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DESIGN CONSIDERATIONS FOR ENCLOSED TURBOFAN/TURBOJET ENGINE TEST CELLS

FOREWORD

One of the strongest motives for documenting the considerations which are judged important in the design of enclosed ground-level testing facilities for turbofan and turbojet engines as described in this work was the generally poor understanding of the aerodynamics associated with the test cell environment. 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. Recent research work has led to a much improved understanding and heightened awareness of the fundamental importance of the aerodynamics of the engine testing environment and has resulted in significantly improved engine test facilities now in use worldwide. This document is intended for individuals associated with the ground-level testing of large and small gas turbine engines and particularly those who might be interested in upgrading their existing or acquiring new test cell facilities.

Turbofan and turbojet engines operating in a ground-level test cell can encounter a number of problems which are directly attributable to the characteristics of the test cell environment. Some of the more important factors which must be considered in the development of test cell designs leading to desired engine operational stability, aerodynamic performance, and acoustic control are described. Test cell performance goals which typically might be used to define "excellent" cell performance are included. When these cell performance goals are achieved, stable and repeatable engine operation can be assured. Recent research conducted in scale model test studies, reinforced by results from a number of full-scale operational experiences, has assisted the evolution of engine test cell design and attacked the need for improved engine test facilities.

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1. SCOPE:

This SAE Aerospace Information Report (AIR) has been written for individuals associated with the ground-level testing of large and small gas turbine engines and particularly for those who might be interested in upgrading their existing or acquiring new test cell facilities.

1.1 Purpose:

There are several purposes served by this document:

a. To provide guidelines for the design of state-of-the-art ground-level enclosed test facilities for turbofan and turbojet engine testing applications.

b. To address the major test cell/engine aerodynamic and acoustic characteristics which can influence the operation of a gas turbine engine and its performance stability in a test cell.

c. To consider acoustic environmental impact and methods to control it.

2. REFERENCES:

2.1 Applicable Documents:

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

2.1.1 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, Paper presented to the AIAA/ASME/SAE/ASEE 22nd Joint Propulsion Conference, Huntsville, Alabama, June 16-18, 1986

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 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

2.1.4 Grunnet, J. L., and Ference, E.: "Model Test and Full-Scale Checkout of Dry-Cooled Jet Runup Sound Suppressors", AIAA Paper No. 82-1239, AIAA/SAE/ASME 18th Joint Propulsion Conference, Cleveland, Ohio, June 21-23, 1982

2.1.5 "Gas Turbine Engine Test Cell Correlation", SAE Aerospace Recommended Practice ARP741, Society of Automotive Engineers, Warrendale, Pennsylvania, Issued March 1976, Reaffirmed October 1982. (Note: This ARP was recently revised and reissued as ARP741 Revision A in September 1993 with substantial changes; the original March 1976 version is the specific reference here)

2.1.6 Oran, F. M., and Schiff, M. I.: "Design of Air-Cooled Jet Engine Testing Facilities", Industrial Acoustics Company, Bronx, New York, 1979.

2.1.7 Ashwood, P. F., et al.: "Operation and Performance Measurements on Engines in Sea Level Test Facilities", AGARD Lecture Series No. 132 (AGARD-LS-132), Advisory Group for Aerospace Research and Development, North Atlantic Treaty Organization, Neuilly Sur Seine, France, 1984

2.1.8 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

2.1.9 Freuler, R. J.: "Recent Successes in Modifying Several Existing Jet Engine Test Cells to Accommodate Large, High-Bypass Turbofan Engines", AIAA Paper No. 93-2542, Paper presented to the AIAA/SAE/ASME/ASEE 29th Joint Propulsion Conference, Monterey, California, June 28-30, 1993

2.1.10 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

2.1.11 Bryan, J. J.: "Turbofan and Turbojet Engine Test Facilities Exhaust System Low Frequency Noise and Infrasound", Engineering Report, General Electric Engine Facility Design Center, Cincinnati, Ohio, September 20, 1985

2.1.12 Karamanlis, A. I., and Pucher, S.: "Strother/Kansas CFM56/F110 GE Test Facility Scale Model Test", General Electric Technical Memorandum, TM No. 85-334, GE Aircraft Engines, Cincinnati, Ohio, July 1985

2.1.13 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

2.1.14 "Gas Turbine Engine Inlet Flow Distortion Guidelines", SAE Aerospace Recommended Practice ARP1420, Society of Automotive Engineers, Warrendale, Pennsylvania, Issued March 1978, Reaffirmed May 1991

2.1.15 "Inlet Total Pressure Distortion Considerations for Gas Turbine Engines", SAE Aerospace Information Report AIR1419, Society of Automotive Engineers, Warrendale, Pennsylvania, Issued May 1983

2.16 Freuler, R. J. and Montgomery, K. A.: "Reducing Large Pressure Fluctuations in an Engine Test Cell by Modifying the Exhaust Blast Basket End Configuration", CEAS/AIAA Paper No. 95-128, Paper presented to the First Joint CEAS/AIAA Aeroacoustics Conference (16th AIAA Aeroacoustics Conference), Munich, Germany, Proceedings of the First Joint CEAS/AIAA Aeroacoustics Conference, Vol. 2, June 1995, pp. 903-909.

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
C_d - flow coefficient
g - gravitational constant
M - Mach number
p - pressure
R - gas constant for air
T - temperature
V - velocity
W - airflow rate
a - cell bypass ratio
g - ratio of specific heats

2.2.2 Abbreviations:

AIAA	American Institute of Aeronautics and Astronautics
AGARD	Advisory Group for Aerospace Research and Development
BM	bellmouth
FC	front cell
ft/s	feet per second
L/D	length-to-diameter ratio
m/s	meters per second
rpm	revolutions per minute
SAE	Society of Automotive Engineers

2.2.3 Subscripts:

amb ambient condition
avg average
BF cell bypass flow
BM bellmouth
Dist distortion
ENG engine
FC front cell
flow flow function
max maximum
min minimum
s static
t total

3. TECHNICAL BACKGROUND:

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. Turbofan and turbojet 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 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, more severe problems such as fan or core stalls may occur and can result in serious engine damage.

The above 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. And although poor cell inlet designs can obviously contribute to distortions in the flow, it is often the case that insufficient or low cell bypass flow is primarily responsible for the formation of engine-ingested vortices, which should be avoided.

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 engines 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 errors due to test cell interference effects or performance measurement instrumentation inaccuracies, 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

3. (Continued):

operational problems can arise because the newer, higher thrust families of engines require substantially more cell airflow than earlier models. Recent research involving scale model test cells has assisted the evolution of engine test cell design and attacked the need for improved engine test facilities (2.1.1, 2.1.2, 2.1.3, 2.1.4).

As an example of this evolutionary change in test cell design, consider for a moment the velocity of the airflow in the front cell region. Previously, design guidelines usually suggested that the front cell velocity preferably be less than 32 ft/s (9.8 m/s) (2.1.5, 2.1.6, 2.1.7). The reasoning was that if the airflow velocity in the test cell is significant, then the operation of the engine in the cell is equivalent to "flying" the engine at a ram pressure ratio greater than 1.0 and at a somewhat higher altitude. Combined with the fact that there are pressure losses through the cell inlet system, it follows that the correction to engine performance measurements to sea level static standard day conditions is greater, since both the total and static pressures in the cell are depressed. The result was that a somewhat higher or larger ram drag correction to the measured thrust would be required. The tendency in test cell design was to limit front cell velocities to keep these corrections very small, and either somehow deal with or mostly ignore and live with the resulting distortions and instabilities in the cell flow. Dealing with such distortions may have involved vortex "destroyers", cross-sectional area modifiers, "horse collars", variable porosity flow treatment devices, or other similar aerodynamic fixes.

Scale model test results, reinforced by a number of full-scale operational experiences (2.1.8, 2.1.9), have shown that the benefits of higher front cell flow velocities now outweigh the desire for a negligible effect due to front cell flow on cell correction factors. The specification of a very large cell size or a limit on the velocity levels in the front cell is unnecessary for accurate cell factor determination. Designing a test cell with such a specification does not take into account the adverse impact of the possibilities of airflow recirculations, unstable engine operation, bellmouth flow distortions, or vortex formation and ingestion. With available analytical methods and up-to-date pressure, temperature, and force measurement instrumentation, cell factor corrections to measured engine thrust and other measured performance parameters can be determined with great accuracy and confidence. In exchange for a somewhat larger but more accurately known cell factor correction, the problems which can potentially be produced by low cell bypass flows are completely avoided and no front cell or test chamber aerodynamic fixes are necessary when a high cell bypass design philosophy is followed.

4. TEST CELL SYSTEM DESIGN CONSIDERATIONS:

Generalized design concepts or features for an engine test cell to accommodate a large, high-bypass turbofan engine are shown in Figure 1. It should be noted that the configuration in the figure is not necessarily an optimum one, 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. Each will be described in terms of its purposes and functional considerations.

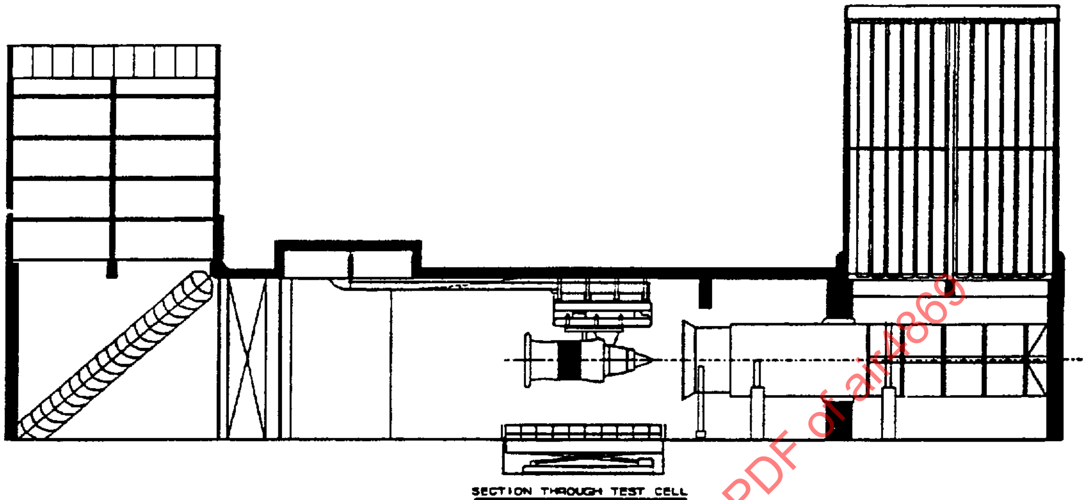

FIGURE 1 - General Design Concepts for an Engine Test Cell for a Large, High-Bypass Turbofan Engine

4.1 Inlet Plenum:

The primary purpose of the inlet plenum or system is to provide a fully uniform, quality flow of air in sufficient quantity to the test chamber. Secondary purposes are to control the propagation of noise which emanates from the front of the engine and to isolate the test chamber from the effects of crosswinds. The components which are generally used in test cell inlet systems are pressure drop screens, turning vanes for vertical inlet stacks with a 90° bend, and acoustic surface treatment and silencer baffles. A vertical inlet stack with its 90° bend and turning vanes provides both good acoustic control and a uniform front cell flow while isolating the test chamber from the effects of outside winds. For adverse wind conditions, scale model test results and full-scale experiences have demonstrated the beneficial insensitivity-to-crosswinds effect produced by the use of an "egg-crate" structure in the top portion of a vertical inlet stack. A properly designed horizontal inlet system with a generous bellmouth-like entrance lip might be used when acoustic requirements are not too restrictive and the prevailing ambient wind conditions do not pose a concern, but a horizontal inlet system can sometimes produce unwanted temperature gradients in the front cell flow field and may have a greater potential for allowing foreign objects or debris into the test chamber.

4.2 Test Chamber:

The purpose of the test chamber is to provide both the mounting system necessary to hold the engine and the various services required for the operation of the engine. The test chamber contains the engine thrust frame, which accommodates engine thrust loads, and cell supporting equipment such as lift platforms, ladders, engine monorails, lighting fixtures, etc. Careful attention must be paid to the design of the test chamber to eliminate or minimize projections into the flow field, particularly into any portion of the flow which ultimately enters the engine bellmouth. Such projections can cause wakes and distortions in the bellmouth flow and produce unwanted variations in engine speed. These flow disturbances can also increase the possibility of vortex formation in the vicinity of the engine bellmouth. For this reason, consideration should be given to those aspects of the test chamber design which affect airflow in the vicinity of the engine to ensure that air is not recirculating and reingested by the engine. A test chamber cross-section which is reasonably square in shape or nearly axisymetric is less likely to have regions of recirculating flow than a cross-section which is rectangular in shape. Reingestion of exhaust gases can produce undesirable temperature distortions in the compressor and adversely affect engine performance. Recirculating flow in the vicinity of the engine can adversely affect the accuracy of the cell factor by increasing its uncertainty. It is noted that reingestion and recirculation are minimized for test cell designs with sufficient cell bypass flow and, conversely, are usually the primary factors affecting engine stability in facilities with low cell bypass.

4.3 Augmentor:

The primary purpose of the augmentor or exhaust collector system is to capture the engine exhaust flow so that it may be directed into the exhaust stack and subsequently out to the ambient atmosphere. Equally important is the secondary or bypass flow in the test cell. This secondary flow is produced by the ejector pumping action resulting from the interaction of the engine exhaust flow with the surrounding cell environment. The effectiveness of this pumping action is influenced by a number of factors, including the engine nozzle/augmentor diameter ratio, the augmentor inlet shape or configuration, the spacing between the engine nozzle and augmentor entrance, the pressure losses in the exhaust system, and the length of the augmentor tube or exhaust collector system (2.1.10). Pumping is also somewhat dependent on the alignment of the engine centerline with the cell centerline and the alignment of the augmentor centerline with the cell centerline. Proper alignment encourages better cell pumping and can reduce engine inlet flow distortions to their lowest possible value.

The length of the exhaust collector influences the degree to which the extremely hot exhaust gases are mixed with the cell bypass flow (and/or secondary cooling flow in those situations where a secondary air inlet is used in the test cell design). It is the success of this mixing process, combined with the availability of sufficient cooling air, that is the key to air-cooled engine test facilities and is particularly important for those test cells which must accommodate both afterburning turbojet engines as well as the large, high-bypass turbofans. To a limited extent, the exhaust collector is useful in controlling the noise which is generated in or near the engine, but it is not able to completely control exhaust jet noise since the peak in the jet noise occurs relatively far downstream from the engine nozzle (2.1.11). The exhaust collector system should produce an exhaust flow which is as uniform as possible in temperature and pressure at the collector exit.

4.3 (Continued):

For air-cooled turbofan test cell designs, an exhaust collector length-to-diameter (L/D) ratio of 4.0 or greater is typically suggested. Alternatively, shorter exhaust systems might be employed where space for augmentor length is not available, but some means of promoting the mixing of the engine exhaust with the cell bypass flow may be required to prevent a substantial loss in cell pumping performance.

While a larger, constant-diameter augmentor is often used to produce the required cell pumping needed for the newer, larger turbofan engines, some careful diffusion of the exhaust collector flow can produce useful improvements in cell pumping as well. The choice between a large constant-diameter augmentor and an augmentor/diffuser combination and the related question of how much augmentor length versus how much diffuser length become important considerations when the test cell is used for a wide variety of engines. This is particularly true when afterburning engines are included in the mix of engine types to be tested in the facility. The key in designing the diffuser section is to strive for high diffusion efficiency while avoiding flow separations. Because of the highly distorted nature of the exhaust collector flow, diffusers with moderate diffusion angles of up to 3 or 4° on the half-angle have been found to perform better than those with larger half-angles nearer to or greater than the traditionally "optimum" value of 6 or 7° (2.1.12).

There is a consideration related to the spacing between the engine exhaust nozzle and the augmentor entrance lip and to the length and diameter of the augmentor tube itself. It is beneficial if the engine spacing and the augmentor size can be specified so that the engine exhaust plume attaches to the cylindrical section of the augmentor tube downstream of the entrance lip but before the start of the diffuser, if present, or the exhaust blast basket or exhaust stack.

4.4 Exhaust Stack:

One purpose for the exhaust stack is to direct the hot exhaust gases up and away from ground levels. A second purpose is to reduce sound levels outside the test cell. The exhaust stack normally includes a flow redistribution device by which the flow is redirected from the augmentor/diffuser system into the stack and upwards through an acoustic silencer package at the stack exit. The combination of the flow-redistribution device and a stack-top acoustic silencer package controls the resonances and noise within the stack and results in achieving the desired sound levels outside (2.1.11, 2.1.13). Some exhaust stack sizing considerations may arise from limits placed on both the uniformity of the velocity distribution and the maximum velocity permitted at the stack exit plane. Limits on the maximum velocity would be due to attempts to control self-generated noise produced by the stack exit flow. In addition, other local regulatory issues may have to be considered in the design of the exhaust stack.

5. FACTORS FOR EVALUATING TEST CELL PERFORMANCE:

Some of the more important factors which must be considered in the development of designs leading to desired engine operational stability, acoustic performance, and mechanical integrity are described. Many of these factors can be expressed in terms of measured or calculated parameters which are often used to quantify and evaluate the performance of the various engine test cell configurations. A generally accepted method of calculating the value for each parameter is also given.

5.1 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:

$$FC_{Dist} = \frac{V_{max} - V_{min}}{V_{avg}} \qquad \text{(Eq.1)}$$

where:

FC_{Dist} = Front cell velocity distortion index
V_{max} = Maximum velocity anywhere in the velocity measurement grid
V_{min} = Minimum velocity anywhere in the velocity measurement grid
V_{avg} = Average front cell velocity

5.2 Front Cell Airflow:

The front cell airflow is the amount of air flowing through the test cell in the region in front of the engine bellmouth. Normally, it is the amount of airflow entering the test cell through the cell inlet. The front cell airflow rate can be determined from the same grid of velocity measurements used to measure the front cell distortion, so long as the cross-sectional area at the measurement plane is accurately known and a proper flow coefficient value is applied. The flow coefficient is a multiplier near to but usually slightly less than unity which adjusts the physical cross-sectional area value to an effective area value. The front cell airflow is calculated as follows:

$$W_{FC} = \frac{p_{FC}}{T_{FC} R} V_{FC} A_{FC} C_{d_{FC}} g \qquad \text{(Eq.2)}$$

5.2 (Continued):

where:

W_{FC} = Front cell airflow rate
p_{FC} = Front cell static pressure
T_{FC} = Front cell static air temperature
V_{FC} = Average front cell velocity
A_{FC} = Front cell cross-sectional area
Cd_{FC} = Front cell flow coefficient

5.3 Bellmouth Total Pressure Distortion:

The engine bellmouth steady state total pressure distortion index is a distortion parameter used to identify the relative severity of the engine inlet airflow field at the engine fan face. An array of several rakes instrumented for total pressure measurement, with several probes or immersions per rake, should be used to quantify the total pressure distribution at the measurement plane. A typical instrumentation arrangement might consist of eight such rakes with five immersions per rake. The distortion index is defined as follows:

$$BM_{Dist} = \frac{p_{max} - p_{min}}{p_{avg}} \quad \text{(Eq.3)}$$

where:

BM_{Dist} = Bellmouth pressure distortion index
p_{max} = Maximum total pressure measured in the fan face
p_{min} = Minimum total pressure measured in the fan face
p_{avg} = Average face total pressure

Other useful inlet flow distortion descriptors are defined and discussed in Reference 2.1.14. Detailed considerations for inlet total pressure distortion for gas turbine engines are presented in Reference 2.1.15.

5.4 Cell Bypass Ratio:

Cell bypass ratio is defined as the ratio of the airflow passing around the engine bellmouth to the airflow entering into the bellmouth. The cell bypass ratio is perhaps one of the more important cell performance parameters for describing the aerodynamic characteristics of a test cell. In combination with the front cell velocity distortion, this ratio determines whether or not bellmouth-ingested vortices will form. It is easily expressed in terms of the front cell flow and the engine flow, i.e.:

$$\text{Cell Bypass Ratio} = \alpha = \frac{W_{FC} - W_{ENG}}{W_{ENG}} \quad \text{(Eq.4)}$$

5.4 (Continued):

where:

W_{FC} = Front cell airflow
W_{ENG} = Engine airflow

The engine airflow is the amount of air flowing into the engine through the bellmouth or engine inlet. Information regarding the determination of engine airflow may be obtained from the engine manufacturer. The engine airflow may also be calculated using the equations given in Appendix A.

The relationship between cell bypass ratio and vortex formation has previously been examined in a model study. Figure 2, taken from Reference 2.1.2, shows how vortex formation is related to cell bypass ratio. The data in Figure 2 show that vortices do not form when the cell bypass ratio is greater than 0.80 for square cross-section test cells. Front cell velocity distortion was held constant at approximately 30% during the vortex formation study. It should be expected that the minimum cell bypass ratio to preclude vortex formation is correspondingly higher for test cells which have higher values of front cell velocity distortion.

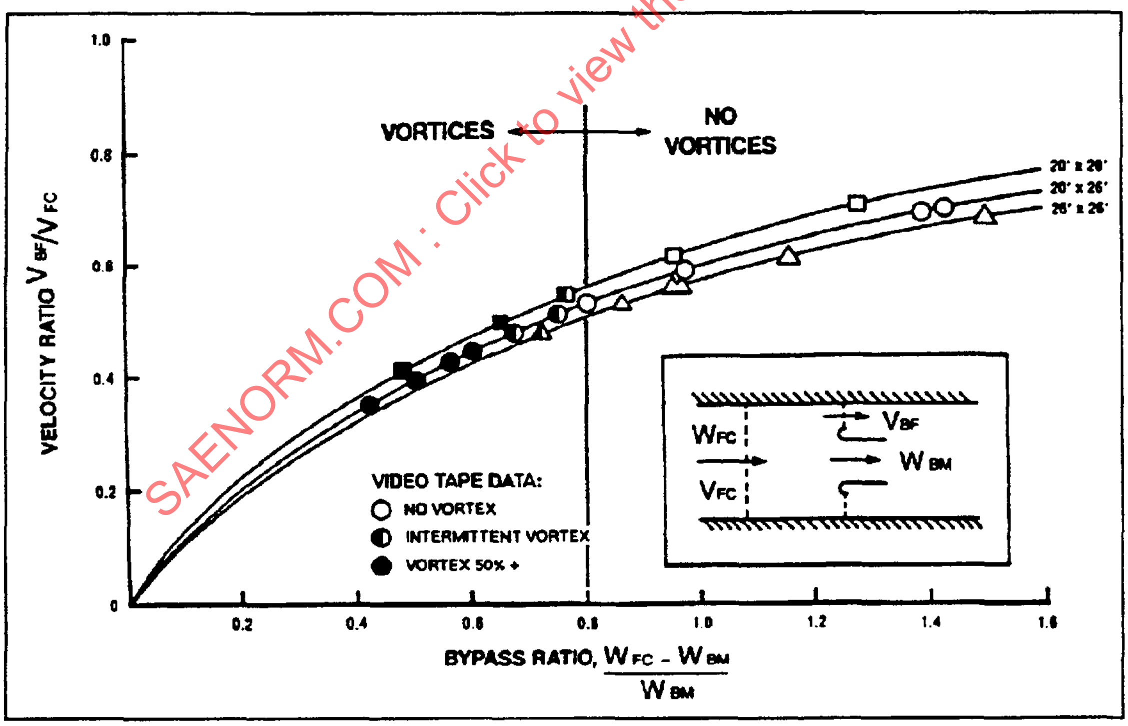

FIGURE 2 - Bellmouth-Ingested Vortex Formation Results as a Function of Cell Bypass Ratio as Determined from Video Tape Records of Flow Visualization (from Reference 2.1.2)