Aviation Rulemaking
Advisory Committee

Foam

Task Group 4

Abstract

This report is the findings of the Fuel Tank Foam and Expanded Metal Products Task Group, which was formed as a portion of the Fuel Tank Harmonization Working Group activity established in January 1998. The FAA initiated this activity by the issuance of a Harmonization Terms of Reference entitled "Prevention of Fuel Tank Explosions" on 16 Dec 1997. The Working Group's stated task was to study means to eliminate or reduce fuel tank flammability and to propose regulatory changes to the FAA Aircraft Rulemaking Advisory Committee.

The Fuel Tank Foam and Expanded Metal Products Task Group's assignment was to provide a feasibility analysis of fuel tank foam and expanded metal products installation systems. The analysis was to focus on the use of foam and expanded metal products in prevention of fuel tank explosion for transport airplane operations. A cost/benefit analysis for fuel tank foam installation systems was to be included for the fleet of aircraft requiring retrofit, for current production aircraft, and for new type design aircraft.

The findings for this Task Group indicates that foam or expanded metal products can be used effectively in the prevention of structural failure of fuel tanks as a result of an explosion. However, when installed foam or expanded metal products will reduce aircraft payload and available fuel volume. These reductions are the two most important factors that would result in severe economic impact for airlines

Summary

This report provides information on two types of materials available for installation inside aircraft fuel tanks which will reduce the risks of hull losses of aircraft in case of explosions:

1. Reticulated polyether foam

2. Expanded metal products.

Both have more than one application, and both will require FAA certification. Some will require extensive qualification tests to aircraft standards. When installed inside fuel tank both materials create its own disadvantages such as weight increase, fuel volume loss, increase pack bay temperature causing degradation of aircraft structural integrity, FOD and maintenance difficulties.

The installation of either system has no real effect on normal fuel system operation and the each system is virtually maintenance free. However, the presence of the materials in the fuel tank greatly impacts the removal/replacement of in-tank components. Time to remove, store, and reinstall the materials must be added to the normal time necessary for fuel system components maintenance. This effect on operational aircraft has been accounted for in the cost estimate.

Foam also requires special handling and wrapping if it is to be out of the tank for an appreciable length of time. Further, foam which is no longer usable, is difficult to dispose of without environmental damage.

Costs associated with using one alternative of each product have been estimated for generic center tanks, which have adjacent heat sources. These estimates account for total cost, i.e., designs, installations, and operations. The estimates are based on data collected from vendors, from the United States Department of Defense, from aircraft manufacturers, and from airlines.

These cost estimates, for center wing tank with adjacent heat source, are summarized in the following two tables:

In service aircraft

Aircraft Size	Foam Nonrecurring	Foam Annual	Exp Metal Nonrecurring	Exp Metal Annual
Large	$390,740	$1,584,121	$848,273	$1,329,017
Medium	$187,427	$653,497	$366,057	$538,951
Small	$64,161	$120,448	$112,605	$88,992

Production Aircraft

Aircraft Size	Foam Nonrecurring	Foam Annual	Exp Metal Nonrecurring	Exp Metal Annual
Large	$353,884	$1,584,121	$811,416	$1,329,017
Medium	$166,334	$653,497	$344,964	$538,951
Small	$54,636	$120,448	$103,081	$88,992

It is estimated that it would cost the industry , in a 10 year period, over 22 billion dollar to use Expanded Metal Products and over 25 billion dollar to use Foam on inservice aircraft.

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References

1. Terms Of Reference, ARAC, FTHWG, January 1998

2. Advisory Group for Aerospace Research & Development, Report No. 771, Fuel Tank Technology

3. MIL-F-87260 (7 February 1992) Foam Material, Explosion Suppression, Inherently Electrically Conductive, For Aircraft Fuel Tank and Dry Bay Areas.

4. MIL-B-83054B, 17 May 1978, Baffle and Inerting Material, Aircraft Fuel Tank

5. MIL-B-87162 Baffle Materials, Explosion Suppression, Expanded Aluminum Mesh, for Aircraft Fuel Tank.

6. Society of Automotive Engineers Aerospace Information Report, AIR4170, 12 February, 1991, Reticulated Polyurethane Foam Explosion Suppression Material for Fuel Systems and Dry Bays.

7. AFWAL-TL-80-2043 Evaluation of Explosafe Explosion Suppression System for Aircraft Fuel Tank Protection.

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1.0 Background of Explosion Suppressive Materials

The explosion suppressive materials acts as suppressants when installed in fuel tanks because they:

1. Act as heat sinks, thus reducing the temperatures at spark points,

2. Break up compression waves that precede flame fronts in an explosion, and

3. Enrich the mixture of vapors in the ullage of fuel tanks, especially in tanks with JP-4 or similar fuels are used.

In this report the two types of Explosion Suppressive Materials under examined are Foam and Expanded Metal Products.

Both types of materials provide passive systems. No moving parts are required, and no cockpit instrumentation equipment is required. When the systems are properly designed and installed, ullage protection is ensured during all ground and flight conditions.

However, there are disadvantages to utilizing these materials:

Both reduce gross take off weight and/or range of aircraft due to the system weight increase and reduction in usable fuel quantities.

Both increase aircraft maintenance down time and labor cost due to the additional time required to drain the tanks, and to remove and replace the products for in tank maintenance.

Foam when installed inside the center wing tank may act as an insulator, which could hinder the thermal dissipation of heat energy produced by the air-condition packs mounted underneath the tank. This could elevate the air-condition packs bay and degrade the surrounding structure integrity.

Storage of removed materials will require special facilities.

Foam does have a limited life (approximately 15 to 20 years). Therefore, disposal of fuel soaked foam will be an environmental issue.

1.1 Foam Products

Military aircraft are highly vulnerable to fires and explosions resulting from combat threats such as gunfire, especially high explosive incendiary (HEI) rounds. During the late 1960s, the United States Air Force began using reticulated polyester polyurethane foam to suppress fires and explosions inside fuel tanks. Figure 1 and Figure 2 are photographs of a typical C-130 tank with foam installed. Since that time, several materials have been tried, the latest being per MIL-F-87260, Reference 4. A typical C-130 requires 1540 pieces of foam. A P-3 requires 1388 pieces. Figure 3 is a photograph of the foam for a P-3 fuel tank.

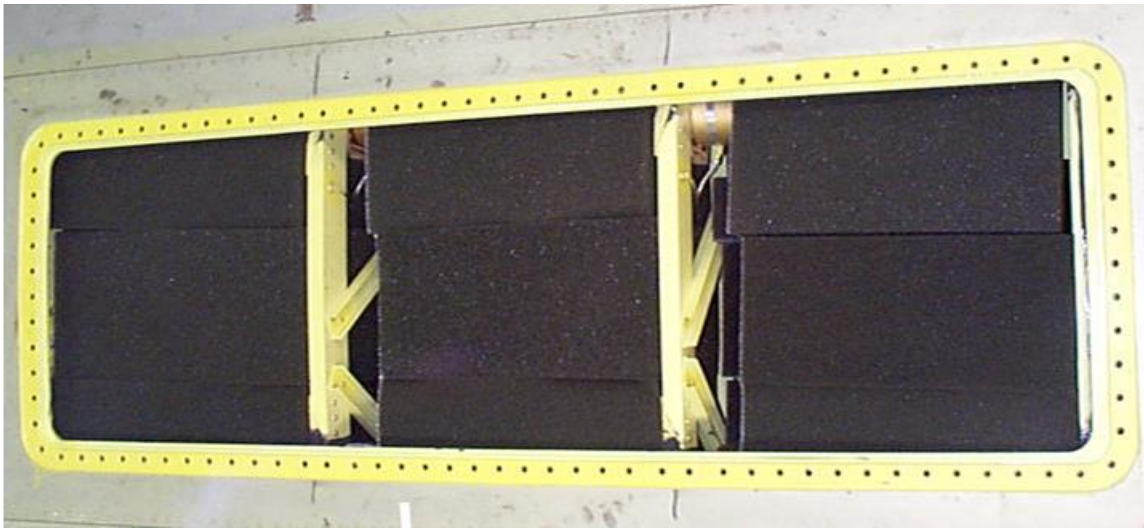

Figure 1 - C-130 Fuel Tank with Foam Installed

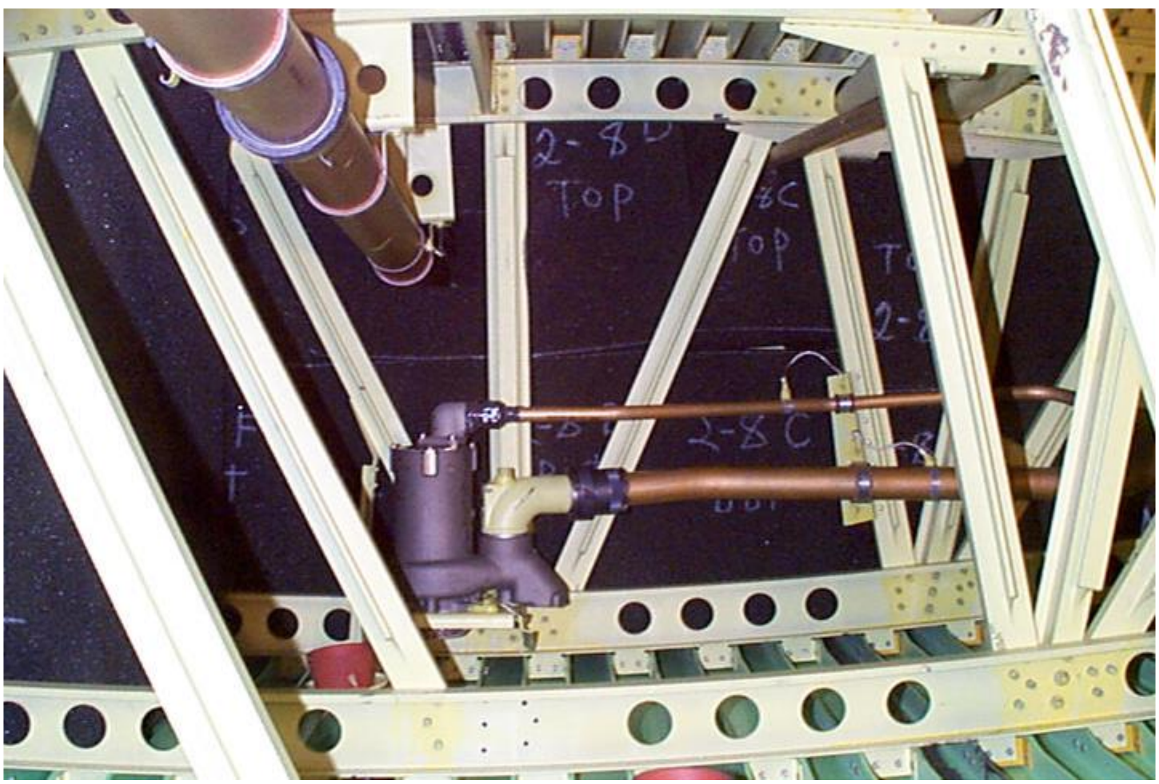

Figure 2 - C-130 Fuel Tank with Foam Installation Ongoing

View Looking Inbd

Soon after the development and incorporation of fuel tank foams, the Air Force discovered that the materials used for the foam were susceptible to hydrolytic degradation. Better materials were developed; producing what is commonly called blue foam.

The blue foam improved hydrolytic stability, but the blue foam had electrical resistance properties much higher than the original foam materials, causing a capacitance effect resulting in static charge potentials greater than 10,000 volts. Soon after incorporation of the blue foam kits, the USAF experienced fuel tank fires in the A-10 and the C-130 aircraft. Thousands of fuel tank fire remnants were discovered in the C-130 fleet, but no loss of an aircraft was ever attributed to fuel tank fires. This static electrical discharge problem led to the development of the conductive foams, which are now being produced and installed in quite a number of USAF and USN aircraft.

Figure 3 - A P-3 Foam Kit Being Prepared for Shipment

1.2 Expanded Metal Products

The expanded metal products have been used in fuel tanks and storage containers, and many tests have been conducted to prove that the products, mostly aluminum alloys, will protect fuel tanks from explosions as a result of internal ignition. However, as of the time this document was written, the United States Department of Defense has not approved any of the expanded metal products for use on any particular aircraft weapon system. MIL-B-87162, Ref. 5, was approved for expanded metal blocks, but the product has been incorporated on a limited basis. Likewise, the FAA has not yet issued a type certificate for any aircraft that uses the expanded metal products for explosion protection. However, this does not mean they are not effective or will never be used. For example, several of the expanded metal products can be purchased in the form of ellipsoidal or cylindrical shaped objects such as those shown in Figure 4. Aircraft fuel tanks will require design changes to incorporate constraining baffles or cages to ensure the particles remain in position, especially in an aircraft without access to the tank interiors from the top of the wings. This and other concerns require more design and development. Figure 5 is a photograph of the expanded aluminum blocks that conform to MIL-B-87162.

1.3 Some Weight Increase and Fuel Volume Loss Comparison

Beside additional maintenance burdens and environment issue the most severe penalties as a result of foam installation, are the fuel volume loss and the weight increase. These two factors directly effect the bottom line of airlines operation. The following tables summarize the weight and fuel volume penalty for the 3 classes of aircraft between the two types of material.

Foam

	Volume Loss (Gallon)	Weight Increase (Lb)
Large	1250	8532
Medium	500	3413
Small	150	1024

Expanded Metal Products

	Volume Loss (Gallon)	Weight Increase (Lb)
Large	600	9362
Medium	240	3745
Small	72	1123

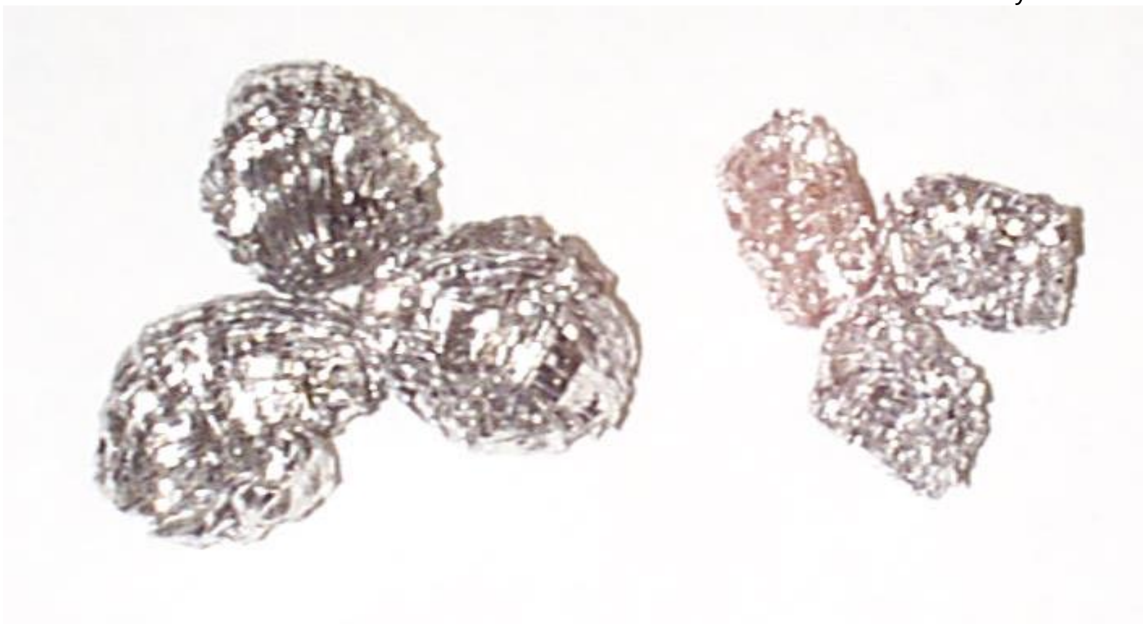

Figure 4 - Ellipsoidal and Cylindrical Shaped Expanded Metal Products

Figure 5 - Expanded Metal Blocks

2.0 Design Alternatives

2.1 Introduction

There are several design alternatives for design and installation of explosion suppression material, both with respect to type of material and installation design. This section will outline the various alternatives, explain the benefits, drawbacks, service experience and anticipated certification requirements of each, and select a baseline alternative based on best proven suitability for transport aircraft. Other alternatives may be suitable for specific applications, as determined by the aircraft manufacturer or modifier and certifying authority; however, additional testing may be required to establish suitability. The alternatives to be considered are:

Fully packed coarse pore reticulated foam

Grossly voided fine pore reticulated foam

Expanded Aluminum Mesh, Block Form

Expanded Aluminum Mesh, Ellipsoid Form

Selective Tank Installation

Selective Installation Around Ignition Sources

Figure 6 presents a graph of explosion overpressure versus void volume for various alternative materials. Table 1 presents a comparison of other properties of various alternative materials, and Table 2 summarizes major advantages and disadvantages of alternative materials and designs. These will be referred to within the sections discussing each alternative.

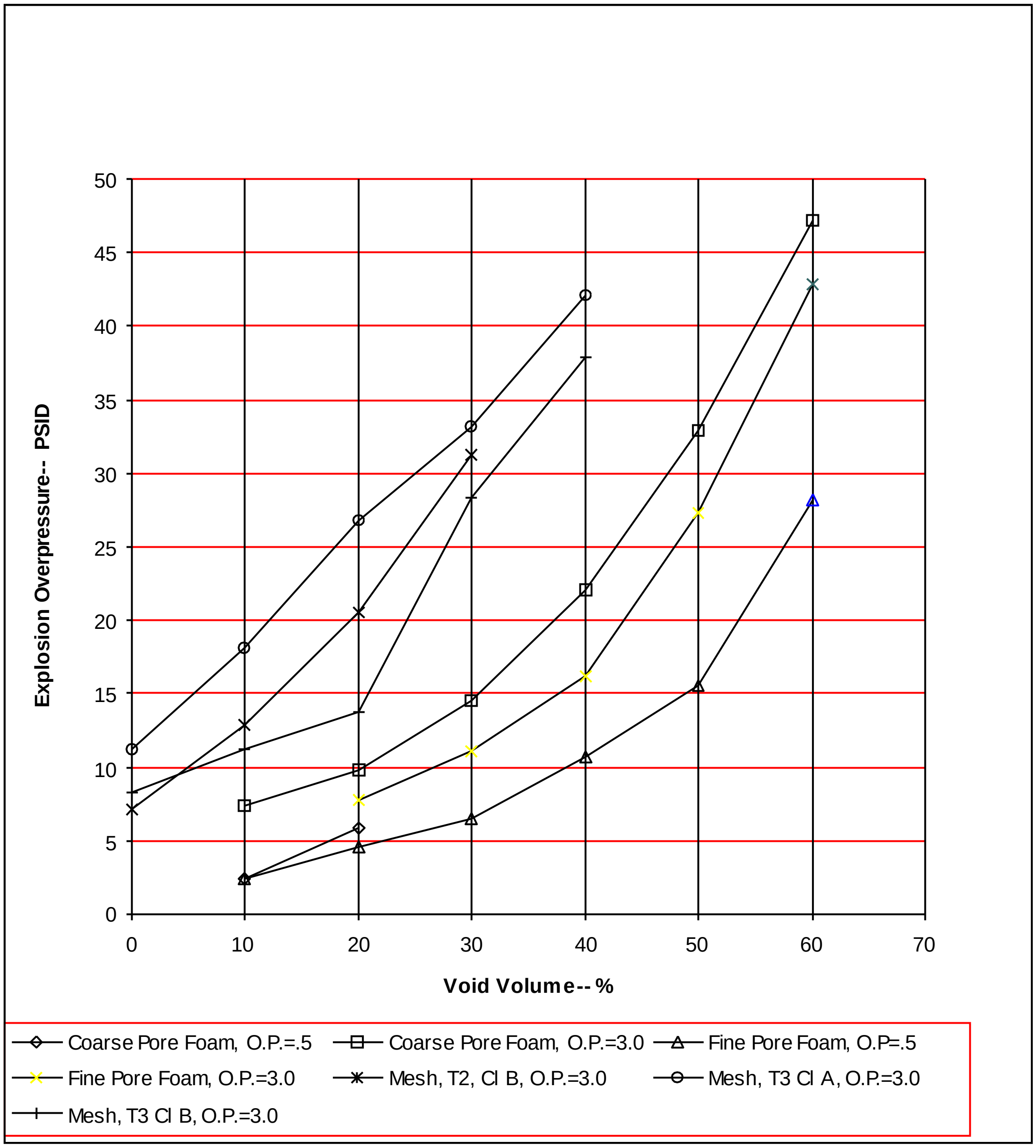

Figure 6

Explosion Overpressure versus Void Volume and Operating Pressure

Comparison Item	**Coarse Pore Foam**	**Fine Pore Foam**	**Aluminum Mesh, Block Type**					**Aluminum Mesh, Ellipsoid Type**
Specification	MIL-F-87260	MIL-F-87260	MIL-B-87162					None
Normal Installation	Fully Packed	Grossly Voided	Fully Packed					Fully Packed
Class, Grade, Type	Class 1 or 2, Grade IC	Class 1 or 2, Grade IIC	Type I	Type II, Class A	Type II, Class B	Type III, Class A	Type III, Class B	N/A
Material	Polyether	Polyether	3000 Series Aluminum Foil					Aluminum Foil
Max. Density, lb/ft^3	1.50	1.50	1.7	2.0	2.3	2.7	3.2	3.0 (est)
Max. Fuel Displacement-%	2.50	2.50	1.2	1.2	1.4	1.6	1.9	1.0—2.0 (est)
Max. Fuel Retention-%	2.50	5.00	1.0	.8	1.0	.8	.9	1.0 (est)
Conductive	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Nominal Pore/Cell Count-No./In.	15	29	3.5	3.1	3.5	3.0	3.4	3.0 (est)
Foil Thickness Mils	N/A	N/A	1.5	2.0	2.0	3.0	3.0	Unknown
Entrained Solid Contamination mg/ ft^3	11.0 Max	11.0 Max	14.0 Max	14.0 Max	14.0 Max	14.0 Max	14.0 Max	Unknown
Estimated Cost, Uninstalled, $/cu. Ft.	12.00-24.00	12.00-24.00	33.00-66.00	33.00-66.00	33.00-66.00	33.00-66.00	33.00-66.00	28.0-75.00

Table 1

Explosion Suppression Material Properties

Note

Variation in uninstalled cost is due to vendor estimate variation and uncertainties as to production quantity and number and configuration of individual blocks.

Type Of Installation	Advantages	Disadvantages
Coarse Pore Foam, Fully Packed	Well proven including transport type aircraft Low overpressure Complete protection	Weight and fuel volume penalties Contamination potential Deterioration potential Maintenance time penalty
Fine Pore Foam, Grossly Voided	Lower weight and fuel volume penalties Complete protection	Higher overpressure Requirement to prevent propagation between bays Foam retention requirement Contamination potential Deterioration potential Maintenance time penalty
Aluminum Mesh, Block Type, Fully Packed	Lower fuel volume penalty Less deterioration potential Complete protection	Not proven in aircraft applications Higher weight penalty More difficult installation and removal Contamination potential Maintenance time penalty
Aluminum Mesh, Ellipsoid Type, Fully Packed	Lower fuel volume penalty Less deterioration potential Complete protection	Not proven in aircraft applications No aircraft application specification or testing Higher weight penalty More difficult installation and removal Contamination potential Maintenance time penalty
Selective Tank Installation	Lower weight, fuel volume, cost, maintenance time penalties	Same as selected material Requirement to prevent propagation to unprotected tanks.
Selective Installation Around Potential Ignition Sources	Much lower weight, fuel volume, cost, maintenance time penalties	Same as selected material Requirement to prevent propagation to unprotected portions of tanks. Difficult to apply to potential ignition sources in other than discrete locations

TABLE 2

Design Alternatives Comparison

2.2 Fully Packed Coarse Pore Reticulated Foam

This alternative consists of installation of reticulated foam with a small amount of voiding so that the foam occupies the majority of the affected tank volume. Current and future design utilizes conductive polyether foam per MIL-F-87260, Class 1, Grade IC or Class 2, Grade IC. These foam grades incorporate improvements to prevent deterioration and electrostatic discharge problems experienced with earlier types of foam, as previously discussed. The difference between Classes is that Class 1 maintains electrical conductivity down to 10 F and Class 2 maintains electrical conductivity down to -20 F. There is currently one qualified manufacturer of the preferred Class 2 foam, however, another manufacturer, qualified for Class 1 foam, is currently undergoing qualification.

The absence of electrical conductivity at these low temperatures is not considered to constitute an ignition source for normally used kerosene type fuels and extensive military experience has shown that ignition of wide cut fuels is not a safety hazard since thousands of ignitions have occurred with no aircraft losses, and no significant aircraft damage except in a few instances of improperly or incompletely installed foam. In many instances, ignition was not detected until the foam was removed and found singed during later maintenance. It may be advisable to prohibit over-wing refueling at low temperatures when using wide cut fuels; however, this situation very rarely occurs and is not considered a significant penalty for transport category aircraft operations.

This alternative has been widely used in all of military transport type aircraft foam installations (C-130 and P-3), many other military aircraft installations, and in certain business jet fuselage tank installations.

The foam is installed in the form of blocks cut into engineering defined shapes. Voids of dimensions recommended in SAE AIR 4170 are located to provide clearance around components such as pumps, valves, fuel quantity probes, flapper valves, plumbing inlets and outlets, etc. Additional voiding up to the limit suitable for the particular application is located in individual blocks and typically consists of 4.0" diameter horizontal holes located so that holes in adjacent blocks do not line up. It is typical for total void volume to not exceed 20%. As can be seen from Figure 6, a 20% void installation with a tank ullage operating pressure of 0.5 psig, which is typical of transport category aircraft, produces a combustion overpressure of 6.0 psig. This is likely to be within the limit pressure capability of most transport aircraft fuel tanks. If necessary, the combustion overpressure could be reduced to 2.5 psig by reducing the void volume to 10%.

Foam blocks are designed to near nominal shape and size, with the specified voids, and become self-supporting by 10-20% swelling when wet with fuel. Retainers or guards are recommended practice only for components with exposed floats, but may also be considered for other components with exposed moving parts, such as flapper valves, and for fuel quantity probes. The number of blocks required is a function of bay size, access opening size, and internal plumbing and structure complexity. A typical practice is to not install foam in sump or pump bay areas where the installation may be difficult and which are always full of fuel down to the fuel level where fuel exhaustion is imminent. Application of this practice to commercial transport aircraft would vary with different fuel system designs. C-130 and P-3 aircraft have tanks, which appear to be of greater complexity than comparable size narrow body airliners. It is beyond the scope of this report to determine design factors for specific aircraft; however, it is estimated that the number of blocks is unlikely to be less than 250 or more than 6,000 over the complete range of transport category aircraft.

Based on the extensive experience and data which show suitability for transport category aircraft, the fully packed reticulated foam system is considered to be the baseline system for purposes of this report, with cost data presented in Section 8.

2.3 Grossly Voided Fine Pore Reticulated Foam

This alternative consists of designs that have a much higher proportion of the fuel tank volume, which is devoid of foam than the baseline fully packed alternative. The intent of this design is to minimize the weight and fuel volume penalties. Current and future design utilizes conductive polyether foam per MIL-F-87260, Class 1 Grade IIC or Class 2, Grade IIC. A typical design would involve tanks divided into bays by spars, bulkheads, and ribs, where the foam is installed at the bay boundaries to prevent explosion propagation from one bay to another. It is necessary to incorporate means to retain the foam in place. Adhesives have been successfully used. Void volumes have been as high as 70%.

Table 1 shows that the density and fuel displacement of fine pore foam is the same as coarse pore foam, while fuel retention is twice as much. It is, therefore, necessary for the void volume to be at least approximately 40% for this alternative to be of benefit. Figure 6 shows a combustion overpressure of 10.7 psig for a void volume of 40% with a tank operating pressure of 0.5 psig. The combustion overpressure rises to 28.2 psig at a 60% void volume where significant benefits are available. The exact amount of overpressure and its extent depends on the expansion characteristics of combustion products and is an application specific function of number of bays, bay size and arrangement, and intercommunication among bays. For this reason, military applications of grossly voided designs have been limited to tanks capable of significant overpressure, such as fighter aircraft wing tanks. The F-15 wing tanks are one example. This design cannot be considered generally suitable for transport category aircraft for this reason, although it may be suitable for some tanks or portions of tanks on some aircraft, if substantiated by tests.

Certification considerations for this alternative are similar to those for fully packed design, discussed in Section 3, with the additional requirements that explosion suppression testing is considered mandatory to determine the amount of overpressure, the ability of the design to prevent propagation between bays, and the ability of the tank structure to withstand the resulting localized overpressure.

A grossly voided reticulated foam design has not been selected as the baseline for transport category aircraft application due to the above considerations, and, therefore, no cost data is presented in Section 8.

2.4 Expanded Aluminum Mesh, Block Form

This alternative consists of a nominally fully packed installation of shaped blocks of expanded aluminum foil mesh. Material is defined by MIL-B-87162, and as shown in Table 1, several different combinations of foil thickness and density are defined. Currently available material has not been qualified to this specification. This generic type of material has been subjected to explosion suppression and material qualification testing, and installation evaluation in several small tanks, as documented in Report AFWAL-TR-80-2043, however there are no known military aircraft applications, including test applications. There may have been a small number of civil and military aircraft applications, either on small experimental aircraft or production aircraft, not in the transport category, approved on an individual aircraft, non-hazard basis.

As shown on Figure 6, overpressure potential is higher than foam under equivalent test conditions. For this reason, explosion suppression testing may be required for at least the first aircraft application.

As shown in Table 1, the aluminum mesh material has a higher weight but lower fuel displacement and retention than foam, with the amount varying depending on the specific type.

Due to the lack of flexibility and compressibility compared to foam, this installation is likely to require a larger number of individual blocks and to be more difficult to handle. Methods to prevent the blocks from shifting and to provide required clearance for components would require development. It is likely that more guards or retainers would be required than for foam.

One item of concern is that effect of long term installation on the integrity of both the mesh material and the protective coatings on the internal tank structure. The mesh material integrity question relates to vibration, sloshing and other mechanical action, since it is less susceptible to material deterioration than foam. MIL-B-87162 addresses this question by requiring slosh tests on both a metal tanks, with the mesh material in contact with representative coating and sealant patches, and on a bladder tank. Report AFWAL-TR-80-2043 addresses these issues in an apparent satisfactory manner except for unresolved questions regarding the tendency of the material to settle and create additional unintended void volume.

Certification for transport category aircraft application would involve considerations similar to those discussed in Section 3 plus expansion to adequately quantify the explosion protection characteristics in relation to the aircraft fuel tank structural capability, and to demonstrate that installation compatibility and continued airworthiness requirements can be satisfied in a consistent manner.

Expanded aluminum mesh in block form in a fully packed installation is considered to be a potentially feasible alternative for transport category aircraft application. Although additional development is required, it is considered sufficiently feasible that cost data is presented in Section 8 for the selective tank installation option (heated center wing tanks) discussed further in Section 2.6.

2.5 Expanded Aluminum Mesh, Ellipsoid Form

This alternative consists of expanded aluminum mesh material similar to that discussed above, except that the material is formed into small ellipsoid or cylindrical shapes, with a maximum dimension of approximately 1-2”. Military aircraft experience is limited to a recent application in an U.S. manufactured helicopter in European service. Little detailed information is available.

Testing has been done to demonstrate explosion suppression capability in applications such as ground vehicle fuel tanks, however the test conditions are not similar enough to provide direct comparison with aircraft application requirements. Weight, fuel displacement, and fuel retention characteristics are estimated to be similar to block form expanded aluminum mesh discussed in Section 2.4.

Installation in tanks with access openings on the top could be done by gravity methods, however, for the more common case of tanks with access openings on the bottom, a method such as blowing in the ellipsoids with forced air would require development. Installation concerns would include requirements for assuring complete filling, especially near the top of the tank, and installation of access covers without escape of the material. Removal of the material for maintenance or inspection would be anticipated to be a problem with either top or bottom openings. Extensive guards to provide component clearance and prevent material entrance into plumbing passages are anticipated to be necessary. Concerns regarding settling of the material are similar to those for block type aluminum mesh material.

Certification for transport category aircraft application would involve considerations similar to those discussed in Section 3 plus expansion to adequately quantify the explosion protection characteristics in relation to the aircraft fuel tank structural capability, and to demonstrate that installation compatibility and continued airworthiness requirements can be satisfied in a consistent manner.

It is unclear whether expanded aluminum mesh in ellipsoid form in a fully packed installation can be considered to be a potentially feasible alternative for transport category aircraft application without further testing and development. It is not selected as the baseline system due to the disadvantages discussed and the lack of aircraft service experience. Cost data is, therefore not presented in Section 8. It is noted, however, that costs would be very similar to the data presented for block type expanded aluminum mesh, subject to satisfactory installation development.

2.6 Selective Tank Explosion Suppression Material Installation

This alternative involves installation of one the alternatives discussed above in only selected tanks instead of all tanks of a particular aircraft model. The considerations, advantages, disadvantages, and certification considerations for the particular type of system would apply in a smaller scale in proportion to the tank volume protected.

One exception that is important for selective tank installation is the possibility of self generated ignition, which could propagate to an unprotected tank. This would apply if the protected tank was interconnected to unprotected tanks in a manner which could propagate an explosion. The most obvious example is tanks interconnected to a common vent surge box, however interconnection through transfer, refuel/defuel, or other systems may require consideration.

The only identified explosion caused by reticulated foam is static electrical charge accumulation and ignition of wide cut fuel at low temperatures where the foam becomes much less conductive. Prohibition of operation with wide cut fuels is considered an acceptable means to address this concern. Another means would be to eliminate any interconnection by which an explosion could propagate. It is uncertain whether other means traditionally used to minimize static charge ignition probability could be substantiated to the necessary high confidence level and extreme improbability of occurrence.

Static electricity charge accumulation is not a consideration with expanded aluminum mesh, however, other ignition modes, such as sparking when the mesh is conducting lightning strike current, would require consideration. This would be a particular concern with composite tanks, which are not widely used in transport category aircraft.

Certification considerations for selective tank explosion suppression material installation in transport category aircraft would involve the considerations applicable to the method chosen, determination of which tanks require explosion suppression, and prevention of explosion propagation to unprotected tanks.

This alternative is considered to be a feasible alternative for transport category aircraft, subject to the considerations discussed, and subject to the requirement to minimize explosion hazards to a required level, as opposed to eliminating them.

2.7 Selective Installation of Foam or Aluminum Foil Around Ignition Sources

This alternative involves installation of explosion suppression material around theoretical potential ignition sources in a manner, which will prevent an ignition at that source from propagating. This involves consideration of the flame arresting characteristics of the material. It should be noted that MIL-F-87260 requires flame arrestor testing of Class IIC fine pore foam at maximum thicknesses of three to five inches, depending on void volume and operating pressure, and that such a requirement is not established for other materials. This is not a critical concern since the flame arresting capability would also be installation dependent and would require testing for any material.

This alternative is most applicable to discrete theoretical potential ignition sources, such as fuel quantity probes, electrical motors and other electrical components within the tanks. Application to more widely spread theoretical potential ignition sources such as wires, potential points of static charge accumulation, or ignition sources external to the tanks, is more difficult, and sources such as these may be more appropriately addressed by other ignition prevention means which are outside the defined scope of this report.

Explosion suppression material installation may take two possible forms, depending on the size and configuration of the fuel systems involved:

The first, which is most applicable to smaller systems or smaller tank bays, would consist of installation in the entire bay where the potential ignition source is located. It would be necessary to assure propagation to adjacent bays is prevented especially where the potential ignition source is located adjacent to a bay boundary with openings.

The second method consists of localized explosion suppression material installation around the ignition source. It would be necessary to suitably retain and restrain the material, and prevent explosion propagation through any joints in the material and at interface boundaries between the material and tank structure or other components.

Means to prevent self induced ignition and explosion propagation in the unprotected portions of the tank, as previously discussed in Section 2.6, are required. Considerations are much the same as discussed in Section 2.6. It is noted that this alternative may have less susceptibility to static charge accumulation in reticulated foam, or lightning strike current in expanded mesh, due to limited amount and specific configuration of the material.

Certification considerations for selective explosion suppression material installation around theoretically potential ignition sources in transport category aircraft would involve the considerations applicable to the material chosen, determination of which ignition sources require explosion suppression, and demonstration of no explosion propagation, either self induced or from the ignition source.

This alternative is considered to be a feasible alternative for transport category aircraft, subject to the considerations discussed, and subject to the requirement to minimize explosion hazards to a required level, as opposed to eliminating them. It is not selected as the baseline alternative, since compliance with the FTHWG Terms of Reference is not entirely clear.

3.0 FAA Certification Requirements

3.1 General

This section discusses FAA certification requirements, which are recommended for the baseline fully packed reticulated foam installation alternative. Other alternatives may include additional certification requirements discussed in Sections 2.2 through 2.7, including demonstration of explosion protection effectiveness, showing absence of self induced ignition hazards, and aircraft

3.2 Similarity and Previous Test or Flight Experience

Explosion suppression testing is not considered to be necessary based on foam qualification testing and extensive military experience. Analysis would determine the void fraction and overpressure from available test data, which would then be compared to allowable tank limit pressure based on existing certification data. Other factors discussed below, such as effects on refueling or fuel flow and pressure delivery, may be acceptable on the basis of similarity for additional models with similar fuel systems and foam installations, after testing on the first model has shown expected minimal effects.

3.3 Additional Analysis and Testing

The following additional analysis and testing is recommended as part of FAA certification:

Flight testing followed by ground inspection is recommended to verify adequacy of the design to properly retain the foam blocks, and to verify adequacy of recommended flushing procedures and contamination inspections.

Usable fuel volume and calibration of fuel quantity indicating systems will be affected by the foam installation and will need to be substantiated during certification. A wet fuel quantity indicating system calibration is acceptable, but not necessarily required, unless otherwise required for the specific type of aircraft and system. Alternative methods would include determination of the reduction in usable fuel either by ground test, or by using the conservative specification or qualification test values, followed by modification of the fuel quantity indication system to incorporate the required scaling factor, and verification of this scaling factor by bench test.

Ground tests for satisfactory refueling, including tank pressure during maximum rate refueling, and for fuel flow and pressure delivery to the engine, and for other operations such as transfer, would be required unless similarity data is available from previous certifications.

Operational documentation requirements for certification include modifications to the Approved Flight Manual, Weight and Balance Manual, Maintenance Manual, Illustrated Parts Manual and other similar documents.

4.0 Safety

4.1 Effectiveness in Preventing Overpressure Hazard

There is extensive military test and operational experience, including thousands of electrostatic self induced ignitions, that indicates that a properly installed fully packed reticulated foam installation is 100% effective in preventing overpressure hazards resulting from any internal or external ignition source. Complete prevention of all hazards when tank structural integrity is breached by mechanism external to the tank cannot be assured due to fire hazards and structural effects of the breach of tank integrity.

4.2 Effects of Range Reduction and Additional Flights

Range would be reduced by up to 5% on flights with full or near full tanks due to the reduced fuel tank capacity. Range would be reduced by the same amount on flights with less than full tanks in cases where weight limitations would not allow sufficient additional fuel to be carried to compensate for foam and retained unusable fuel weight. Range would be reduced by 0-5% on flights where the aircraft is near, but not at the fuel capacity or weight limit. Range reduction due to increased weight on other flights is not a factor, since sufficient additional fuel could be carried to compensate for the increased fuel burn.

If it is assumed that all flights carry no more than the fuel required by the applicable operating regulations, there would be no safety impact due to range reduction. Validation of this assumption is beyond the scope of this report. It is noted, however, that there could be a reduction in the capability to carry more fuel, at the discretion of the operator or flight crew, than the amount required.

It is considered reasonable and conservative to estimate a 1% increase in departures due to the fuel penalty when limited by tank capacity or weight. Applying the 1987 to 1996 overall worldwide hull loss rate of 1.60 per million departures documented in the same industry response, this results in a rate of .016 losses per million departures due to additional departures. It is noted that these statistics involve FAR 121 type operations, however, it is considered reasonable to conclude that they are also representative of operations involving transport category regional airlines and business aircraft.

4.3 Effects of Weight Increase

The weight increase for a flight with full tanks is insignificant due to the foam weight being compensated for by reduced fuel capacity due to displaced fuel. The weight increase for flights with less than full tanks is 5% of the total fuel capacity weight, assuming sufficient fuel is carried for equal range. If the flight is weight limited, there is a potential safety hazard associated with human error resulting in exceeding weight limits. If the flight is not weight limited, the increased weight will still reduce aircraft runway and climb performance and therefore, represents some level of hazard in the event of human error or combination of adverse conditions, such as wind shear, where a small difference in performance could have a decisive impact on the outcome. These effects are not considered quantifiable and would present very low hazards considering normal certification and operational practices. The historical record does not support an assessment of the hazards of such a small performance decrement due to a weight difference equal to 5% of fuel capacity or approximately 1.5-2.5% of maximum takeoff weight.

4.4 Personnel Hazards

The primary personnel hazard associated with a fully packed reticulated foam installation are those associated with maintenance personnel contact with fuel wetted foam and fire protection issues associated with fuel wetted foam during maintenance activities, either during tank entry or when the foam is removed for maintenance. It is noted that fuel wetting of the foam is reduced significantly by extended drainage and tank ventilation time periods prior to tank entry. It is considered that these hazards can be sufficiently mitigated by expansion of existing maintenance precautions associated with these hazards, and that human error or failure to follow procedures is possible but no more hazardous than existing aircraft, especially when considering the potential reduction in fuel tank explosion hazard vulnerability during maintenance. The time and difficulty associated with tank ventilation with foam installed tends to mandate the use of respirators by in-tank maintenance personnel. As discussed in Section 2.2, there is a theoretical personnel hazard associated with over wing refueling using wide-cut fuels at extremely low temperatures, which could be prevented by prohibiting this operation.

5.0 Aircraft Hazards or Effects

5.1 General

This section will address potential theoretical hazards associated with reticulated foam. Some of these are not actual hazards, but the discussion is included due to questions typically raised. These discussions apply to the baseline fully packed reticulated foam installation in all tanks. Other potential hazards associated with other design alternatives are discussed in Section 2, and generally would require resolution during FAA certification.

5.2 Electrostatic Charge Hazards

As discussed in detail in Section 2.2, MIL-B-87162 reticulated foam becomes non-conductive and a potential ignition source for volatile wide cut fuels at extremely low temperatures. Military experience with previous non-conductive foams has included thousands of such incidents with no aircraft losses, and aircraft damage limited to several isolated cases of improper foam installation. This experience, combined with very infrequent use of wide cut fuels, is sufficient to assess that no hazard potential exists for fully packed installations of all tanks. Other design alternatives would require additional hazard assessment as part of certification, as discussed in Section 3.

5.3 Aircondition Pack Bay Temperature and Structure Degradation

All of the foam applications in this report evolve around center wing tanks with adjacent heat source. The heat source in this discussion is the air-condition pack located underneath the center wing.3

In normal operation the center wing structure acts as a heat sink to dissipate the heat rejected by the air-condition pack. This heat transfer causes the fuel inside the fuel tank to heat up and increases the flammability of the fuel vapor. Although foam installed inside the fuel tank would not act as an insulator to prevent external heat transfer, and is not expected to significantly affect natural convection internal heat transfer due to its open cell construction, a significant reduction in heat transfer could cause some adverse effects such as:

The pack bay temperature will raise and could trip the over heat detection system. This will cause nuisance alerts and or dispatch delays.

The elevated temperature in some aircraft pack bay could reach over 200 F and this will degrade the strength of the surrounding structure, which is made of mostly Aluminum.

To minimize this potential thermal problem the pack bay temperature must be carefully analyzed, tested with the foam installed. And in some case some source of pack bay ventilation will be required to reduce the pack bay temperature to an acceptable level. The cost estimate in this report does not include pack bay ventilation scheme.

5.4 Fuel Contamination and Foam Deterioration

Research into military and very limited civil, experience with reticulated foam has established three potential mechanisms by which fuel contamination may become a safety issue. These are:

Fabrication or installation debris resulting from the initial installation or replacement.

Contamination introduced during in-tank maintenance or foam removal and reinstallation.

Contamination due to foam deterioration caused by age and environmental exposure.

Military experience has shown no widespread problems with these types of contamination. Several sources indicate an absence of problems since polyether foam was introduced in the mid 1970's, however, there is evidence, not well quantified, of occasional occurrences of foam deterioration and a limited number, on the order of one or two, of incidents of engine flameout attributed to fuel contamination. Favorable experience has included foam installed in aircraft without deterioration since the introduction of second generation polyether foam in the mid 1970's, satisfactory completion of laboratory tests on foam which has been installed for extended periods, and environmental tests required for qualification under extremes of temperature and humidity. It is reported that contamination symptoms involving a small proportion of foam combined with a large proportion of other materials are typically, somewhat incorrectly, attributed to foam. Fuel contamination related to foam could occur in several ways:

Contamination can be caused by fabrication residue following initial installation or replacement. Procedures to prevent or minimize this include mechanical agitation of the foam blocks after they are cut to remove residue, multiple fuel system flushing operations combined with fuel cleanliness checks, and more frequent fuel filter inspections during the initial operation period following installation. It is noted that there are variations in flushing procedures among different military units and that those units experiencing the most problems were using the least thorough procedures.

Contamination can be caused by failure to protect the foam from external contamination, either when it is not installed in the aircraft or during in-tank maintenance. It is absolutely essential that the foam be protected from contamination during storage and handling. There is evidence that clothing other than 100% cotton clothing is preferable for in tank maintenance. Cotton clothing rubbing against foam tends to generate contamination from both, but primarily from the clothing. The flushing procedures discussed above are also pertinent. It is typical practice that replacement of more than 25% of the foam in the tank requires flushing.

Contamination can be caused by foam deterioration. The ultimate life and distribution of useful life of modern polyether foam is not known with certainty. Unfavorable factors include high heat and humidity, including heat associated with any heat exchangers in the fuel tank. Available information indicates that continuous exposure to temperatures up to 150 F and intermittent exposure to temperatures up to 240 F does not cause deterioration. Available information indicates that these temperatures would not be exceeded in center wing tanks with adjacent heat sources. It is noted that information necessary to quantify long term cumulative heat exposure versus deterioration effects is not available. Contamination is typically first detected either by particles in fuel filters or during physical inspection inside the tanks. As previously noted, military experience has not shown significant deterioration problems, and there has not been established a required replacement interval. Limited experience in business jets with foam in fuselage tanks has shown that one model has a required replacement interval of eight years and that a different model from a different manufacturer has no replacement interval and no reported problems. The model with the required replacement interval has shown no overt symptoms of contamination, such as flameouts or particles in drained fuel or fuel filters or filter bypass indications. The interval was established by fleet sampling for items such as foam discoloration and loss of mechanical properties, both of which are normal tendencies of fuel soaked foam, thus raising the possibility the required replacement is unnecessarily conservative. It is pertinent to note that the model involved represents a small fleet (32 aircraft) which may limit the usefulness of this service experience.

Military aircraft experience most relevant to transport category aircraft is the experience with C-130 and P-3 aircraft. Of these aircraft, the amount of experience on the C-130 is far more extensive. AGARD Report No. 771 states that C-130 experience includes 54 production installations from 1968 to 1970, 85 production installations since 1983, and about 500 retrofit installations. Although exact details are not available, it is possible to estimate C-130 fleet experience with foam installed to be on the order of 10^6 to 10^7 flight hours. This experience has included no known accidents, including single or multiple engine shutdowns, caused by foam related contamination. There is one known P-3 single engine shutdown associated with early foam contamination and less rigorous flushing procedures by the unit involved. This experience is sufficient to conclude that foam related engine shutdowns occur at a much lower rate than shutdowns due to other causes, and that foam related contamination is not a common cause event for multiple engine shutdowns when considering the mitigating factors discussed below.

It is concluded that the potential hazards associated with foam related contamination and deterioration can be sufficiently mitigated by careful adherence to cleanliness and flushing procedures, verification of cleanliness and flushing procedure effectiveness during certification, and careful inspection of foam condition at major periodic inspections. As additional civil service history is obtained, it may be possible to justify less extensive procedures. It is possible that it may be advisable, from an economic risk standpoint, to replace the foam in a major portion of a fleet during scheduled major maintenance near the ten year time frame, while a smaller portion would continue operation to demonstrate continued durability.

5.5 Effects on Other Fuel System Components

Military experience has shown only one adverse effect other than the occasional contamination problems discussed above, which mainly affect fuel filters and engine fuel heat exchanges. This effect is erratic fuel quantity indications when improperly installed foam causes the conductive foam to contact fuel capacitance probes. This is mainly a problem with traditional low level alternating current capacitance systems in which the outer probe element forms part of the circuit, and which typically use exposed probe terminals. Some newer systems, which do not have these features, are less likely to be affected. It may be advisable for the design of potentially affected systems to include retainers to insure positive clearance around fuel quantity probes. This would not only mitigate any safety hazards associated with this condition, but it would also eliminate the economic penalty associated with repairing the condition.

5.6 Corrosion, Water Retention, and Biological Contamination

Concerns are sometimes expressed with regard to the corrosion potential associated with foam. These concerns include the foam itself rubbing against the tank structure and protective finish, water retained by the foam, and biological growth in the water retained by the foam. Extensive military and limited civil experience has not shown these to be problems, except for one limited use non-qualified type of foam which was treated for conductivity improvement following manufacture, and which did cause corrosion problems. It is important to note that foam does not hold water or fuel like a sponge, and that there is essentially no known difference in the ability of water in foam to drain compared to water suspended in fuel. It is further noted that the primary means to protect against corrosion does not change with the installation of foam and includes such items as maintaining the integrity of corrosion protective finishes and adherence to good housekeeping procedures. Based on this experience, it is concluded that corrosion potential with foam installed does not exceed that currently experienced and that the installation of foam does not represent an additional safety hazard.

One further issue is whether foam will increase the amount of water condensation in the tanks due to the greater surface area exposed to moist air in the ullage. This phenomenon is most severe when an aircraft cold soaked at altitude descends into warm moist air, which is drawn in to the tank and comes into contact with cold interior surfaces. The presence of foam will not change the amount of moisture subject to condensation or the much larger heat capacity of structure and fuel compared to air in the ullage. It may, however, change the rate of condensation, and, therefore, the amount condensed in the time prior to refueling or natural warming of the structure and fuel. It is readily observable that cold soaked structure not in direct contact with fuel warms to ambient temperature much more rapidly than structure in contact with fuel. This reduces condensation potential and would occur with foam in the ullage space due to the limited thermal capacity and thermal conductivity of foam. A severe, but not extreme, case of air at 100 F and 100% relative humidity contacting tank interior surfaces at 0 F results in condensation of approximately .05 pound of water per pound of dry air if 100% condensation occurs. If the tank is 10% full of fuel, this results in a volumetric water concentration of .055% water in the fuel, compared to the sump capacity of .10% of entire tank volume required by FAR 25.971. This water concentration is higher than the .02% free water specified for fuel icing by FAR 25.951 but would be reduced to within this limit by refueling or removal of the water through sump drains. It is, therefore, concluded that any additional water condensation does not constitute a safety hazard, however, additional research would be required if it were necessary to determine the rate and exact amount of such condensation.

5.7 Other Equipment Hazards or Effects

This type of hazard is related to the fire hazards to ground equipment and facilities associated with handling and storage of fuel wetted foam when it is removed from the aircraft. It has been previously discussed, and is sufficiently mitigated by use of designated storage equipment and facilities and use of standard fire protection procedures.

7.0 Overall Safety Assessments

Based on the historical record, foam was assessed as effective in four operational overpressure events and of unknown effectiveness in four operational overpressure events also involving breach of tank integrity and external fire. Negative effects over this time period would include potential for five additional accidents due to increased flights based on the .016/million departure rate and the 317 million departures for the airline transport fleet. Factors, which could improve the overall foam safety effectiveness, include the possibility that foam would be effective in some or all of the unknown events. Factors which could degrade the overall foam safety effectiveness would include the possibility of events caused by those negative factors previously discussed, which were assessed as very low-non-quantifiable hazards that could be sufficiently mitigated, or the possibility that reduced range would, in fact, have negative safety effect.

The above overall safety assessment applies primarily to airline transport aircraft, of approximately 100 seats or more in size, in primarily Part 121 operations. An overall assessment based on the historical record for regional airline aircraft and business jets would be entirely negative due to the absence of any historical overpressure events. It is acknowledged that these aircraft have had less fleet operating time exposure, by perhaps an order of magnitude. If it were assumed that an overpressure event were to occur in the near future, the overall safety assessment for aircraft losses would be similar to that for airline transport aircraft, although fatalities to the traveling public would be lower for regional aircraft and much lower for business jet aircraft. It is also possible, however, that the absence of overpressure events may be due to other design and operational factors beyond the scope of this report. It is, therefore, not possible to conclude that foam installation would produce positive effects for regional transport and business jet aircraft. It is noted, however, that these aircraft may have reduced susceptibility to any potential hazards associated with reduced range, due to the greater tendency to fly multiple flight legs without refueling, for operational and economic reasons, and the resulting greater fuel reserves on many flight legs.

8.0 Cost Analysis

The two types of material, which evaluated for cost, in this report are: Foam with 100% filled and Expanded Metal Products. Both are installed on aircraft center wing tank with adjacent heat source. Two classes of aircraft are considered in this cost for the 2 types of material. The first one is retrofit cost for aircraft that are in service and the second is for new and or production aircraft.

The cost is broken down into nonrecurring and recurring cost.

Nonrecurring Cost

The nonrecurring cost is made up of:

Engineering

Tooling and Planning

Test and certification

Operation and Customer Support

Material (Foam requires replacement each 15 year period)

Cost of disposal of material

Infrastructure is the storage facility required to store foam or expanded metal during maintenance.

Recurring Costs

The recurring cost is made up of:

Fuel burn cost to carry the added weight

Additional maintenance cost

Loss of revenue when aircraft operate at maximum weight limit and or fuel capacity.

The next four tables provide a complete cost structure for the 2 types of material used on the two classes of aircraft

Foamfor Inservice Aircraft			
One time cost	Large	Medium	Small
Development	$10,546	$5,536	$3,430
Installation	$345,147	$154,559	$57,234
Infrastructure	$35,047	$27,332	$3,497
Total Per Aircraft	$390,740	$187,427	$64,191
Total Effected Aircraft	$501,710,160	$205,607,419	$394,525,989
Total Industry Cost	**$1,101,843,568**		
Annual Recurring			
Foam Replacement	$23,239	$10,395	$3,843
Additional Fuel Burn	$66,453	$22,216	$7,202
Loss of Revenue	$1,455,773	$596,726	$99,739
Additional Maintenance	$38,656	$24,160	$9,664
Total per Aircraft	$1,584,121	$653,497	$120,448
Total effected Aircraft	$2,034,011,364	$716,886,209	$740,634,752
Total Industry Cost	**$3,491,532,325**		

Foamfor Production Aircraft			
One time cost	Large	Medium	Small
Development	$8,210	$4,169	$2,536
Installation	$310,627	$134,833	$48,603
Infrastructure	$35,047	$27,332	$3,497
Total Per Aircraft	$353,884	$166,334	$54,636
Annual Recurring			
Foam Replacement	$23,239	$10,395	$3,843
Additional Fuel Burn	$66,453	$22,216	$7,202
Loss of Revenue	$1,455,773	$596,726	$99,739
Additional Maintenance	$38,656	$24,160	$9,664
Total per Aircraft	$1,584,121	$653,497	$120,448

Expanded Metal Products for Inservice Aircraft			
One time cost	Large	Medium	Small
Development	$11,581	$6,186	$3,869
Installation	$801,645	$332,539	$105,239
Infrastructure	$35,047	$27,332	$3,497
Total Per Aircraft	$848,273	$366,057	$112,605
Total Effected Aircraft	$1,089,182,532	$401,564,529	$692,408,145
Total Industry Cost	**$2,183,155,206**		
Annual Recurring			
Additional Fuel Burn	$72,917	$24,377	$7,899
Loss of Revenue	$1,217,444	$490,414	$71,429
Additional Maintenance	$38,656	$24,160	$9,664
Total per Aircraft	$1,329,017	$538,951	$88,992
Total effected Aircraft	$1,706,457,828	$591,229,247	$547,211,808
Total Industry Cost	**$2,844,898,883**		

Expanded Metal Products for Production Aircraft			
One time cost	Large	Medium	Small
Development	$9,245	$4,819	$2,975
Installation	$767,124	$312,813	$96,609
Infrastructure	$35,047	$27,332	$3,497
Total Per Aircraft	$811,416	$344,964	$103,081
Annual Recurring			
Additional Fuel Burn	$72,917	$24,377	$7,899
Loss of Revenue	$1,217,444	$490,414	$71,429
Additional Maintenance	$38,656	$24,160	$9,664
Total per Aircraft	$1,329,017	$538,951	$88,992

8.1 Assumptions

Foam requires replacement every 15 years.

Cost to destroy foam is the same as cost to destroy jet fuel at 79 cents /lb.

2 days for down time is estimated for installation. Cost is estimated as the cost of money for this period.

1 day added to production span time for installation of foam on production aircraft - Cost is estimated as the cost of money for this period.

Development cost per aircraft is the development cost per model multiplied by the number of models, and divided by the number of aircraft with heated center wing tanks.

Aluminum mesh and foam costs provided by vendors (aluminum mesh costs approximate same as foam)

Fuel cost is 62 cents per gallon.

Annual fuel burn cost is computed using the cost estimator spreadsheet provided by Task Group 8.

Loss of revenue is computed using the cost estimator spreadsheet provided by Task Group 8.

Interest rate is 7%

Loss of revenue is calculated using long mission flights. The assumption is 50% of flights are weight limited and 50% are fuel limited.

Cost information in this report is only for aircraft with center wing tank with adjacent heat source.

Storage facility cost is estimated at $150,000, $100,000 and $75,000 for large, medium and small aircraft respectively.

There are 100, 100 and 150 maintenance bases for large, medium and small aircraft respectively.

Three storage facilities are required at each base.

END