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Design Considerations for Enclosed Turboprop Engine Test Cells

FOREWORD

Enclosed turboprop engine test cells are needed to provide a controlled environment during engine testing. Ever increasing sophisticated engine technology, performance requirements and safety and environmental concerns continually generate the need to improve test cell designs. This SAE Aerospace Information Report (AIR) will assist those involved in designing new or significantly modified enclosed turboprop engine test cells used to test propeller equipped engines by documenting design considerations compiled from a broad spectrum of industry and government specialists in this field. The intent is to provide a general discussion of design features that impact the capability of the test cell to provide safe, accurate and repeatable performance tests of propeller equipped bare and complete nacelle quick engine change (QEC), configured engines. The information provided is also intended to add to the understanding of the significance of the aerodynamics of the propeller equipped enclosed engine test cell environment.

Propeller equipped turboprop engines operating in an enclosed engine test cell generate/encounter conditions directly attributable to the design characteristics of the test cell. Although in a very broad sense some of the conditions are common to all engine test cells, there are some that are unique to operations of propeller equipped engines in enclosed test cells. This report provides some of the most important factors that must be considered when designing an enclosed test cell for testing those engines. Desired engine performance, aero/thermodynamics, acoustic capability, mechanical integrity and safety requirements are described.

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1. SCOPE:

This document is offered to provide state-of-the-art information about design factors that must be considered in the design of new or significantly modified engine test cells used to test propeller equipped turboprop engines in either QEC or bare engine configurations. The report does not address design considerations for test cells designed to test turboprop engines with dynamometer type load absorption devices because they are essentially tested as turboshaft engines. Design considerations for those test cells are presented in AIR4989, Reference 2.1.

1.1 Purpose:

a. Provide guidelines for factors that must be considered to design state-of-the-art enclosed engine test cells used to test propeller equipped turboprop engines.

b. Provide empirical data/information about aerodynamic characteristics of propeller equipped engine testing in enclosed test cells.

c. Provide empirical acoustic data/information from propeller equipped engine test operations in enclosed test cells.

2. REFERENCES:

2.1 AIR4989 - Design Considerations for Enclosed Turboshaft Engine Test Cells.

2.2 NFPA 423 - Standard for Construction and Protection of Aircraft Engine Test Facilities.

2.3 Naval Air Warfare Center, Patuxent River Maryland, Propulsion Support Equipment Branch, TECHEVAL Multi-Capability Turboshaft/Prop Engine Test Facility Complex, A/F 37T-16(v)1, 2 and A/F 37T-19(v)2, 3, Report No. 48L-95-027 dated 19 October 1995.

2.4 AIR5026 - Test Cell Instrumentation.

2.5 AIR5305 - Containment Safety Design Guide for Test Cells.

2.6 Joint Report to Congress on the Environmental Protection Agency-Department of Transportation Study of Nitrogen Oxide Emissions and Their Control From Uninstalled Aircraft Engines in Enclosed Test Cells, dated September 1994.

2.7 Naval Air Test Center Facilities Operation and Evaluation Report, A/F 37T-19(v) 1 Turboprop Engine Test Facility, Futema, Japan, 13600 Ser. SY53J/100 dated 10 March 194.

2.8 Naval Air Warfare Center, Lakehurst, New Jersey, Design Data Report Acoustic Evaluation of NAS Brunswick, Maine, Report No. NAWCADLKE-DDR-487100-0004, dated 18 April 1997.

3. TECHNICAL BACKGROUND:

Enclosed turboprop engine test cells in use today vary from modified reciprocating engine test cells, to simple open end shelters with adjoining control cab, to state-of-the-art facilities designed for current and future engine testing. These test cells are designed to either test turboprop engines connected to a dynamometer type load absorption device or engines with a propeller installed. Design considerations for test cells incorporating dynamometers are presented in AIR4989 and will not be addressed here except for comparison purposes if necessary.

Turboprop engines operating in enclosed test cells can encounter problems directly attributable to the cell design characteristics. These problems can be minor such as fluctuating engine speed, and temperature and shaft horsepower (SHP) indications which can cause unnecessary test rejection and costly engine rework or in worst cases engine overtemperature or stalls resulting in serious engine damage or catastrophic failure. Most of these problems are caused by insufficient or distorted airflow through the test cell inlet and front cell area or insufficient exhaust section flow area. These conditions have even more detrimental effect on propeller equipped engines than on engines tested with dynamometers because of their effect on the propeller speed and service life.

4. TEST CELL SYSTEM DESIGN CONSIDERATIONS:

General design concepts illustrating the major features of enclosed turboprop engine test cell designs are shown in Figures 1, 2, 3, and 4. The major structural sections of the test cells are an inlet, test chamber, an orifice wall and augmentor tube in some designs, and an exhaust section. Each must be tailored for its specific function and also be compatible with the other sections to achieve proper aero/ thermodynamic and acoustic performance of the engine test cell. Each section will be described in terms of its purpose and functional performance. Fire protection guidelines of NFPA 423, Reference 2.2, should be followed when designing new or modified test facilities.

The test chamber and exhaust sections of test cells used to test propeller equipped engines are subjected to severe buffeting from the propeller wake which causes damage to ancillary equipment and instrumentation cables and hoses. Some cases of structural damage reportedly have been encountered in both old and more recently built test cells. Particular attention should be given to this operating condition during test cell design efforts.

Noise pollution concerns are increasing the need for enclosed engine testing and improved test cell noise attenuation. The low frequency noise generated by propeller equipped engines is particularly noticeable and should be addressed in the test cell design considerationis.

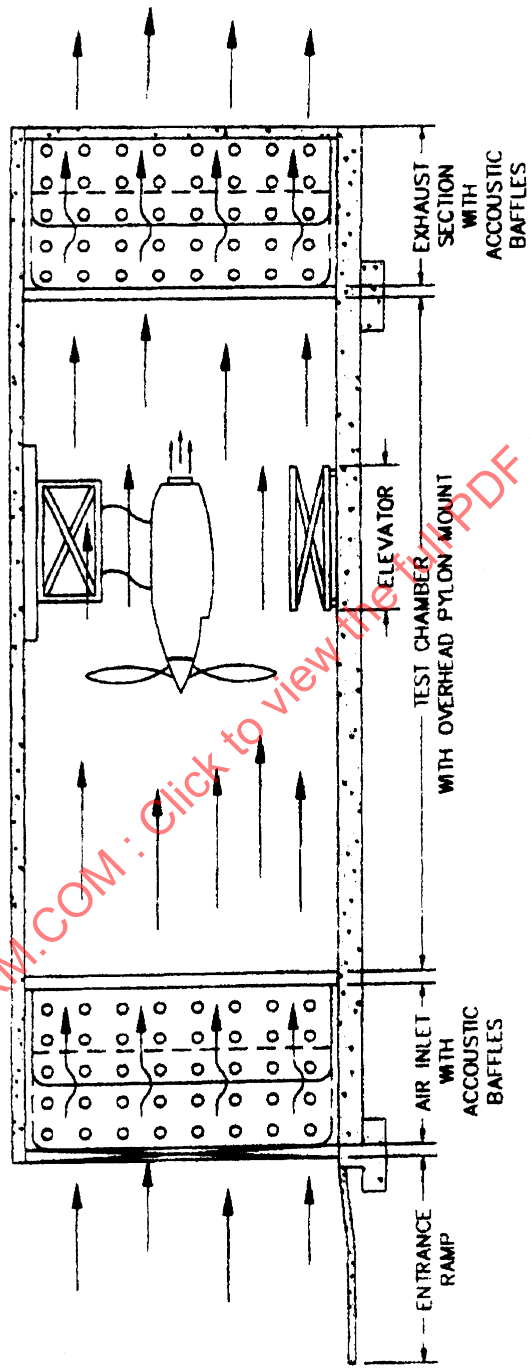

FIGURE 1 - Turboprop Engine Test Cell With Horizontal Inlet and Exhaust Sections Without Inlet Courtyard or Orifice Wall

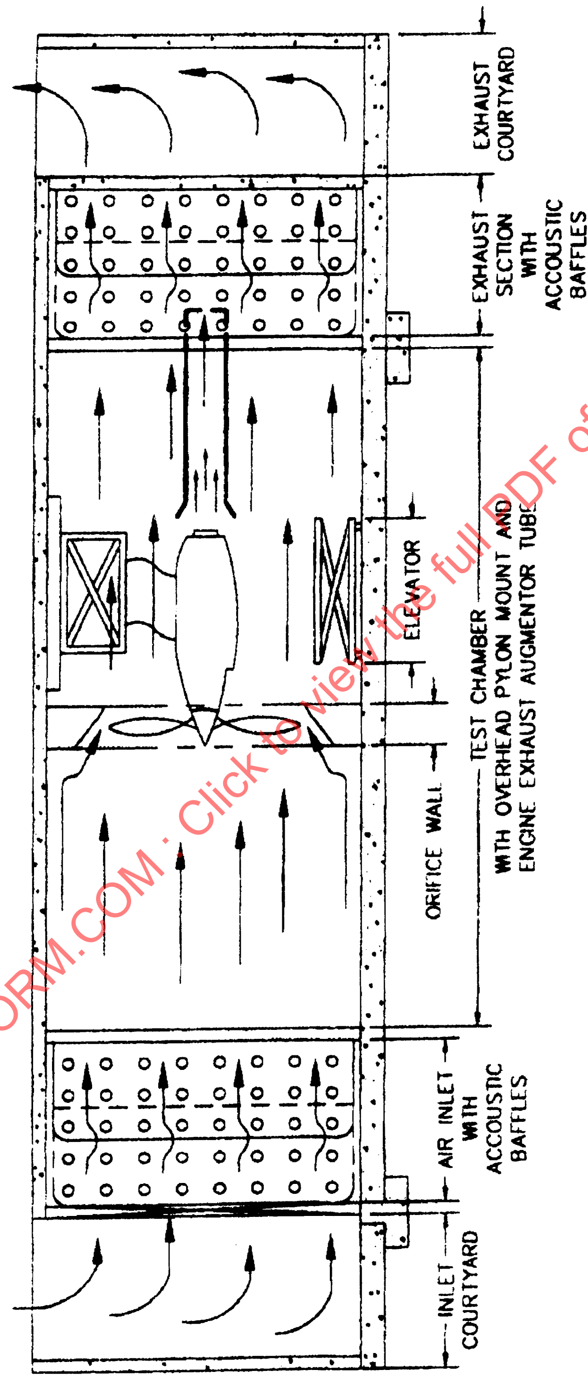

FIGURE 2 - Turboprop Engine Test Cell With Horizontal Inlet and Exhaust Sections With Inlet and Exhaust Courtyards and Orifice Wall

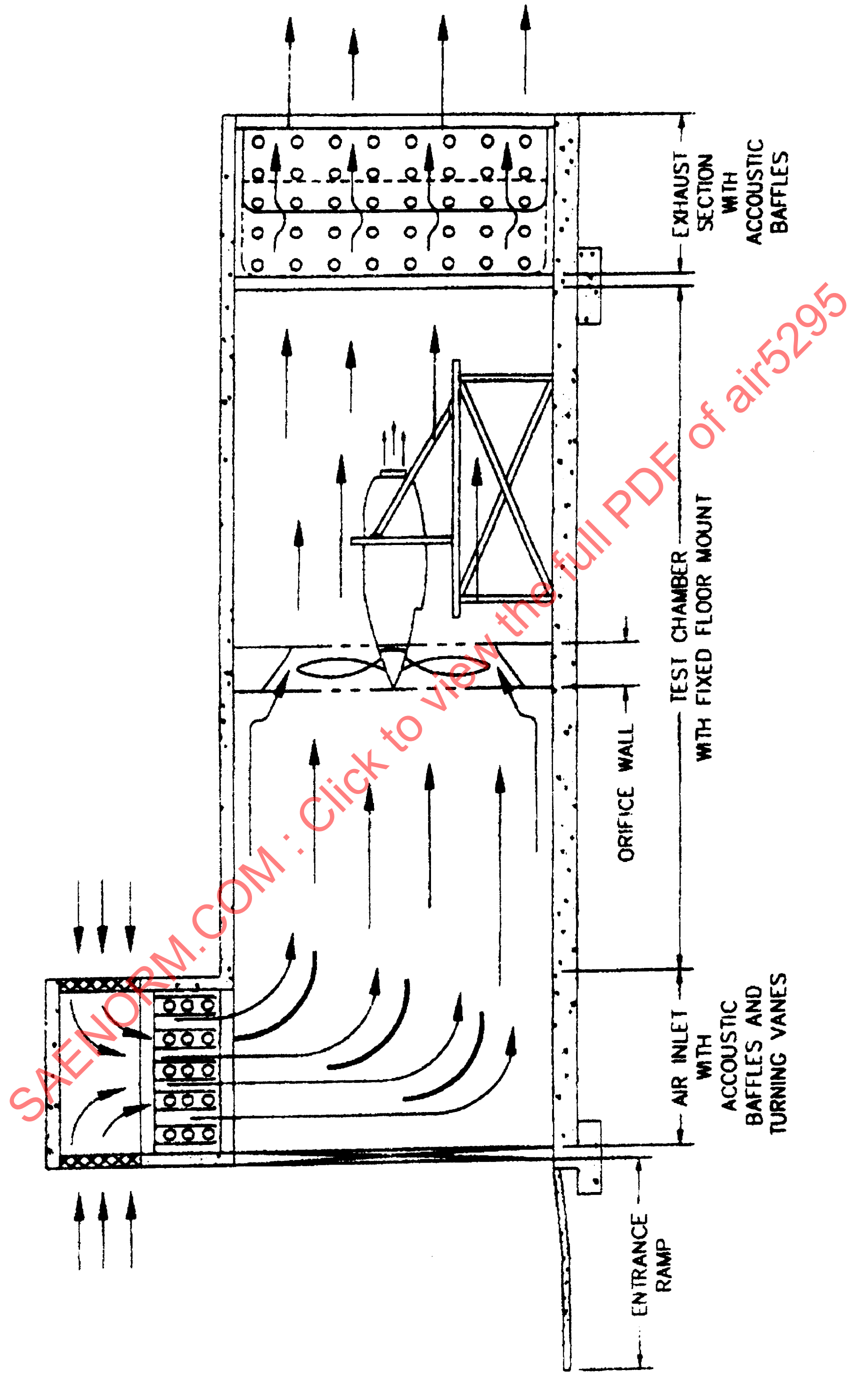

FIGURE 3 - Turboprop Engine Test Cell With Vertical Inlet and Horizontal Exhaust Sections and Orifice Wall

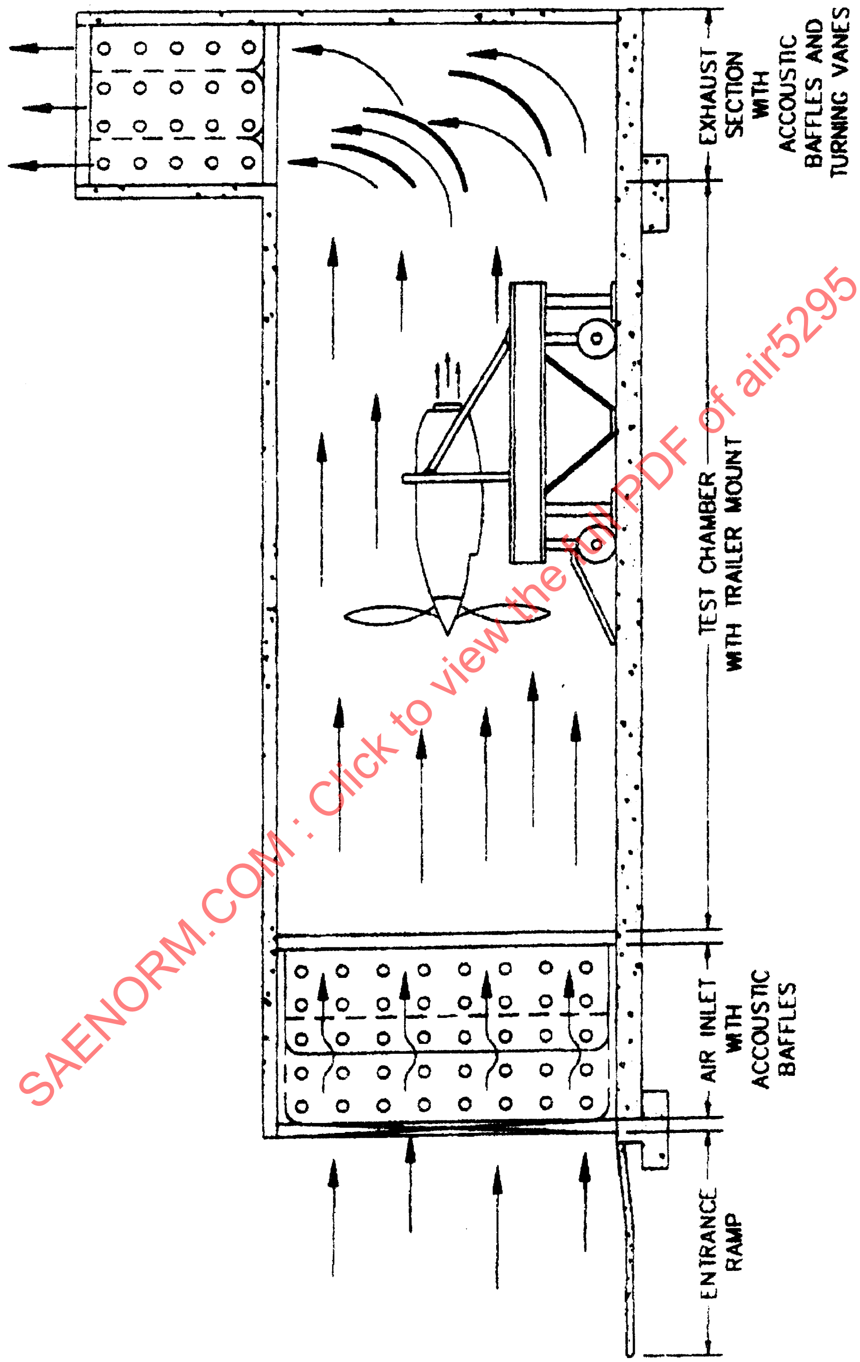

FIGURE 4 - Turboprop Engine Test Cell With Horizontal Inlet and Vertical Exhaust Sections Without Inlet Courtyard or Orifice Wall

4.1 Inlet Section:

The primary purpose of the inlet section is to provide a sufficient uniform flow of air to the engine and propeller in the test chamber. It is designed to reduce the effect of crosswinds and attenuate the noise generated by the propeller and engine.

Most inlet sections are designed to provide either straight through horizontal airflow or, through the use of turning vanes, vertical to horizontal airflow to the test chamber, propeller and engine. Horizontal inlet sections theoretically should provide more uniform airflow than vertical inlets and are less expensive to build. However, because they may be more affected by crosswinds and require more on-going foreign object damage (FOD), hazard control and extra noise attenuation the cost savings would be reduced. Vertical inlet sections require the additional vertical structure, turning vanes and possibly an additional pressure drop screen all of which add significantly to the cost of the test cell. Designers should thoroughly analyze the proposed site for a test cell considering prevailing winds, adjacent structures, proximity of personnel not involved in engine testing, potential for generating FOD hazards, i.e., vehicle and personnel traffic and certainly local noise tolerance/ ordinances before deciding on the design configuration.

Erosion resistant concrete should be used in “brick and mortar” design test cell inlets. Corrosion resistant metals should be used in prefabricated test cells. Acoustic treatment should be provided that doesn’t lose its effectiveness when subjected to rain/sleet/snow. It should be designed to keep the acoustic material dry so that the material will not drop to the bottom of its containment space as a result of frequently being wet. There should be no protrusions, recesses or uneven surfaces in the inlet structure that would distort uniform airflow. Basic temperature and pressure sensors should be incorporated connected to control room monitors. The design should ensure that all mechanical connections are secured with captive nuts, bolts, pins, etc., to reduce FOD potential. An engine access/service door large enough to allow a propeller equipped engine to be moved into the test chamber may be located in the front of the test cell or to the side depending on the overall configuration of the cell. If it is desired to delay installing the propeller until after the engine is installed in the test cell propeller handling features should be included in the cell design. Easy access to all areas of the inlet should be included to allow periodic inspections. A drainage system may be required depending on the average amount of precipitation in the area and the inlet configuration. Sufficient uniform airflow to the engine and propeller in the test chamber is dependent on a well designed inlet. Every effort should be made to provide this feature which is key to accurate stable repeatable engine performance testing.

4.2 Test Chamber:

The test chamber provides the space for engine mount systems which may be overhead or floor mounted assemblies or trailer assemblies. When an overhead mount system is employed, an elevator/hydraulic lift with adequate ventilation of the pit to dissipate fuel/oil fumes should be included in the design. The chamber must be large enough to allow continuation of sufficient uniform airflow from the inlet to the propeller and engine. It should be large enough to provide adequate clearance between the tips of the propeller and the floor, walls and ceiling to prevent reverse airflow pressure pulses acting on the propeller which may cause unstable engine performance and accelerated structural fatigue of the propeller blades. Orifice walls surrounding the propeller are sometimes used to reduce the possibility of encountering this condition especially in small (relative to propeller diameter) or vertical inlet configured test cells. They are also used to reduce the total airflow through the test cell to improve its noise abatement capability. When an orifice wall is incorporated in the test chamber design the tip clearance obviously is between the propeller and the orifice ring surface and is determined by each engine and propeller manufacturer. Although it is generally accepted that orifice walls/rings are needed for enclosed turboprop test cells, many do not incorporate them and two recently designed turboprop cells show they are not always necessary. The Canadian Forces test cell in Greenwood, Nova Scotia does not incorporate an orifice wall/ring and was approved by Hamilton Standard for testing T56 engines with their propellers and has successfully operated for 10 years or more with no adverse effect on the propellers or engines. This was confirmed during telephone conversations with the test cell operating personnel on three different occasions in 1997 and 1998. Although this test cell does not incorporate exhaust system acoustic baffles it is not certain that their introduction would cause any significant adverse effect. It would depend on the amount and positioning of the baffles. Recent model and full scale test results discussed in Section 5 indicate that exhaust baffles alone may not have as great an effect on turboprop engine test cell exhaust flow and recirculation as previously believed. More recently a U.S. Navy turboprop test cell in Sigonella, Italy was operated without its orifice wall in place because it did not align with the engines to be tested. The orifice wall was moved aside, except for approximately 4 ft protruding in the cell, the abutting wall left in place and the engine operated satisfactorily during technical evaluation tests (Reference 2.3). Designers should thoroughly analyze (model tests/cost analysis/computer modeling), the need for orifice walls/rings, which are very expensive, before incorporating them in test cell designs. If cost is not a constraint then an orifice wall/ring should be considered to enhance and control the airflow through the test cell.

4.2 (Continued):

The test chamber incorporates all of the umbilical connections to the engine usually from a service panel mounted on a wall with cable trays or conduits to the engine or from a service panel mounted on the engine mount frame. The chamber may also incorporate most of the ancillary equipment such as lights, pumps, fire extinguisher and airstart systems and related wiring and plumbing. The designer should try to keep these systems or components to a minimum and recess or locate them externally if possible. High intensity lights should be located to ensure they are not personnel hazards. All system mechanical components, plumbing, wiring, cable trays, etc., located forward of and behind the propeller must be designed with captive connectors and be strong enough and located in the test chamber to withstand the propeller blast in both normal and reverse pitch. The floor of the test chamber should incorporate a fuel/oil/water separator drain system to collect and dispose of those liquids that would become fire, personnel, or environmental hazards. The floor area should be free of any protrusions or recesses that can be trip hazards. A service water system should be included to facilitate washdown of the area and should incorporate freeze protection if necessary.

The test chamber should incorporate a fire extinguisher system designed to be automatically and manually activated. Manual activation capability should be available in both the control cab/room and test chamber. The current most commonly used fire extinguisher systems are water deluge and chemical (Halon, F134, carbon dioxide) systems. Water deluge systems can be activated immediately upon detection of a fire with no harmful effect on personnel who might be in the test chamber. This fast employment of the system will minimize personnel hazard and damage to the engine and test chamber. A water deluge system does not require the use of a fire door in the test cell inlet. Test cells designed with chemical fire extinguisher systems do require fire doors in the inlet sections to choke off airflow and eliminate the draft through the cell when the door is open which dilutes/dissipates the chemical fog. Also, in the automatic mode of operation a time delay must be incorporated to allow any personnel in the test chamber to evacuate because of the hazards of chemical systems and to allow the engine speed to spool down to avoid damage to it and possibly the test chamber. If the door is closed with the engine running at speeds above flight idle compressor stalls may be encountered and/or the fire door may collapse.

Some turboprop test chamber designs include engine exhaust augmentor tubes to direct engine exhaust gases outside of the test chamber. These are usually test cells with vertical exhaust sections. This design concept may not be necessary if there is no exhaust gas recirculation to the engine inlet and sufficient airflow from the propeller blast mixes with the exhaust gases and lowers the temperature of the mix below the maximum allowable temperature impinging on the acoustic baffling normally incorporated in most test cell exhaust sections.

4.2 (Continued):

The test chamber section normally includes an instrumentation and control room that contains all of the engine and test cell instrumentation and fire extinguisher system alarms and controls. It may be an integral part of the test chamber structure or can be a self-contained prefabricated module with an observation window abutted to the test chamber. The control room should be large enough to accommodate at least three operator/observers, have adequate space to access the instrumentation and control consoles for repair and should incorporate acoustic treatment to keep the sound level at or below specified limits for intelligible speech communications, commonly called speech interference level (SIL). SIL is the arithmetic average of the octave band levels from 500, 1,000, and 2,000 Hz bands. The acceptable level for SIL is 60 dB. The control room should be ergonomically designed especially to provide the primary operator simultaneous ready manipulation of controls, ease of scanning critical instrumentation and direct line of sight or remote camera viewing of the engine under test. Emergency engine shutdown and fire extinguisher controls should be prominently identified and within easy reach of the primary operator. Descriptions of test cell control room instrumentation systems are not provided in this report. Detail description and discussion of those systems are available in AIR5026, Reference 2.4.

The test chamber usually incorporates a window to the test cell instrumentation and control room. It is usually made from a number of panes of shatterproof glass and includes some method to prevent condensation accumulation between the panes or in the case of a modular instrumentation and control room between its window and the test chamber window. The window must be large enough and properly located to allow the test operator a view of the complete engine side facing the window but should not be in the plane of rotation of the engine and propeller. Mirrors or closed circuit TV cameras should be included in the test chamber design to provide continuous viewing of the opposite side of the engine and the remainder of the test chamber. Test cells can also be designed with no observation windows and instead depend on video cameras to monitor the entire engine and test chamber. Color TV cameras provide much more effective viewing than black and white cameras. The walls of the test chamber should be designed to contain fragments or complete rotor/ propeller impact resulting from catastrophic engine/propeller failure. Containment is being addressed in detail in ARP5305 being prepared by the EG-1E Committee. Panic bar equipped personnel access doors should be incorporated to provide access to and from the control room and egress to the outdoors on the opposite side of the test chamber.

4.3 Augmentor:

Some older turboprop test cells include engine exhaust augmentors to direct the hot exhaust gases out of the test chamber to the exhaust section. In most cases they are not needed in new designs if the test cell is sized properly. If employed the augmentor should be designed to withstand the turbulent propeller blast in the aft end of the test chamber. It should be as straight and short as possible to facilitate exhaust gas flow and avoid overheating the air in the aft end of the test chamber. Aero/thermodynamic and acoustic fatigue conditions should be considered in any augmentor design.

4.4 Exhaust Section:

The exhaust section is designed to direct the propeller blast and engine exhaust gas out of the test cell and attenuate noise. It may be vertical or horizontal and will usually include acoustic baffle panels, and for vertical exhausts, turning vanes to redirect the airflow from horizontal to vertical. The design must ensure that there is a relatively free flow of air and exhaust gases so that there is no reverse flow to the forward end of the test chamber. As in the inlet the acoustic treatment must be designed to withstand water saturation without losing its noise attenuating capability. A drain system should be included in the exhaust section floor incorporating a fuel/oil/water separator or connected to the separator in the test chamber.

The exhaust section design should specify high strength, erosion resistant concrete or for prefabricated test cells, high temperature corrosion resistant metal. The need for high temperature concrete should be considered. A temperature sensing system should be included to allow the operator to monitor the temperatures in this area. Once again, all mechanical connection designs should specify captive connector devices, in this case to prevent the ejection of loose parts from the exhaust section presenting a serious personnel safety hazard. The exhaust section should be designed to provide quick and easy access and adequate lighting to all its areas to allow for periodic inspections. Vertical exhaust sections should incorporate safety ladders to catwalks to facilitate inspection of the upper parts of the stack and acoustic treatment. The acoustic baffles should be designed to be easily removed, repaired and replaced.

Particulate emission control should be considered during design of the test cell. Although a few water scrubber and mist eliminator systems are in use, at present no cost effective technology exists that can completely control particulate emissions from aircraft engine test cells. Gaseous emissions are more difficult to control and no cost effective technology of any kind exists to control gaseous emissions from aircraft engine test cells. This was discussed in detail in the Joint Report to Congress on the Environmental Protection Agency-Department of Transportation Study of Nitrogen Oxide Emissions and Their Control From Uninstalled Aircraft Engines in Enclosed Test Cells dated September, 1994, Reference 2.6. Local ordinances should be studied and complied with as much as possible.

5. EMPIRICAL AERODYNAMIC DATA/INFORMATION:

Empirical data from two turboprop test cell tests, References 2.3 and 2.7, indicates that inlet velocities of 40 to 50 ft/s provide a good testing environment if the airflow is sufficiently uniform. This represents these specific cases and stable cell performance might be achieved at different values with different test cell designs. Normal cell depression of 1 to 2 in of water usually provides acceptable flow. Use of an orifice plate will alter this in the vicinity of the engine inlet. These tests have shown that there can be a static pressure drop on the order of 2.5 in of water across the orifice but it did not adversely effect engine performance. Correlation tests showed a ram effect in the inlet of a T56-A-425 engine which results from the propeller design, i.e., cuffed blades.

Exhaust sound attenuation baffles in turboprop test cells have always been thought to have a very significant effect on cell exhaust section airflow. Recent model and full scale tests of U.S. Navy test cell designs with no exhaust baffles showed reverse flows on one side of the cells. This indicates that the effect of exhaust baffles alone may not be as great as is generally assumed. The exhaust blast from turboprop test cells is not very hot but has enough velocity to cause concern about personnel safety and property damage. Raw data acquired during full scale tests of a 4500 SHP engine in a cell with no exhaust baffling showed wind velocity up to 50 mph at 200 ft behind the engine at its centerline.

There appears to be no firm standard aerodynamic design guidelines for designing enclosed turboprop test cells for testing propeller equipped engines. The general design considerations discussed in this document can be applied to any specific design.

6. EMPIRICAL ACOUSTIC DATA/INFORMATION:

Acoustic data measured at two enclosed turboprop engine test cells, References 2.3 and 2.8, indicate that typical enclosure acoustic treatment (perforated paneling and basalt wool/fiberglass filling) can provide attenuation to reduce internal cell engine noise of 132 dB (126 dBA) to average outdoor levels of 95 dB (84 dBA) measured around a circle of 250 ft radius from the engine. This is overall general acoustic performance. The data in Table 1 from engineering tests of the two turboprop engine test cells was analyzed and shows the comparison between the two cells, one with inlet and exhaust acoustic treatment and the other with neither. The data in Table 1 shows the noise measurements in dBA from the noise measured at the engine inside the test chamber to measurement points immediately outside of the test cell inlets and exhausts and at 100 and 250 ft from the test cell.

TABLE 1 - Noise Level in dB/dBA

	At Opening	100 ft	250 ft
Inlet With Acoustics	120/106	116/ 104	103/96
Inlet Without Acoustics	129/122	120/ 112	108/101
Exhaust With Acoustics	125/115	107/97	101/89
Exhaust Without Acoustics	127/120	115/ 103	97/84

6. (Continued):

It can be seen that the near and far field (100 and 250 ft) inlet noise levels are more intense than the exhaust noise in the turboprop facility recorded data except in the unit with acoustics where levels at the inlet opening are less than the exhaust. Review of octave band data at this location indicate that exhaust noise was most likely radiating forward from the engine run room, thereby reducing the dBA values with low frequency instead of the engine inlet high frequency spectra at this location. The unit with acoustics does not have a propeller orifice ring, which would retain high frequency in this area and radiate higher dBA values at this location.

It is noted that the design of the inlet acoustic baffles must be developed in order to control low frequency tonal noise radiating from the propeller, typically in the 31.5 to 125 Hz octave frequency bands.

By comparison, it is noted that thrust engine facilities naturally radiate more intense exhaust noise spectra. Furthermore, the noise spectra at selected measurement locations were predominantly low- and mid-band frequencies, as compared to the wideband frequency distribution, which is the spectral characteristic of thrust engines. Applying this knowledge to the design phase of a facility would mandate more concentration on perforated metal panels with larger diameter holes than panels for thrust engines. However, there is not the strict requirement for high temperature insulation of exhaust panels since the prop wash exhaust is in the 200 to 300 °F range instead of the 300 to 500 °F range of thrust engine exhaust gases in that area.

Specific design guidelines/specifications must include calculations of a composite effect of various sound attenuation coefficients of doors, baffles, panels, etc. Therefore, it is difficult to develop “rule of thumb” guidelines for acoustic treatment of test cells because of the myriad design configurations employed.

6. (Continued):

The acoustic data discussed herein is a sample of T-56 engine operational noise spectra and shows that infra-sound damage is not a concern in these test cells. The lowest octave band recorded in the sample data is 37.5 Hz center frequency. The pressure level of this lowest band was less than the level of the 125 Hz band, which indicates that the infra-noise regime of the spectra of this engine is most likely not a design problem; i.e., the level of 127 dB for the 125 Hz band compares to the level of 112 dB for the 37.5 Hz band.

The actual construction and design of structural rigidity or foundation components will necessarily be concerned with lower frequencies (below 20 Hz) which may be generated by the engine air flow and propwash moving through the enclosure and which may resonate with the natural response modes of the enclosure. Designers are cautioned to examine the engine spectra to assure that the audible range frequencies are greater than the infra-noise band to preclude inadvertant structural resonances. A narrow band analysis of 20 Hz and below should be performed.

7. 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 and acoustic performance are described below. 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. Sufficient empirical data from a model or full scale tests is not available to quantify typical values or ranges for these factors. However, it can be assumed that distortion indices as high as those for turbofan/jet engine test cells specified in ARP4869, Design Considerations for Turbofan/Jet Engine Test Cells, are reasonable. Even higher values may be acceptable because of the effect propellers and orifice walls/rings have on straightening airflow into engine inlets.