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Modeling Techniques for Jet Engine Test Cell Aerodynamics

RATIONALE

Revision based on the 5 Year Review.

FOREWORD

One of the strongest motives for developing the scale modeling techniques to allow investigation of engine test cell aerodynamics as described in this work was the generally poor understanding of the aerodynamics associated with the ground level testing of turbofan and turbojet engines within enclosed testing facilities. In those instances where the understanding was not so poor, there sometimes remained a lack of appreciation for the fundamental importance of the aerodynamics of the engine testing environment. It is known that such a poor understanding or a lack of appreciation for the importance of the aerodynamics of the testing environment can and does lead to disastrous consequences. With proper attention to scale modeling techniques, the aerodynamics of a jet engine test facility can readily be investigated and documented. Modifications to a test cell based on scale model test results can lead to a stable and reliable full-scale operating environment for the testing of aircraft engines indoors. A much improved understanding and heightened awareness of the fundamental importance of the aerodynamics of the engine testing environment have resulted in significantly improved engine test facilities now in use world-wide.

ABSTRACT

Research studies focusing on jet engine test cell aerodynamics, acoustics, and cell flow characteristics as affecting engine performance can be conducted with scale models for a variety of test cells. Such studies require the simulation of a number of jet engines in rather accurate detail, both as to geometry and as to flow characteristics. It has been demonstrated that simulators of low-bypass afterburning turbojets, high-bypass turbofans, turboshaft engines (without propellers), and unducted fan engines can be designed, fabricated, and successfully operated using either high-pressure air ejector systems or turbine driven systems for the motive power. Specific components of a test cell such as inlets or exhaust sections alone may be tested independently by employing a vacuum source and bellmouth to simulate engine inlet flow or compressed air and scaled nozzle to simulate engine exhaust flow. The peculiar problems associated with scale model testing and engine simulators and the methods which can be used to attack these problems are described.

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1. SCOPE

This SAE Aerospace Information Report (AIR) has been written for individuals associated with ground level testing of turbofan and turbojet engines and particularly for those who might be interested in investigating the performance characteristics of a new test cell design or of proposed modifications to an existing test cell by means of a scale model test.

1.1 Purpose

The purpose of this information report is two-fold:

1.1.1 Provision of Guidelines

One of the primary purposes of this report is to provide guidelines for performing a scale model test of new configurations of and/or proposed modifications to a ground level enclosed test facility for turbofan and turbojet engine applications, i.e., a jet engine test cell.

1.1.2 Discussion of Considerations

Another important purpose is to address the major considerations when performing such a model test in the two main areas of the engine test cell model and the simulation of the engine. Requirements for the scale model test cell hardware and the associated instrumentation are presented and discussed. The requirements and considerations for the simulation of the engine are given, along with some of the special considerations which should be made when air ejector systems are the motive power for the simulator.

2. REFERENCES

The following publications for a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of the other publications shall 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 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 Applicable Documents

The following is a list of some applicable references and documents used in the preparation of this report:

2.1.1 Ashwood, P. F., and Mitchell, J. J.: "The Uniform Engine Test Programme", AGARD Advisory Report No. 248 (AGARD-AR-248), Advisory Group for Aerospace Research and Development, North Atlantic Treaty Organization, Neuilly Sur Seine, France, February 1990

2.1.2 Freuler, R. J., and Dickman, R. A.: "Current Techniques for Jet Engine Test Cell Modeling", AIAA Paper No. 82-1272, Paper presented to the AIAA/SAE/ASME 18th Joint Propulsion Conference, Cleveland, Ohio, June 21-23, 1982

2.1.3 Freuler, R. J.: "An Investigation of Jet Engine Test Cell Aerodynamics by Means of Scale Model Test Studies with Comparisons to Full-Scale Test Results", Ph.D. Dissertation, The Ohio State University, Columbus, Ohio, December 1991

2.1.4 Karamanlis, A. I., Sokhey, J. S., Dunn, T. C., and Bellomy, D. C.: "Theoretical and Experimental Investigation of Test Cell Aerodynamics for Turbofan Applications", AIAA Paper No. 86-1732, AIAA/ASME/SAE/ASEE 22nd Joint Propulsion Conference, Huntsville, Alabama, June 16-18, 1986

2.1.5 Lee, J. D., and Freuler, R. J.: "Engine Simulator Techniques for Scaled Test Cell Studies", AIAA Paper No. 85-1282, Paper presented to the AIAA/SAE/ASME/ASEE 21st Joint Propulsion Conference, Monterey, California, July 1985

2.1.6 MacLeod, J. D.: "A Derivation of Gross Thrust for a Sea-Level Jet Engine Test Cell", Division of Mechanical Engineering Report No. DM-009, National Research Council Canada, Ottawa, Ontario, 1988

2.1.7 SAE Committee EG-1, Aerospace Propulsion Systems Support Equipment: "Design Considerations for Enclosed Turbofan/Turbojet Engine Test Cells", Subcommittee EG-1E, Gas Turbine Engine Test Facilities and Equipment, SAE Project Number EG-1-E87-3, Society of Automotive Engineers, Warrendale, Pennsylvania, Draft AIR dated September 1990

2.1.8 Karamanlis, A. I., Freuler, R. J., Lee, J. D., Hoelmer, W., and Bellomy, D. C.: "A Universal Turboshaft Engine Test Cell - Design Considerations and Model Test Results", AIAA Paper No. 85-0382, Paper presented to the AIAA 23rd Aerospace Sciences Meeting, Reno, Nevada, January 1985

2.1.9 Dickman, R. A., Hoelmer, W., Freuler, R. J., and Hehmann, H. W.: A Solution for Aero-Acoustic Induced Vibrations Originating in a Turbofan Engine Test Cell", AIAA Paper No. 84-0594, Paper presented to the AIAA 13th Aerodynamic Testing Conference, San Diego, California, AIAA Conference Proceedings CP841, March 1984, pp. 99-108

2.1.10 Kromer-Oehler, S. L. and Dietrich, D. A.: "Computational Analysis of the Flow Field in an Engine Test Cell", AIAA Paper No. 84-0285, paper presented to the AIAA 22nd Aerospace Sciences Meeting, Reno, Nevada, January 9-12, 1984

2.1.11 Barton, J. M.: "The Role of Computational Fluid Dynamics in Aeropropulsion Ground Testing", Journal of Aircraft, Vol. 10, October 1984, pp. 745-750

2.1.12 Freuler, R. J. and Montgomery, K. A.: "Allison Gas Turbine Division Model AG9130/DDG-51 Ship Service Gas Turbine Generator Air Intakes Scale Model Test Report", Allison Gas Turbine Division Report No. EDR 14737, Allison Gas Turbine Division, Indianapolis, Indiana, September 20, 1990

2.1.13 Smith, T. E.: "LM1600 Bravo-Romeo Project - Wind Tunnel Test to Determine Engine Inlet Flow Quality", General Electric Technical Memorandum, TM No. 90-460, GE Aircraft Engines, Cincinnati, Ohio, November 1990

2.1.14 Eckert, D., van Ditshuizen, J. C. A., Munniksma, B., and Burgsmuller, W.: "Low Speed Twin Engine Simulation on a Large Scale Transport Aircraft Model in the DNW", ICAS Paper No. 84-2.10.4, Proceedings of the 14th Congress of the International Council of the Aeronautical Sciences, Vol. 2, Toulouse, France, September 10-14, 1984

2.1.15 Harris, A. E. and Paliwal, K. C.: "Civil Turbofan Propulsion System Integration Studies Using Powered Testing Techniques at ARA, Bedford", AIAA paper No. 84-0593, Proceedings of the AIAA 13th Aerodynamic Testing Conference, San Diego, California, AIAA Conference Proceedings CP841, March 1984, pp. 74-98

2.1.16 Wagenknecht, C. D., Hoff, G. E., and Norbut, T. J.: "Performance Calibration Results for a Compact Multimission Aircraft Propulsion Simulator", AIAA Paper No. 82-0254, Paper presented to the AIAA 20th Aerospace Sciences Meeting, Orlando, Florida, January 11-14, 1982

2.1.17 Smith, G. D., Matz, R. J., and Bauer, R. C.: "Analytical and Experimental Investigation of Ejector- Powered Engine Simulators for Wind Tunnel Models", AEDC-TR-76-128, Arnold Engineering Development Center, Arnold Air Force Station, Tennessee, January 1977

2.1.18 Hoelmer, W. and Freuler, R. J.: "Lufthansa German Airlines, Frankfurt Test Cell Aero Evaluation, Scale Model Test Program", International Engine Support Operations Memorandum Report, GE Aircraft Engines, Cincinnati, Ohio, June 10, 1988

2.1.19 Minardi, J. E. and Von Ohain, H. P.: "Thrust Augmentation Study of High Performance Ejectors", AFWAL-TR-83-3087, Flight Dynamics Laboratory, Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, Ohio, November 1983

2.1.20 Lau, J. C.: "Effects of Exit Mach Number and Temperature on Mean-Flow and Turbulence Characteristics in Round Jets", Journal of Fluid Mechanics, Vol. 105, 1981, pp. 193-218

2.1.21 Quinn, B.: "Ejector Performance at High Temperatures and Pressures", Journal of Aircraft, Vol. 13, December 1976, pp. 948-954

2.2.22 SAE Committee EG-1E, " Inlet Air Flow Ramps for Gas Turbine Test Cells", AIR 5306, May 2000.

2.2 Symbols and Abbreviations

The following parameters, abbreviations, and subscript notations are used in this report:

2.2.1 Parameters

A	cross-sectional area, square inches or square feet
C_d	flow coefficient, non-dimensional
g	gravitational constant, feet per second per second
$\dot{m}$	mass flow rate, slugs per second
M	Mach number, non-dimensional
p	pressure, pounds per square inch, pounds per square foot, or inches of water
R	gas constant, square feet per square seconds-degrees Rankine
Re	Reynolds number, non-dimensional
T	temperature, degrees Rankine
V	velocity, feet per second
W	airflow rate, pounds (mass) per second
α	cell bypass ratio, non-dimensional
γ	ratio of specific heats, non-dimensional
ρ	density, slugs per cubic foot

2.2.2 Abbreviations

AIAA	American Institute of Aeronautics and Astronautics
AGARD	Advisory Group for Aerospace Research and Development
BM	bellmouth
EPS	ejector-powered simulator
FC	front cell
GE	GE Aircraft Engines
PVC	polyvinyl chloride

rpm	revolutions per minute
SAE	Society of Automotive Engineers
TPS	turbine-powered simulator
UETP	Uniform Engine Test Programme

2.2.3 Subscripts

amb	ambient condition
avg	average
BM	bellmouth
Dist	distortion
e	nozzle exhaust plane
FC	front cell
flow	flow function
max	maximum
min	minimum
s	static
t	total
x	station where $p = p_\infty$
∞	local ambient

3. TECHNICAL BACKGROUND

Gas turbine engine manufacturers and their customers have the requirement to test engines for the purposes of determining performance, verifying repairs, and insuring proper functioning of all engine systems prior to the installation of an engine and its use on-wing. Inherent in such testing is the need to determine engine performance in absolute terms with a high degree of accuracy in a reliable, repeatable testing environment. An important, central issue to gas turbine engine testing is the conflict between the need for accuracy of performance measurements and the need for a reliable, repeatable test environment. An outdoor "free-air" test environment represents the best possible "ideal" condition in terms of thrust measurement. When an engine is tested on an outdoor stand under no-wind conditions, it draws only the air required to satisfy the thermodynamic cycle with the result that all the measured thrust force is considered to be the "true" thrust of the engine (see 2.1.6).

Thus, it would seem that the proper approach for all ground-level testing of engines might be to use outdoor, "free-air" test stands. Since testing at an outdoor stand is so strongly dependent on the weather and wind conditions, it should be obvious that such an approach is not practical when faced with the requirement of a reliable and repeatable test environment. Additionally, of course, the use of outdoor facilities can result in objectional noise pollution. As a consequence, they are likely to be located in more remote, less accessible areas. Accordingly, it is standard practice to conduct most jet engine testing indoors in specialized test facilities, and to correct for the various effects that alter the performance measurements of an engine when it is operated inside a building. In order to determine the actual performance characteristics of an engine when tested indoors, the interaction between the engine and the test cell environment must be understood and evaluated. This has a direct analogy to determining wind tunnel interference effects which are required for a proper understanding of aerodynamic performance characteristics of models tested in wind tunnels.

To underscore the importance of understanding performance measurements from engine test facilities, one of the most extensive experimental and analytical programs ever sponsored by the Advisory Group for Aerospace Research and Development (AGARD) is cited (see 2.1.1). This program, "The Uniform Engine Test Programme" or UETP, was proposed by the Propulsion and Energetics Panel and approved by AGARD in 1980. The objectives of the program were:

a. "To provide a basis for upgrading the standards of turbine engine testing within AGARD countries by comparing test procedures, instrumentation techniques and data reduction methods, thereby increasing confidence in performance data obtained from engine test facilities, and

b. To compare the performance of an engine measured in ground-level facilities and in altitude facilities at the same nondimensional conditions and establish the reasons for any differences."

The UETP involved testing two turbojet engines in five countries using four altitude test facilities and four ground-level test beds. The testing program began in 1981 and extended over a period of approximately seven years. The program has had an historic importance in that for the first time it has made possible direct comparison of engine performance as measured in a closely controlled test program over a range of altitudes and flight speeds, in different facilities, and using different methods of data acquisition and reduction according to 2.1.2. One of the key contributions of the UETP to the participating countries was the derivation and implementation of a standard methodology for objective assessment of the quality of measured engine performance in the various test facilities. Each participant in the UETP found anomalies in his/her test facility and evaluation techniques which have caused an internal re-evaluation. Problems varied in degree, but in some cases the problem would not have been discovered without the ability to compare to other facilities (see 2.1.1). It should come as no surprise that two of the performance parameters most closely studied were engine thrust and specific fuel consumption.

The correction to measured thrust for the so called "test cell effect" is variously known as the test cell correlation factor, cell correction factor, facility modifier, or simply, cell factor. The cell factor results primarily from the momentum of the air approaching the engine acting as a headwind, which reduces indicated engine thrust. It is also modified by pressure forces acting on engine surfaces which differ from those that would be felt in the outdoor environment. In practice, a number of the measured engine performance factors besides thrust must be adjusted for the "test cell effect", and so a set of modifiers or factors must be determined. In spite of the need to accurately determine the cell factor, testing indoors has the significant advantages of being able to operate with limited restrictions imposed by unfavorable weather conditions, of offering the opportunity for noise control and abatement, and of allowing a wider choice of locations. But even before the cell correlation factors can be determined, the first and most important step is to provide the proper indoor testing environment.

A ground level jet engine test cell may be defined as an enclosed structure with an engine mounting mechanism which is intended to provide conditions for stable, repeatable, and accurate engine performance testing. Aircraft turbojet and turbofan engines operating in a test cell can encounter a number of problems which are directly attributable to the characteristics of the test cell environment. These problems can be as minor as unsteady engine speed and thrust variations. This leads directly to increased uncertainty about other engine performance measurements, since many engine performance parameters are referenced either to engine inlet conditions at the compressor or fan face, or to the engine rpm. In these "minor" cases, the engine performance is unstable and not repeatable and often can cause an unnecessary test rejection and a subsequent costly rebuild. In the worst situations, major problems such as fan or core stalls may occur and can result in serious engine damage, an example of which is shown in Figures 1 and 2.

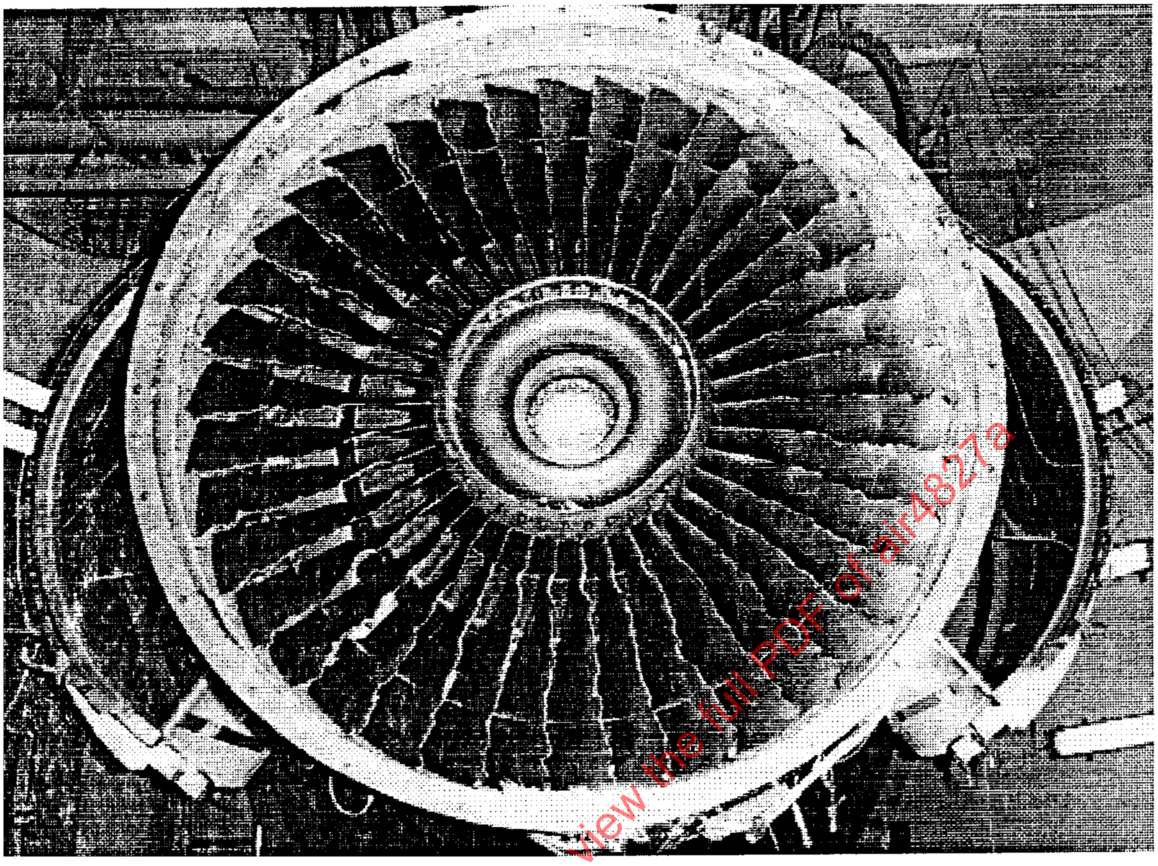

FIGURE 1 - PHOTOGRAPH OF THE DAMAGE SUSTAINED BY A LARGE, HIGH-BYPASS TURBOFAN ENGINE AS A RESULT OF AN INCIDENT RELATED TO A SEVERE TEST CELL AERODYNAMIC PROBLEM

FIGURE 2 - CLOSE-UP PHOTOGRAPH OF THE ENGINE DAMAGE
SUSTAINED AS A RESULT OF AN INCIDENT RELATED
TO A SEVERE TEST CELL AERODYNAMIC PROBLEM

The "minor" performance problems are generally caused by pressure or temperature distortions arising from aerodynamic characteristics peculiar to the flow field of the test cell. More specifically, the problems are related to the design of the cell inlet and exhaust systems and to the cell bypass ratio, which is the ratio of the airflow bypassing the engine completely to that which directly enters the engine inlet or bellmouth. When one test cell is used for several types of engines differing in configuration and orientation, in engine thrust levels, in bellmouth inlet flow requirements, and in exhaust temperatures, the probability of distorted flows with some engines is increased.

Although poor cell inlet designs is the primary factor that leads to distortions in the flow, insufficient or low cell bypass flow can also contribute to the formation of engine-ingested vortices. A dramatic example of this feature of operating an engine in a test cell with a low cell bypass flow is shown in Figure 3. The figure shows a photograph of a strong, well-defined vortex being ingested into the flight cowl inlet of a turbofan engine operating in a test cell with a rather low cell bypass ratio, estimated to have been no greater than approximately 0.46. Visualization of the vortex formation was produced by the condensing of water moisture in the air as a result of the extremely low pressures which exist in the core of the vortex structure. The cell bypass ratio is most strongly influenced by the flow characteristics of the test cell exhaust system. Previous model studies had established that there is a minimum bypass ratio required to insure that vortices are not formed even with a low-distortion cell inlet geometry (2.1.2). This minimum cell bypass ratio provides sufficient forward cell velocity to prevent flow separation on the test cell walls in the region immediately in front of the engine inlet. Flow separation in this area is one of the conditions necessary to allow the formation of an inlet vortex. In addition, adequate cooling of the exhaust system components of many cells depends entirely on the bypass flow.

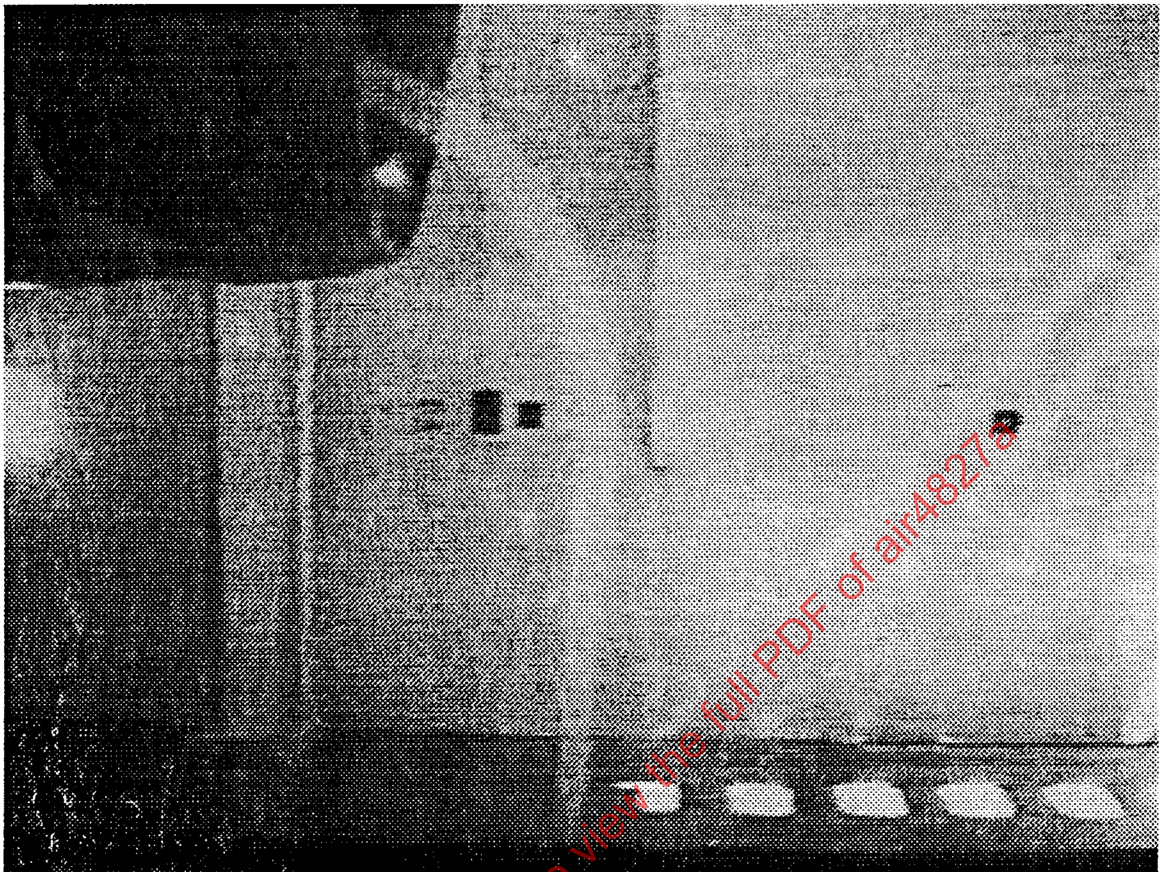

FIGURE 3 - PHOTOGRAPH OF A STRONG, WELL-DEFINED VORTEX BEING INGESTED BY AN ENGINE OPERATING IN A TEST CELL WITH A LOW CELL BYPASS RATIO

3.1 Model Testing as a Tool

Model testing is a useful tool for researching adverse interactions between cell and engine flows, for investigating sound pressure level control or acoustic treatment systems, for developing new cell designs, and for modifying existing cells both to reduce construction costs and to optimize cell performance (2.1.2, 2.1.4, 2.1.8, and 2.1.9). This is accomplished by identifying the various test cell variables and evaluating the cost/performance trade-offs based on the careful analysis of test results. Such a model test program can be supplemented with theoretical and analytical predictions where practicable (2.1.4, 2.1.10, and 2.1.11) to extend the test results and provide a data base and a set of guidelines for conducting future tests. Once this data base has been verified by comparison and correlation with full-scale measurements, it may be applied directly to other full-scale test cell applications which are similar in nature. The same experimental and prediction techniques used to create the original data base may then also be used to establish a starting point for those applications which are unusual or markedly different. The emphasis in this report is on the description of the modeling techniques developed, both for the test cell and the engine simulators.

In model test cell research, there are two areas which are of critical importance to the success or failure of the experimental investigation to produce meaningful results. The first of these is the modeling of the test cell geometry in sufficient detail as to ensure the correct aerodynamics of the system. The second is the simulation of the engine configuration in relative size, placement, and flow characteristics, i.e., ensuring that the engine inlet flow and exhaust momentum are correctly modeled. A brief discussion of engine test cells is first presented in Section 4. Then, Section 5 describes the modeling considerations and instrumentation techniques which can be used in a scale model test cell experimental study. Section 6 contains a detailed account of engine simulation requirements and considerations. This latter section includes a brief description of an ejector-powered engine simulator used in some previous model test programs, a simulator for the CF6-80C2 high-bypass turbofan engine produced by GE Aircraft Engines.

4. ENGINE TEST CELLS

4.1 Test Cell Design Considerations

A modern ground level jet engine test cell facility must be able to accommodate the larger engines of today's aircraft as well as a wide range or mix of engine types with differing thrust levels. Such a facility must also provide an aerodynamic environment of good quality for the operation of the engine, have small uncertainty errors due to test cell interference effects or performance measurement instrumentation accuracies, and include better acoustic treatment to minimize environmental disturbances. Enclosed test cell design concepts have evolved as turbofan and turbojet engines and their operational needs have developed, although not as rapidly. Test cell related engine operational problems can arise because the newer, higher thrust families of engines require substantially more cell airflow than earlier models. Recent research involving model test cells (2.1.2, 2.1.4, 2.1.8, and 2.1.9) has assisted the evolution of engine test cell design and attacked the need for improved engine test facilities.

The test cell design considerations which have evolved for turbofan or turbojet engine test cells have been carefully documented elsewhere (2.1.2, 2.1.3, 2.1.4, 2.1.6, and 2.1.7), particularly in References 2.1.3 and 2.1.7, and will not be repeated here. Generalized design concepts or features for an engine test cell to accommodate a large, high-bypass turbofan engine are shown in Figure 4. It should be noted that this is not necessarily an optimum configuration, but rather it is intended only to illustrate the major features of an engine test cell. The major structural elements or sections of the cell are the inlet plenum, the test chamber, the augmentor/diffuser or exhaust collector, and the exhaust stack. Each must be tailored for its specific function and at the same time be compatible with the other elements to achieve proper aerodynamic and acoustic performance of the entire test cell system.

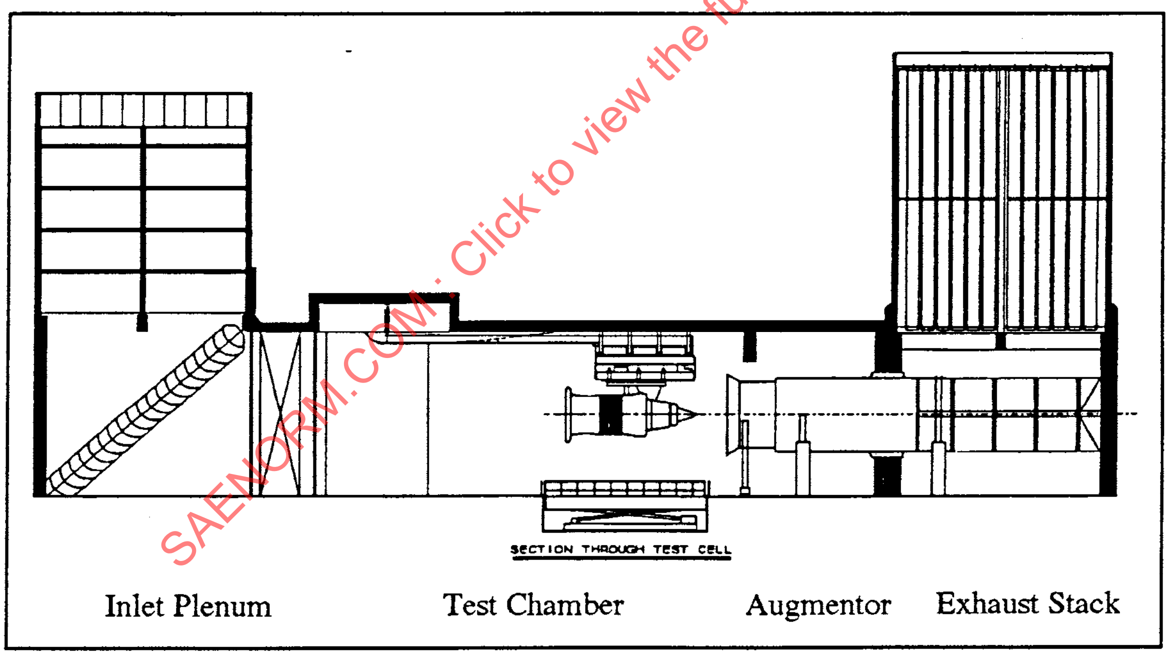

FIGURE 4 - GENERAL DESIGN CONCEPTS FOR AN ENGINE TEST CELL FOR A LARGE, HIGH-BYPASS TURBOFAN ENGINE

4.2 Test Cell Performance Requirements

Important performance assessment criteria include front cell flow field distortion and engine fan face distortion. The front cell, and consequently the engine bellmouth flow field, should be uniform to avoid excessive engine speed fluctuations and thrust measurement uncertainty. The front cell flow field is strongly influenced by the test cell inlet design. For example, the type of cell inlet (horizontal or vertical with 90 degree turning) and the use of turning vanes, screens, and silencers or baffles all influence the uniformity and quality of the front cell flow field. Likewise, the addition of lighting fixtures, engine monorails, personnel access stairways and catwalks, or any other projections into the flow field can distort the airflow in the front cell and thereby cause distortion in the engine fan face flow. In an extreme case, airflow distortion can encourage the formation of engine inlet vortices that can result in core engine stalls and prevent useful testing from being conducted (see Figure 2).

Another performance requirement is the need for sufficient cell bypass flow since engine-ingested vortices will be formed when insufficient bypass airflow exists in the cell, as was shown earlier in Figure 3. A uniform, low-distortion front cell airflow field combined with sufficient test cell bypass flow provides undistorted engine inlet air and discourages the formation of bellmouth vortices. It is also desirable that the test cell performance be basically independent of outside wind direction and magnitude so that testing can be conducted without unnecessary restrictions due to weather. Acoustic performance requirements are described by limits on sound pressure levels in the audible frequency range necessary to meet local environmental restrictions and operational limitations. Additionally, because high-energy, low frequency pressure waves can excite mechanical vibration modes in the test cell structure and surrounding buildings, limits on sound levels in the infrasound range (typically ≤ 20Hz) are required since unique pressure levels can be generated by test cells in that frequency range. These low frequency pressure oscillations can reach amplitudes that cause failure of test cell components such as exhaust tubes and sound treatment panels. Obviously the test cell has to be both a good neighbor and provide an acceptable work environment.

5. TEST CELL MODELING TECHNIQUES

5.1 Selection of Scale Factor

The selection of a geometric scale factor for a test cell model study will likely be driven by simple considerations related to model size and availability of materials. Some early work (see 2.1.2) had been conducted with a scale factor of 1:17.6, chiefly because of the physical size and performance characteristics of an existing turbine-powered engine simulator. Other recent research efforts related to turboshaft engine test cells and to marine and industrial gas turbine applications (2.1.8, 2.1.12, and 2.1.13) have typically employed a scale factor of 1:5 or 1:8. A scale factor of 1:12 was selected for the several large, high bypass turbofan engine test cell model studies described in 2.1.3, primarily because it produced a test cell model which was of manageable size and weight and was easily fabricated from available materials. A properly chosen scale factor will allow the fabrication of test cell model and engine simulator parts without the need to resort to highly specialized machining techniques or to the use of miniaturized, specialized parts in most cases. Drive air supply requirements for the engine simulator will also be a consideration under the category of "manageable" size.

In any aerodynamic scale modeling endeavor, some consideration of the effects of Reynolds number on the aerodynamic results must be given. The Reynolds number is a nondimensional ratio of the inertia forces and the friction forces in the airflow and is used to distinguish between laminar and turbulent boundary layer flow. In particular, boundary layer transition from laminar to turbulent and the effects of where and how that transition occurs are strongly related to the Reynolds number. The difference between full-scale and model scale Reynolds number will arise predominately and directly as a consequence of the geometric scale factor. The effect in test cell modeling is to reduce the value of the Reynolds number, but in most cases, the reduction corresponding to a scale factor of up to one-twelfth is not sufficient to drastically alter the usually turbulent boundary layer characteristics of the test cell flow field. Careful consideration must still be given to the modeling of those geometric features which might be affected by the thickness of the boundary layer or might produce a laminar boundary layer separation.

5.2 Model Hardware Requirements and Considerations

Engine test cell models can be constructed of predominately acrylic sheet and wood or steel. Acrylic sheet material, usually 0.75 inches in thickness, can be used for nearly all flat-surfaced walls and elsewhere as needed to permit a variety of flow visualization techniques to be employed during the course of a test program. Wood or steel should be used primarily in the exhaust system of the model, particularly for exhaust collectors, augmentors/diffusers, and for some exhaust stacks, either because of the unavailability of acrylic tube in the correct diameters or because aerodynamic loads will be of some concern. Acoustic silencer packages which employ baffle or batt designs can be fabricated from wood, while silencer systems which use a muffler tube design can be made from acrylic or PVC tubing. Exhaust blast baskets can be fabricated from thin sheets of punched steel plate of appropriate porosity or percentage open area. A simple "universal" engine mounting system, which is supported external to the test cell model and not by the model of the test cell thrust frame, can be used for thrust force data. This mounting system should be designed to accommodate the thrust of the engine simulator while permitting a reasonable range of movement both parallel to the engine centerline and perpendicular to it.

The ability to easily study a variety of model test cell configurations quickly will be key to acquiring a wide range of model test data in a relatively short time period and in a cost-effective manner. The test cell model should be constructed so that various model subsections can be easily and quickly modified or exchanged for entirely different subsections with no major impact on the other model sections. For example, the cell inlet system can be optimized easily using interchangeable inlet system parts and acoustic baffle packages. Turning vanes installed in vertical inlet sections with a 90 degree turn should be easily installed or removed. A variety of flow-straightening or pressure drop screen configurations and porosities can be tried. Acoustic silencer packages of several designs should be fabricated such that they are easily slid in or out of the vertical inlet or front cell section and added or removed from the exhaust stack. For testing of the different exhaust system concepts, the various sections of the exhaust system should be flanged at several joints where alternate configurations of exhaust collectors, augmentor tubes, diffusers, and exhaust blast baskets or other flow-redistribution devices can be tried.

A test cell model fabricated according to these guidelines would, strictly speaking, not be an aero- acoustic model, but rather an aerodynamic model only. This is because while the aerodynamic flow path features would be modeled accurately, those portions of the test cell which would normally have acoustic treatment would be modeled with "hard", non acoustic surfaces and materials. The use of an acoustically "hard" test cell scale model does not preclude the investigation of certain acoustic aspects of test cell design however. Exhaust system resonances, aerodynamically generated acoustic tones, and infrasound problems can still be investigated since some features of such problems are more dependent on flow path geometry than on surface treatment.

An example of an engine test cell scale model employed in a prior study (see 2.1.3) is shown in Figure 5. The photograph shows the complete model with the engine simulator installed. Also shown are the engine mounting system used, including the simulator's air supply strut and thrust measuring system, and the drive system used for traversing the velocity measurement probes across a plane in the front cell region. This particular model was chosen for comparison purposes to the test cell schematic diagram shown earlier in Figure 4.

5.3 Model Test Cell Instrumentation Techniques

The test cell model and engine simulator should be instrumented extensively to obtain detailed flow information at the various stations of interest through the entire test cell model and engine simulator flow paths. The majority of the data will be pressure data or velocity data. Simple thermocouples can be employed for the measurement of airflow temperatures as needed.

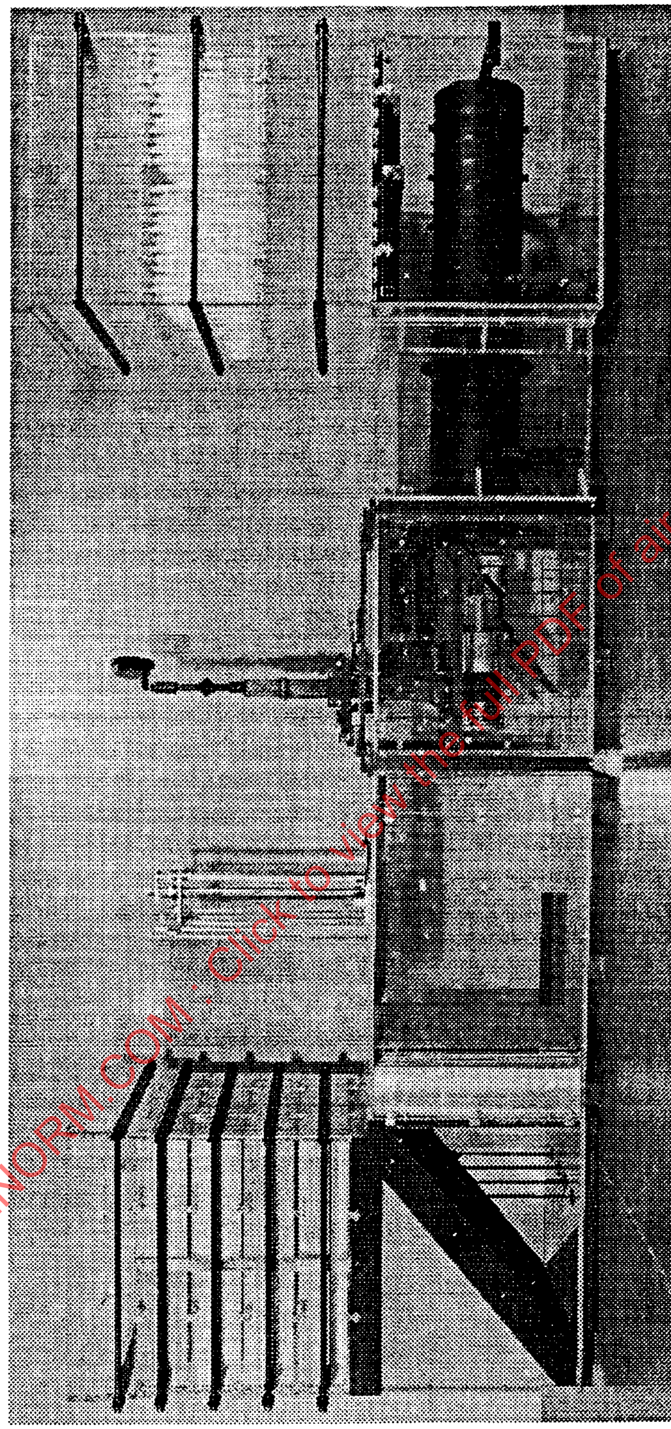

FIGURE 5 - TYPICAL LARGE TURBOFAN ENGINE TEST CELL SCALE MODEL,
SIMILAR TO CONCEPTUAL DESIGN SHOWN IN FIGURE 4,
WITH CF6-80C2 ENGINE SIMULATOR INSTALLED

Most total and static pressures can be acquired by either a mechanically or electrically multiplexed pressure scanning system. The full-scale pressure range of each scanning unit's pressure transducer should be selected to provide the best possible utilization of the transducer range for the pressure being measured, i.e., the smallest pressures should be assigned to the pressure scanner with the most sensitive transducer, and so on. Separate pressure transducers might be employed as appropriate for some pressures, particularly the engine simulator's drive air supply pressures. Each pressure transducer should be "bench" calibrated after installation in the model setup and prior to the first test by applying a set of known pressures to the measurement side of the transducer to determine the sensitivity of each transducer. At some stations of interest in the test cell model such as the front cell region, total pressures can be measured by kiel probes located at centers of equal areas. In other locations such as in the engine bellmouth and exhaust nozzles and in the test cell exhaust augmentor tubes, several total pressure rakes with a number of individual impact tubes per rake should be used to determine the total pressure distribution.

Velocity data in a measurement plane in the front cell region of the model can be acquired by several channels of hot film anemometry. When hot film anemometry probes are employed, careful attention to their calibration must be given. Each hot film should be calibrated by exposing the sensor to a set of known air velocities in a full-immersion cross-flow facility to determine the fourth order polynomial coefficients used to compute velocity as a function of the hot film sensor's output voltage. Velocity measurements in the front cell region can be made by an array of these hot film probes traversed from the ceiling to the floor of the model across the centers of equal area strips, with data collected at several positions across the span of the traverse. A probe drive system instrumented with a potentiometer will allow a precise determination of the position of the hot film probes as they are traversed. A typical installation of the hot film probes with traversing system in the front cell region of a model test cell is shown in Figure 6. Usually, the velocity distribution in a measurement plane will be defined by an M x N array of measurements where M, the number of hot film probes, might typically be five and N, the number of positions where velocity data points are to be acquired, might be nine. From such a 5 x 9 set of measurements a 5 x 5 subset could be selected for direct comparison to data typically collected in full-scale test cell facilities. This 5 x 5 subset should be selected to provide 25 measurements which are made at the center of equal area sections in the front cell region. As an alternative to hot film anemometry, a laser velocimetry system could be used to acquire velocity data in a front cell measurement plane.

Thrust force data can be acquired from a simple engine simulator mounting system which is supported external to the test cell model, not by the scale model of the test cell thrust frame. One such system (see 2.1.3) consisted of a mounting block system which was clamped around the air supply strut for the engine simulator's ejector system. This mounting/clamping block pivoted freely about an axle supported by roller bearing assemblies installed in pillow blocks at one end of the mounting block. At the other end of the mounting block was a single reaction point. The thrust force reaction was directed either onto a steel cantilevered beam instrumented with strain gages or onto a conventional load cell. This mounting system arrangement clamped around the air supply strut with the reaction force directed onto a conventional load cell is shown in Figure 7. The output of the strain gage or load cell system should be able to be calibrated by a dead-weight center-line pull technique with the engine simulator installed. Thrust information can also be calculated from engine exhaust flow parameters if sufficient measurements are made to quantify the engine exhaust flow at both the fan and core nozzle exits. The thrust produced at the exhaust exit plane of the engine simulator can be calculated using the equations defined later in Section 6.

All instrumentation electronics should be powered up continuously to provide the best long-term stability possible. An electronic recalibration of all pressure transducers should be performed before each run to assure that proper zero reading values are recorded and that all variations of sensitivities from bench calibration data are accounted for fully. Electronic zero reading values from hot film sensors should be updated at the beginning of each testing session. The ambient pressure and temperature should also be acquired at the beginning of each testing session and updated throughout the day as required.

Flow visualization consisting primarily of either yarn tufts or smoke can be recorded on video tape for post-test playback and study. Tufts are often useful for qualitatively defining the cell flowfield in the vicinity of the engine and particularly on the engine bellmouth lip. Dense smoke produced by commercially available smoke bombs or a smoke generator can also be employed for flow visualization, but normally not in the same model setup during which measurements are acquired.

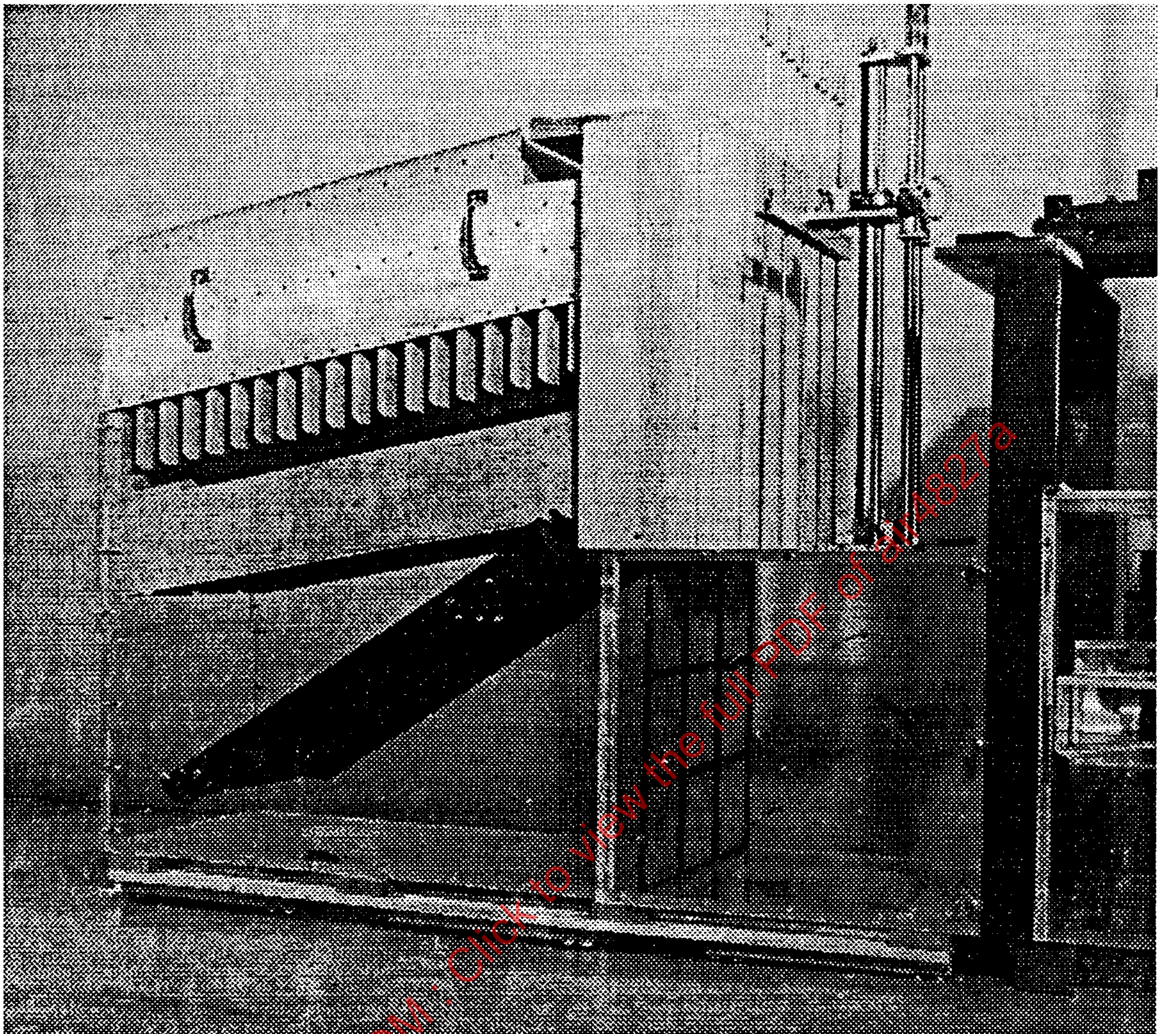

FIGURE 6 - PHOTOGRAPH OF A TYPICAL INSTALLATION OF HOT FILM PROBES WITH TRAVERSING SYSTEM IN THE FRONT CELL REGION OF A MODEL TEST CELL

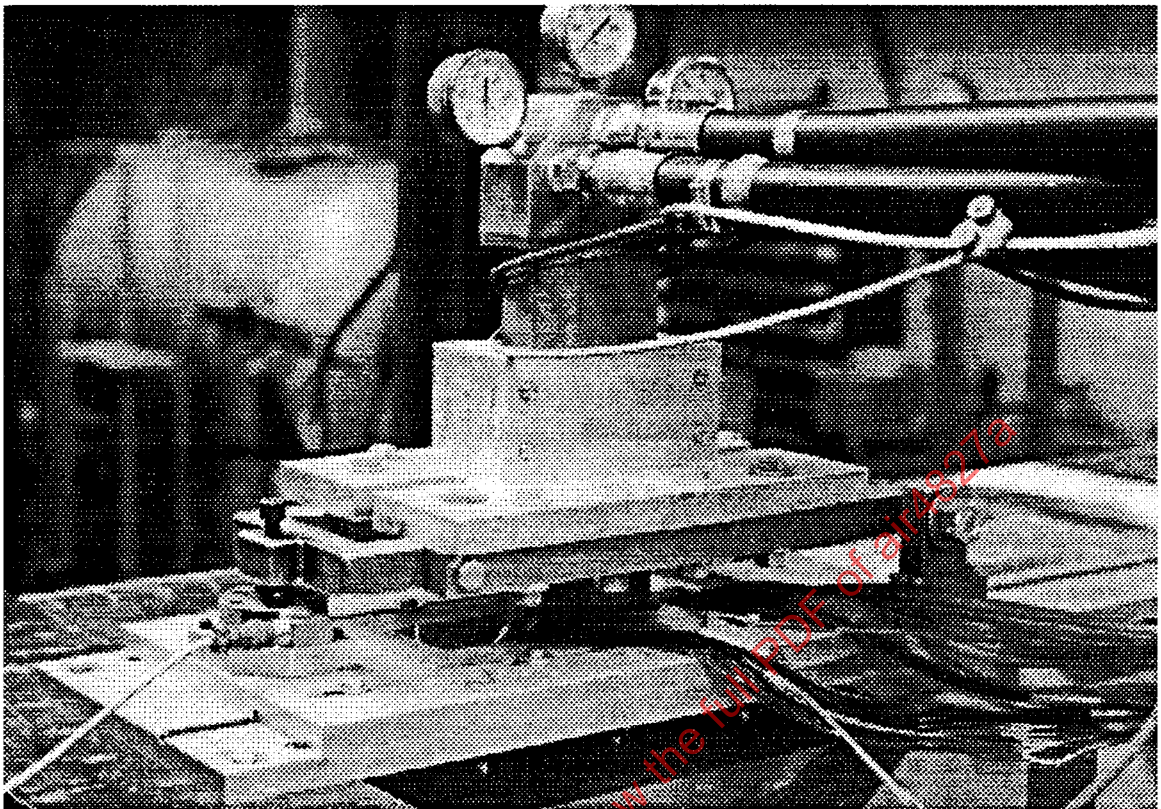

FIGURE 7 - PHOTOGRAPH OF A TYPICAL INSTALLATION OF THE EJECTOR DRIVE AIR SUPPLY STRUT FOR THE ENGINE SIMULATOR AND THE THRUST MEASURING SYSTEM USING A CONVENTIONAL LOAD CELL FOR THE FORCE MEASUREMENT

5.4 Model Data Acquisition and Reduction

It is advantageous to the model test program if all measurements from the pressure scanning system, thermocouples, and hot film anemometers are acquired under computer control for each data point in the model test program. A robust, fully interactive software package will likely prove to be expedient and most useful to the scale model test program. For scale model test cell testing, the data acquisition and reduction tasks which will need to be performed include, but may not be limited to, the following:

a. System and data initialization

b. Pre-run and postrun on-line sensor calibration and integrity checking

c. Data collection, including a real-time display of simulator thrust and drive air pressure, pressure scanning system data acquisition, and traversing hot film probe data collection

d. Data reduction involving complete summarization of all sensor data and extensive data analysis for the pressure measurements made on the test cell and the engine and for the velocity measurements made in the front cell region

e. Archival saving of all raw data

f. Postrun termination

Data reduction to the commonly used engineering units for engine performance testing will likely be performed on-line by the computer program integrated within the data acquisition software package. The same reduction program could also be used to re-reduce data from model test runs stored in the file of archived raw data. A computer-produced report of the reduced model test data would be available within a matter of seconds after each run was completed and the format of the report can be configured specifically to the requirements of each particular scale model test cell research program. The reduction program should present the results in both model scale and equivalent full- scale terms, making interpretation of the results much easier and directly comparable to known or familiar full-scale quantities. The promotion of model test values and results to equivalent full-scale quantities is simplified when a one-twelfth model scale factor is used. Values which enter directly as the scale factor are simply multiplied by twelve, or in the case of dimensions, inches are simply interpreted as feet. Values which depended on a reference area, such as thrust or airflow, are simply multiplied by the square of the scale factor, or 144.

6. ENGINE SIMULATION

6.1 Engine Simulator Requirements

Some previous studies have used turbine-powered simulators (TPS) for cell investigations (see 2.1.2) and for wind tunnel tests (2.1.14, 2.1.15, and 2.1.16) while others have used ejector-powered simulators (EPS) (2.1.3, 2.1.4, 2.1.8, 2.1.17, and 2.1.18). In the engine simulator techniques described here, the EPS type was developed for reasons of greater flexibility in operation as well as economy and ruggedness. When a moderately large supply of dry, high-pressure air is available, the application of ejector-powered techniques to scaled model jet engines is natural. However, many of the requirements and considerations discussed are applicable to the TPS type as well.

In the simulation of the total test cell environment, the engine must be modeled in relative size, shape, and location and the simulation must provide the correct scaled engine inlet and exhaust flows effects (see Figure 8). The relative importance among each of these features varies with the type of engine and/or test cell. For turbofan and turbojet engines, the jet exhaust provides the motive power for the cell bypass flow by induction whereas for a turboshaft engine (or turboprop operating without the propeller) an additional means of pumping may be required to produce adequate cell bypass flow. This is particularly true when the turboshaft engine flow path from inlet to exhaust is not in-line with the exhaust system of the test cell.

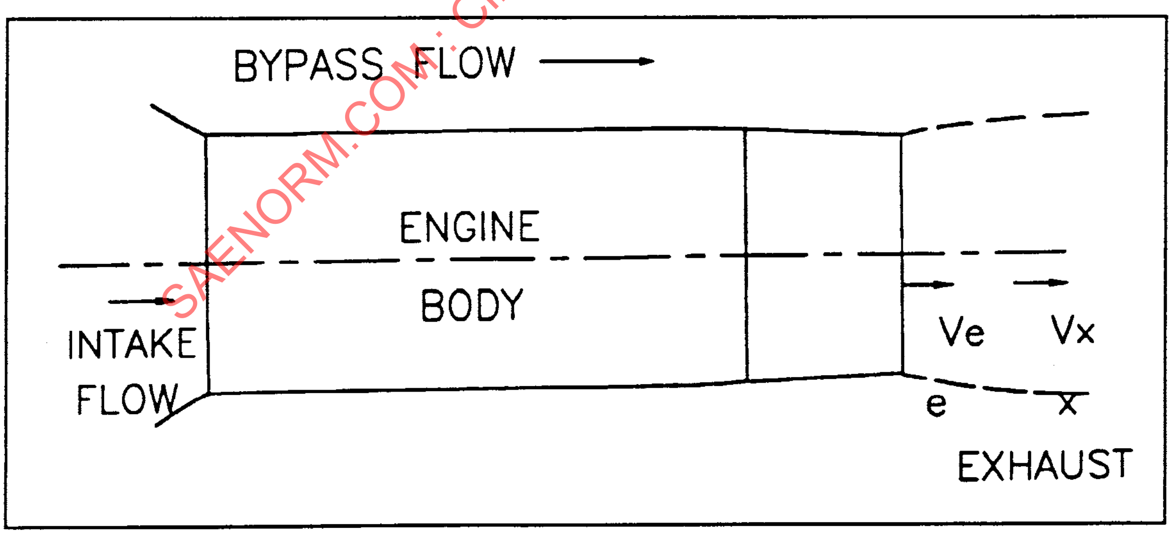

FIGURE 8 - ENGINE SIMULATOR AND EXTERIOR FLOW FEATURES

The physical shape of the installed engine must be modeled in general shape and size, including the numerous supporting structures and associated slave hardware and instrumentation. These details are important to the extent that they can influence or distort the flow field in the cell in the vicinity of the engine bellmouth and to the extent to which they may affect the cell bypass flow.

A critical item for the simulator is the engine inlet or bellmouth flow. Thus, the bellmouth installation must be modeled with precision and the inlet airflow (scaled and corrected) must be available over the entire range of engine operation. With the EPS, the ejector systems internal to the engine body can be used to induce the necessary bellmouth flow.

In simulating the exhaust, careful consideration must be given to the fact that the full-scale engine exhaust temperature is much higher than that of the simulator. Depending on the nature of the jet engine being simulated and the particular test cell in which the engine is to be operated, some compromises may become necessary. For test cell installations where the engine exhaust provides the primary cell flow augmentation, it may be correctly argued that the exhaust momentum is the governing parameter, since ejector/mixer analyses show that it is through the mixing-transfer of this momentum that the secondary flow, i.e., the cell flow, is induced (see 2.1.19). Although there is some experimental evidence on the mixing effectiveness of hot versus cold flows (2.1.20, 2.1.21), other features dominate the engine simulator problem. It can be noted at this point that the exhaust momentum (or more precisely, the exhaust plane thrust) is of primary importance in the application of engine simulators to wind tunnel models of complete aircraft configurations as well.

The exhaust plane thrust is given by the expression

$$\text{Thrust} = A_e[(p_e - p_\infty) + \rho_e V_e^2] \qquad \text{(Eq. 1)}$$

For a subsonic exhaust, the exhaust static pressure, p_e, equals the ambient pressure, p_∞, and only the momentum terms need to be considered. When the exhaust is supersonic, as is typically the case for a low-bypass turbojet with afterburning, then p_e differs from p_∞ in the general case. However, the exhaust flow jet equilibrates in pressure a short distance downstream so that the local thrust is

$$\text{Thrust}_x = A_x \rho_x V_x^2 \qquad \text{(Eq. 2)}$$

where A_x is the "plume" cross-sectional area and p_x is equal to p_∞. In the test cell environment, p_∞ is approximately barometric, and jet pluming will be found to be negligible or, in some cases, negative; that is, when p_∞ is greater than p_e, the exhaust jet size is less than the diameter of the exhaust nozzle. Generally for the test cell engine simulator, A_x is approximately equal to A_e and the difference may be important only for certain particular augmentors. Since the thrust is given by

$$\text{Thrust}_x = A_x \rho_x V_x^2 = \dot{m} V_x = \dot{m} M_x \sqrt{\gamma R T_x} \qquad \text{(Eq. 3)}$$

and

$$A_e \rho_e V_e^2 = \gamma p_e M_e^2 A_e \qquad \text{(Eq. 4)}$$

where $\dot{m}$ is the engine exhaust mass flow, these relations provide the basis for calculating the simulator exhaust plane thrust. An obvious, important parameter is the temperature. If all other parameters were to be the same, then the simulator mass flow must be increased over that of the full-scale engine by a factor of the square root of the temperatures. This factor may be between two and three for an afterburning turbojet simulated by cold-flow ejectors. For turbofan engine exhausts of lower temperature levels, the usual "corrected constant", or flow function,

$$m_{flow} = \frac{\dot{m}\sqrt{T_t}}{p_t A} \qquad \text{(Eq. 5)}$$

may be used to calculate the required exhaust flow. In either case, it is seen that the exhaust flow in the simulator is increased over the scaled hot flow by the same predominate temperature-related factor. This excess flow may be supplied in the form of ejectors internal to the engine simulator, and it is precisely this feature which forms the basis for the design of ejector-powered engine simulators.

For the higher-temperature engine exhausts, such as those of afterburning turbojets, other features complicate the problem and make "simultaneous" simulation of both exhaust nozzle geometry and exhaust momentum impossible. Some compromise is usually necessary depending on the particular engine/cell installation being modeled. The EPS technique can be very flexible in this respect, allowing some careful parametric variations in the exhaust configurations. Specifically, at the temperature of an afterburning turbojet exhaust, the specific heat ratio, γ, is approximately 1.25 compared to the usual value of 1.4 for cold air and the gas constant, R, is also slightly different due to both the elevated temperatures and the combustion products in the exhaust flow. These differences directly affect the calculation of the mass flow required for thrust simulation. Both γ and R strongly affect the nozzle geometric area ratio and the pressure ratio for a given Mach number. Thus, to achieve the desired thrust level for the turbojet engine, it may be necessary for all exhaust flow variables in the simulator to differ from their counterparts in the full-scale engine. In the test cell environment, small changes in exhaust geometry (A_e) may become important in those situations where the cell augmentor is closely-coupled to the engine exhaust.

6.2 Engine Simulator Design Considerations

In order to achieve the simulation discussed above, the internal engine configuration and the ejector system must be considered. The pertinent features are shown schematically in Figure 9 and include the engine inlet and exhaust flows, the ejector system, the mixing zone, and the ejector air supply. The entire unit is necessarily bounded in physical size and shape by the geometry of the full-scale engine.

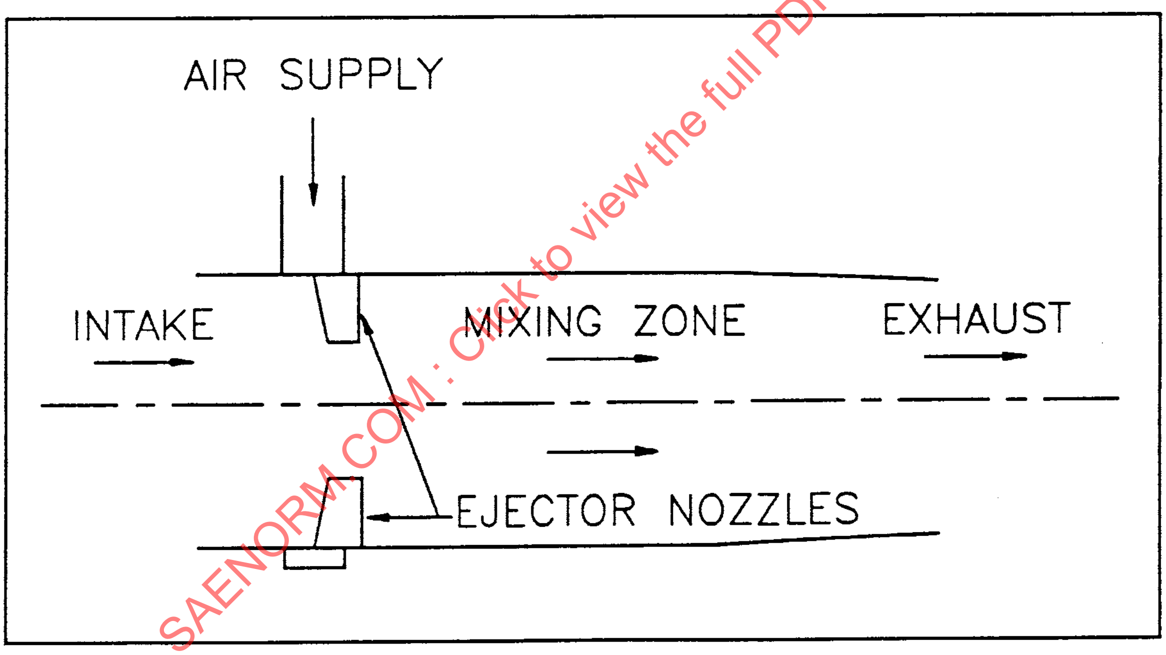

FIGURE 9 - EJECTOR-POWERED ENGINE SIMULATOR INTERIOR FLOW FEATURES

From the previous discussions, it is apparent that if the geometry is approximately maintained and if the exhaust Mach number is nearly that of the full-scale engine, then the temperature of the ejector air relative to that of the engine exhaust will determine the ejector air mass flow rate. The question as to whether this flow rate is adequate for inducing the required inlet flow is necessary. In a number of cases, particularly for the smaller turboshaft engines and low-bypass turbojets, it will be found that the required ejector airflow will be more than sufficient for this purpose, and, in fact, it will sometimes be necessary to provide some means of limiting the engine inlet flow to its proper level. This may be done by spoiling the inlet flow downstream from the metering station in the engine bellmouth or by choking the flow. In some engine configurations, it may be feasible to size the ejector system so that the inlet flow is choked at the ejector station. In the case of a large turbofan engine simulation however, the exhaust exit area usually has a strong controlling effect on the engine inlet flow such that some compromise in the exhaust nozzle exit area is typically required. This compromise in exhaust exit area subsequently leads to a reduction in exhaust Mach number as well.

Adequate mixing of the ejector flow with the induced bellmouth flow is desired so that the engine exhaust flow will be comparatively uniform. Since the length required for the jet exhaust (from the ejector) to be effectively mixed with the induced inlet flow is roughly 15 to 20 diameters, it will be necessary to eject the drive flow through a large number of small nozzles.

As an example of the application of the engine simulation techniques just described, one-twelfth scale engine simulators have previously been designed and built for the GE CFM56-3 (see Figure 10) and the GE CF6-80C2 (2.1.5). The ejector system of these turbofan engine simulators was a set of supersonic nozzles in swept struts, fed by an annular high pressure air supply plenum. The ejector strut station was designed to choke the bellmouth flow to the proper level for the maximum take-off engine operating condition, but bellmouth flow actually is limited first by the engine exhaust nozzle exit area. The length internal to the simulator body available for mixing was short and thus required that the ejection be accomplished through a very large number of rather small nozzles. Each ejector strut contains a long, narrow air chamber fabricated by a "deep pocket" electro- discharge machining process. The downstream edge of each ejector strut contained conical supersonic nozzles with constant-area throat sections which were selectively spaced to achieve the desired engine exhaust flow conditions. In the case of the CF6-80C2 engine simulator, 26 ejector struts and over 375 nozzles were used. Rather than deal with two separate flows for simulation of the fan and core exhaust, an axisymmetric flow splitter was used downstream from the ejector strut station to split the mixed flow as needed into the fan and core flows in accordance with their relative thrust levels. The centerbody required for proper simulation of the core exhaust nozzle was simply extended forward to the ejector station. The fan cowl, the fan/core flow splitter, and the centerbody were fixed together by means of a pair of orthogonal struts which could easily be removed; in addition, by threading the centerbody and the fan cowl, the entire aft end of the simulator could be quickly disassembled for installing or changing instrumentation. It should be noted that the use of such a flow splitter may not be appropriate for all engine types or engine simulator applications.

Figure 11 (from Reference 2.1.3) shows a photograph of the CF6-80C2 ejector-powered engine simulator as installed in a scale model test cell. Just visible inside the simulator bellmouth is one of the total pressure rakes located at the bellmouth metering station. The ejector drive air supply strut at the top of the simulator passes through the model of the test cell thrust frame to the externally mounted engine support and thrust measurement system shown earlier in Figure 7. The small tubes running along the outside of the aft end of the simulator are connected to the total pressure rakes and static taps located in the fan and core nozzles.

7. TEST CELL AERODYNAMIC PARAMETERS TO BE OBTAINED

Some of the more important measured or calculated parameters which are often used to quantify and evaluate the performance of the various engine test cell configurations for scale models and full-scale facilities are described below. A generally accepted method of calculating the value for each parameter is also given.

7.1 Front Cell Velocity Distortion

The front cell velocity distortion factor or index, calculated from a grid of velocity measurements in a test cell plane upstream of the engine inlet or bellmouth, can be used as a general indicator of test cell airflow uniformity or quality. A typical minimum grid spacing might be a matrix of 5 x 5 measurement locations, or a total of 25 points located at the centers of equal areas. The velocity measurement plane should be located about three or four bellmouth throat diameters in front of the bellmouth entrance plane, yet not too close to any silencer baffles or flow-conditioning screen support frames in the inlet system or front cell region. A location in the front cell which is midway between the bellmouth and the last flow-straightening screen might also be chosen. The velocity distortion parameter is defined as follows:

$$FC_{Dist} = \frac{V_{max} - V_{min}}{V_{avg}} \quad \text{(Eq. 6)}$$