AEROSPACE INFORMATION REPORT

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Inlet Airflow Ramps for Gas Turbine Engine Test Cells

RATIONALE

This document has been determined to contain stable technology which is not dynamic in nature.

STABILIZED NOTICE

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1. SCOPE:

This SAE Aerospace Information Report (AIR) has been written for individuals associated with the ground-level testing of gas turbine engines and particularly for those who might be interested in upgrading their existing engine test facility to meet the airflow requirements for higher thrust engine models. The intellectual property rights on the material contained in this document are protected by US Patent Number 5,293,775 dated March 15, 1994 assigned to United Technologies Corporation, Hartford, Connecticut, USA. Any individual, or organization, attempting to use the system described in this document should get a clearance from United Technologies Corporation, to avoid any potential liability arising from patent infringement.

1.1 Purpose:

To provide guidelines for inlet airflow ramps for gas turbine engine test cells.

2. REFERENCES:

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 Freuler, R.J., Dickman, R.A., Current Techniques for Jet Engine Test Cell Modeling. AIAA-82-1272, Presented at the 18th Joint Propulsion Conference, June 21-23, 1982, Cleveland, Ohio.

2.1.2 De Siervi, F., Viguier, H.C., Greitzer, E.M., Tan, C.S., Mechanisms of Inlet-Vortex Formation, Journal of Fluid Mechanics, 1982, volume 124, pp. 173-207.

2.1.3 Glenny, D.E., Pyestock, N.G.T.E., Ingestion of Debris into Intakes by Vortex Action, Ministry of Technology, 1970, Aeronautical Research Council, C.P. no. 1114.

2.1.4 Clark, T., Peszko, M., Roberts, J., Muller, G., Nikkanen, J., United States Patent, Patent Number 5,293,775, March 15, 1994, Assignee: United Technologies Corporation, Hartford, Conn.

2.1.5 "Design Considerations for Enclosed Turbofan/Turbojet Engine Test Cell", SAE Aerospace Information Report AIR4869, Society of Automotive Engineers, Warrendale, Pennsylvania, Issued October 1995.

2.1.6 "Modeling Techniques for Jet Engine Test Cell Aerodynamics", SAE Aerospace Information Report AIR4827, Society of Automotive Engineers, Warrendale, Pennsylvania, Issued May 1993.

2.1.7 "Test Cell Instrumentation", SAE Aerospace Information Report AIR5026, Society of Automotive Engineers, Warrendale, Pennsylvania, Issued November 1996.

2.1.8 "Turbofan and Turbojet Gas Turbine Engine Test Cell Correlation", SAE Aerospace Recommended Practice ARP741 Rev. A, Society of Automotive Engineers, Warrendale, Pennsylvania, Revised September 1, 1993.

2.2 Symbols and Abbreviations:

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

2.2.1 Parameters:

LOSS	pressure loss at vortex center
Pt	total pressure
Q	dynamic pressure (1/2 ρV^2)
V	velocity
W	airflow rate
ΔPt	pressure difference between inlet Pt and vortex core Pt
α	cell bypass ratio
ρ	air density

2.2.2 Abbreviations:

D	inlet diameter
FC	front cell
ft	feet
ft/s	feet per second
H	engine centerline height
kg/s	kilograms per second
kN	kiloNewtons
lbm/s	pounds-mass per second
m	meters
SAE	Society of Automotive Engineers

2.2.3 Subscripts:

BYPASS	cell bypass flow
ENG	engine
ENGINE	engine
FC	front cell
VORTEX	inlet vortex

3. TECHNICAL BACKGROUND:

Due to the introduction of a new generation of high thrust turbofans, stability and stall problems can be encountered when larger and more powerful engines are operated in an engine test facility. This is generally due to the momentary or steady formation of an inlet vortex. Inlet vortices form near the engine inlet bellmouth where local deceleration in airflow causes an adverse pressure gradient resulting in flow separation along the adjacent surfaces of ceiling, floor, or walls. An inlet vortex is formed when a stagnation point, due to velocity shear, exists in the vicinity of the engine inlet. Severe velocity and pressure distortion at the engine inlet plane will result where conditions are present that permit inlet vortex formation. Vortex ingestion by the fan can cause noise and small performance shifts while a vortex that enters the engine core is likely to cause compressor surge or stall. Severe engine damage can result from a compressor surge or stall and, therefore, it is unacceptable to operate an engine for testing under conditions that permit this event to occur.

Experiments conducted by Freuler and Dickman for jet engine test cell modeling concluded that inlet vortices can be suppressed by test cell operation at a bypass ratio (see 3.1) of 0.8 or greater (2.1.1). Vortex formation from the cell floor has also been generally characterized to be a function of engine centerline height to inlet diameter (H/D) as described in references 2.1.2 and 2.1.3. The potential for vortex formation as a function of distance to engine room surfaces and inlet diameter applies to the adjacent walls and ceiling as well. Decreasing this ratio with the engine inlet bellmouth closer to the adjacent ceiling, floor or wall surfaces increases the potential for a vortex to form.

Traditional test cell design practices recommend that an engine test cell should operate at a bypass ratio of 0.8 or greater to ensure that inlet vortex formation is adequately suppressed. As airlines and maintenance shops expand their services to include engine testing for higher thrust turbofans, a minimum bypass ratio of 0.8 may not be achieved within the existing facility. Based on traditional design practices the solution to this problem is to construct a new and larger facility or to make significant modifications to the existing facility that will increase cell bypass ratio to the recommended 0.8 level. In either case, the major concern to the facility operator with both of these options is cost. Significant capital expenditures are required for construction of a new test facility and the cost of modifications to increase cell airflow is dependent upon the work scope involved. Cell modifications to increase airflow can vary greatly from relatively minor adjustments to the existing equipment such as increasing the open area or perforations in the exhaust basket, to extensive facility reconfigurations where replacements are required for major structural components such as the inlet plenum, ejector tube, or exhaust stack.

In order to meet the requirements for the new generation of high thrust turbofans, Pratt & Whitney has developed an inlet ramp system. This patented system (2.1.4) minimizes the occurrence of airflow stagnation which can cause an inlet vortex to form at the adjacent wall, floor or ceiling surfaces of the test cell. With the inlet ramp system in place an engine can be operated in a test cell with a bypass ratio as low as 0.4. This is significantly lower than the 0.8 level which is generally considered acceptable for vortex free engine operation and provides an alternative solution that requires no modifications to increase cell airflow.

3.1 Cell Bypass Ratio:

Cell bypass ratio is defined as the ratio of airflow that passes around the engine to the airflow that enters the engine bellmouth. Cell bypass ratio is an important cell performance parameter for describing test cell aerodynamic characteristics. Cell bypass ratio can be expressed in terms of front cell airflow and engine airflow and it is calculated as shown in Equation 1:

$$\text{Cell Bypass Ratio } (\alpha) = (W_{FC} - W_{ENG}) / W_{ENG} \qquad \text{(Eq. 1)}$$

where:

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

Cell bypass ratio is a facility airflow characteristic that may be easily confused with a similar term "bypass ratio" which is used for describing a turbofan engine design characteristic. Bypass ratio as it applies to turbofan engine performance is the ratio of engine airflow from fan discharge to the engine airflow attributed to core engine discharge.

Cell bypass ratio describes the induced cell airflow that occurs because the engine and test cell work together as an ejector pump. Figure 1 illustrates two cell bypass ratio conditions, with the dark shaded areas representing engine airflow (W_{ENGINE}) and the light shaded areas representing the airflow from the front cell that bypasses the engine (W_{BYPASS}). The two bypass airflow conditions illustrated in Figure 1 represent the flow fields for a small and a large engine operated at take-off thrust. In both cases the bypass airflow cross-sectional area increases as it passes the engine inlet, and this diffusion of the bypass streamtube results in a static pressure rise which may cause flow separation. In the case of the smaller engine with the 150% cell bypass ratio the adverse pressure gradient is small and no flow separation occurs. But for the larger engine with 30% cell bypass ratio the adverse pressure gradient is much more extreme and flow separates at the wall. Velocity shear in this separated region provides the circulation necessary to form a vortex, which is then accelerated and ingested by the engine. The conservation of angular momentum in the accelerating vortex creates very low pressure at the vortex center, and this pressure distortion may cause engine compressor stall to occur.

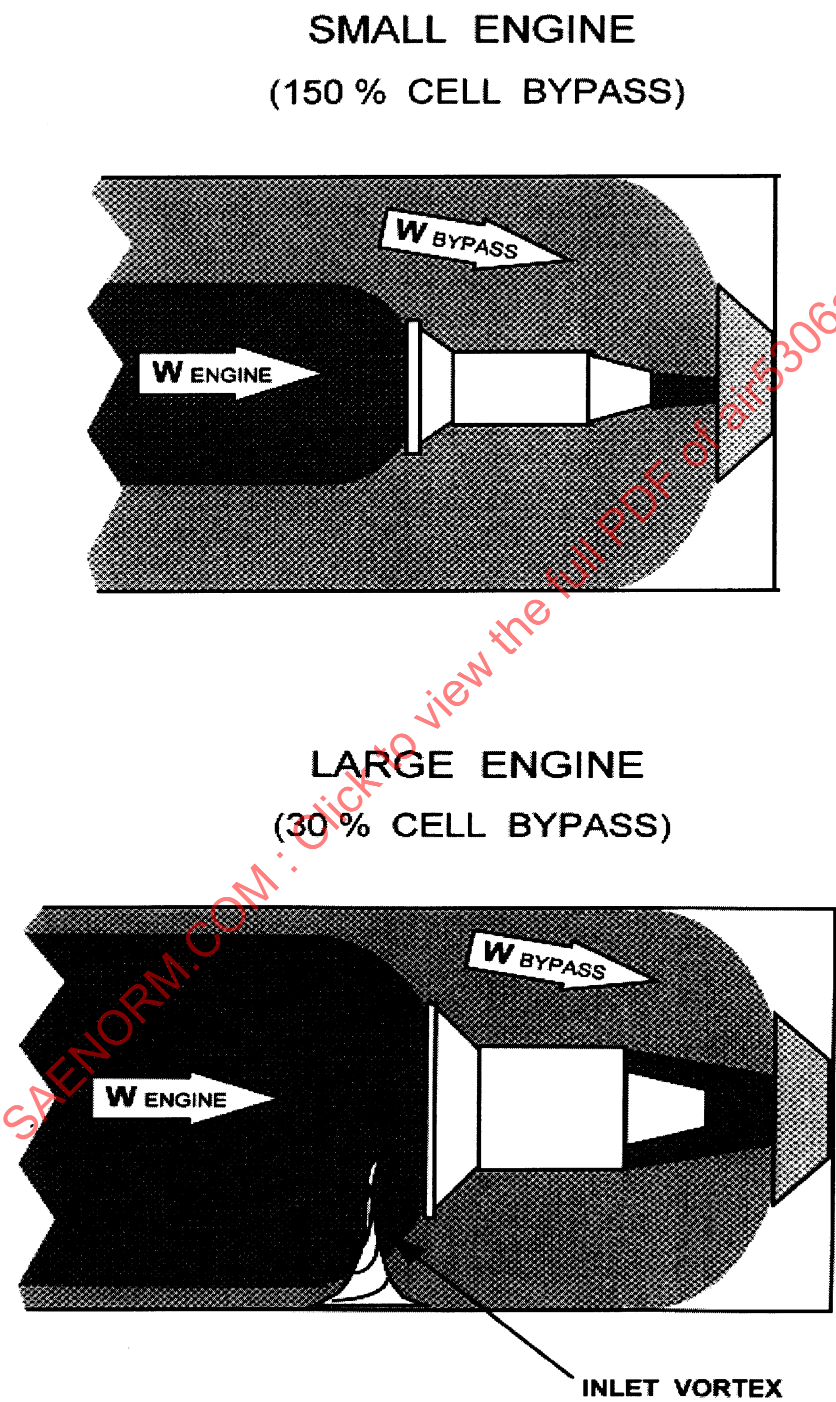

FIGURE 1 - Comparison of Bypass Airflow Regions for Two Cell Bypass Ratios

4. INLET RAMPS:

4.1 Description:

The inlet ramp system is an engine room installed aerodynamic device that resembles a "picture frame" as shown in Figure 2. The inlet ramp system is typically mounted to the engine room ceiling on a pair of rails that allows the system to move forward and aft to accommodate various engine model inlet plane locations. The lower section of the system is hinged so that it can swing to one side and allow easy equipment access to the test stand and engine. Typical construction for this system would include a mechanical tubing frame with the forward surfaces covered with sheet metal. Corrosion resistant materials are recommended for low maintenance and an automated positioning feature can be added if the engine models tested require different inlet ramp positions.

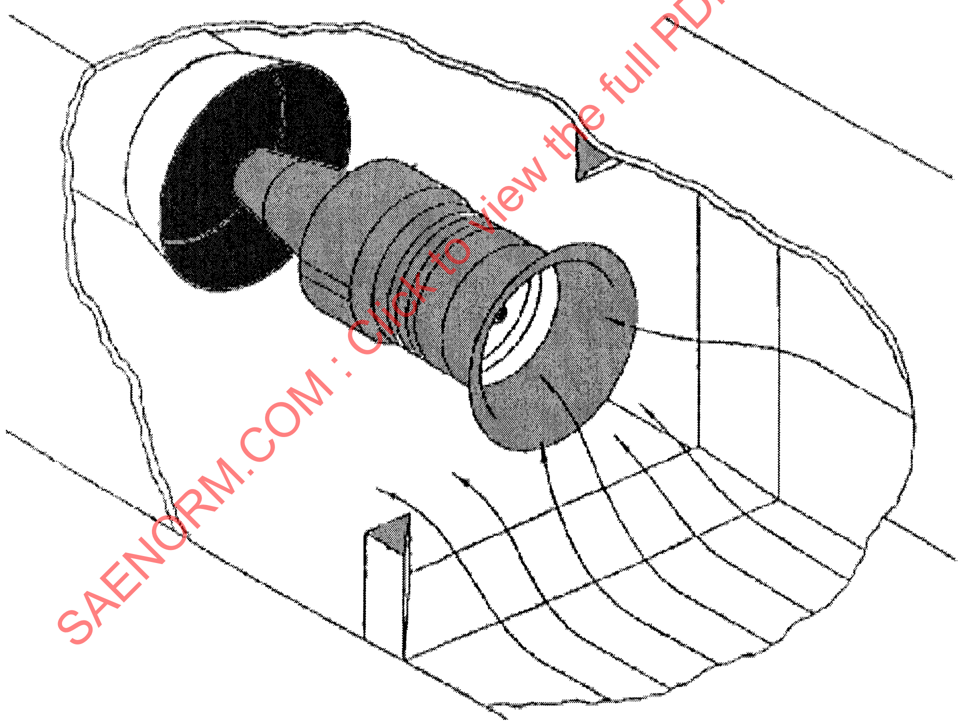

FIGURE 2 - Test Cell With Inlet Ramps

4.2 Application:

The inlet ramp system can be a cost effective method to meet higher thrust engine airflow requirements for existing engine test cells. Maintenance shops that are precluded from testing higher thrust engine models in an existing facility because of airflow limitations can find that the inlet ramp system provides a suitable solution. As is the case with any aerodynamic upgrade under consideration each facility needs to be evaluated individually to determine the suitability of the inlet ramp system for a particular application.

4.3 Engine Room Requirements:

A primary cell design criteria to achieve vortex free airflow is the size of the engine room or test chamber in which the engine is installed. Figure 3 shows square engine room size versus engine airflow for two cell bypass ratios. Using a front cell velocity of 15.24 m/s (50 ft/s) and the minimum 0.8 cell bypass ratio, engines with takeoff airflow ratings up to 1020 kg/s (2250 lbm/s) will run successfully in an engine room that is 10 m x 10 m. But an engine rated at 1315 kg/s (2900 lbm/s) will require a larger engine room with dimensions of 11.4 m x 11.4 m (point "A"). For an existing facility where this requirement cannot be met, inlet ramps provide a practical option. As indicated by point "B", inlet ramps will enable operation at a cell bypass ratio as low as 0.4. This will allow an engine rated at 1315 kg/s (2900 lbm/s) airflow to be tested in the original 10 m facility with no additional cell modifications. Thus, the relatively minor addition of inlet ramps make it possible to run engines with about 30% greater airflow than currently recommended by AIR4869 guidelines (2.1.5). This concept can be used in test cells with non-square cross-sections by scaling the inlet ramp size to the shortest wall dimension.

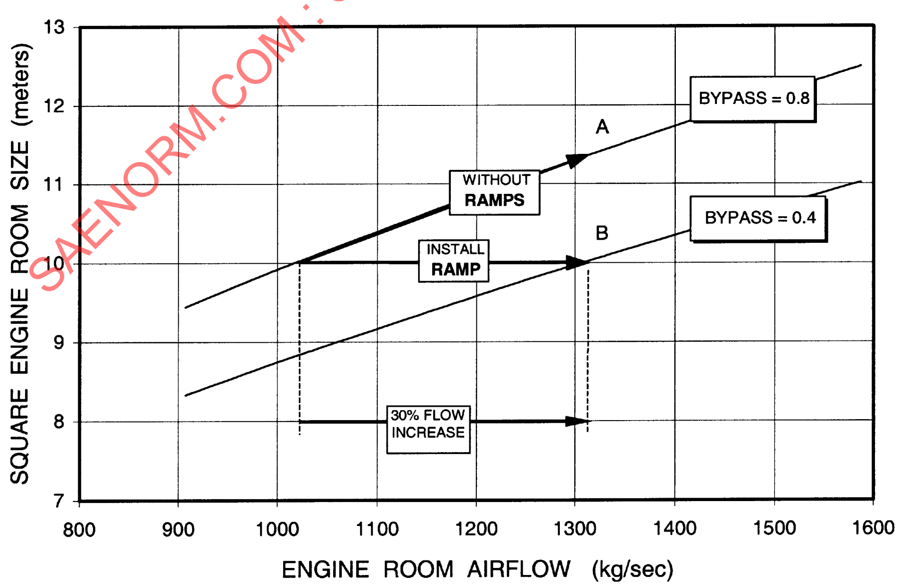

FIGURE 3 - Engine Airflow Versus Test Cell Size
V_{FC} = 15.24 m/s (50 ft/s)

4.4 Ejector Tube Requirements:

The downstream ejector tube diameter combined with pressure losses due to flow restrictions determines the bypass ratio the test facility will achieve for any given engine installation. Although each installation is unique, Figure 4 shows the tube diameter versus test cell bypass ratio typically required for two engine airflow rates. The 787 kg/s (1735 lbm/s) engine airflow line (an engine in the 267 kN (60 klb) thrust class) indicates that an ejector tube diameter of 3 m (9.84 ft) can allow a 1.2 cell bypass ratio. Points "A" and "B" show two options available if it is desired to use this typically configured facility for testing a 400 kN (90 klb) engine class with 1236 kg/s (2750 lbm/s) engine airflow. Option "A" is to replace the ejector tube with one having a diameter of at least 3.4 m (11.15 ft) to increase the cell bypass ratio to the required 0.8 level. The alternative "B" is to retain the existing ejector tube but install inlet ramps which will allow stable operation down to 0.4 cell bypass ratio. Inlet ramps are a cost effective alternative to ejector tube replacement that also minimizes cell down time. (Note that the first alternative may also require modification to the test cell inlet and exhaust systems to handle the increased total cell airflow.)

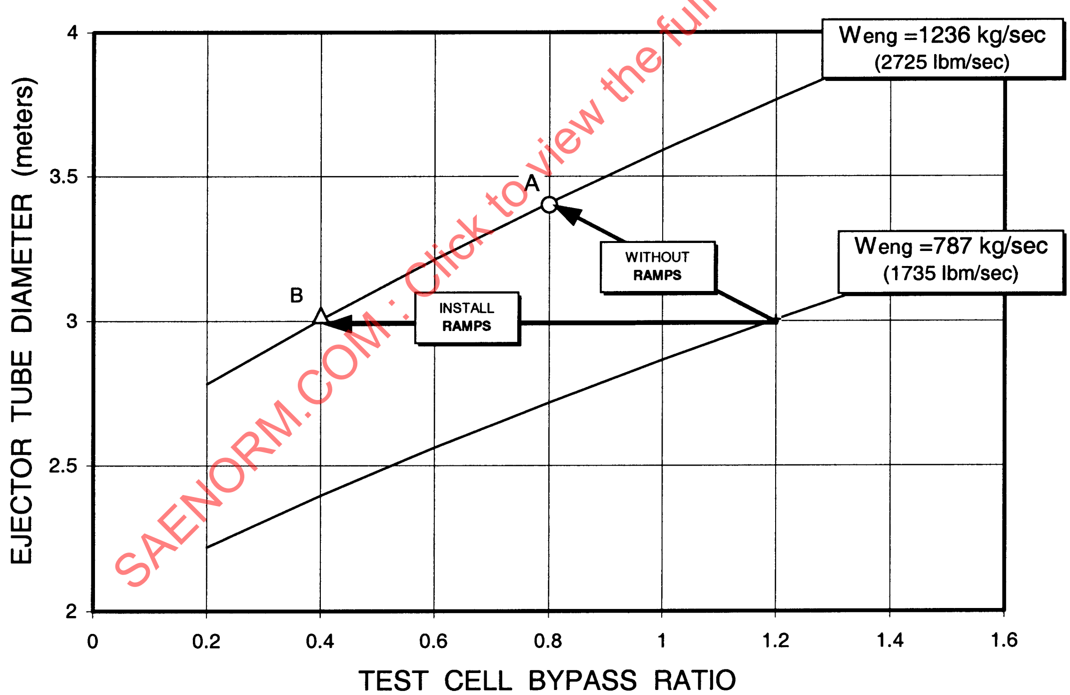

FIGURE 4 - Ejector Tube Diameter Versus Cell Bypass Ratio
W_{FC}/Tube Area = 244 kg/s-m^2 (50 lbm/s-ft^2)