



AEROSPACE INFORMATION REPORT

AIR5450

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Advanced Ducted Propulsor In-Flight Thrust Determination

RATIONALE

AIR5450 has been reaffirmed to comply with the SAE five-year review policy.

INTRODUCTION

Prior to 1978, there were no industry or government standards for determining in-flight thrust. In 1978, the SAE Propulsion Division and the Aerospace Council organized a group of knowledgeable experts into the SAE E-33 Committee to address this subject on a technical basis. In 1985 the Committee published AIR1703, which discussed methodologies and examples of in-flight thrust determination for low bypass turbofan engines and a companion document, AIR1678, which addressed the process for estimating uncertainty of in-flight thrust. Since then, the E-33 Committee and its Subcommittees have published a series of documents on the subject:

1986: SP-674 - In-flight Thrust Determination and Uncertainty

This document contains both AIR1703 and AIR1678 with six explanatory papers containing examples of using the methodologies and other explanatory material.

1993: AIR4065 - Propeller/Propfan In-flight Thrust Performance

This document addresses in-flight thrust determination issues particular to propeller powered aircraft.

1998: AIR4979 - Estimation of Measurement Uncertainty in Engine Tests Based on NATO AGARD Uniform Engine Test Program

This document describes a "round robin" test program to determine typical bias/systematic errors associated with world class engine test facilities in North America and Europe. The document describes test results relating to facility random and systematic measurement uncertainty determined from comparison testing of a J-57 engine in various altitude (ATF) and sea level (GLTF) test facilities.

1998: AIR5020 - Time Dependant In-flight Thrust Determination

This document addresses use and limitation of using time dependant "quasi-steady" measurements made during aircraft maneuvers to determine in-flight thrust

2000: AIR1678A - A refined update of the original AIR1678 consistent with other world standards (ASME PTC-19.1)

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Documents
Document Sharing Hub

2007: AIR5925 - Measured Uncertainty Applied to Cost Effective Testing

This document addresses utilization of uncertainty methodology to reduce test costs by choosing optimum instrumentation and measurement techniques.

The E-33 Committee is also in the process of revising one AIR document:

AIR1703A - In-flight Thrust Determination

This document is a revision of the original AIR1703 to make the presentation and format clearer and easier to understand, based on input from users. It also modernizes and expands the examples and other explanatory material.

The current document (AIR5450) and all of the above documents have been written to be “stand alone”, and each is useful in its own right. The methods and processes described in them have been widely used throughout the industry, in the United States and around the world. They are, however, closely interconnected, and together, provide a broad coverage of the in-flight thrust and uncertainty determination processes. They are all consistent in fundamental methodologies and processes. They provide information to arrive at a sound process to determine in-flight thrust/uncertainty for the various types of powerplants propelling modern aircraft.

The purpose of the current document is to present information and guidance on the selection of methods (including the effects on uncertainty) to predict and assess propulsion system thrust during flight development programs of Advanced Ducted Propulsor (ADP) engines. The document is intended to be a technical guide, but not a standard or legal document. It presents a variety of test options and correlation methods for thrust determination that may be considered for the new generation of high bypass ratio, low fan pressure ratio Advanced Ducted Propulsor (ADP) turbofan engines. These potentially larger high bypass ratio engines may preclude the use of conventional testing methods and facilities. Thrust determination methods for turbojets and lower bypass ratio turbofans were documented in AIR1703, and open rotor propeller/propfan in-flight thrust determination was addressed in AIR4065. There are several distinctly different methods that can be used for these two categories of propulsion systems. The ADP thrust characteristics fall between these extremes. The intention of this document is to provide information on the options available for ADP thrust determination, and an assessment of the various thrust correlating methods unique to the ADP. The reader will note that frequent references are made to AIR1703 and AIR4065 because, depending on size and circumstance, those methods can still be appropriate, and the detailed descriptions are omitted herein.

FOREWORD

The technology advances and the demand for more efficient transport airframe/propulsion systems have led to the evolution of the Advanced Ducted Propulsor (ADP). Increases in propulsive efficiency have been most important in the changes in overall efficiency (by approximately a factor of two) from the earlier turbojets and turbofans to the current and future high bypass ratio engines. Although no dividing line between ADP engines and conventional turbofan engines exists, ADP engines are characterized as having much higher bypass ratios (>10) and much lower fan pressure ratios (<1.5) than conventional turbofan engines. Two distinctive features common to many ADP engines are a geared fan drive and some form of variable geometry (variable nozzle area or variable pitch fan blades). Because of the lower fan pressure ratios and higher airflows, significant changes in the fan operating characteristics may arise due to Mach number and installation effects. Furthermore, increased thrust sensitivity to measurement uncertainties requires improved thrust determination methods and test techniques. Ideally these methods need to address the airframe effects on the engine installed performance for the determination of both cruise thrust and low speed thrust.

The ADP operating characteristics present additional new problems relative to accurate in-flight thrust determination. The larger ADP configurations may be too large for existing indoor and altitude test facilities. Some of the new problems are related to the very large size of these engine systems that can have twice the airflow and be 50 percent larger than conventional turbofans for the same thrust (see Figure 1). This makes them difficult to install without creating aerodynamic interference and nacelle/wing interactions that could affect wing performance, engine operation, and in-flight thrust determination. Engine-out aerodynamic drag is high due to the large engine and nacelle cross sectional area. The large engine diameter, with potentially high scrubbed friction area, requires a short inlet that may lead to inlet distortion affecting airflow and fan exhaust pressures used for in-flight thrust determination.

Large, long-range transports are being developed and larger ones are being studied which require very high thrust levels that exceed 100,000 lb thrust. ADP engines at this thrust level can exceed 15 ft in diameter and 6,000 lb/s in corrected air flow as shown in Figure 1. These size and airflow levels greatly stretch or exceed the current full-scale altitude test facility capabilities and may require facility modification or further development to accommodate this engine size. Or, alternatively, new thrust determination methods must be considered.

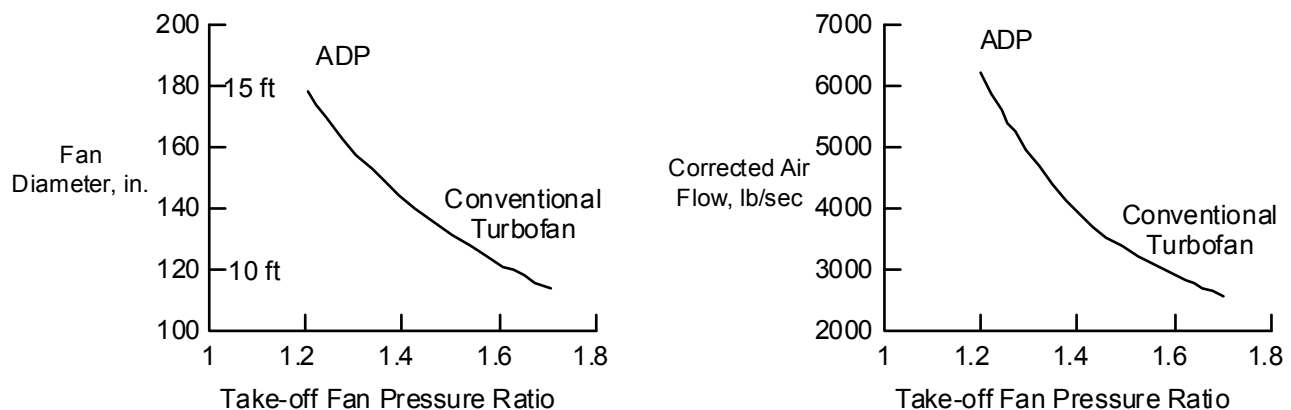


FIGURE 1 - APPROXIMATE FAN DIAMETER AND AIR FLOW TO MEET
100,000 LB TAKE-OFF THRUST

The test altitude and airflow envelopes of three major full-scale engine Altitude Test Facilities (ATF) are shown in Figure 2. Typical climb airflow operating conditions for engines with fan diameters of 110 to 160 in are also shown. The Wilgoos and Pyestock (now closed) facility capabilities are exceeded for engine fan diameters larger than about 110 in. For typical climb airflows, the AEDC facility will suffice at typical transport cruise altitudes (30,000 to 35,000 ft) for 110 to 140 in engines, but will be inadequate for the 160 in engine. The typical climb operating conditions used in Figure 2 are compared in Figure 3 with the flight envelope of a typical long range transport aircraft; potential maximum operating conditions are identified. Engine airflow at these maximum conditions will be higher than shown in Figure 2 and thus the applicability of existing ATFs will be further limited. Alternative calibration and correlation methodologies need to be developed since developing the appropriate altitude test facility and capability would be extremely costly, and the associated cost of testing would also be extremely high.

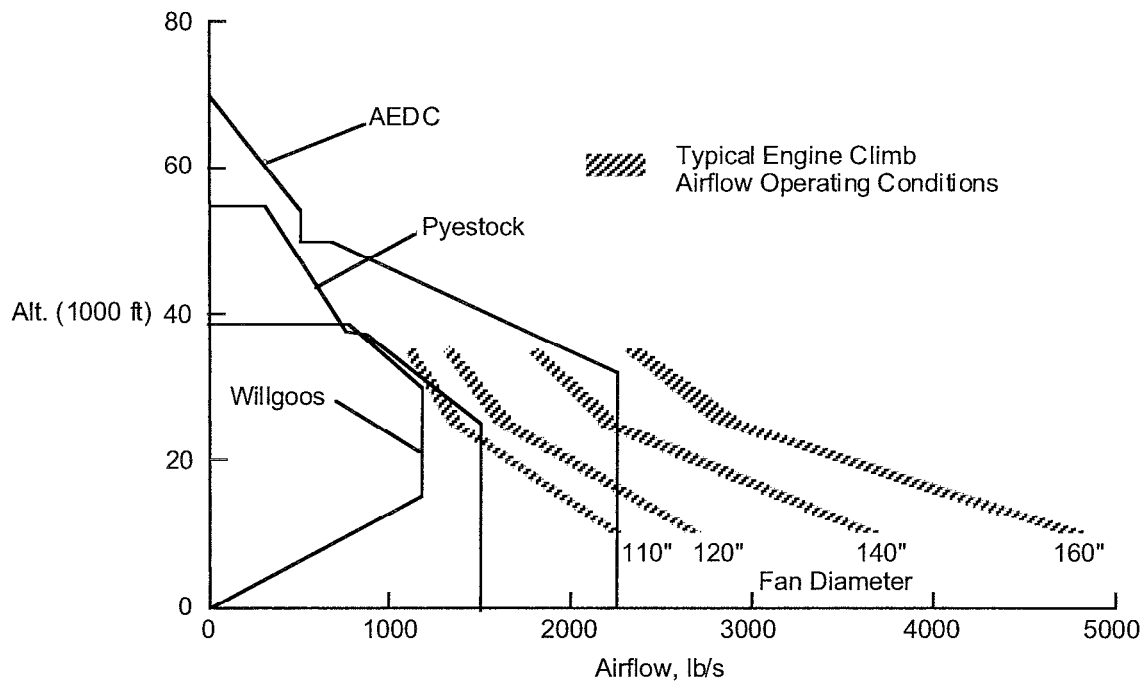


FIGURE 2 - ATF TEST ENVELOPES COMPARED WITH POTENTIAL ADP AIRFLOW REQUIREMENTS

Relative to conventional turbofan engines, ADP engines are potentially more sensitive to external flow field effects. Operating line shifts will affect the exit profiles and pressure losses that have significantly greater effects on ADP in-flight thrust determination than for conventional turbofan engines where the shift is much less. Maximum airflow occurs at take-off for conventional turbofans while it occurs at maximum climb for the ADP. This makes full-flow static testing difficult for ADP engines without inlet air conditioning or waiting for cold weather.

The difficulty of determining and correlating thrust coefficient for ADP in-flight thrust determination is exacerbated by the low fan nozzle-pressure-ratios of these engine systems. The sensitivity of ADP thrust to pressure measurement at sea level take-off is nearly three times that of a conventional turbofan. In addition, due to the low fan pressure ratio at cruise, the gross to net thrust ratio is 3:1 to 4:1 for the ADP as compared to 2:1 to 2.5:1 for the conventional turbofan, which makes the task of accurately determining ADP in-flight thrust more difficult.

In the following sections this document explores a number of options for in-flight thrust determination of an ADP, and indicates potential accuracy of the methods. The determination of in-flight thrust is a complex task that depends upon careful planning and meticulous attention to detail throughout the test program. It is important that the participants involved (engine and airframe manufacturers, military service, government agency, commercial customer, etc.) agree at the outset on the definitions and the methods to be used for demonstration. Provision for flexibility and redundant methods are important to provide for unforeseen difficulties with a particular method.

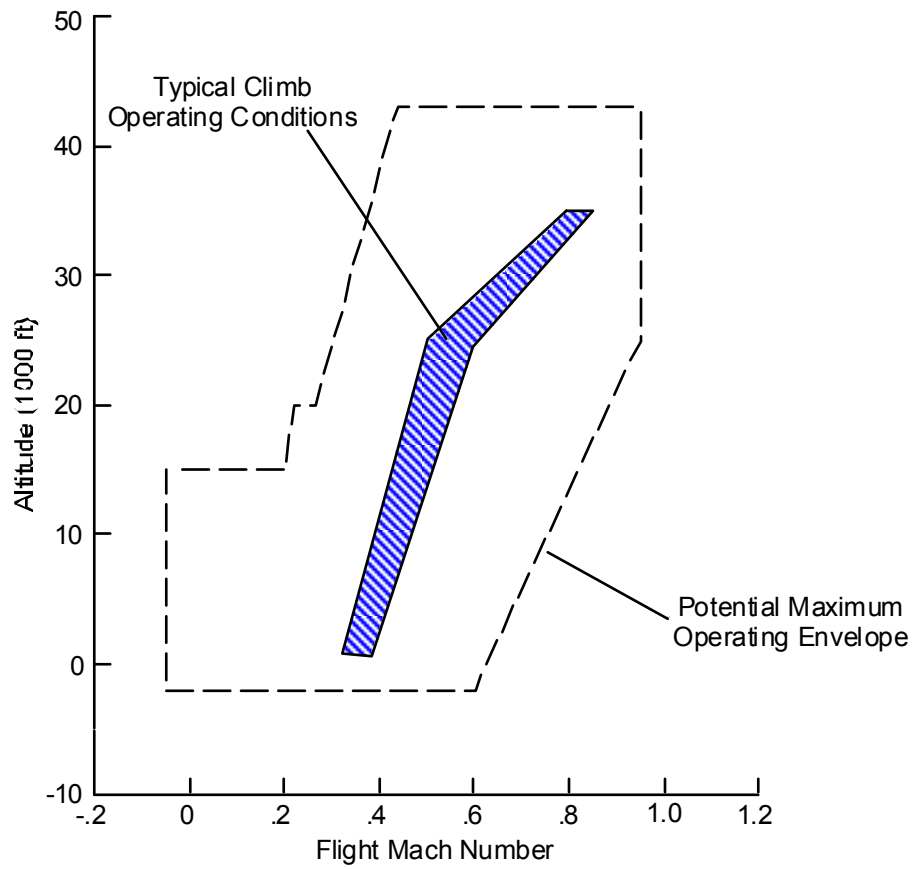


FIGURE 3 - TYPICAL TRANSPORT FLIGHT ENVELOPE WITH CLIMB OPERATING CONDITIONS NOTED

TABLE OF CONTENTS

1.	SCOPE	11
1.1	Document Roadmap	11
2.	REFERENCES AND NOMENCLATURE	13
2.1	Applicable Documents	13
2.1.1	SAE Publications	13
2.2	Related Publications	13
2.2.1	AGARD Publications	13
2.2.2	AIAA Publications	13
2.2.3	Air Force Flight Dynamics Laboratory Publications	14
2.2.4	Sighard F. Hoerner Publication	14
2.2.5	Book distributed by the School of Engineering, University of Dayton, Dayton, Ohio 45469	14
2.2.6	SAE Publications	14
2.2.7	NASA Publications	14
2.3	Nomenclature	15
3.	DEFINITIONS AND METHODOLOGY	22
3.1	Dual-Stream (ADP) Engine Thrust	23
4.	ENGINE CONCEPTUAL DESIGN AND CONFIGURATIONS	28
4.1	Propulsion Design	28
4.2	Configuration Examples	32
4.2.1	Configuration Evolution	33
4.3	Specific Configuration Examples	34
4.3.1	Pratt & Whitney Configuration	34
4.3.2	General Electric Configuration	35
4.3.3	Allison Configuration	35
4.3.4	Pratt & Whitney Canada Corp.'s (P&WC) Configuration	37
5.	INSTALLATION CONSIDERATIONS	38
5.1	Installation Effects on the Airframe	40
5.1.1	Wing Mounted Installations	40
5.1.2	Aft Fuselage-Mounted Installations	44
5.2	Installation Effects on the Powerplant	44
5.3	Implications on In-Flight Thrust Determination and Testing	45
6.	THRUST METHOD OPTIONS	45
6.1	Overall Performance Methods	47
6.1.1	Thrust-Low Rotor Speed Correlation	47
6.1.2	Thrust-Fuel Flow Correlation	51
6.1.3	Thrust-Low Pressure Turbine Inlet EPR (Core EPR or CEPR) Correlation Using ATF	55
6.1.4	Thrust-Low Pressure Shaft Torque Correlation Using ATF	59
6.2	Gas Path/Nozzle Methods	63
6.2.1	Exhaust Nozzle Coefficients Using ATF	63
6.2.2	Compound Flow Analysis Methodology Comments	83
6.2.3	Gas Path/Nozzle Method Using GLTF and Residual Error	83
6.2.4	Static Pressure Correlation Option	93
6.3	Simulator Methods	97
6.3.1	Turbine Powered Simulator in an ATF	99
6.3.2	Turbine Powered Simulator in a Wind Tunnel	99
6.4	Use of Cycle Models for In-Flight Thrust Determination	100
6.4.1	Analysis Techniques Using Analysis and Synthesis Methods (AnSyn)	101
6.4.2	Traditional Method – Test Bed Analysis (TBA) Calculations	101
6.4.3	Cycle Match Method	102
6.4.4	Use of AnSyn Analysis to Correct Data	104
6.4.5	User's Perspective	104
6.4.6	Advantages Over Traditional TBA	105
6.4.7	Advantages for Engine Diagnostics	106
6.4.8	Cycle Model Accuracy and Sensitivity	106
6.5	Power Management Considerations	106
6.5.1	Control Parameter and Measurement Uncertainty	106

6.5.2	Control Parameter Selection and Production Variability.....	107
6.5.3	Summary.....	108
7.	AERODYNAMIC AND PROPULSION TESTING	108
7.1	Scale-Model Testing	108
7.1.1	Aerodynamic Model Testing	108
7.1.2	Propulsion Model Testing	111
7.1.3	Model Data Build-Up to Full-Scale.....	126
7.2	Engine Ground Test.....	127
7.2.1	Validation of Ground Test Facility.....	128
7.2.2	Simulation of Flight Test Environment.....	128
7.3	Engine Altitude Testing	130
7.3.1	Test Configurations.....	132
7.3.2	Test Measurements	133
7.3.3	Measurement Uncertainty.....	134
7.3.4	Data Acquisition/Processing System	135
8.	IN-FLIGHT THRUST VALIDATION	136
8.1	Engine Model Validation	137
8.1.1	Pre Flight Test Model.....	138
8.1.2	Engine Personalization	138
8.1.3	Bleed Effects and Power Offtakes	138
8.1.4	Post Flight Test Model	139
8.2	Total Airplane Considerations.....	139
8.2.1	Flight Test Techniques.....	139
8.2.2	Steady-State Maneuvers	140
8.2.3	Quasi-Steady-State Maneuvers.....	140
8.2.4	Dynamic Maneuvers	141
8.3	Thrust/Drag Closure.....	141
9.	THRUST UNCERTAINTY ANALYSIS	141
9.1	Error Propagation.....	142
9.2	Influence Coefficients-Propagation of Uncertainty Components.....	142
9.2.1	Correlated Effect Assumptions	144
9.3	Engine Model	147
9.4	Measurement and Math Model Uncertainty.....	155
9.5	Net Thrust Uncertainty- Method Comparison and Discussion	157
10.	OTHER OPERATING MODES REQUIRING CONSIDERATION	159
10.1	Engine-Out Thrust-Minus-Drag.....	159
10.1.1	Flight Testing.....	159
10.1.2	Analytical Methods.....	159
10.1.3	Subscale Rig Testing	163
10.2	Reverse Thrust Operation.....	169
10.2.1	Thrust Reverser Use.....	170
10.2.2	ADP Thrust Reverser Candidates	172
10.2.3	Determination of Reverse Thrust.....	175
APPENDIX A	ADP IN FLIGHT THRUST CALCULATION, BPR = 6.....	180
APPENDIX B	ADP IN FLIGHT THRUST CALCULATION, BPR = 12.....	187
APPENDIX C	ADP IN FLIGHT THRUST CALCULATION, BPR = 15.....	194
APPENDIX D	GENERALIZED THRUST – LOW ROTOR SPEED ($N_{1,R}$) COORELATION USING ATF BYPASS RATIO 6 ENGINE AT CRUISE CONDITIONS	201
APPENDIX E	GENERALIZED THRUST – LOW ROTOR SPEED ($N_{1,R}$) COORELATION USING ATF BYPASS RATIO 12 ENGINE AT CRUISE CONDITIONS	206

APPENDIX F	GENERALIZED THRUST – LOW ROTOR SPEED ($N_{1,R}$) COORELATION USING ATF BYPASS RATIO 15 ENGINE AT CRUISE CONDITIONS	211
APPENDIX G	GENERALIZED THRUST – LOW ROTOR SPEED ($N_{1,R}$) COORELATION USING ATF BYPASS RATIO 6 ENGINE AT TAKEOFF CONDITIONS	216
APPENDIX H	GENERALIZED THRUST – LOW ROTOR SPEED ($N_{1,R}$) COORELATION USING ATF BYPASS RATIO 12 ENGINE AT TAKEOFF CONDITIONS	221
APPENDIX I	GENERALIZED THRUST – LOW ROTOR SPEED ($N_{1,R}$) COORELATION USING ATF BYPASS RATIO 15 ENGINE AT TAKEOFF CONDITIONS	226
APPENDIX J	GENERALIZED THRUST – FUEL FLOW ($W_{F,R}$) COORELATION USING ATF BYPASS RATIO 6 ENGINE AT CRUISE CONDITIONS	231
APPENDIX K	GENERALIZED THRUST – FUEL FLOW ($W_{F,R}$) COORELATION USING ATF BYPASS RATIO 12 ENGINE AT CRUISE CONDITIONS	236
APPENDIX L	GENERALIZED THRUST – FUEL FLOW ($W_{F,R}$) COORELATION USING ATF BYPASS RATIO 15 ENGINE AT CRUISE CONDITIONS	241
APPENDIX M	GENERALIZED THRUST – FUEL FLOW ($W_{F,R}$) COORELATION USING ATF BYPASS RATIO 6 ENGINE AT TAKEOFF CONDITIONS	246
APPENDIX N	GENERALIZED THRUST – FUEL FLOW ($W_{F,R}$) COORELATION USING ATF BYPASS RATIO 12 ENGINE AT TAKEOFF CONDITIONS	251
APPENDIX O	GENERALIZED THRUST – FUEL FLOW ($W_{F,R}$) COORELATION USING ATF BYPASS RATIO 15 ENGINE AT TAKEOFF CONDITIONS	256
APPENDIX P	GENERALIZED THRUST – CORE ENGINE PRESSURE RATIO (CEPR) COORELATION USING ATF BYPASS RATIO 6 ENGINE AT CRUISE CONDITIONS	261
APPENDIX Q	GENERALIZED THRUST – CORE ENGINE PRESSURE RATIO (CEPR) COORELATION USING ATF BYPASS RATIO 12 ENGINE AT CRUISE CONDITIONS	266
APPENDIX R	GENERALIZED THRUST – CORE ENGINE PRESSURE RATIO (CEPR) COORELATION USING ATF BYPASS RATIO 15 ENGINE AT CRUISE CONDITIONS	271
APPENDIX S	GENERALIZED THRUST – CORE ENGINE PRESSURE RATIO (CEPR) COORELATION USING ATF BYPASS RATIO 6 ENGINE AT TAKEOFF CONDITIONS	276

APPENDIX T	GENERALIZED THRUST – CORE ENGINE PRESSURE RATIO (CEPR) COORELATION USING ATF BYPASS RATIO 12 ENGINE AT TAKEOFF CONDITIONS	281
APPENDIX U	GENERALIZED THRUST – CORE ENGINE PRESSURE RATIO (CEPR) COORELATION USING ATF BYPASS RATIO 15 ENGINE AT TAKEOFF CONDITIONS	286
APPENDIX V	GENERALIZED THRUST – TORQUE (TRQ_L) COORELATION USING ATF BYPASS RATIO 6 ENGINE AT CRUISE CONDITIONS	291
APPENDIX W	GENERALIZED THRUST – TORQUE (TRQ_L) COORELATION USING ATF BYPASS RATIO 12 ENGINE AT CRUISE CONDITIONS	296
APPENDIX X	GENERALIZED THRUST – TORQUE (TRQ_L) COORELATION USING ATF BYPASS RATIO 15 ENGINE AT CRUISE CONDITIONS	301
APPENDIX Y	GENERALIZED THRUST – TORQUE (TRQ_L) COORELATION USING ATF BYPASS RATIO 6 ENGINE AT TAKEOFF CONDITIONS	306
APPENDIX Z	GENERALIZED THRUST – TORQUE (TRQ_L) COORELATION USING ATF BYPASS RATIO 12 ENGINE AT TAKEOFF CONDITIONS	311
APPENDIX AA	GENERALIZED THRUST – TORQUE (TRQ_L) COORELATION USING ATF BYPASS RATIO 15 ENGINE AT TAKEOFF CONDITIONS	316
APPENDIX BB	GAS PATH/NOZZLE METHOD USING ATF BYPASS RATIO 6 ENGINE AT CRUISE CONDITIONS	321
APPENDIX CC	GAS PATH/NOZZLE METHOD USING ATF BYPASS RATIO 12 ENGINE AT CRUISE CONDITIONS	326
APPENDIX DD	GAS PATH/NOZZLE METHOD USING ATF BYPASS RATIO 15 ENGINE AT CRUISE CONDITIONS	331
APPENDIX EE	GAS PATH/NOZZLE METHOD USING ATF BYPASS RATIO 6 ENGINE AT TAKEOFF CONDITIONS	336
APPENDIX FF	GAS PATH/NOZZLE METHOD USING ATF BYPASS RATIO 12 ENGINE AT TAKEOFF CONDITIONS	341
APPENDIX GG	GAS PATH/NOZZLE METHOD USING ATF BYPASS RATIO 15 ENGINE AT TAKEOFF CONDITIONS	346
APPENDIX HH	GAS PATH/NOZZLE METHOD USING GLTF AND RESIDUAL ERROR (RERR) BYPASS RATIO 6 ENGINE AT CRUISE CONDITIONS	351
APPENDIX II	GAS PATH/NOZZLE METHOD USING GLTF AND RESIDUAL ERROR (RERR) BYPASS RATIO 12 ENGINE AT CRUISE CONDITIONS	358

APPENDIX JJ	GAS PATH/NOZZLE METHOD USING GLTF AND RESIDUAL ERROR (RERR)	
	BYPASS RATIO 15 ENGINE AT CRUISE CONDITIONS	365
APPENDIX KK	GAS PATH/NOZZLE METHOD USING GLTF AND RESIDUAL ERROR (RERR)	
	BYPASS RATIO 6 ENGINE AT TAKEOFF CONDITIONS	372
APPENDIX LL	GAS PATH/NOZZLE METHOD USING GLTF AND RESIDUAL ERROR (RERR)	
	BYPASS RATIO 12 ENGINE AT TAKEOFF CONDITIONS	379
APPENDIX MM	GAS PATH/NOZZLE METHOD USING GLTF AND RESIDUAL ERROR (RERR)	
	BYPASS RATIO 15 ENGINE AT TAKEOFF CONDITIONS	386

1. SCOPE

The emerging ultra high bypass ratio ADP engines, with nozzle pressure ratios significantly lower, and bypass ratios significantly higher, than those of the current turbofan engines, may present new in-flight thrust determination challenges that are not specifically covered in AIR1703. This document addresses candidate methods and the additional challenges to the thrust determination for these ADP engines.

These novel challenges result in part from the fact that some large ADP engines exceed present altitude test facility capabilities. The traditional methods of nozzle coefficient extrapolation may not be most satisfactory because of the increased error due to the ADP higher ratio of gross to net thrust, and because of the increased sensitivity of in-flight thrust uncertainty at the lower fan nozzle pressure ratio. An additional challenge covered by this document is the higher sensitivity of ADP in-flight thrust uncertainty to the external flow field around the engine, and the changes in this flow field due to aircraft configuration and operations.

Calibrations for in-flight thrust determination for these ADP engines may have to be based on other alternate methods. Recently, large size turbo powered simulators (TPS) of propulsion systems (including the nacelle) have been developed and thus provide a new capability for in-flight thrust determination. Furthermore Computational Fluid Dynamic (CFD) analysis may prove to be a viable supplement to ground (sea level) engine testing and sub-scale model coefficient extrapolations to cruise conditions. These recent developments are described within along with their associated error assessments.

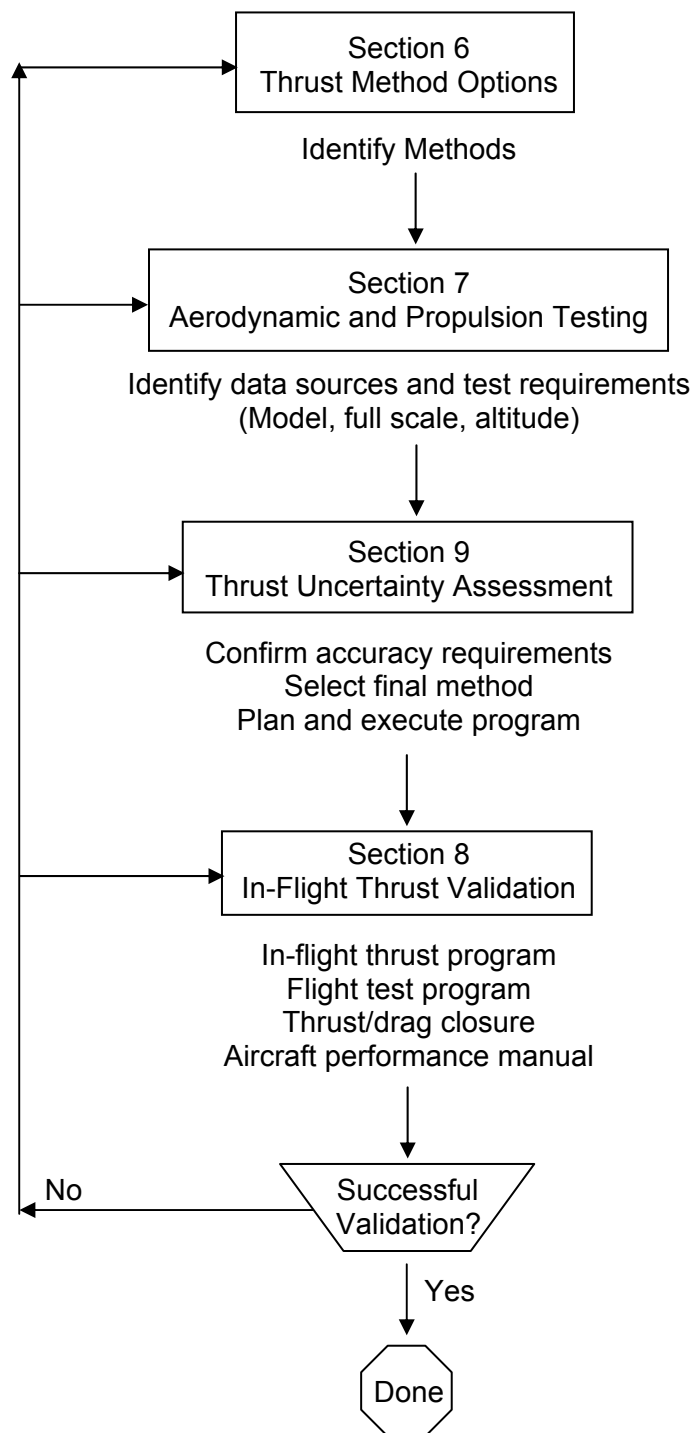
The candidate thrust methods build on the work presented in AIR1703. The document includes a comprehensive uncertainty assessment conducted per AIR1678 to identify the major thrust determination options. Fundamental to this uncertainty assessment are the influence coefficients relating in-flight thrust calculation uncertainty to the measured parameters and derived coefficients. These influence coefficients were developed from three typical public domain, generic engine cycle models.

For the major potential thrust determination options, the overall thrust and airflow calibration processes are defined in detail. Road maps are included showing model, engine and flight-tests, measurements and correlations, calibration procedures and analyses. The document addresses the pros and cons of each of the major thrust determination options, including a discussion of the key assumptions and expected uncertainties.

1.1 Document Roadmap

The following schematic shows how to use this document. The type of thrust method used is dependent on several factors such as: the nature of the program itself and whether it's a new aircraft and engine or a re-engine program; the performance and guarantee requirements; the thrust accuracy required; the available budget; the power management parameter; etc.

Sections 3 through 5 provide methodology and background information relevant to the challenges of integrating an ADP propulsion system into an aircraft. The key engineering activity to determine the validated in-flight thrust performance is focused in Sections 6 through 9.



2. REFERENCES AND NOMENCLATURE

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org.

AS755	Aircraft Propulsion System Performance Station Designation and Nomenclature
AIR1678	Uncertainty of In-Flight Thrust Determination
AIR1703	In-Flight Thrust Determination
AIR4065	Propeller/Propfan In-Flight Thrust Determination
ARP4990	Turbine Flowmeter Fuel Flow Calculations
AIR5020	Time-Dependent In-Flight Thrust Determination
SP-674	In-Flight Thrust Determination and Uncertainty

2.2 Related Publications

The following publications are provided for information purposes only and are not a required part of this SAE Aerospace Technical Report.

2.2.1 AGARD Publications

Available from NASA Center for Aerospace Information (CASI), 800 Elkridge Landing Road, Linthicum Heights, MD 21090-2934.

AGARD-CP-124	A Survey of Drag Prediction Techniques Applicable to Subsonic and Transonic Aircraft Design
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2.2.2 AIAA Publications

Available from American Institute of Aeronautics and Astronautics, 1801 Alexander Bell Drive, Suite 500, Reston, VA 22091.

AIAA-84-0593	Civil Turbofan Propulsion System Integration Studies Using Powered Testing Techniques at ARA, Bedford
AIAA-87-2921	Installation of Innovative Turbofan Engines on Current Transport Airplanes
AIAA-89-2486	Design and Testing of a Common Engine and Nacelle for the Fokker 100 and Gulfstream G-IV Airplanes
AIAA-90-2015	Design and Analysis of a Large-Plug Inlet ADP Nacelle and Pylon
AIAA-90-2146	Analysis of Installed Wind Tunnel Test Results on Large Bypass Ratio Engine/Nacelle Installations

AIAA-93-0528	An Installed Nacelle Design Method Using Multiblock Euler Solver
AIAA-94-2554	Next Generation Propulsion Simulation Equipment for Use in Wind Tunnels
AIAA-95-1820	Inverse Design of Nacelles Using Multi-Block Navier Stokes Codes
AIAA-97-0641	Re-Engineering the Design Process Through Computation
AIAA-98-3112	Model Engine Performance Measurement From Force Balance Measurement (Also published as NASA/TM-1998-208486)

AIAA Progress in Astronautics and Aeronautics, Vol.98 "Thrust and Drag: Its Prediction and Verification"

Raymer, D. P. AIAA Education Series, "Aircraft Design: A Conceptual Approach" 3rd Edition

2.2.3 Air Force Flight Dynamics Laboratory Publications

Available from NTIS, Springfield, VA 22161.

TR-72-136	Rapid Engineering Calculation of Two Dimensional Turbulent Skin Friction
TR-73-144	Development of an Empirically Based Computer Program to Predict the Aerodynamic Characteristics of Aircraft
TR-78-100	Symposium on Transonic Aircraft Technology (TACT)

2.2.4 Sighard F. Hoerner Publication

Available from Dr.-Ing. S. F. Hoerner, 148 Busteed Drive, Midland Park, NJ 07432.

Hoerner Fluid-Dynamic Drag

2.2.5 Book distributed by the School of Engineering, University of Dayton, Dayton, Ohio 45469

Nicolai, L. M. Fundamentals of Aircraft Design

2.2.6 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org.

SAE Paper 861720	Ultra High Bypass Engine Applications to Commercial and Military Aircraft
SAE Paper 912129	Some Practical Aspects of Viscous Drag Reduction Concepts
SAE Paper 942140	PW4084 Engine Testing in Altitude & Sea-Level Test Facilities
SAE Paper 942141	Computational Support to Engine Test

2.2.7 NASA Publications

Available from NASA Center for AeroSpace Information (CASI), 7121 Standard Drive, Hanover, MD 21076-1320.

NASA TM 106575 NEPP Programmers Manual (NASA Engine Performance Program) Volume 1

2.3 Nomenclature

For consistency in nomenclature, the slug, lb, ft, s system is used for U.S. Customary. However, calculations in the appendix tables used the lbm, lb, ft, s system.

Roman	Description	U.S. Customary Units	SI Units
alt	Altitude	ft	m
A	Area	ft ²	m ²
ADP	Advanced Ducted Propulsor	-	-
AnSyn	Analysis and Synthesis method	-	-
A_0/A_1	Capture-area ratio = mass-flow ratio	-	-
A_{seal}	Frontal area of spool lip (ATF test set-up)	ft ²	m ²
ATF	Altitude Test Facility	-	-
A_{wet}	Wetted area	ft ²	m ²
b	Measurement bias	-	-
BPR	Bypass ratio, $W_{\text{bypass}}/W_{\text{core}}$	-	-
chrg.	Chargeable cooling flow	-	-
C_D	Drag coefficient or Discharge coefficient	-	-
C_{Dp}	Pressure drag coefficient	-	-
CEPR	Core Engine Pressure Ratio, $P_{t4.5}/P_{t2}$	-	-
C_f	Friction coefficient	-	-
CFD	Computational Fluid Dynamics	-	-
C_G	Gross thrust coefficient	-	-
C_L	Lift coefficient	-	-
C_P	Specific heat at constant pressure	BTU/slug	Cal/g
C_V	Specific heat at constant volume	BTU/slug	Cal/g
C_v, C_f	Specific thrust coefficient based on ideal convergent-divergent nozzle expansion	-	-
C_x	Specific thrust coefficient based on ideal convergent nozzle expansion	-	-
ds	area of surface element	ft ²	m ²



Roman	Description	U.S. Customary Units	SI Units
D	Drag force (for subscripts see ϕ)	lb	N
D_{AFS}	Aircraft system drag at full-scale reference conditions	lb	N
Det	Engine deterioration correlation parameter	-	-
EPR	Engine Pressure Ratio, P_{t5}/P_{t2}	-	-
ERAM1	Inlet ram recovery	-	-
$f()$	Function of argument within ()	-	-
f/a	Fuel to air ratio	-	-
F	Force or absolute stream force	lb	N
F_{EX}	Excess thrust	lb	N
F_G	Gross thrust and gauge stream force	lb	N
F_G^*	Modified gross thrust at core or bypass nozzle exit	lb	N
F_{IPF}	Installed propulsive force	lb	N
F_M	Measured test stand force	lb	N
F_N	Net thrust between stations 0 and 9	lb	N
F_N'	Overall net thrust between stations 0 and ∞	lb	N
F_N^*	Modified net thrust	lb	N
F_{RAM}	Ram drag or free-stream momentum	lb	N
FDRUSP	Flight Data Reduction Using Synthesis Program	-	-
FEGV	Fan Exit Guide Vanes	-	-
FF	Form Factor	-	-
FI	Interference Factor	-	-
FPC	Residual error fan pressure correlation	-	-
FPR	Fan Pressure Ratio, P_{t13}/P_{t12}	-	-
FSE	Full-Scale Engine	-	-
FTB	Flying Test Bed	-	-

Roman	Description	U.S. Customary Units	SI Units
g	Gravitation constant	ft/s ²	m/s ²
GLTF	Ground Level Test Facility	-	-
GTP	Gross Thrust Parameter	-	-
H	Enthalpy	BTU/slug	J/g
HPC	High Pressure Compressor	-	-
HPT	High Pressure Turbine	-	-
HPX	Horse power extraction	HP	W
I _{sp}	Specific thrust	-	-
IFTD	In-Flight Thrust Determination	-	-
ISA	International Standard Atmosphere	-	-
k	Measurement sensitivity factor or Sand grain diameter	- ft	- m
L	Length	ft	m
LHV	Fuel heating value	BTU/slug	J/kg
LPT	Low Pressure Turbine	-	-
m	Mass flow rate	slug/s	kg/s
M	Flight Mach number	-	-
MCL	Maximum Climb	-	-
N	Engine rotational speed	rpm	rps
NPR	Nozzle Pressure Ratio	-	-
PLA	Power Lever Angle	deg	deg
P _s	Static pressure	lb/ft ²	N/m ²
P _{s0}	Free-stream static pressure	lb/ft ²	N/m ²
P _t	Total pressure	lb/ft ²	N/m ²
P _{t4.5}	LPT inlet total pressure	lb/ft ²	N/m ²

Roman	Description	U.S. Customary Units	SI Units
P_{t0}	Free-stream total pressure	lb/ft ²	N/m ²
q	Dynamic pressure	lb/ft ²	N/m ²
q_0	Free-stream dynamic pressure	lb/ft ²	N/m ²
Q	Energy	BTU	J
QF, Q_{fuel}	Energy of Fuel	BTU	J
R	Gas constant	ft-lb/slug R	J/kg K
R_N	Reynolds number	-	-
RERR	Residual Error	-	-
RNI	Reynolds Number Index	-	-
s	Measurement precision	-	-
S	Surface or reference area	ft ²	m ²
SC_D	Ratio of discharge coefficient to a model (i.e. scale model test) or reference value	-	-
SC_v	Ratio of thrust coefficient to a model (i.e. scale model test) or reference value	-	-
SG	Fuel specific gravity	-	-
SLS	Sea Level Static	-	-
$SW_{4.1R}$	High pressure turbine flow function	slug/s	kg/s
T	Thrust force	lb	N
TBA	Test Bed Analysis	-	-
TCS	Turbulence Control Structure	-	-
TPS	Turbine Powered Simulator	-	-
TRQ_L	Low-pressure shaft torque	lb-ft	kg-m
TSFC	Net thrust specific fuel consumption	slug/h/lb	kg/s/N
T_t	Total temperature	R	K
V	Velocity	ft/s	m/s
V_0	Free-stream velocity or flight speed	ft/s	m/s

Roman	Description	U.S. Customary Units	SI Units
W	Either mass flow rate or aircraft weight	slug/s or lb	kg/s or kg
WTAP	Flow parameter, $(W_{1A}T_{t1}^{0.5})/(P_{t1}A_{1A})$	$(s\sqrt{R})/ft$	$(s\sqrt{K})/m$
W_F	Fuel mass flow rate	slug/h	kg/s
x/c	Percent of wing chord	-	-

Greek	Description	U.S. Customary Units	SI Units
α	Angle of attack	deg	deg
γ	Specific heat ratio = C_P/C_V	-	-
δ	Non-dimensional pressure = $P/P_{s0, SL, STD}$	-	-
Δ	Parameter incremental change	-	-
η	Efficiency factor	-	-
η_R	Intake pressure recovery = P_{t2}/P_{t0}	-	-
θ	Non-dimensional temperature = $T/T_{s0, SL, STD}$ or Influence coefficient	-	-
λ	Angle between free stream flow direction and a plane tangent to the surface	deg	deg
τ	shear stress	lb/ft ²	N/m ²
ν	Kinematic viscosity	ft ² /s	m ² /s
ϕ	Axial gauge force on a body or Stream tube surface or Reverser efflux effective angle	lb - deg	N - deg
ϕ_B	Pressure area or buoyancy force in engine test facility	lb	N
ϕ_{CCAB}	Axial gauge force on external surface of core cowl afterbody between stations 19 and 9	lb	N
ϕ_D	Scrubbing force in engine test facility	lb	N
ϕ_{FB}	Axial gauge force on engine forebody	lb	N

Greek	Description	U.S. Customary Units	SI Units
ϕ_{FCAB}	Axial gauge force on external surface of fan cowl afterbody between maximum nacelle diameter and station 19	lb	N
ϕ_{plug}	Axial gauge force on plug surface downstream of station 9	lb	N
ϕ_{POST}	Axial gauge force on post exit streamtube between stations 9 and ∞	lb	N
ϕ_{PRE}	Axial gauge force on pre-entry streamtube between stations 0 and 1	lb	N
ϕ_{pylon}	Axial gauge force on pylon surface within bypass streamtube	lb	N
Exponents	Description		
x	Parameter used with non-dimensional temperature, θ , to correlate N_1 data		
y	Parameter used with non-dimensional temperature, θ , to correlate W_F data		
Subscripts	Description		
0,1,2,etc.	Internal station designations (see Figure 4 reproduced from ARP755C)		
a and b	Test cell ambient conditions		
act	Actual value (distinguished from "ideal")		
AC	Aircraft		
AFS	Airframe system		
avg, AVG	Average		
adi	Adiabatic		
b	Burner		
bypass	Bypass or secondary flow		
B	Bleed		
calc	Calculated		
con	Convergent ideal nozzle		
core	Core or Primary		
CCAB	Core cowl afterbody		

Subscripts	Description
eff	Effective value of V at exit from a convergent-divergent nozzle which, when multiplied by W_{act} , gives $F_{G,act}$, or effective flow area
EXH	Exhaust
fan, f	Fan or bypass
flex-con-di	Flexible convergent-divergent ideal nozzle
FB	Force Balance
FCAB	Fan cowl afterbody
FSE	Full-Scale Engine
H	High-pressure engine spool
I	Indicated
IM	Inlet Momentum
id	Ideal value (distinguished from "actual")
INL	Inlet
Int	Internal
j	Jet
L	Low-pressure engine spool
max, MAX	Maximum
min, MIN	Minimum
NAC	Nacelle
PB	Pressure Buoyancy
p	Propulsive
Poly	Polytropic
R	"Reduced"; non-dimensional parameter
REF	Reference value or conditions
r	Rotation
s	Static conditions
supp	Suppression

Subscripts	Description
SLB	Spool Lip Buoyancy
STD	Standard (temperature or pressure)
t	Total conditions
thermal	Thermal cycle
TRIM	Aircraft trim related
Vent	Under cowl cooling air
wet	Wetted surface for friction force
∞	Free-stream conditions

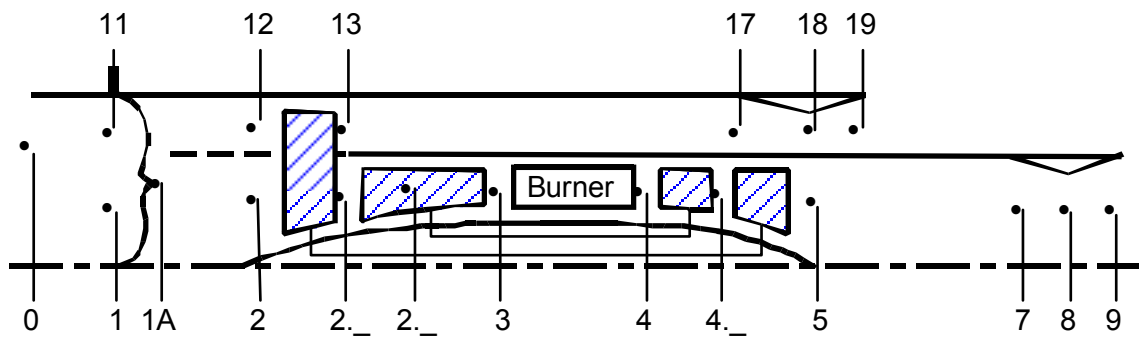


FIGURE 4 - DEFINITION OF STATION NUMBERS (ADAPTED FROM FIG. 2-2 OF AS755D)

3. DEFINITIONS AND METHODOLOGY

A detailed discussion of thrust definitions and methodology is provided in AIR1703 and AIR5020 for turbofans and turbojets. These definitions and methodology apply in principle to higher bypass ratio propulsion systems such as the ADP. It is in the application of those definitions and methodology that the distinctive features of the ADP may require new approaches.

The fundamental approach to control volume analysis and thrust/drag accounting remains the same for ADP and turbofan engines. This Section presents the main points of thrust/drag accounting and in-flight thrust determination methodology described in AIR1703 (the reader is referred to the reference for details) and highlights areas where the distinctive characteristics of the ADP may be expected to require new techniques to achieve high confidence in in-flight thrust determination.

Thrust is defined here and in AIR1703 as the engine reactionary force acting on the airplane. The concept of installed propulsive force, F_{IPF} (Eq. 1), is central to the definition of in-flight thrust for turbofan and turbojet engines and carries over unchanged to the ADP (see equations 2.12 and 2.13 in AIR1703). For steady, level flight where excess thrust in the flight direction is zero

$$F_{IPF} = F_N^* - \Delta F_{INL} - \Delta F_{EXH} - \Delta F_{TRIM} = D_{AFS}$$

(Eq. 1)

where:

- D_{AFS} = Airframe system drag at full-scale reference conditions as reflected in the aircraft drag polar (see Appendix C in AIR1703).
- F_{IPF} = Installed propulsive force that is obtained from net thrust with adjustments for deviations from full-scale reference conditions.
- F_N^* = Modified net thrust accounting for installation effects of inlet internal performance, nozzle internal performance, bleed air extraction, and shaft power extraction at the full-scale reference conditions.
 $F_N^* = F_G^* - F_{RAM}$ (see Eq. 6 for F_G^*)
- ΔF_{INL} = External force increment between a reference inlet geometry with a reference airflow (used to establish the airplane drag polar) and the actual inlet geometry and airflow at any operating point.
- ΔF_{EXH} = External force increment between a reference exhaust system geometry with a reference airflow (used to establish the airplane drag polar) and the actual exhaust system geometry and airflow at any operating point.
- ΔF_{TRIM} = External control-surface-trim force increment associated with operating the propulsion system at other than the chosen propulsion system reference conditions.

The individual components of F_{IPF} including modified net thrust, F_N^* , and the throttle dependent inlet and exhaust forces ΔF_{INL} and ΔF_{EXH} may differ significantly in form and magnitude for the ADP. These differences may require changes in traditional methods for evaluating ΔF_{INL} and ΔF_{EXH} , for both sub-scale model and full-scale engine testing. Evaluation of ΔF_{INL} and ΔF_{EXH} for turbofan engines has generally been accomplished by using separate subscale models of the engine inlet and exhaust systems because the interaction between the two is assumed to be negligible. Because of increased diameter and more compact ADP nacelle design (see Section 4), the close-coupled inlet and exhaust systems could interact with each other. Model tests to quantify ΔF_{INL} , ΔF_{EXH} and any coupled interactions will be more demanding than the isolated tests currently utilized for turbofan engines. Thus, simultaneous inlet and exhaust testing on a complete nacelle model may be required for ADP engines. In this case, ΔF_{INL} and ΔF_{EXH} would be combined into a single term, ΔF_{NAC} , that is a function of A_0/A_1 , A_{19} , P_{t19}/P_{s0} , A_9 , and P_{t9}/P_{s0} .

Such a change in test technique would result in a force change for the complete nacelle (ΔF_{NAC}) and F_{IPF} would be represented by Eq. 2. Note that ΔF_{TRIM} is assumed to be zero in this equation; this assumption will be applied for the remainder of this section.

$$F_{IPF} = F_N^* + \Delta F_{NAC} \quad (\text{Eq. 2})$$

3.1 Dual-Stream (ADP) Engine Thrust

A discussion of installed propulsive force for a dual-stream engine (see Figure 5) is contained in AIR1703. Using the nomenclature shown in Figure 5 and Table 1, the installed propulsive force, F_{IPF} , of a dual-stream engine can be written as Equation 3. Discussion of thrust definitions and methodology for ADP engines in this document begins with this commonly used equation.

$$F_{IPF} = -W_0 V_0 - \int_0^1 (P - P_{s0}) dA - \phi_{INL} + \phi_{FCAB} + W_{19} V_{19} + (P_{s19} - P_{s0}) A_{19} + \phi_{CCAB} + \phi_{pylon} + W_9 V_9 + (P_{s9} - P_{s0}) A_9 + \phi_{plug} \quad (\text{Eq. 3})$$

where the ϕ terms are combined pressure and friction forces as defined in Eq. 4.

$$\phi = \int_{\text{surface}} [(P_s - P_{s0}) + \tau(\cot \lambda)] dA \quad (\text{Eq. 4})$$

where:

τ = shear stress acting on the area of a surface element ds

λ = Angle between free stream flow direction and a plane tangent to the surface element ds

dA = $(\sin \lambda)ds$ = area of surface element, ds , projected on a plane normal to the free stream flow direction

The integral in Eq. 4 is taken over the surfaces of interest. Thus, ϕ_{INL} is the pressure and friction forces acting on the engine nacelle between the inlet flow stagnation point and the maximum nacelle diameter; ϕ_{FCAB} is the pressure and friction forces acting on the engine nacelle between the maximum nacelle diameter and the bypass duct exit; ϕ_{CCAB} is the pressure and friction forces acting on the primary exhaust cowl between the bypass duct exit and the primary nozzle exit; ϕ_{pylon} is the pressure and friction forces acting on the portion of the pylon scrubbed by the bypass duct exhaust; and finally, ϕ_{plug} is the pressure and friction forces acting on the plug surface downstream of the primary nozzle exit.

Common terminology for the various terms in Eq. 3 is given in Table 1. The word descriptions of the individual terms in Table 1 use conventional terminology such as suction, drag and thrust based on the expectations of the direction of the force vector for each term (i.e., suction and thrust terms are expected to provide a force in the upstream direction while drag terms are expected to provide a force in the downstream direction). However, it should be noted that any of these terms could be negative or positive depending on the sign of the pressure term and the magnitude of the friction force (always acts in the downstream direction). For example, if the pressure recovery on the nacelle aft of the maximum diameter was such that $\int (P_s - P_{s0})dA$ over the axially projected area from the maximum nacelle diameter to the bypass exit produced a positive value and was larger than the friction force, then the value of the ϕ_{FCAB} term would be positive and, although the term is called a drag, it would actually be producing a force in the upstream or thrust direction. On the other hand, if the pressure recovery on the nacelle aft of the maximum diameter was such that $\int (P_s - P_{s0})dA$ over the axially projected area from the maximum nacelle diameter to the bypass exit produced a negative value, then the value of the ϕ_{FCAB} term would be negative and it would produce a force in the downstream or drag direction. All other ϕ terms in Table 1 can be evaluated in a similar manner. It should also be noted that the literature contains other word descriptions for some of the engine components such as "bypass" or "secondary" for the term "fan", "primary" for the term "core", and "boattail" or "nozzle" for the term "afterbody". All of these terms are equivalent.

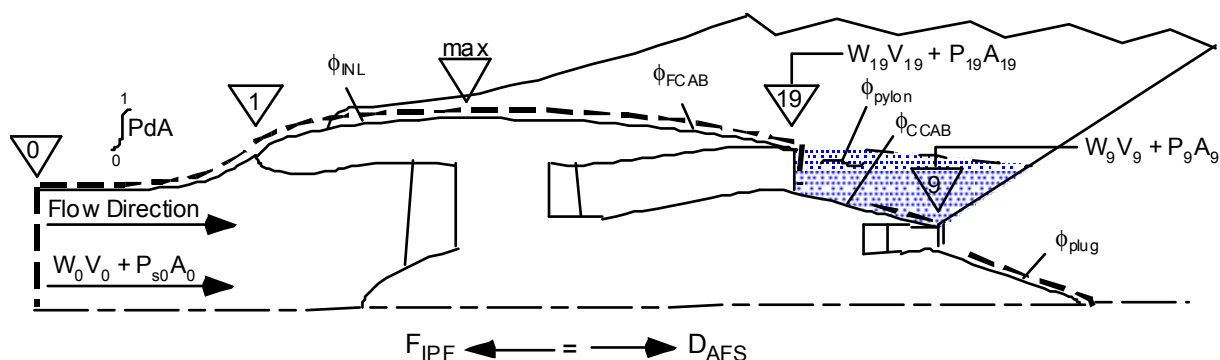


FIGURE 5 - FORCE COMPONENTS FOR DUAL-STREAM ENGINE

TABLE 1 - DEFINITION OF TERMS THAT COMPRISE F_{IPF}

Inlet Drag	Ram Drag		$-W_0V_0$
	Inlet Spillage Drag	Additive Drag	$-\int_0^1 (P-P_{s0})dA$
		Lip Suction	$-\phi_{INL}$
Fan Cowl Afterbody Drag	Nacelle External Afterbody Drag Term		ϕ_{FCAB}
Bypass (Fan) Duct Modified Gross Thrust, F_{G19}	Bypass Duct Thrust	Momentum Term	$W_{19}V_{19}$
		Pressure Term	$(P_{s19}-P_{s0})A_{19}$
	Drags associated with bypass (fan) exhaust flow	Core Cowl Afterbody Drag	ϕ_{CCAB}
		Pylon Drag	ϕ_{pylon}
Primary (Core) Modified Gross Thrust, F_{G9}^*	Primary Thrust	Momentum Term	W_9V_9
		Pressure Term	$(P_{s9}-P_{s0})A_9$
	Drag associated with primary (core) exhaust flow	Plug Drag	ϕ_{plug}
Installed Propulsive Force (Equals sum of parts)			F_{IPF}

Equations 5 and 6 define the modified gross thrust for a dual-stream engine.

$$F_G^* = F_{G9}^* + F_{G19}^* \quad (\text{Eq. 5})$$

$$F_G^* = W_9V_9 + (P_{s9}-P_{s0})A_9 + \phi_{plug} + W_{19}V_{19} + (P_{s19}-P_{s0})A_{19} + \phi_{CCAB} + \phi_{pylon} \quad (\text{Eq. 6})$$

Equation 7 provides the equivalent formulation of modified net thrust for a dual-stream turbofan engine.

$$F_N^* = \underbrace{-W_0V_0}_{\text{Ram Drag } (F_{RAM})} + \underbrace{W_{19}V_{19} + (P_{s19}-P_{s0})A_{19} + \phi_{CCAB} + \phi_{pylon}}_{\text{Bypass (Fan) Duct Modified Gross Thrust } (F_{G19}^*)} + \underbrace{W_9V_9 + (P_{s9}-P_{s0})A_9 + \phi_{plug}}_{\text{Primary (Core) Modified Gross Thrust } (F_{G9}^*)} \quad (\text{Eq. 7})$$

The formulation of Eq. 7 is the basis for a practical thrust/drag accounting system. The quantity F_N^* includes all of the forces measured in an engine test (i.e. primary cowl, pylon and plug forces induced by primary and bypass stream flow) adjusted for the effects of flight velocity. When thrust is defined this way, model and full-scale engine test results (which measure the forces) may be applied to determine F_{IPF} . Test methodology to determine F_N^* is described in AIR1703 for turbofan engines. Advanced ducted propulsor engine test considerations are discussed in Section 7 of this report.

To provide the reader with an indication of the relative magnitude of the terms that make up installed propulsive force for a dual-stream engine (Eq. 3), two numerical examples based on isolated CFD analysis are shown in Table 2. A comparison of these examples also indicates the relative importance of the same thrust components for a typical (BPR=6.5) state-of-the-art turbofan engine and an advanced technology ADP (BPR≈20). The numerical values are normalized by the installed propulsive force, F_{IPF} . It can be seen from the examples that the sum of the spillage drag (additive drag and lip suction) and recompression drag are about the same percentage of F_{IPF} for both propulsion systems. It should be noted that based on past experience, the nacelle shape (from station 1 to station 19) requires testing to optimize the contour and minimize the impact of inlet spillage and recompression drag. It can also be noted from the examples given that the ram drag and bypass (fan) duct modified gross thrust are much larger percentages of F_{IPF} for the ADP (BPR≈20) system than for the BPR=6.5 turbofan engine. Thus, similar percentage errors in measuring these parameters will have more consequences for ADP systems than was the case for typical turbofans. Similarly, the consequence of an error in measuring the primary (core) modified gross thrust will be less for an ADP. These results help give insight into the allocation of testing resources for ADP engines.

TABLE 2 - NUMERICAL EXAMPLES BASED ON ISOLATED CFD ANALYSIS.

$$F_{IPF} = -W_0V_0 - \underbrace{\int_0^1 (P-P_{s0})dA - \phi_{INL} + \phi_{FCAB}}_{\Delta F_{NAC}} + \underbrace{W_{19}V_{19} + (P_{s19}-P_{s0})A_{19} + \phi_{CCAB} + \phi_{pylon} + W_9V_9 + (P_{s9}-P_{s0})A_9 + \phi_{plug}}_{F_G^*}$$

THRUST COMPONENT	BPR=6.5 M=0.83 alt=35K	BPR≈20 M=0.83 alt=35K
W_0V_0 Ram Drag	213%	339%
$\int_0^1 (P-P_{s0})dA$ Additive Drag	-19%	-22%
ϕ_{INL} Lip Suction	19%	21%
ϕ_{FCAB} Recompression Drag	-3%	-2%
ΔF_{NAC}	-3%	-3%
$W_{19}V_{19} + (P_{s19}-P_{s0})A_{19} + \phi_{CCAB} + \phi_{pylon}$ Bypass Duct Modified Gross Thrust = F_{G19}^*	260%	409%
$W_9V_9 + (P_{s9}-P_{s0})A_9 + \phi_{plug}$ Primary (Core) Modified Gross Thrust = F_{G9}^*	56%	33%
$F_N^* = F_{G19}^* + F_{G9}^* - \text{Ram Drag}$	103%	103%
$F_{IPF} = F_N^* + \Delta F_{NAC}$	100%	100%

As indicated previously and shown in Figure 6A, evaluation of external inlet and exhaust system forces for turbofan engines has generally been accomplished by using separate subscale model tests of the engine inlet and exhaust systems (also see Section 7). It should be noted that these methods are employed as part of the overall nacelle performance development process as opposed to using CFD. While CFD may provide performance trends, test data are currently used to obtain nacelle/ exhaust performance levels. Wind-on external nacelle tests using a force balance are conducted to determine cruise drag and engine-out separation characteristics. These data must be corrected for nacelle internal losses; the internal drag levels and flow calibrations that are used to reduce wind tunnel data are provided by separate inlet calibration tests.

Internal drag is provided in terms of thrust coefficients based on the ideal thrust calculated from the charging station total-pressure to ambient static-pressure ratio. The calibrations provide the model internal drag, which when subtracted from the overall drag, gives the external inlet and bypass cowl drag (see Figure 6B). Another method used to investigate nacelle drag is through the use of momentum rakes that are used to derive external inlet forces. Usually several momentum rakes equally spaced circumferentially around the facility piping are used; the rakes are rotated to sample the external flow field around and downstream of the inlet model. The test technique described above and illustrated in Figures 6A and 6B assumes that no interactions occur between the inlet and exhaust system. But, because of the close coupling of the inlet and exhaust systems for ADP nacelle designs, the inlet and exhaust system interaction could be significant on these propulsion systems. Simultaneous inlet and exhaust testing on a complete ADP nacelle model such as that shown in Figure 6C could account for this interaction. Such a test would yield the complete force change on the entire nacelle (ΔF_{NAC}). Procedures for removing the internal forces would have to be developed to utilize this test technique. Additional details on this method are contained in Section 7.

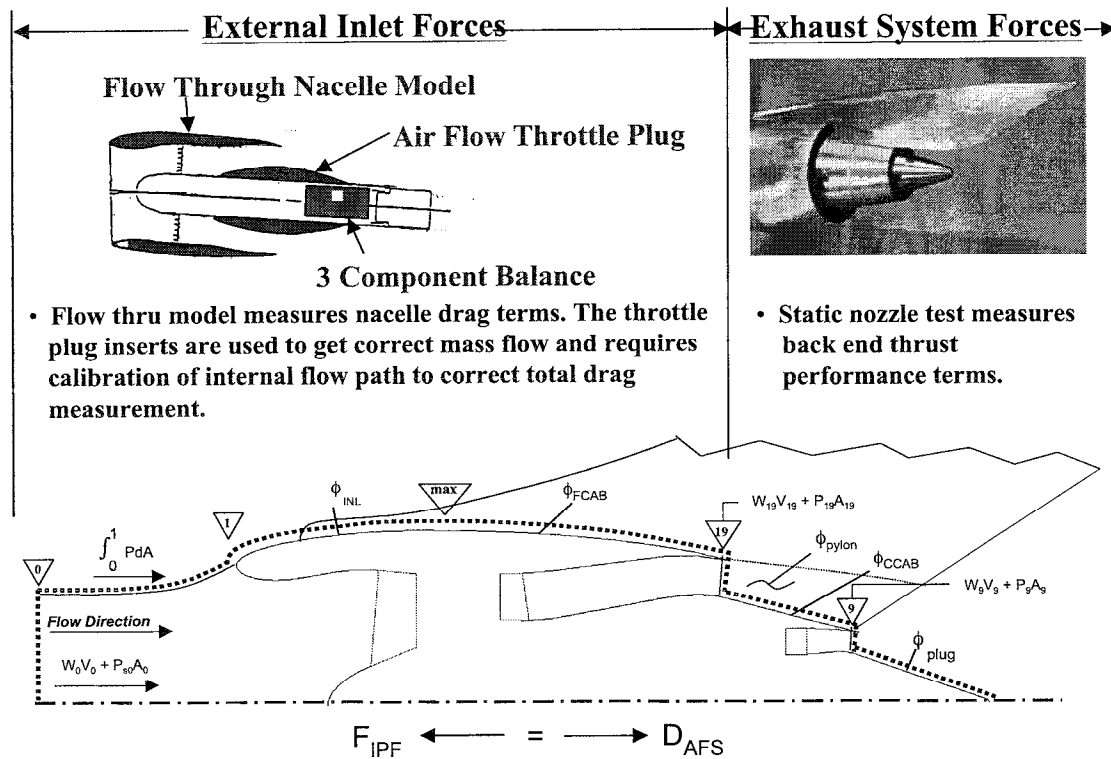


FIGURE 6A - TEST PROCEDURE FOR DETERMINING INSTALLED PROPULSIVE FORCE

External Inlet Forces Are Determined by Subtracting Internal Losses From Total Measured Inlet / Nacelle Thrust - Drag

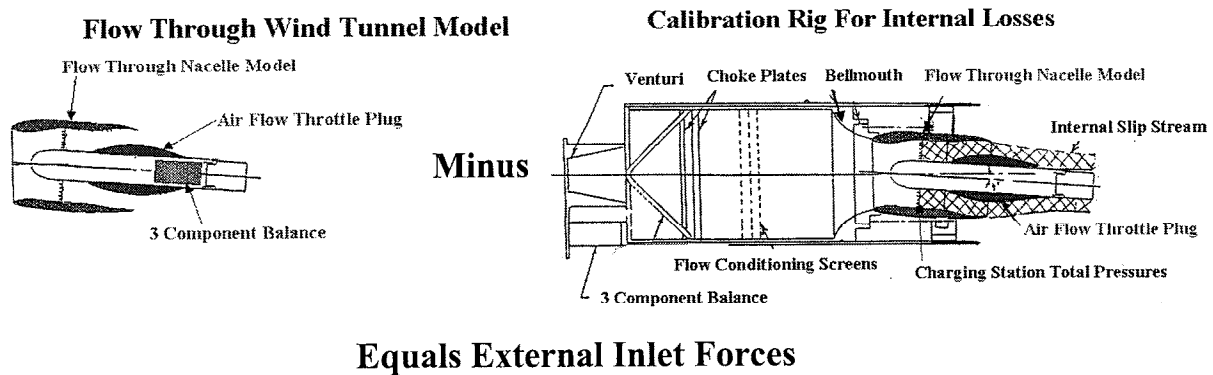
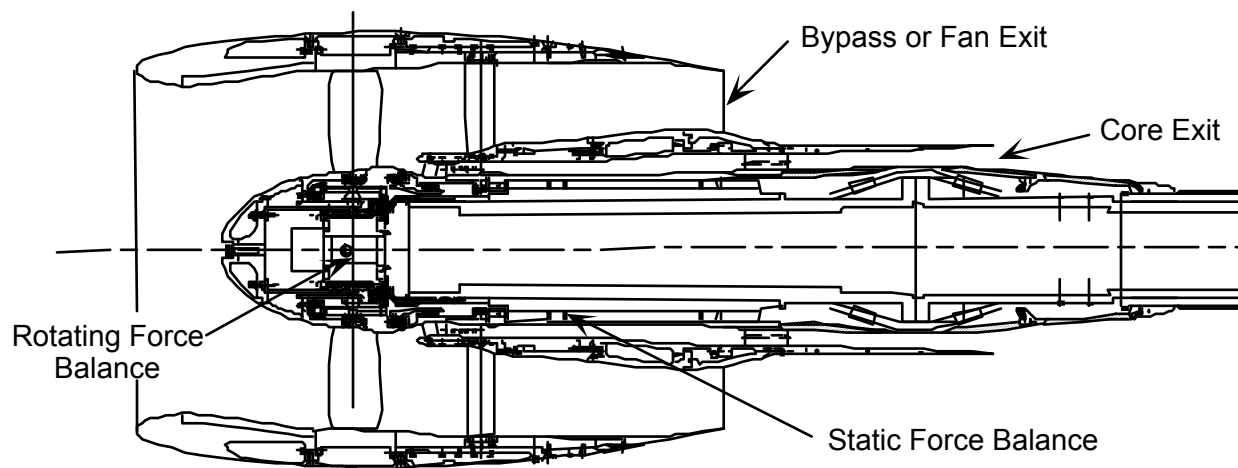


FIGURE 6B - TEST PROCEDURE FOR DETERMINING NACELLE EXTERNAL FORCES

NASA/P&W 22-Inch Fan/Nacelle Test Hardware

FIGURE 6C - TURBINE POWERED SIMULATOR FOR USE IN DETERMINING ΔF_{NAC}

4. ENGINE CONCEPTUAL DESIGN AND CONFIGURATIONS

4.1 Propulsion Design

First, some background information is appropriate to gain a perspective as to the reasons why gas turbine engine designers exploit higher bypass ratio, lower fan pressure ratio systems. Turbofan engines perform a series of processes that convert chemical energy to heat to mechanical energy and ultimately to thrust power. The efficiency of the first three of these is characterized by the thermal efficiency of the cycle (η_{thermal}) and the last by the propulsive efficiency (η_p). The product of these two efficiencies gives the overall system efficiency. The principle components that contribute to η_{thermal} are the burners (which have an efficiency near 1.0), and the turbine and compression systems. These components have been developed intensely by researchers and engine manufacturers to minimize the aerodynamic losses; they are also extremely expensive to develop. This is particularly true for the high spool of two and three spool engines. Consequently, future engines will most likely use a common or existing core, or scaled versions of them, for multiple applications. Therefore, core engine thermal efficiency is not an issue in the determination of the overall cycle parameters for these cases. However, increases in propulsive efficiency have been most important in the changes in overall efficiency (by approximately a factor of two) from the earlier turbojets and turbofans to the current and future high bypass ratio engines.

A prime discriminator in the determination of propulsive efficiency is the characteristics of the bypass system in separate flow turbofan engines. To illustrate the basic physics, a simple model of the engine in which all of the flow leaving the engine is taken to be at the conditions of the fan bypass stream is employed. This is a reasonable approximation since, for the engines of interest in this document, the bypass stream produces approximately 90-percent of the thrust. The sketch shown in Figure 7 identifies the principal parameters of this model.

Ideally, the mechanical energy of the fan is converted into an increase in Kinetic Energy (KE) of the bypass stream, which upon passing through the engine is:

$$\frac{1}{2} W_0 (V_j^2 - V_0^2)$$

The propulsive efficiency is thus:

$$\eta_p = \frac{\text{Thrust Power}}{\text{Overall Mechanical Power Produced}} = \frac{\text{Thrust} \times V_0}{\text{Increased KE}} = \frac{W_0(V_j - V_0)V_0}{\frac{1}{2}W_0(V_j^2 - V_0^2)}$$

or:

$$\eta_p = \frac{2}{\frac{V_j}{V_0} + 1}$$

This relationship shows that high propulsive efficiency occurs at values of V_j/V_0 close to unity. Consequently, there is a benefit to minimizing the contribution of the hot, high velocity core engine exhaust, which drives the configuration to high bypass ratios as shown by the bare engine optimum curve (lower line) in Figure 8. Furthermore, it is also beneficial to reduce the bypass jet velocity by reducing fan pressure ratio. These benefits are the motivation for going to ADP engines.

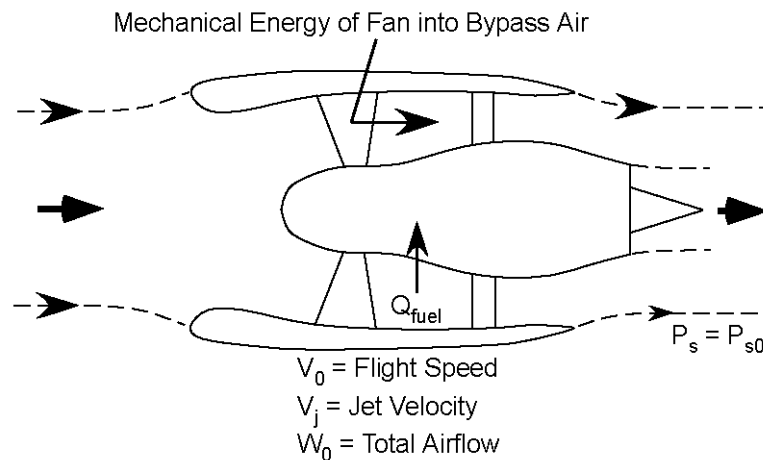


FIGURE 7 - SIMPLIFIED ADP TURBOFAN ENGINE MODEL

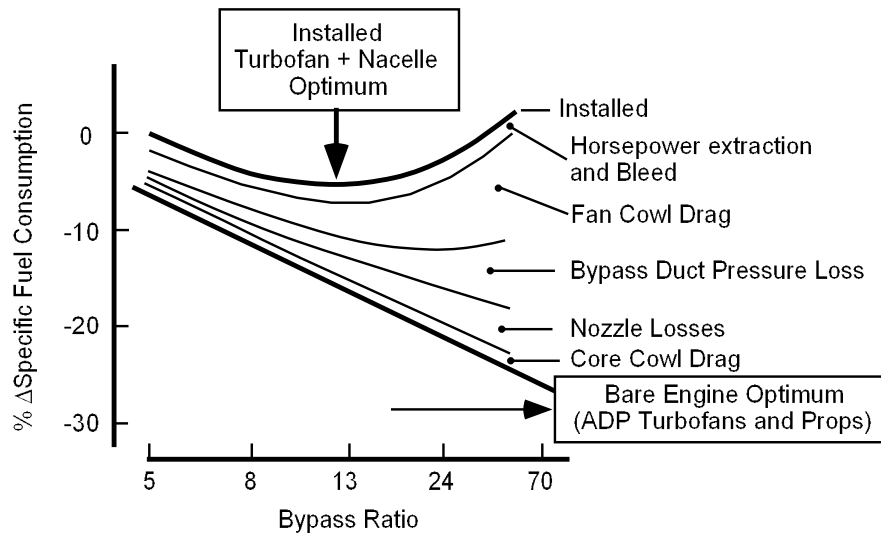


FIGURE 8 - POTENTIAL EFFICIENCY BENEFIT FOR ADP SYSTEMS

However, the benefits of reducing V_j/V_0 must be tempered by the consequences this ratio has on specific thrust of the engine. Neglecting external pressure-area forces, the momentum equation gives net thrust (F_N) as:

$$F_N = W_0(V_j - V_0)$$

The specific thrust (I_{sp}) is the thrust per unit of momentum flux in the engine inlet stream and is expressed as:

$$I_{sp} = \frac{F_N}{W_0 V_0} = \frac{V_j}{V_0} - 1$$

Note that the relationship between propulsive efficiency and specific thrust are defined solely in terms of V_j/V_0 and is an inverse relationship as shown in Figure 9.

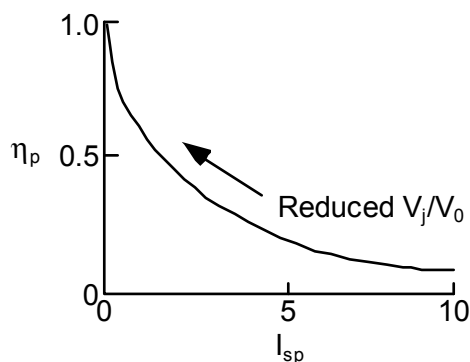


FIGURE 9 - PROPULSIVE EFFICIENCY AND SPECIFIC THRUST RELATIONSHIP

As V_j/V_0 is reduced, specific thrust decreases. Therefore, in order to maintain an absolute thrust level, mass flow must increase. Since fans are designed at or near maximum flow capacity, fan flow area (diameter) must increase to increase the mass flow. This in turn increases weight, cost, and drag, and introduces difficulties in the engine installation on the aircraft. These trades must be made to determine the optimum engine design. Historically such trades have kept the bypass ratios relatively low and the fan pressure ratios relatively high. However, with technology advances in materials and aerodynamic design, the optimum turbofan plus nacelle "bucket" location on the installed engine curve (upper line) in Figure 8 is constantly moving to the right.

Relative to conventional turbofan engines, the fan pressure ratio of ADP engines is low and has a higher sensitivity to Mach number or ram pressure ratio and altitude effects as shown in Figure 10. The extensive operating line shifts will affect the exit profiles and pressure losses that have significantly greater effect on ADP in-flight thrust determination than for conventional turbofan engines where the shift is much less. Maximum airflow occurs at take-off for conventional turbofans while maximum fan airflow occurs at maximum climb for the ADP. This makes full flow static testing difficult for ADP engines without inlet air conditioning or waiting for cold weather. Because of the lower fan pressure ratios and higher airflows, significant changes in the fan operating characteristics may arise due to installation effects.

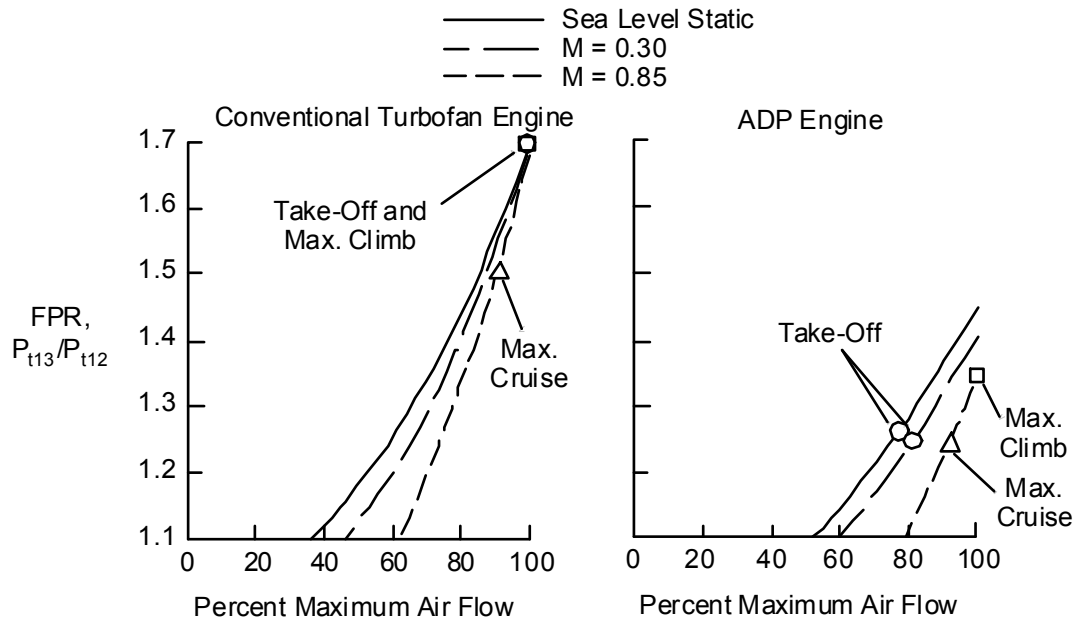


FIGURE 10 - TYPICAL OPERATING CHARACTERISTICS

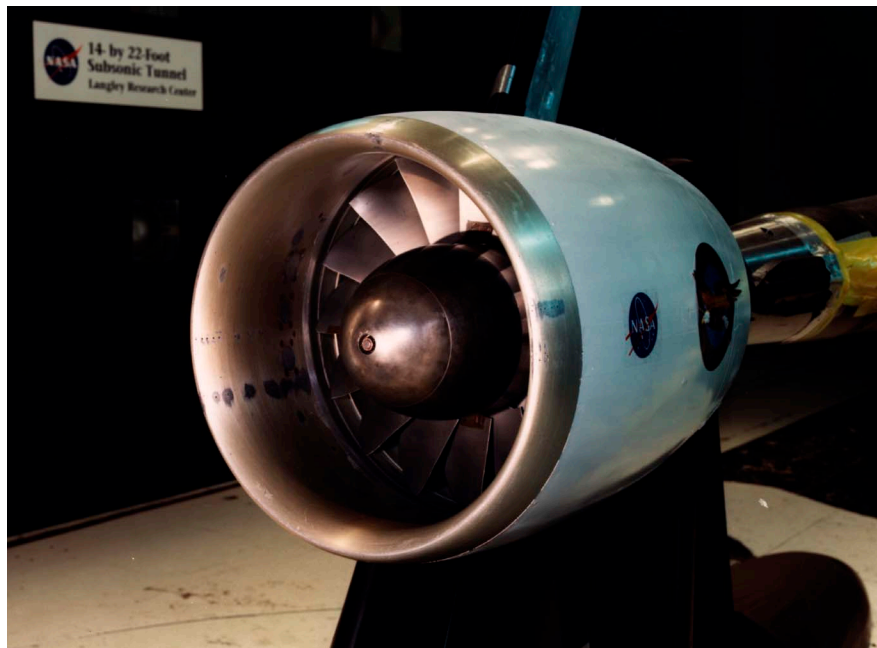


FIGURE 11 - PHOTOGRAPH OF ADP SIMULATOR

Increased thrust sensitivity to measurement uncertainties requires improved thrust determination methods and test techniques. These methods need to address the airframe effects on the engine-installed performance for the determination of both cruise thrust and low speed thrust. One method being utilized by industry in conjunction with NASA is the use of large-scale propulsion simulators for fan and nacelle development. A photograph showing a typical large-scale (fan diameter = 17 in) propulsion simulator is presented in Figure 11.

The difficulty of determining and correlating thrust coefficient for ADP in-flight thrust determination is exacerbated by the low fan nozzle-pressure-ratios of these engine systems. The sensitivity of ADP thrust to pressure measurement at sea level take-off is nearly three times that of a conventional turbofan as shown in Figure 12. In addition, due to the low fan pressure ratio at cruise, the gross to net thrust ratio is 3:1 to 4:1 for the ADP as compared to 2:1 to 2.5:1 for the conventional turbofan, which is a multiplier that increases the cruise sensitivity and makes the task of accurately determining ADP in-flight thrust even more difficult.

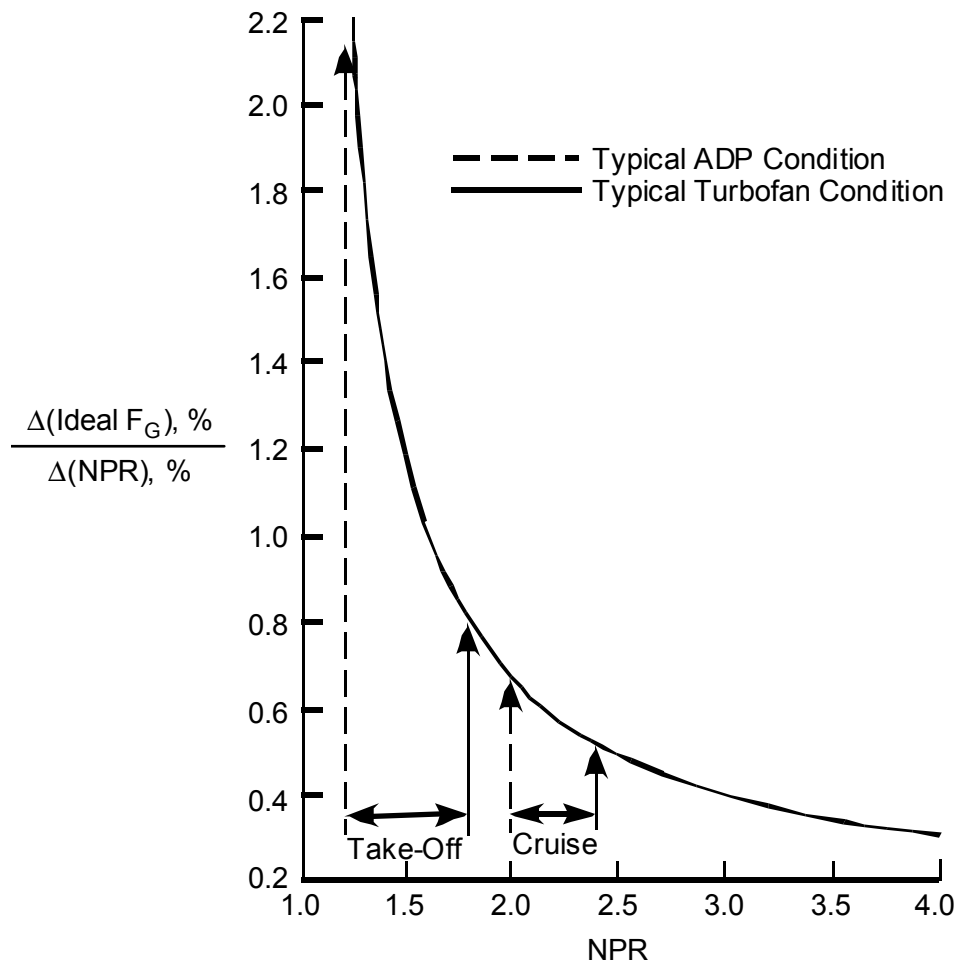


FIGURE 12 - EFFECT OF PRESSURE LOSS ON IDEAL GROSS THRUST (CONSTANT AIRFLOW)

4.2 Configuration Examples

This section will present candidate propulsion systems that may not be covered by the turbofan in-flight thrust document, AIR1703, or the unducted prop/prop-fan document, AIR4065. These propulsion systems may not be amenable to testing in current altitude test facilities that have finite physical size and airflow limits as discussed in Section 7.

4.2.1 Configuration Evolution

There has been a continuous quest for higher bypass ratios to achieve higher propulsion efficiency beginning in the mid to late 1960s with the introduction of the General Electric (GE) TF-39 and Pratt & Whitney (P&W) JT9D engines. This is evident in Figure 13, which shows that the design trend versus certification date is toward higher bypass ratio engines. If this trend continues, the higher thrust versions of ultra high-bypass-ratio engines will eventually exceed the air supply capabilities of current altitude test facilities.

As the bypass ratio and airflow increase, the bypass portion of the propulsor becomes the dominant thrust contributor because the fan duct thrust is approximately 90-percent of the total system thrust. Therefore it is vital that the cruise fan efficiency be maintained at high levels. High fan efficiency at low velocities (low fan pressure ratio or FPR) is most readily achieved by reducing fan tip speed. This also improves the acoustics of the propulsion system. However, the lower expansion ratios associated with low speed operation and the high blade loading drives the fan operating line toward surge, and maintaining the same nozzle/fan geometry at take off as at cruise results in inadequate surge margin. Thus at low FPR, variable geometry (fan nozzle area and/or fan blade angle) may be required to move the operating line and/or surge line away from each other. Fan nozzle area can be opened up to drop the operating line, or fan blade angle changed, to increase surge margin (or both). This process is illustrated in Figure 14. These features are evident in some of the specific configuration examples that follow.

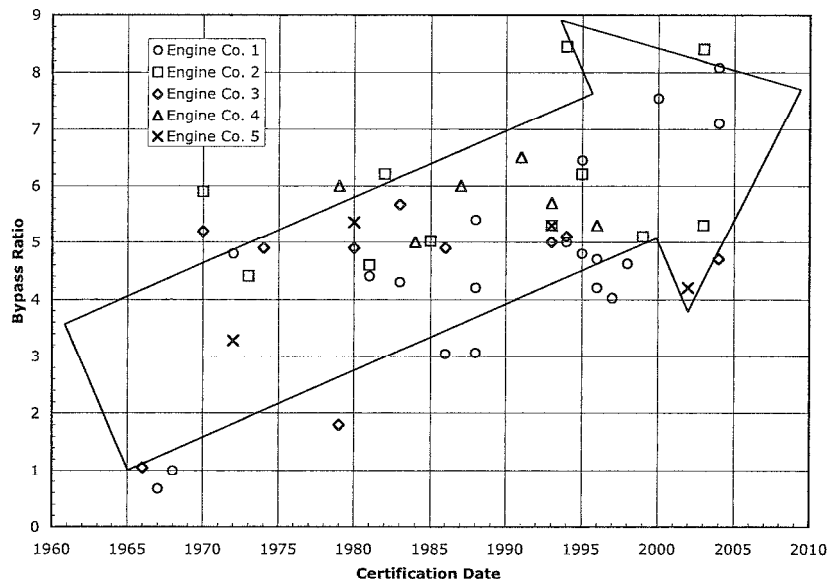


FIGURE 13 - TREND TOWARD HIGHER BYPASS RATIOS

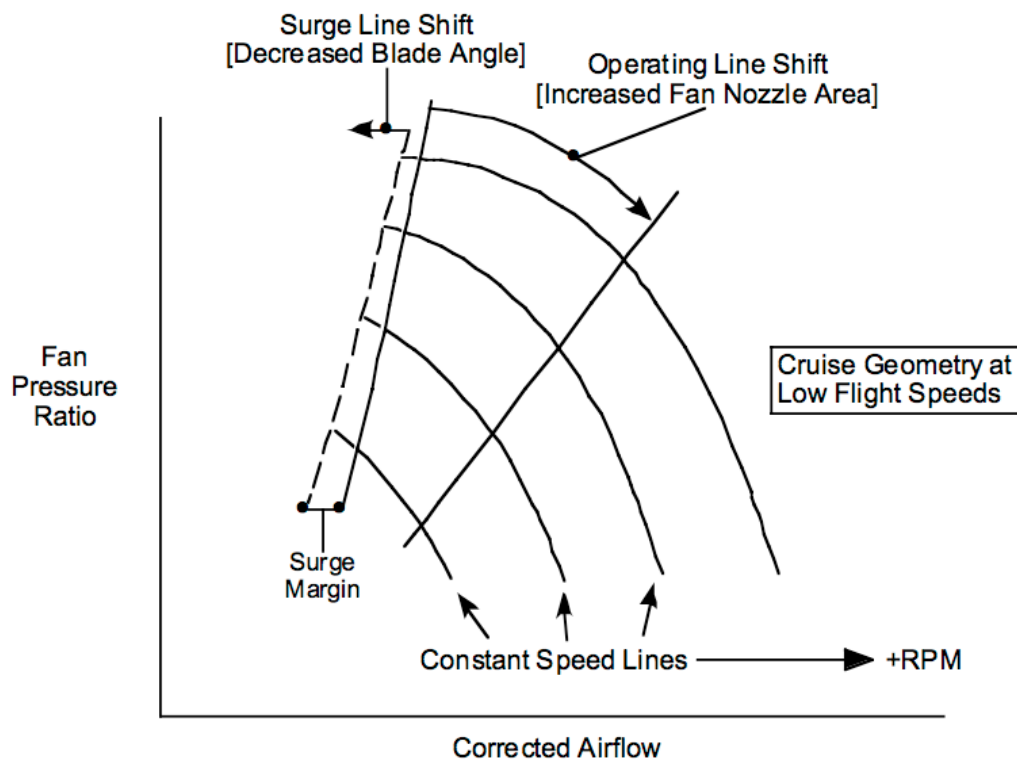


FIGURE 14 - EXAMPLE FAN MAP

4.3 Specific Configuration Examples

Three configuration examples of advanced subsonic engines were assessed as part of the NASA Advanced Subsonic Technology (AST) program. The study engines were for an Entry In Service (EIS) date of 2005, and incorporate lower pressure ratio and higher bypass ratio than current engines.

4.3.1 Pratt & Whitney Configuration

The Pratt & Whitney Advanced Ducted Propulsor (ADP) concept, and its main technology features are shown in Figure 15. Low tip speed fan operation (800 to 1000 ft/s) is accomplished through the use of a fan drive gear system. This allows the power turbine to run at high RPM and keeps the turbine efficiency high and the fan speed low. Transmission of turbine power at high RPM keeps the torque of the low spool down, resulting in a smaller shaft diameter and a light weight, high power density core. Low fan pressure ratios (1.2 to 1.35) give high propulsive efficiency, at a bypass ratio of 10 to 15. Low speed operability is accomplished with variable fan blade pitch, reducing blade pitch for takeoff. The blades also rotate into a reverse flow position, providing reverse thrust and eliminating the fan cowl thrust reverser system and its associated weight and performance penalties. Elimination of the reverser also facilitates a slim line nacelle design, reducing the cowl diameter and length, thereby reducing duct loss, external drag, and nacelle weight. For comparison, the current PW4084 engine has a fan pressure ratio of 1.5 to 1.7 and bypass ratio of 6 to 7.

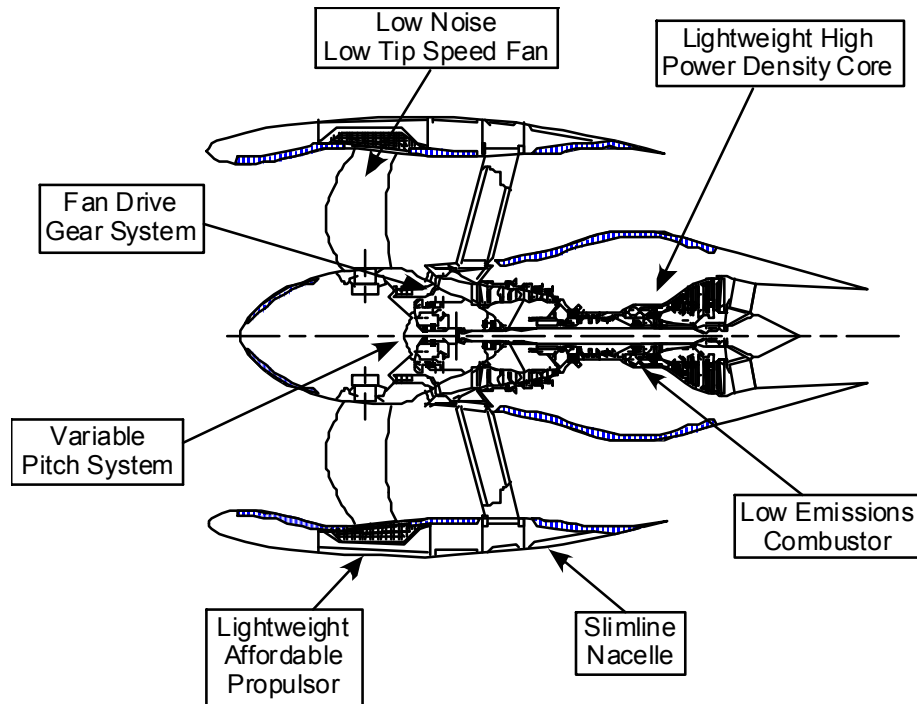


FIGURE 15 - THE PRATT & WHITNEY ADVANCED DUCTED PROPULSOR CONCEPT

4.3.2 General Electric Configuration

The General Electric Aircraft Engines entry in service (EIS) 2005 configuration and its main technology features are shown in Figure 16. The advanced study engine's fan pressure ratio and bypass ratio are in the range of 1.3 to 1.5 and 10 to 20, respectively. That compares to the current GE90 engine with a fan pressure ratio of about 1.5 and bypass ratio of 8.4.

The GE ADP engine has a direct drive, fixed pitch fan. Fan operating line shift from high altitude cruise to low speed operation and takeoff is accomplished with a variable area nozzle. A cascade reverser/blocker door is used in the fan cowl for reverse thrust operation.

4.3.3 Allison Configuration

The Allison Engine Company EIS 2005 configuration, a high bypass ratio regional turbofan engine, is shown in Figure 17. This advanced study engine's fan pressure ratio and bypass ratio are also in the range of 1.3 to 1.5 and 10 to 20, respectively. The engine shown has a fixed pitch fan, but incorporates a gear reduction system to keep high fan efficiency and to reduce noise. Although regional aircraft place a high premium on purchase price and weight, this high bypass ratio engine uses a high pressure ratio core and low NOx combustor, and may incorporate advanced materials to reduce weight.

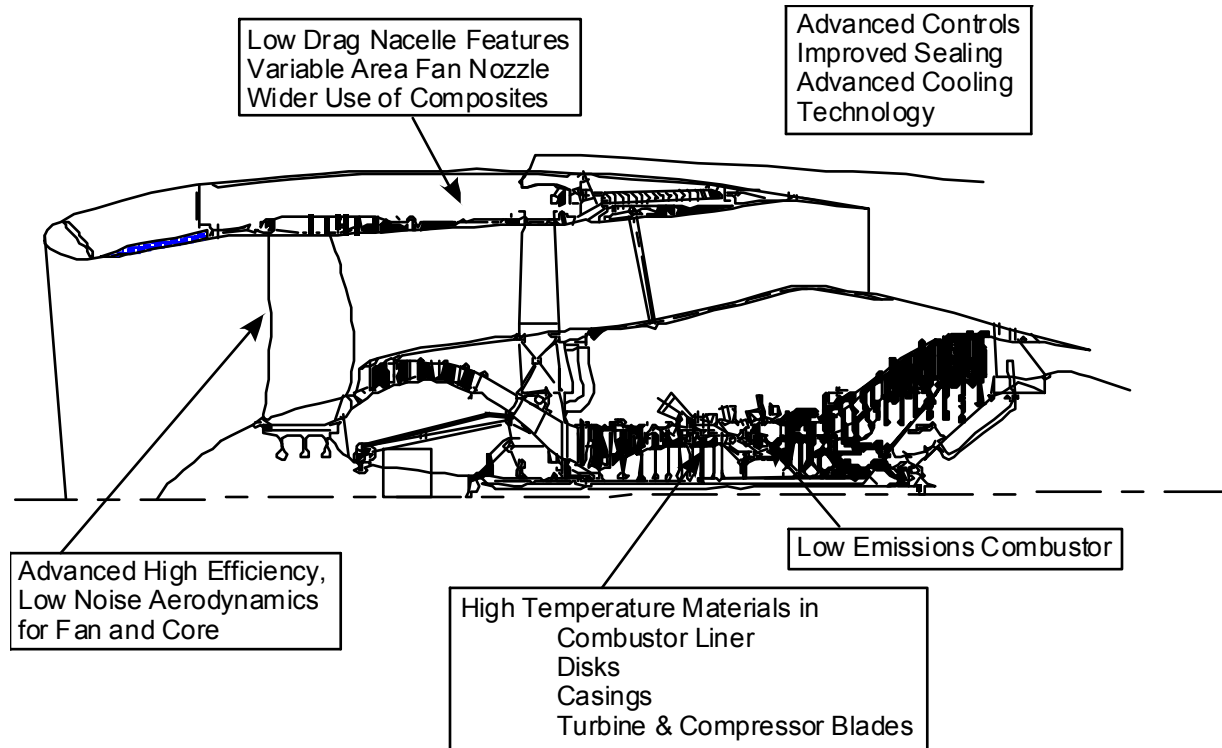


FIGURE 16 - THE GENERAL ELECTRIC EIS 2005 TURBOFAN ENGINE CONCEPT

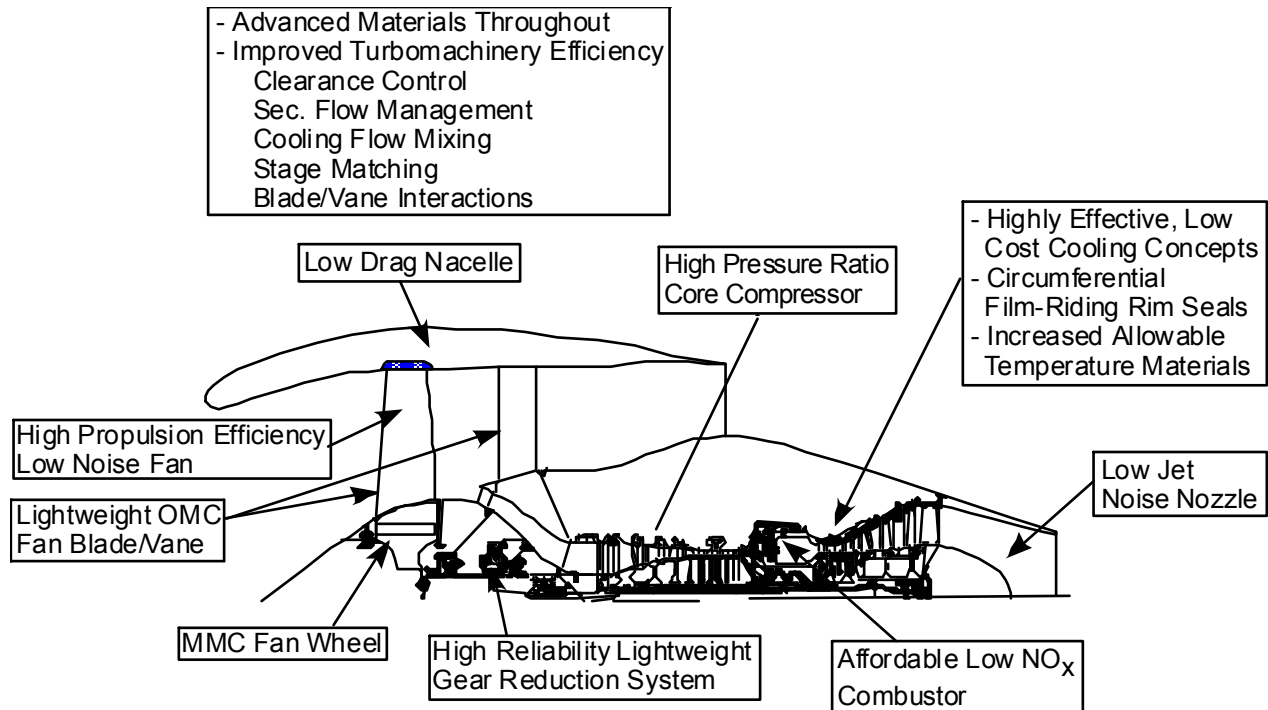


FIGURE 17 - THE ALLISON EIS 2005 TURBOFAN ENGINE CONCEPT

4.3.4 Pratt & Whitney Canada Corp.'s (P&WC) Configuration

The P&WC EIS 2005 PW800 configuration, a new advanced technology geared turbofan family, is shown in Figure 18. This advanced engine is designed for the next-generation of 50 to 100+ passenger regional aircraft and large business jets covering a 10,000 to 20,000 lb thrust range. The PW800 burns 10% less fuel than current engines, with low emissions (CO, HC and NO_x) under Zurich 5 requirements to cater for the more stringent limits anticipated in the future. The powerplant is quiet with a cumulative margin better than -24 dB relative to stage 3 requirements. This is well below stage 4 levels. The geared configuration provides one more degree of freedom to optimize the integration of a series of new generation technologies by allowing the fan, low pressure compressor and low pressure turbine to all operate at their most effective speeds. The slower fan speed contributes to very low noise levels and high efficiencies while the higher speed for the low pressure turbine and low pressure compressor augments the work capability of each stage, allowing an efficient engine configuration with fewer stages. It follows that having fewer parts than a conventional ungeared design reduces maintenance and operating costs while preserving low weight and high performance.

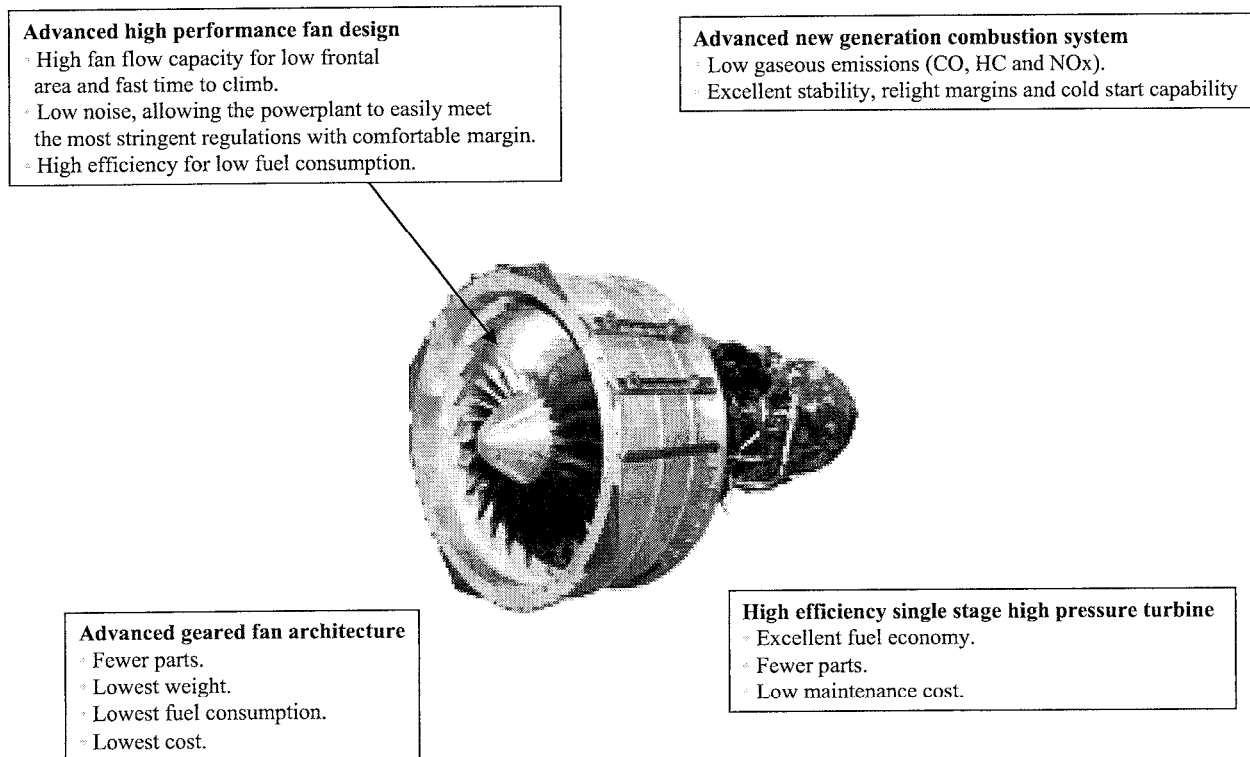


FIGURE 18 - THE PRATT & WHITNEY CANADA PW800 TURBOFAN

5. INSTALLATION CONSIDERATIONS

This section extends the previously defined concepts and definitions to include the potential impact of various configuration, mission, design, and integration decisions on the airplane and ADP propulsor force accounting systems. Many of the factors that must be considered in making these decisions are discussed in AIR1703 and AIAA-84-0593. Aircraft engine installations differ significantly. Powerplant configurations include variations in nacelle diameter and geometry, bypass ratio (split between fan and core flows), and fan/core nozzle concepts as indicated in AIAA Papers 90-2015 and 90-2146. Airframe/ engine integration concepts include wing-mounted and aft fuselage-mounted engine installations. Depending on the installation, engine/pylon interactions can occur on the wing, fuselage, and other airframe components. Similarly, these airframe components can cause interactions on the engine nacelle and powerplant.

ADP powerplants, because of their larger diameters and higher weights, present the airplane designer with a more formidable installation challenge than current powerplants offer. Figure 19 shows a comparison of a conventional engine installation with an ADP engine installation. It is obvious from this comparison that the physical size of ADP engines will have some impact on airplane design (e.g., wing dihedral angle and/or landing gear length). In practice, mechanical and aerodynamic considerations severely restrict the physical envelope in which the nacelle must fit (even for current engines). Several examples of these constraints are depicted in Figures 20 to 22.

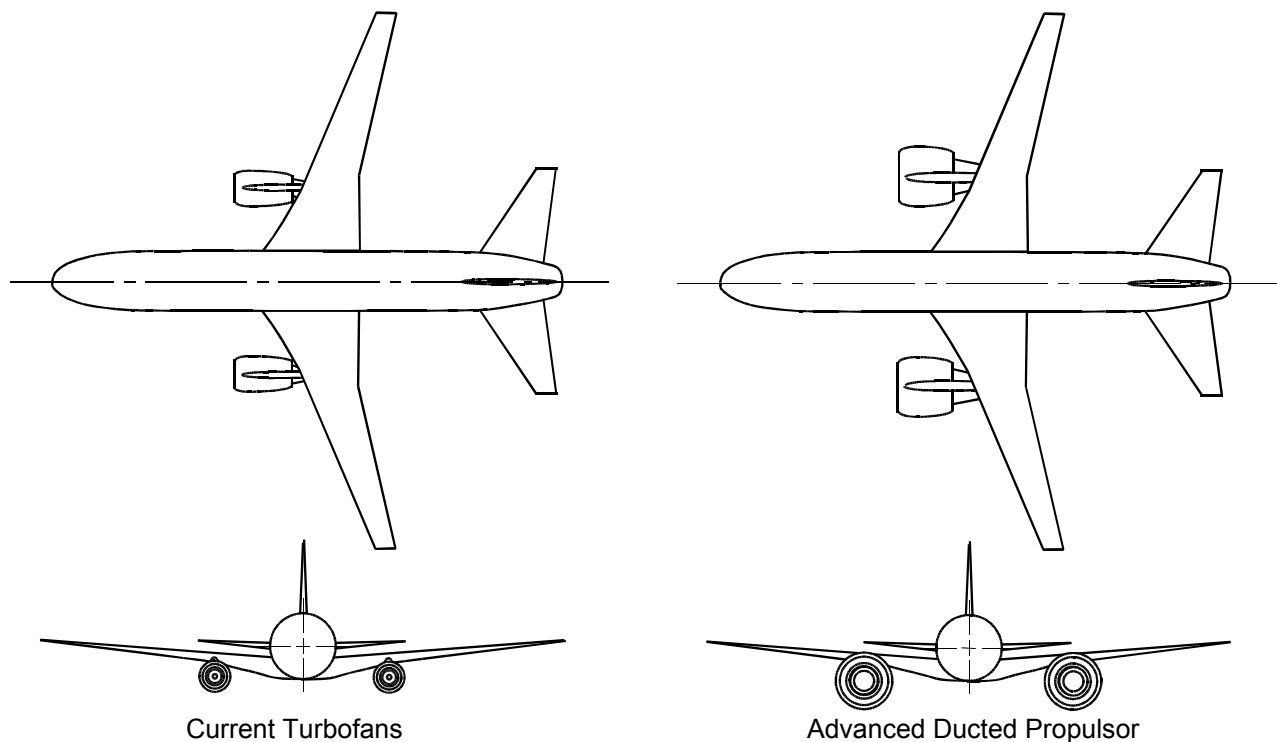


FIGURE 19 - COMPARISON OF CURRENT TURBOFAN AND ADP ENGINE INSTALLATIONS

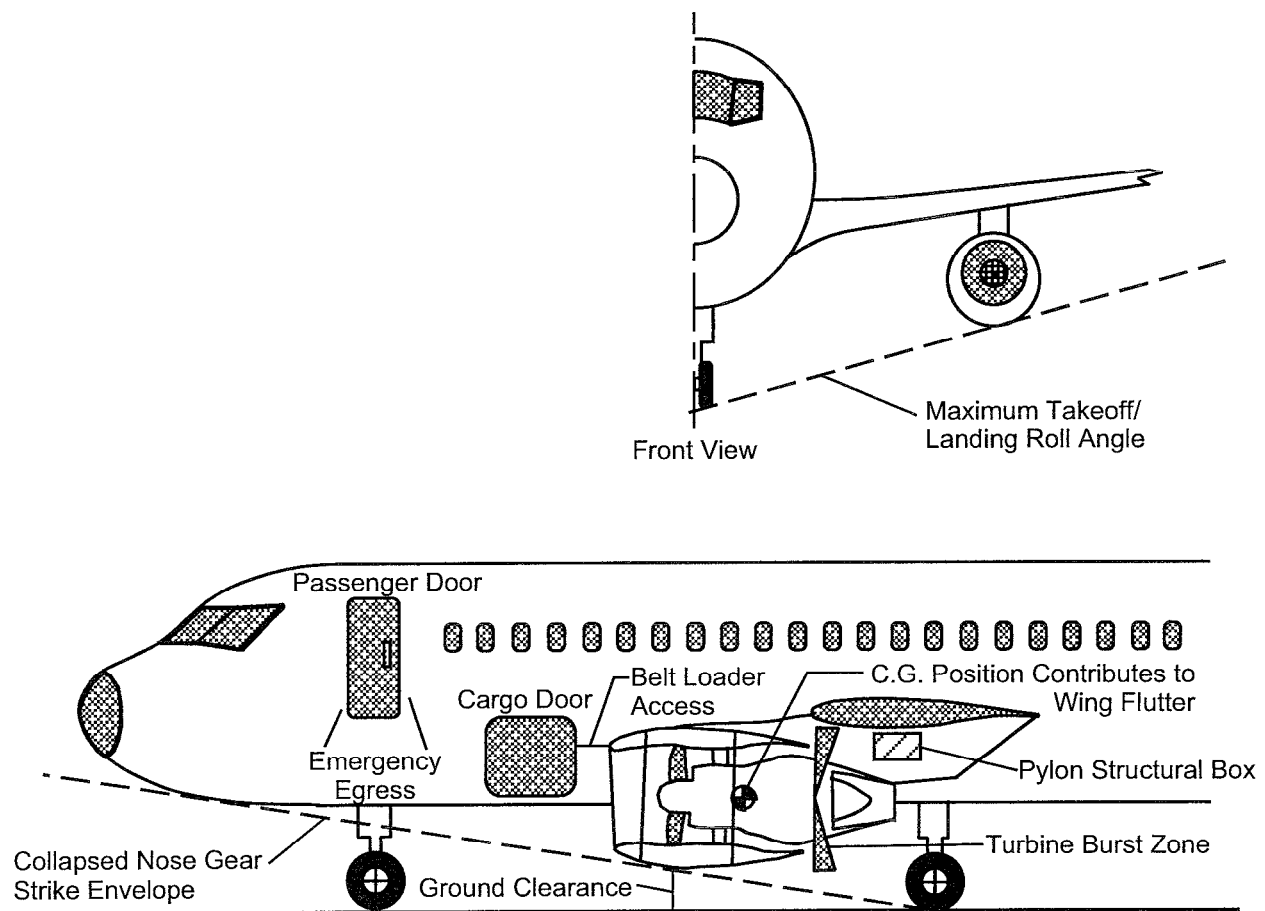


FIGURE 20 - MECHANICAL CONSIDERATIONS FOR WING-MOUNTED NACELLE INSTALLATIONS

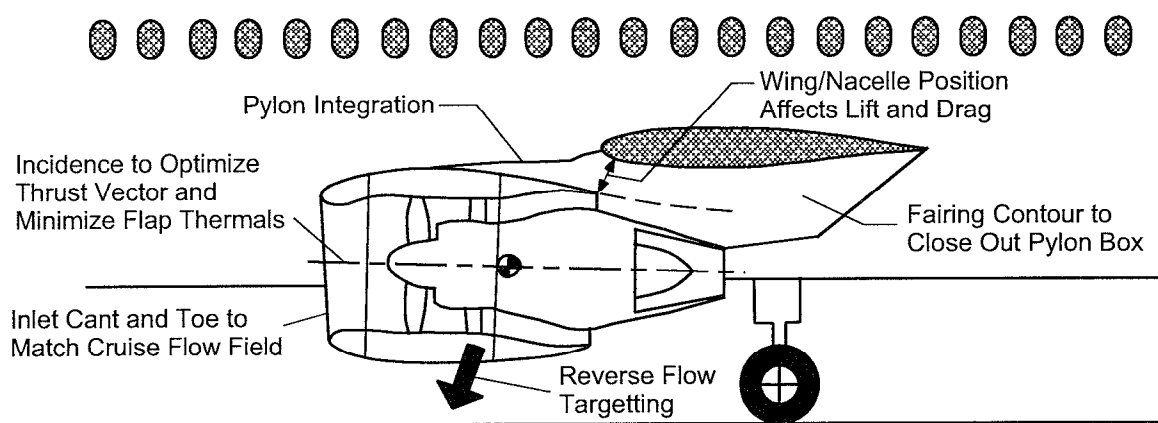


FIGURE 21 - AERODYNAMIC CONSIDERATIONS FOR WING-MOUNTED NACELLE INSTALLATIONS

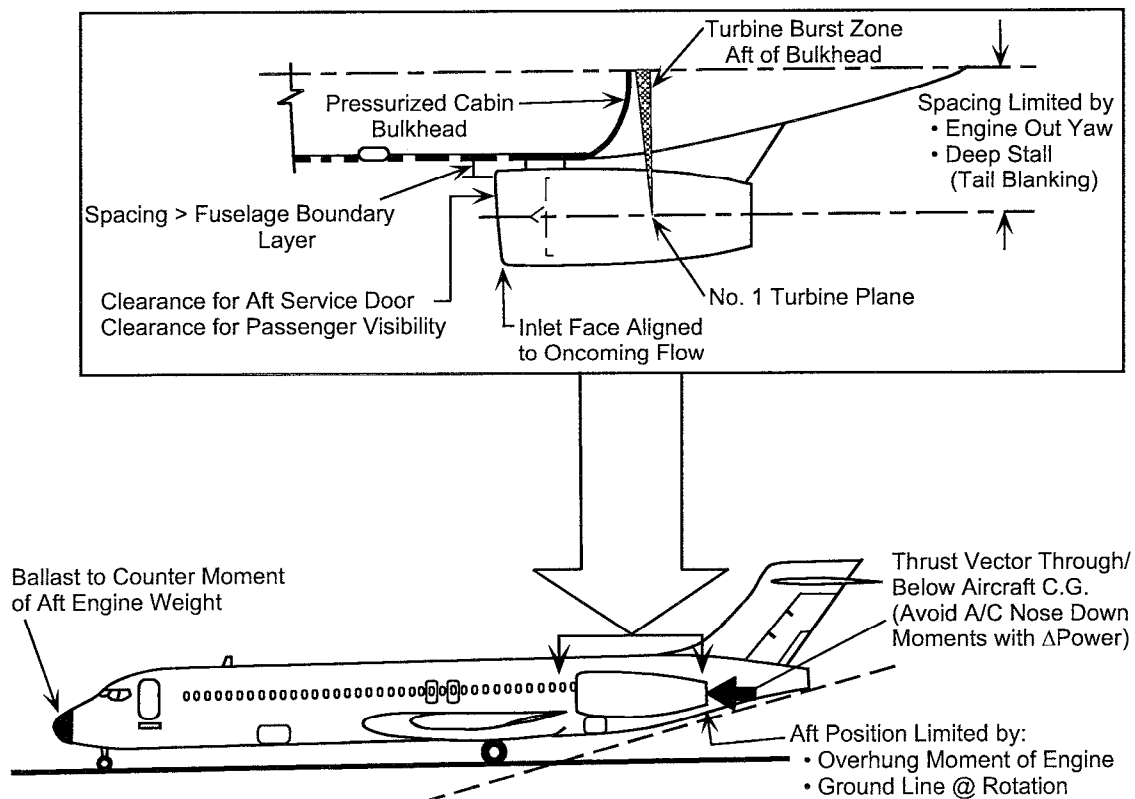


FIGURE 22 - INSTALLATION CONSIDERATIONS FOR AFT-MOUNTED NACELLES

5.1 Installation Effects on the Airframe

Integration of the powerplants with the airframe has always been a delicate exercise for the aircraft manufacturers as discussed in SAE Papers 861720 and 912129, and AIAA Papers 87-2921 and 89-2486. As the state of the art has advanced, aircraft manufacturers have successfully integrated engines having fan diameters of 120 in or more with current large, long-haul, twin-engine aircraft. However, the ultra long-range routes envisioned for the future will place new constraints on propulsion efficiency. These constraints may dictate new very high BPR ADP engines with even larger fan diameters in order to reduce specific fuel consumption (which can be traded for aircraft weight, range, or payload). Advanced Ducted Propulsors designed for long-haul aircraft could have fan diameters up to 160 in, or even larger. Installation of ADP engines of this size will be highly challenging because of their huge relative size (see Figure 19) and, to a lesser extent, to their heavier weight.

5.1.1 Wing Mounted Installations

The increased diameter and weight of the ADP engine and nacelle may adversely affect wing lift, drag, and structural weight if the engine pylon/nacelle is not carefully integrated as discussed in SAE Papers 861720 and 912129, and AIAA-87-2921. The ADP engine/airframe integration required to achieve a preferred nacelle location is discussed in the following paragraphs.

Current clean wing designs are pushed to the limit of today's technology such that the installation of any propulsion package, but especially the large diameter nacelles associated with ADP powerplants, can potentially cause large adverse effects such as shock formation and/or separation on the wing performance. These performance interactions must be accounted for, either experimentally or with CFD. Three-dimensional Navier-Stokes CFD codes are fully capable of providing initial visibility into these effects early in the design cycle (see AIAA-97-0641), especially at cruise conditions where separation effects are expected to be minimal and reasonable absolute drag levels can be predicted. Typical CFD capabilities are demonstrated by the results shown in Figures 23 to 25. These results on a NASA transport wind tunnel model were produced by Bombardier Aerospace utilizing a multi-grid finite-volume Euler code (MGAERO) coupled to an integral boundary layer method.

In addition, inverse design methods coupled with CFD codes can produce wing designs that account for pylon/nacelle installation effects on wing performance and eliminate some of the concern over integrating such large engines with the wing. Final quantification of these effects, and verification of absolute performance, still require experimental validation.

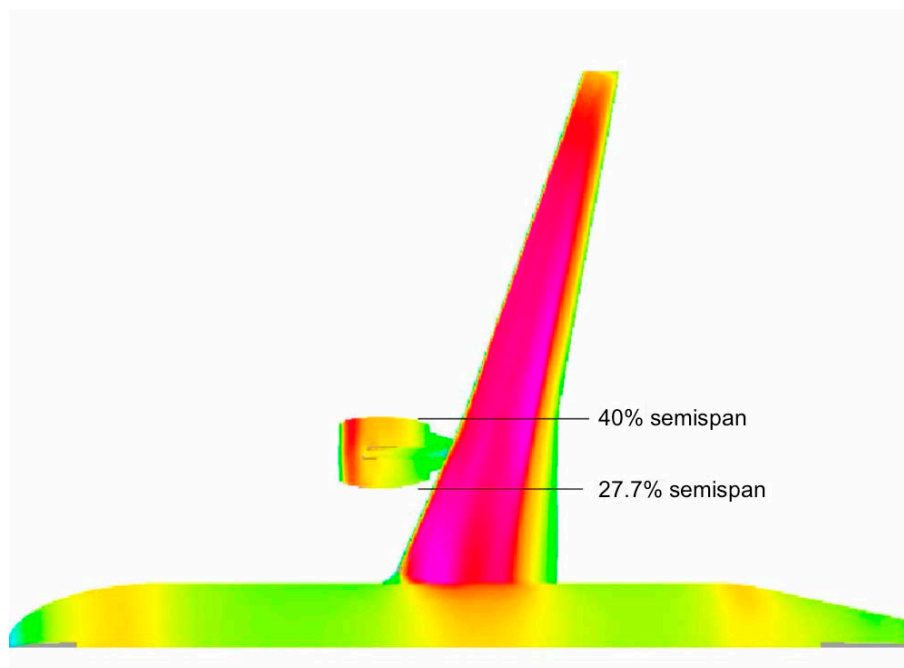


FIGURE 23 - CFD STATIC PRESSURE DISTRIBUTION ON $M = 0.77$ CRUISE TRANSPORT WITH CONVENTIONAL NACELLE

Longitudinal and vertical locations relative to the wing will be dictated by a compromise between nacelle/pylon/wing/exhaust interactions and other airplane system requirements. Issues associated with both of these considerations will be exacerbated by the higher weight and larger size of ADP powerplants. For example, both upwash and safety considerations suggest moving the powerplant forward. However, this move would also increase the wing spar moment and impact flutter boundaries. The larger size and weight of ADP powerplants will almost certainly produce subsonic transport configurations with closer coupled wings and nacelles. Potential disadvantages of this design feature are adverse interactions on wing lift, drag, and stability caused by the closer proximity of both the nacelle and the exhaust flow to the wing.

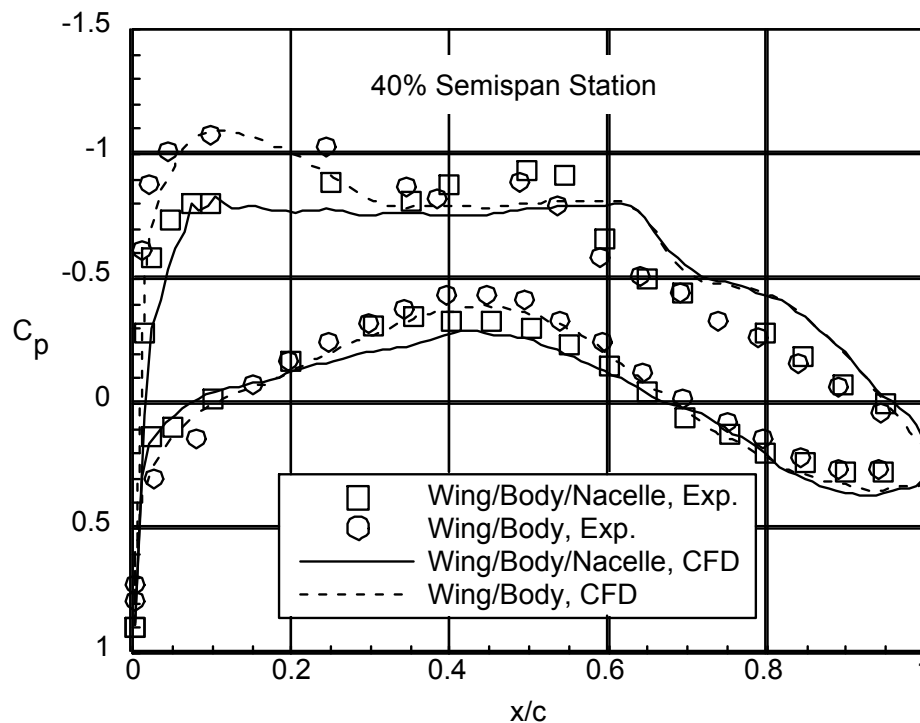


FIGURE 24 - COMPARISON OF CFD AND EXPERIMENTAL WING STATIC PRESSURES

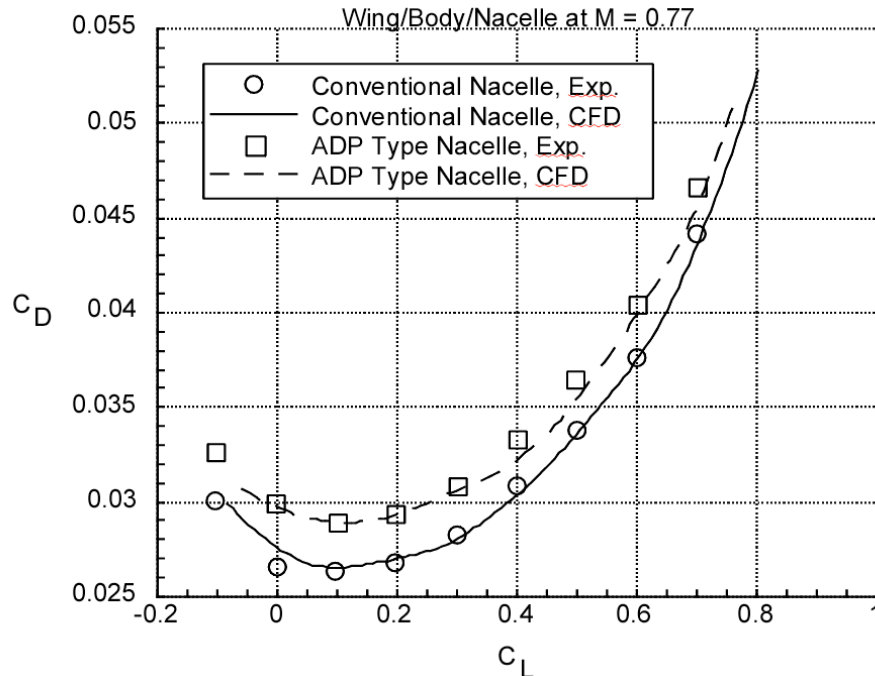


FIGURE 25 - COMPARISON OF CFD AND EXPERIMENTAL DRAG POLARS

Other installation considerations for wing-mounted ADP powerplants exist in addition to the ones described above. Some, such as integration with the wing high lift system and the thrust reverser system, will be discussed later in this Section and in Section 10.

5.1.1.1 Twin-Engine Aircraft

For low-wing aircraft, the optimum aerodynamic engine position may not be achievable because of landing gear length constraints which cause the engine to be too close to the wing. This may lead to performance compromises in both cruise (discussed previously) and high-lift flight regimes. A partial solution to these compromises may be non-symmetric nacelles. Elliptic inlets have already been incorporated into some Boeing 737 models.

A typical ADP installation with high lift devices extended is illustrated in Figure 26. The larger fan size of the ADP can aggravate the engine-out control problems just after take-off. If the wing flaps are not waste-gated around the entire fan exhaust streamtube as illustrated in the figure, there is likely to be a significant powered-lift increment at take-off. This throttle-dependent lift may seem beneficial, but the loss of this increment on one wing during one engine out produces a roll that is a flight safety issue. The waste-gating approach minimizes the roll problem but also reduces high-lift flap area and maximum take-off lift. This compromises airplane takeoff performance for a given field length. The compromise associated with the waste-gating design approach is aggravated by ADP installations because the flap cutouts required to pass the fan exhaust streamtube are much larger for ADP engines than required for current turbofan engines.

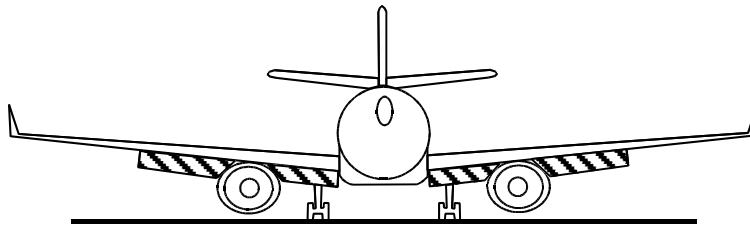


FIGURE 26 - TYPICAL TWIN-ENGINE, LOW-WING ARRANGEMENT WITH WASTE-GATED FLAPS

An alternative design approach is a high-wing configuration such as illustrated in Figure 27. High-wing configurations permit adequate exhaust stream separation from the wing such that the engine-out roll is eliminated without waste gating the flaps and without compromising the landing gear.

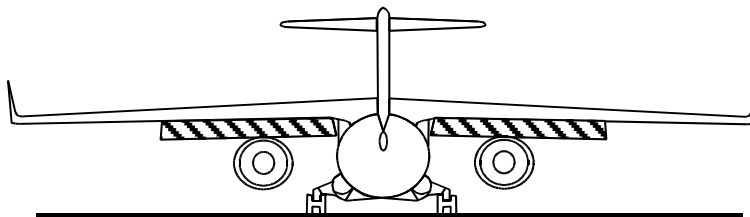


FIGURE 27 - TYPICAL TWIN-ENGINE, HIGH-WING ARRANGEMENT WITH CONTINUOUS FLAPS

5.1.1.2 Four-Engine Aircraft

Fan growth to ADP size does not appear to present new problems for four-engine arrangements such as illustrated in Figure 28, other than reduced ground clearance for low wings. Relative to conventional engine installations, an ADP engine out event is worse for airplane performance in terms of controllability (higher moments). This will be a less sensitive issue on an ADP four-engine configuration than on an ADP twin-engine configuration.

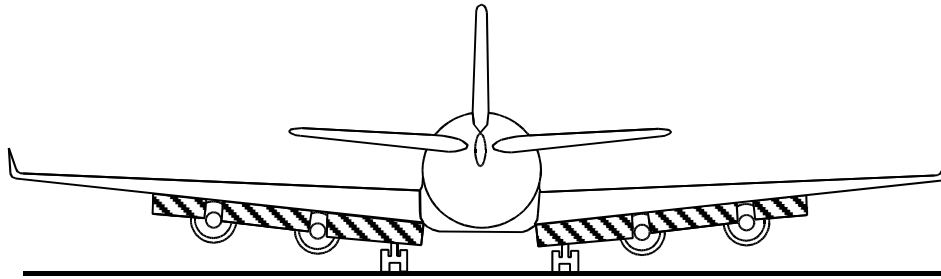


FIGURE 28 - LARGE, 4-ENGINE ARRANGEMENT WITH WASTE-GATED FLAPS (CORE ONLY)

5.1.2 Aft Fuselage-Mounted Installations

While wing-mounted engines appear to offer fewer installation problems than aft-fuselage mounted engines, the ADP may be retrofitted onto existing aft-mount aircraft to improve their economics. A typical aft fuselage-mounted engine installation is illustrated in Figure 29. Such applications will pose installation problems that could cause performance compromises as indicated in AIAA-89-2486. The increased weight of the larger ADP will adversely affect operational flexibility by shifting the empty center of gravity rearward. Also, in order to maintain rotation ground clearance, the engine centerline may have to go up.

Aerodynamic interference becomes important for the aft-mount if the fan cowl is near the wing. For the ADP, the larger size of the inlet and its closer proximity to the wing upper surface tend to unload the wing root area at cruise conditions. This localized unloading results in increased induced drag unless the affected components are recontoured.

In addition, the engine exhaust streamtube may pass in close proximity to horizontal tail surfaces for aft fuselage-mounted engines (see Figure 29). The larger fan diameter of ADP powerplants will exacerbate any exhaust interference effects by bringing the exhaust streamtube even closer to the aircraft control surfaces. Any exhaust interference effects on aircraft stability and control must be carefully considered for these ADP applications.

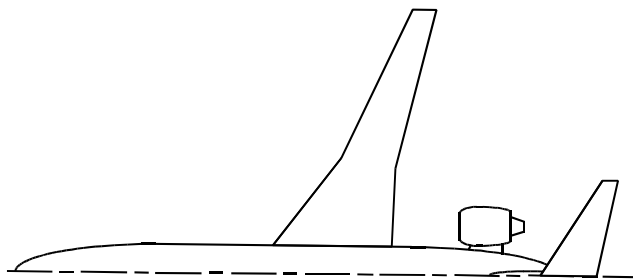


FIGURE 29 - TYPICAL AFT FUSELAGE-MOUNTED ENGINE ARRANGEMENT

5.2 Installation Effects on the Powerplant

The installation effects on the powerplant can be divided into nacelle external performance effects (primarily drag) and engine internal performance effects (primarily thrust). These effects are discussed in AIAA Papers 90-2015 and 90-2146.

Installation effects on ADP nacelle external performance, such as interference from the wing or fuselage, result from the same flow mechanisms as for current turbofan installations. However, because ADP nacelles will probably be more closely coupled to other airplane components, especially for wing-mounted installations (see 5.1.1), there is a concern that interference effects on nacelle drag may be larger for ADP installations. Similar to installation effects on the wing, current CFD codes can provide an early diagnosis of interference effects on nacelle external performance. As discussed in AIAA Papers 93-0528 and 95-1820, inverse design methods coupled with CFD codes are even capable of designing nacelle geometry to provide some desired characteristic (e.g., a favorable pressure distribution for laminar flow), even in the presence of another airplane component such as a wing.

Because of its very low pressure ratio (see Figure 1), ADP internal performance can be very sensitive to installation effects. Since the ADP fan nozzle is not choked at takeoff, for initial climb and for low power cruise, any external flow field disturbance can feed upstream into the fan duct and impact internal or thrust performance. The ADP fan nozzle will also be more sensitive to nozzle suppression effects (change in nozzle back pressure) than current turbofan engines. This is not only because of lower ADP pressure ratios, but also because the ADP nacelle will be more closely coupled to the airframe. To minimize this effect, the fan exit should be located in a region where P_{s19} , at cruise, is near free-stream static pressure. However, this must be done without placing the turbine section in line with a critical structure to ensure that safety is not compromised. Closely coupled wing locations could also be undesirable for the ADP inlet which, being rather large, may experience higher inlet distortion due to a widely varying upwash flow field induced by the wing. Similar inlet distortion problems may also occur for aft fuselage-mounted ADP installations because of inlet proximity to the wing downwash flow field.

5.3 Implications on In-Flight Thrust Determination and Testing

The equations for the thrust accounting system are applicable to any type of turbofan powered aircraft, including ADP installations. Since performance accounting systems are intended to cover a wide range of operating conditions, the evaluation of installation effects (e.g., throttle-dependent force increments) will require considerable experimental testing. Advancements in CFD technology may allow elimination of one experimental test cycle in this process.

The large size of ADP powerplants may require new or expanded test techniques and plans. For example, because of the expected close coupling of the ADP powerplant with other airplane components, clean airplane (powerplant removed) drag polar testing and isolated nacelle testing may be academic exercises for these installations. In addition, until CFD codes are validated for power effects, the validation of ADP powered airplane configurations will likely require installed turbine powered simulator (TPS) models in propulsion integration wind tunnel tests because of the larger interactions expected between the airframe and inlet/exhaust flows. These larger interactions would result from closer engine/airframe coupling and larger inlet/exhaust streamtubes associated with ADP installations. A solution to ADP force accounting problems may exist in considering the aircraft drag polar with flow-through nacelles as a reference condition, and defining throttle-dependent force increments with aircraft scale model tests utilizing installed TPS units. These techniques are described in Section 7. The design and use of TPS units are also discussed in AIAA Papers 84-0593 and 94-2554.

As mentioned in Section 4, many ADP powerplants include some form of variable geometry such as variable nozzle exit area or variable pitch fan blades. These variable geometry features will impact the inlet streamtube, nacelle geometry, and/or exhaust streamtube. Force increments (including airframe, nacelle and mutual interference components) resulting from these changes from the reference condition must be accounted for during experimental and CFD studies. Other force accounting increments that must be defined during the process are the effects of inlet mass-flow ratios and operating nozzle pressure ratios, which differ significantly from the reference conditions. Other factors that would result in changes to nacelle shape (e.g., smart structures) or exhaust flow leakage (e.g., thrust reverser incorporation; see 10.2) must also be accounted for.

6. THRUST METHOD OPTIONS

After giving careful consideration to the installation of very high bypass ratio engines, the next step is to select an in-flight thrust methodology. Sections 6 to 9, which form the core of this document, address the various aspects involved in the selection process:

- Section 6 identifies and details various potential thrust method options which can be considered for ADP in-flight thrust calculation. These methods involve scale model and/or full-scale engine as well as component testing. Power management considerations are also discussed.
- Section 7 reviews all those different tests on an individual basis, covering methods as well as very high bypass ratio engine specifics.
- Section 8 deals with in-flight thrust validation; both flight testing specifics, including installation effects and thrust/drag closure.

- Finally, Section 9 details in-flight thrust uncertainty assessment. Uncertainty spreadsheets are presented that illustrate in-flight thrust uncertainty for each thrust method option based on engine cycle data and instrumentation accuracy.

In the typical competitive aircraft business, where time and money are critical to success, the airframe and engine manufacturers would make their in-flight determination method selection and contractual agreement based on a trade-off between:

- The target uncertainty for in-flight thrust
- The amount of instrumentation and testing (hence time and resources) required to support the thrust method options considered.
- Facility availability

Four methods of defining in-flight thrust are described in Section 4 of AIR1703: Overall Performance, Gas Path/Nozzle Analysis, Nozzle Exit Transverse, and Trunnion Method. Of these methods, the most commonly applied to commercial turbofans are the first two: overall performance and gas path/nozzle analysis. This section presents detailed descriptions of potential methods for use with ADP engines. In addition, considerations relative to power management of very high bypass ratio engines are included. In order that the discussion of each method be complete and stand alone, some text has been repeated in the discussion of the methods. The section is structured as follows:

6.1 Overall Performance Methods

- 6.1.1 Thrust-low rotor speed correlation using ATF
- 6.1.2 Thrust-fuel flow correlation using ATF
- 6.1.3 Thrust-low power turbine inlet EPR (Core EPR or CEPR) correlation using ATF
- 6.1.4 Thrust-low power shaft torque correlation using ATF

6.2 Gas Path/Nozzle Methods

- 6.2.1 Exhaust nozzle coefficients using ATF
- 6.2.2 Compound flow analysis methodology comments
- 6.2.3 Method using GLTF and residual error
- 6.2.4 Static pressure correlation option

6.3 Simulator Methods

- 6.3.1 TPS in ATF
- 6.3.2 TPS in wind tunnel

6.4 Use of cycle models for in-flight thrust determination

6.5 Power management considerations

6.1 Overall Performance Methods

Overall performance methods relate in-flight thrust to one or more commonly measured engine parameters, typically an engine power setting parameter. A preliminary relationship with the chosen parameter is first identified in wind-off tests conducted at an Altitude Test Facility and/or Ground Level Test Facility (ATF or GLTF). With appropriate analytical adjustments for installation and flight effects, such as free-stream suppression and inlet recovery, a first-pass in-flight thrust correlation is then defined. Figures 30 through 37 illustrate the in-flight thrust calculation process for four potential thrust-correlating parameters: corrected low rotor speed (N_1/θ_2^x), corrected fuel flow ($W_F/\delta_2\theta_2^y$), LPT inlet pressure ratio (CEPR), and low-pressure shaft torque (TRQ_L). The attractive part of overall performance methods is that they do not require specific experimental instrumentation, such as pressure rakes, and are therefore easier and cheaper to use. A drawback is that those methods are very configuration dependent, and therefore require a lot of analytical adjustments, with their associated uncertainty.

6.1.1 Thrust-Low Rotor Speed Correlation

Low rotor speed (N_1) is a logical correlation parameter to consider for an overall performance method, since more than 70% of engine gross thrust comes from the bypass stream (the higher the bypass ratio, the bigger the bypass stream contribution). Figures 30 and 31 illustrate the two major test phases of the N_1 correlation in-flight thrust determination process: altitude test facility and aircraft testing.

6.1.1.1 Altitude Test Facility Testing

In Figure 30 an altitude test facility is used to generate a base correlation of corrected engine gross thrust and corrected total inlet airflow against corrected low rotor speed for lines of constant Mach number. As evidenced on Figure 30, measured parameters are:

- W_{1A} : Total inlet airflow, from upstream venturi, or from bellmouth
- P_{t1A} : Inlet total pressure, from inlet rakes
- T_{t1A} : Inlet total temperature, from inlet rakes
- A_{1A} : Inlet highlight area
- A_{seal} : Seal area (detached bellmouth)
- N_1 : Low pressure spool speed
- F_M : Measured thrust, from thrust load cells
- P_{s0} : Ambient cell pressure, from cell static pressure measurements.

At this stage, several comments apply:

- Engine gross thrust and total inlet airflow, as well as N_1 are best corrected relative to fan face conditions (Sta. 2 on Figure 30), since inlets at altitude test facilities and on aircraft are different. Inlet ram recovery characteristics (ERAM1A on Figure 30) are therefore needed, typically from wind tunnel testing and/or CFD calculations.

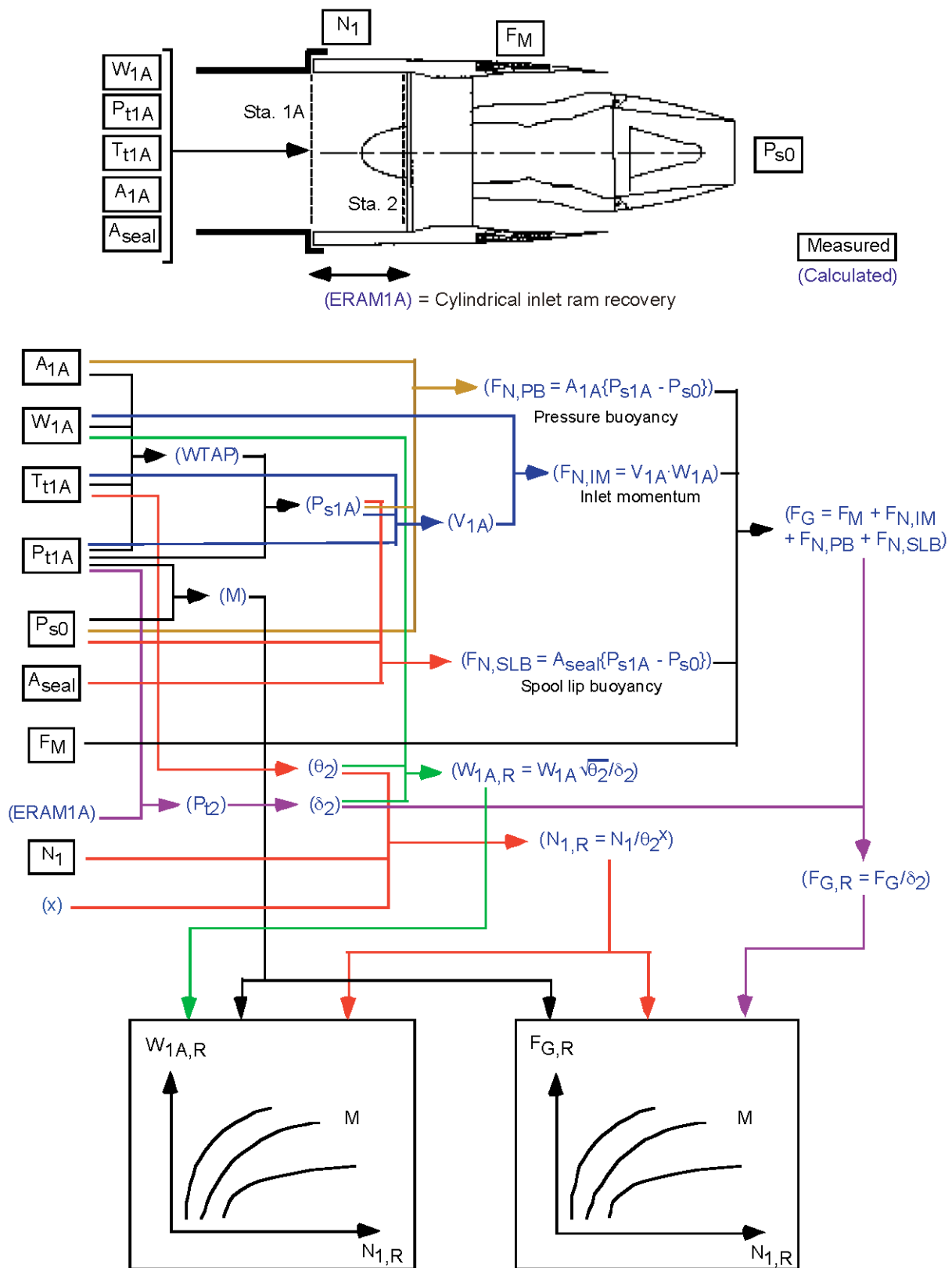


FIGURE 30 - THRUST - LOW ROTOR SPEED CORRELATION: ATF TESTING

- P_{s1A} , inlet static pressure, may be measured; Figure 30 features another option, where P_{s1A} is calculated from the inlet flow parameter WTAP:

$$WTAP = \frac{W_{1A} \times \sqrt{T_{t1A}}}{P_{t1A} \times A_{1A}} = \left(\frac{P_{s1A}}{P_{t1A}} \right)^{\left(\frac{1}{\gamma} \right)} \times \sqrt{\frac{2}{R(\gamma-1)} \left[1 - \left(\frac{P_{s1A}}{P_{t1A}} \right)^{\left(\frac{\gamma-1}{\gamma} \right)} \right]}$$

- Low rotor speed theta exponent (x on Figure 30) can be identified from tests at constant corrected engine gross thrust with different inlet air temperatures; then corrected low rotor speeds are equal. An illustration of the calculation process is provided in Table 3.

TABLE 3 - LOW ROTOR SPEED CALCULATION PROCESS

Runs at constant corrected engine gross thrust	Run 1	Run 2
Low rotor shaft speed	N_1	N_1'
Total inlet air temperature	T_{t1A}	T_{t1A}'
Theta ($\theta_1 = T_{t1A}^\circ R / 518.67$)	θ_1	θ_1'
N_1 theta exponent	x	

with:

$$x = \frac{[\log(N_1) - \log(N_1')]}{[\log(\theta_1) - \log(\theta_1')]}$$

- Ideally, the goal is to have a zero slope on corrected results when plotted versus the ambient test temperature.
- Since the nacelle used in an altitude test facility is usually not the one which will be flown on the aircraft, it is recommended to measure nacelle leakage, and nozzle areas (identifying both throat and exit areas if applicable).
- It is good practice to also plan a sea level static test of the engine, typically in an outdoor facility, to cleanly get the actual static performance signature.
- During testing in an altitude test facility or an outdoor testing facility, actual humidity needs to be measured and corrections applied.

6.1.1.2 Aircraft Testing

During aircraft testing, as evidenced in Figure 31, measured parameters are:

- P_{t1} : Total pressure, from aircraft air data system
- T_{t1} : Total temperature, from aircraft air data system
- P_{s0} : Ambient pressure, from aircraft air data system, or trailing cone
- N_1 : Low rotor speed
- $W_{B,fan}$: aircraft fan air bleed, from calibrated pipes or heat exchanger model
- $W_{B,core}$: aircraft core air bleed, from calibrated pipes
- HPX: aircraft mechanical power extraction

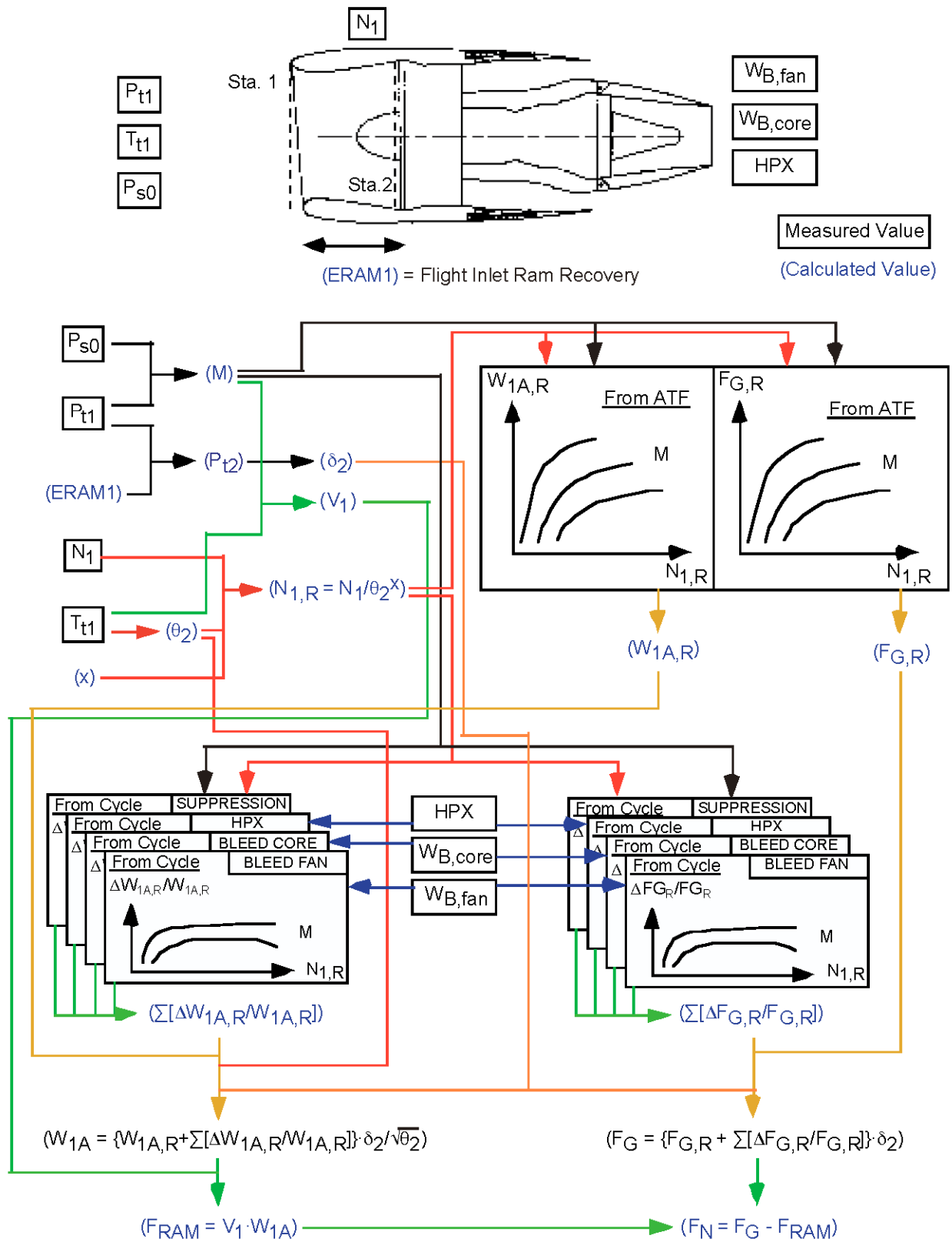


FIGURE 31 - THRUST - LOW ROTOR SPEED CORRELATION: AIRCRAFT TESTING