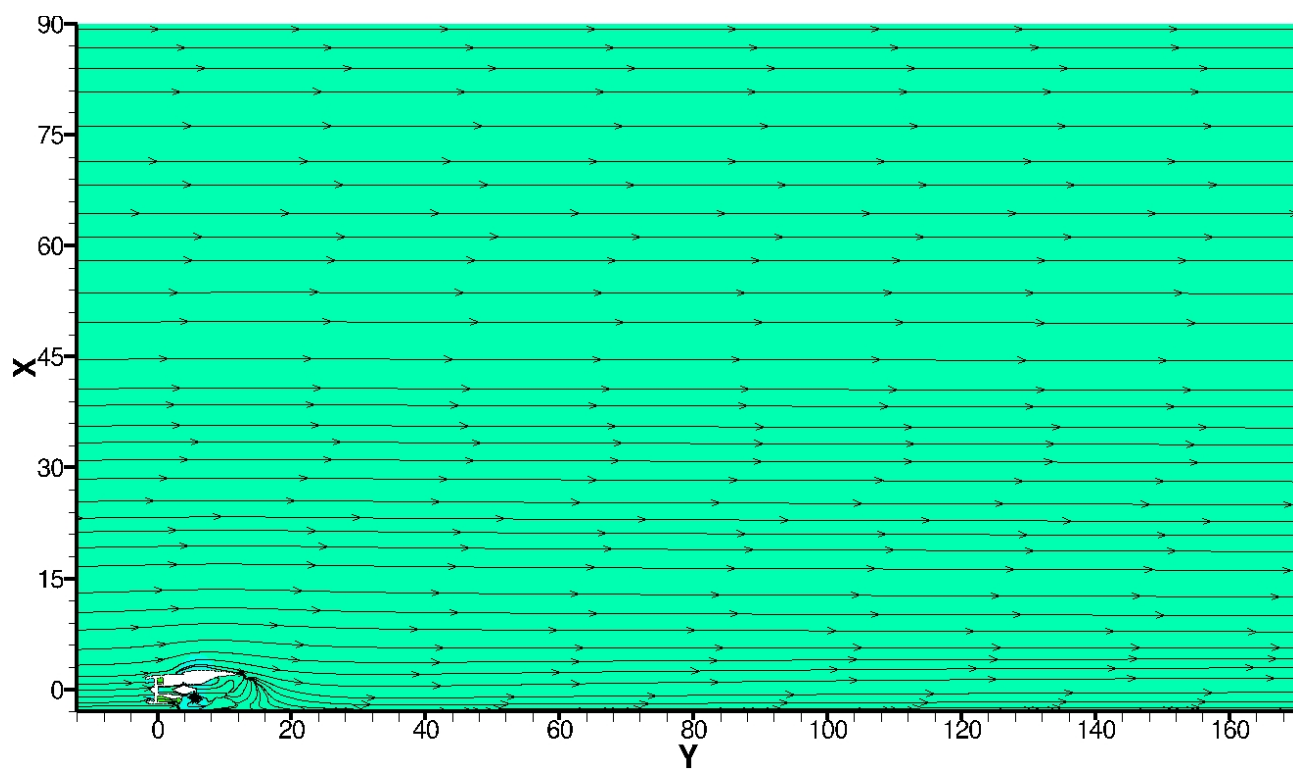
iii) Mach no Contours, 40 Deg Core Mounted Target Reverser with Kicker Plate, $M=0.211$, $FNPR=1.574$



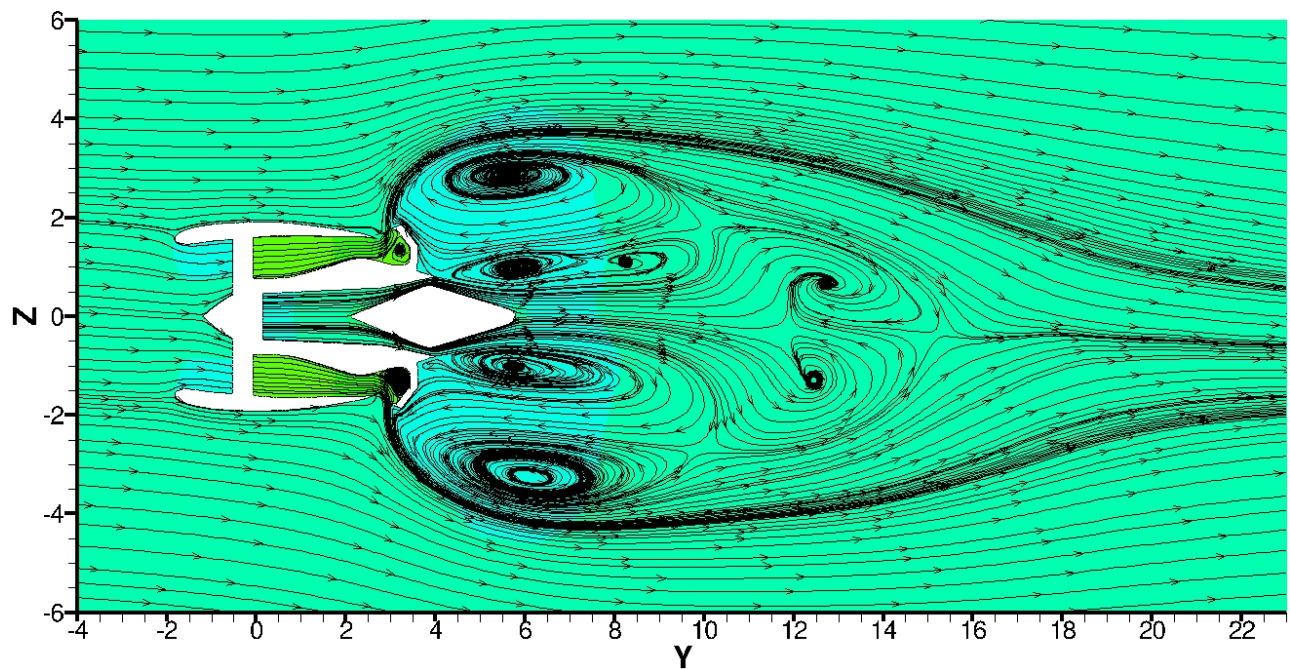
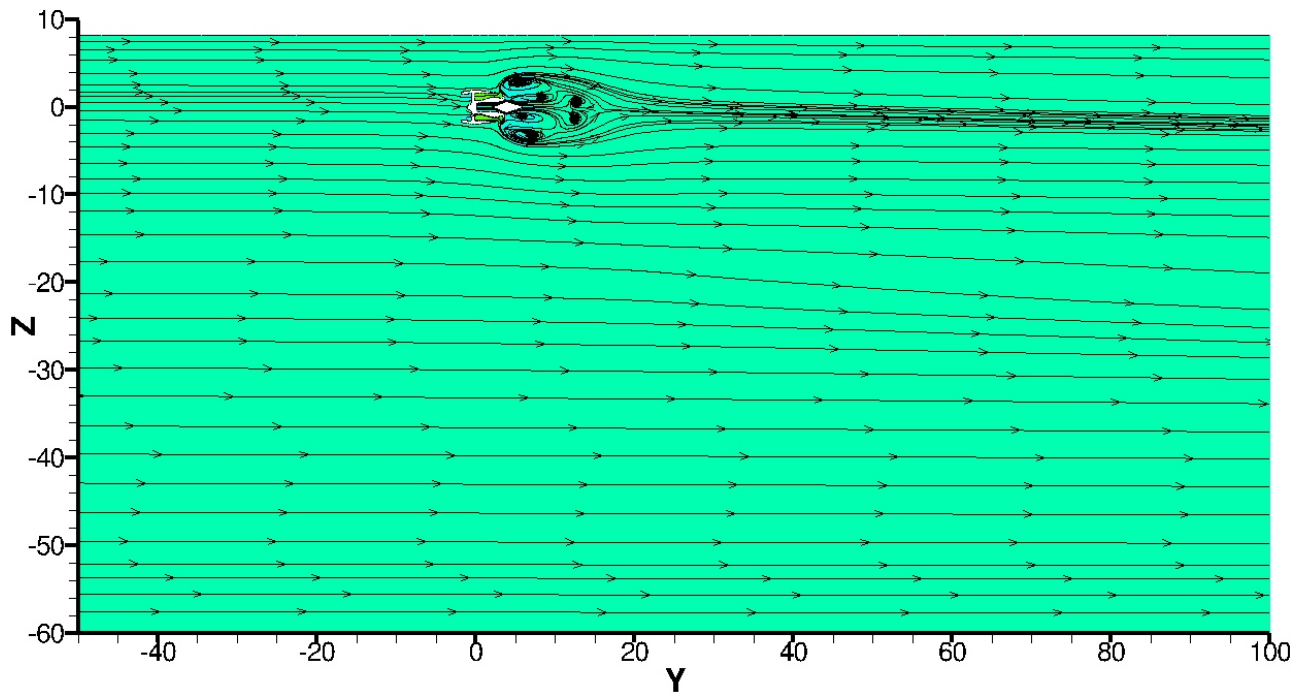
Appendix A5.7 – Total Pressure Contours

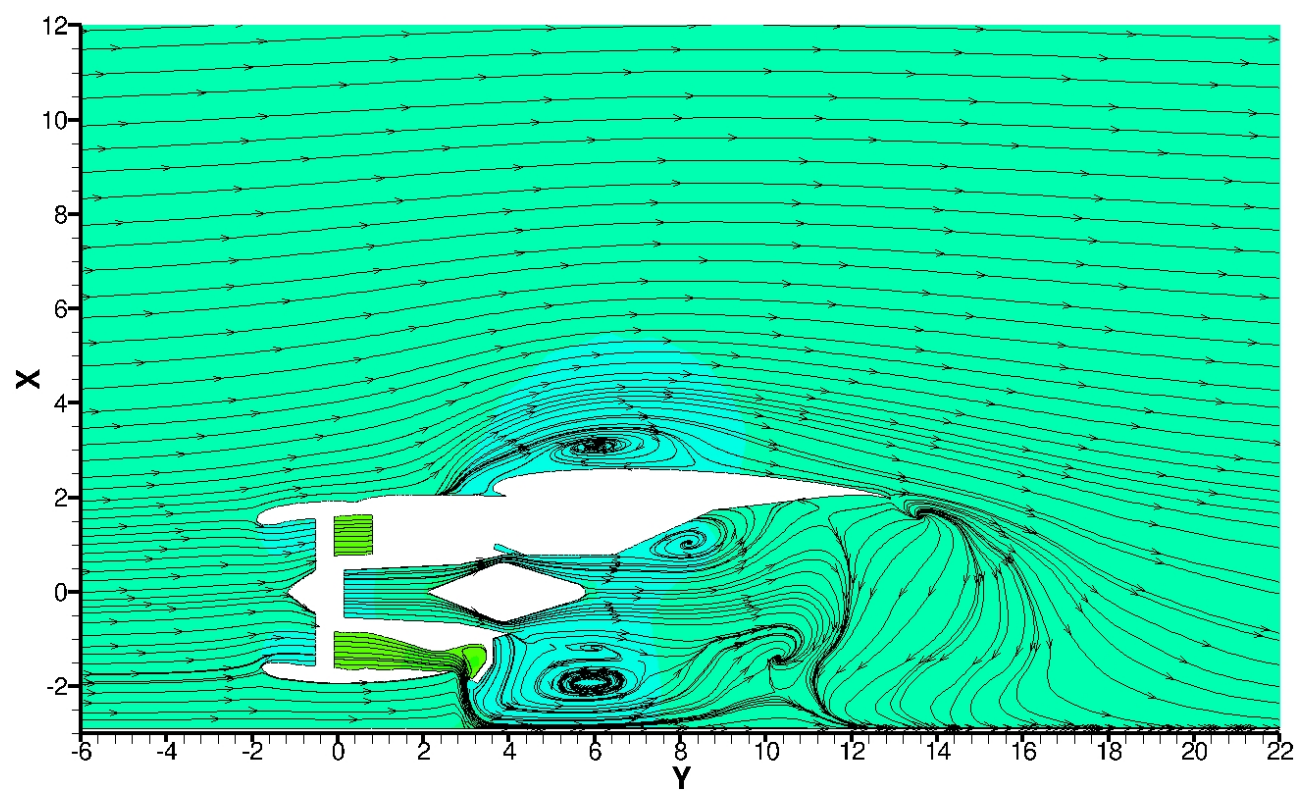
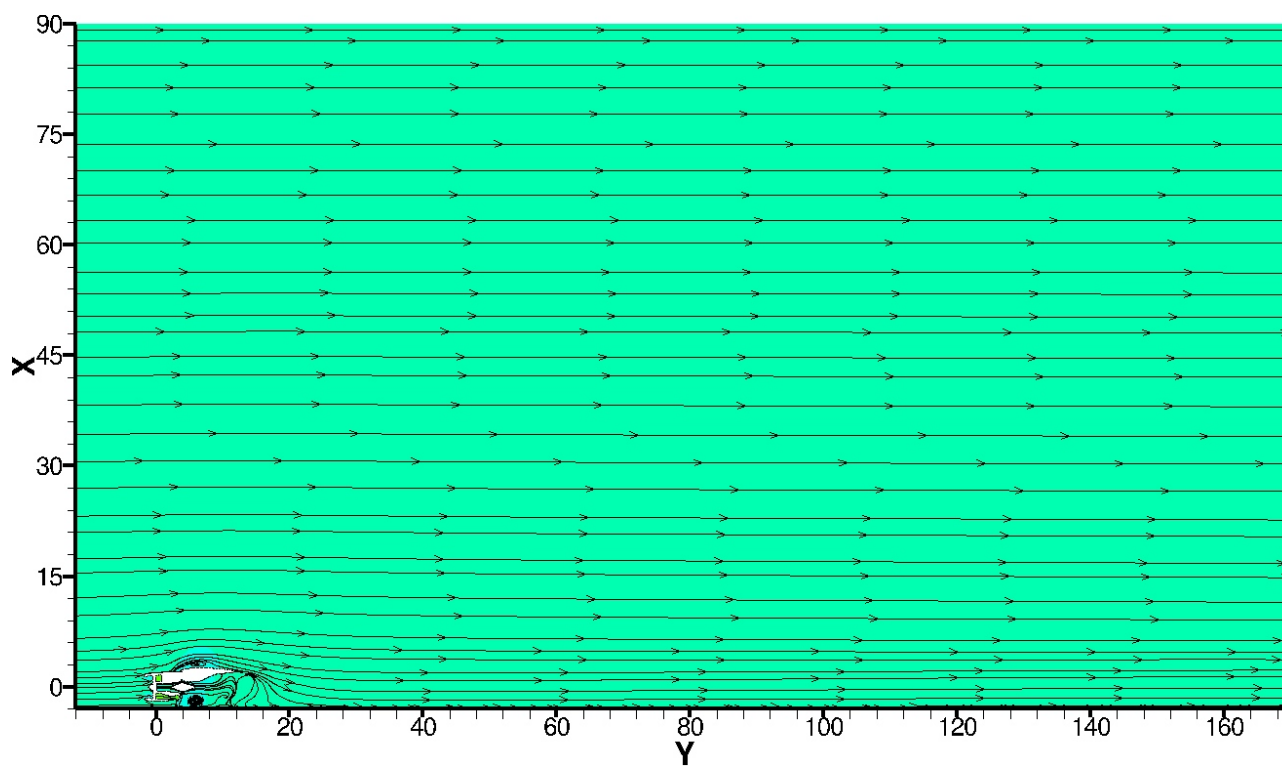
Streamline Plots, 40 Deg Core Mounted Target Reverser with Kicker Plate, $M=0.211$,
 $FNPR=1.218$



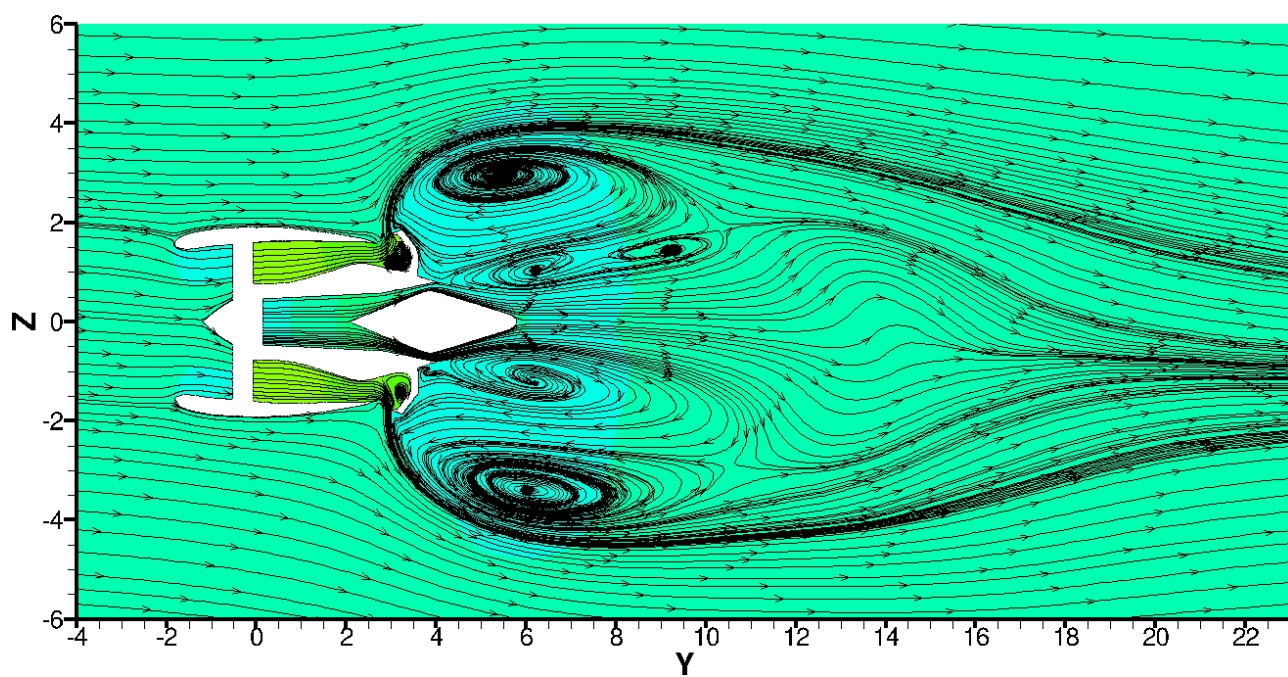
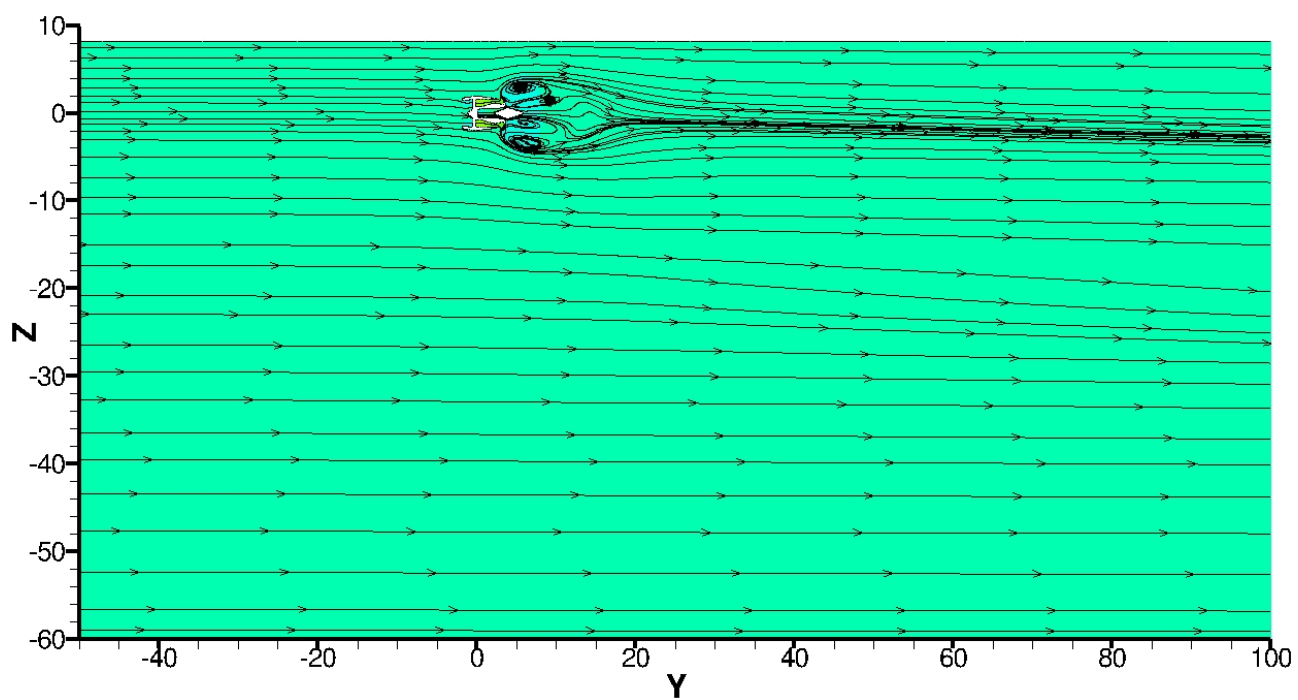


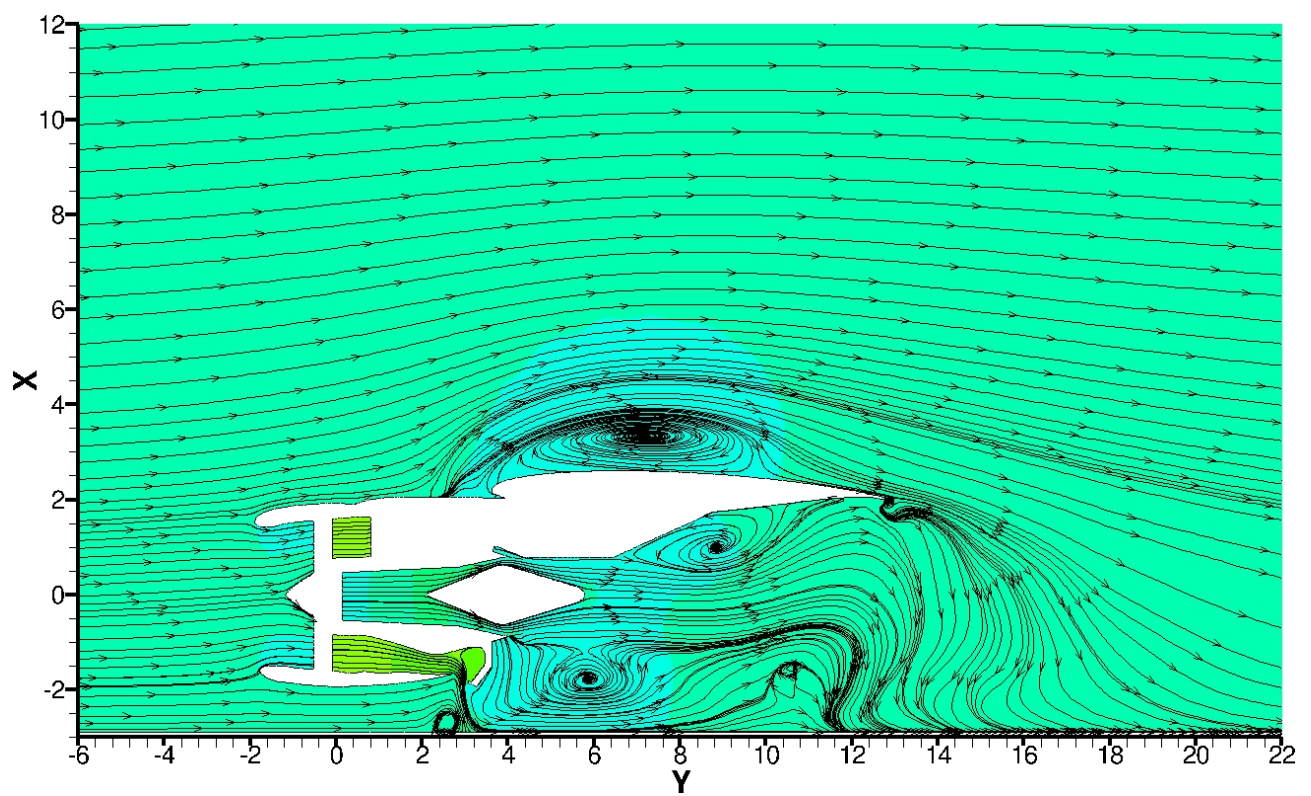
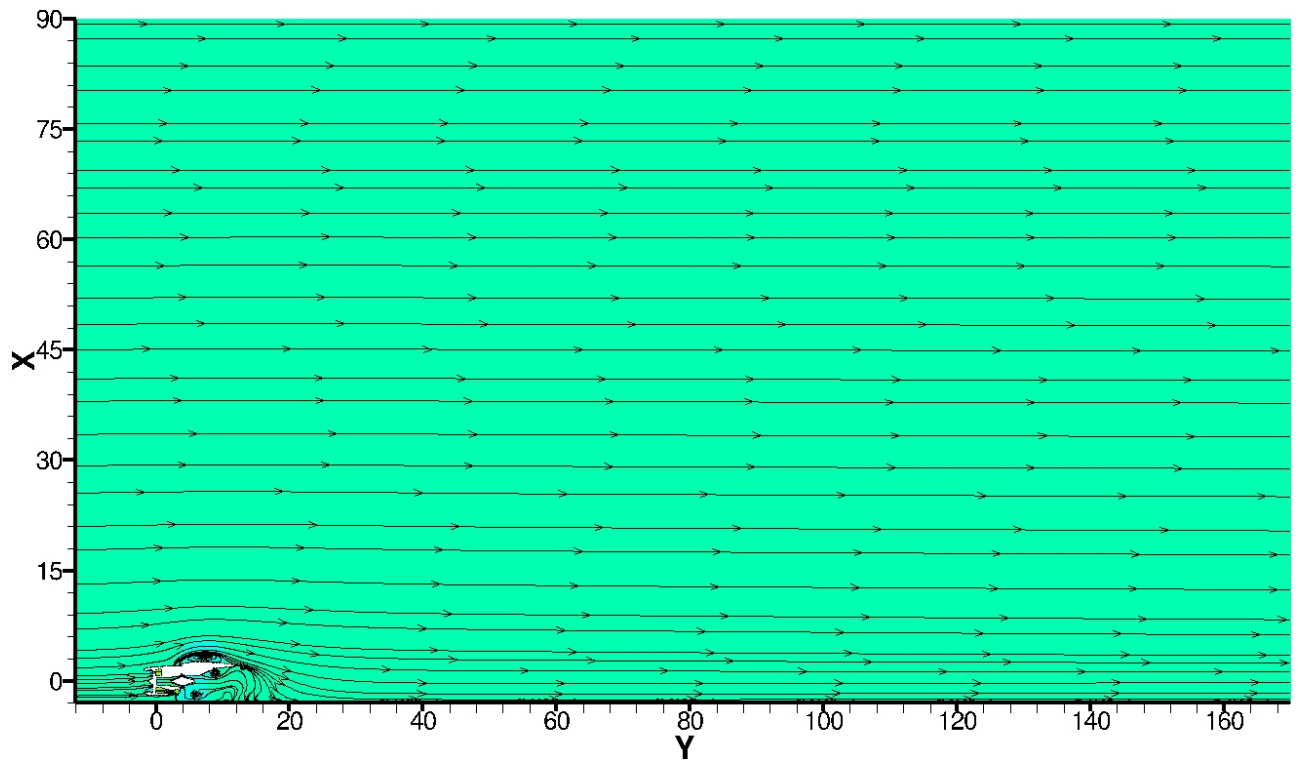
Streamline Plots, 40 Deg Core Mounted Target Reverser with Kicker Plate, $M=0.211$,
 $FNPR=1.2187$



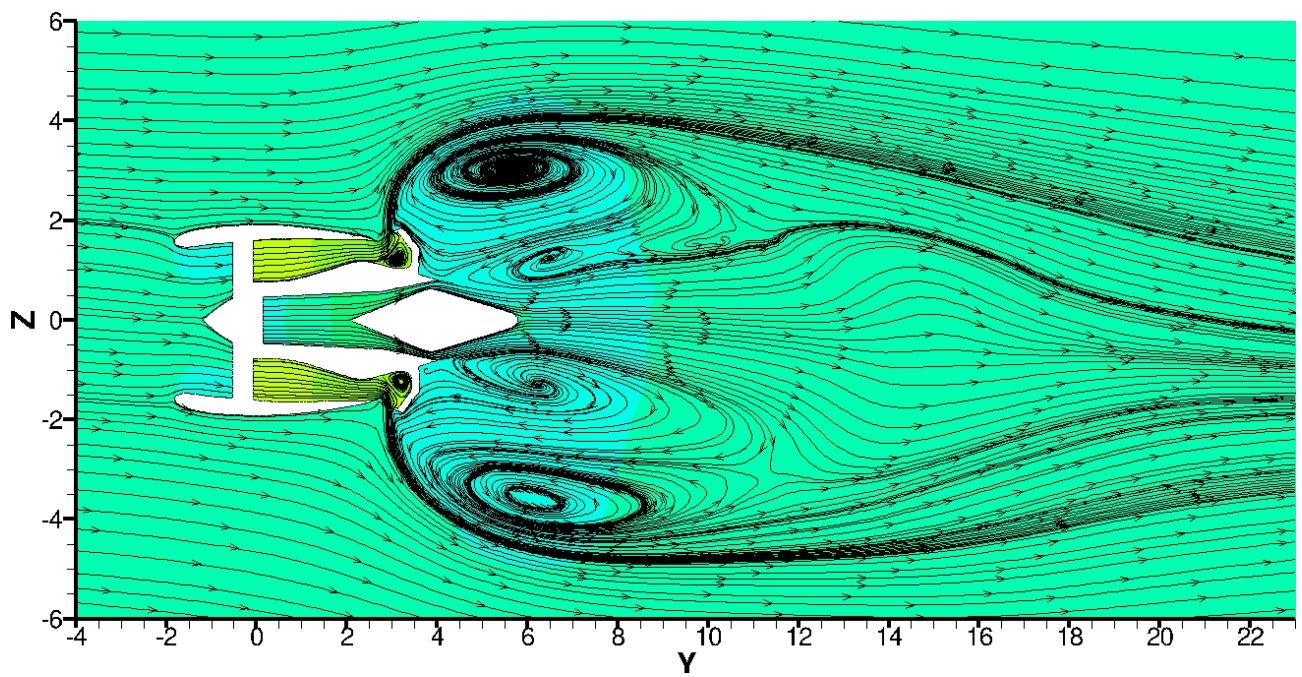
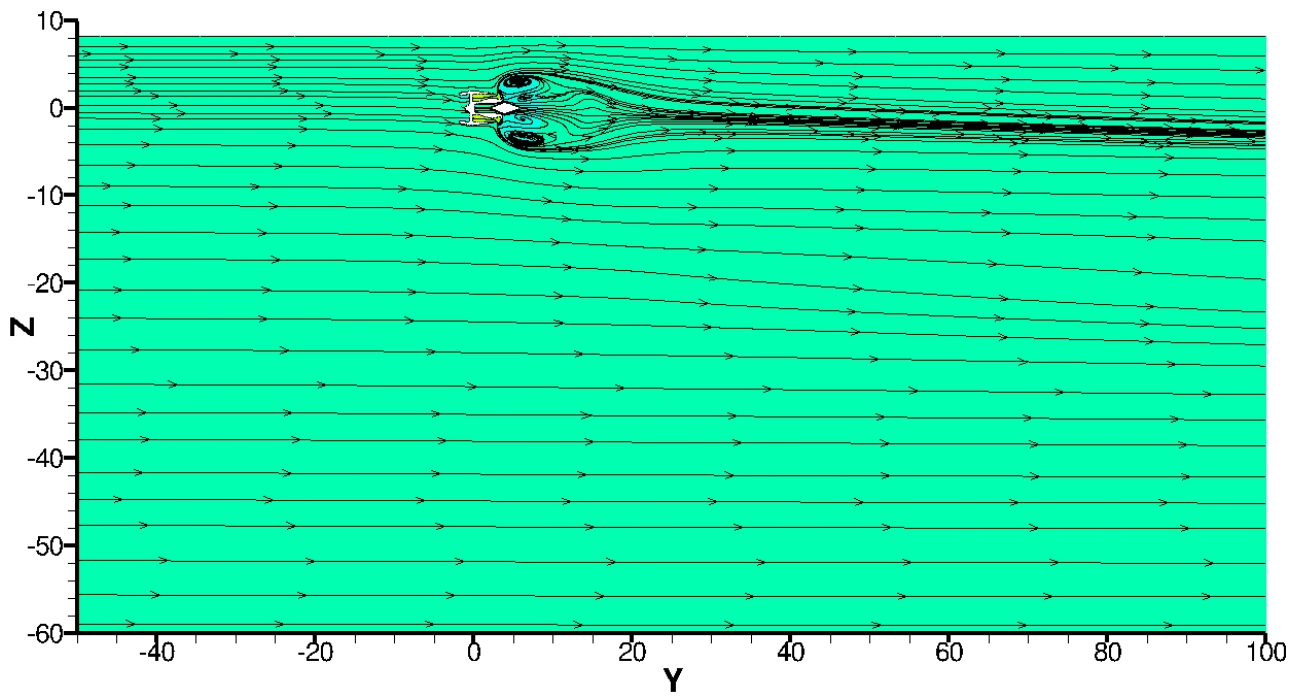


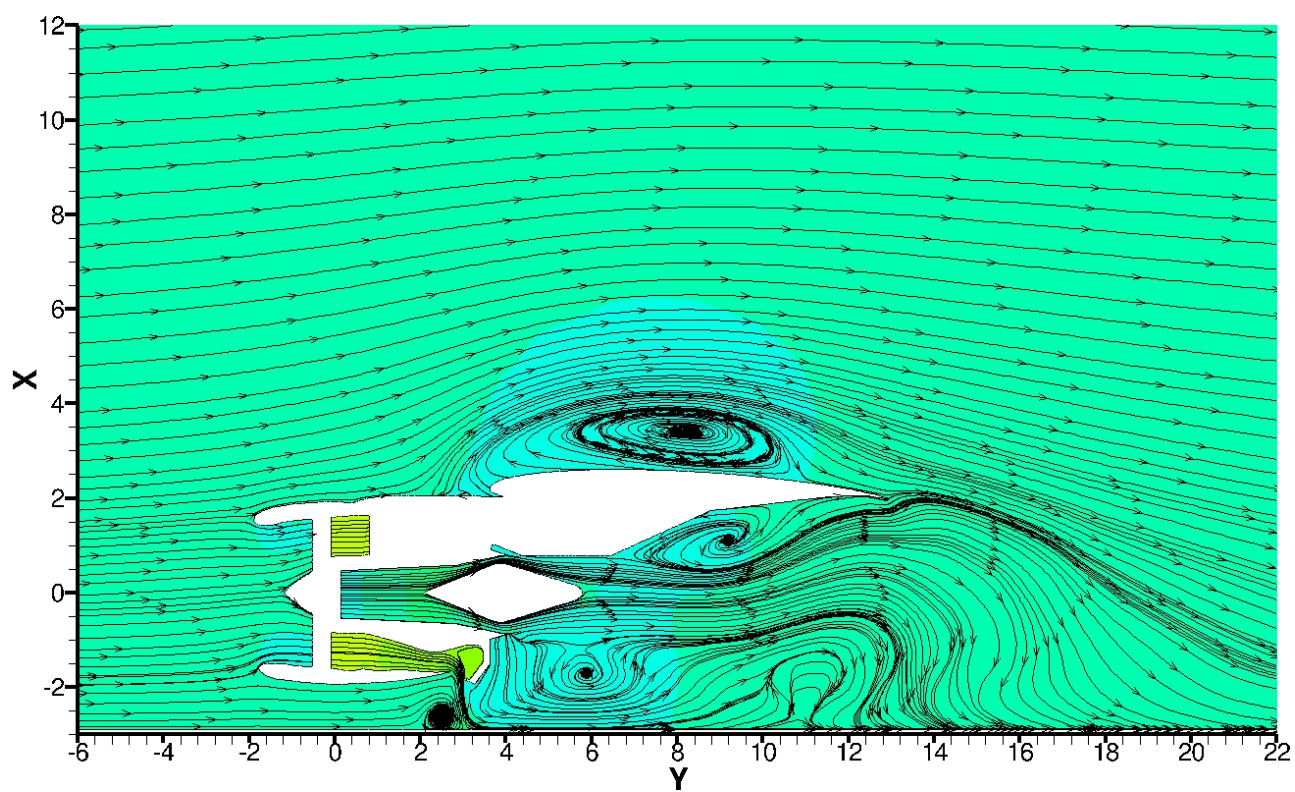
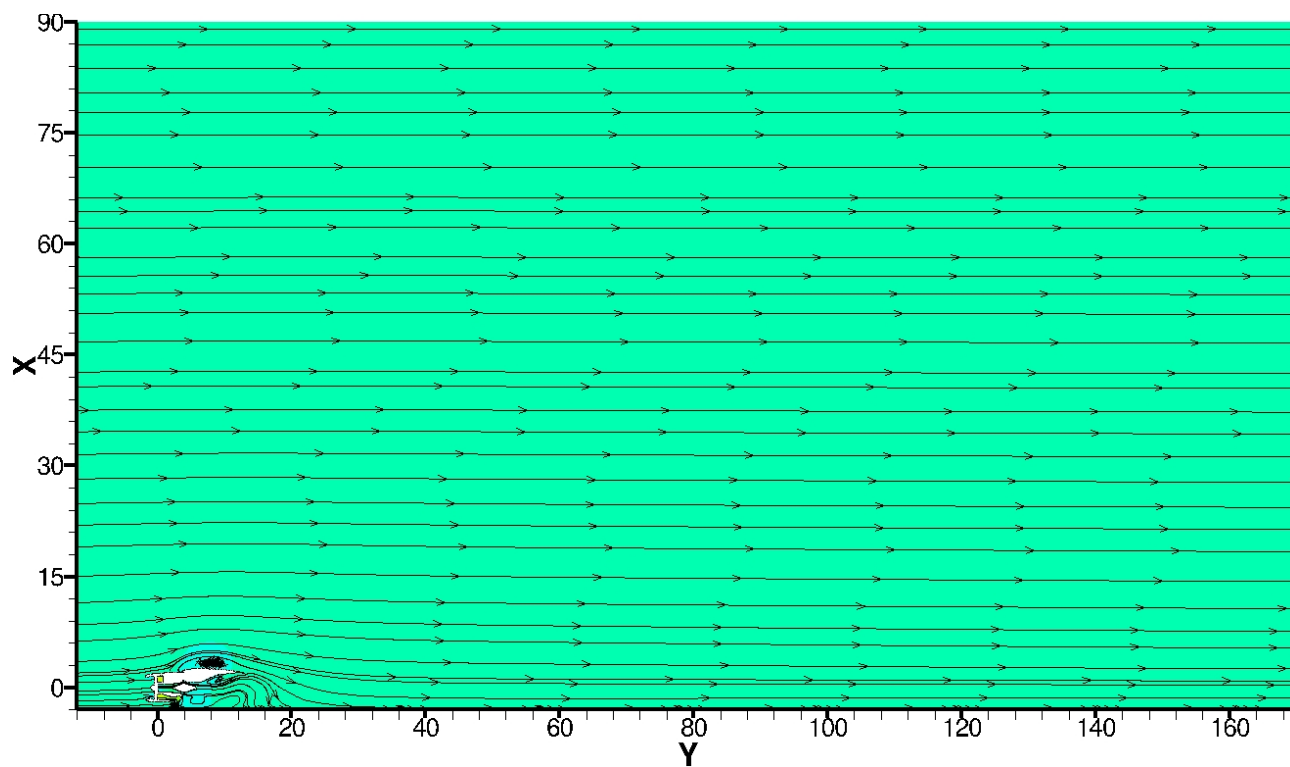
Streamline Plots, 40 Deg Core Mounted Target Reverser with Kicker Plate, $M=0.211$,
 $FNPR=1.317$



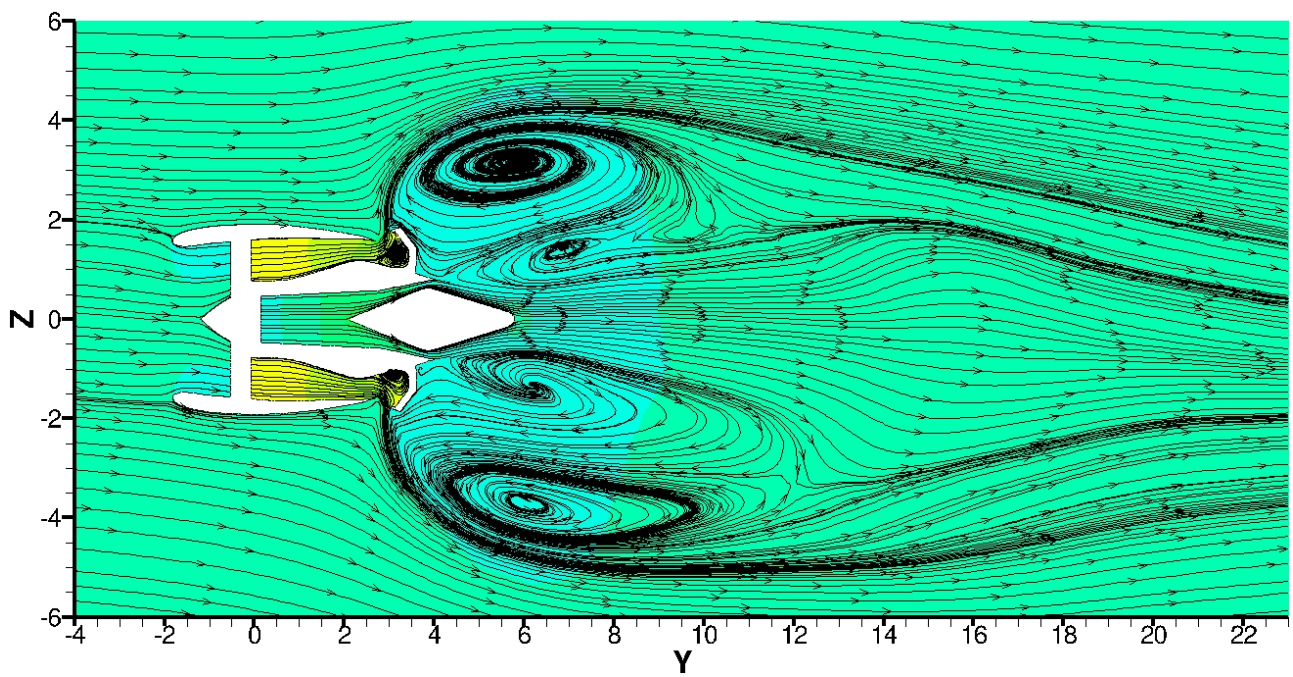
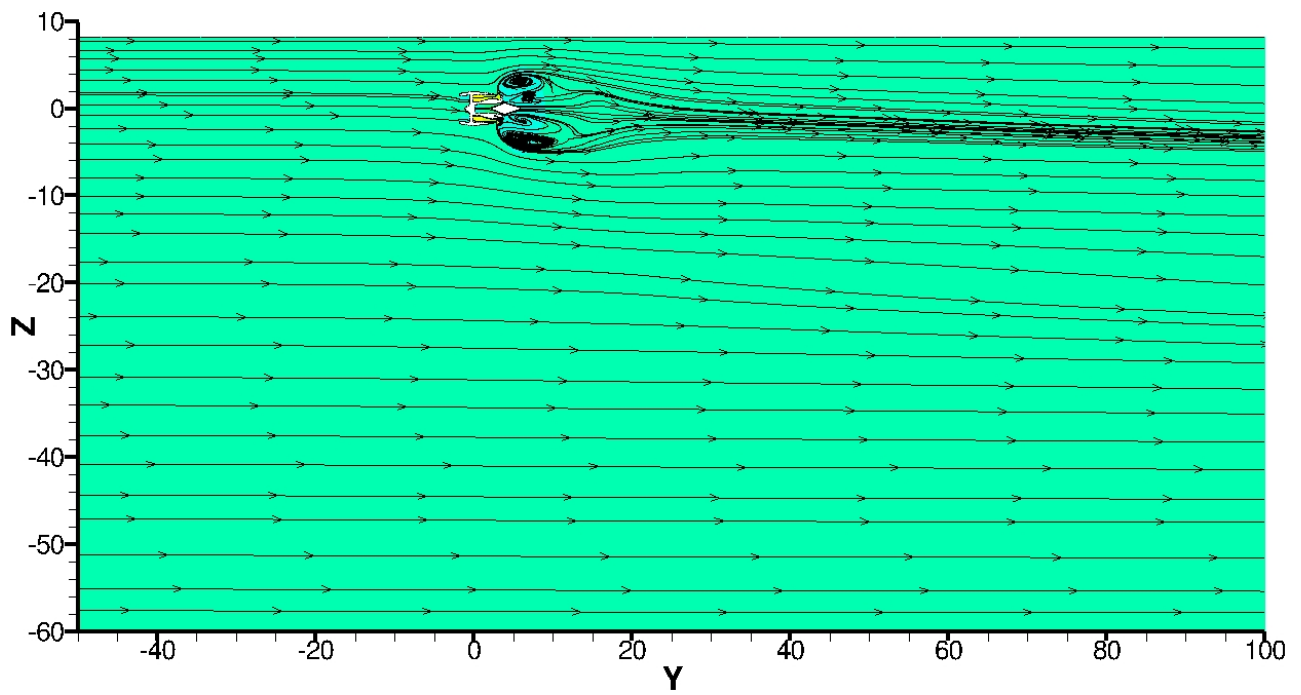


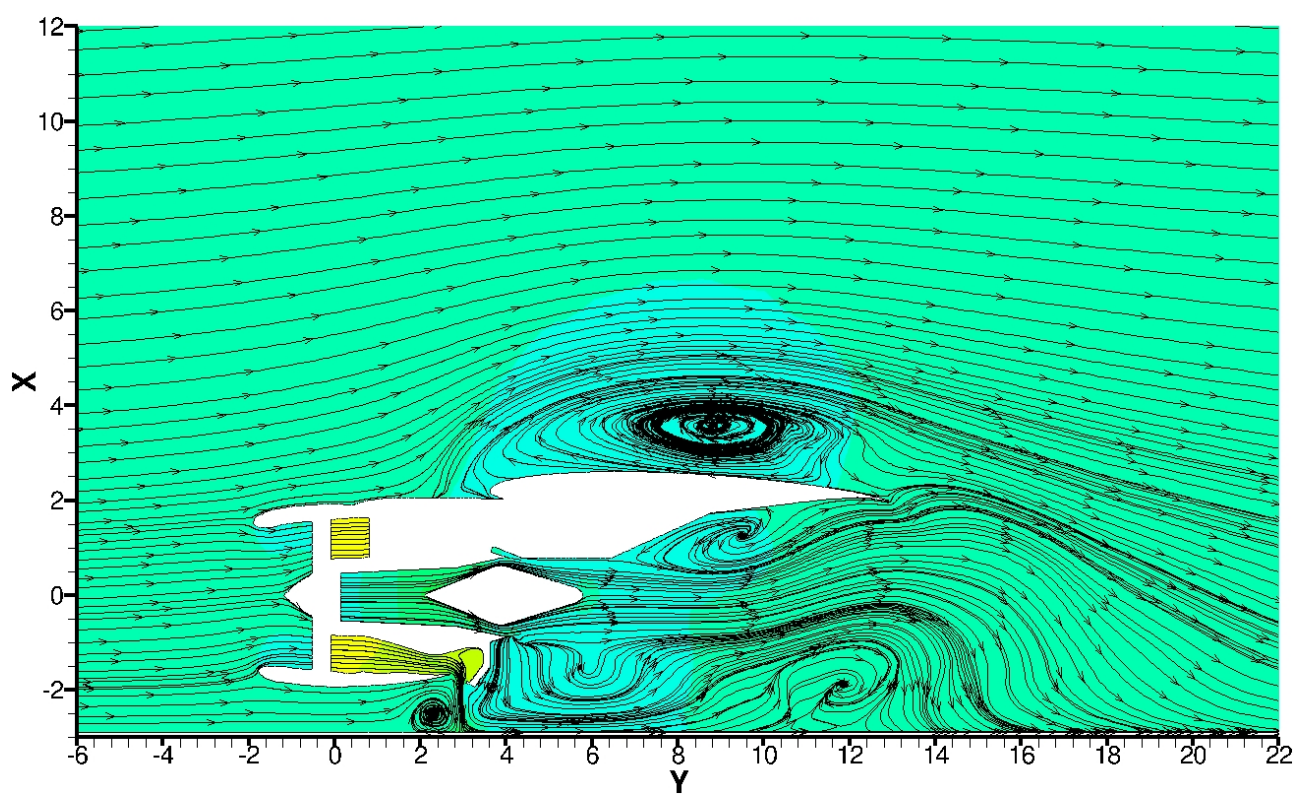
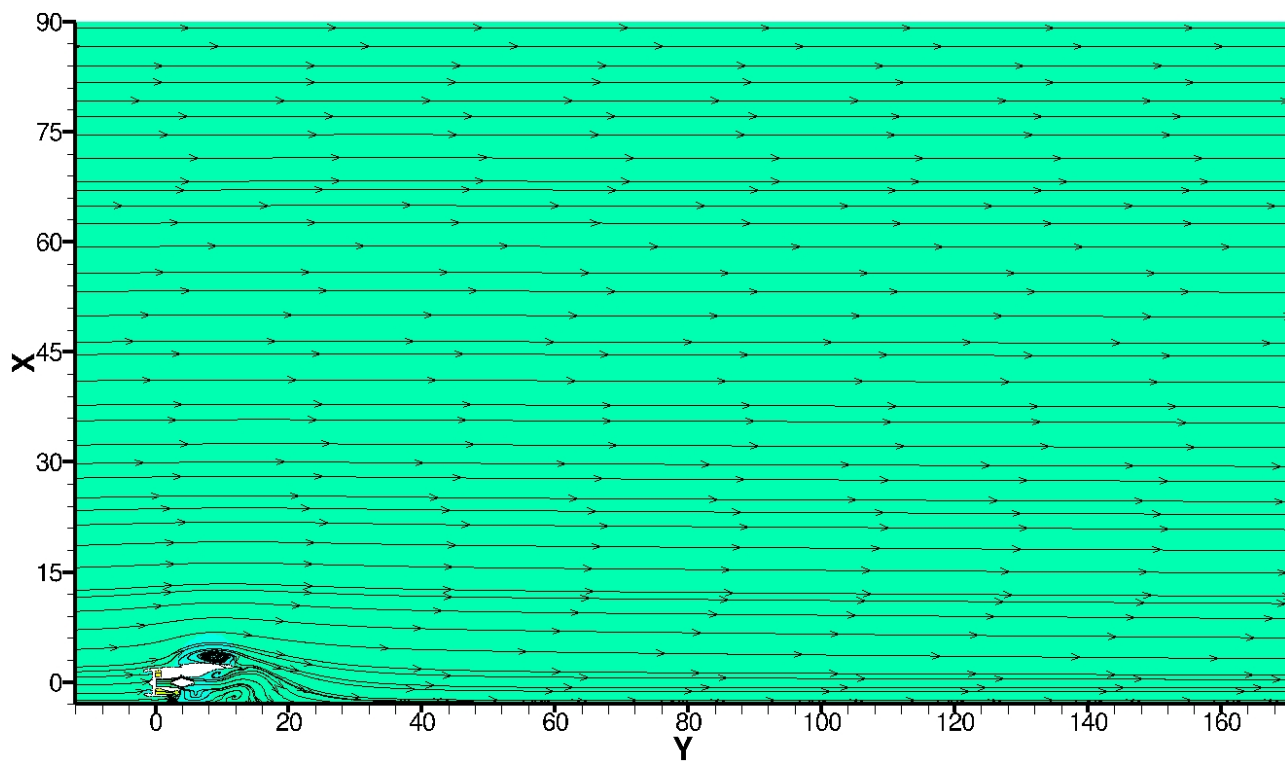
Streamline Plots, 40 Deg Core Mounted Target Reverser with Kicker Plate, $M=0.211$,
 $FNPR=1.366$



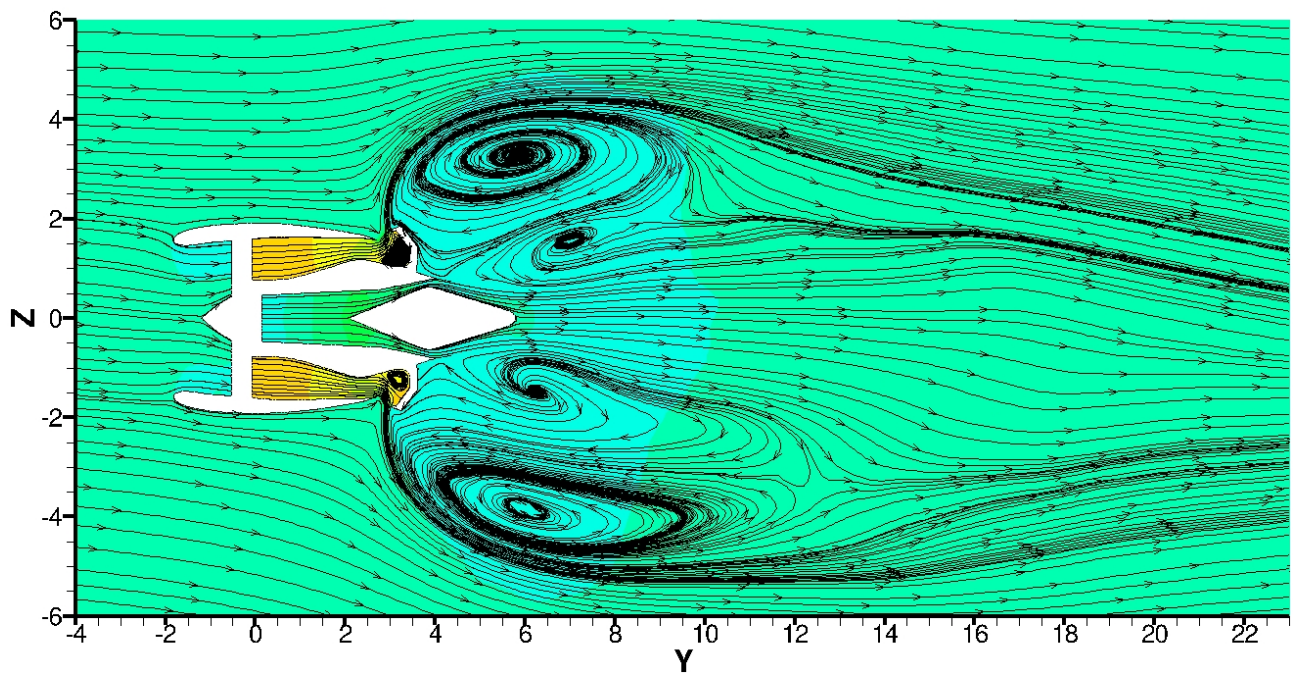
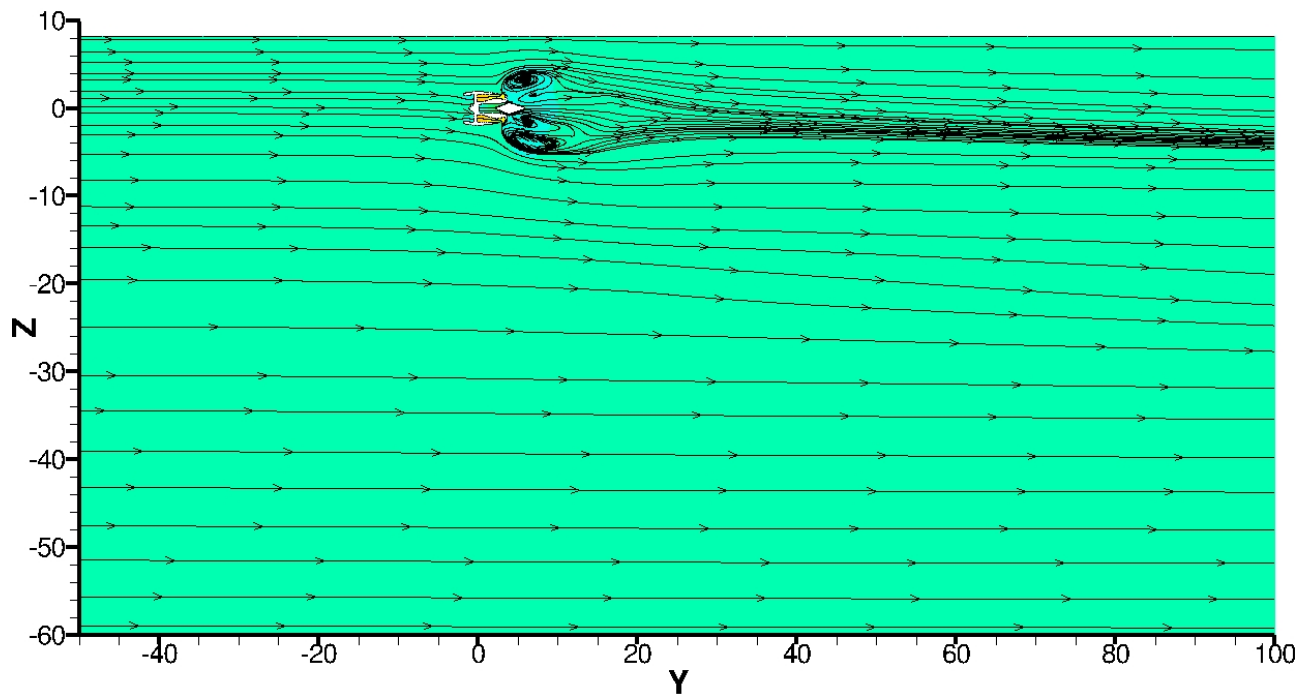


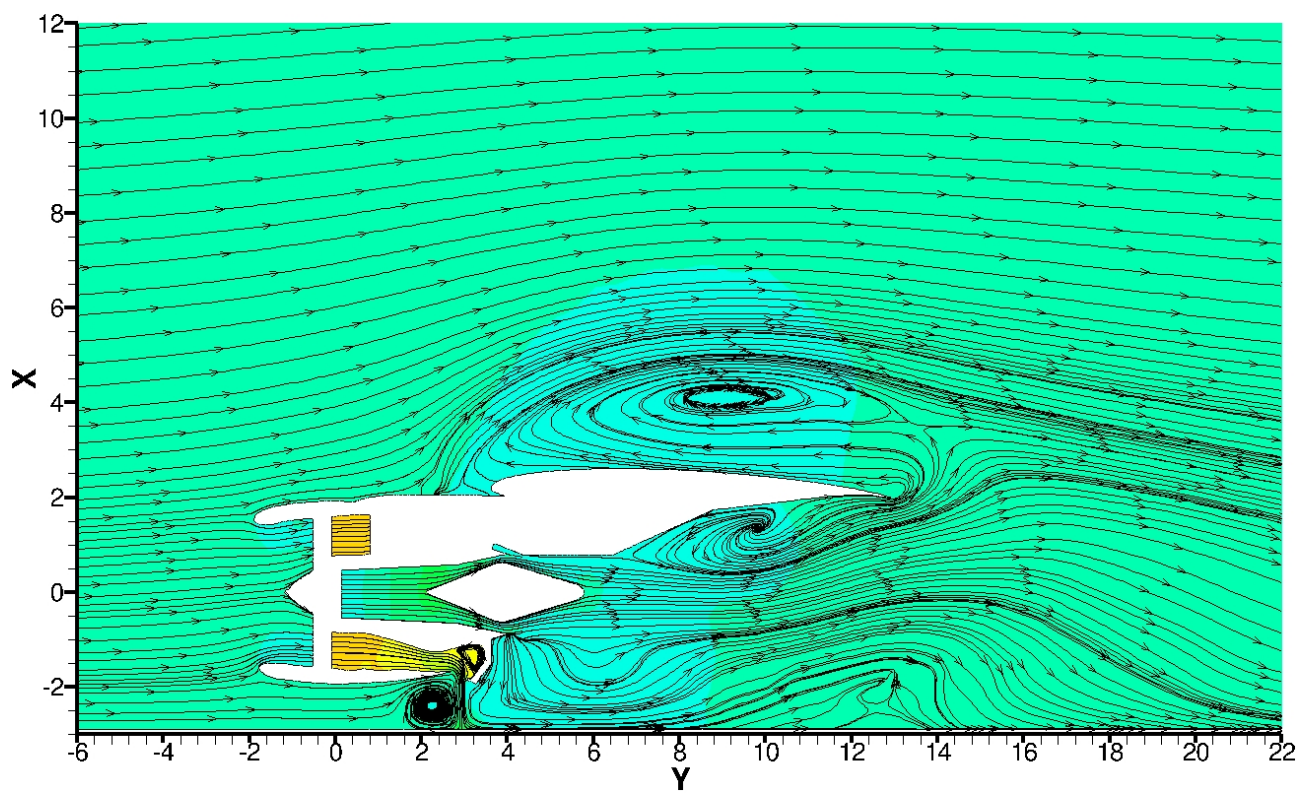
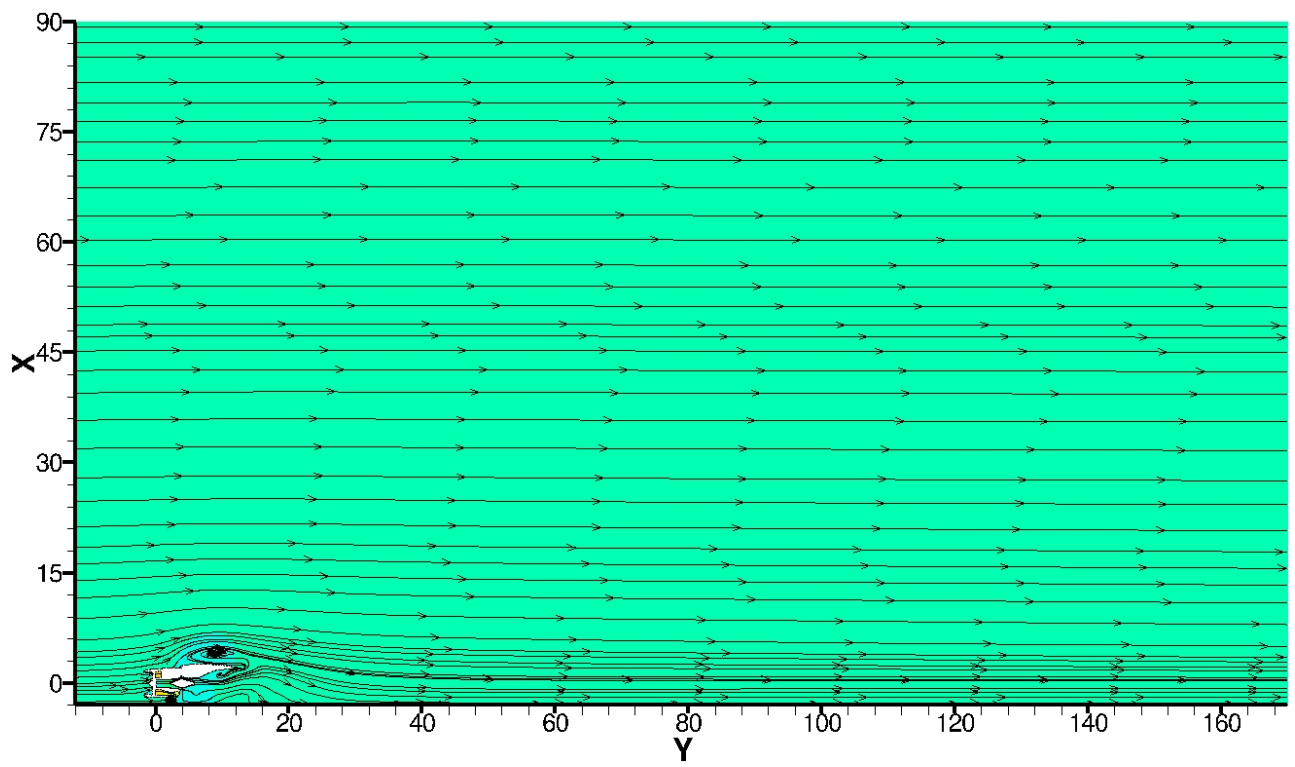
Streamline Plots, 40 Deg Core Mounted Target Reverser with Kicker Plate, $M=0.211$,
 $FNPR=1.416$



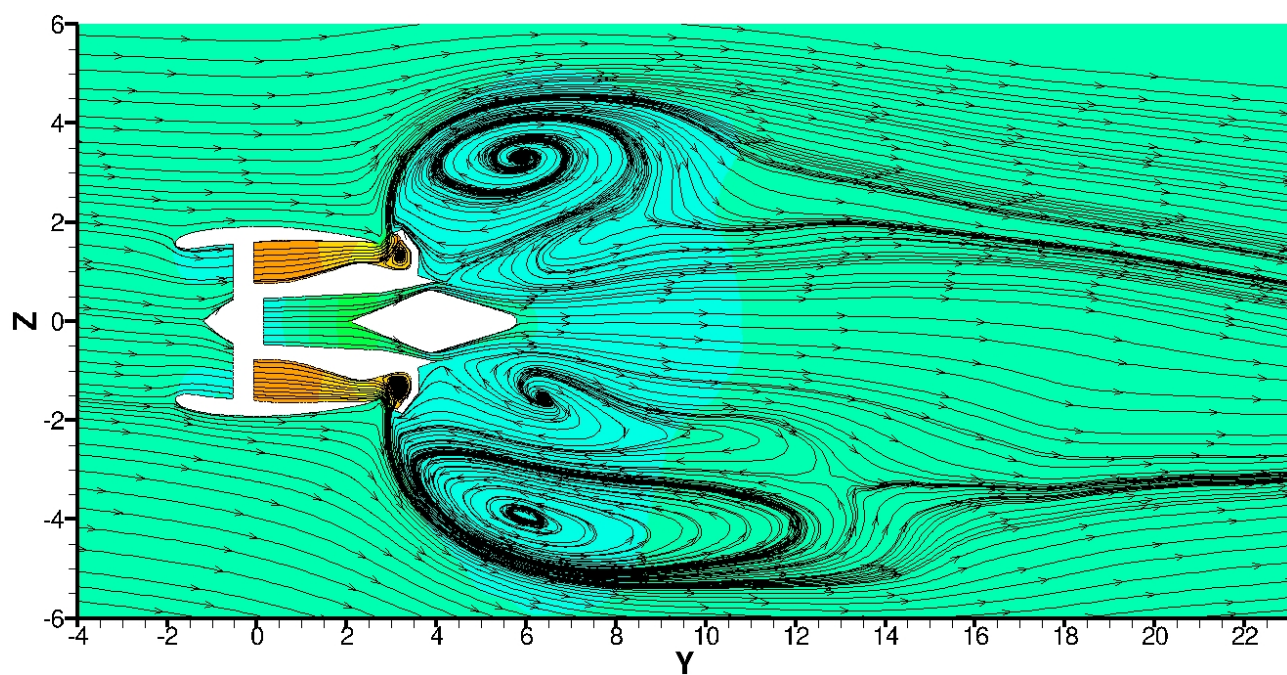
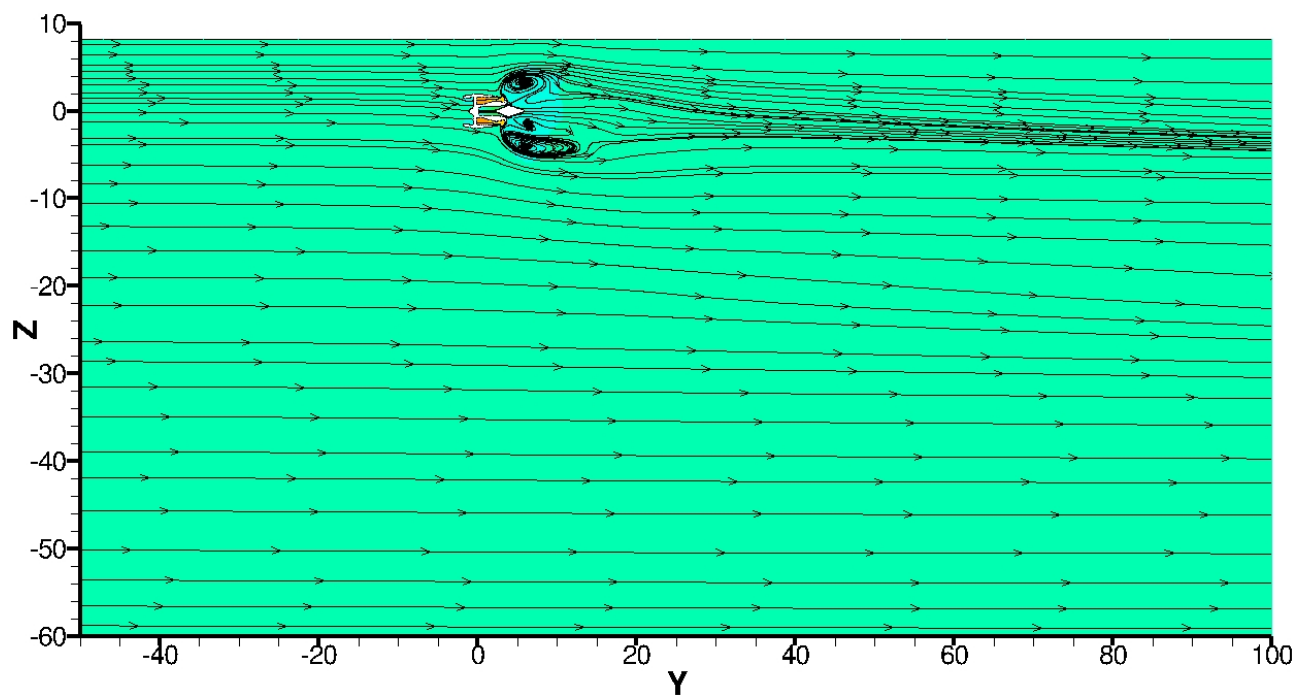


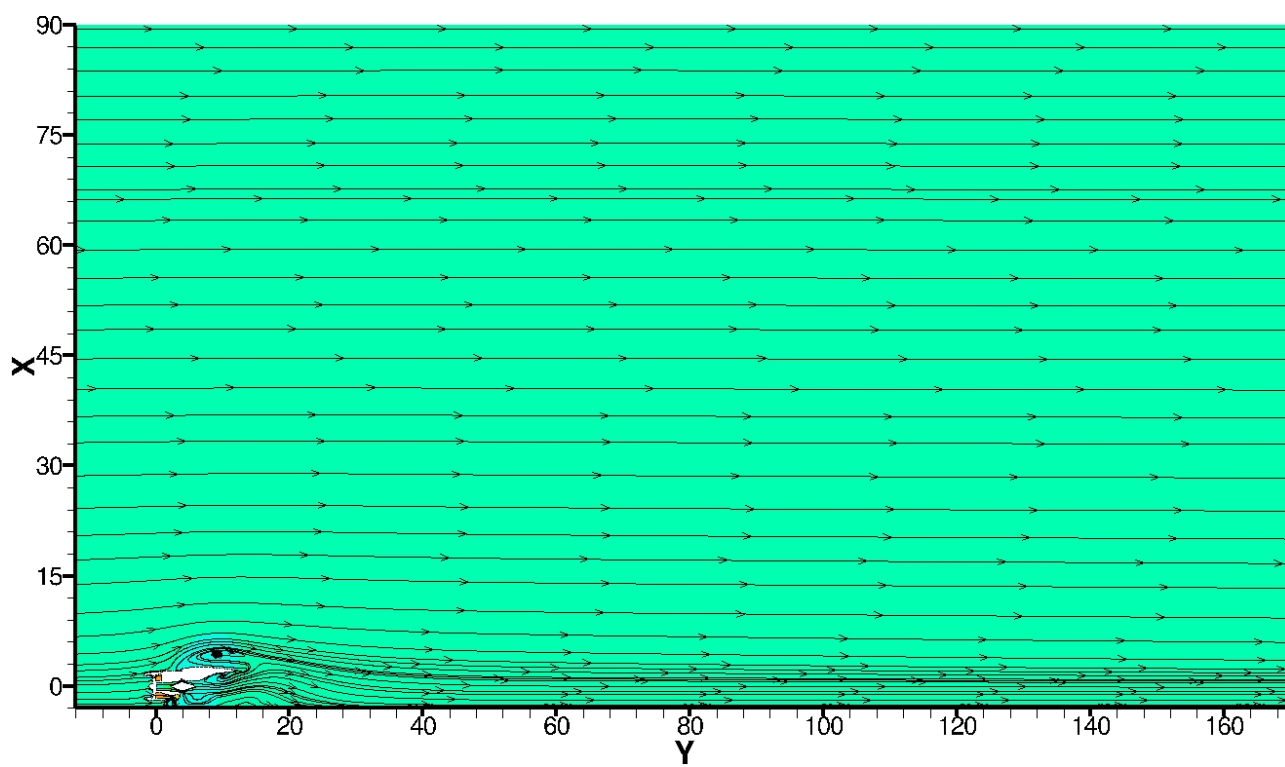
Streamline Plots, 40 Deg Core Mounted Target Reverser with Kicker Plate, $M=0.211$,
 $FNPR=1.475$



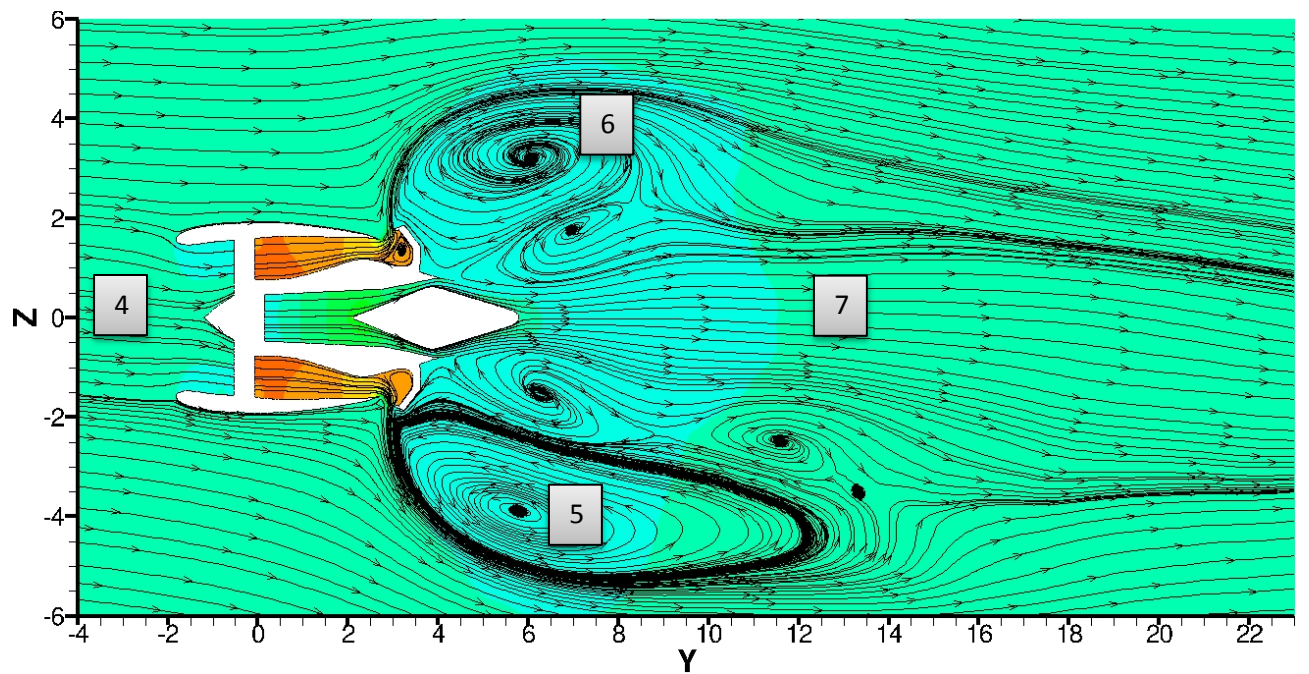
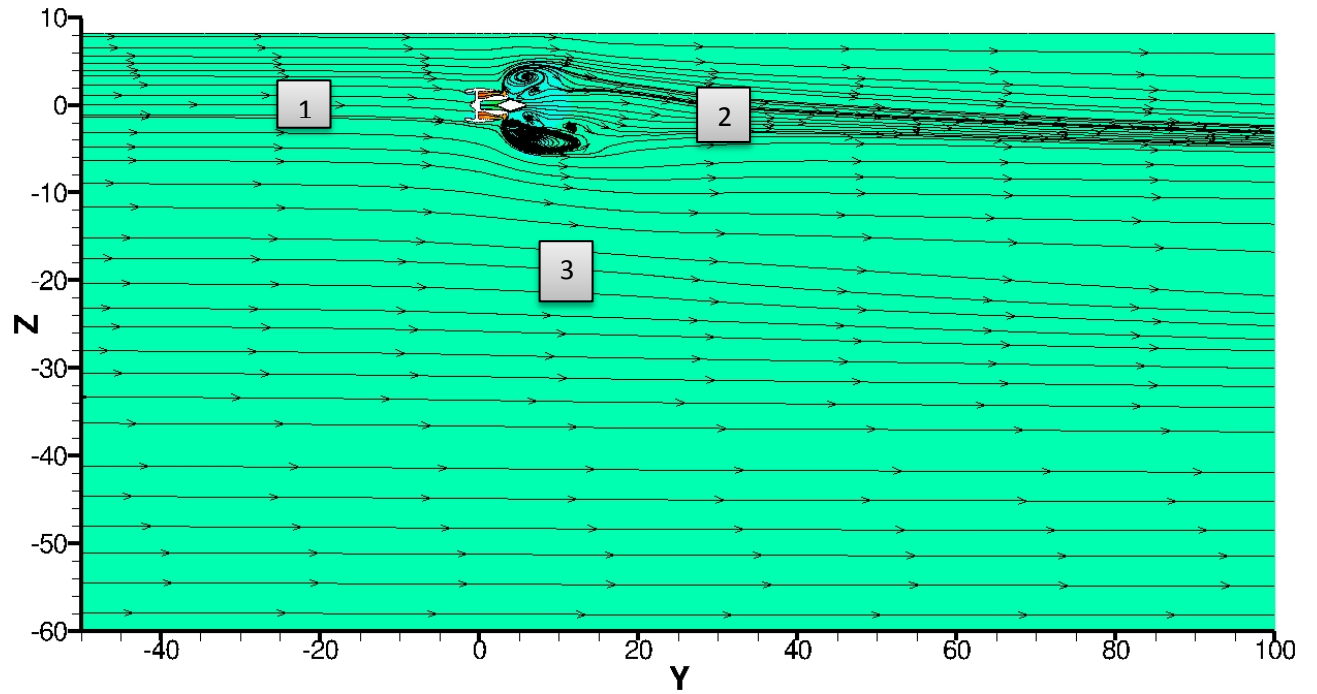


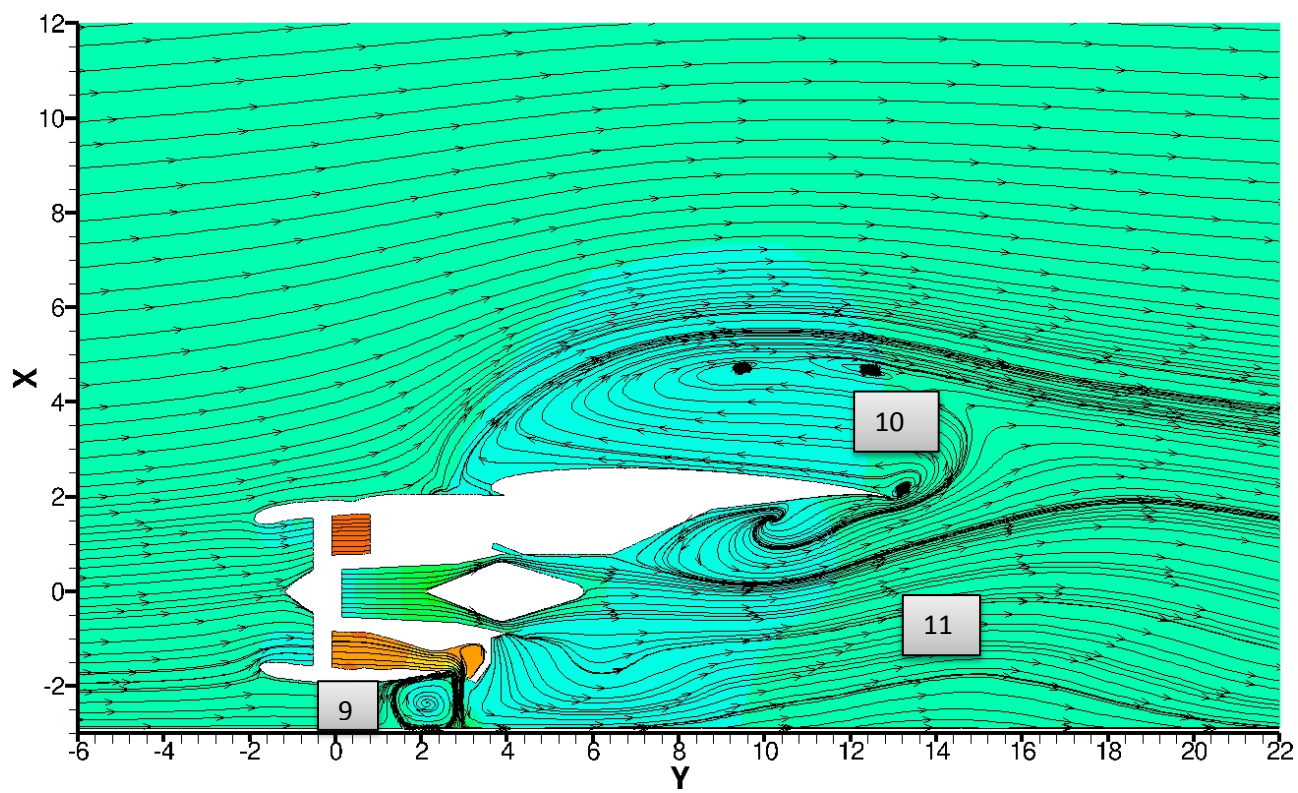
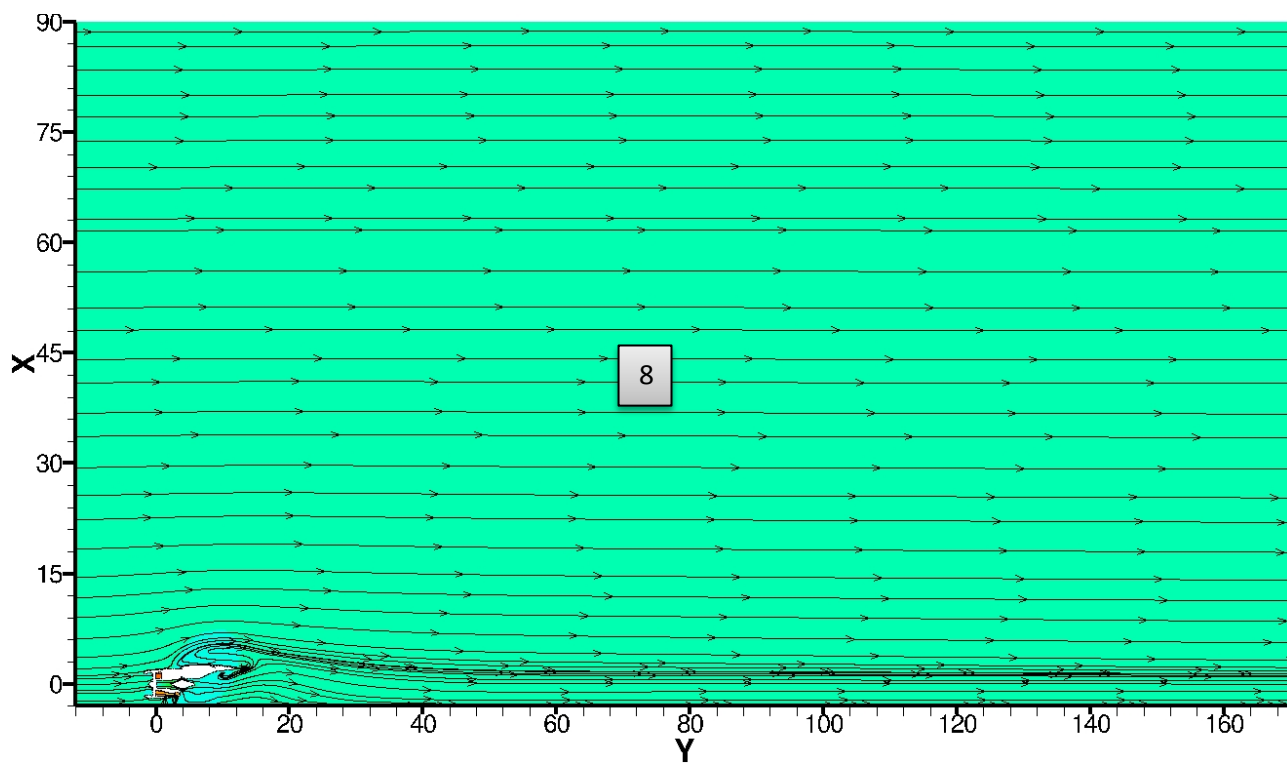
**Streamline Plots, 40 Deg Core Mounted Target Reverser with Kicker Plate, $M=0.211$,
 $FNPR=1.535$**





**Streamline Plots, 40 Deg Core Mounted Target Reverser with Kicker Plate, $M=0.211$,
 $FNPR=1.574$**

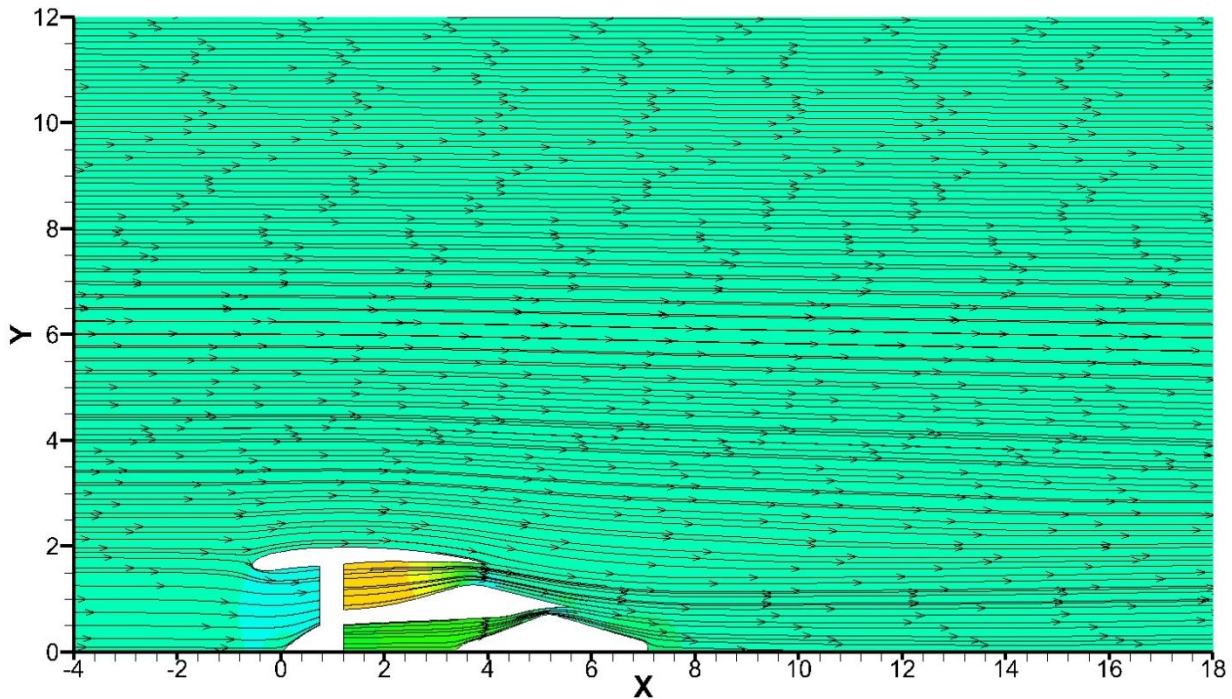




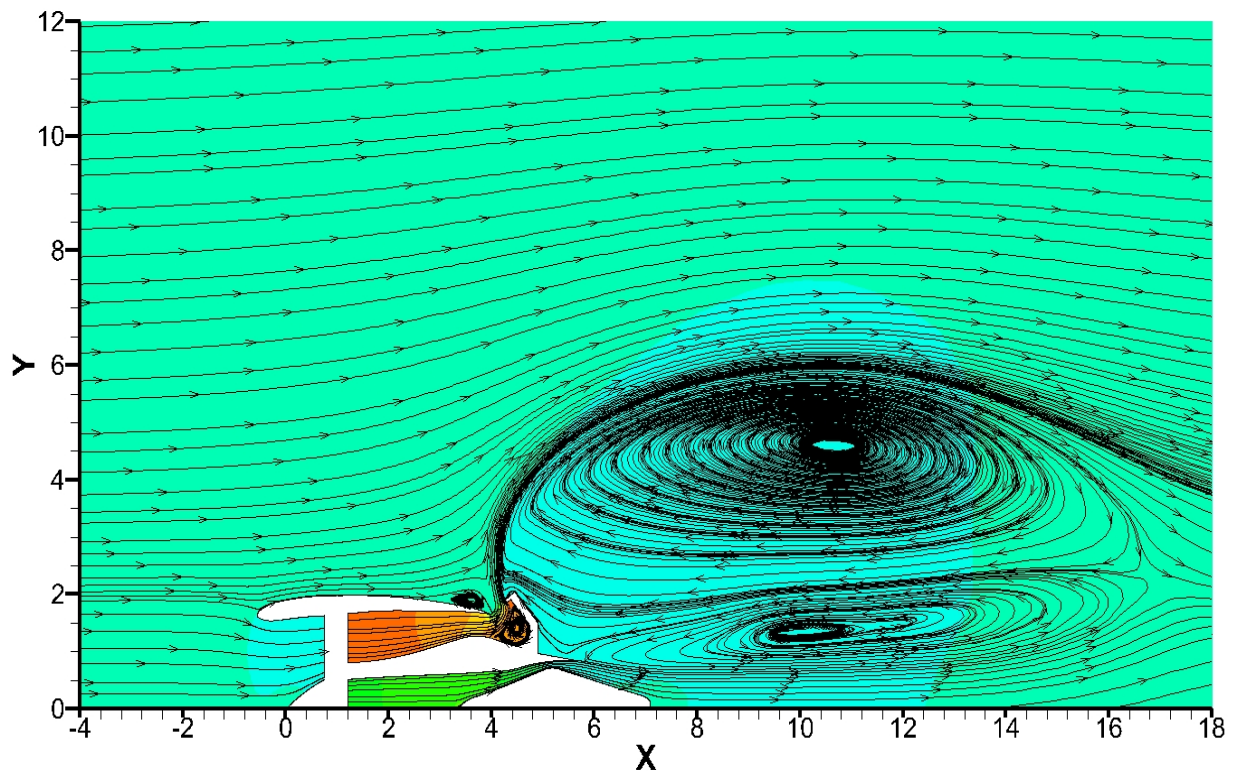
Appendix A6: Reverse Thrust 40 Degree with and without kicker plate at Static Condition, $M=0.211$

Appendix A6.1 –Streamlines Plots

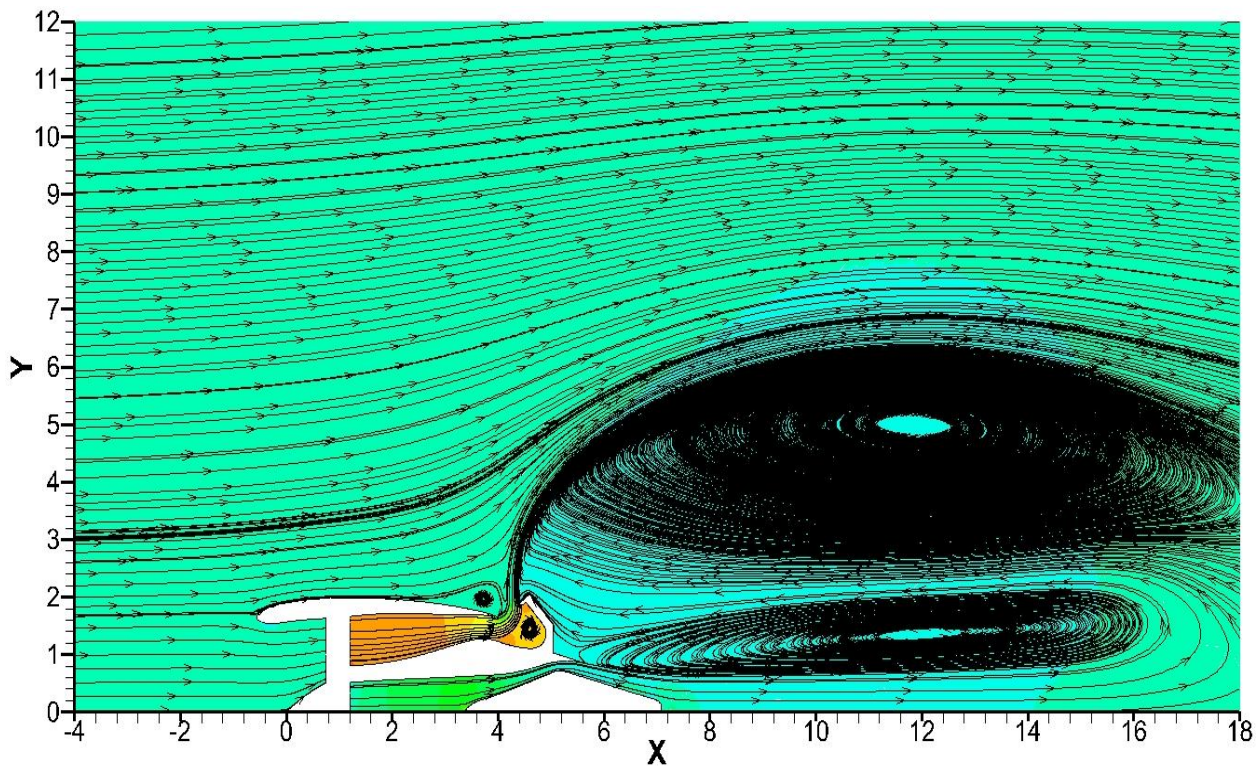
Streamlines Plot, Forward Thrust, $M= 0.211$, Fan Outlet Pressure = 159 KPa (Baseline Case)



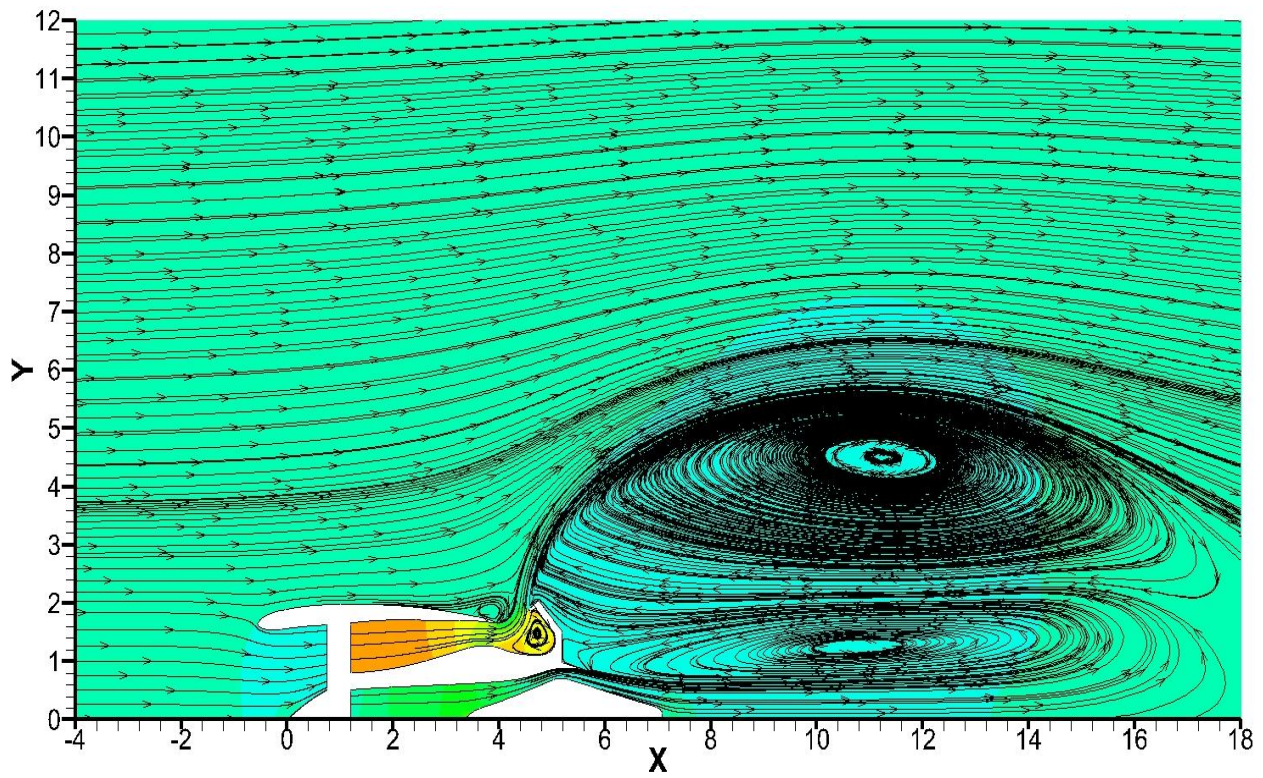
Streamlines Plot, Reverse Thrust, $M= 0.211$, Fan Outlet Pressure = 159 KPa (Baseline Case), same design was used in 3D analysis, Configuration; $D_{rev} = 1.869\text{m}$, $L = 0.2873\text{m}$, Reverser Area = 4.185m^2



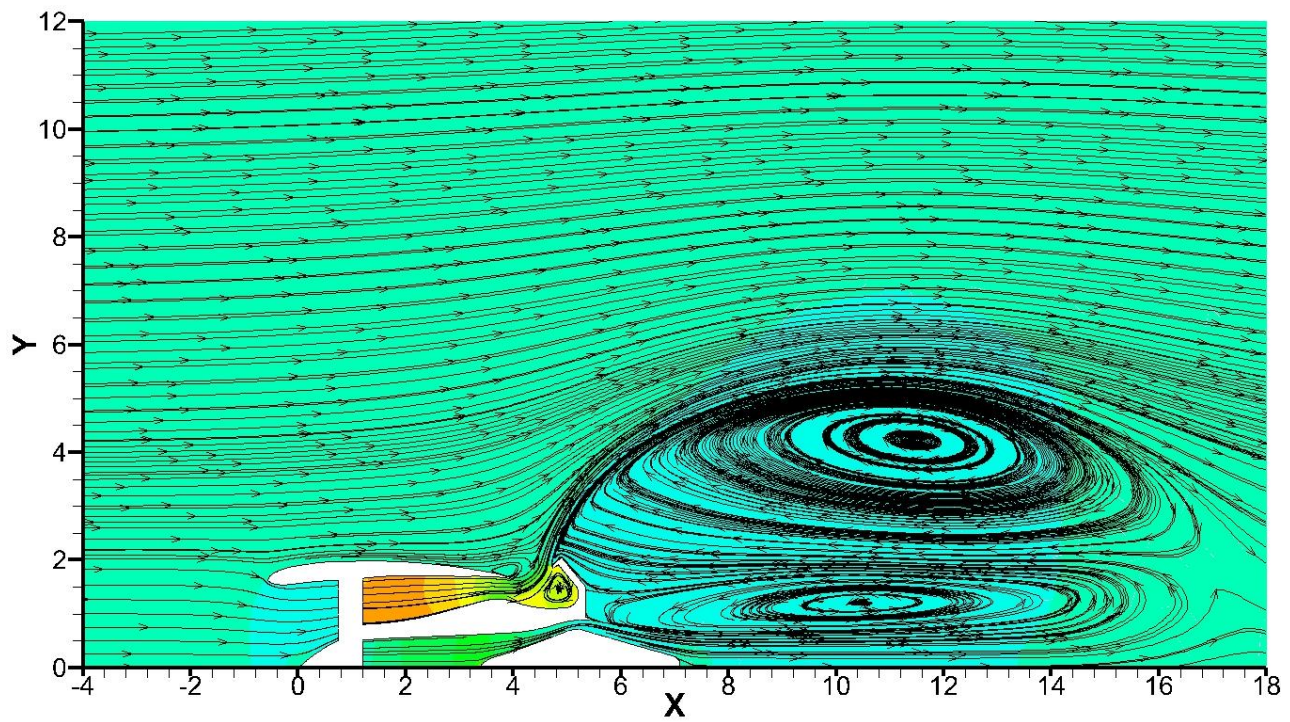
Configuration; $D_{rev} = 1.869\text{m}$, $L = 0.437\text{m}$, Reverser Area = 5.486m^2



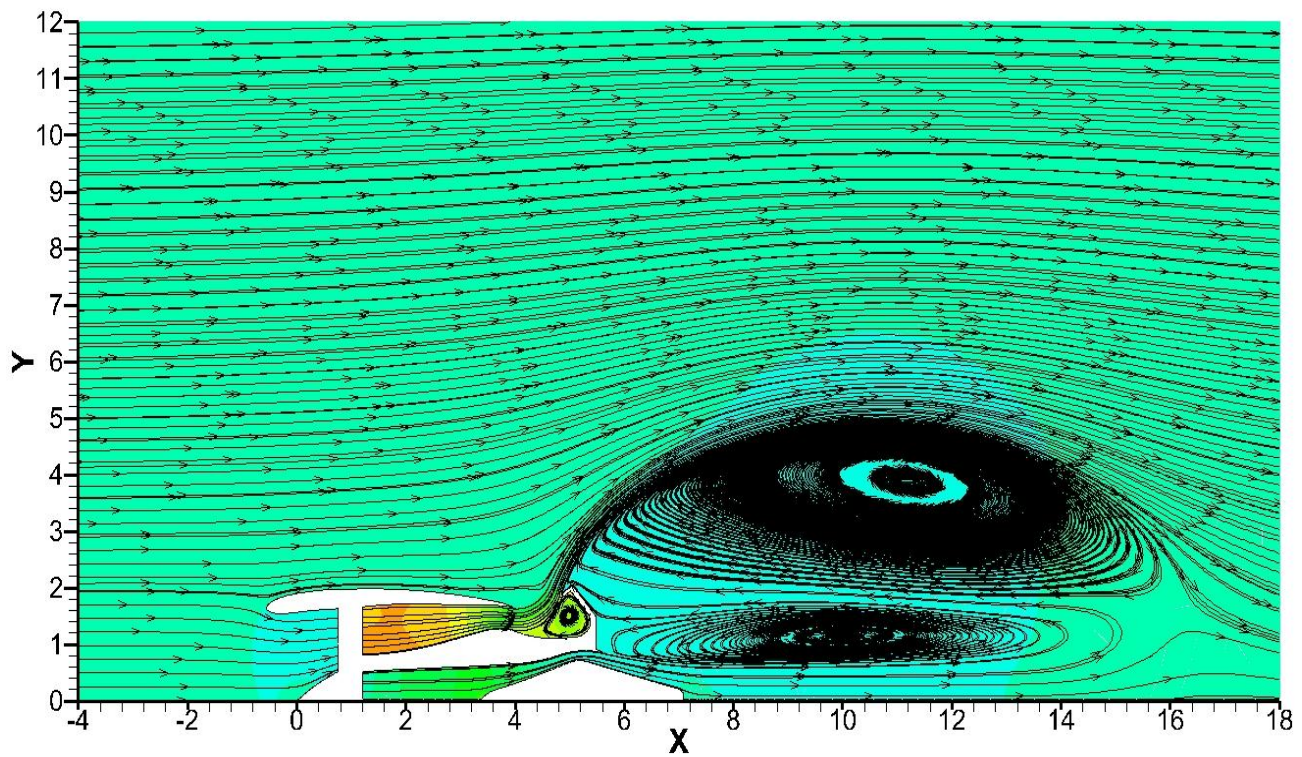
Configuration; $D_{rev} = 1.869\text{m}$, $L = 0.587\text{m}$, Reverser Area = 6.975m^2



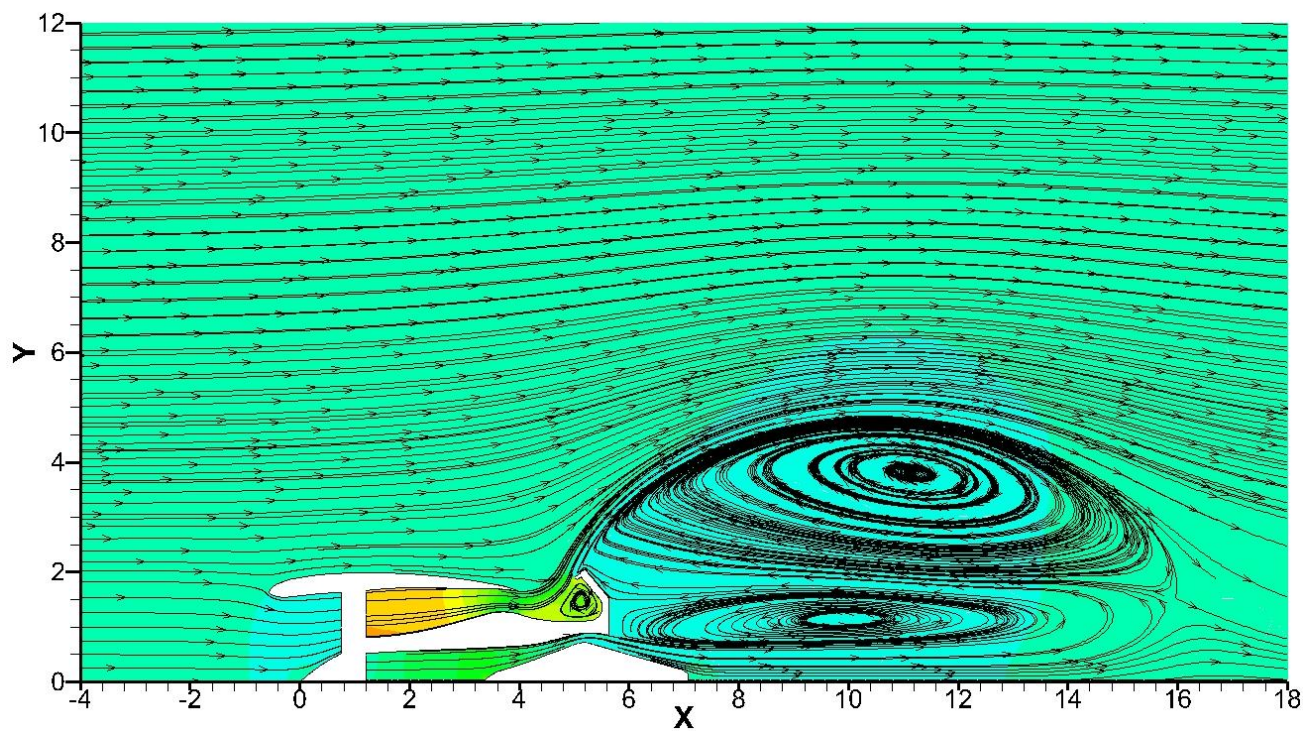
Configuration; $D_{rev} = 1.869\text{m}$, $L = 0.737\text{m}$, Reverser Area = 8.524m^2



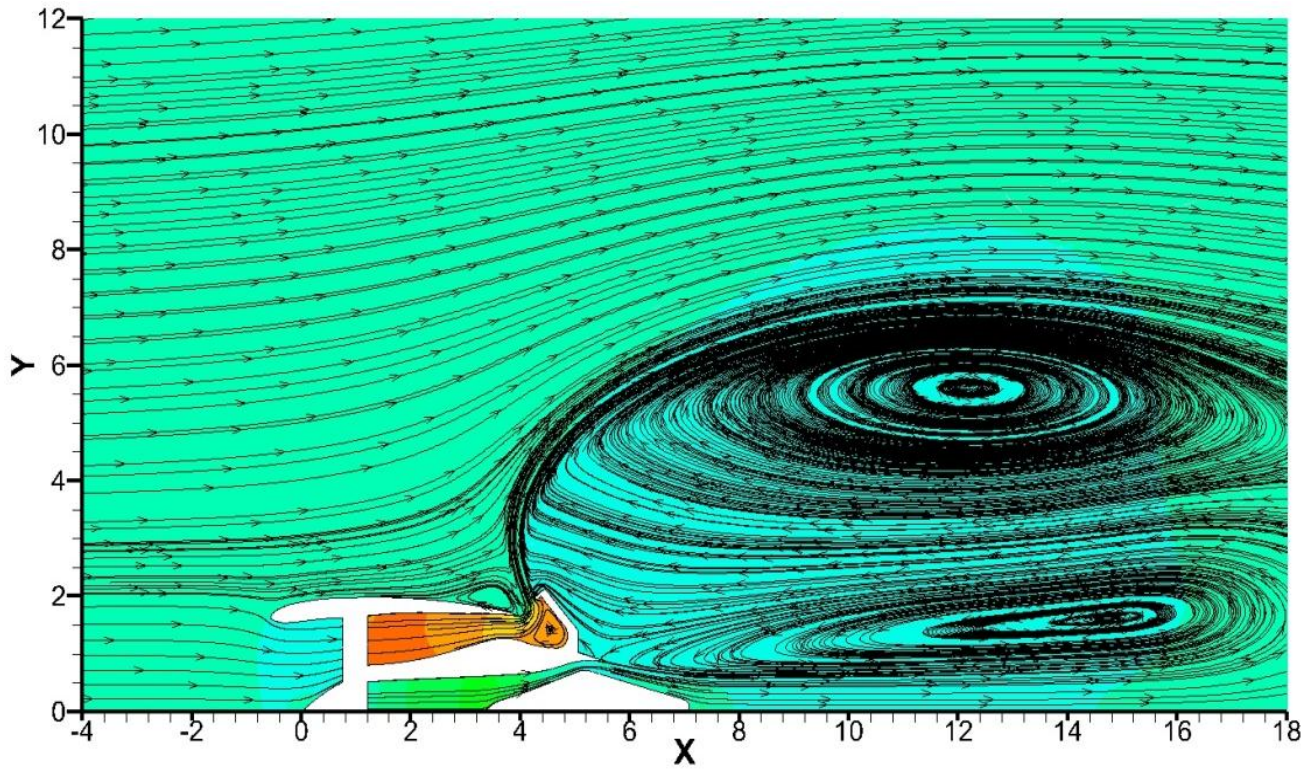
Configuration; $D_{rev} = 1.869\text{m}$, $L = 0.887\text{m}$, Reverser Area = 10.103m^2



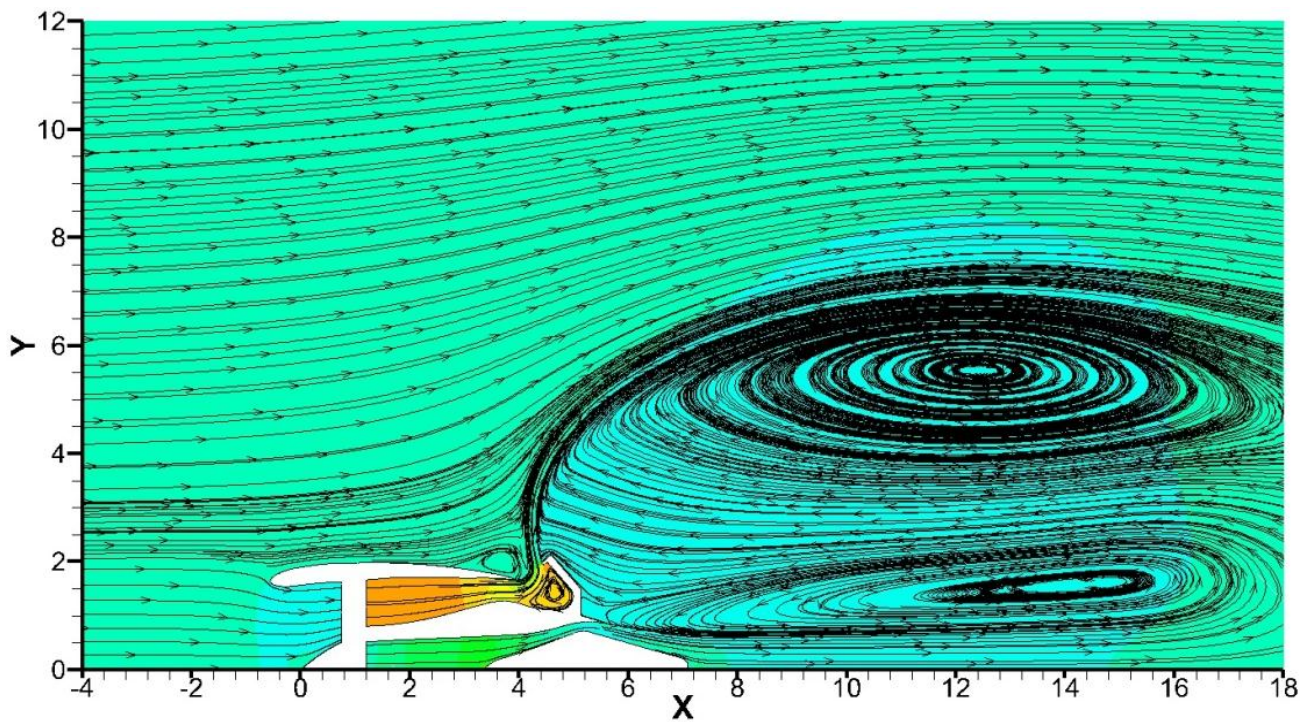
Configuration; $D_{rev} = 1.869\text{m}$, $L = 1.037\text{m}$, Reverser Area = 11.710m^2



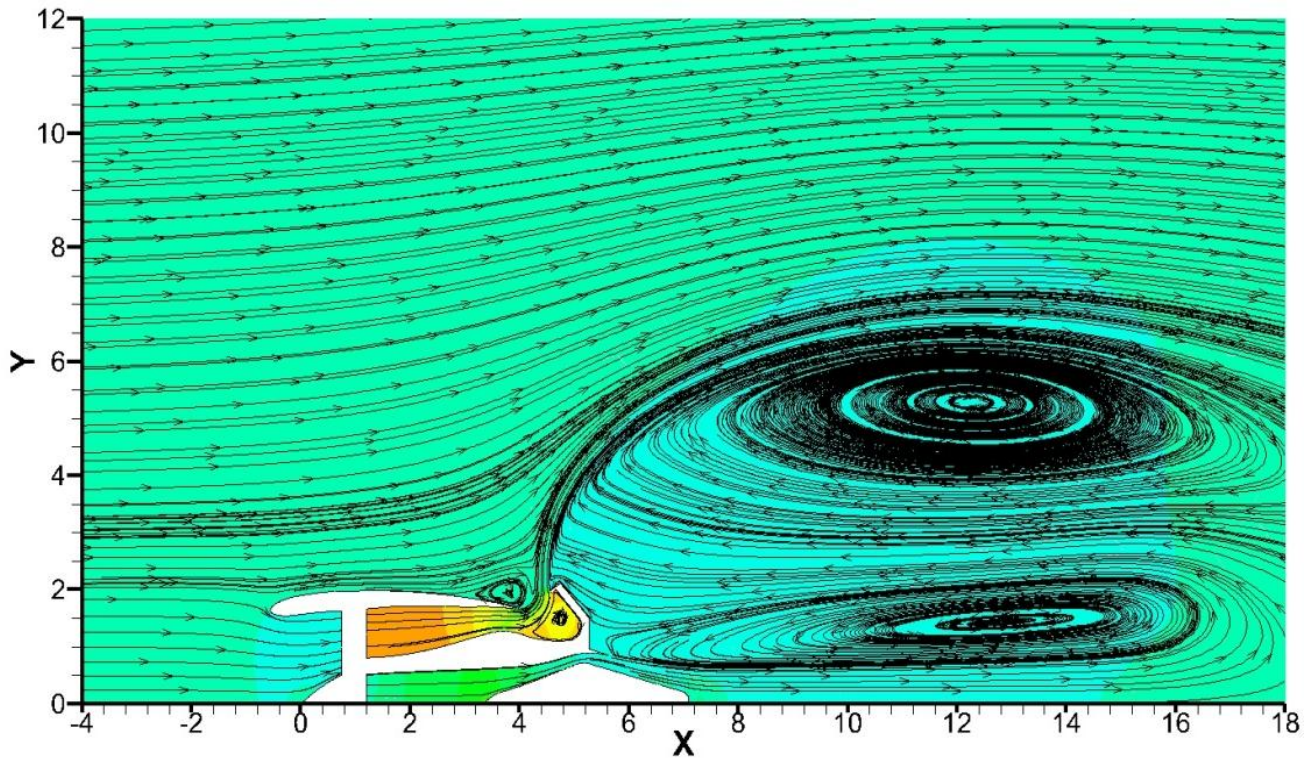
Configuration; $D_{rev} = 1.954\text{m}$, $L = 1.0287\text{m}$, Reverser Area = 4.8890m^2



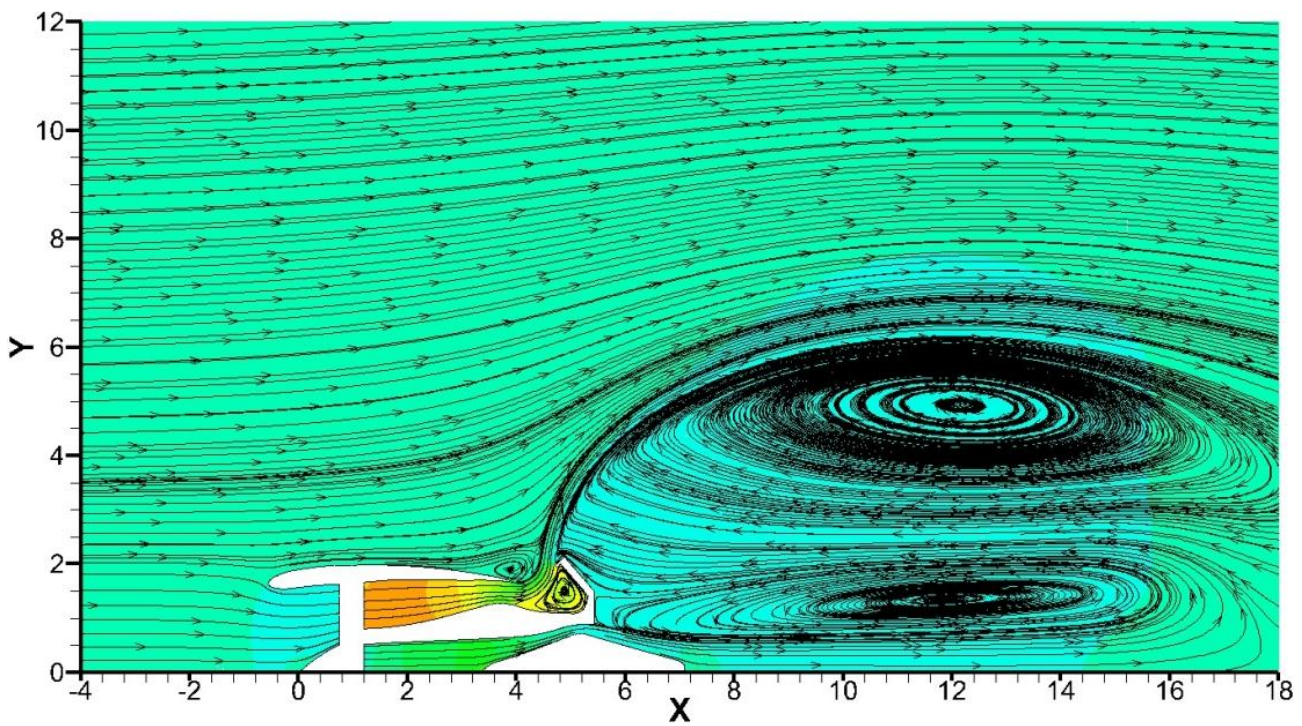
Configuration; $D_{rev} = 1.954\text{m}$, $L = 0.437\text{m}$, Reverser Area = 6.114m^2



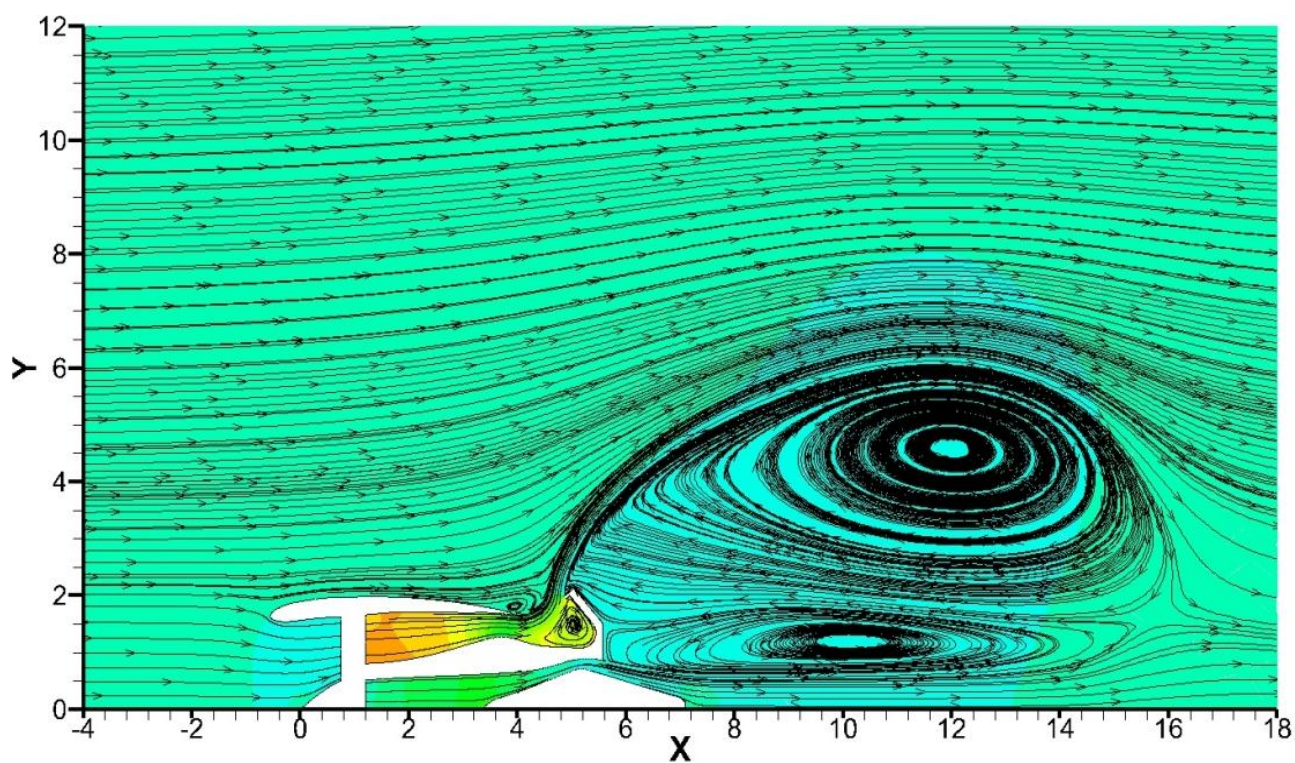
Configuration; $D_{rev} = 1.954\text{m}$, $L = 0.587\text{m}$, Reverser Area = 7.560m^2



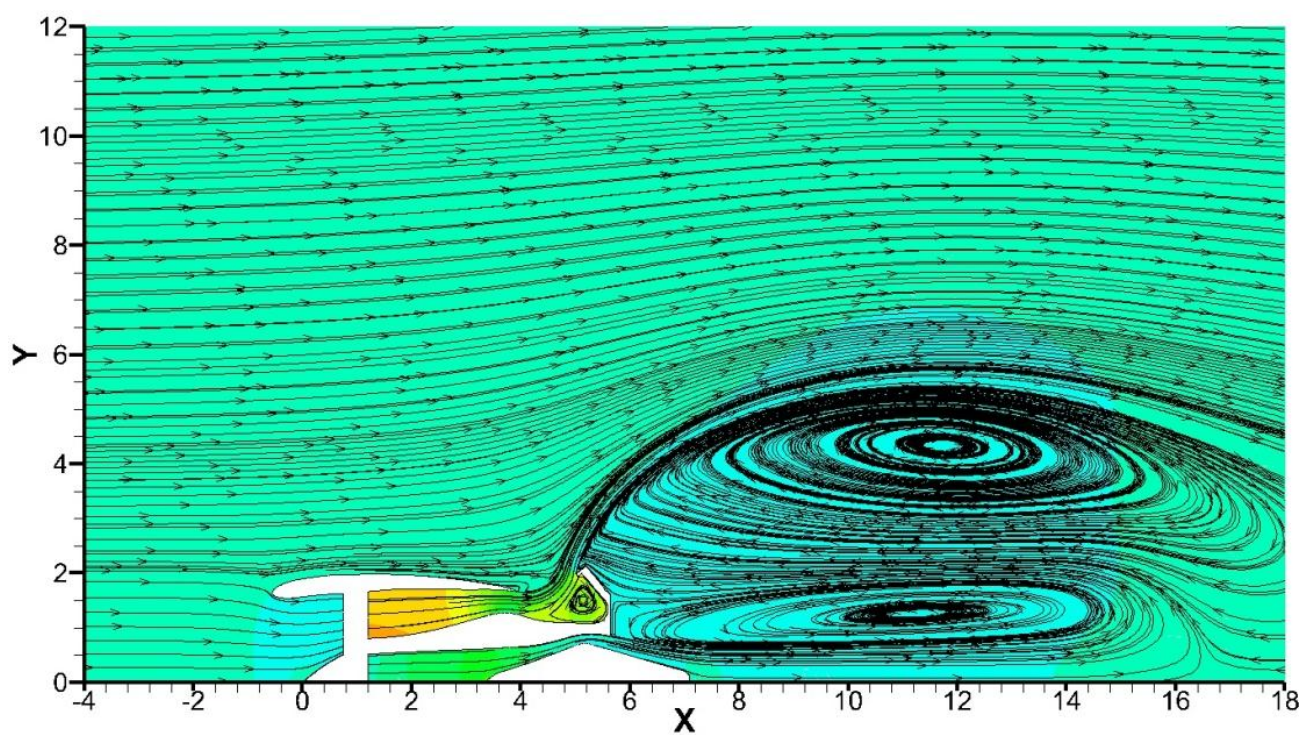
Configuration; $D_{rev} = 1.954\text{m}$, $L = 0.737\text{m}$, Reverser Area = 9.073m^2



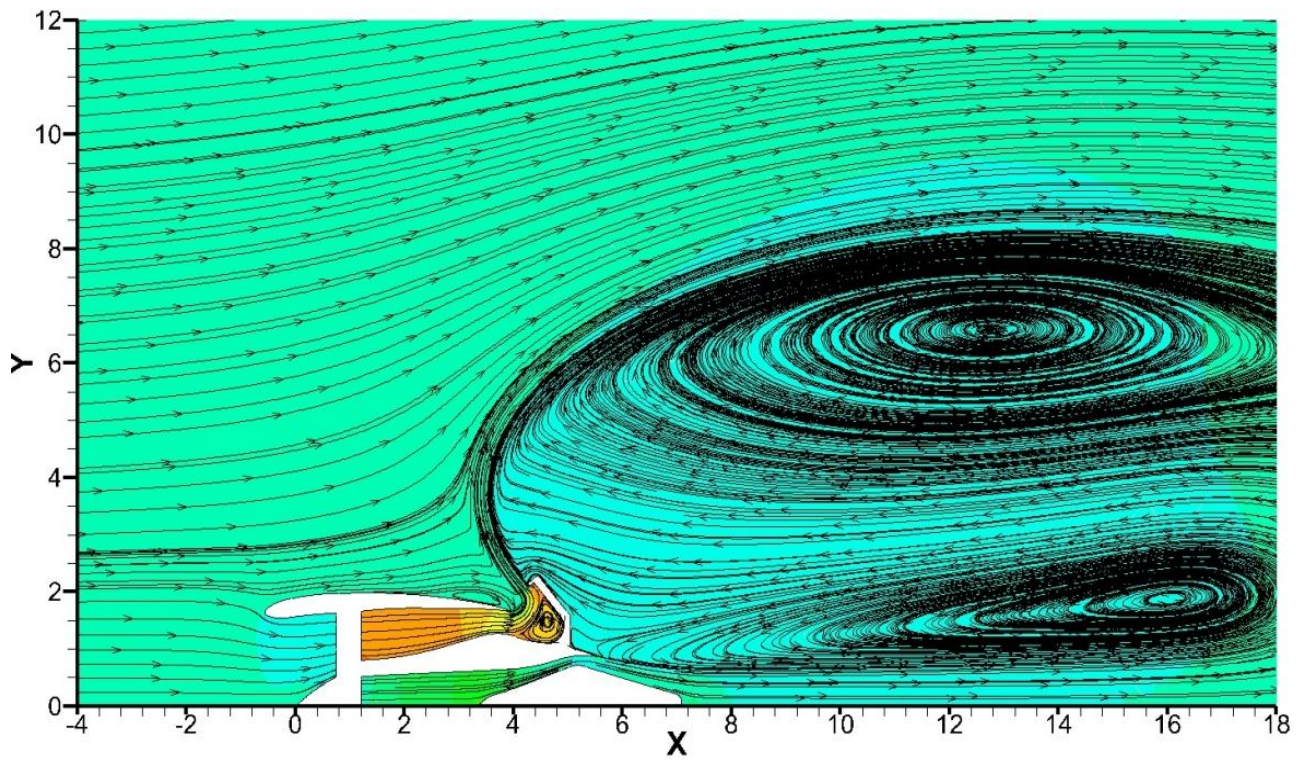
Configuration; $D_{rev} = 1.954\text{m}$, $L = 0.887\text{m}$, Reverser Area = 10.639m^2



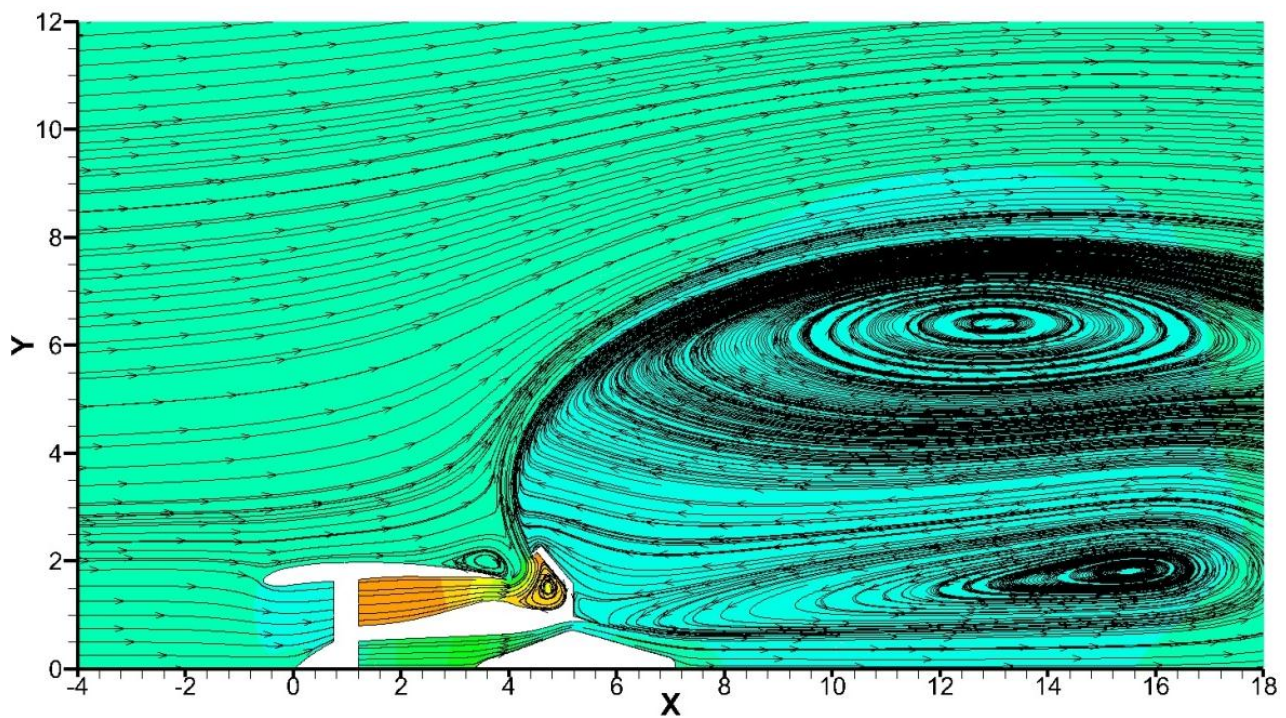
Configuration; $D_{rev} = 1.954\text{m}$, $L = 1.037\text{m}$, Reverser Area = 12.23m^2



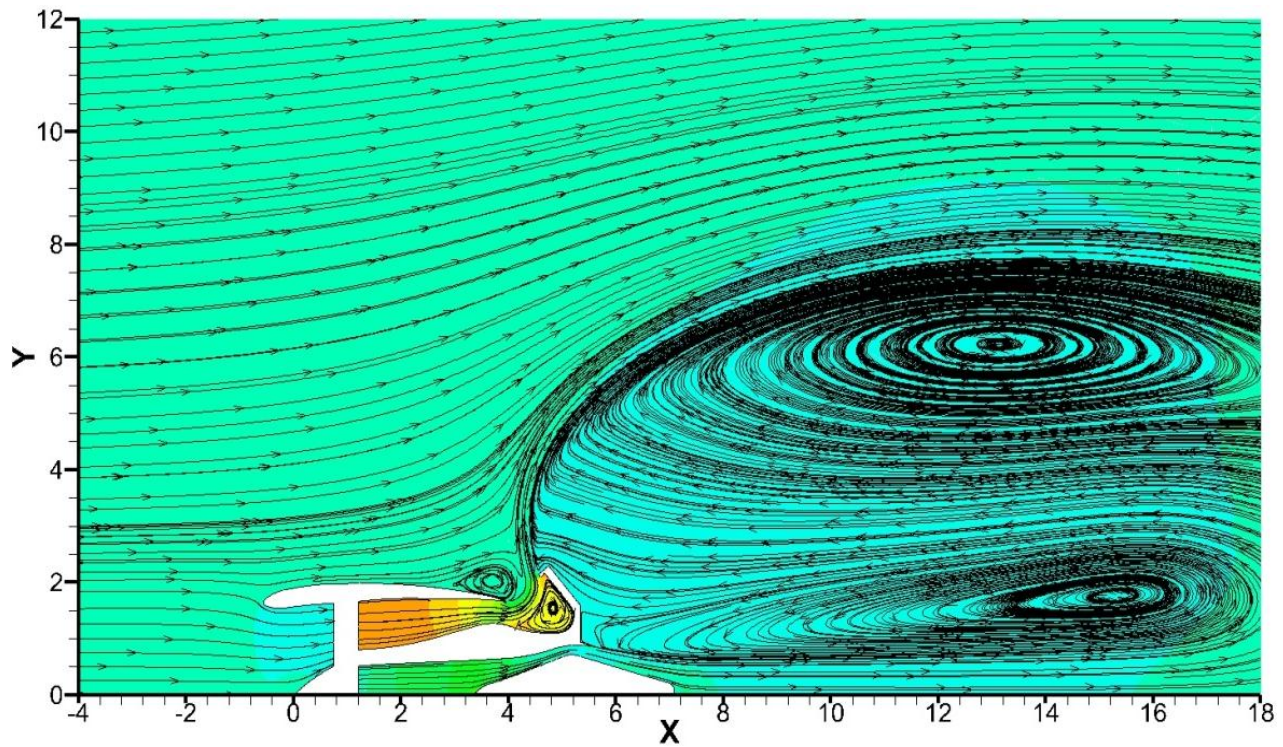
Configuration; $D_{rev} = 2.117\text{m}$, $L = 0.287\text{m}$, Reverser Area = 6.695m^2



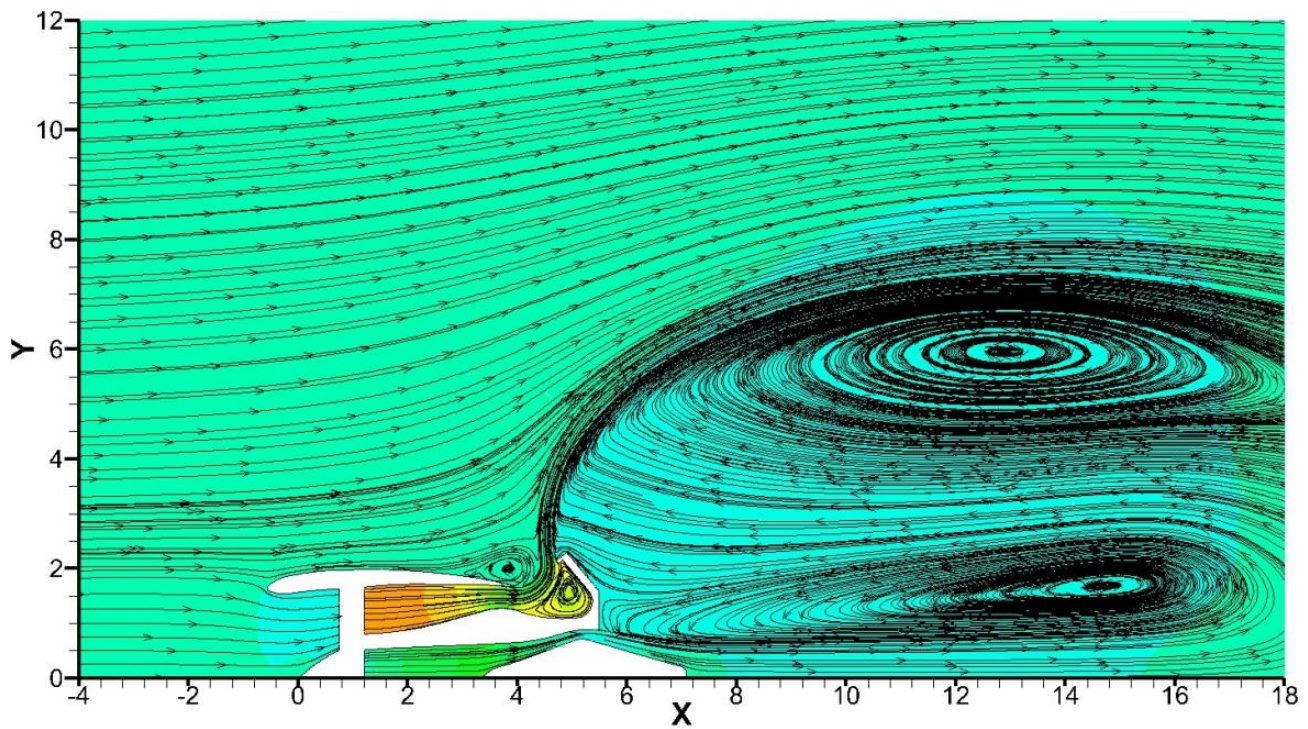
Configuration; $D_{rev} = 2.117\text{m}$, $L = 0.437\text{m}$, Reverser Area = 7.716m^2

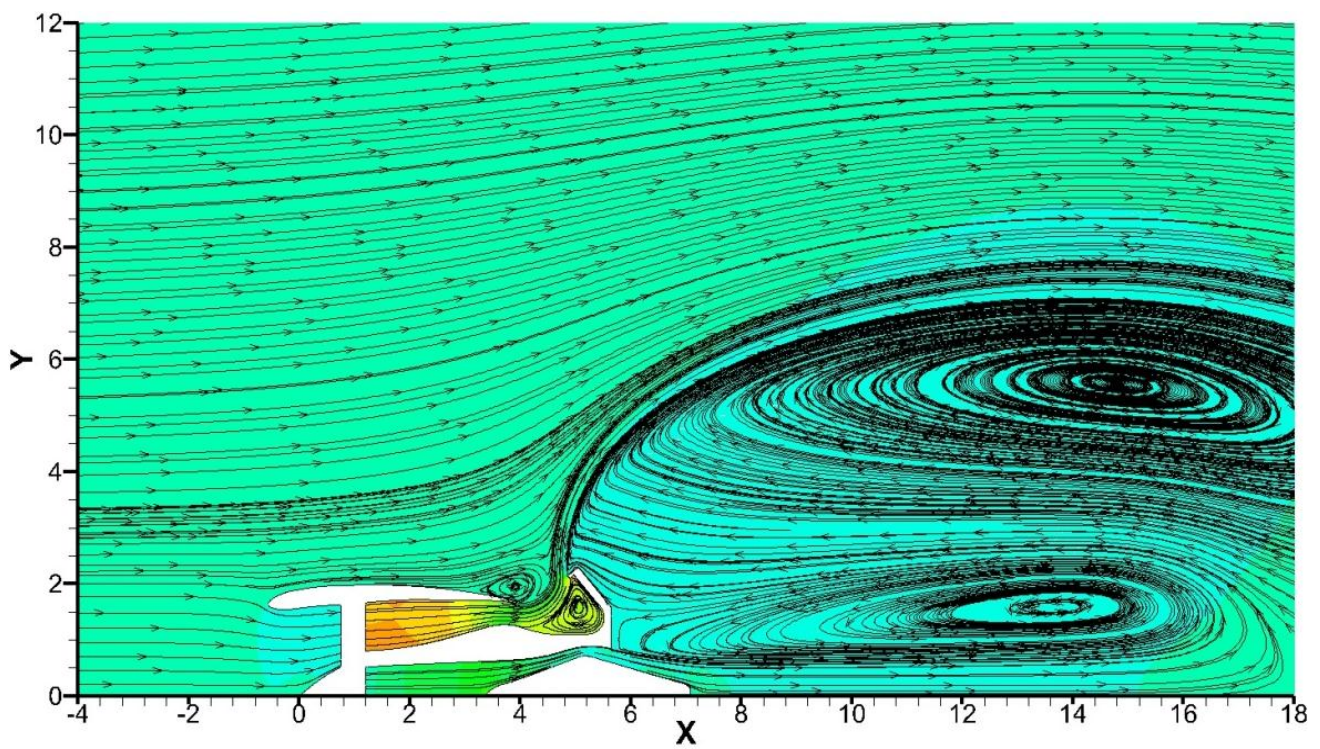
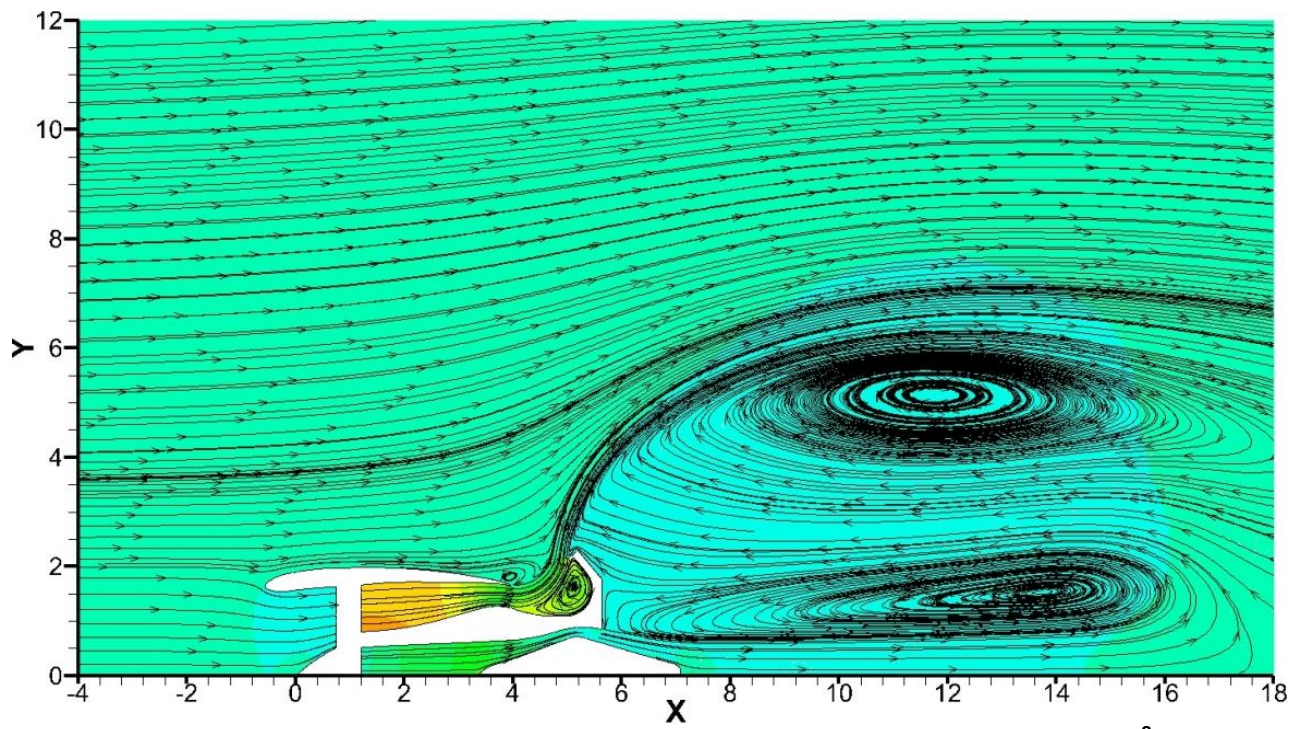


Configuration; $D_{rev} = 2.117\text{m}$, $L = 0.587\text{m}$, Reverser Area = 8.990m^2

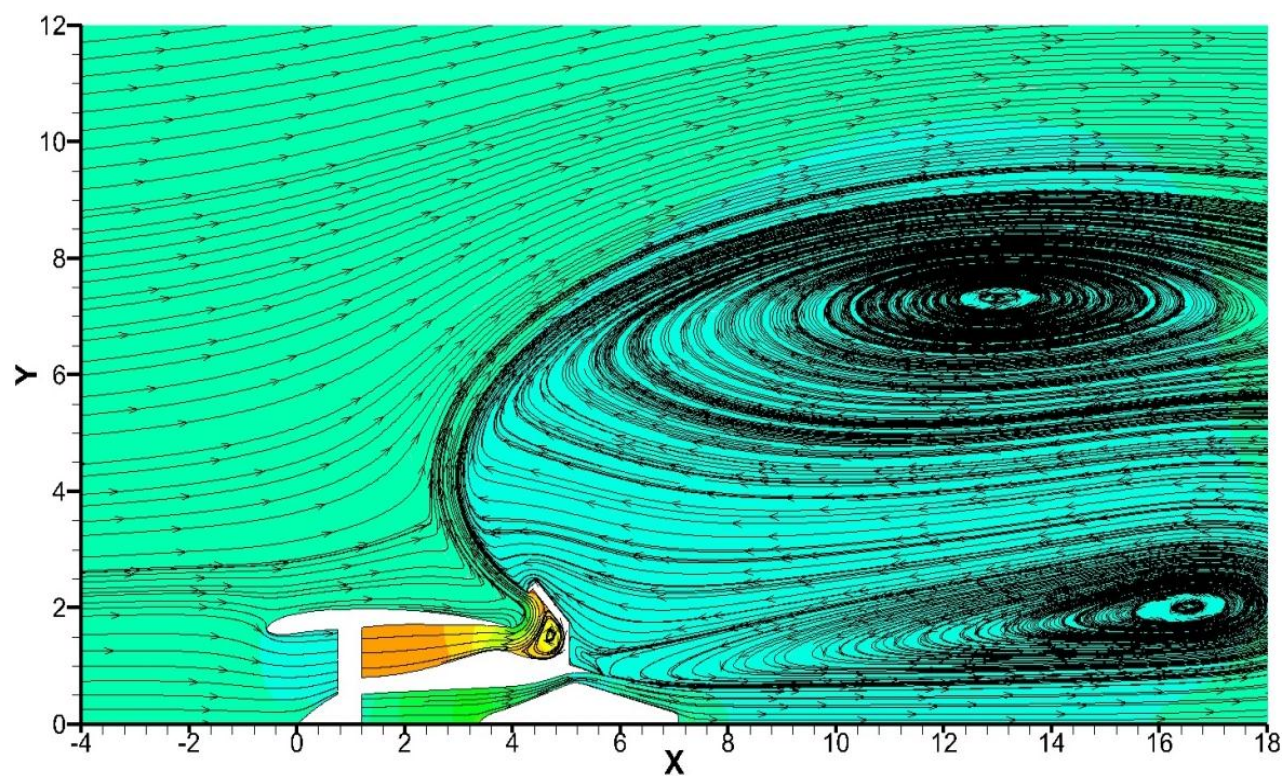


Configuration; $D_{rev} = 2.117\text{m}$, $L = 0.737\text{m}$, Reverser Area = 10.408m^2

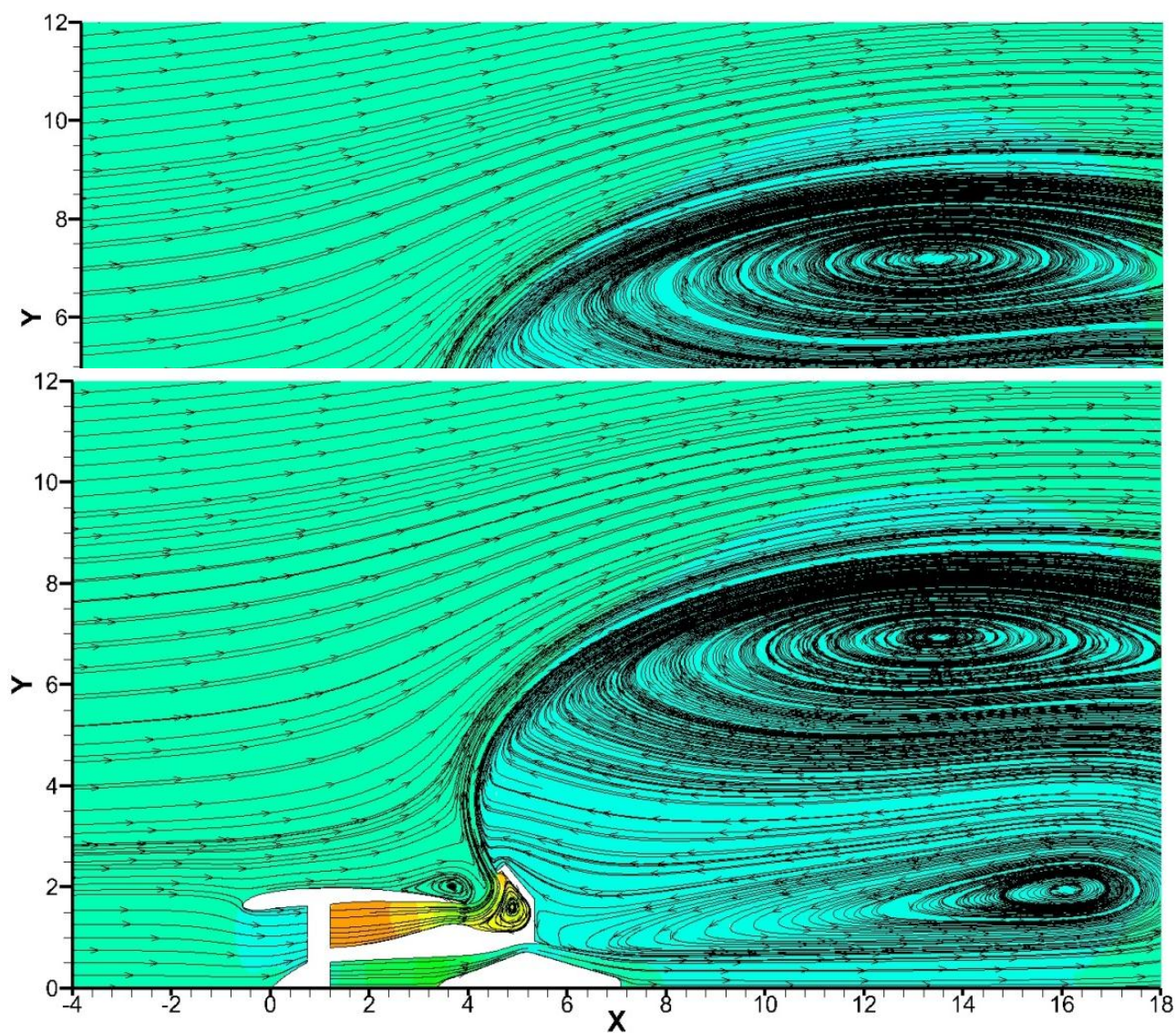




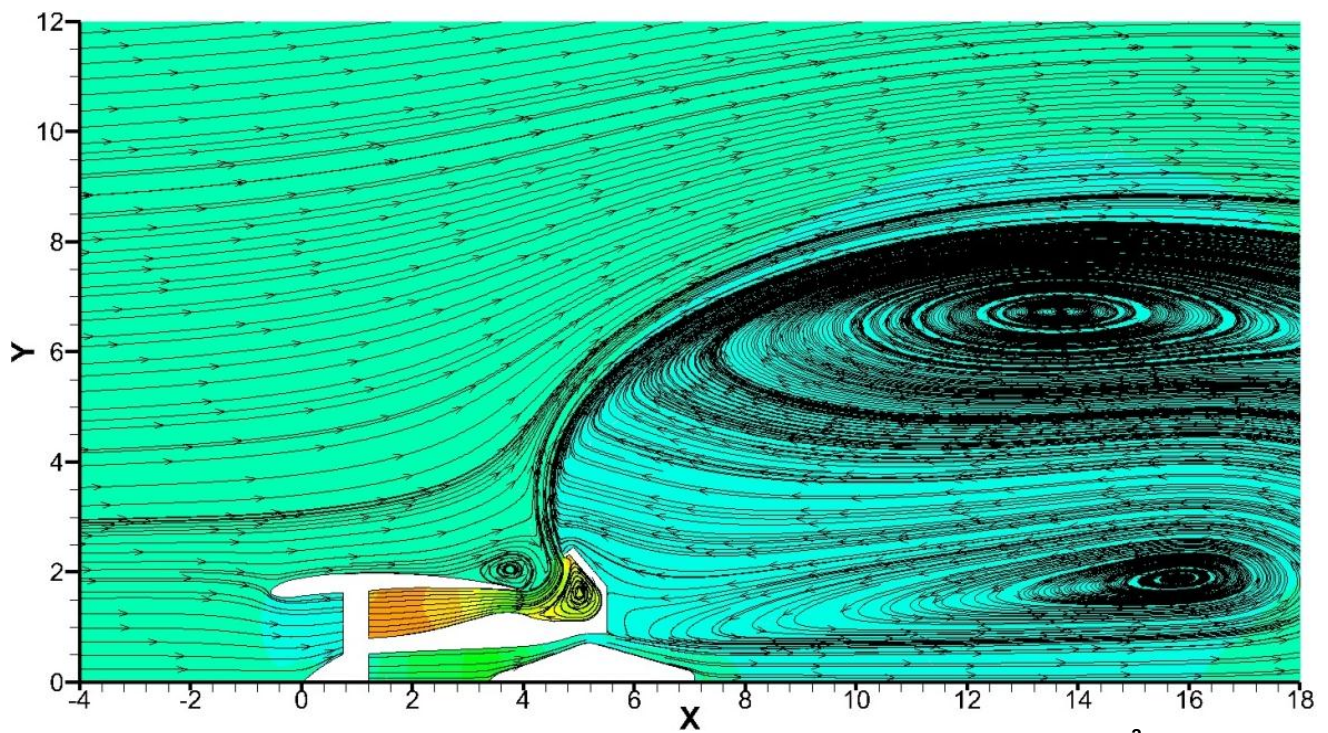
Configuration; $D_{rev} = 2.280\text{m}$, $L = 0.287\text{m}$, Reverser Area = 8.743m^2



Configuration; $D_{rev} = 2.280\text{m}$, $L = 0.437\text{m}$, Reverser Area = 9.635m^2

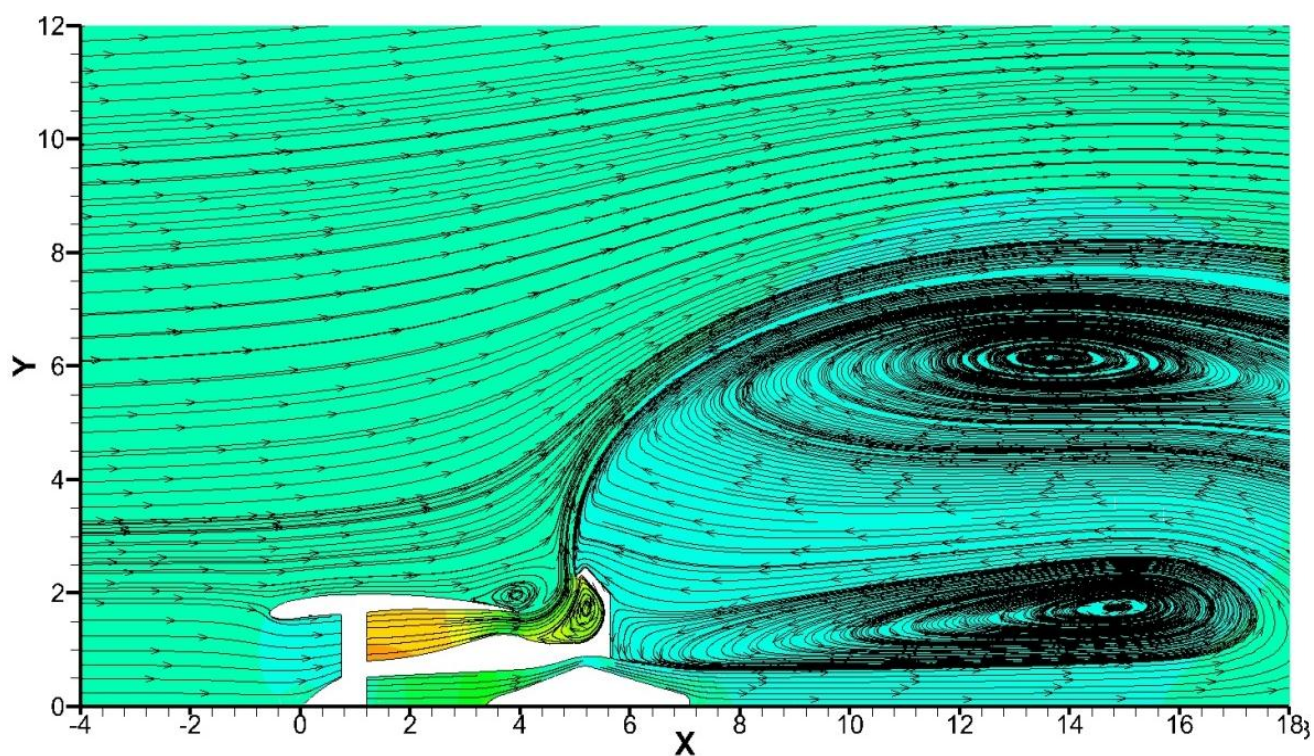


Configuration; $D_{rev} = 2.280\text{m}$, $L = 0.737\text{m}$, Reverser Area = 12.081m^2

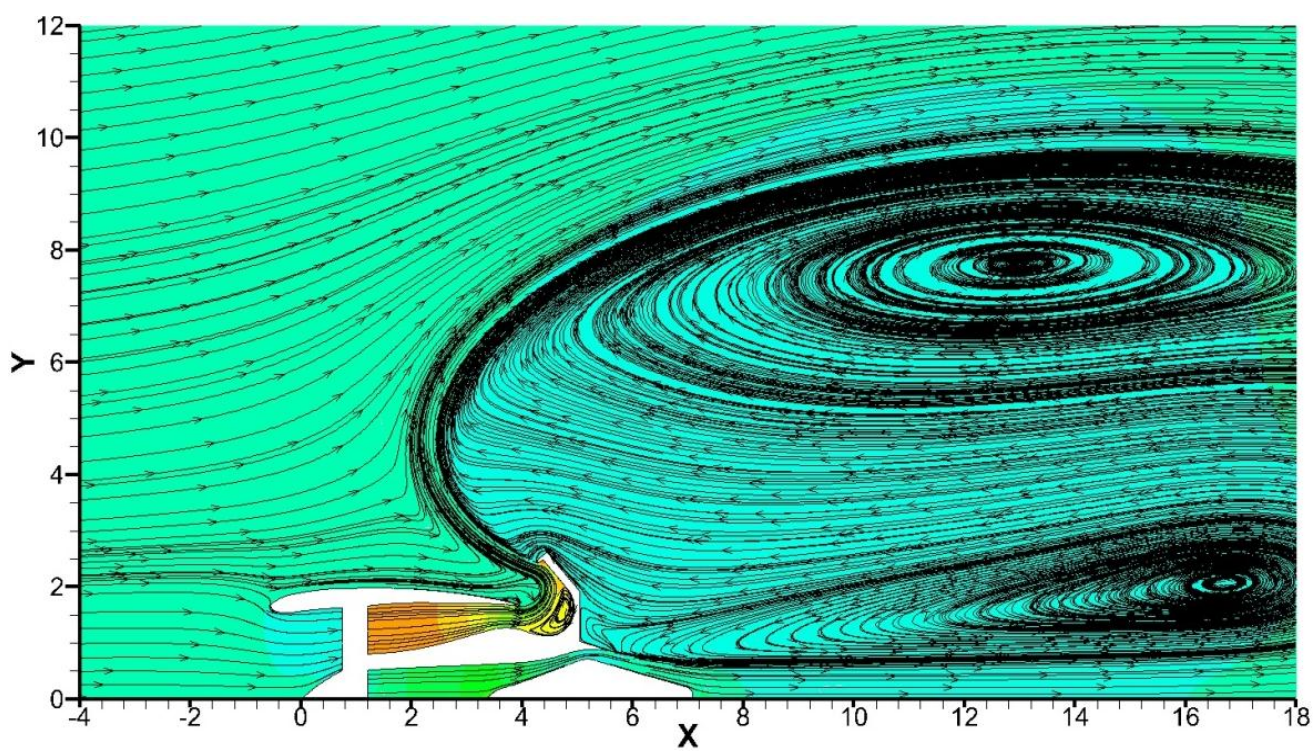


Configuration; $D_{rev} = 2.280\text{m}$, $L = 0.887\text{m}$, Reverser Area = 13.516m^2

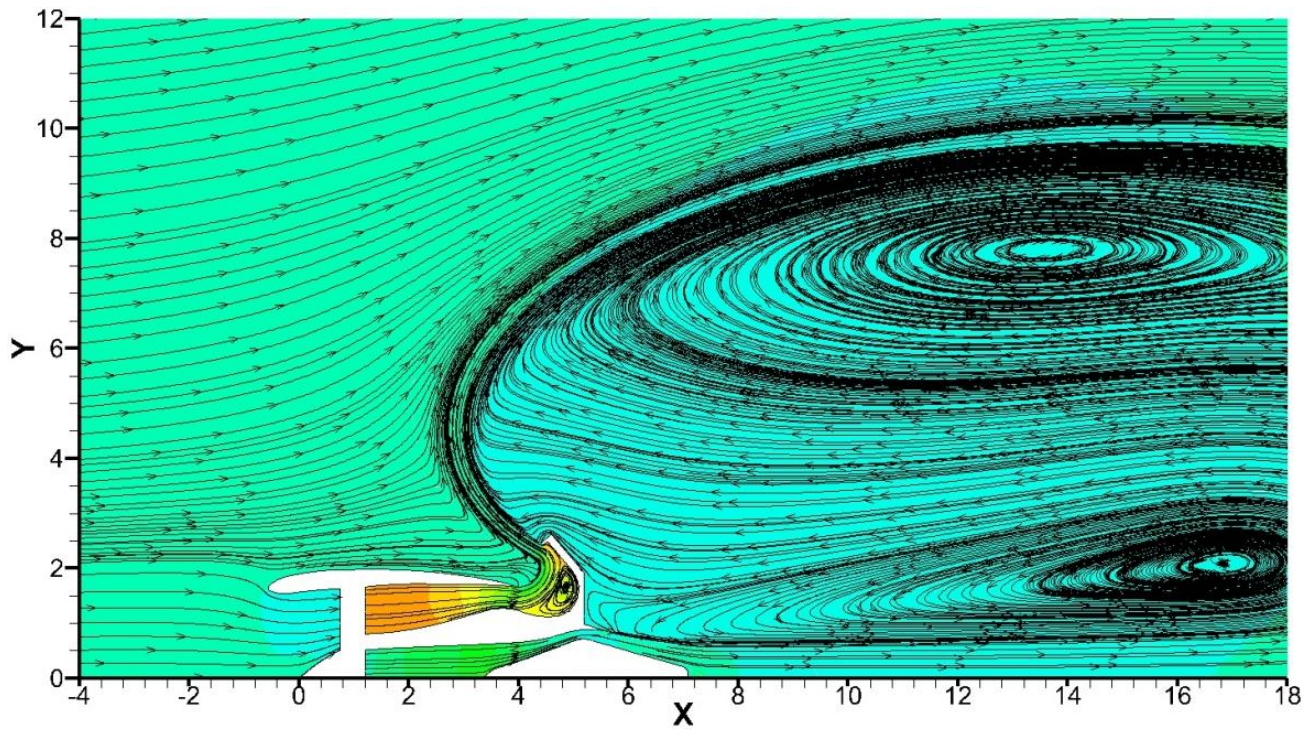
Configuration; $D_{rev} = 2.280\text{m}$, $L = 1.037\text{m}$, Reverser Area = 15.041m^2



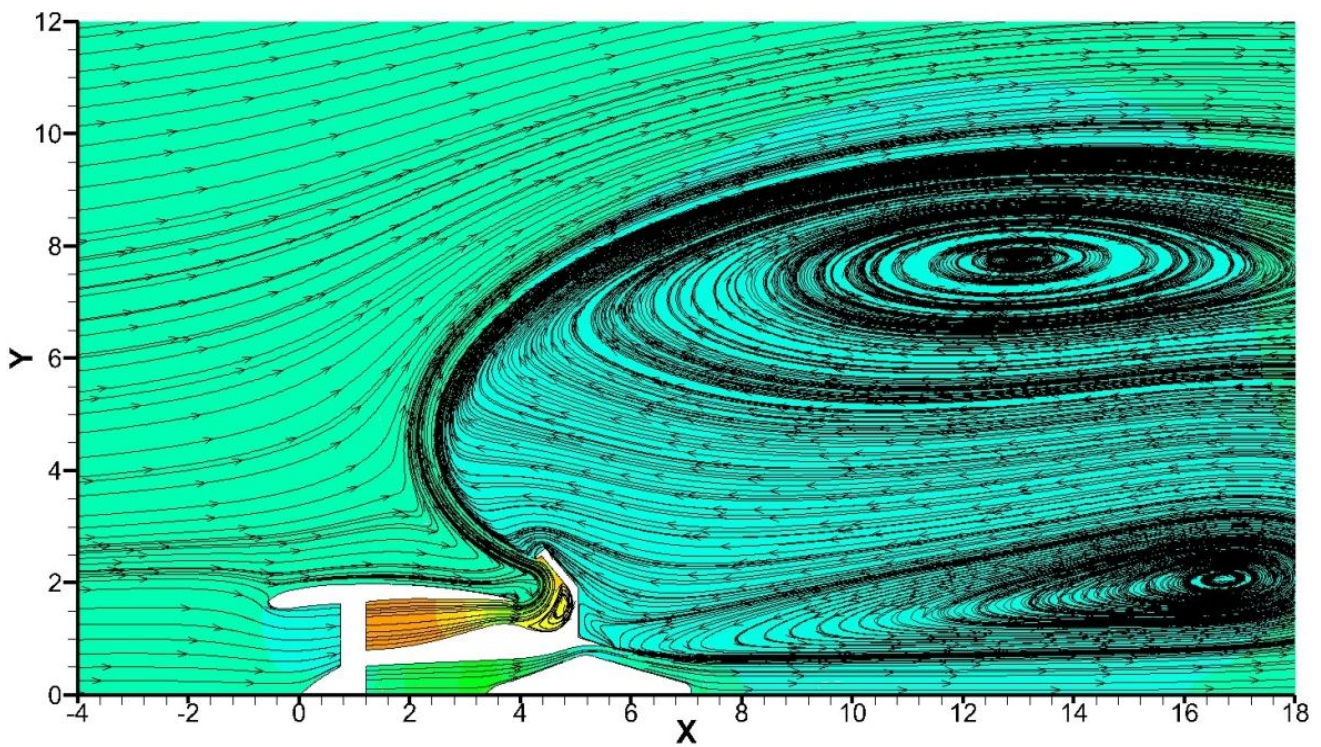
Configuration; $D_{rev} = 2.443\text{m}$, $L = 0.287\text{m}$, Reverser Area = 11.046m^2



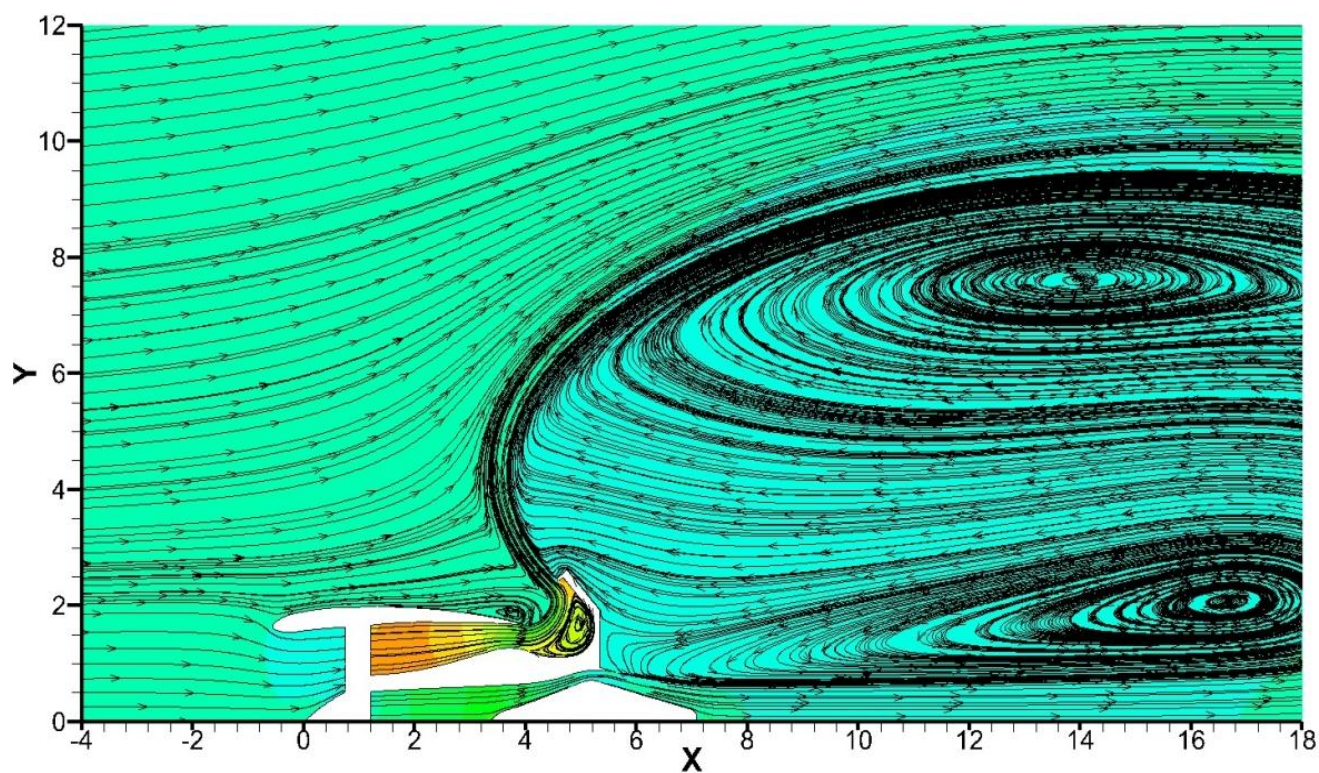
Configuration; $D_{rev} = 2.443\text{m}$, $L = 0.287\text{m}$, Reverser Area = 11.046m^2



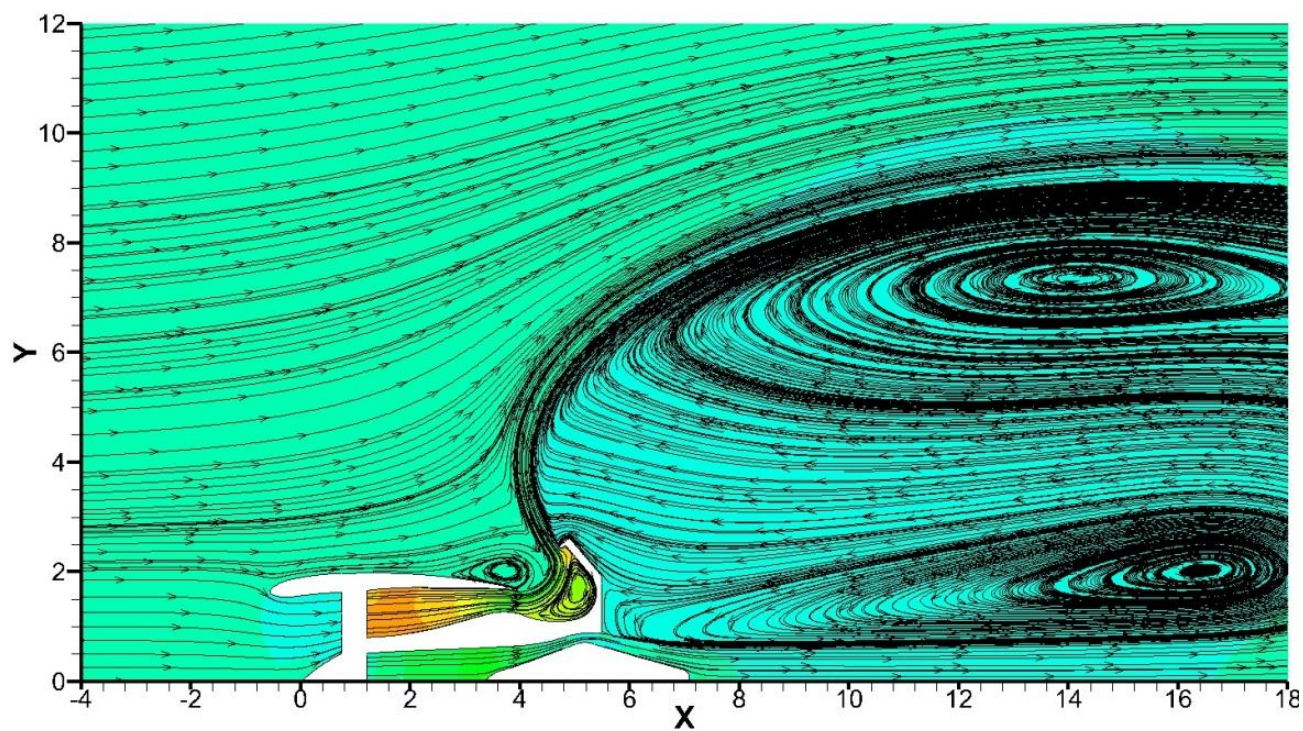
Configuration; $D_{rev} = 2.443\text{m}$, $L = 0.437\text{m}$, Reverser Area = 11.824m^2



Configuration; $D_{rev} = 2.443\text{m}$, $L = 0.587\text{m}$, Reverser Area = 12.843m^2



Configuration; $D_{rev} = 2.443\text{m}$, $L = 0.737\text{m}$, Reverser Area = 14.052m^2



Configuration; $D_{rev} = 2.443\text{m}$, $L = 0.887\text{m}$, Reverser Area = 15.404m^2

