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Structural Design and Construction Considerations for Enclosed Turbofan/Turbojet Engine Test Cells

RATIONAL

This SAE Aerospace Recommended Practice is intended to provide guidance and recommendations for concrete test cell structures that must resist the effects of normal engine operating loads, dynamic loads due to engine failure, over pressures and cell depression loads, acoustic and environmental loads and engine projectiles.

FOREWORD

This document discusses the structural design and construction considerations for design of structures used for testing turbofan and turbojet engines. The document presents general design and construction information along with information for limiting damage and injuries from projectiles.

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1. SCOPE

This SAE Aerospace Recommended Practice (ARP) is 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 constructing new or adding to existing engine test cell facilities.

1.1 Purpose

The purpose of this document is to provide general guidelines for the design and construction of concrete test cell structures that will resist the effects of normal engine operating loads, dynamic loads due to engine failure, over pressures and cell depression loads, acoustic and environmental loads and engine projectiles.

2. REFERENCES

2.1 Applicable Documents

The following publications form 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.

2.1.1 SAE Publications

Available from SAE International, 400 Coomonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org.

2.1.1.1 AIR4869 Design Considerations for Enclosed Turbofan/Turbojet Engine Test Cells

2.1.1.2 AS567 Safety Cable, Safety Wire, Key Washers and Cotter Pins for Propulsion Systems, General Practices for Use of

2.1.2 AIA Publications

Available from Aerospace Industries Association, 1000 Wilson Boulevard, Suite 1700, Arlington, VA 22209-3928, Tel: 358-1000, www.aia-aerospace.org.

2.1.2.1 NASM33540 Safety Wiring, Safety Cabling, Cotter Pinning, General Practices for

2.1.3 FAA Publications

Available from Federal Aviation Administration, 800 Independence Avenue, SW, Washington, DC 20591, Tel: 866-835-5322, www.faa.gov.

2.1.3.1 DOT/FAA/AR-99/71 Full-Scale Tests of Lightweight Fragment Barriers on Commercial Aircraft

2.1.3.2 DOT/FAA/AR-99/8, I Improved Barriers to Turbine Engine Fragments: Interim Report I

2.1.3.3 DOT/FAA/AR-99/8, II Improved Barriers to Turbine Engine Fragments: Interim Report II

2.1.3.4 DOT/FAA/AR-99/8, III Improved Barriers to Turbine Engine Fragments: Interim Report III

2.1.3.5 DOT/FAA/AR-99/8, IV Improved Barriers to Turbine Engine Fragments: Interim Report IV

2.1.3.6 DOT/FAA/AR-99/8, V Improved Barriers to Turbine Engine Fragments: Interim Report V

2.1.3.7 DOT/FAA/AR-98/22 T53-L-13L Turbine Fragment Containment Test

2.1.4 NFPA Publications

Available from National Fire Protection Agency, 1 Batterymarch Park, Quincy, MA 02169-7471, Tel: 617-770-3000, www.nfpa.org.

2.1.4.1 NFPA 68 Technical Committee on Explosion Protection Systems, Guide for Venting of Deflagrations

2.1.4.2 NFPA 423 Technical Committee on Airport Facilities, Standard for Construction and Protection of Aircraft Engine Test Facilities

2.1.4.3 NFPA 220 Technical Committee on Building Construction, Standard on Types of Building Construction

2.1.5 U.S. Government Publications

Available from Documant Automation and Production Service (DAPS), Building 4/D, 700 Robbins Avenue, Philadelphia, PA 19111-5094, Tel: 215-697-6257, http://assist.daps.dla.mil/quicksearch/.

2.1.5.1 ARMY TM 5-1300 Structures to Resist the Effects of Accidental Explosions

2.1.6 Other Publications

2.1.6.1 American Concrete Institute (ACI), Building Code Requirements for Reinforced Concrete (ACI 318-95) and Commentary (ACI 318R-95), ACI Committee 318, 1995.

2.1.6.2 American Concrete Institute (ACI), Code Requirements for Nuclear Safety Related Concrete Structures, Special Provisions for Impulsive and Impactive Effects, ACI Committee 349, Appendix C, 1985.

2.1.6.3 American Society of Civil Engineers (ASCE), Design of Blast Resistant Buildings in Petrochemical Facilities, Task Committee on Blast Resistant Design of the Petrochemical Committee of the Energy Division of ASCE, 1998.

2.1.6.4 Smith, P.D. and Hetherington, J.G.: Blast and Ballistic Loading of Structures, Butterworth-Heinemann Ltd., Oxford, England, 1994.

2.1.6.5 Samara, Mufid: Nonstructural Considerations in Design of Blast-Resistant Buildings, Practice Periodical on Structural Design and Construction, ASCE, 1998.

2.1.6.6 Mays, G.C. and Smith, P.D., Eds: Blast Effects on Buildings, Thomas Telford, London, England, 1995.

2.1.6.7 Kar, A.K., Local Effects of Tornado-Generated Missiles, Journal of the Structural Division, Proceeding of ASCE, Vol. 104, No. ST5, May 1978.

2.1.6.8 American Concrete Institute (ACI), Environmental Engineering Concrete Structures (ACI 350), ACI Committee 350, 1989.

2.1.6.9 American Concrete Institute (ACI), Fiber Reinforced Concrete (ACI 544.1R), ACI Committee 544, 1996.

2.1.6.10 American Concrete Institute (ACI), Measurement of Properties of Fiber Reinforced Concrete (ACI 544.2R), ACI Committee 544, 1989.

2.1.6.11 Shockey, Donald, Erlich, David, and Simons, Jeffrey, Lightweight Fragment Barriers for Commercial Aircraft, 18th International Symposium on Ballistics, San Antonio, Texas, November, 1999.

2.1.6.12 American Society of Civil Engineers (ASCE), Minimum Design Loads for Buildings and Other Structures, ANSI/ASCE 7.

2.1.6.13 International Code Council, International Building Code (IBC).

2.2 Terms and Abbreviations

The following terms and abbreviations are used in this report.

ACI	American Concrete Institute
areal density	dry fabric weight, a two-dimensional measure of density
ASCE	American Society of Civil Engineers
cm	centimeter
FOD	Foreign Object Damage - caused by items being ingested into the engine
ft	foot or feet
ft-lb	foot-pound, a measure of energy
f/s	feet per second
g	gram or grams
IBC	International Building Code
kips	1000 pounds
lb	pound or pounds
m/s	meters per second
OSHA	Occupational Safety & Health Administration
PSF	Pounds per square foot
rebar	Steel reinforcement used in concrete construction
Z	Quantity limiting distribution of flexural reinforcement, Section 10.6 of Reference 2.1.6.1

3. BACKGROUND

During testing of turbofan and turbojet engines parts or assemblies may fail. Also, during scientific investigations, sometimes it is necessary to deliberately test parts to failure.

In the case of machinery rotating at very high rates, such as turbofan and turbojet engines, the failure of one part can quickly lead to damage to other parts and to a general failure of the apparatus to withstand circumferential forces. When the failure has progressed that far, rotating parts fly off in various directions with great velocity and great energy. These parts can carry other parts or subassemblies with them. As these projectiles strike other objects, they can create additional projectiles. Due to their high velocity, even small, lightweight projectiles can injure personnel, damage equipment, or even damage the test cell structure itself.

Reference 2.1.6.2 states that projectile loads cause both local effects and overall structural effects. It defines the local effects of penetration, perforation, scabbing (also called backface spalling), spalling and punching shear.

An expensive solution in preventing structural damage would be to provide shielding for portions of the structure, particularly in the test chamber. But, extensive shielding could interfere with operations and is likely to be very expensive. A more reasonable approach is to use good design and construction practices to provide a structure that, although damaged, will be repairable, that will limit further injury to personnel and damage to equipment and that will not collapse.

4. TEST CELL STRUCTURAL DESIGN CONSIDERATIONS

4.1 Structural Loads

4.1.1 Normal Loads

Turbofan and turbojet engines are not supported directly by the building structure. Between the engine and the structure are devices called thrust frames or thrust stands. These devices support the engines and transfer the engine dead load and live load to the structure. The structural engineer must obtain the thrust frame forces and connection details from the thrust frame manufacturer.

Other normal loads include dead loads, live loads and the environmental loads specific to the facility site. Environmental loads are discussed below.

Each test cell must be designed by a qualified industry professional on a case-by-case basis.

4.1.2 Over Pressure Load

Turbofan and turbojet engines do not explode. Although a failure may appear to be an explosion because it happens quickly and although some of the fuel may appear to explode, the mechanism is not an explosion. Positive over pressures are created. However, the rate of pressure increase is considerably less than that caused by an explosive device. Also, since by definition, the engine must be running to cause the over pressure in the first place, there is considerable relief venting through the inlet and exhaust openings. Special consideration must be made for special fuels such as natural gas. These fuels have significantly different properties that will impact any sudden release of energy calculation and design.

Test cell structures have performed well when over pressure is considered as a static load condition. Over pressure loads should be assigned live load factors but there is only a low probability of the maximum over pressures occurring simultaneously with the maximum environmental loads. If such a combination did occur, it is expected that the structure would sustain inelastic deformations but continue to function.

Each test facility must be designed to meet the requirements and criteria dictated by the test article, such as, physical size, thrust, noise and aerodynamics. Reference 2.1.1.1 provides additional guidance with respect to these issues.

4.1.3 Typical air-breathing, sea level test cells up to 120 000 pounds of thrust shall be designed for over pressures of 150 PSF Augmenter and exhaust stack wall pressures shall be designed for 200 PSF Cell Depression: Air flowing through the test chamber at high velocities creates a net suction (depression) on the inside walls of the structure. This negative pressure is only present while an engine is being tested. Cell depression pressure should be considered a live load with a low to medium probability of occurring simultaneously with the highest environmental loads. Normal operating cell depression values range from 4 to 12 inches of water gage. A growth factor of 3 inches of water gage provides additional margin for future growth and capability. By applying a safety factor of 1.5 to the previously stated values, normal air-breathing, sea level test cells should be designed for maximum cell depressions of 100 PSF.

Each test cell must be evaluated on a case-by-case basis. Minor changes to the gas path in the test cell can significantly change the cell depression. These loads may significantly impact the integrity of the structure and ancillary components (such as, doors, viewing windows, mechanical and electrical penetrations). It is strongly recommended that a qualified industry professional be consulted prior to testing a higher thrust or higher energy engine, or prior to modifying the gas path of a test cell.

4.1.4 Environmental Loads

The typical environmental loads associated with any structure are applicable to engine test cells design. These loads include the dead loads, construction loads, live loads from equipment and the engine supports (thrust frames), cranes/monorails/doors/floor tracks, movable lift platforms and fixed stairs and work platforms, roof and floor live loads, rain, ice and snow loads, wind loads and seismic loads. Local and national building codes (such as References 2.1.6.12 and 2.1.6.13) should be consulted for the minimum load values and application points and for load combinations. The above-mentioned pressure loads should be combined with environmental loads but at a reduced probability of the maximums occurring simultaneously.

4.1.5 Projectiles

4.1.5.1 General

In the case of machinery rotating at very high rates, such as turbofan and turbojet engines, the failure of one part can quickly lead to damage to other parts and to a general failure of the apparatus to withstand circumferential forces. When the failure has progressed that far, rotating parts fly off in various directions with great velocity and energy. These parts can carry other parts or subassemblies with them. As these projectiles strike other objects, they can create additional projectiles. Due to their high velocity, even small, lightweight projectiles contain considerable uncontrolled energy and can injure personnel, damage equipment, or even damage the test cell structure itself.

Fortunately, engine projectiles are usually deformable, have very localized effects and have a very limited existence. Unfortunately, their energy is usually imparted to fixed objects such as the walls, floor and roof of the test cell. The structural elements impacted by projectiles must be designed to absorb the energy of the particles while preventing compromise of the structural system, preventing penetration of the structure and preventing spalls on the opposite face of the concrete element (backface spalling) from endangering neighboring personnel and equipment.

Describing the weight, shape, velocity and energy potential of engine projectiles and developing formulas to predict the consequences of impact is beyond the scope of this paper. Reference 2.1.6.7 provides information and references for tornado-generated projectiles on concrete barriers. Although not written specifically for engine test cells, if the engine manufacturer can describe typical projectiles, the empirical formulas and information on local effects (such as penetration, perforation, backface scabbing) may be applied to concrete test cells. Reference 2.1.6.7 states that there is normally no penetration for missiles of materials with hardness numbers less than that of the concrete in the structure. However, there may still be scabbing or spalling on the backface.

References 2.1.6.4 and 2.1.5.1 also provide penetration prediction equations, explanations and additional references which may be useful in a detailed design for specific projectiles. Figure 12.14 of Reference 2.1.6.4 gives recommended slab thicknesses to eliminate scabbing based on projectile caliber, projectile mass, striking velocity and concrete strength.

At a minimum, the structure must act as a barrier to prevent penetration and perforation. Reference 2.1.6.2 recommends that the provisions contained in its Section C.7.2.1 be followed. However, provisions of that section do not preclude scabbing. Scabbing can become secondary projectiles. These projectiles have considerably less energy than the primary projectiles but they can still cause injury or damage. To prevent scabbing, it is necessary to attach a scab plate or ballistic wall covering to the back side of the structural element or to use a greater wall thickness. Commentary Section C.7 in Reference 2.1.6.2 contains guidance concerning using various empirical formulas for determining concrete thicknesses to prevent penetration and scabbing.

4.1.5.2 Reports

The Federal Aviation Administration (FAA) has sponsored research to mitigate the effects of uncontrolled engine projectiles. References 2.1.6.11 and 2.1.3.1 through 2.1.3.7 describe these tests and state conclusions.

The tests were designed to investigate materials for safer cabins for commercial aircraft, but the results can be used to estimate projectiles in test cells and to provide safer test cell environments.

The various fuselage impact tests confirm that Aramid fibers can provide an efficient fragment barrier for use in aircraft. One report stated: “For fragments weighing around 175 g (0.4 lb), traveling at the maximum velocities expected for uncontained fragments around 265 m/s (780 f/s), three or four plies of Zylon, with areal densities around 0.05 g/cm^2 (0.1 lb/ft^2) extending across a single vertical frame element, will likely be sufficient to prevent penetration.” It also stated: “For large fragments weighing between 400 and 600 g (0.9 to 1.3 lb) and traveling at maximum expected uncontained fragment velocities, eight to ten plies of Zylon, with areal densities of around 0.15 g/cm^2 (0.3 lb/ft^2), appear to be sufficient to prevent penetration.” Zylon is a proprietary product made of polybenzoxazole (PBO) [generically called Aramid].

Another FAA report stated, “Three plies of polybenzoxazole (PBO) Zylon woven fabric glued to the outboard side of the insulation packet and weighing only 0.05 g/cm^2 (0.1 lb/ft^2) prevented a 166 g (0.37 lb) sharp-edged fan blade fragment impacting edge-on at 230 m/s (756 ft/s) from penetrating into the cabin. The absorbed energy of 4400 joules (3250 ft-lb) is nearly an order of magnitude greater that that absorbed by the unreinforced fuselage wall. The results confirmed that high-strength polymer fabrics offer an extremely effective, low-weight solution for mitigating the effects of uncontained turbine engine fragments on commercial aircraft.”

The information from these tests can be applied to test cells. Naturally, the thick concrete wall will absorb significant energy from projectiles however, it may be necessary to use ballistic wall coverings to prevent concrete spalls from impacting personnel.

4.1.6 Dynamic Loads

Frequency information many not be available on the various engines to be tested. If information is available, the designer should check that the frequencies and modal participation factors of the structure are dissimilar from those of the engines. Computer models will be necessary for this level of analysis.

The engine support mounts will dampen impact loads from the engine to the structure. However, if these loads are expected to occur with regularity, the designer should consider fatigue.

The structural engineer must obtain the dynamic forces related to the blade out condition from the thrust frame manufacturer. The thrust frame manufacturer must coordinate these forces with aircraft engine manufacturer as these forces, frequency and response with vary greatly from one engine to another.

4.2 Selection of a Structural System

Some structural systems may not be suitable for use in an environment where projectiles may damage important structural components. Systems where only a few members are responsible for the stability of the entire structure are not desired. For example, pre- or post-tensioned elements may not be desirable. If the pre- or post-tensioning tendons were suddenly severed by projectiles, the structure may collapse. Even a standard, popular system like a truss may not be suitable. Large projectiles may bend or sever very important bracing members or connection points and thus compromise the entire structural element Chord and diagonal elements of open web steel joists are probably too light-weight not to be damaged by all but the smallest engine projectiles.

The selected structural system must ensure that local compromise of one element does not spread to other elements, eventually causing collapse of major elements and the entire or majority of the structure.

Such systems could be used for a test cell structure if one or more design conditions accounted for the removal of key structural components during an engine test (a redundant structure). These contingencies can be quickly evaluated using computer analysis techniques. The key design consideration is to apply the full load expected during any test and to simulate the missing element or elements.

An additional consideration is that the damage should be repaired easily. For example, although a designer may provide a redundant design while using pre- or post-tensioning elements, if these elements are severed, it may be very difficult to insert replacement elements.

Therefore, it is very desirable to select structural systems where missing elements do not cause progressive collapse or the design should provide redundant structural systems which are easily repaired.

The structural system used very successfully for many years is concrete flat slabs and walls. Because of their membrane action, properly designed and detailed, vertical and horizontal slabs are very redundant and offer considerable inelastic strength. The concrete can be designed thick and massive to prevent penetrations, perforations and scabbing when impacted with projectiles.

4.3 Foundations

Test cell structures are typically concrete. Walls, ceilings and floors for the inlet plenum, test chamber, augmentor and exhaust stack (see Reference 2.1.1.1) are large and massive to provide proper air flow and to limit acoustic emissions. This type of structure requires a foundation system that will support continuous heavy loads without significant settlement.

A qualified geotechnical engineer must be consulted to provide sampling, testing and site-specific foundation recommendations. The geotechnical engineer’s investigation and conclusions should be stated in a report provided to the structural engineer. At a minimum, the report should state allowable long-term and short-term bearing pressures, lateral earth pressures, groundwater conditions, site preparation, select fill and compaction requirements, frost depth, expected settlements and information for seismic design. It should contain the geotechnical engineer’s detailed and specific recommendation for foundations, for slabs-on-grade, for cement type and for mitigating settlements and any undesirable subsurface conditions (such as, poor drainage, weak soil layers, high pH values, high soluble sulfates, high chloride ion contents, expansive soils and liquefaction). Other engineering disciplines need other information provided by the geotechnical engineer report such as, electrical resistivity of the soil and recommendations for pavements.

Acoustic waves and vibrations from jet engines are imparted to the test cell structure directly through steel and concrete connections and through the air. These waves and vibrations continue through the structure but are slowly damped to unnoticeable levels. For improved operations and work environments in adjacent structures (such as engine maintenance bays, offices or control rooms), it is undesirable to allow acoustic waves and vibrations from the test cell to be transferred to those structures. To prevent vibrations from being transferred, it is recommended that isolation joints between the test cell and adjacent structures be provided.

4.4 Reinforcement Design

To prevent the need for extensive structural repairs after an engine failure, the structure should not be designed for inelastic action. However the reinforcement details should ensure full development of both concrete and reinforcement well into the inelastic range of response. The elastic design provisions given in Reference 2.1.6.1 should be followed, with the following exceptions:

Reference 2.1.6.1 contains provisions for detailing concrete when a structure is located an area of high seismic risk. These provisions ensure that the structure (especially connections and areas of high shear) will function as expected and be able to attain strengths in the inelastic range. Such provisions should be followed whether the structure is in a high seismic region or not.

In accordance with Reference 2.1.6.4, elements should be reinforced symmetrically. Where wall and slab thicknesses permit, reinforcing should be in two layers. This enables the compression reinforcement to carry all compressive stresses if the concrete in the compression zone is crushed or spalled.

Reference 2.1.6.4 also suggests that the main flexural steel and enclosed concrete should be ‘laced’ together. Among several benefits, this also restrains the compression reinforcement from buckling and helps to spread out any effects of non-uniform loading. While laced reinforcement could be used, it would be extremely uneconomical to do so, but may be warranted in certain cases. Even if not laced, higher amounts of “shear” reinforcement or transverse reinforcement will perform a similar function.

A minimum reinforcement ratio of 0.0018 in^2/in^2 should be used in all components in the test chamber.

Reinforcement splices should be located so as not to coincide with any stress concentrations.

In general, reinforcing bars should be spaced fairly close together to ensure that any cracked concrete between layers of reinforcement would not dislodge from the element. Reference 2.1.5.1 states that tests have indicated that a maximum spacing of approximately 15 inches will ensure confinement of concrete with two layers of reinforcement. Smaller spacings are preferred for areas of the test chamber immediately around the engine. Spacings associated with reducing crack widths in water containment type structures may be appropriate. Reference 2.1.6.8 states rebar spacing should be no more than 12 inches and that Z values should be no greater than 115 kips per inch.

Fiber reinforced concrete and welded wire fabric may be used to reduce the possibility of concrete fragments becoming dislodged. See 4.4.7.

Reference 2.1.5.1 recommends that for ease of construction single leg stirrups with 135 degree hooks are adequate and should be used as shear reinforcement in slabs and walls.

4.5 Materials

4.5.1 General

Concrete materials should conform to the materials specifications in Reference 2.1.6.1.

Reference 2.1.6.2 states that because of the rapid strain rates that occur in structural elements under impact or impulsive loading, both the concrete and reinforcing steel will exhibit strengths that are higher than those under static loading conditions.

Reference 2.1.4.2 states:

a. Test cell walls, ceilings and floors shall be at least Type II (222) construction. Reference 2.1.4.3 defines Type II (222) construction using approved noncombustible or limited-combustible materials for walls, columns, beams, girders, trusses, arches, floors and roofs. In general, the reference requires 2-hour fire-resistance ratings for Type II (222). One-hour fire-resistance ratings are acceptable for selected structural members that support only a roof and for roof construction.

b. Thermal and acoustic materials used within the test cell shall be noncombustible.

c. Test cells shall be without basements or below grade areas other than recesses necessary for sumps, drains or lifting platforms.

4.5.2 Concrete Strength

Reference 2.1.6.7 states that stronger concrete decreases the depth of projectile penetrations. Reference 2.1.5.1 recommends that the minimum concrete strength should be 4000 psi with higher strengths desirable.

Normal weight (not light weight) concrete should be used because light weight concrete has low acoustic performance and fractures easily.

Cementitious materials such as silica fume, fly ash, blast furnace slag and natural pozzolans may be used.

High strength concrete (HSC) (F’c > 10 000 psi) is not desired for several reasons:

a. Design criteria for HSC has not been formalized.

b. HSC has greater sensitivity to material selection and construction procedures. Extensive trial batching may be required.

c. Fire resistance is not improved.

d. Shear strength is not improved.

e. Although HSC has less microcracking and although fracture energy may be increased (depending on material selection), failure at ultimate may be more brittle than normal strength concrete.

4.5.3 Aggregate Size

Reference 2.1.6.7 states that aggregate size has an effect on the concrete thickness required to prevent perforation and backface spalling with the larger aggregate sizes allowing decreased thickness. Therefore, the largest aggregate size consistent with the size and density of rebar should be used.

Reference 2.1.5.1 recommends a maximum aggregate size of 1 inch. This limit facilitates the placement of concrete, particularly where the cover over the reinforcement is held to a minimum.

4.5.4 Concrete Slump

Reference 2.1.5.1 recommends that because of the large amounts of reinforcement, the concrete slump used is usually on the high end of slumps permitted for conventional construction. A slump of 4 inches is recommended. Water reducing admixtures may be considered.

4.5.5 Chemical Admixtures

Use of chemical admixtures that improve placement and consolidation while maintaining high strength are desirable.

4.5.6 Reinforcing Steel

With a minimum yield strength of 60 000 psi, ASTM A 615 Grade 60 reinforcing steel is considered to have adequate strength. However, under ultimate loading elongation is only 8%. Also, there is no control over chemical composition which means that A615 is not easily weldable. Therefore, A615 rebar may not have sufficient ductility. ASTM A 706 is a low alloy steel reinforcement which may be more suitable. It has a yield strength of 60 000 psi, 14% elongation at ultimate and chemical composition controls. A706 is weldable. Further recommendations in Reference 2.1.5.1 should be followed.

4.5.7 Fiber Reinforcement

Fiber reinforcement is insufficient to replace the vertical and horizontal reinforcing bars required for test cells. However, fiber reinforcement may be added to improve ductility and durability, to reduce micro-cracking and to greatly inhibit spalling, penetration, perforation and scabbing.

0.5 to 2.0 percent fiber reinforcement creates a fine network of random steel or synthetic fibers that tightly knit the cement paste. Fibers in and around the course aggregate “bridge” the microscopic gaps that develop under normal curing and under load. These embedded fibers improve the energy absorption and shatter resistance of concrete under crushing and impact loads. They also enhance the bond between the concrete and reinforcing bars.

References 2.1.6.9 and 2.1.6.10 should be consulted for additional information.

Firmly embedded fibers and concrete will not dislodge but loosely or marginally embedded fibers or concrete may dislodge during engine testing. Prior to the initial use of the test cell, it may be necessary to rub concrete surfaces to ensure that loose fibers or small pieces of concrete (such as “fins” and weak paste around formwork) are removed.

4.5.8 Ballistic Wall Coverings

Aramid (aromatic polyamide) fibers are known as ballistic fibers and are used in protective clothes (most often flack or bullet-resistant vests), bomb-resistant blankets and covers, helmets, shields, lining vehicles and for shelters and safe rooms walls and doors. Several brand name products are:

a. Kevlar by Dupont

b. Twaron by Akzo Nobel

c. Spectra (a polyethelene) by Honeywell

d. Zylon (a PBO) by Toyobo

Aramid fibers are used to make fabrics used in various proprietary wall-covering products. They are tested in accordance with recognized U.S. or international standards such as Underwriter’s Laboratory (UL) 572, Bullet-Resistant Equipment, and the U.S. Department of Justice, National Institute of Justice (NIJ) Standard 0108.01, Ballistic Restraint Protective Materials.

Several brand-name wall-products are:

a. ArmorCore Bullet-Resistant Panels by Waco Composites, Ltd.

b. Insulgard by GE Polymershapes

c. Blast Protective Wall Covering System by Achidatex

d. K-Armored or Millibar by New Necessities

These wall-coverings would be glued or bolted to one side of the test cell wall. They could also be applied to doors or used as drop-down sheets over windows during emergencies.

4.6 Construction

4.6.1 General

At a minimum, the quality of work should conform to the requirements in Reference 2.1.6.1.

4.6.2 Quality of Work

Quality concrete work with particular attention to the interior surface finish and the minimization of construction joints is important. The contractor should be required to have trained inspectors on site and laboratory work. The contractor should be required to have regular construction and quality control meetings. There should also be special pre-construction conferences to discuss and to address the owners and inspectors concerns prior to starting each phase of the work. On-going work should be inspected and approved by the owner’s representative. The construction contract may call for the owner to approve a sample surface made by the contractor prior to further construction.

Proper consolidation techniques are extremely important to prevent weak areas of honeycombed and exposed aggregate. When such areas are discovered in conventional structures they are usually patched. Patching inside the test cell is not desired and could be difficult and expensive.

Proper wet curing techniques are also important so that the concrete will attain its design strength and to minimize shrinkage cracking.

Reference 2.1.6.4 recommends that the erection sequence should be carefully planned to enable all reinforcing steel to be correctly placed. Also, efforts should be made to optimize the integrity of the structure and to locate vertical and horizontal construction joints so as to avoid stress concentration regions.

4.6.3 Concrete Cover

Reference 2.1.5.1 recommends that in all cases the minimum concrete cover should conform to Reference 2.1.6.1 and wherever possible, this value should also be the maximum thickness of concrete cover.

4.6.4 Anchorage

All embedments should be cast into the surrounding concrete. Expansion anchors should never be used. Anchors which can not be cast into the concrete must be epoxied into place. Long embedment lengths should be provided.

Items embedded in the test chamber walls, floor and roof should be mounted at multiple points with deep embedments. If struck, the deeper embedment will remain in place and the shattered and cracked surface concrete will not affect the structural integrity of the embedded. Such embedments will be more easily repaired.

4.6.5 Form Ties

Form tie holes must not be patched. The patch materials may become dislodged by vibrations during normal operations and become FOD or they may be dislodged by engine projectiles.

4.6.6 Connections to Prevent Engine FOD (Captivation of Fasteners)

All connections within the test cell including acoustical panels and baffles, turning vanes, screens, platform, doors, mechanical items, electrical items, pipe and conduit and their supports, should be lock-wired, have lock nuts or be welded to prevent components from loosening during normal operation of the test cell. Extremely small screws, nuts and bolts which can not be lock-wired should not be used. Where avoidance is not possible, these small fasteners must have a permanent, high strength, fast curing, thread locking adhesive compound applied so they will not loosen. Further information on lock-wiring can be found in References 2.1.1.2 and 2.1.2.1.

Elevated intake stacks and intake screens are used to prevent items from the exterior of the structure from being brought into test area by the air stream.

4.6.7 Final Cleanup and Repairs to Concrete Surfaces

Prior to the initial use of the test cell, it may be necessary to rub concrete surfaces to ensure that all construction debris, loose reinforcing fibers and small pieces of concrete (such as “fins” and weak paste around formwork) are removed from ceilings, walls and floors. Water blasting and power grinding can be used. However, grit or sand blasting should not be used because these methods will force small particles into crevices. During engine testing structural vibrations will cause these particles to dislodge and migrate out of the crevices and into the air stream. Any finishing operation should be followed by appropriate FOD inspections and cleaning (such as, thorough vacuuming).

Minor and major repairs to incorrectly formed or damaged concrete surfaces should be undertaken only with the Engineer’s and Owner’s full knowledge and approval. Minor repairs are particularly susceptible to vibrating loose during normal operations of the test cell. Small pieces of hard or soft objects are easily ingested into jet engines. These objects can cause irreparable damage to the expensive engine and lead to a catastrophic failure. Reference 2.1.6.4 requires that any patches should be of sufficient size to be fully anchored to bi-directional reinforcement. Non-moving cracks can be closed with structural-grade (such as epoxy) crack fillers.