AEROSPACE INFORMATION REPORT

AIR1903™ REV. A

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Superseding AIR1903

(R) Overview and History of Aircraft Inerting Systems

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RATIONALE

The document is being revised to update the document and to prevent duplication with ARP6078. The document updates include changing the title, the scope, and the rationale of the document.

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1. SCOPE

An airplane fuel tank inerting system provides an inert atmosphere in a fuel tank to minimize explosive ignition of fuel vapor.

This SAE Aerospace Information Report (AIR) deals with the three methods of fuel tank inerting systems currently used in operational aircraft: (1) on-board inert gas generation systems (OBIGGS), (2) liquid/gaseous nitrogen systems, and (3) halon systems. The OBIGGS and nitrogen systems generally are designed to provide full-time fuel tank fire protection; the halon systems generally are designed to provide only on-demand or combat-specific protection.

This document also addresses other design considerations that affect fuel tank flammability such as fuel tank pressure and other methods for reducing fuel tank flammability.

This AIR does not treat the subject of explosion suppression foam (ESF) that has been used for fuel tank explosion protection on some military aircraft. ESF is also available for retrofit for commercial airplanes. The primary disadvantages of foam are weight, reduction of usable fuel, and the added maintenance complexity when the foam must be removed for tank maintenance or inspection. AIR4170 is an excellent reference for the use of ESF for fuel tank explosion protection.

Note that across the military and commercial aviation industry, different terminology has been used regarding fuel tank inerting. In military applications, the system is referred to as on-board inert gas generation system (OBIGGS). Regulatory agencies use the term flammability reduction means (FRM). OEMs in commercial applications use several terms: fuel tank inerting system (FTIS), flammability reduction system (FRS), inert gas system (IGS) and nitrogen generation system (NGS).

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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 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 examption has been obtained.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

AIR4170 Reticulated Polyurethane Foam Explosion Suppression Material for Fuel Systems and Dry Bays

ARP6078 Aircraft Fuel Tank Inerting Systems

2.1.2 EASA Publications

Available from European Union Aviation Safety Agency, Konrad-Adenauer-Ufer 3, D-50668 Cologne, Germany (for visitors and for mail over 1 kg) and Postfach 10 12 53, D-50452 Cologne, Germany (for mail 1 kg or less); Tel: +49 221 8999 000, www.easa.europa.eu.

CS-25 Certification Specifications for Large Aeroplanes

2.1.3 FAA Publications

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

14 CFR Part 25 Airworthiness Standards: Transport Category Airplanes

AC 25.981-2A Advisory Circular, Fuel Tank Flammability

2.1.4 U.S. Government Publications

Anderson, C.L. “Test and Evaluation of Halon 1301 and Nitrogen Inerting Against 23 mm HEI Projectiles,” Technical Report AFFDL-TR-78-66; 1978

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Mowrer, D.W., Bernier, R.G,; Enoch, W., Lake, R.E., and Vikestad, W.S. “Aircraft Fuel System Fire and Explosion Suppression Design Guide,” USAAVSCOM TR 89-D-16; JTCG/AS 89-T-005; 1990

Notice of Proposed Rule Making; Reduction of Fuel Tank Flammability in Transport Category Airplanes; Docket Number FAA-2005-22997

Special Federal Aviation Regulation 88; Transport Airplane Fuel Tank System Design Review, Flammability Reduction, and Maintenance and Inspection Requirements; 2001

Stewart, P.B. and Starkman, E.S. “Inerting Conditions for Aircraft Fuel Tanks,” WADC Technical Report 55-418; 1955

Summer, S.M. “Limiting Oxygen Concentration Required to Inert Jet Fuel Vapors Existing at Reduced Fuel Tank Pressures - Final Phase,” DOT/FAA/AR-04/8; 2004

Tyson, J.H. and Barnes, J.F. “The Effectiveness of Ullage Nitrogen-Inerting Systems Against 30-mm High-Explosive Incendiary Projectiles,” Report JTCG/AS-90-T-004; 1991

2.2 List of Terms and Abbreviations

AIR Aerospace Information Report

API Armor Piercing Incendiary

ARAC Aviation Rulemaking Advisory Committee

ASM Air Separation Module

ESF Explosion Suppression Foam

FAA Federal Aviation Administration

FAR Federal Aviation Regulation

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FTHWG	Fuel Tank Harmonization Working Group
FTIHWG	Fuel Tank Inerting Harmonization Working Group
FTIS	Fuel Tank Inerting System
FRM	Flammability Reduction Means
FRS	Flammability Reduction System
HEI	High Energy Incendiary
IGS	Inert Gas System
JTCG/AS	Joint Technical Coordinating Group on Aircraft Survivability
LFL	Lower Flammability Limit
NGS	Nitrogen Generation System
NEA	Nitrogen-Enriched Air
NPRM	Notice of Proposed Rule Making
OBIGGS	On-Board Inert Gas Generation System
OEA	Oxygen-Enriched Air
OSHA	Occupational Safety and Health Administration
PM	Permeable Membrane Air Separation Technique
PPM	Pounds per Minute
PSA	Pressure-Swing Adsorption process
SFAR	Special Federal Aviation Regulation
Squib	Electric Explosive Device
UFL	Upper Flammability Limit
U.S.	United States
USAAVSCOM	United States Army Aviation Systems Command
Ullage	Vapor Space

3. BACKGROUND

An aircraft fuel tank inerting system provides an inert atmosphere in the ullage space of a fuel tank to prevent a fire and resulting explosion from propagating throughout the ullage. The ullage is the space above the liquid fuel in the tank and generally consists of a mixture of atmospheric air and a small quantity of fuel vapor. Although rare, an ullage fire occurs when oxygen from the atmospheric air and fuel vapor burn inside the fuel tank. Ullage fires are highly undesirable because they can lead to a pressure rise inside the tank that cannot be discharged through the fuel tank vent quickly enough to prevent a large-scale failure of the fuel tank structure and the airframe in which it is contained or to which it is attached.

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In general, a fire can occur when the three sides of the so-called “fire triangle” are present in the necessary ranges at the same time. The three sides of the fire triangle are fuel, oxidizer, and a heat source. In the case of an ullage fire, the three sides of the fire triangle are represented as follows:

- **Fuel**: Jet fuel vapor which has volatilized from the liquid fuel.
- **Oxidizer**: Atmospheric oxygen that is present in the ullage space.
- **Heat source**: The initial heat source can originate inside the fuel tank, such as from a shorted electrical wire, or outside the fuel tank, such as from an incendiary projectile that penetrates the fuel tank. In either case, the flame front initiated by either of these sources serves as the heat source necessary to sustain the fire as it moves through the ullage.

The mechanics of ullage fires are presented in NIST Special Publication 1069 chapter 2. In addition, the document contains thorough coverage of aircraft fuel tank safety, especially the history of aircraft fuel tank protection systems.

A fuel tank inerting system serves to neutralize the oxidizer side of the fire triangle by reducing the oxygen present in the ullage to a level below which a fire can be sustained. Fuel tank inerting is the process of introducing a sufficient quantity of inert gas into the ullage to displace a portion of the gas present and thereby dilute the oxygen concentration of the resulting mixture to a safe level.

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4. INERT AND FLAMMABILITY LIMITS

4.1 Inerting Limits

The inert limit (also called the limiting oxygen concentration (LOC)) is the volumetric oxygen concentration (percent of oxygen in ullage gas by volume) below which there is not enough oxygen present in a fuel-air mixture to sustain combustion. The earliest tests to determine the inert limit used visible light as the criterion for determining whether a combustion reaction had taken place. More recent testing, including that done by the FAA, has used pressure rise as the criterion for defining whether a hazardous combustion reaction occurred. The lower and upper flammability limits are the fuel vapor concentrations below and above which the mixture is too lean or too rich to support combustion.

The inert limit for an inerting or flammability reduction system is specified by the military customer or the regulatory agency (e.g., FAA). Different tests to verify the inert limit have been performed over the years with fairly consistent results (refer to WADC Technical Report 55-418, JTCG/AS-90-T-004, AFFDL-TR-78-66, and DOT/FAA/AR-04/8). The military inert limit is more stringent (lower oxygen limit) than the one used in commercial aviation due to the difference in design practices and safety factors accounted for in addition to the condition of the energy considered in the context of fuel tank explosion. The ignition energy threat for military applications considers a range of ignition sources, including the high-explosive incendiary projectiles (HEI), which presents much higher energy than ignition sources typical in commercial applications.

The higher the ignition source energy, the lower the oxygen concentration needs to be in order to prevent the reaction until the oxygen concentration would not support combustion. The tests also show that the inert limit increases at altitudes above sea level. At altitude the atmospheric pressure is lower compared to sea level. Assuming ideal gas law, volumetric fraction (volumetric concentration) of oxygen in air corresponds to the ratio of partial pressure of oxygen to total pressure, and it is equal to the mole fraction. Consequently, for a given volume, the same oxygen percent corresponds to lower partial pressure and lower number of molecules at altitude than at sea level.

4.1.1 Nitrogen Inerting

While the inert limit test results are consistent, different customers have applied different safety factors in the top-level system requirements for different aircraft platforms. The U.S. Navy has applied a 9% oxygen concentration by volume inert limit at all altitudes. The U.S. Air Force has specified different inert limits for different applications; including 9%, 12% on ground, and the oxygen concentration versus altitude curve for nitrogen inerting from the WADC Technical Report 55-418 that defines the inert limit as 9.8% at sea level increasing to 11.5% at 40000 feet. The FAA defines the inert limit as 12% at sea level increasing linearly to 14.5% at 40000 feet (refer to DOT/FAA/AR-04/8).

A ballistic penetration can, in theory, increase the flammability of an ullage by creating a fuel spray (refer to WADC Technical Report 55-418 and Technical Report AFAPL-TR-73-76); however, the test data in WADC Technical Report 55-418 show that there is no difference in the inert limit for the ballistic penetration of a fuel tank compared to a sufficiently large, internally generated ignition source (where the magnitude of ignition energy is a key point). A ballistic penetration of a full fuel tank can cause significant pressure rise and accompanying structural damage due to hydrodynamic ram (refer to DOT/FAA/AR-96/95), even when the tank is inert. This structural damage can occur if the projectile penetrates the portion of the tank below the fuel level and does not cause an explosion because the fuel-air mixture is too rich. If there is insufficient ullage volume to absorb the shock created in the incompressible liquid, the resulting hydrodynamic shock can cause damage. This scenario needs to be accounted for in the design of fuel tank system independently of inerting considerations.

The difference between military and commercial fuel tank inerting system is not only in the ignition energy threat, but also overall mission and service requirements. Compared to commercial applications, military systems have more stringent inert limit (need to reduce oxygen to lower concentration) requirements, possibly different dispatch requirements, and more stringent flight profiles. Military inerting systems are typically sized to keep the oxygen concentrations below the inert limit throughout an entire mission and do not take into system sizing whether the fuel tank is inherently flammable or not. Therefore, they are designed to eliminate fuel tank flammability exposure for every flight.

The commercial systems, on the other hand, are designed to reduce flammability exposure averaged over the entire fleet. The CFR (and CS) 25.981(b), which is a requirement that drives commercial inerting application, is a requirement for flammability reduction means (FRM) intended as a safety enhancement system that is in addition to and separate from the 25.981(a) ignition protection. Commercial systems reduce flammability exposure over the entire fleet using statistical analysis that accounts for whether the fuel tank is inherently flammable (using fuel tank temperature and comparison with lower and upper flammability limits defined as a function of fuel flash point and altitude), as well as whether the fuel tank oxygen content is below the inert limit. In addition, the commercial aircraft can be dispatched without FRM (inoperative system with MEL duration for maintenance).

4.1.2 Halon Inerting

Halon—for example, Halon 1301 or 1211—affects combustion by displacing oxygen, but also interferes chemically with the combustion reaction. This interference results from halon reacting with the transient combustion products (free radicals) that are necessary for rapid and violent flame propagation. Note that use of halon is being phased out due to its ozone depletion and global warming potentials.

Higher energy ignition sources require higher concentrations of halon to prevent explosion. A 6% by volume concentration of halon is sufficient to protect a tank against explosion from an internally generated spark; a 9% concentration is required to protect against 0.50 caliber armor piercing incendiary (API) threats; and a 20% concentration is required to protect against 23 mm high energy incendiary (HEI) threats (refer to USAAVSCOM TR 89-D-16).

4.2 History of Inerting System Design

The earliest inerting systems were devised to protect military airplanes. Inerting (or other means of fuel tank protection) for commercial airplanes began to be considered in the late 1990s following the loss of Trans World Airlines Flight 800, which was caused by a center fuel tank explosion.

4.2.1 Military Applications

This section provides an overview of fuel tank inerting used in prior military applications. For more detail, refer to “The Evolution of On-Board Inert Gas Generation Systems (OBIGGS),” SAFE Journal; Vol. 20, No. 1; 1990.

Following World War II, there were several proposed designs that used engine exhaust, separate combustion devices, and dry ice to produce inert gasses. Other proposed systems used reactors through which the ullage gasses were passed to remove oxygen. None of these systems were ever operationally deployed.

The B-57, F-86, and F-100 airplane designs used stored gaseous nitrogen systems to provide several minutes of inerting. These systems required servicing and did not have the capacity to keep the tanks inert during descent.

The A-6 and F-16 airplanes use stored halon to provide on-demand inerting similar to the stored nitrogen systems on the B-57, F-86, and F-100.

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The XB-70, SR-71, and the C-5 airplanes use stored liquid nitrogen systems that can keep the fuel tanks inert continuously throughout the flight. The logistics and maintenance effort required to regularly service the liquid nitrogen are the main disadvantages to this approach.

The CH-53 and AH-64 helicopters and the V-22 airplane were fielded with pressure-swing adsorption (PSA) on-board inert gas generation systems (OBIGGS). These systems generate a continuous supply of nitrogen-enriched air (NEA) to the fuel tanks.

The C-17 was originally designed with a PSA OBIGGS that generated more inert gas than needed during cruise and stored the surplus at high-pressure for descent. The system used a compressor and an array of high pressure storage bottles. The system was complex and the compressor presented reliability issues. So, a next generation of OBIGGS was designed and implemented to replace the PSA system with a continuous flow permeable membrane (PM) OBIGGS sized for the complete flight profile thus obviating the need for inert gas storage capability.

The F-22, F-35, P-8A, and KC-46A airplanes all were designed with a continuous flow PM OBIGGS.

The Airbus A400M military transport was designed with a basic OBIGGS to meet safety requirements as well as an enhanced palletized system for more stringent military requirements.

The Alenia C-27J military transport was designed with a basic OBIGGS to meet safety requirements.

The HAL Dhruv and UHT Tiger from Airbus Helicopters were also equipped with ASM-based inerting systems.

4.2.2 Commercial Applications

In 1998, the FAA tasked a Fuel Tank Harmonization Working Group (FTHWG) Aviation Rule-Making Advisory Committee (ARAC) to study potential fuel tank safety improvements in response to the New York, July 1996 center tank explosion in climb. The committee studied both on-board and ground based inerting systems, pack bay ventilation, explosion-suppressing foam, and higher flash-point fuels. None of the options studied were determined to be feasible for commercial use at the time, but the committee recommended further investigation of on-board and ground-based inerting and pack bay ventilation (refer to Aviation Rulemaking Advisory Committee, “Fuel Tank Harmonization Working Group Final Report”).

In response, the FAA tasked a Fuel Tank Inerting Harmonization Working Group (FTIHWG) ARAC in 2001 to further investigate fuel tank inerting. The committee sized a range of both on-board and ground-based systems to reduce center fuel tank flammability exposure to the wing tank level based on a 10% oxygen concentration inert limit. These options could not be demonstrated to be economically feasible, but the on-board flammability reduction systems were shown to have greater potential than a military style OBIGGS designed to keep the tanks inert during all possible flight conditions. Ground-based inerting systems were unattractive, because of the logistical impact of servicing each airplane with NEA before every flight and the airport infrastructure costs associated with distributing NEA to each gate (refer to Aviation Rulemaking Advisory Committee, “Fuel Tank Inerting Harmonization Working Group Final Report”).

In 2001, the FAA issued Special Federal Aviation Regulation (SFAR) 88 that mandated a special safety analysis of potential fuel tank ignition sources and published Amendment 25-102 where 25.981(c) required manufacturers to minimize flammability.

During this same time period, the FAA was conducting laboratory tests to determine the appropriate inert limit for commercial application. That ignition testing was done for energy levels that are lower than for the military applications, yet still conservative for commercial applications. The FAA ground testing showed that with a 1 J ignition spark, 12% O_2 was acceptable on the ground. Refer to DOT/FAA/AR-04/8. With off-stoichiometric mixtures, the oxygen concentrations must be higher than 12% before a significant pressure rise occurs. When the on-board flammability reduction systems were re-sized based on the less stringent oxygen inert limit, it enabled inerting the fuel tanks of commercial applications using the smaller systems. The FAA installed and demonstrated prototype center tank flammability reduction systems on a Boeing 747 (refer to DOT/FAA/AR-04/41) and an Airbus A320 (refer to DOT/FAA/AR-03/58).

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In 2005, the FAA issued a Notice of Proposed Rule Making (NPRM) to mandate flammability reduction for the commercial airplane fleet (refer to NPRM Docket Number FAA-2005-22997). FAR 25.981 was revised in September, 2008, within the Amendment 25-125 to limit fuel tank flammability exposure to that of conventional aluminum wing tank levels for new airplane designs. Amendment 25-125 defines the upper and lower inherent flammability limits (UFL and LFL) as functions of altitude and fuel flash point in the Appendix N 25.4(3)(ii) and the inert limit as a function of altitude in the definitions of the Appendix N 25.2(h). See 4.4.1 and Section 7.

All commercial airplane flammability reduction systems to date use permeable membrane air separation technology to generate a continuous flow of NEA at a sufficient rate to reduce the fleet-average flammability exposure for that airplane model to a level below that of a conventional aluminum wing tank.

4.3 Other Considerations

The primary benefits of an inerting or flammability reduction system are to reduce the likelihood of a fuel tank explosion and to prevent fire. There are other secondary benefits and potential risks that must be mitigated in the design.

4.3.1 Secondary Benefits

- **Reduced water in the fuel**: The NEA supplied to the tanks is filtered and very dry. The lower average humidity in the ullage should result in less water condensation onto the inner tank surfaces.

- **Reduced nozzle coking**: Thermal stability at the combustion fuel nozzles in the engine may be improved, although the level of improvement is difficult to quantify. In equilibrium with air, fuel contains a significant quantity of dissolved oxygen, and this oxygen plays a role in subsequent chemical reactions that produce insoluble deposits in fuel flow passages and coking in fuel nozzles. When nitrogen inerting is employed, much of the dissolved oxygen evolves from the fuel. Also, the low oxygen concentration in the ullage minimizes the oxygen that could be dissolved in the fuel from the ullage.

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4.3.2 Potential Risks

- **Asphyxiation during maintenance**: Exposure to low oxygen content inert atmospheres (including NEA leakage) can lead to asphyxiation of maintenance personnel. Existing maintenance access procedures for the fuel tanks already require purging with air to health safe limits (minimum of 19.5% oxygen content per OSHA), but additional placards may be used to emphasize that procedures must be followed. The procedures are in place for in-tank maintenance and outside of tank where the hazards may exist.

- **NEA leakage**: NEA leakage into an occupied space can create an asphyxiation hazard. NEA leakage or system malfunction that could result in NEA being introduced to occupied spaces must be considered. Consideration of this risk includes other aircraft system failure modes such as loss of cabin pressure.

- **Fuel tank over-pressure**: NEA presents additional inflow to the fuel tank and, therefore, there is a risk of increase in fuel tank pressure and/or potential loss of fuel overboard through vents due to continuous addition of NEA into fuel tank ullage space when venting capacity is limited due to failures in any of the components that can affect ullage pressure. Detailed safety assessments of venting capacity and various failure modes, including during airplane maneuvers and refueling must be addressed in the system design.

- **Static discharge**: Potential electrostatic hazard effects of NEA bubbling through electrostatically charged fuel during or after refueling and time for charge relaxation needs to be considered. Also, provisions must be included to preclude static buildup on the ASM or other inerting system components.

- **OEA leakage**: Oxygen concentration above 21% presents a hazard because it lowers the energy required for ignition. The exhaust or leakage of the oxygen-enriched air (OEA) waste gas must be considered to ensure that it is not exhausted near any potential fuel sources and that it is quickly dispersed into the ambient air.

- **Anaerobic microbes**: Anaerobic microbes are very corrosive. These microbes only multiply in the complete absence of oxygen and, therefore, have not been a problem in any inerting systems fielded to this point.

- **Constant venting at altitude**: A continuous flow of NEA into the fuel tanks during cruise creates a continuous flow of ullage gas out of the fuel tank vents. This ullage gas may contain unburned hydrocarbons which may have ozone depletion and/or greenhouse gas implications.

- **Connection of a high pressure air source to the fuel tanks**: Many OBIGGS use conditioned engine bleed air as a source of pressurized air for the ASMs. The bleed air connection creates a new potential fuel tank heat source, especially during failure modes, which must be addressed in the system design. Similarly, provisions must be made to prevent fuel or fuel vapors from back-flowing into the system or air supply source.

- **Fuel backflow**: Provisions must be made to prevent fuel or fuel vapors from back-flowing into the inerting or air supply source.

4.4 Civil Aircraft Regulations

The following regulations pertain to commercial transport aircraft. A detailed discussion of certification requirements is found in ARP6078 section 3.1.

4.4.1 FAA Regulations

Requirements for prevention of fuel tank explosions are found in 14 CFR 25.981 Amendment 125 and Part 25 Appendices M and N. These requirements call for either:

- A means of flammability reduction for all fuel tanks that do not meet the standard for flammability that is defined as an conventional unheated aluminum wing tank or 3% fleet-wide flammability exposure, whichever is greater, and definethe compliance through a statistical method (Monte Carlo analysis). Guidance for compliance with the regulation can be found in AC 25.981-2A.

- Or, a means is provided to mitigate the effects of an ignition of fuel vapors within that fuel tank such that no damage caused by an ignition will prevent continued safe flight and landing per CFR 25.981c.

The 14 CFR 26.33, 26.35, 26.37, and 26.39 require OEMs to install flammability reduction means (FRM) in production and to create retrofit kits. The 14 CFR 121.1117, 125.509, and 129.117 require operators to install FRM in retrofit. Operators of N-registered aircraft were mandated to retrofit fleets (50% completion by 12/27/2014, 100% by 12/27/2017).

4.4.2 EASA Regulations

EASA certification requirements for fuel tank flammability for new transport category type design applicants may be found in CS-25 Book 1, 25.981 and Appendices M and N, as well as in CS-25 Book 2, AMC 25.981(b)(1), AMC 25.981(b)(2), and AMC to Appendix N. Notably there are two significant distinctions between the EASA requirements and those of the FAA:

a. EASA CS 25.981(b)(1) requires limiting tank heat and energy input to the extent practicable, including limiting warm day ground operation tank temperature rise.

b. EASA CS 25.981(b)(3) explicitly requires that if flammability reduction is needed, then all fuel tanks have to meet the requirements of Appendix M. While the FAA 25.981(b)(2) states that any fuel tank other than a main fuel tank on an airplane must meet the flammability exposure criteria of Appendix M to this part if any portion of the tank is located within the fuselage; however, there may still be considerations that would require main tanks to meet the Appendix M25.1.

5. INERTING TECHNIQUES

5.1 On-Board Inert Gas Generation Systems (OBIGGS)

OBIGGS systems reduce the flammability of fuel tanks by introducing nitrogen-enriched air (NEA) to the fuel tanks which renders them inert. NEA is generated by separating the nitrogen and oxygen components of a high-pressure air stream (bleed air or compressed cabin air). The NEA is supplied to the fuel tanks or fuel vent system and the oxygen-enriched air (OEA) is exhausted overboard. There is no routine inert gas servicing required. Two different air separation technologies have been fielded: permeable membrane and pressure-swing adsorption. ARP6078 section 4 contains information on flammability reduction using inert gas systems.

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5.2 Stored Nitrogen Systems

Stored nitrogen systems (liquid or gaseous) slowly meter the stored nitrogen to the fuel tanks or fuel vent systems. Both liquid and gaseous storage systems operate at relatively high pressures. Both liquid and gaseous storage systems require frequent servicing on the ground between flights.

5.3 Halon Systems

Halon inerting systems are part-time or on-demand systems. The halon agent is stored in sealed containers until the pilot anticipates a need for inerting (e.g., combat or thunderstorms). An explosive squib fires or an isolation valve opens upon command and allows the halon to vaporize and flood the fuel tanks. It is theoretically possible to design a halon system that provides full-time inerting protection, similar to the stored liquid nitrogen systems; however, this is not practical, because of the high cost and the ozone-depleting characteristic of halon. Because of regulations to curb ozone depletion, halon is no longer manufactured and is, therefore, not likely to be incorporated into future inerting system designs.

6. SYSTEM DESIGNS

6.1 On-Board Inert Gas Generation Systems (OBIGGS)

6.1.1 Permeable Membrane OBIGGS

Permeable membrane (PM) air separation modules (ASMs) contain many thin, hollow fibers through which pressurized air passes (Figure 1A). The individual fiber walls are composed of a very thin membrane surface supported by a porous structure so that some of the oxygen and nitrogen molecules in the pressurized air permeate through the fiber walls (Figure 1B). The membrane and porous support are made from the same material in some fibers and from different materials in others. The membrane material is selected and fabricated, using very specialized techniques, so that oxygen molecules permeate more readily than nitrogen. As the air passes through the length of the fiber, more and more oxygen is progressively removed. These oxygen molecules (and the limited nitrogen that permeates) are collected into a waste gas stream and are typically exhausted overboard. The product gas from all of the fibers is collected at the end of the module and the resulting NEA is ducted to the tank(s) to be inserted.

The oxygen concentration in the NEA stream can vary greatly depending on the pressure difference and pressure ratio across the fiber (i.e., inlet versus waste pressures), the fiber temperature, and the NEA flow rate through the module. Permeable membrane systems typically include devices to control the inlet air temperature and filtration to prevent contamination (Figure 2).

In some cases, engine bleed air pressures are sufficient to produce NEA at the required flow rate and oxygen concentration. In other cases, engine bleed air pressures are boosted with a supplemental compressor. In still other cases, a separate compressor pressurizes cabin air for the PM ASM.

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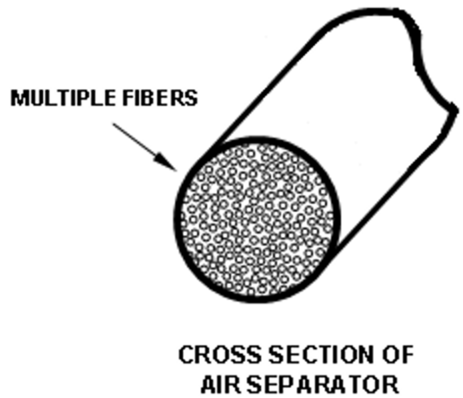

Figure 1A - Canister filled with hollow fibers

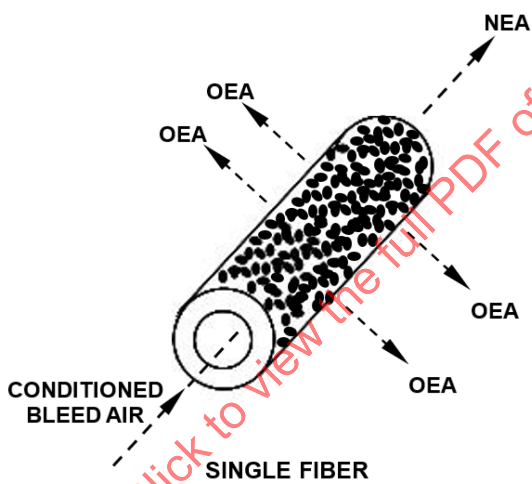

Figure 1B - Expanded view of an individual fiber

Figure 1 - Permeable membrane air separation module

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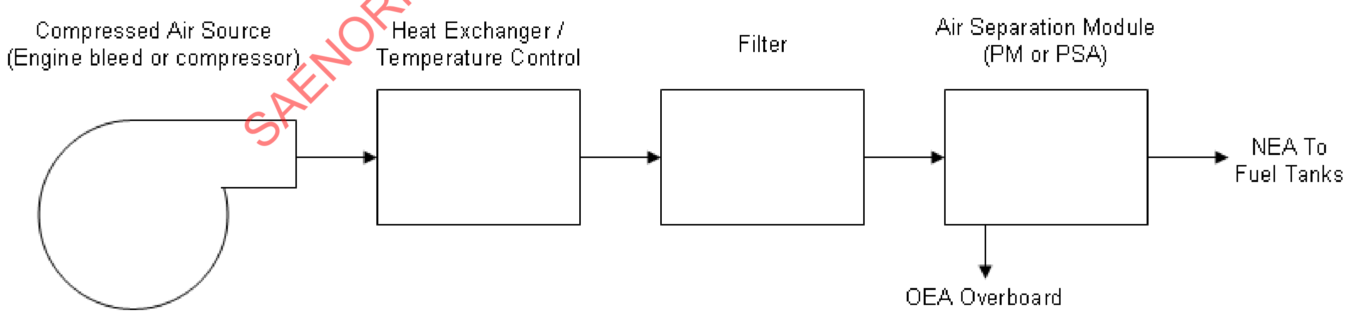

Figure 2 - Schematic of typical PM or PSA OBIGGS

6.1.2 Pressure-Swing Adsorption OBIGGS

Pressure-swing adsorption (PSA) ASMs contain at least two canisters filled with a molecular sieve material (Figure 3). The molecular sieve is a solid material that contains many adsorption sites that preferentially adsorb oxygen molecules compared to nitrogen molecules. Pressurized air is passed through one canister and many of the oxygen molecules adsorb onto the sieve material. Some nitrogen adsorbs as well. NEA is produced from the canister until most of the adsorption sites are filled. At that point, a valve switches the pressurized air source to the fresh canister and the non-operating canister is vented to ambient pressure. At the low pressure, the adsorbed oxygen and nitrogen molecules are released from the molecular sieve material and are exhausted overboard. A constant supply of NEA is produced by continuously alternating the pressure supply and exhaust vent between the different canisters.

Similar to the PM ASM, the oxygen concentration in the NEA product from a PSA ASM is strongly dependent upon the pressure difference (i.e., pressure-swing) between the inlet supply and the exhaust and also the NEA flow rate produced by the module. Like the PM module, the bleed air supplied to the PSA module must be cooled from the typical bleed air temperatures (though the ASM temperature doesn't change the oxygen concentration as dramatically in a PSA module as it does in a PM module). As a result, pressure-swing adsorption systems have components very similar to PM OBIGGS. PSA OBIGGS typically include inlet air temperature control, filtration, and are supplied by engine bleed air, boosted bleed air, or compressed cabin air.

6.2 Stored Nitrogen Systems

Stored liquid nitrogen systems (Figure 4) include cryogenic dewars with provisions to vent nitrogen as it boils off (even though the dewars are extremely well insulated, heat transfer from outside would otherwise cause the internal pressure to continuously rise as more and more liquid transitioned to the gas phase). Stored liquid nitrogen systems also include provisions to warm the nitrogen after it leaves the dewars to ensure that only gaseous nitrogen enters the tanks.

Gaseous nitrogen (Figure 5) is typically stored in pressure vessels. Gaseous nitrogen storage requires a much larger volume than an equivalent-mass liquid nitrogen storage system.

Both stored liquid and gaseous nitrogen systems include metering devices to regulate the flow to the tanks to minimize waste of the stored nitrogen.

6.3 Halon Systems

Halon systems (Figure 6) have an advantage over stored nitrogen systems, because halon can be stored as a liquid at high pressure in a sealed container at room temperature. The halon vaporizes as it expands to ambient pressures and the stored pressure drives the flow once the squib fires or the isolation valve opens. As a result, the halon from the storage bottle can be ducted directly to the tank to be protected. A heater may be employed to force residual halon from the bottle into the tank.

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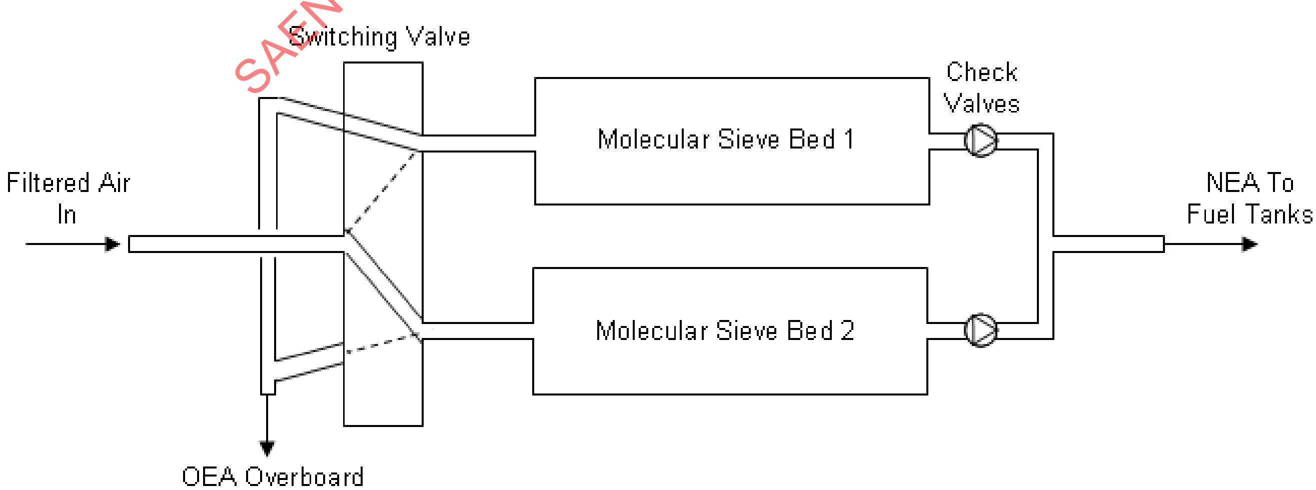

Figure 3 - Schematic of typical PSA inerting system

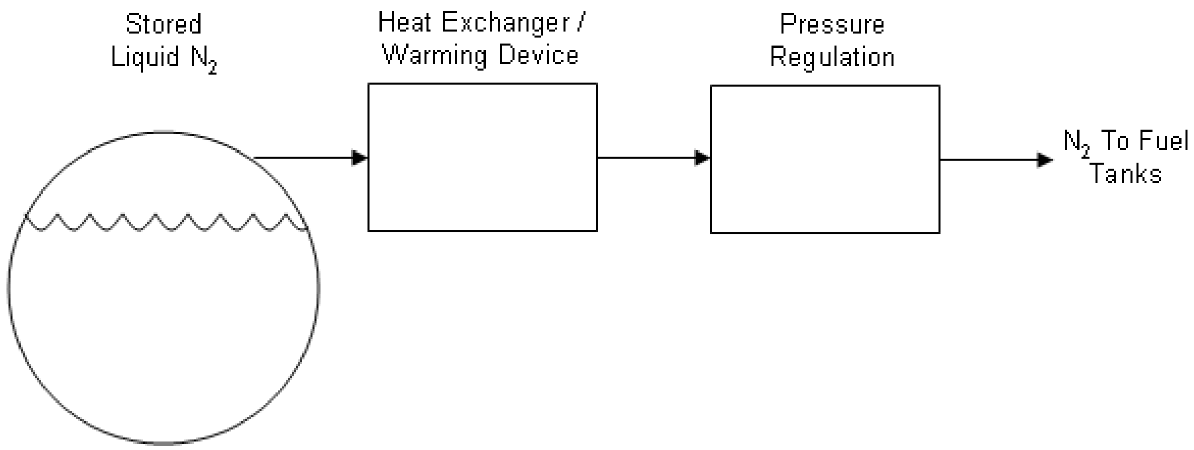

Figure 4 - Schematic of typical stored liquid nitrogen inerting system

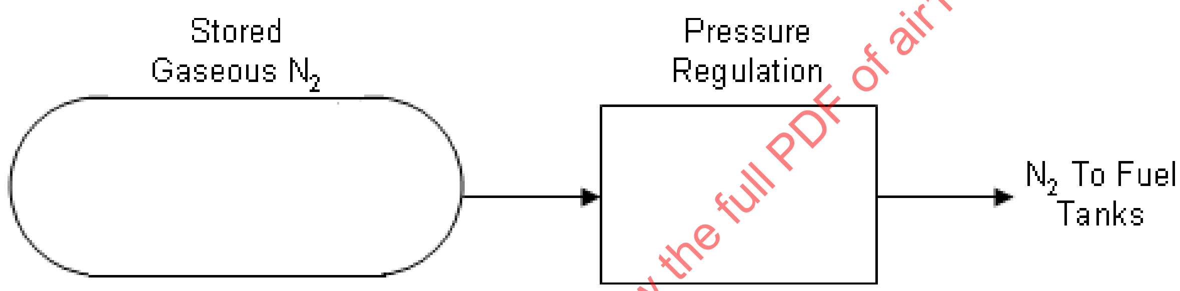

Figure 5 - Schematic of typical stored gaseous nitrogen inerting system

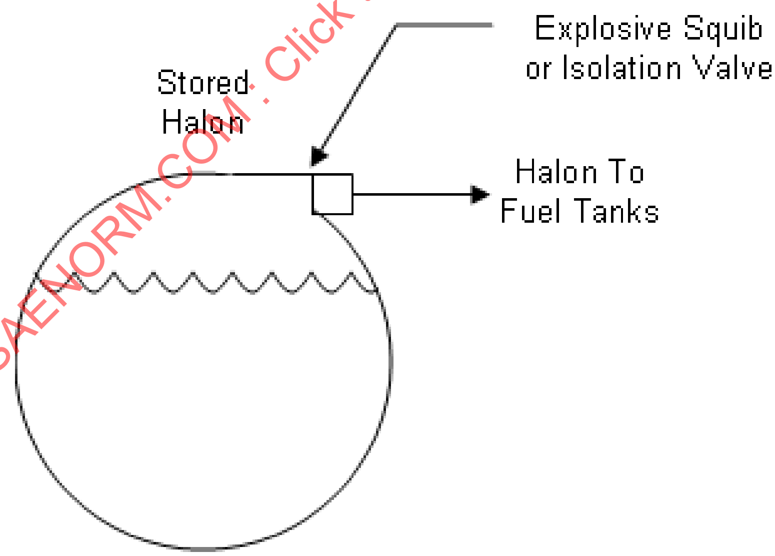

Figure 6 - Schematic of typical halon inerting system

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