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Inlet/Engine Compatibility - From Model to Full Scale Development

RATIONALE

The intent of this document is to capture the experience and lessons learned since approximately 1967 necessary to ensure that model-scale inlet total-pressure recovery and distortion data faithfully represent the corresponding full-scale inlet recovery and distortion characteristics.

This document contains information that is fundamental to the discipline of inlet-engine compatibility and is expected to remain stable for the foreseeable future.

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FOREWORD

The SAE S-16 Committee, Turbine Engine Inlet Flow Distortion, is pleased to dedicate this document to Mr. Gregg Turley. Gregg was a member of the Committee from 2001 until his untimely death in 2006. Gregg will be remembered for his quiet, understated approach and bringing his knowledge, perceptions, and range of experiences to tasks at hand including this document. This document is a collection of lessons learned since the late 1960s by practitioners of this discipline including those of Gregg while working at Northrop Grumman Corporation. These will be a resource to both new and experienced inlet/engine compatibility practitioners for decades to come.

This document has been cleared for public release per Case Number 88ABW-2010-2038.

The SAE S-16 Committee welcomes input from both industry and government organizations relative to the contents of this document. Please feel free to address any comments on this document to the Chairman, SAE S-16 Committee.

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1. SCOPE

This document reviews the state of the art for data scaling issues associated with air induction system development for turbine-engine-powered aircraft. In particular, the document addresses issues with obtaining high quality aerodynamic data when testing inlets. These data are used in performance and inlet-engine compatibility analyses. Examples of such data are: inlet recovery, inlet turbulence, and steady-state and dynamic total-pressure inlet distortion indices. Achieving full-scale inlet/engine compatibility requires a deep understanding of three areas: 1) geometric scaling fidelity (referred to here as just “scaling”), 2) impact of Reynolds number, and 3) ground and flight-test techniques (including relevant environment simulation, data acquisition, and data reduction practices). The Model-to-Full Scale Subcommittee of the S-16 Turbine Engine Inlet Flow Distortion Committee has examined archives and has obtained recollections of experts regarding air induction system development experience to produce this document.

1.1 Purpose

The primary objective of this document is to provide a consolidated record of what is known regarding the effectiveness of wind-tunnel scale-model testing in the prediction of full-scale flight characteristics such as inlet recovery, inlet turbulence, and steady-state and dynamic total-pressure inlet distortion. Discussion is offered regarding these findings in light of our current knowledge and understanding. Based on this discussion material, the SAE S-16 Committee has been able to achieve consensus on lessons learned and to provide recommendations.

1.2 Application

This document focuses on turbine-engine-powered military air vehicles, including some recent advanced aircraft air-induction systems. No information is provided for commercial transport high-bypass turbofan installations, small turbo-jet/turbofan aircraft, turboprop aircraft, turbine-engine-powered missiles, ground vehicle installations, or auxiliary power units. However, many of the lessons learned and recommendations made in this document are applicable to these installations as long as the user recognizes and understands the limitations of the information that he/she is attempting to use. This statement is based on anecdotal discussions with engineers who work or have worked on such installations and who have judiciously and successfully applied these lessons and recommendations.

2. REFERENCES

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications will apply. The applicable issue of other publications will be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited here, 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 Applicable Documents

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.

ARP1420	Gas Turbine Engine Inlet Flow Distortion Guidelines
AIR1419	Inlet Total-Pressure-Distortion Considerations for Gas-Turbine Engines
AIR5866	An Assessment of Planar Waves
AIR5686	A Methodology of Assessing Inlet Swirl Distortion

2.2 Applicable References

- 2.2.1 Aerodynamics Research Branch, NACA Headquarters, “Bibliography of NACA and Other Reports on Air Inlets and Internal Flows,” NACA RM No. 8J05, October 1948.

- 2.2.2 Surber, L.E., and Robinson, C.P., "Survey of Inlet Development for Supersonic Aircraft," AIAA 83-1164, June 1983.
- 2.2.3 Smith, Robert, Jr., "Marrying Airframes and Engines in Ground Test Facilities – An Evolutionary Revolution," AIAA 95-0950, September 1995.
- 2.2.4 Davis, W.F. and Sherrer, R., "Aerodynamic Principles for the Design of Jet-Engine Induction Systems," NACA RM A55F16.
- 2.2.5 Alford, J.S., GER-1404, General Electric, "Inlet Flow Distortion Index," International Days of Aeronautical Sciences, Paris, France, May 1957.
- 2.2.6 Schweikhard, W.G., and Dennon, S.R., "Review and Evaluation of Recent Developments of Melick Inlet Dynamic Flow Distortion Prediction," NASA CR 4061, May 1987, p. 78.
- 2.2.7 Air Force Aero Propulsion Laboratory, "Proceedings of the Air Force Airframe – Propulsion Compatibility Symposium," AFAPL TR-69-103, June, 1970.
- 2.2.8 Burcham, F.W., and Hughes, D., "Analysis of Inlet-Flight Pressure Fluctuations Leading To Engine Compressor Surge of an F-111A Airplane for Mach Numbers to 2.17," AIAA Paper No. 70-624, June, 1970.
- 2.2.9 Behal, J.A., Belga, M.H., and Simons, D.E., "Wind Tunnel/Flight Data Correlation, Final Report Vol. I, II, III, and IV," AFFDL TR-71-105, October 1971.
- 2.2.10 Stevens, C.H., Spong, E.D., Nugent, J., and Neumann, H.C., "Reynolds Number, Scale, and Frequency Content Effects on F-15 Instantaneous Distortion," AIAA 79-0104, January 1979.
- 2.2.11 Smeltzer, D.B., Smith, R.H., and Cubbison, R.W., "Wind Tunnel and Flight Performance of the YF-12 Inlet System," AIAA 74-621, July 1974.
- 2.2.12 Stevens, C.H., Spong, E.D., and Hammock, M.S., "F-15 Inlet/Engine Test Techniques and Distortion Methodologies Studies, Vol. I, Technical Discussion," NASA CR 144866, June 1976.
- 2.2.13 Farr, A.P., "Evaluation of F-15 Inlet Dynamic Distortion," AIAA 73-784, August 1973.
- 2.2.14 Farr, A.P., and Schumacher, G.A., "System for Evaluation of F-15 Inlet Dynamic Distortion," Progress in Astronautics and Aeronautics, Vol. 34, Instrumentation for Airbreathing Propulsion, Fuhs, A. E. and Kingery, M., Editors, The MIT Press, 1974, pp. 59-76.
- 2.2.15 Imfeld, W.F., "The Development Program for the F-15 Inlet," AIAA 74-1060, October 1974.
- 2.2.16 Webb, L.D., Whitmore, S.A., and Jannsen, R.L., "Preliminary Flight and Wind Tunnel Comparisons of the Inlet/Airframe Interaction of the F-15 Airplane," AIAA 79-0102, January 1979.
- 2.2.17 Webb, L.D., Andryich, V., and Whitmore, S.A., "Flight and Wind Tunnel Comparisons of the Inlet/Airframe Interaction of the F-15 Airplane," NASA TP 2374, November 1984.
- 2.2.18 Johnson, R.H., "Inlet Distortion Scaling of Wind Tunnel Model Results," NASA CR-143840, December 1976.
- 2.2.19 Johnson, R.H., "Comparison of Inlet Distortion from Flight and Wind Tunnel Tests," NASA CR-144864, April 1978.
- 2.2.20 Haagenson, W.R., and Randall, L.M., "Inlet Development for the B-1 Strategic Bomber," AIAA-74-1064, October 1974.
- 2.2.21 Graham, F.J., "Results of a 0.1-Scale B-1 Inlet Model at Transonic and Supersonic Mach Numbers," AEDC-TR-71-219, October 1971.

- 2.2.22 Riddell, J.F., "Results of a 0.2-Scale B-1 Inlet Verification Model Test at Transonic and Supersonic Mach Numbers," AEDC-TR-72-156, October 1972.
- 2.2.23 Mace, J., Turley, G., and Ball, R., "Wind Tunnel to Flight Correlations of F/A-18E/F Inlet Performance," AIAA Paper 2009-5459, August 2009.
- 2.2.24 Hall, G.R. et al., "Development of the F/A-18 E/F Air Induction System," AIAA-93-2152, June 1993.
- 2.2.25 Kidman, D.S., Reagan, P.V., and Malloy, D.J., "Comparison of Inlet Compatibility Results from Subscale Wind Tunnel and Full-Scale Flight Tests of the F/A-22 Aircraft with the F119-PW-100 Engine," ISABE-2005-1169, September 2005.
- 2.2.26 Shepard, D., "A Two-Dimensional Interpolation Function for Irregularly-Spaced Data," Proceedings of the 1968 23rd ACM National Conference, January 1968, pp. 517-524.
- 2.2.27 McCallum, B.N., "F-16 Inlet Stability Investigation," AIAA-89-2465, 1989.
- 2.2.28 McDonald, T. and Barter, S., "F-16 Conformal Fuel Tank Initial Envelope Expansion," Society of Experimental Test Pilots 45th Meeting, September 2001.
- 2.2.29 Hurwitz, W.M. and Whitcomb, K.G., "Flight Test Validation of B-2 Inlet/Engine Compatibility: A Risk Management Approach," AIAA 97-3157, July 1997.
- 2.2.30 Gridley, M.C. and Cahill, M.J., "ACIS Air Induction System Trade Study," AIAA-1996-2646, July 1996.
- 2.2.31 Braslow, A.L. and Knox, E.C., "Simplified Method for Determination of Critical Height of Distributed Roughness Particles for Boundary-Layer Transition of Mach Numbers from 0 to 5," NACA TN 4363, 1958.
- 2.2.32 Braslow, A.L., Harris, R.V., Jr., and Hicks, R.M., "Use of Grit-Type Boundary-Layer-Transition Trips on Wind Tunnel Models," NASA TN D-3579, 1966.
- 2.2.33 Arend, D.J., "Evaluation of an Innovative Supersonic Boundary Layer Transition Device – Phase I Results," AIAA Paper No. 98-3422, July 1998.
- 2.2.34 Rae, W.H., Jr. and Pope, A., "Low-Speed Wind Tunnel Testing," John Wiley and Sons, New York, New York, 1984.
- 2.2.35 Beale, D.K., Cramer, K.B., and King, P., "Development of Improved Methods for Simulating Aircraft Engine Inlet Distortion in Turbine Engine Ground Tests," AIAA Paper No. 2002-3045, June 2002.
- 2.2.36 Brimelow, B., Collins, T.P., and Pfefferkorn, G.A., "Engine Testing in a Dynamic Environment," AIAA Paper No. 74-1198, October 1974.
- 2.2.37 Steenken, W.G. et al., "Factors Affecting Inlet-Engine Compatibility During Aircraft Departures at High Angle of Attack for F/A-18 Aircraft," National Aeronautics and Space Administration Report TM-1999-206572, February 1999.

2.3 Additional References

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

- 2.3.1 Amin, N.F. and Hollweger, D.J., "F/A-18 Inlet/Engine Compatibility Flight Test Results," Journal of Aircraft, Vol. 20, Number 8, August 1983.
- 2.3.2 Arend, D.J. and Saunders, J.D., "An Experimental Evaluation of the Performance of Two Combination Pitot Pressure Probes," AIAA Paper 2009-1073, January 2009, p. 16.

- 2.3.3 Beaulieu, W. D., Boyd, Jr., H. E., Kostin, L. C., and Martin, A. W., "Propulsion System Flow Stability Program (DYNAMIC), Phase II Final Technical Report, Part VI Inlet Turbulence Scaling," AFAPL-TR-69-113, Part VI, February 1970.
- 2.3.4 Martin, A.W., "Propulsion System Flow Stability Program (DYNAMIC), Phase II Final Technical Report, Part I Summary," AFAPL-TR-69-113, Part I, February 1970.
- 2.3.5 Yuhas, A.J., Ray, R.J., Burley, R.R., Steenken, W.G., Lechtenberg, L., and Thornton, D., "Design and Development of an F/A-18 Inlet Distortion Rake: A Cost and Time Saving Solution," October 1995.
- 2.3.6 Blackwell, J.A., Jr., "Preliminary Study of Effects of Reynolds Number and Boundary-Layer Transition Location on Shock-Induced Separation," NASA TN-5003, 1969.
- 2.3.7 Bowditch, D.N. and Coltrin, R.E., "A Survey of Inlet/Engine Distortion Compatibility," NASA TM-83421, June 1983.
- 2.3.8 Brunner, D.W., Marshall, F.L., Marrs, K.J., Edwards, W.E., Pascoe, R.A., and Forner, J.A., "Development of the Integrated Propulsion System for the AGM-86A Air Launched Cruise Missile," AIAA 76-916, September 1976.
- 2.3.9 Burcham, F.W. and Bellman, D.R., "A Flight Investigation of Steady-State and Dynamic Pressure Phenomena in the Air Inlets of Supersonic Aircraft," AGARD CP-91-71, Paper No. 24, September 1971.
- 2.3.10 Burcham, F.W. and Bellman, D.R., "A Flight Investigation of Steady-State and Dynamic Pressure Phenomena in the Air Inlets of Supersonic Aircraft," NASA TMX-67495.
- 2.3.11 Cawthon, J.A., Truax, P.P., and Steenken, W.G., "Supersonic Inlet Design and Airframe-Inlet Integration Program (Project Tailor-Mate)," AFFDL-TR-71-124, Vol. III, May 1973.
- 2.3.12 Colbourne, D.E. and Flitcroft, J.E., "Prediction and Measurement of Time-Variant, Three-Dimensional Flows in Military Aircraft Intakes," Paper No. 4, AGARD CP-301, May 1981.
- 2.3.13 Coulam, Robert F., "Illusions of Choice – Robert MacNamara; The F-111; The Problems of Weapons Acquisition," ISBN 0-691-07583-2, Princeton University Press, 1977.
- 2.3.14 Cox, R.A. "Low Speed, Flat Plate, Carborundum Grit Trip Strip," AIAA International Meeting & Technical Display, AIAA Paper No. 80-0868, May 1980.
- 2.3.15 Cubbison, R.W., Meleason, E.T., and Johnson, D.F., "Performance Characteristics from Mach 2.58 to 1.98 of an Axisymmetric Mixed-Compression Inlet System with 60-Percent Internal Contraction," NASA TM X-1739, February 1969.
- 2.3.16 Hall, G., Hurwitz, W.M., Tiebens, G., Norby, W.P., Singhsinuk, P., and Wilt, C.E., "Development of the F/A-18E/F Air Induction System," AIAA 93-2152, June 1993.
- 2.3.17 Hodder, B.K., "An Investigation of Engine Influence on Inlet Performance," NASA CR 166136, January 1981.
- 2.3.18 Huges, D.L., Holzman, J.K., and Johnson, H.J., "Flight-Determines Characteristics of An Air Intake System on an F-111A Airplane," NASA TND-6679.
- 2.3.19 Younghans, J.L. et al., "Low Speed Effects of Reynolds Number and Lip Geometry on High Bypass Ratio Inlet Performance," AIAA 82-0059, June 1982.
- 2.3.20 Wasserbauer, J.F., Meleason, E.T., and Burstadt, P.L., "Experimental Investigation of the Performance of a Mach 2.7 Two-Dimensional Bifurcated Duct Inlet with 30 Percent Internal Contraction," NASA TM 106728, May 1996.
- 2.3.21 Surber, L.E. and Stava, D.J., "Supersonic Inlet Performance and Distortion During Maneuvering Flight," AGARD CP-91-71, Paper No. 25, September 1971.

- 2.3.22 Leamer, P.C. and Kennon, I.G., "Experimental Investigation of a 0.15-Scale Model of an Underfuselage Normal Shock Inlet," NASA CR 3049.
- 2.3.23 MacMiller, C.J., and Haagenson, W.R., "Unsteady Distortion Characteristics with the B-1B," NA-86-1490A, 68th Specialists Meeting of the AGARD Propulsion and Energetics Panel on Engine Response to Distorted Inflow Conditions, Munich, Germany, September 1986.
- 2.3.24 MacMiller, C.J., and Haagenson, W.R., "Unsteady Inlet Distortion Characteristics with the B-1B," Paper No. 16, AGARD CP-400, March 1987.
- 2.3.25 Motycka, D.L., "Comparison of Model and Full Scale Inlet Distortion for Subsonic Commercial Transport Inlets," AIAA 84-2487, 1984.
- 2.3.26 Norby, W.P., "Small Scale Inlet Testing for Low Cost Screening Applications," AIAA-90-1926, July 1990.
- 2.3.27 Reukauf, P.J., Schweikhard, W.G., and Arnaiz, H., "Flight-Test Techniques for Obtaining Valid Comparisons of Wind-Tunnel and Flight Results From Tests on a YF-12 Mixed-Compression Inlet," AIAA 74-1195, October 1974.
- 2.3.28 Wasserbauer, J.F., Shaw, R.J., and Neumann, H.E., "Design of a Very-Low-Bleed Mach 2.5 Mixed-Compression Inlet with 45 Percent Internal Contraction," NASA TMX-3135, March 1975.
- 2.3.29 Robins, P.J., "Research into the Effects of Scale and Fan Influence on Intake Performance. Report 1. Test on a Full Scale 'S' Duct," Rolls-Royce IAR 00017, September 1972.
- 2.3.30 Robins, P.J., "Research into the Effects of Scale and Fan Influence on Intake Performance. Report 2. Test on a Full-Scale Pod Intake," Rolls-Royce IAR 00018, September 1972.
- 2.3.31 von Doenhoff, A.E. and Horton, E.A., "A Low-Speed Experimental Investigation of the Effect of a Sandpaper Type of Roughness on Boundary-Layer Transition," NACA TN 3858, 1956.
- 2.3.32 Schweikhard, W.G. and Montoya, E.J., "Research Instrumentation Requirements for Flight/Wind Tunnel Tests of the YF-12 Propulsion System and Related Flight Experience," Progress in Astronautics and Aeronautics, Vol. 34, Instrumentation for Airbreathing Propulsion, Fuhs, A.E. and Kingery, M., Editors, The MIT Press, 1974, pp.19-39.
- 2.3.33 Schweikhard, W.G. and Cubbison, R.W., "Preliminary Results From Wind Tunnel and Flight Tests of the YF-12 Propulsion System," NASA TMX-56016, 1973.
- 2.3.34 Sherman, D.A., Motycka, D.L., and Oates, G.C., "Experimental Evaluation of a Hypothesis for Scaling Inlet Turbulence Data," AIAA 71-669, June 1971.

2.4 Symbols and Abbreviations

AEDC	Arnold Engineering Development Center
AFB	Air Force Base
AFSC	Air Force Systems Command
AIP	aerodynamic interface plane
AIR	Aerospace Information Report
AOA, α	angle of attack
AOS, β	angle of sideslip
APC	Airframe Propulsion Compatibility

ARP	Aerospace Recommended Practice
BLC	boundary layer control
CFD	computational fluid dynamics
D	diameter
EAID	engine auxiliary inlet door
ECS	environmental control system
FLT	full-scale flight-test vehicle
FM	frequency modulation
FOD	foreign object damage
FSCP	full-scale with cold pipe
FSE	full-scale with engine
GE	General Electric
H	height of diverter
HARV	High Angle-of-Attack Research Vehicle
ICD	Interface Control Document
IEC	inlet/engine compatibility
KC	distortion descriptor sensitivity coefficients
L	length
LEX	leading edge extension
m	massflow rate
M	Mach number
MDC	McDonnell Douglas Corporation
NACA	National Advisory Committee for Aeronautics
NASA	National Aeronautics and Space Administration
NATF	Navy Advanced Tactical Fighter
P	pressure
$\bar{P}$	time average pressure
P_t	total pressure
PRS	fan/compressor stability pressure ratio

PRSM	fan/compressor stability pressure ratio margin
P&W	Pratt & Whitney
q	dynamic pressure
R	gas constant for air
R_x, R_L	Reynolds number based on length
R_k	Reynolds number based on surface roughness
RPM	revolutions per minute
S	Strouhal number
SAE	Society of Automotive Engineers
SAFS	secondary airflow system
SPO	system program office
STOVL	short takeoff / vertical landing
T	temperature
$\bar{T}$	time average temperature
T_t	total temperature
TFX	Trigraph for Joint Air Force – Navy Project resulting in F-111A/B
Tu	turbulence
V	velocity
WAT	corrected mass flow
Y_{DIV}	boundary layer diverter offset
ΔPC	ARP 1420 circumferential distortion descriptor
ΔPR	ARP 1420 radial distortion descriptor
$\Delta PRMS$	root mean square pressure variation
ΔPRS	fan/compressor stability pressure ratio change
Δx	boundary layer transition length
θ	circumferential angular position
γ	specific heat ratio of air
f	frequency
δ'	boundary layer displacement thickness
k	surface roughness height

μ	viscosity
ν, ν_k	kinematic viscosity
τ	time scale
u, u_k	velocity in boundary layer

Subscripts

$0, \infty$	freestream
2	aerodynamic interface plane (AIP) measurement station
cb	centerbody
FS	full scale
max	maximum
min	minimum
MS	model scale
st	shock trap

Distortion Descriptors

IDC	GE circumferential distortion index
IDL	GE combined descriptor
IDR	GE radial distortion index
IDT	GE total distortion index
$K_\theta, K_{\theta_{\text{theta}}}$	Pratt & Whitney circumferential descriptor
K_{a2}	Pratt & Whitney combined descriptor

3. INTRODUCTION

Since the introduction of turbine engines into aircraft, practices used for developing, testing, and evaluating inlets have evolved, largely due to three influences. The first influence is the expanding speed, maneuver, and survivability envelopes of aircraft. The second is the improved understanding of the effects that highly turbulent flows, in particular, have on engine operability. Finally, the third is the desire to reduce technical, schedule, and cost risks. This evolution has occurred over the time span of a single generation of engineers. The SAE S-16 Committee deemed it prudent to capture the background and lessons learned leading to current practices used for wind-tunnel testing, computational techniques, and flight testing of inlet systems.

The design process leading to a final configuration of an inlet system is iterative in balancing technical and programmatic goals or requirements. During these iterations, the evolution of the inlet and its integration into the airframe relies heavily on wind-tunnel testing and computational fluid dynamic (CFD) analyses. Currently, wind-tunnel testing of subscale inlet models remains the primary tool for acquiring dynamic total-pressure data at the aerodynamic interface plane (AIP), and is the primary source for inlet data used for judging the compatibility of the propulsion system before flight. Inlet/engine compatibility deficiencies can be identified and modifications proposed based on subscale inlet test data.

Practices for inlet development, test, and evaluation are constantly being improved to fit within this evolving, iterative design process. During the early design stages of a program, the design proceeds using empirical databases and CFD tools to assess the need for alterations to the inlet's moldline and its integration with the airframe. These analyses are typically done using full-scale geometry and flight conditions. As the design proceeds and the moldlines are sufficiently matured, the practice of testing subscale inlet models in wind tunnels is introduced. In doing so, there is an assumption based on fluid dynamic theory that data obtained using a subscale model in the tunnels is correlated with the corresponding data of the full-scale vehicle in flight. Experiences garnered and reported on by this generation of engineers have shown that this assumption is largely correct.

In early reports, "scaling" had two distinct meanings. The first meaning referred to the geometric relationship between the subscale model and its components, and the corresponding full-scale geometry. The second meaning referred to the mathematical relationship between the data obtained on the subscale model in the tunnel and data obtained on the full-scale flight vehicle. Both relationships are examined in this report. That is to say, techniques are examined for scaling the geometry to obtain similar flow conditions about the subscale and full-scale geometries. And the correlations of data taken with subscale models in wind tunnels to data taken with corresponding full-scale vehicles at flight conditions are examined.

Information in this document is arranged to provide insight into the state of the art, and outlines the path that practitioners followed to arrive at this state. Inlet/airframe integration practices took a dramatic turn with the development of the F-111 aircraft. The next section reviews the practices before the F-111. It also examines the pivotal events surrounding the F-111's inlet development. Case studies of inlet systems developed after the F-111, from the timeframe of the RA-5C to the F-22, are presented. The intent is to portray the evolution of scaling practices for developing, testing, and evaluating inlet systems. Current scaling practices are reviewed along with lessons learned by this generation of engineers.

4. BACKGROUND

The understanding of inlet dynamic distortion as a consideration for inlet/engine operability in gas turbine powered aircraft has been improving since the late 1960s. In the mid-1970s, as the destabilizing effects of inlet dynamic distortion in gas turbine engines were better recognized, the SAE S-16 Committee on Turbine Engine Inlet Flow Distortion established guidelines for its characterization and formulated a methodology for correlating the resulting effect on turbine-engine compression-system aerodynamic stability. The resulting recommendations outlined in ARP1420 and AIR1419 have been adopted in various forms in essentially every major aircraft turbine-engine installation design since then. Although the specific methodology used in each program has varied in practice, the essential components and inherent assumptions have been the same.

Aircraft systems developed prior to the F-111 had no insight that an inlet's dynamic total-pressure distortion had a destabilizing effect on engine operability. At most, there was recognition that steady-state total-pressure distortion was important (e.g., steady-state distortion methodology was applied in the development of the B-58 (Reference 2.2.1)). Examining these early systems listed in Table 1 provides insight into the evolution of inlet integration for early military aircraft, and specifically boundary-layer management approaches. For additional insight, an excellent survey of inlet development is provided in Reference 2.2.2.

TABLE 1 - EARLY AIRCRAFT PROGRAMS OFFERING INSIGHT INTO THE EVOLUTION OF INLET/AIRFRAME INTEGRATION TECHNOLOGY

Aircraft	Engines	First Flight Date
P-59	I16-GE	1942
P-80	J33-A-21	1944
F-89	J35-A-35	1948
F-100	J57-P-21A	1953
F-101	J57-P-55	1954

During and after the development of the F-111 aircraft, researchers focused on understanding and developing methods to assess the effect that inlet dynamic total-pressure distortion had on engine operability. This work included the development of methodologies for simulating dynamic distortion using subscale models tested in wind tunnels and measuring such distortion in flight test. Most military aircraft programs initiated after the F-111 development benefited from this research. A reduced number of these programs have had both wind-tunnel and flight-test elements, thus allowing an evaluation of our understanding and ability to correlate inlet total-pressure-recovery and dynamic-distortion data between subscale models tested in wind tunnels and full-scale aircraft tested in flight. Some of these aircraft programs that have readily accessible data are listed in Table 2 and are examined in Section 5.

TABLE 2 - AIRCRAFT PROGRAMS OFFERING WIND TUNNEL TO FLIGHT CORRELATIONS OF INLET RECOVERY AND DYNAMIC TOTAL-PRESSURE DISTORTION

Aircraft	Engines	First Flight Date
F-111	TF30-P-103	1964
RA-5C*	J79-GE-10	1958
YF-12	J58	1963
F-15	F100-PW-100	1972
B-1A	F101-GE-100	1974
F-16	F110-GE-100	1989 (Re-engine activity)
B-2	F118-GE-100	1989
F/A-18 E/F	F414-GE-400	1998
F-22	F119-PW-100	1990

*The RA-5C aircraft was developed before the F-111. It was, however, used as a flight-test vehicle for inlet dynamic distortion research after the F-111 experiences and before subsequent aircraft developments.

4.1 Evolution of Inlet Development, Test, and Evaluation Practices Prior to the F-111

Development of inlet systems used in early turbine-powered aircraft did not involve the use of subscale inlet testing (Reference 2.2.3). Instead, generic inlet shapes were tested by NACA and industry in wind tunnels at relatively large scale to establish pressure loss and airflow data. These were isolated inlet models in contrast to integrated inlet/forebody models. Total-pressure distortion did not appear to be a consideration. Inlets used on these early aircraft were first tested during full-scale flight tests. Based on historical references, correlation of subscale inlet data (when subscale inlet models were employed) was not considered necessary in the calculation of installed engine performance. Any performance or operability problems that arose were solved on the full-scale vehicle. A combination of factors resulted in these early practices being successful, including low-diffusion (small cross-sectional area changes) diffusers, subsonic flight speeds, and benign maneuverability envelopes. Also, many early turbine engines used centrifugal compressors that, when compared with axial compressors, are relatively insensitive to total-pressure distortion.

An example of solving inlet problems during full-scale development of these early aircraft is inferred from the P-59 aircraft (Figure 1). Little information regarding the development of this aircraft (circa 1943–1945) has survived. Examination of the remaining example of this aircraft, in the National Museum of the United States Air Force at Wright-Patterson AFB, suggests addition of an internal boundary-layer diverter system after the aircraft's initial fabrication (Figure 2).



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FIGURE 1 - INLET INSTALLATION OF THE BELL P-59



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FIGURE 2 - P-59 INLET APERTURE AND DIVERTER

The appearance of the internal diverter in the P-59, seen in Figure 2, suggests that this was added to the full-scale hardware to alleviate some problem (Reference AIR5866). Pilots of these early aircraft reported a disconcerting phenomenon that came to be known by the descriptive term “duct rumble.” This phenomenon is now believed to be associated with self-sustained flow oscillations. Evidently, designers thought that the diverter would remove the forebody boundary layer and solve the problem. The evidence of developmental problems associated with the forebody boundary-layer management seems to be a harbinger of installations where sub- to-full-scale solutions would have to be developed (i.e., the scaling of the boundary-layer diverter). And it illustrates a problem repeatedly underestimated by inlet designers over the years.

Pilots encountered a similar forebody boundary-layer problem during flight tests of the P-80 seen in Figure 3. They reported “rumble” (Reference 2.2.4) in the P-80 bifurcated inlet duct before an effective fuselage boundary-layer diverter was developed. It was reported that this “rumble” was due to a side-to-side flow imbalance between the two branches of the bifurcated duct. [This phenomena is now referred to as twin-duct instability.] Again, it is not clear whether wind-tunnel tests of subscale inlets were ever involved, but designers came to understand that inlet/engine compatibility could be compromised by viscous-flow interactions. They realized as well that the best way to avoid operability problems, especially as they moved into supersonic flight, was to prevent (or at least minimize) boundary-layer entry into the inlet.



FIGURE 3 - P-80 INLET INSTALLATION

Soon, aircraft developers began to include boundary-layer diverters with side-mounted inlet installations in the initial design rather than wait until the full-scale design was well established (e.g., F-89 seen in Figure 4). In these configurations, they adopted the use of external boundary-layer diverters that employed wedges or “plows” to divert the fuselage boundary layer more efficiently than had been possible with internal diverters.



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FIGURE 4 - F-89 INLET/DIVERTER INSTALLATION

Many of these early turbine-powered aircraft incorporated inlets whose performance would not have been affected significantly, if at all, by the presence of the airframe. As a case in point, the F-100 aircraft (Figure 5) incorporated a simple nose inlet where the primary effect of the airframe design would be associated with duct length and the resultant buildup of boundary layer in the diffuser. Otherwise, the inlet performance would be adequately determined from the available NACA and industry test data on isolated subscale inlet models in wind tunnels.



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FIGURE 5 - F-100F INLET INSTALLATION

Later, with the introduction of supersonic aircraft such as the F-89, F-101, F-102, and F-105, external diverters employed splitter plates to avoid interaction of the inlet's normal-shock wave with the fuselage boundary layer. An example of this is the F-101 aircraft (Figure 6). Eventually, when wind-tunnel tests of integrated inlet/forebody subscale models became the norm for side-mounted installations, the standoff distance of the splitter plate and diverter from the fuselage was not geometrically scaled on subscale models. Instead, the standoff distance was scaled by the thickness of the local fuselage boundary-layer to avoid its ingestion at all anticipated test conditions. This process, in general, was assumed to work best for large-scale (approximately 1/4-scale) models in which the viscous effects within the inlet itself were not far removed from those found at full scale.



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FIGURE 6 - F-101 INLET CONFIGURATION WITH EXTERNAL DIVERTER AND SIDEPLATE

4.2 The F-111 Inlet/Engine Compatibility Experience

During the 1940s and early 1950s, the approach to inlet/engine compatibility could best be described as an art rather than as a science. In 1956, NACA published the document, "Aerodynamic Principles for the Design of Jet-Engine Induction Systems" (Reference 2.2.4). This document was considered the "bible" for air-induction-system design and inlet/engine compatibility. The document included an extensive list of references and, in addition, an extensive bibliography. If the document itself did not have specific guidance for a given application, something useful usually could be found in the references or the bibliography. However, there were only one or two references that described some sort of numerical methodology relative to inlet distortion at the compressor face other than the simple relationship of maximum-minus-minimum pressure divided by the average pressure.

This document served the industry in the late 1950s and early 1960s. However, many instances of inlet/engine operability or compatibility problems were encountered, as were discussed in Section 4.1. By 1958, General Electric had defined a numerical inlet distortion methodology (Reference 2.2.5) for the GE J79 turbojet engine. This methodology was used extensively (and successfully) in the development of the inlets for the General Dynamics B-58A supersonic aircraft. Up to this time, low-response compressor-face probes measured the pressures used in the numerical distortion methodology, although several instances of concern about unsteadiness of the inlet flow were mentioned.

The F-111 program represented a turning point in the field of inlet/engine compatibility. The Requests for Proposals for the dual service TFX (later the F-111) were issued October 1961. Other important dates for the F-111 program are listed below for reference in the discussion that follows:

- General Dynamics announced as winner—November 1962.
- First flight—December 1964.
- Production contract —April 1965.
- First production aircraft delivery—July 1967.
- Production completed—November 1976.

The F-111 (Figure 7) incorporated significant advances in aircraft/propulsion configuration complexity as noted in the following list:

- First afterburning turbofan engine.
- Largest range of afterburner thrust modulation to date—50% to 100%.
- Twin-spool engine for military aircraft.
- Low pressure rotor—three-stage fan plus six-stage low-pressure compressor.
- High pressure rotor—seven-stage high-pressure compressor.
- Airframe—twin engine.
- Variable sweep wing.
- Armpit inlet location—1/4th axisymmetric with translating centerbody, double-cone, second-cone variable angle.
- Primary mission design points: Mach 1.2 dash at sea level, Mach 2.2 at altitude, 16 degrees angle-of-attack at Mach 2.2, and over-speed to Mach 2.5.



FIGURE 7 - INLET SYSTEM FOR THE F-111

The engine for the F-111 was the Pratt & Whitney TF-30. By the time the program started, Pratt & Whitney had defined a numerical inlet distortion methodology (KD2, Reference 2.2.6) for the engine. The validity of the methodology was verified using distortion screen testing in ground test cells. Wind-tunnel tests of the inlet with forebody showed that the steady-state distortion levels were acceptable; thus, no engine stalls were predicted. The wind-tunnel tests used steady-state probes located at the compressor face.

Note that engine stalls did occur during a full-scale wind-tunnel test of the inlet/engine system. This test hardware had a partial forebody and wing designed to provide the correct local Mach number and flow angles at the inlet and was tested with an operating engine at static and supersonic conditions. However, the wind-tunnel tests were performed at higher altitudes than were in the vehicle flight envelope. As a result, the wind-tunnel Reynolds number was lower than what the actual flight Reynolds number would be, possibly producing nonrepresentative test conditions. Because of this and because the steady-state distortion levels were acceptable, the consensus judgment was that there would not be any engine-related issues with flight tests.

Early flight testing of the F-111 was, however, plagued with engine stalls. The stalls resulted from dry power throttle transients, afterburner lights, afterburner zone changes, aircraft angle of attack changes, and inlet spike and cone angle off-schedule conditions. High-response instrumentation installed on the flight-test vehicles showed high levels of flow turbulence (total-pressure RMS levels) at the compressor face, but low-response instrumentation showed acceptable total-pressure distortion levels. Thus began a series of tests and changes to the engine and the inlet configuration that lasted for several years.

The period from 1965 to 1969 was a time of intensive investigation to determine the causes of engine stall and to develop an approach for predicting these stalls. Many theories were postulated. There were many analysis and test programs by industry, universities, Air Force, Navy, and NASA Laboratories. Included among these programs was an experimental investigation conducted at the Air Force Arnold Engineering Development Center (AEDC) in which an XB-70 inlet simulator and YJ93 engine were tested in the supersonic tunnel of the Propulsion Wind Tunnel Facility (Reference 2.2.7). During these tests, the engine appeared to drift into stall during conditions that were otherwise thought to have sufficient stability margin. Flight tests of the XB-70 aircraft had also encountered engine stalls. The project conducted further ground tests to study the effects of inlet-generated turbulence and distortion on YJ93 engine flow instabilities. These tests showed that high levels of turbulence, albeit with low levels of distortion, resulted in the engine drifting into stall, even after as much as 8 minutes on test condition.

This time period of investigation culminated in the "Aircraft-Propulsion System Compatibility Symposium" held in Miami Beach, Florida, on June 24 through 26, 1969. The various papers given at this symposium are collected in Reference 2.2.7. The keynote address at this symposium by Mr. Joe Jones, Deputy Assistant Secretary of the Air Force, Research and Development, included this quote, which summarizes the history of this time period:

"Yet, on the first attempt to exploit the potentials of the turbofan engine in an afterburning configuration for the supersonic multi-mission F-111 fighter aircraft, severe stability and installation difficulties were encountered that had not been anticipated. Possibly the general success in adapting the turbofan to the relatively simple pod-mounted installations on subsonic transport-type aircraft had tended to mask certain of the problem potentials of the more sophisticated supersonic installation. The significant engineering challenges in the missile and space programs and the general success being achieved may also have in itself contributed a lulling effect. Additionally, the Government and industry engineering management environment of that period, coupled with new fixed price incentive contractual relationships, created an additional obstacle to a broad scale and rapid attack on the fundamental engineering problems at the outset. Internally, within the Air Force, the technical laboratories had become sufficiently separated from the SPO [Systems Project Office] organizations that they lacked a proper understanding or sense of responsibility for the technical problem being encountered. Finally, the engine and airframe contractors, operating under the terms and conditions of their individual contracts with their own specifications, performance guarantees, correction of deficiency clauses, and schedule problems, were not prone to become involved in each other's efforts anymore than was absolutely necessary. As a result of this general environment, when confronted with serious inlet/engine stability and nozzle/airframe backend problems on the F-111, we found ourselves with too little fundamental knowledge and with the various engineering groups constrained by an awkward management and contractual relationship. Even more recently, many of the same constraints were initially prevalent in developing a solution for the F-4E/J-79 installation problems. Fortunately, the system did finally awaken and reveal its resiliency. Once the seriousness of these problems was recognized and appreciated, ad hoc arrangements were made and the military laboratories, SPO technical personnel, NASA, and airframe and engine contractor teams rose to the challenge and initiated the necessary collaborative effort to effect solutions. But, the time lag had been costly."

Plourde and Brimelow found that time-dependent patterns lasting on the order of one rotor revolution produced the same loss of stability margin as a steady-state pattern (Reference 2.2.7). This insight was found by putting a turbulence generator with a plug in front of a TF30 engine. In the later parts of the F-111 flight-test program, data were collected using this general approach, but the time scale was different than the one rotor revolution. Later, the time scale was changed to correspond to the Plourde and Brimelow criteria even before the paper was published. Their initial test data suggesting this approach was gathered in the spring 1968 and was passed on to the F-111 program. Application of this approach in the later stages of the F-111 flight-test program contributed significantly to solving most of the engine stall problems.

The Society of Automotive Engineers Committee S-16 was formed at the request of the Air Force in 1971. Its charter was to develop a single methodology to address the inlet/engine compatibility problem using the knowledge that had evolved in this period of extensive research. The Committee was composed of members from the airframe and engine industries, the military, and the NASA Laboratories.

After several meetings (some of which were very contentious), a general consensus was reached that the Plourde and Brimlow approach was valid and should be the basis of the methodology. This consensus was supported by F-111A flight-test data reported by Burcham and Hughes (Reference 2.2.8). After considerable additional debate (supported by analysis), the S-16 Committee agreed that a simple universal methodology for all engines was not possible (much to the disappointment of the military and airframe community). It was at this point that a more general approach was adopted, allowing the Committee to develop descriptors applicable to all engines, while recognizing that various coefficients and constants would have to be determined for specific engines.

Progress was slow even though the Committee was meeting four times a year during this initial time period. The Committee's first document, ARP1420, was published in March 1978 after approximately 20 meetings. The ARP1420 approach requires the airframe manufacturer to gather high-response total-pressure data at the AIP on their inlet models and calculate distortion descriptors consistent with the specific numerical approach for a given engine. The location of the AIP, and its associated set of instrumentation, within an inlet is mutually agreed upon by the airframe and engine manufacturers following the guidelines in ARP1420.

The correlation of model- to full-scale high-response data gathered consistent with ARP1420 seems to be adequate to ensure successful airframe development programs with few (if any) compatibility problems (fidelity of the model scale to full scale is required). This approach, which was derived from military aircraft with engines having inlet guide vanes, continues to serve the industry well as demonstrated in Section 5, Case Studies. Applications of the basic ARP1420 methodology to vehicles that have significant configuration differences from those that formed the basis for this methodology should address the fundamental tenets of that methodology.

5. CASE STUDIES

A number of military aircraft programs have conducted subscale wind-tunnel tests and corresponding full-scale flight tests to develop the inlet system and verify its performance. Some of these programs documented their wind-tunnel and flight data such that correlations between the two were examined. This affords the Committee an opportunity to examine how well inlet recovery and dynamic distortion obtained in the wind tunnel corresponds to that eventually measured in flight. Another set of programs, while not providing correlations directly, provided insight or lessons for use in future development programs. Both types of programs are presented in this section as case studies.

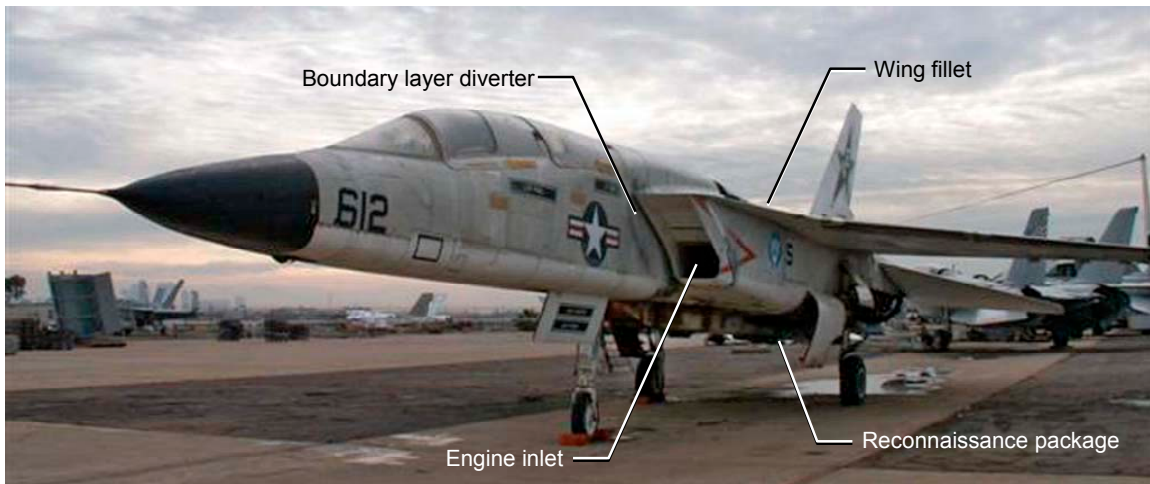
5.1 Case Studies Offering Correlations

The following case studies provide findings associated with correlating inlet performance and dynamic pressure distortion measured in wind tunnels with that found in flight tests. This section is organized in chronological order, proceeding from the earliest known examination of model- to full-scale data correlations through more recent experiences. This approach is taken because it highlights an improved understanding of inlet-engine compatibility and test techniques. The results of these case studies are discussed, where available, as they relate to geometric scaling fidelity, Reynolds number effects, ground/flight-test techniques, and correlating wind-tunnel to flight inlet recovery and total-pressure distortion data. Finally, a relevant summary, as reported by the original authors, is presented along with observations by this Committee having the benefits of 30 years of hindsight.

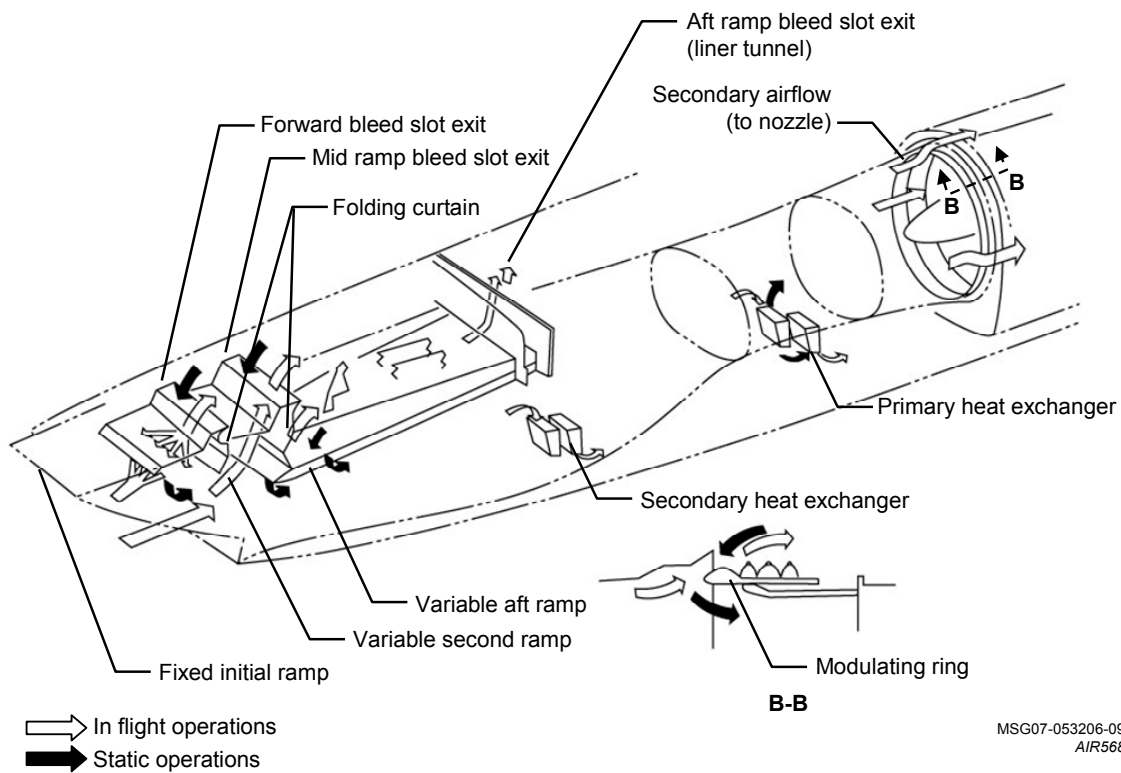
5.1.1 RA-5C Case Study

The RA-5C case study is presented not because it had an inlet/engine compatibility issue, but because it was selected as a testbed aircraft to examine, for the first time, issues associated with scaling inlet dynamic-distortion data from ground to flight tests. The Air Force Systems Command (AFSC) formed the Airframe-Propulsion Compatibility (APC) Committee as an ad hoc group with members drawn from the Air Force's Aero Propulsion Laboratory, Flight Dynamics Laboratory, and Aeronautical Systems Division to work the F-111 inlet/engine compatibility issues. Later, members of the APC Committee, as ordered by the AFSC Commander, initiated research and development programs to provide a technology base of inlet/engine compatibility information for future systems. One of these programs, conducted during 1969–1971, used the RA-5C aircraft as a test vehicle. Its primary objective was to develop techniques for correlating wind-tunnel and flight-test inlet performance data (Reference 2.2.9). Both scaling and Reynolds number effects were independently studied. This program is the first known to report on these issues.

The twin-engine RA-5C had two inlet apertures, each mounted on opposite sides of the fuselage ahead of the wing. A diverter was employed to standoff the inlet aperture from the forebody boundary layer. The external-compression inlets were two-dimensional, variable horizontal-ramp geometries and operated at a Mach 2 design point with two oblique shock waves followed by a normal shock wave. Each duct had a small amount of offset and a ratio of length to engine-face diameter of 6.6. A photograph of the aircraft and schematic of the inlet geometry is provided in Figure 8.



(A) RA-5C AIRCRAFT AND INLET/AIRFRAME INTEGRATION



(B) RA-5C INLET DETAILS

FIGURE 8 - RA-5C INLET SYSTEM

5.1.1.1 Test Item Configuration

The RA-5C program was unique in that data from two subscale models and the full-scale flight vehicle were obtained allowing the influence of model scale and Reynolds number to be examined. The wind-tunnel test series included two models of different scales; specifically, a 0.125-scale model and a 0.228-scale model were tested. Photographs of the wind-tunnel models are provided in Figure 9. Geometric similarity of the forebody, ramps, duct, engine bullet-nose, secondary flow apertures, and protuberances were maintained for the port (left) inlet of each model. The starboard (right) inlets were faired over and only a small span of the port wing was included. The height of the full-scale diverter, $H_{div FS}$, was set to a computed local boundary-layer thickness, δ_{FS} , at Mach 2 and 50,000-foot altitude, i.e., $H_{div FS} / \delta_{FS} = 1$. The diverter height for each subscale model, $H_{div MS}$, was such that the ratio $H_{div MS} / \delta_{MS} = 1$ where δ_{MS} was the local boundary-layer thickness computed at Mach = 2 and nominal tunnel conditions. No information was available regarding the use of boundary-layer transition grit on the wind-tunnel models.

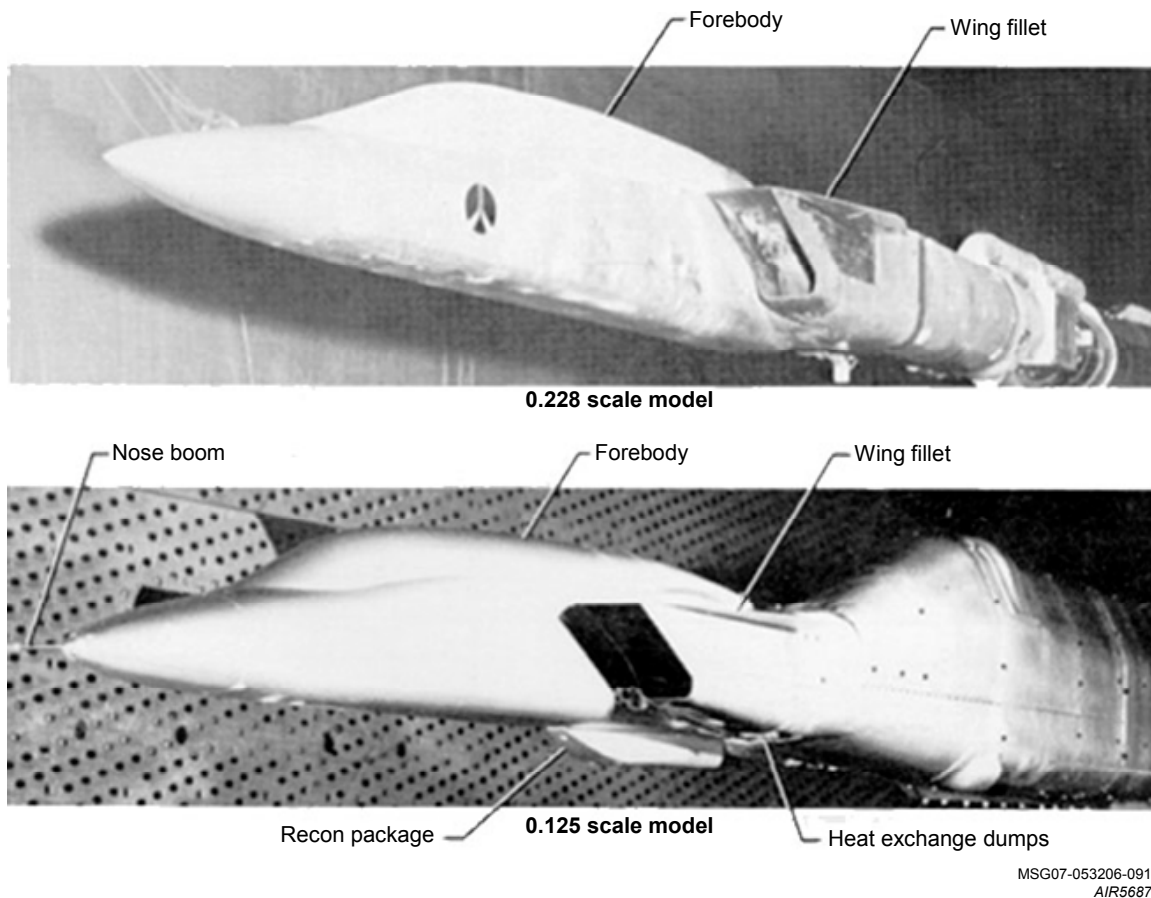


FIGURE 9 - RA-5C INLET WIND-TUNNEL MODELS

5.1.1.2 Test Conditions

The ground tests were conducted in the AEDC's 16-foot transonic and 16-foot supersonic propulsion wind-tunnel facilities at Mach numbers ranging from 0.65 to 2.0. The 0.125-scale model was strut mounted while the larger 0.228-scale model was sting mounted. At the Mach numbers reported here, the inlets were operated as flowthrough systems. Data were obtained over an angle-of-attack and sideslip range of -4 degrees to $+18$ degrees and -10 degrees to $+10$ degrees, respectively. Flight tests were conducted from the North American Rockwell, Columbus Division facility, in Columbus, Ohio.

5.1.1.3 Data Acquisition, Processing, and Analysis

The measured database included steady-state and dynamic total pressures from the two subscale models and the flight-test aircraft. The AIP of each model was instrumented with 30 high-response transducers mounted in rakes at similar locations and orientations. The probes at the AIP were arranged with five per rake and located on centers of equal area. Pressure measurements for the 0.125-scale model were made using a concentric steady-state and dynamic pitot probe with a 0.125-inch outer-diameter and a length-to-diameter ratio of about 10. The larger 0.228-scale model used a unique probe with a 0.083-inch outer-diameter pitot probe of length-to-diameter ratio of about 3. Additionally, each probe consisted of a single tube for measuring the total pressure. Then, within the rake housing, the single tube branched with one leg measuring the steady-state pressure while the other leg was routed to the dynamic pressure transducer also located inside the rake housing.

The flight-test vehicle also employed a 30-probe arrangement similar to the subscale models. The flight-test measured steady and dynamic pressures using concentric pitot probes similar to those used during the testing of the 0.125-scale model in the wind tunnel. However, each pitot probe was a 0.500-inch outer-diameter tube of length-to-diameter ratio of about 2.

The dynamic-data acquisition system used at AEDC was capable of measuring pressures at frequencies up to 8 kHz. At each test point, the dynamic data were recorded for about 20 seconds and stored using a 72-channel FM multiplex tape system. During the post-test data analysis, the dynamic data were digitized and filtered such that the resultant data had cutoff frequencies of 4 kHz for the 0.228-scale model and 8 kHz for the 0.125-scale model.

The flight-test steady-state data were recorded at 120 samples per second using a pulse code modulator. The dynamic data were FM multiplexed onto an onboard tape recorder. Both the steady and dynamic data were then sent to the flight-test ground station using telemeter links. The record length used in flight tests to obtain dynamic data was 7.5 seconds.

5.1.1.4 Results and Discussion

These data provided insight into the effects of model scale and Reynolds number on total-pressure recovery. Each scale (0.125, 0.228, and full scale) was tested over a range of Reynolds and Mach numbers. The Reynolds number length scale, L , was the distance from the leading edge of the inlet ramp to the diffuser exit. The data presented here (Figure 10) are reported as "match airflow" and presumed to be at engine airflow for sustained flight at that Mach number. For any constant scale and Reynolds numbers, the recovery is seen to decrease with increasing Mach number largely due to losses across the inlet's shock waves (follow Curve A in Figure 10). For any constant scale and Mach number, recovery increases with Reynolds number presumably due to thinning boundary layers (follow Curve B in Figure 10). Of note though, for any constant Mach and Reynolds number, recovery generally decreases with model scale with an exception at Mach 1.8 for the wind-tunnel models (follow Curve C in Figure 10).

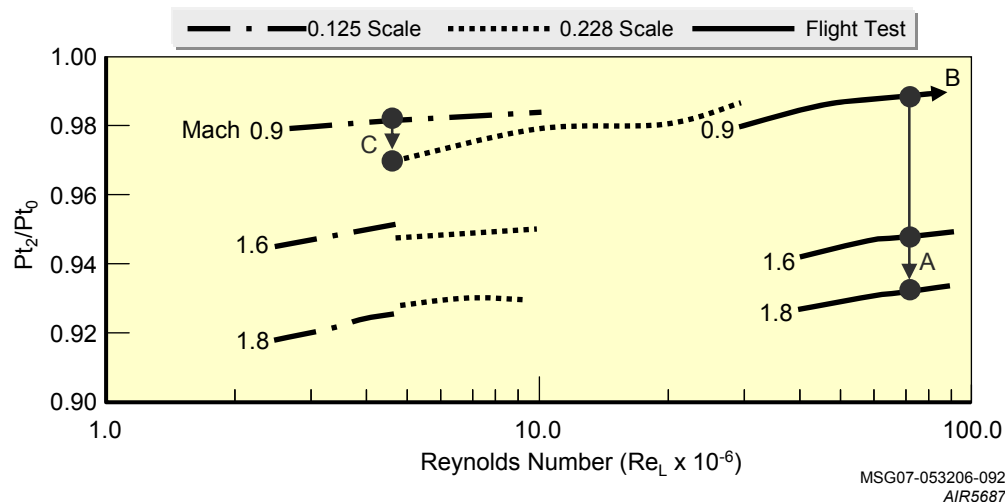


FIGURE 10 - VARIATION OF TOTAL-PRESSURE RECOVERY WITH REYNOLDS AND MACH NUMBERS, AND SCALE

This database also provided insight into the behavior of dynamic pressure distortion with changes in scale, Mach and Reynolds numbers. Several distortion indices were computed and screened, but the index K_{θ} is selected for review here since circumferential distortion generally is stressed for engine operability. See Reference 2.2.10 for a description of the K_{θ} distortion index. For any constant scale and Reynolds numbers, the distortion is seen (Figure 11) to increase with Mach number, probably due to interactions of boundary layers with the inlet's shock waves. For constant scale and Mach number, distortion generally decreases with Reynolds number probably due to thinning boundary layers. There were exceptions, however, for which the causes were not reported. Changes in scale with constant Mach number reportedly produced surprising trends. At Mach 0.9, distortion generally increased with model scale and Reynolds number. At supersonic flight speeds, however, distortion was lowest for the 0.228-scale model regardless of Reynolds number.

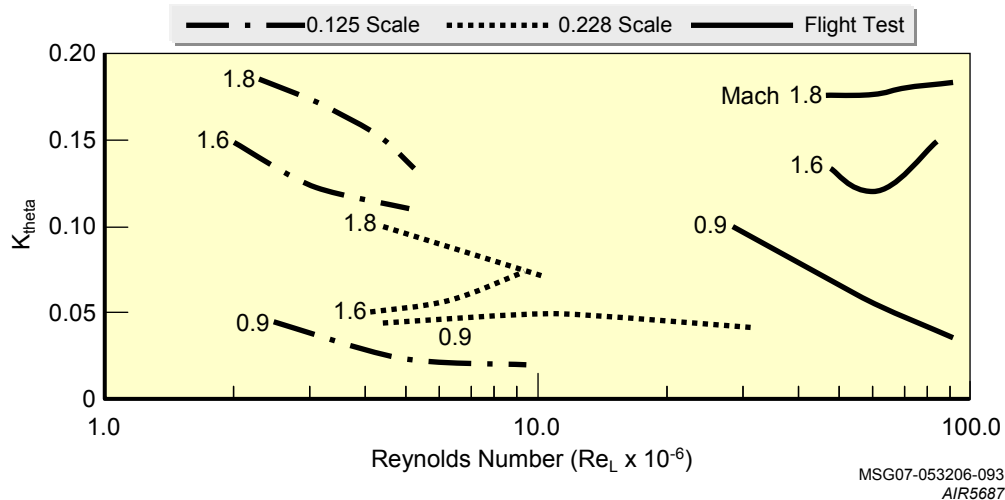


FIGURE 11 - VARIATION OF DYNAMIC CIRCUMFERENTIAL DISTORTION WITH REYNOLDS NUMBER

5.1.1.5 Findings of the Original RA-5C Study

At the time, relevant findings from this program were summarized as:

- Recovery increased with Reynolds number.
- 0.125-scale model was of sufficient size to obtain recovery and dynamic-distortion data.
- A record length of 7.5 seconds provided stabilized data in flight test.

5.1.1.6 S-16 Committee Observations of RA-5C Data

Today, several key observations are noted pertaining to wind-tunnel to flight correlation for recovery and distortion. These data produced results that generally follow expected trends based on aerodynamic similarity rules. Recovery measured using the 0.125-scale model at Reynolds number used in wind tunnels could be used to estimate flight recovery. No reason is seen to use a larger scale wind-tunnel model. At similar Mach numbers, a recovery improvement of up to 1% may be expected for a Reynolds number correction from wind-tunnel to flight test.

The measurements indicate that, except at supersonic speeds, dynamic circumferential distortion decreased with increasing Reynolds number for constant Mach number and scale. Other observations of dynamic distortion from this database are less clear. For example, while similar levels of distortion were measured on the 0.125-scale model and the full-scale vehicle, the 0.228-scale model yielded noticeably lower distortion. Several factors are offered to explain this. First, the 0.228-scale model used probes having a small length-to-diameter ratio to measure the dynamic pressure data; this might have introduced a bias in the measurements. Second, the small length-to-diameter ratio of the flight probes might have introduced a bias.

5.1.2 YF-12 Case Study

The YF-12 program allows comparison of inlet data from a 1/3-scale wind-tunnel model, a full-scale nacelle wind-tunnel model with and without engine, and full-scale flight tests (Reference 2.2.11).

5.1.2.1 Test Item Configuration

The YF-12 had an axisymmetric mixed-compression inlet (Figure 12) designed for a cruise Mach number of 3.2. The inlet had a translating centerbody spike with a 26-degree included angle; the spike also provides throat area control. Boundary-layer bleed, using porous surfaces, was located upstream of the inlet throat on the centerbody. Boundary-layer bleed on the cowl was in the form of a shock trap slot at the throat station. Forward bypass doors controlled the position of the normal-shock wave, while the aft bypass doors provided airflow matching with the engine. The inlets were wing mounted, with slight inward and downward cant (3.24 and 6.82 degrees, respectively). This placed a slight bend in the subsonic diffuser.



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FIGURE 12 - YF-12 INLET AND INSTALLATION

All wind-tunnel models had the same scaled contours for the translating spike centerbody and diffuser moldlines. Both the 1/3-scale inlet model and the full-scale inlet model with cold-pipe were terminated with a massflow plug. The full-scale inlet model and flight-test inlet had fixed louvered exits for the centerbody bleed and forward bypass, while the 1/3-scale inlet model had ducted exits with variable area that were used to match bleed massflow ratio to full scale. The full-scale inlet with engine and the flight hardware routed the shock trap bleed and aft bypass to an ejector for engine cooling. The full-scale inlet without engine and the 1/3-scale inlet model controlled this flow with variable valves. Finally, the full-scale and flight hardware had 32 internal tubes to pass the shock trap bleed flow aft, while the 1/3-scale inlet model had 8 area-scaled tubes external to the model. These model differences are shown in Figure 13. The forebody of the flight configuration introduced some nonuniformity on the inlet approach flowfield. Mach number variation at the cowl plane was about 2.5%, and sideslip variation was as much as 4 degrees. The upwash angle at the cowl plane was not significantly affected.

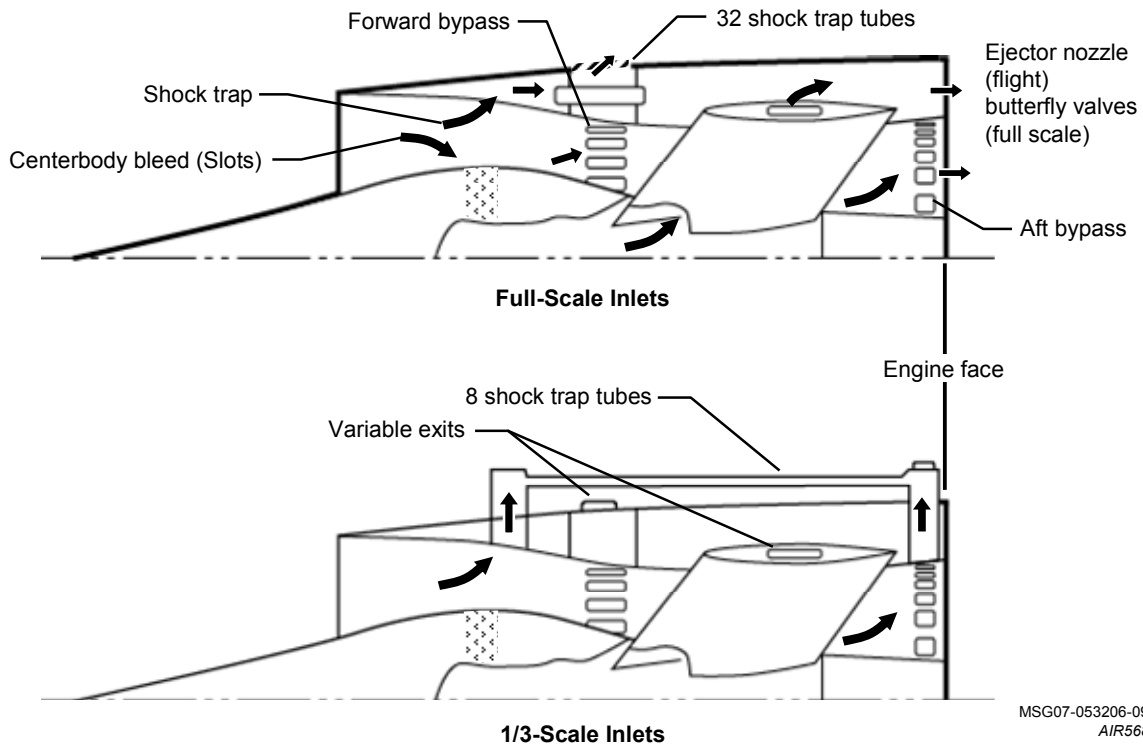


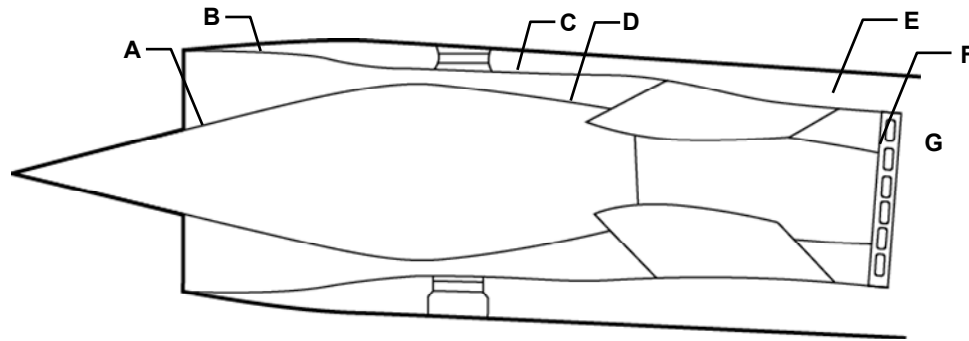
FIGURE 13 - YF-12 INLET MODEL DETAILS

5.1.2.2 Test Conditions

Test articles for the YF-12 included wind-tunnel models at 1/3-scale and full-scale, as well as the full-scale flight-test aircraft. The full-scale wind-tunnel model was tested with and without an engine. The 1/3-scale model was tested at the NASA Ames 8- by 7-foot wind tunnel and in both the 9- by 7-foot and 11- by 11-foot Unitary Plan wind tunnels. The full-scale inlet, with and without an engine, was tested at the NASA Lewis 10- by 10-foot wind tunnel. All ground test models were isolated inlets.

5.1.2.3 Data Acquisition, Processing, and Analysis

Pressure instrumentation for each model varied (Figure 14). Of particular note is the difference in number of dynamic total-pressure probes on the engine-face rakes (denoted by Column F in Figure 14). The 1/3-scale inlet model had 40 dynamic probes (8 rakes, 5 rings) clocked 15 degrees from top dead center, while the full-scale inlet model and flight tests had 24 dynamic probes (6 rakes, 4 rings) clocked 5 degrees from top dead center. No information was found concerning the data processing.



NASA Research Center	Scale	Type	Location of Pressure Sensors							
			A	B	C	D	E	F	G	Total
			Number of Sensors							
Ames	1/3	Steady State	73	32	84	44	47	40	-	320
		Dynamic	12	6	16	12	1	40	-	87
Lewis	Full	Steady State	75	58	128	94	45	52	-	402
		Dynamic	-	11	27	-	12	24	-	74
Flight	Full	Steady State	9	17	43	22	7	50	3	151
		Dynamic	4	4	8	8	5	46	5	80

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FIGURE 14 - YF-12 INLET MODEL INSTRUMENTATION DETAILS

5.1.2.4 Results and Discussion

This section discusses the geometric scaling fidelity, Reynolds number effects, and ground test techniques.

Comparison of the inlet performance and distortion at Mach 2.8 is shown in Figure 15. The data show variation of total-pressure recovery, various massflow rates, and steady-state distortion as a function of engine massflow ratio (m_2/m_∞) for three models at similar Reynolds numbers. These data were obtained by varying the forward bypass doors. The variation of pressure recovery with engine massflow ratio correlates very well between the three models, although the flight-test inlet remained started to a higher total-pressure recovery than the wind-tunnel models. There are discrepancies in the shock trap (m_{st}/m_∞) and centerbody bleed (m_{cb}/m_∞) massflow ratios, which were attributed to differences in bleed passage geometry in the 1/3-scale inlet wind-tunnel model and leakage in the flight-test inlet. Total-pressure distortion was increased when measured on full-scale hardware compared to that obtained on the 1/3-scale model.

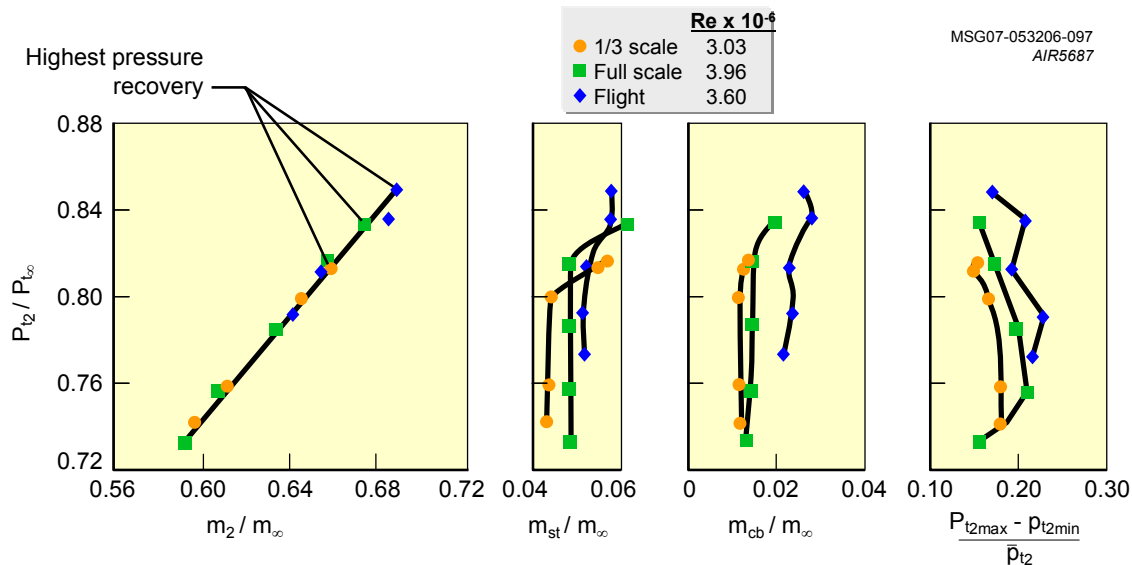


FIGURE 15 - YF-12 PERFORMANCE AND DISTORTION, MACH 2.8

Inlet performance and distortion at Mach 2.1 is compared in Figure 16. For this Mach number, the inlet was operating at reduced massflow ratio compared to the Mach 2.8 data. In this case, the correlation of total pressure was not as good, with the flight-test inlet operating at higher massflow ratios. It was noted that the flight-test data were obtained with the inlet operating at a higher corrected airflow than the ground test data. Massflow ratios of the shock trap and centerbody bleed systems were similar to the Mach 2.8 data. The distortion between the three models was similar except for the highest airflow conditions where differences were found.

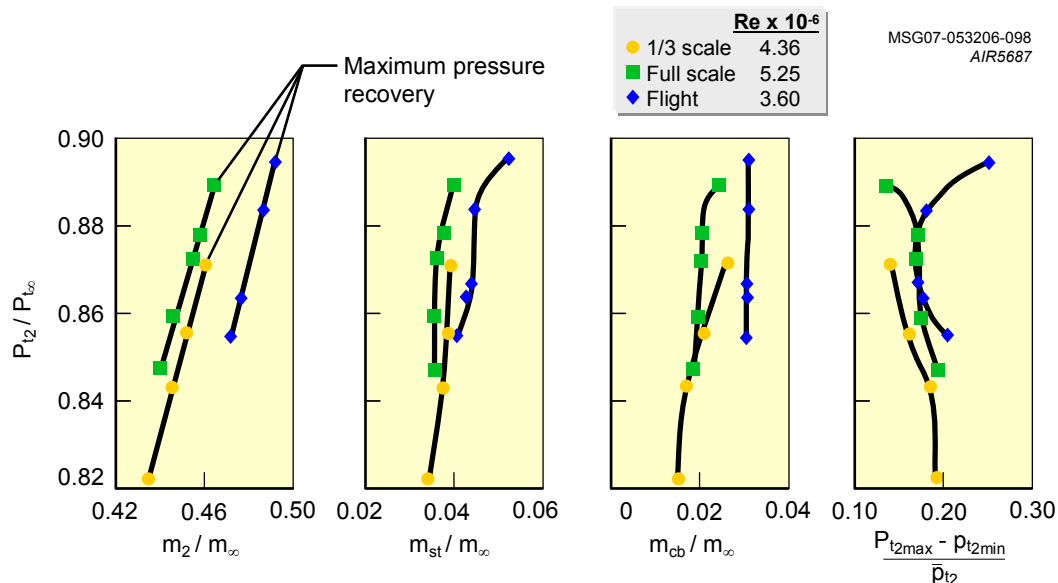


FIGURE 16 - YF-12 PERFORMANCE AND DISTORTION, MACH 2.1

5.1.2.5 Findings of the Original YF-12 Studies

The results of the original YF-12 research indicated:

- Wind-tunnel results were a satisfactory indication of flight performance when inlet operating conditions were matched.
- Testing at less than flight Reynolds numbers did not affect data comparisons.
- Nonuniform flow at flight conditions did not have a detrimental effect on inlet performance.

In general, comparison of steady-state data between ground and flight test was of sufficient quality that expectations were that similar comparisons would be found using inlet dynamic data.

5.1.2.6 S-16 Committee Observations of YF-12 Data

The results of the YF-12 case study highlight the need to ensure consistent inlet operating conditions for mixed-compression inlets. Seemingly insignificant geometry or secondary massflow control variations can result in substantial differences in total-pressure recovery and distortion. It is felt, however, that when geometric and aerodynamic similarity is maintained, then satisfactory correlation between ground and flight-test inlet data will be found. No references presenting the dynamic total-pressure data have been found.

5.1.3 F-15 Case Study

NASA sponsored an effort with McDonnell Douglas Corporation (MDC), currently The Boeing Company, to determine if time-variant distortion data taken from a subscale inlet model could be used to accurately predict the distortion levels for the full-scale vehicle (Reference 2.2.12). F-15 subscale inlet data obtained by MDC during the F-15 development program were compared with F-15 flight-test inlet data obtained by NASA during an F-15 inlet/engine compatibility flight-test program. Other researchers (References 2.2.13 to 2.2.17) documented the F-15 development and compared the full-scale inlet flight data with both full-scale and subscale wind-tunnel data.

5.1.3.1 Test Item Configurations

The F-15 inlet configuration was a two-dimensional external compression, overhead variable capture area design with three horizontal compression ramps and an internal diffuser ramp. This inlet is seen in Figure 17. Boundary-layer bleed systems included the porous surfaces on the second and third ramps, a throat slot bleed, and inboard/outboard sidewall bleeds. The throat slot flow exits through a bypass door for inlet/engine airflow matching. The inlet was offset from the fuselage with a boundary-layer diverter to preclude the ingestion of the fuselage boundary layer.

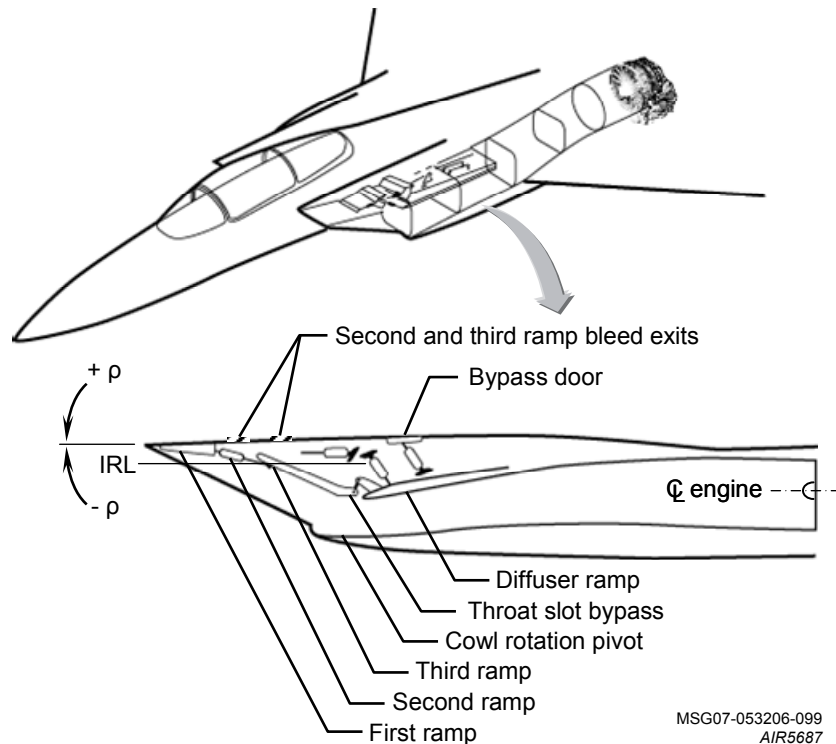


FIGURE 17 - F-15 INLET CONFIGURATION