Aviation Rulemaking Advisory Committee

Fuel Tank Inerting

Task Group 3

Abstract

This report is the findings of the Inerting 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 reduce or eliminate fuel tank flammability and to propose regulatory changes to the FAA Aircraft Rulemaking Advisory Committee.

The Inerting Task Group’s assignment was to provide a feasibility analysis of fuel tank inerting systems. The analysis was to focus on reducing or eliminating exposure to explosive mixtures for transport airplane operations. A cost/benefit analysis for inerting systems was to be included for the fleet of aircraft requiring retrofit, for current production aircraft, and for new type design aircraft.

Summary

The Inerting Task Group studied the technologies offered by the respondents to the FAA's Request for Information. Several technologies for providing inert gas were reviewed including carbon dioxide in gaseous form and as dry ice, nitrogen in gaseous and liquid form, and exhaust gas.

The group analyzed the impacts of carrying an on-board inerting system versus a ground-based system. In addition, the group studied the cost and benefit of inerting the center wing tank only versus inerting all of the aircraft's fuel tanks. Finally, two methods of purging oxygen from the tank were reviewed i.e. "scrubbing" the fuel and "washing" the ullage space above the fuel.

A ground-based system provides the potential for the least costly (non-recurring cost) system on the aircraft. However, it requires a substantial investment in ground equipment to supply inerting gas, plus the recurring costs of the inerting gas and operation of the equipment.

Scrubbing fuel at the airport fuel farm, or on the aircraft during refueling, is the least effective form of tank inerting. The ullage remains flammable during taxi, takeoff, and initial climb until inert gas evolves from the fuel. As fuel is consumed from a fuel tank, ambient air flows in to replace it and raises the oxygen concentration. The tank may only be inerted for the latter portion of climb and the beginning of cruise and is highly dependent of the initial fuel load. Clearly, this method provides little added protection to today's design. In addition, this method would provide no added protection for empty fuel tanks, as was the case for the TWA800 center wing tank.

Ground-based ullage washing is effective when considered in combination with the normal changes to fuel temperature during a flight. On average, the exposure to a flammable, non-inert ullage is approximately 1%.

On-board systems could provide inert gas throughout the flight and offer zero exposure to a flammable, non-inert ullage. There are several existing methods for providing nitrogen on board an aircraft. It can be stored as a gas in bottles or as a liquid in Dewar bottles, such as on the C-5. Either of these would require replenishment at an airport, which adds to the cost of the airport infrastructure.

An alternative to storing gases or liquids, on-board inert gas generating systems (OBIGGS) separate nitrogen from engine bleed air. Such systems exist on military aircraft today, notably the C-17 as well as some fighters and helicopters. All of these systems extract a performance penalty from the aircraft. A new aircraft design offers the best opportunity to minimize these penalties. Current production aircraft and the retrofit fleet may incur redesign and operational penalties that make them uneconomical to fly. Operational compromises will almost certainly be required. Many of today's aircraft do not have enough bleed air available to supply these systems.

Whatever the type of inerting that might be used, there are potential hazards to personnel. Gaseous inerting agents present a suffocation hazard and liquid nitrogen presents the additional hazards of freezing trauma to skin and eyes.

Several other on-board systems were reviewed. Exhaust gas from the jet's engines and auxiliary power unit (APU) was deemed infeasible primarily because the exhaust contains too much oxygen. Carbon dioxide in gaseous and solid (dry ice) form was also deemed infeasible because it's a greenhouse gas that adversely affects the environment. Also, except for nitrogen systems, none of the systems were mature enough to be considered for installation on commercial aircraft. Nitrogen is the best candidate at this time.

The following table provides a summary of the cost and benefit of each system.

Technology	**Effectiveness**	**Cost over 10 Years (US Dollars)**
On-board Liquid Nitrogen for All Tanks	100%	$35.7B
On-board Gaseous Nitrogen for All Tanks	100%	$33.9B
Air Separator Modules for All Tanks	100%	$37.3B
Air Separator Modules for the Center Tank	100%	$32.6B
Ground-based Ullage Washing with natural Fuel Cooling for Center Tank	99%	$4B with gaseous nitrogen $3B with liquid nitrogen

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1. Introduction

Task Group 3, the Fuel Tank Inerting Group, of the Fuel Tank Harmonization Working Group was tasked to assess current and future technologies which could drastically reduce or eliminate flammable mixtures in fuel tanks of Part 25 aircraft. Inerting systems provide an inert gas to displace the oxygen in the fuel and/or ullage resulting in a mixture that cannot sustain combustion.

In early 1997, the FAA issued a Request for Comment asking the industry and the public to propose and evaluate methods to reduce fuel tank flammability. Those respondents who recommended inerting suggested the use of nitrogen, carbon dioxide, or exhaust gases from engines or fuel burners as the inerting agent. Task Group 3 contacted all of these respondents to learn more about their proposals and worked with several of them to determine the viability of their proposals for existing and future aircraft.

Many of the respondents had hardware available or in the prototype stage and so were best able to provide estimated cost, weight, and size of their proposed hardware for our evaluation. Some of the respondents provided their conceptual ideas or patent information. Given more time, the Task Group would have attempted to better define the concepts and make an estimate of the cost, weight, and size of the system for inclusion in the report. While this wasn't possible, due to the short time available for the task, the Task Group felt it important to include the conceptual ideas for future reference. The Task Group also commented on the potential benefits and problems of the proposed technology when fitted to a present day aircraft.

The Task Group also evaluated methods of displacing the oxygen in the fuel and/or ullage with inert gas. We evaluated on-board systems to provide inerting gas on the aircraft at all times during a flight as well as ground-based systems that provide inert gas to the aircraft prior to flight. Fuel "scrubbing" and ullage "washing" were studied for effectiveness and efficient use of the inert gas.

2. References

2.1. Documents

[1] "Test and Evaluation of Halon 1301 and Nitrogen Inerting against 23MM HEI", Charles Anderson, AFFDL-78-66, May 1978

[2] "A Study of the Blast and Combustion Over-Pressure Characteristics of the 23MM High Explosive Incendiary-Tracer (HEI-T)", Charles M. Pedriani and Thomas Hogan, USAAVRADCOM-TR-80-D-33, November 1980

[3] "Inerting Conditions for Aircraft Fuel Tanks", Paul B. Stewart and Ernest S. Starkman, at University of California, WADC Technical Report 55-418, September 1955

2.2. Interviews

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3. Background

3.1. How Inerting Technology Works

Inerting, as applied to aircraft fuel tanks, can be defined as the inclusion of a gas in the ullage prior to ignition of the vapor that will suppress that ignition, independent of the fuel air mixture. The gas used can be one that simply reduces the oxygen available for combustion, such as nitrogen, or one that chemically interferes with the combustion process, such as Halon 1301.

Although the military has investigated and used many types of inerting systems (and gasses) the presently available and viable systems all use nitrogen as the inerting gas. Systems using exhaust gas (B-50), CO2 and dry ice (B-47 and B-36) where used by the military but discontinued because of technical problems. Systems using flame-suppressing agents (Halon 1301) are presently being used on some smaller military aircraft. However, the ban on the production of Halon 1301 and the lack of any replacement agent makes that a nonviable technology for commercial use. Therefore, the only presently viable and acceptable inerting gas is nitrogen.

Nitrogen inerting works by reducing the oxygen concentration in the fuel tank ullage below that necessary to support combustion. Literature indicates that at 9% oxygen or below no reaction will occur in a tank with Jet A fuel regardless of the fuel air mixture or the ignition energy. Some testing has indicated that for most conditions 10-11% oxygen levels provides the same level of protection. Oxygen levels above the no reaction level but below 16% have been shown to provide some protection and reduce the pressure rise in reactions that do occur.

In order to initially inert a fuel tank with nitrogen, the nitrogen must be introduced into the tank in such quantity as to reduce the oxygen level below the desired 9%. In order to maintain an inert tank additional nitrogen must be introduced to counter the oxygen in the air drawn into the tank due to pressure changes and fuel usage. In addition, dissolved oxygen in the fuel released into the ullage as the pressure on the fuel decreases must be diluted with additional nitrogen. In order to minimize the need for additional nitrogen, systems normally include check valves at the fuel tank vents to maintain a slight pressure differential to ambient. This minimizes the introduction of air (21% oxygen) during minor pressure changes. Scrubbing (bubbling nitrogen through the fuel) prior to takeoff can reduce dissolved oxygen in the fuel.

Present inerting systems require the use of additional nitrogen during flight. The nitrogen is either loaded prior to flight and stored in liquid or gaseous form onboard, or generated in-flight by separating the components of air. The liquid nitrogen systems require ground based refilling at all landing locations, and a cryogenic nitrogen storage vessel onboard. Additional valving and plumbing is necessary to make sure only gaseous nitrogen enters the fuel tanks. Onboard inert gas generating systems (OBIGGS) can be of two types, the molecular sieve or the permeable membrane. Both types of systems require compressed air, usually engine bleed air, and produce a mixture of nitrogen enriched air (NEA) that is not pure nitrogen (but is usually less than 5% oxygen).

The molecular sieve utilizes a minimum of two beds of oxygen adsorbing medium, such as zeolite. As air passes through the medium oxygen is adsorbed. Thus, the gas that passes through is nitrogen rich. That gas is collected and passed on as the bed is back flushed, with the enriched oxygen gas exhausted overboard. Two beds are used such that as one is collecting nitrogen enriched gas the other is being cleansed of adsorbed oxygen.

The permeable membrane system is comprised of many very small hollow tubes made of a material that allows all the constituents of air to pass through more easily than nitrogen. Air is supplied to the tubing under pressure. Oxygen from the air permeates the tubing walls and is collected and exhausted overboard. What is left is nitrogen enriched air (NEA) usable for inerting.

3.2. Why Military Uses This Technology

The US military looks at aircraft vulnerability based on the mission for that aircraft. Inerting systems are installed on combat aircraft and aircraft likely to be fired upon during the conduct of its mission. The inerting system is designed to enhance the ability to survive enemy fire into a possibly explosive fuel tank. Although the military owns and operates many commercial type aircraft (including Air Force One, a Boeing 747) none of those aircraft have inerting systems or any other method of explosion protection for the fuel tanks.

Initial inerting systems, such as on the C5, utilized stored liquid nitrogen. These systems are heavy and rely on a large ground support system. As technology has advanced, the OBIGGS systems have become more practical. The system weight and inlet airflow and pressure to volume of nitrogen produced has vastly improved. All of the recently designed and installed nitrogen inerting systems have been of the OBIGGS type.

3.3. Military Service Experience and History with this technology

Very little data is available publicly on the effectiveness or reliability of nitrogen inerting systems presently used on military aircraft. What can be ascertained is that they are very effective in preventing fuel tank vapor ignition and the reliability (maintainability) is a problem. Information presented at the Transport Fuel Flammability Conference, October 7-9, 1997 in Washington DC. showed that the major reliability problems were with the Air Separation Module, ASM Filter and the Compressor. The valves and sensors had a high degree of reliability. Overall system Reliability was said to be <200 hours between failures and <100 hours between maintenance. Information presented on the C-5 indicated a similar reliability (maintainability) problem. The main problem on the C-5 was reported as the storage and refrigeration system for the LN2.

4. Design Alternatives

There are several possible design alternatives for an inerting system. The various options are:

1. a self-contained system on the aircraft;
2. a completely ground-based system (no aircraft-mounted equipment);
3. a hybrid system with the distribution pipes on the aircraft and the inert gas supply on the ground;
4. a hybrid system with the distribution pipes and a small inert gas supply on the aircraft and a ground-based inert gas supply for initially inerting the fuel tanks.

In addition, the system could be used to inert the body tanks only (center wing tanks and fuselage-mounted tanks) or all of the fuel tanks.

Also, there are three methods of inerting the fuel tank:

1. “fuel scrubbing”;
2. “ullage washing”;
3. providing inert gas to the tanks as fuel is depleted or during altitude changes.

There are a variety of gases that will inert fuel tanks and a variety of means to produce those gases. Lastly, there is a system for enriching the ullage above the upper flammability limit, which will be briefly discussed.

4.1. Self-contained (aircraft-based) system

An aircraft-based system has a supply of inerting gas, regulators to supply the gas to the fuel tanks at acceptable pressures, and vent check valves to prevent outside air from diluting the inert gas in the tanks.

The primary advantage to this system is that the fuel tanks will stay inert for most or all of the flight provided the system can maintain the flow demanded by the aircraft operation. The primary disadvantages are additional system weight, cost, loss of range due to the added weight, and loss of revenue because the aircraft can no longer carry as many passengers or as much cargo.

4.2. Ground-based system

This design alternative involves inerting the fuel at the airport’s fuel storage tanks or with a mechanism between the fuel trucks and the aircraft. This design is the best for the aircraft because no equipment is added. However, without a supply of inerting gas, air will eventually enter the aircraft fuel tank and raise the oxygen level so that the fuel tanks will not be inerted at some time during the flight. The safety of this alternative will be discussed in section 8.

4.3. Hybrid systems

Another alternative would be to install an inert gas distribution system in the aircraft fuel tanks and leave the supply of inerting gas on the ground. This reduces the weight impact on the aircraft compared to an aircraft-based system. Again, without a supply of inerting gas on the aircraft air will eventually enter the tank and raise the oxygen level so that the fuel tanks will not be inerted at some time during the flight.

Another alternative is to install the inert gas distribution system and a small inert gas supply on the aircraft while retaining the inert gas supply on the ground. The concept is that the ground-based supply of inert gas would be used to inert the fuel tanks during refueling. During flight the aircraft's inert gas supply would provide inert gas to the fuel tanks as the fuel is depleted and during altitude changes. This system could be sized to keep the fuel tanks inert throughout the flight but it obviously adds more weight to the aircraft than the ground-based system or the hybrid system above.

4.4. Body Tank or All Tanks

The Working Group's preliminary findings showed that the wing tanks were less likely to have a flammable mixture than the body tank. A safety analysis of the historical fuel system events showed that the wing tanks have demonstrated an acceptable level of safety and no further improvement is required. (Reference the report by Task Group 1.) A variation of all of the arrangements in sections 4.1 through 4.3 would distribute inert gas to the body tank only. This would put the inert gas where it is most needed, simplify the system, and minimize the cost and weight impact to the aircraft.

4.5. Fuel Scrubbing

Fuel scrubbing uses inerting gas to dilute the dissolved air in the fuel. This could be accomplished in the aircraft during refueling (Ref. Figure 1), or at the airport storage tanks when the fuel is delivered from the refinery. The scrubbers would be built in to the refueling system of the tank (or put inline between the truck and the aircraft) and mix the inerting gas with the fuel as the tank is filled.

During climb the air in the fuel, which is mostly nitrogen due to the scrubbing, will evolve out of the fuel to the ullage. This inerts the ullage during climb and for the early portion of the cruise flight phase. However, the ullage is not inert during refueling, taxi and takeoff. Refer to Figures 2 and 3.

Scrubbers require a minimum flow in order to work properly. If the flow from the truck or refinery is too slow then the inert gas will not be mixed into the fuel and it will not be inerted. The scrubber also adds some pressure drop to the system so more time would be required to fill the fuel tank(s). The primary disadvantage to fuel scrubbing is that it only works if a tank receives fuel. An empty tank, such as the TWA800 center tank, would not be inerted. Refer to Figure 4.

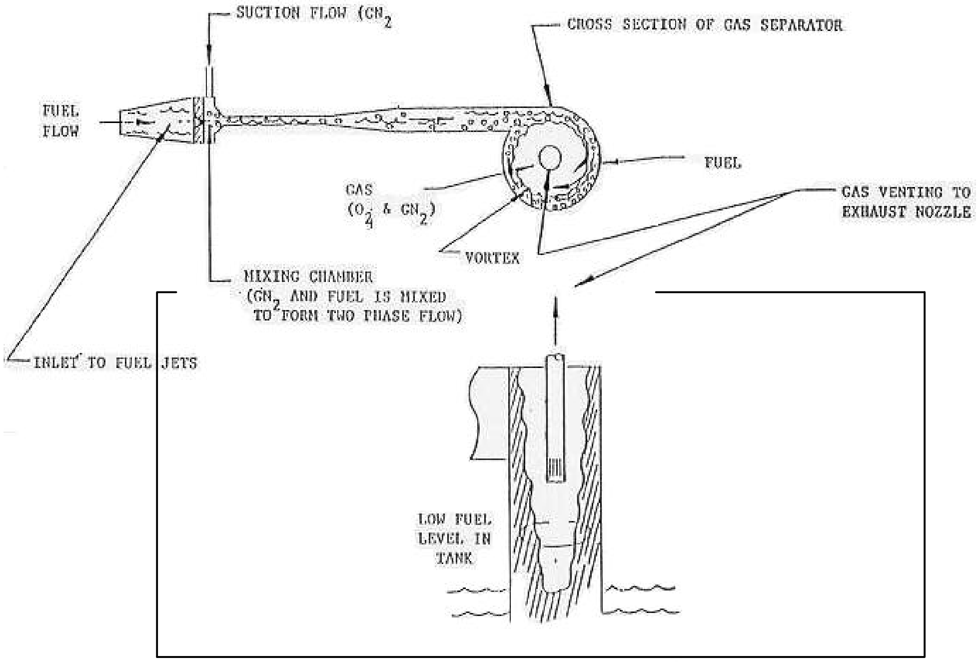
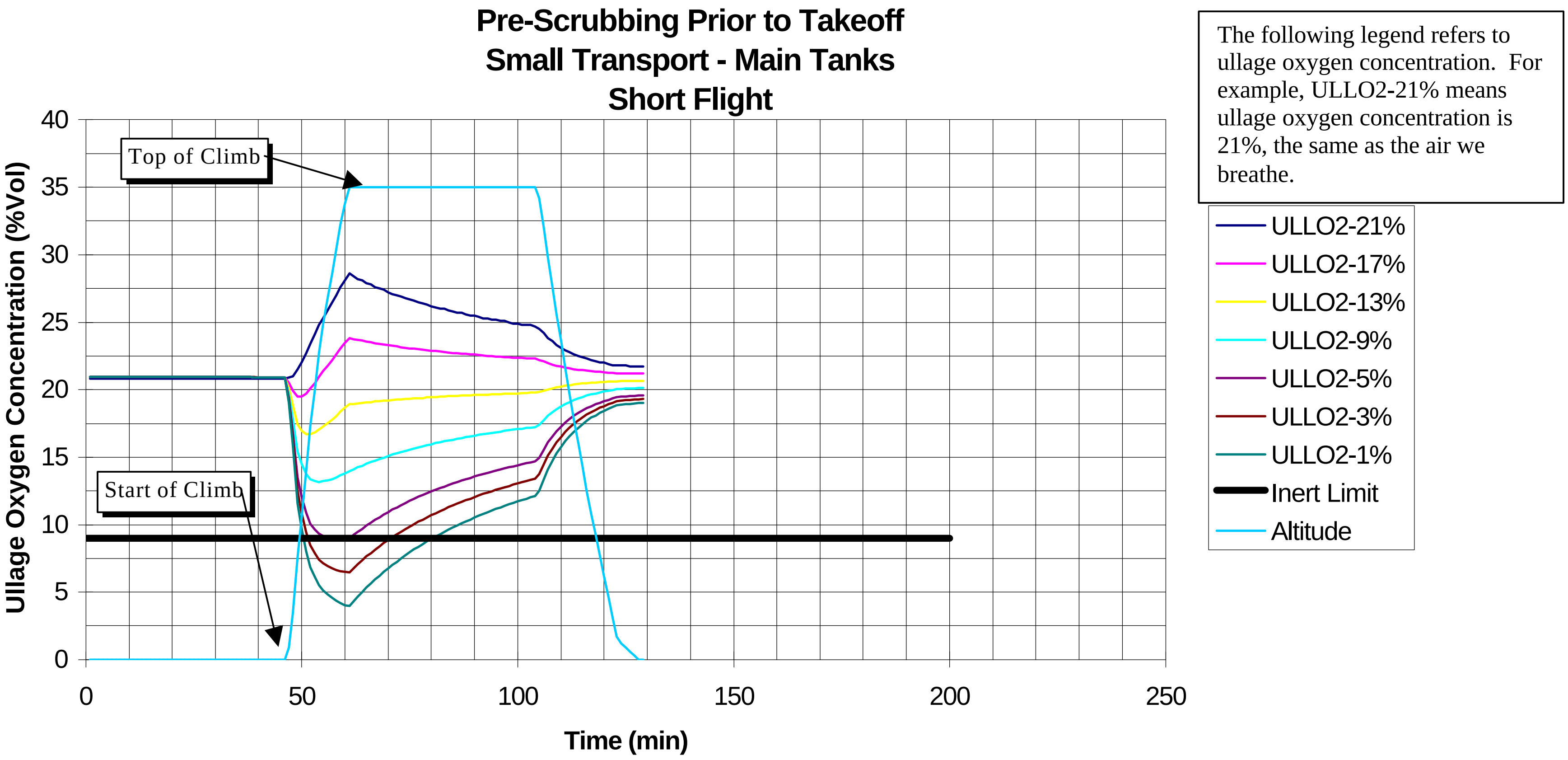


Figure 1
Cross Section of Fuel Scrubbing System
Mounted in a Fuel tank



The following legend refers to ullage oxygen concentration. For example, ULLO2-21% means ullage oxygen concentration is 21%, the same as the air we breathe.

Figure 2 – This figure shows the effect of scrubbing the fuel in the wing (main) tanks during refueling. Note that the ullage oxygen concentration remains at 21% until the start of climb when dissolved nitrogen and oxygen evolve out of the fuel. The oxygen concentration reaches a minimum (or maximum, depending on initial oxygen concentration) at the top of climb just as the aircraft's cruise phase begins. The oxygen concentration then begins to rise (or fall) as the fuel is depleted and ambient air replaces it.

Also, note that if the fuel is not scrubbed during refueling (the ULLO2-17 and -21% line) then the ullage oxygen concentration actually increases during climb as oxygen evolves out of the fuel. Oxygen dissolves and evolves more readily than nitrogen.

The following legend refers to ullage oxygen concentration. For example, ULLO2-21% means ullage oxygen concentration is 21%, the same as the air we breathe.

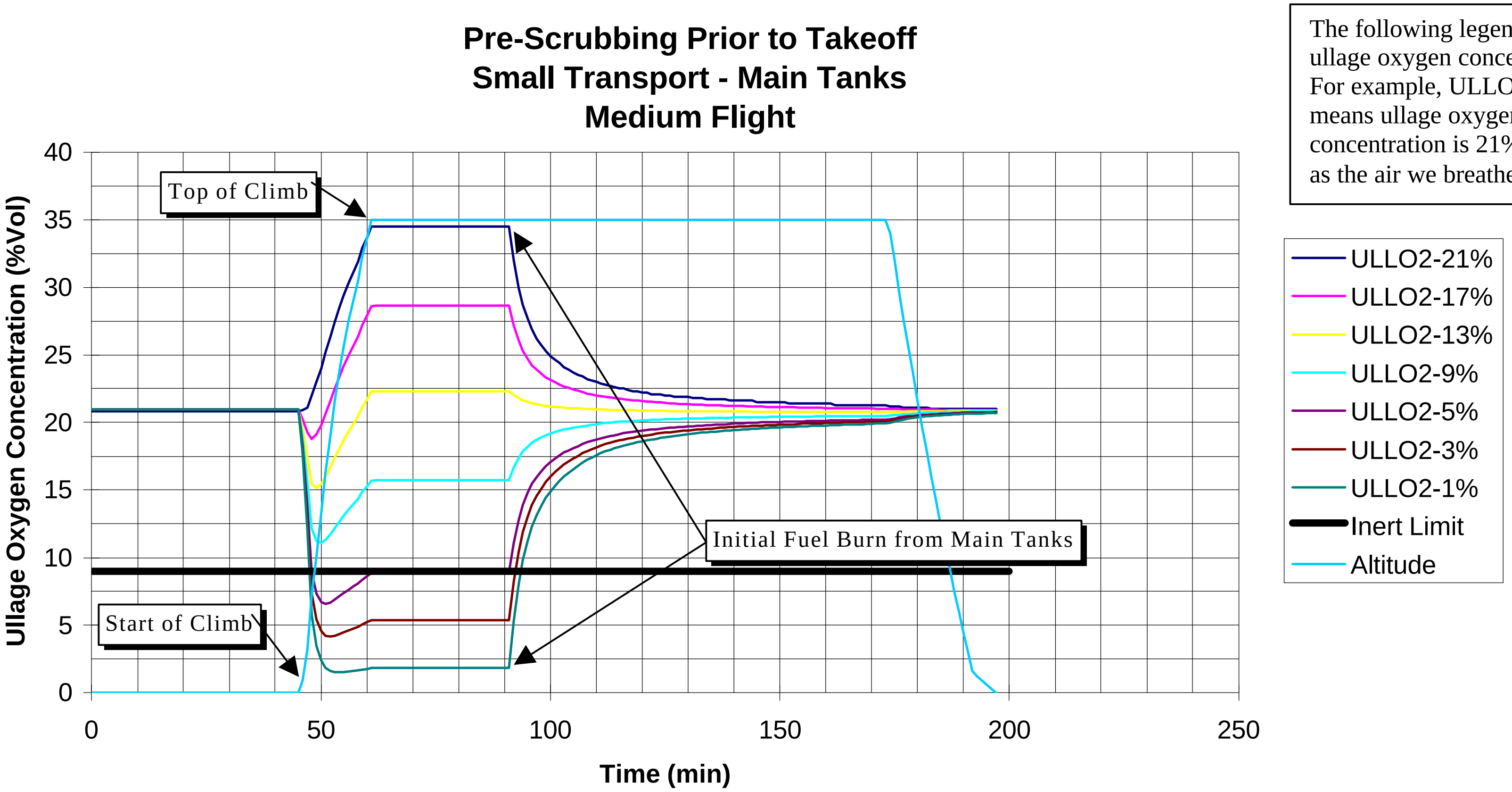
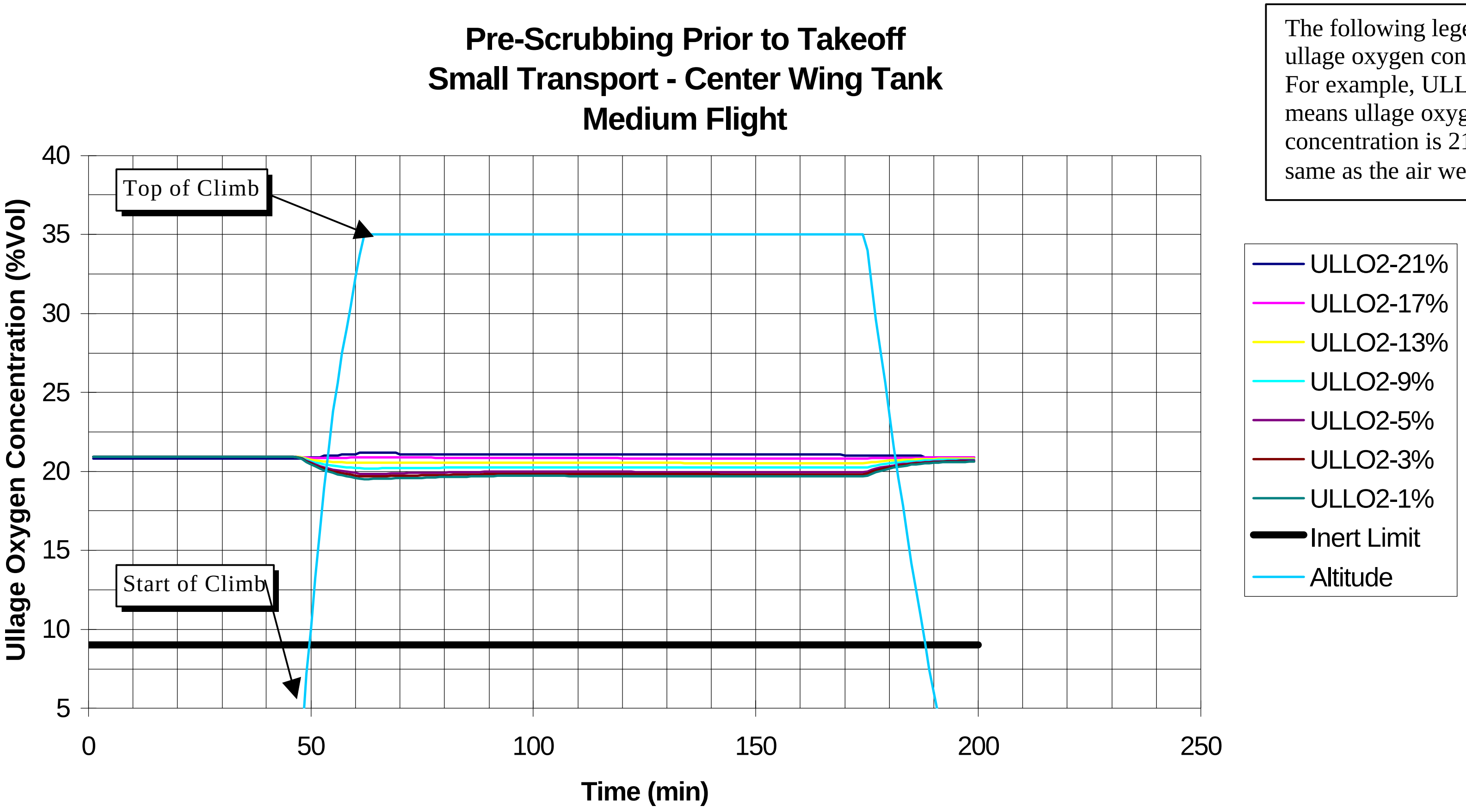


Figure 3 – This figure shows the effect of scrubbing the fuel in the wing (main) tanks during refueling. This differs from the previous figure because it’s a medium length flight that requires fuel in the body tank (center wing tank) as well as the wing tanks. The center fuel is depleted before the wing fuel is used so the oxygen concentration remains constant in the wing tanks for a period of time. Note that there is a slight increase of oxygen concentration right after the start of climb due to evolving oxygen.



The following legend refers to ullage oxygen concentration. For example, ULLO2-21% means ullage oxygen concentration is 21%, the same as the air we breathe.

Figure 4 – This figure shows that scrubbing is not very effective for fuel tanks that have a small amount of fuel because there’s only a small amount of nitrogen evolution from the fuel compared to the large air volume in the ullage space.

4.6. Ullage Washing

Ullage washing uses inert gas to dilute the air above the fuel. Refer to Figure 5. To be effective, this can only be accomplished on the aircraft. A truck or cart with inerting gas would be connected to a distribution system in the aircraft to deliver the inerting gas to the fuel tanks. Alternatively, an onboard system could provide the inerting gas to the distribution system.

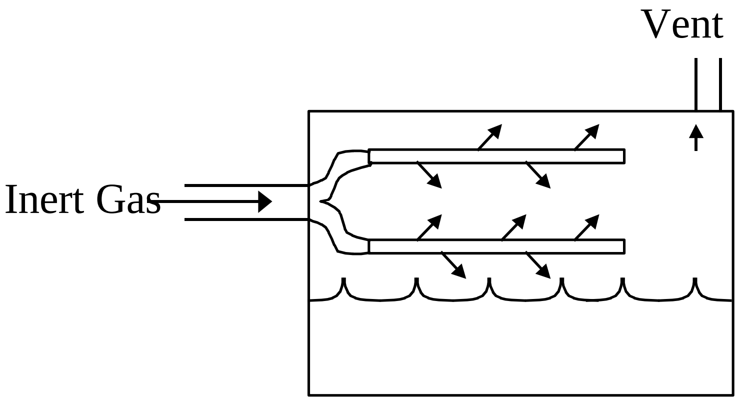


Figure 5 - Cross-Section of Ullage Washing System

The primary disadvantage to ullage washing is that it requires more nitrogen to inert the fuel tank than fuel scrubbing requires. There's also a potential for fuel tank structural damage if the source of inerting gas isn't regulated properly. Ullage washing works well in tanks with little fuel but is ineffective in tanks that are full of fuel. This is because the dissolved oxygen in the fuel evolves out during climb and mixes with the inert gas causing the ullage to exceed a 9% oxygen concentration. A large amount of fuel also means more oxygen is introduced into the tank as fuel is depleted and raises the oxygen concentration above the inert level. On the other hand, an empty tank will stay inerted until descent when the pressure change causes ambient air to enter the fuel tank. Ullage washing of a tank with a fuel quantity of 25% or less using NEA that contains 5% oxygen or less will remain inert until descent, provided there is no ventilation of the tank during operation. Figures 6 and 7 show the effectiveness of ullage washing for a nearly full and a partially full tank. Figures 8, 9, and 10 show that the combination of ullage washing and the normal drop in fuel temperature during a flight can help to limit a fuel tank's exposure to a flammable, non-inert ullage.

A combination of fuel scrubbing and ullage washing avoids the problem of evolving oxygen for nearly full tanks. The ullage oxygen concentration decreased during climb. However, as the fuel is depleted from the tanks the oxygen concentration eventually exceeds 9% because ambient air replaces the depleted fuel.

Ullage washing combined with normal fuel temperature changes did prove effective. A statistical analysis combined fuel temperature and flash point, calculated by Task Group 5, with the ullage oxygen concentration that occurs on typical flights in the body (center wing) tank. This generated a time of exposure to a flammable, non-inert ullage. On average, the aircraft was exposed less than 1% of the time. Figures 8 and 9 show a sample of the fuel temperature, flash point, and ullage oxygen concentration for two of the several thousand flight conditions that were studied. This represents a significant improvement over present aircraft. The cost of this system will be provided in Section 9.

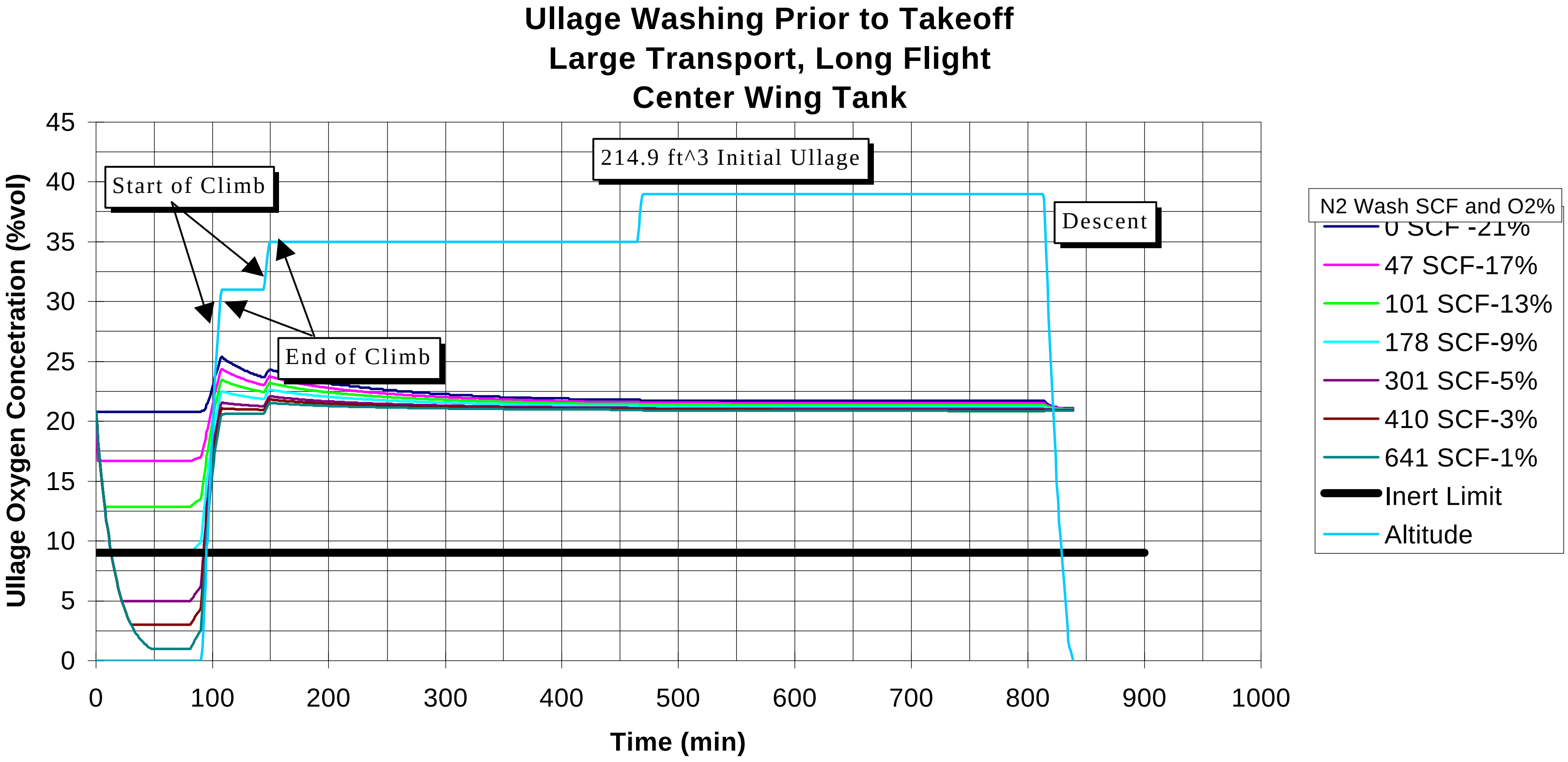


Figure 6 - Ullage washing has little effect on a tank with a large fuel quantity. Because of the large fuel quantity, a great deal of air evolves from the fuel during climb into the relatively small ullage space. The nitrogen in the ullage is diluted by the evolving air and quickly exceeds 9% oxygen.

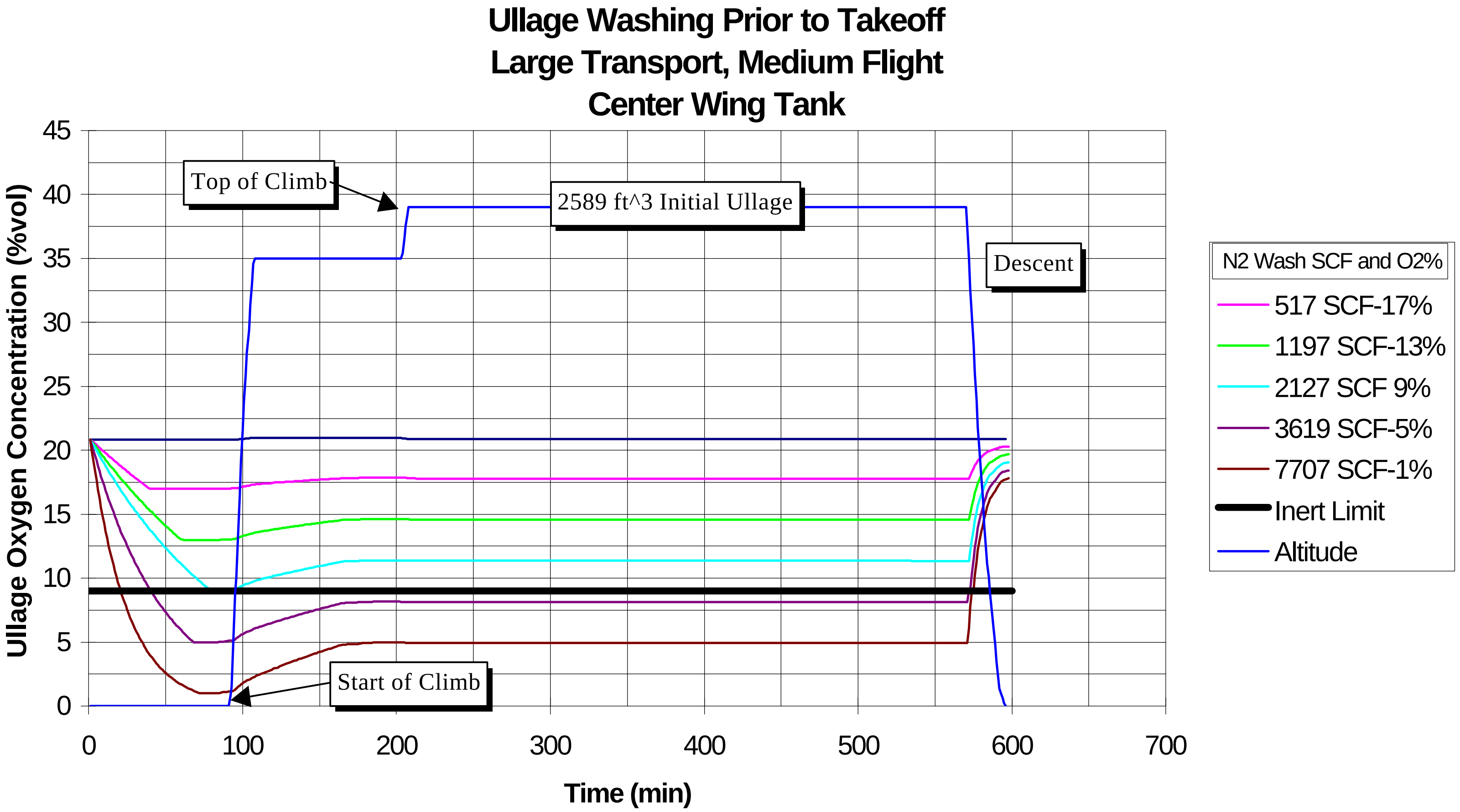
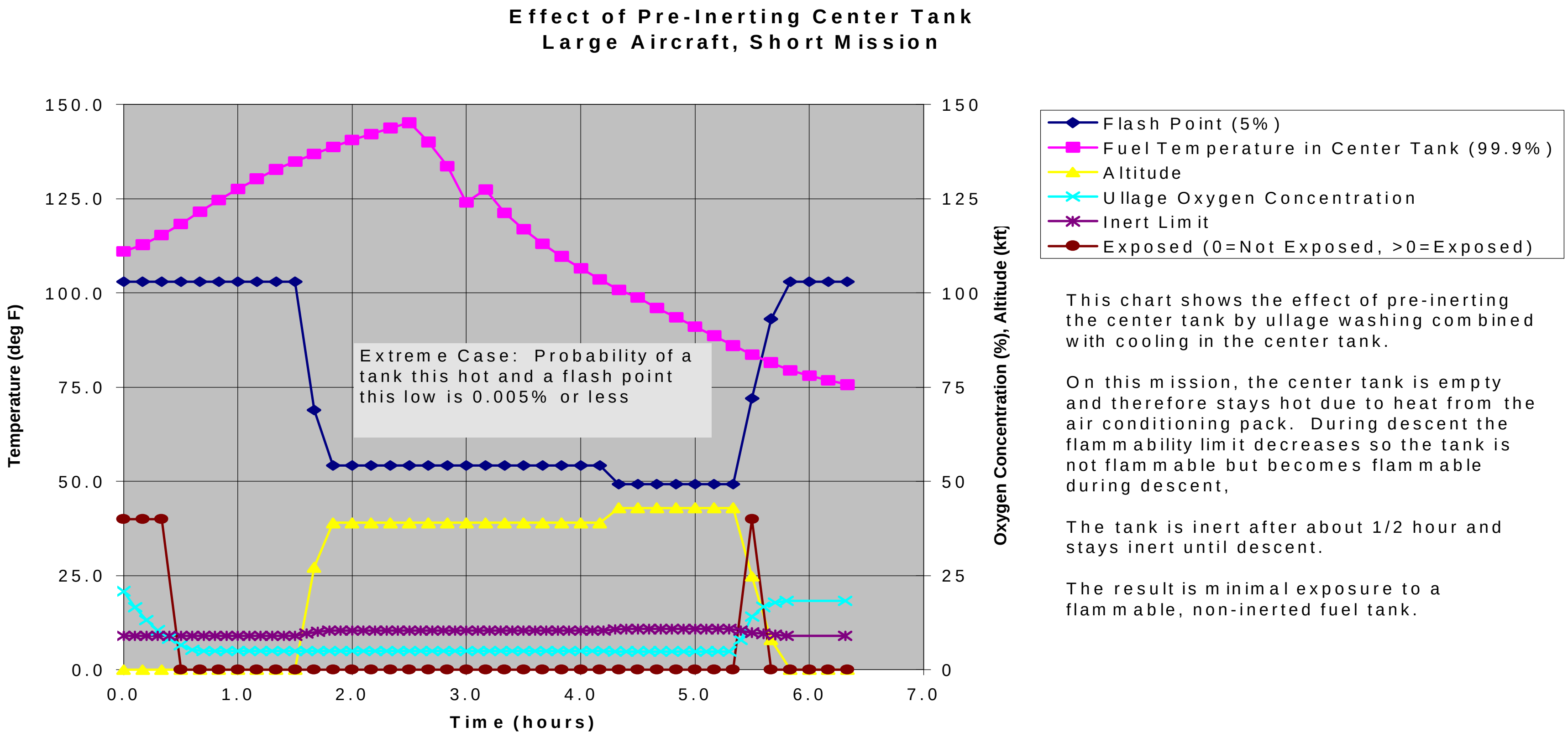


Figure 7 - Ullage washing is quite effective for a tank with little or no fuel (like the TWA800 center tank). The small quantity of fuel does not evolve enough air to dilute the nitrogen in the ullage. As a result, the tank will remain inerted until descent at which time ambient air enters the tank through the vent system.



This chart shows the effect of pre-inerting the center tank by ullage washing combined with cooling in the center tank.

On this mission, the center tank is empty and therefore stays hot due to heat from the air conditioning pack. During descent the flammability limit decreases so the tank is not flammable but becomes flammable during descent,

The tank is inert after about 1/2 hour and stays inert until descent.

The result is minimal exposure to a flammable, non-inerted fuel tank.

Figure 8 Ullage washing on the ground helps to limit exposure to a flammable, non-inert fuel tank. This chart represents an extremely hot day combined with a very low flash point fuel. The likelihood of this combination is less than 0.005%. Also, the body (center) tank is empty for this mission.

The chart shows that the tank is flammable for most of the flight because the fuel tank temperature is higher than the flash point of the fuel. However, the oxygen concentration drops below the inert limit at about ½ hour into the mission and stays there until descent (at about 5.5 hours in the mission). So the tank is only exposed at the beginning of the mission and for about 15 minutes during descent as shown by the brown (exposed) line. Most flights would be exposed for an even lesser amount of time.

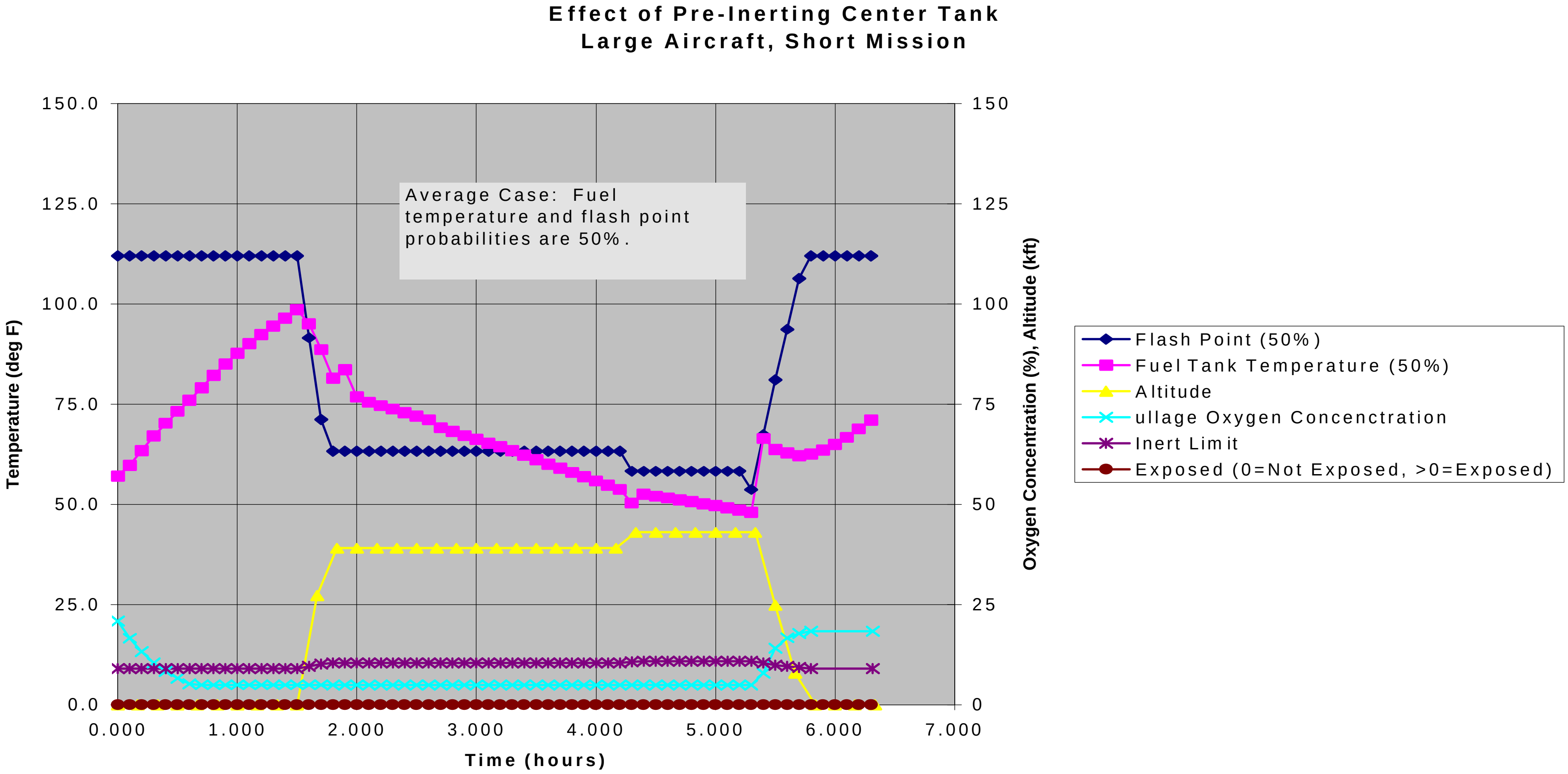


Figure 9 Ullage washing on the ground limits exposure to a flammable, non-inert fuel tank essentially to zero probability. This chart represents an average day combined with an average flash point fuel. The body (center) tank is almost filled for this mission.

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4.7. Inert Gas Supply

Several methods of supplying inerting gas were presented to the task group. Most of the methods used nitrogen, but carbon dioxide and exhaust gas were also presented.

4.7.1. Nitrogen

There are three types of nitrogen supplies: liquid nitrogen in Dewar bottles, gaseous nitrogen in high-pressure storage bottles, and gaseous nitrogen extracted from engine bleed air as mentioned in Section 3.1. Some of this technology exists while some of it is still in development.

Liquid nitrogen and gaseous nitrogen in storage bottles both require servicing at the airport to refill them. The on-board inert gas generating system (OBIGGS) does not require refilling but does require periodic maintenance and filter changes.

The two types of OBIGGS available presently are molecular sieve and permeable membrane. Molecular sieve systems have been in use since 1975 on various military aircraft. Molecular sieves adsorb oxygen from the air and can operate with source air pressures as low as 20 psig and temperatures between –20 ^{o}F and +120 ^{o}F. They are sensitive to liquids however and may need to be replaced if wetted. The adsorbed oxygen must also be flushed from the sieve at regular intervals. In operation, this means that two molecular sieves must be available and a valve cycles the source air between them to maintain a constant flow of inerting gas.

By contrast, permeable membrane systems are completely passive. They rely on the polymer membranes to separate nitrogen from air. These systems have been in commercial use since 1975 but have only recently been applied to aircraft. Permeable membranes work best with source air pressures of 60 psig and temperatures near 140 ^{o}F. A reduction of source air pressure to 30 psig would require approximately 3 times more membrane material to maintain the same output flow. A reduction to 15 psig would require 10 times more material. Thus, the system weight and its impact on the aircraft are sensitive to the source pressure.

Permeable membranes are also sensitive to source air flow. More source air is required to provide better purity (lower oxygen concentration). Three times more source air is required to achieve an oxygen concentration of 3% than for an oxygen concentration of 9%. The impact on aircraft resources can be minimized if a higher oxygen concentration can be permitted. Contaminates that could plug the membrane material would also require more bleed air to get the same effectiveness as an unplugged membrane.

4.7.2. Carbon Dioxide

There are three types of carbon dioxide (CO2) supplies: solid CO2 kept in cold storage (dry ice), gaseous CO2 in high-pressure storage bottles, and products of combustion. The dry ice and gaseous CO2 in bottles require servicing at the airport. Servicing for the combustion system is dependent on whether fuel or carbon is burned. Carbon combustion would require frequent servicing. Fuel combustion would likely require only periodic maintenance for filter changes, etc. These systems are conceptual at this time although dry ice was tried briefly in the 1950s.

It takes less carbon dioxide than nitrogen to inert a fuel tank. However, carbon dioxide dissolves into solution and evolves out of solution more readily than nitrogen. Consequently, fuel boost pump cavitation may occur because of altitude changes, pressure loss in fuel pipes or any other event that causes pressure changes. However, carbon dioxide was not pursued further in this study because it is a greenhouse gas that adversely affects the environment. Its use might be subject to future environmental restrictions or banned completely. Therefore, a more detailed study would be required to determine the feasibility of carbon dioxide as an inerting agent.

Due to the lack of hardware and test data required to complete a cost/benefit/feasibility analysis, this solution was not evaluated for this report.

4.7.3. Exhaust Gas

The use of exhaust gas was suggested as a means to inert the fuel tanks without adding bulky storage systems to the aircraft. The system would be self-contained and would likely only require periodic maintenance for filter changes. This is a concept only. There is presently no technology to evaluate at this time. Therefore, it was not considered further for cost, benefit, or feasibility in this report. However, there are some concerns with the concept.

Jet engines and auxiliary power units (APUs) do not burn fuel at a stoichiometric mixture ratio. They burn the fuel leaner than stoichiometric so that the exhaust gas is higher in oxygen than the typical combustion process. The oxygen level can range from 11% to 15% depending on the power setting for the engine and other factors. These levels are too high to be considered inert.

The exhaust stream of commercial aircraft engines is primarily ambient air due to the high fan-bypass ratio of these engines. This air contains 21% oxygen and is not inert. The lower oxygen concentrations (11-15%) must be drawn from the turbine section directly, or very close behind it, to avoid the fan bypass air. This section of the engine is typically at 1000 ^{o}F or higher and special materials are required to withstand the heat. Any penetration of the turbine case to install a bleed line would weaken the turbine case and increase the chance of engine damage from temperature stresses and vibration. Re-certification would be required to install a bleed line in the turbine case for existing engines and the cost would likely be prohibitive. A failure of the bleed line would create an unacceptable hazard to the aircraft.

Although the autoignition temperature of fuel is 450 ^{o}F, the exhaust gas must be cooled to 160 ^{o}F or less before it can be introduced into the fuel tank to protect components, fuel tank sealants, protective coatings, and fuel bladders. A large precooler would be required to reduce the gas temperature from >1000 ^{o}F to < 160 ^{o}F. Most transport aircraft have their engines mounted on the wings near the fuel tank so the location of a precooler is limited to the engine or engine pylon. On many aircraft, the addition of a larger, or an additional, precooler is not feasible due to space limitations in the pylon area. Other locations, such as the cargo compartment or the fuselage area could also be difficult due to space limitations and the need to provide outside cooling air to the precooler. This would require a duct and two air scoops on the side of the aircraft that add to the drag.

Another concern is a high concentration of water vapor in jet engine exhaust that would have to be removed before reaching the fuel tank. This is not desirable as water causes tank corrosion, promotes the growth of microbes in the fuel, and possibly would freeze at high altitude and block fuel pump inlets. Aircraft manufacturers design to avoid water in fuel tanks and the airlines perform frequent ground checks to make sure water is removed from the tanks before flight. Anything that adds water would require more systems and/or more frequent checking to avoid these problems.

There is also a fuel burn penalty for using exhaust or turbine gas. Turbine gases contribute to the energy needed to drive the engine fan to produce thrust. Exhaust gases expand and help to produce thrust. If some of the gas is diverted for other purposes then there is less thrust. The throttle setting must be increased to make up for the loss of thrust so more fuel is consumed. The estimated fuel penalty would be 5-10%.

Finally, there are contaminates in the exhaust gas that would have to be filtered prior to being introduced into the fuel tank. This would add to the size, cost, weight and maintenance of this method. There is a concern about the corrosive effects of the oxides of nitrogen and sulfur in the exhaust gases on the fuel system and tank. Filters would have to be maintained and a monitoring program would be required to avoid adverse affects to the fuel tank.

4.7.4. Fuel Enrichment of the Ullage

This concept atomizes fuel in the ullage space of the tank providing an atmosphere that is too rich for combustion. A pump would be energized when a tank sensor determined that the ullage might be combustible. The tank could never be emptied because there wouldn’t be any fuel to atomize into the ullage. The minimum fuel volume within a tank could not drop below 10% of the tank volume. This is a concept only. There is presently no technology to evaluate at this time. Therefore, it was not considered further for cost, benefit, or feasibility in this report. However, there are some concerns with the concept.

The primary concern for this system is that it could increase the severity of a post-crash fire if the tank was damaged. It’s also unclear if the sensor would deteriorate due to aging, how it predicts flammability, and what effect fuel slosh would have on it.

5. Installation Requirements

Ground-based fuel tank inerting consists of fuel scrubbing and ullage washing. Aircraft-based inerting consists of these same methods plus supplying inert gas to the tanks as fuel is depleted and/or during descent.

5.1. Installation of Ground-Based Inert Gas Supply

A ground-based inerting system requires a source of inerting gas at the airport. The most likely sources are liquid nitrogen or gaseous nitrogen produced by an air separation plant similar to, but larger than, the air separation equipment previously discussed. There are several manufacturers of air separation plants that may be willing to install a plant for free because their profit is obtained by selling the nitrogen to the airport's customers (airlines). The gaseous nitrogen could then be delivered to the aircraft by truck or by a pipeline between the plant and the terminal buildings. Another possibility would be portable air separation plants on trucks that could drive up to the aircraft prior to refueling.

Liquid nitrogen would probably have to be trucked into the airport storage area. The liquid nitrogen could then be delivered to aircraft by a separate truck or by a pipeline between the storage facility and the terminal buildings.

Figure 11 shows a typical airport arrangement. The fuel farm is located far from the terminal buildings. In this case, the distance from the fuel farm to the farthest terminal building is approximately 2 miles. The most likely location for a nitrogen storage facility is near the fuel farm. A pipeline from the nitrogen storage facility to the terminal buildings is a major construction project at most airports and will likely disrupt operations if the runways, taxiways or ramps have to be torn up to add the pipeline.

A better solution for the airport would be to scrub the fuel as it is delivered from the refinery. The inerting gas plant could be located nearby to provide nitrogen directly to the scrubbers with less disruption to the airport operations. However, this would still be a major change to the airport's fuel storage facility and could disrupt fuel delivery to the airlines during installation. In addition, fuel scrubbers decrease the flow rate into the fuel tanks, as previously discussed. At a time when refineries can barely keep up with current demand, due to the limitations of delivery pipelines between the refineries and the airports, this could have severe consequences for the airlines.

Another option is to deliver the nitrogen to the terminal with trucks. An additional truck near an aircraft at the terminal increases the risk of accidents with potential damage to the aircraft. If the trucks are carrying liquid nitrogen then there is an additional risk of spilling it on aircraft or people.

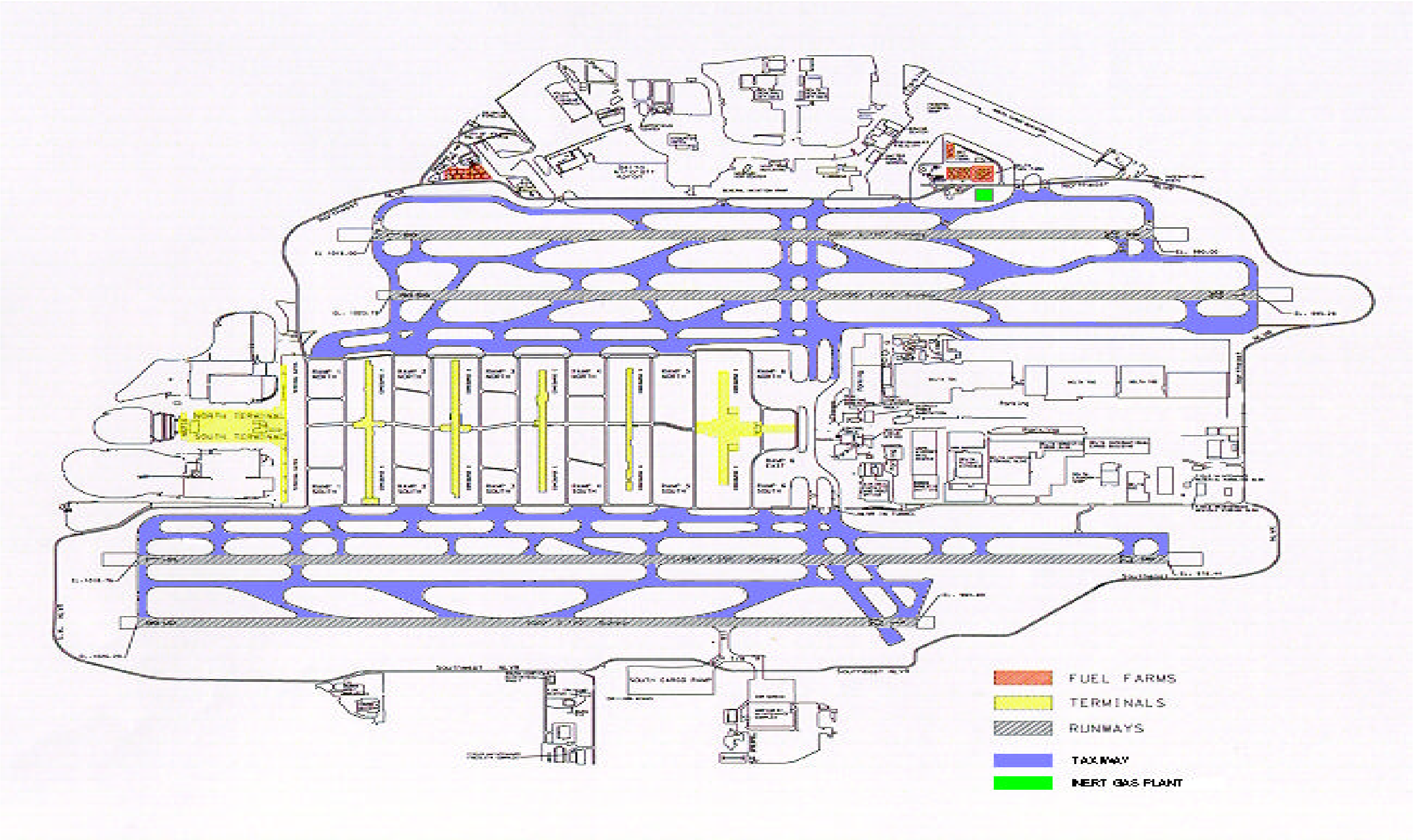

Figure 10 - Typical Airport Layout

The last option considered is to place small nitrogen generation units at each terminal. The effect on airport operations would probably be less than that caused by running a pipeline from a central nitrogen unit. Unit installation could be phased to minimize the impact on terminal gate operations. However, the economies of scale would probably not be realized and the overall cost might be equal to or greater than a central unit.

No attempt was made to estimate the cost impact of adding a nitrogen storage or generating facility to an airport's infrastructure. This would have required reviewing the layout of several hundred airports to determine the most likely location for the facility, the cost of construction in the local area of each airport, local building codes, etc. An attempt was made to estimate the cost of trucks carrying nitrogen from the storage facility to the terminal buildings. A basic assumption was that there would be one nitrogen truck for every fuel truck at the airport.

5.1.1. Ground-based scrubbing

Ground based scrubbing occurs during aircraft refueling or during the filling of the airport's fuel storage tanks. This can be accomplished in one of three ways: scrubbing the fuel as it comes from the refinery into the airport storage tanks or from the airport storage tanks to the airport fuel pit/trucks; scrubbing the fuel during refueling of the aircraft using a ground-based scrubber; and scrubbing the fuel during refueling using an aircraft-based scrubber. The first method, scrubbing the fuel as in enters the airport storage tanks or fuel pit/truck, does not require any aircraft equipment but requires modifications to the airport infrastructure or fuel trucks. The second method also does not require aircraft modification but requires that a device be coupled to the fuel pit/truck and that a source of inerting gas be available. The third method requires that fuel scrubbers be added to the aircraft and a supply of inerting gas be available during refueling.

5.1.2. Ullage Washing

Washing the tank ullage with nitrogen would require aircraft modifications to include a servicing/supply port, check valve, isolation valves and a distribution system. The servicing/supply port provides a means for introducing nitrogen into the aircraft tank(s). The distribution system provides nitrogen to vented tanks or incorporates isolation valves to selected tanks. Vent box mounted check or climb/dive valves prevent ambient air from diluting the nitrogen in the fuel tanks. The check valve prevents fuel from exiting the nitrogen servicing port.

Although the installation of ullage washing components would be similar for all aircraft, distribution systems will vary according to the fuel tank size and location on the aircraft. Distribution systems on aircraft with non-traditional tanks, e.g. tail tanks, would require more elaborate distribution systems. Ullage washing does not require any fuel delivery modifications, but would require minor airframe modifications.

5.2. Installation of Aircraft-Based Fuel Tank Inerting

5.2.1. Overview

Aircraft inerting systems will require extensive aircraft modifications. Aircraft inerting systems require the same equipment as the hybrid system plus a means of inert agent development, inert agent storage, and possibly indication systems and oxygen sensors. With the exception of inert agent generation, all aircraft inerting systems are principally the same. The currently viable technologies are nitrogen storage and air separation. Future possibilities may include exhaust gas and CO2.

5.2.2. Air Separation

Permeable membranes and molecular sieves both require a conditioned air source to develop the nitrogen enriched air. Currently, the only air source available in flight is engine bleed air.

On medium and large aircraft, bleed air could be obtained from either existing pneumatic systems or the ECS systems. Many smaller turboprop aircraft simply do not have sufficient bleed air available to spare; therefore, small transport aircraft would require an additional source separate from the engine to supply bleed air.

Present day aircraft are optimized for certain flight regimes and their systems are highly integrated. Engine bleed air is used by the environmental control system to pressurize the cabin and by the anti-ice system to minimize wing and tail icing. Under some flight conditions, such as takeoff or descent, all of the engine bleed air is used for existing aircraft equipment. There isn't any more available to supply OBIGGS systems. This was found to be the case for four of the six generic airplanes studied. (Data was not available for the other two aircraft types.) The suppliers assumed an ullage washing system and a gas purity of 9% for their calculations but the lack of bleed air prevented the OBIGGS systems from supplying inert air to the fuel tanks throughout the flight profiles.

5.2.3. Exhaust Gas

While the Task Group does not believe that this technology is currently viable, it may be of value to aircraft designers in the future.

The collection of engine exhaust gas would require the installation of a bleed air port within the engine's turbine stage(s). Since nearly all engines use fan air to assist in cooling the engine's turbine, the location of the bleed air port would have to be properly located to avoid the fan air. Tapping into an existing engine turbine stage would require extensive and costly engine re-work and re-certification.

Adding to the complexity of installing an exhaust bleed-air port, engine exhaust systems will require conditioning, filtering, overheat protection and a distributing system. For estimating purposes, existing ECS systems could provide a minimum baseline for determining the size and cooling requirements of an engine exhaust system.

Engine exhaust gas contaminates include high levels of sulfur, nitrogen, oxygen, water, carbon dioxide, hydrocarbons and other engine ingested chemical compounds. These contaminates must be filtered to avoid introducing corrosives into the fuel tanks and the resultant structural integrity inspections that would be required.

5.2.4. Combustion (Carbon Dioxide) Systems

While the Task Group does not believe that this technology is currently viable it may be of value to aircraft designers in the future.

Combustion systems are currently in the concept or prototype stage of development. The following description is based on the information provided to the Task Group by a supplier of a prototype system.

Combustion inerting systems require that a combustion process occur to develop carbon dioxide (CO2) which is used as the inerting agent. To support the combustion process, a combustion chamber is required which operates at extremely high temperatures and appears to be large in size and shape. The hot CO2 would be cooled to the required temperature using air-to-air heat exchangers and a source of cool air. These systems must be treated as a fire hazard, which requires they be located in existing fire zones or that a fire zone be created specially for them. A combustion system could be frugal with aircraft resources requiring little power or bleed air for operation.

5.2.5. Cryogenic Systems

Cryogenic inerting systems require a system reservoir to store liquid agent. Sizing of reservoirs is dependent on aircraft application and is sensitive to changes in external pressures and temperatures.

Due to pressures and temperatures within the vessel, containment vessels tend to be very large and bulky. Although larger aircraft could accommodate these vessels, smaller aircraft might not so easily accommodate them. Also, to accommodate these vessels, aircraft will require extensive airframe structural modifications and/or analysis to insure the airframe’s integrity.

5.3. Installation Requirements for All Inerting Systems

5.3.1. Ground-based Systems

Installation of ground based inerting systems at a minimum will require approximately 51 man-hours over an elapsed time of 70-75 hours. Table 1 summarizes total expected installation effort to inert the center wing tank.

Table 1 – Installation Time for Ground-Based Center Tank Inerting System

	Small Aircraft		Medium Aircraft		Large Aircraft	
BASIC SYSTEM REQUIREMENTS	Hours	Men	Hours	Men	Hours	Men
Drain Tanks	1	2	1.5	2	2	2
Open Tanks	1	2	1	2	1	3
Purge Fuel Tanks	24	1	24	1	24	1
Install Quick Disconnect	4	2	1	2	1	2
Install Check Valve	2	1	1	1	1	1
Install Regulator	2	1	2	1	2	1
Install Indication System	7.5	2	7.5	2	7.5	2
Install Climb/Dive Valve	6	2	6	2	6	2
Test System	2	2	2	2	2	2
Close/Seal tanks	1	2	1	2	1	3
System Leak Check	2	2	2	2	2	2
TOTAL INSTALLATION ELAPSED TIME	50.5		51		51.5	
TOTAL INSTALLATION MANHOURS	71		72		75	

5.3.2. Aircraft-based Systems

All aircraft inerting systems may require an indication system in the cockpit and at the servicing location. Cockpit indication provides for crew monitoring while servicing location indication provides for maintenance monitoring. Indication systems will vary in complexity based on the type of inerting agents used and the arrangement of the fuel tanks to be inerted. Indicating systems would warn crews and/or maintenance personnel of the loss of system operation and any degradation of function. Indicator sizing requirements are comparable on all fleet types but would be more restrictive on smaller transport aircraft due to limited space within cockpits.

Installation of aircraft inerting systems at a minimum will require approximately 60 man-hours over an elapsed time of 150 hours. Smaller aircraft would require smaller distribution systems, but may require additional installation time for components since accessibility and spacing are at a premium. Engine bleed air and/or engine exhaust systems would add 15 man-hours per engine exclusive of any engine re-work, if necessary. Reservoirs and indication systems will add 30 and 15 man-hours respectively. Tables 2, 3 & 4 provide estimates of installation effort.

Table 2 – Installation Time for Aircraft-Based OBIGGS System (All Tanks)

	Small Aircraft		Medium Aircraft		Large Aircraft	
AIR SEPARATION TECHNOLOGY	Hours	Men	Hours	Men	Hours	Men
Basic Effort (Above)	71	-----	72	-----	75	-----
Module Installation	15	2	15	2	15	2
Engine Bleed/Exhaust Collection	7.5	2	7.5	2	3.75	4
Bleed/Exhaust Conditioning and Distribution System	4	2	6	4	12	6
Filtration System	2	2	2	2	2	2
TOTAL ELAPSED TIME	60.5		61		61.5	
TOTAL MAN HOURS	127		144		196	

Table 3 – Installation Time for Aircraft-Based Combustion System

	Small Aircraft		Medium Aircraft		Large Aircraft	
COMBUSTION TECHNOLOGY	Hours	Men	Hours	Men	Hours	Men
Basic Effort (Above)	71	-----	72	-----	75	-----
Combustion Vessel	15	2	15	2	15	2
Distribution System	3	2	5	2	8	2
TOTAL ELAPSED TIME	60.5		61		61.5	
TOTAL MAN HOURS	107		112		121	

Table 4 – Installation Time for Aircraft-Based Cryogenic (Liquid Nitrogen) System

	Small Aircraft		Medium Aircraft		Large Aircraft	
CRYOGENIC TECHNOLOGY	Hours	Men	Hours	Men	Hours	Men
Basic Effort (Above)	71	-----	72	-----	75	-----
Cryogenic Vessel	15	2	15	2	15	2
Distribution System	3	2	5	2	8	2
TOTAL ELAPSED TIME	60.5		61		61.5	
TOTAL MAN HOURS	107		112		121	

6. Technical Data

The following data provides estimates of the impact of the various systems on the generic aircraft that formed the basis of this study. Several suppliers spent long hours analyzing the generic aircraft data and sized their systems accordingly. The suppliers based their estimates on an analysis of the various generic aircraft, specifically their fuel volume, mission length, starting fuel volume, engine bleed performance, climb and descent rates, and the setting of the vent check valves that keep ambient air out of the fuel tanks.

6.1. Weight

The following weights, in Table 5, are a composite of the weights estimated by various suppliers of air separation modules. The suppliers assumed that at least 30 psig to 60 psig of engine bleed air would be available at the necessary flows and that the bleed air would be cooled to an acceptable temperature for the module. Ullage washing was assumed, which requires less purity of the nitrogen and minimizes the bleed air requirement. This system was intended to inert all fuel tanks on the aircraft.

Because of the lack of available bleed air on present day aircraft and the resulting lack of inerting during some phases of the flight profile, OBIGGS systems are not considered a viable option for incorporation into existing aircraft or for retrofit. Therefore, there is no air separator weight estimate for present day aircraft or for those requiring retrofit.

The additional system weight consists of precoolers to cool the engine bleed air for the air separator modules, fans to blow cool air over the precoolers during ground operations, water/dust separators to avoid contaminating the air separation modules, valves to control flow to the tanks and to shut off some of the air separator modules during cruise (when only “make up” gas is required to replace depleted fuel), a distribution system, pressure sensors, pressure regulators, oxygen sensors, and vent check valves.

Table 5
Future Aircraft Air Separator Technology Weight

	Large Transport	Medium Transport	Small Transport	Regional Turbofan	Regional Turboprop	Business Jet
Module Weight (lbs.)	805	408	158	134	110	173
Additional System Weight (lbs.)	1547	941	558	522	486	581
Total Weight (lbs.)	2352	1349	716	656	596	754

For present day aircraft and those requiring retrofit, a system that does not require bleed air is a better match for the aircraft. However, they carry the penalty of higher weight than the air separation technology. The following estimate, in Table 6, is based on a liquid nitrogen storage system sized to inert all fuel tanks on the aircraft.

The additional system weight consists of a distribution system, fuel scrubbers, pressure sensors, pressure regulators, oxygen sensors, electrical wiring, mounting hardware, finish installation cover panels, and vent check valves. Since this installation had not been previously analyzed, the additional system weight for the air separator technology was semi-arbitrarily divided by two for this estimate. For this estimate, fuel scrubbing and a "make-up" system were assumed since this requires less nitrogen than ullage washing. (A "make-up" system replaces the consumed fuel with inert gas instead of letting ambient air replace the consumed fuel.) This assumption is valid since liquid nitrogen is pure i.e. it contains no oxygen.

Table 6
Present Day Aircraft Liquid Nitrogen Technology Weight

	Large Transport	Medium Transport	Small Transport	Regional Turbofan	Regional Turboprop	Business Jet
LN2 Weight + Storage Vessel & Controls (lbs.)	1611	765	230	179	128	262
Additional System Weight (lbs.)	774	642	558	551	543	564
Total Weight (lbs.)	2385	1407	788	730	671	826

6.2. Size (cargo/passengers/fuel displaced)

The suppliers of air separation modules have only grossly estimated the approximate size of their module package. The largest would occupy the equivalent of a cube that is 5 feet on each side while the smallest would be approximately 14 inches on each side. Due to the severe time constraint imposed by the FAA for this study, the Task Group has been unable to determine the size of the additional equipment needed to mount the air separator modules and cool the engine bleed air to acceptable levels. It is probable that the package would be double the size of the module package and displace some cargo, as the cargo compartment is the most likely location for mounting this equipment. Therefore, no cost will be associated with this item and the Task Group will assume that it is somewhat compensated by the weight penalty listed in section 6.1 and it's associated costs listed in Section 9.

6.3. Cost

The following module costs, in Table 7, are a composite of the costs estimated by various suppliers of air separation modules. The costs quoted are for a shipset of modules where a shipset has the capability to inert all fuel tanks on the aircraft. Design and installation costs will be discussed in Section 9.

Table 7

Future Aircraft Air Separator Technology Cost

Shipset Cost (US Dollars)	Large Transport	Medium Transport	Small Transport	Regional Turbofan	Regional Turboprop	Business Jet
Modules	$606,000	$304,000	$113,000	$95,000	$77,000	$125,000

7. FAA Certification Requirements

7.1. Similarity/Previous Test or Flight Experience

There is no previous test or flight experience in commercial aircraft. In addition, it is not yet clear what regulations might be enacted by the FAA for the certification of fuel tank flammability reduction systems. Thus, the certification requirements and costs cannot be estimated at this time.

7.2. Additional Analysis and Testing

Analysis and testing is dependent of the regulation. Since it is not yet clear what requirements might be enacted by the FAA, the Task Group cannot estimate the certification requirements or costs to comply with the new regulation. However, there are existing requirements for the certification of aircraft systems that would be expected to apply to inerting. The costs to comply with the existing requirements are shown as part of the design cost in Section 9.

7.3. Other Effects on Aircraft

All of the systems add substantial weight to the aircraft. Some existing aircraft could be re-certified for the additional weight allowing the airlines to carry the same payload as they currently do. However, there will be some impact on operations resulting from the increased weight. Runway lengths for takeoff and landing will increase slightly. Fuel costs will increase also and these are estimated in Section 9.

All of the proposed systems utilize a vent check valve to keep the inert gas in the tank and to delay the introduction of ambient air. By holding inert gas in the tank during climb and cruise, the vent check valves cause the wing to become slightly pressurized. By keeping ambient air out of the tank during descents, the vent check valves allow the tank to be slightly compressed by outside air. The fuel tank structure may have to be re-certified to show that it still complies with all strength requirements imposed by the FAA due to the change in loads.

Air separation technologies may be viable for some aircraft that can supply the required engine bleed air. This may require re-certification of the engine by the engine manufacturer and re-certification of the aircraft by the aircraft manufacturer to show that the additional bleed air requirement does not adversely impact engine operation and aircraft performance. In addition, it is possible that during certain phases of the flight the loss of an engine and its bleed air may require operational changes. For example, the loss of one engine’s bleed air on a twin may require choosing between pressurizing the cabin or inerting the fuel tanks.

8. Safety

8.1. Effectiveness in Preventing Overpressure Hazard

Military, live-fire testing has demonstrated that nitrogen inerting prevented catastrophic tank over pressures with an ullage oxygen concentration from 12% [1] and 10% [2] at sea level for up to 23mm high energy incendiary (HEI) rounds. The military has adopted 9% oxygen concentration as the inert limit. Laboratory testing showed that inert limits for combustion increased with altitude from less than 10% to over 13% oxygen concentration from sea level to 60 kft [3]. Since the 9% oxygen concentration limit prevents tank over-pressures for energetic ignitions sources up to 23mm HEI rounds, this would also protect against any internal threats from within intact commercial aircraft fuel systems. However, in events where the fuel system has ruptured from other causes allowing air to enter the fuel system or fuel to leak, nitrogen inerting may not prevent fuel fires or explosions inside or outside the fuel system.

8.2. Evaluation against Historical Commercial Aircraft Overpressure Events

The list of commercial aircraft over-pressure events is presented in Table 1. An evaluation of the effectiveness of a full time inerting system is also shown in Table 1, assuming the inerting system was functional and the entire fuel/vent system was inerted at the time of the incident. Inerting may not have prevented catastrophic results in all of the events where the fuel tanks were open or had been open for maintenance or ruptured from other causes. These are the engine separation events (3,4, and 5), the 727 sabotage event (6), and ground maintenance events where the tanks were open or had been opened (13 and 14). The evidence in the727 bomb-sabotage event (6) suggested that the force caused by the bomb blast compromised the structural integrity in this area, causing a fuel tank rupture, fire, and in-flight structural breakup of the right wing. Whether, the initial bomb blast would have caused a hull loss without the subsequent fire is not known. Also, it is not known that if had the fuel tank been inerted if the subsequent fire would have occurred. Therefore, we can only conjecture whether inerting would have prevented a hull loss in this sabotage event.

Inerting could have prevented the catastrophic results in all of the remaining events, the lightning strikes (1 and 2), refueling events (9-12), the TWA and PAL CWT events (7 and 8), and the DC9 ground maintenance event (15).

Table 8
Evaluation of Effectiveness of Inerting For Historic Fuel Tank Explosion Events

		Operational Phase				Ignition Source					
No.	Year – airplane	Inflight	Ground Ops	Ground Maint.	Refueling	Lightning	Overwing Fire - Inflight	Static Discharge	Sabotage	Unknown	Could Inerting[1] have prevented catastrophic outcome?
1	1963 – 707	X				x					Yes
2	1976 – 747	X				x					Yes
3	1965 Eng Sep 707	X					x				No
4	1970 Eng Sep DC8	X					x				No
5	1992 Eng Sep 707	X					x				No
6	1989 - 727 Sabotage	X							x		Unknown
7	1996 - 747 TWA	X								x	Yes
8	1990 – 737-300 PAL		X							x	Yes
9	1970 – 727				x			x			Yes
10	1970 – 727				x			x			Yes
11	1973 – DC8				x					x	Yes
12	1989 – Beech 400				x			x[2]			Yes
13	1967 – 727			x				x			No
14	1974 – DC8			x						x	No
15	1982 – DC9			x						x[3]	Yes

[1] Assuming fuel/vent system was inert at the time of the incident

[2] Static charge generated by non-conductive foam in another tank

[3] Suspect Dry Running Boost Pump

8.3. Negative Impacts

The impacts to the aircraft have been previously covered in Sections 4 and 5.

8.4. Increased Landings due to Range Reduction (due to added system weight)

The Task Group was not able to define all of the cost impacts due to the limited time frame for the report.

8.5. Increased Landings due to Extra Fuel Consumed

The Task Group was not able to define all of the cost impacts due to the limited time frame for the report.

8.6. Personnel Hazards

All inerting systems are designed to minimize the accumulation of oxygen in a confined space. Nearly all inerting systems produce environments hostile to humans. In all cases, a person will lose consciousness if exposed to an inert atmosphere. Death is possible if the person cannot be removed from the inerted fuel tank within a few minutes.

Liquid nitrogen systems require the cryogenic transport and/or storage of nitrogen in liquid form, which boils at -195 °C or -315 °F. Transport, storage and handling of liquid nitrogen requires precautions to prevent severe skin burns upon contact.

Gaseous nitrogen systems lessen the burn risk associated with liquid nitrogen. However, the pressurized containers present a hazard. A broken bottle or distribution line can flood the compartment with nitrogen causing asphyxiation. The high pressure gas escaping the bottle or line could injure someone nearby. And if the storage bottle mounting hardware was loosened, to change the bottle for example, the bottle could move rapidly and injure someone.

Like liquid nitrogen, carbon dioxide generators using dry ice pose the same threat of severe skin burns and asphyxiation.

Combustion systems that produce carbon dioxide and exhaust gas inerting systems operate at high temperatures. There is a potential for severe burns while servicing the equipment.

All types of inerting systems will require almost daily interaction with maintenance and other ground personnel of all cultures and education levels. Inerting system dangers will grow proportionally with the desire to launch an aircraft, and mistakes will be made.

8.7. Aircraft Hazards or Effects

Fuel tank inerting adds additional threats to aircraft from additional system complexity, pressure vessel ruptures and failure modes that may impact other systems.

Inerting systems using heat also pose threats. Burn chambers/engine exhaust systems expose aircraft and occupants to the threat of extreme heat if unconfined. Besides the obvious threat of fire, structural airframe damage is also possible. Airframe structure heated beyond design limitations loses strength, which is not apparent to visual inspections. With temperatures nearing 900°F for chambers and 1000°C for engine exhaust, system failures could easily start a chain reaction resulting in hull loss with little warning.

Aircraft weight and balance must also be considered for all aircraft inerting systems and will vary with aircraft size and system size.

8.8. Other Equipment Hazards or Effects

Equipment required to support inerting systems also pose threats. Ground support equipment will require maintenance and testing to verify proper operation. The same threats that could occur on the aircraft are possible with ground support equipment

Existing airport gate and ramp space is already congested with numerous types of support equipment. Each piece of new equipment introduced in the airport ramp areas increases the likelihood of accidents. Accidents involving cryogenic vessels will dramatically increase the severity of injury to ground personnel and aircraft and/or equipment.

Waste products associated with the combustion type inerting systems require the disposal of burned carbon. Due to the high temperatures, there is a threat to the aircraft, personnel and storage facilities during removal of hot waste product. Exposing the airport ramp environment to the hot waste product could be comparable to an open flame in the area. Generally, open flames are kept at least 50 feet from the aircraft. A combustion system will require careful design to eliminate these hazards.

The production of CO2 is also an environmental concern as a “green-house” gas. The Environmental Protective Agency (EPA) has successfully lobbied for the passage of numerous clean air acts. The EPA’s vigilance in preventing “green-house” gases may prevent or severely restrict the use of this technology.

9. Cost Impact

9.1. Retrofit

9.1.1. Air Separator Technology

The Task Group was not able to define all of the cost impacts due to the limited time frame for the report.

9.1.2. Liquid Nitrogen Technology

The Task Group was not able to define all of the cost impacts due to the limited time frame for the report.

9.1.3. Simple Hybrid System

The Task Group was not able to define all of the cost impacts due to the limited time frame for the report.

9.2. Current Aircraft

9.2.1. Air Separator Technology

Air separator technology requires more bleed air than is available from present day aircraft. Therefore, this technology is not considered viable and no costs are provided for current aircraft. However, the cost of this technology for future aircraft has been estimated in section 9.3.

9.2.2. Liquid Nitrogen Technology – All Tanks

The following liquid nitrogen storage bottle costs were provided by the suppliers. The other costs are scaled from estimates made by Boeing for the OBIGGS system in the industry response (July 1997) to the FAA Request for Comment. This system includes check valves, distribution pipes, pressure regulators, control orifices, pressure sensors, and climb/dive check valves.

The Task Group was not able to define all of the cost impacts due to the limited time frame for the report, so they are left blank. The system was assumed to be installed only on aircraft with heated body tanks and provides inerting for all tanks. The Task Group was not able to determine if the Regional Turbofan and Turboprop had heated body tanks for this analysis. Therefore, the cost estimate for these aircraft is unknown.

Table 9
Present Day Aircraft with Heated Body Tanks, Liquid Nitrogen Technology, Non-recurring Costs

Fleet Cost (US Dollars)	Large Transport	Medium Transport	Small Transport	Regional Turbofan	Regional Turboprop	Business Jet
LN2 Bottle	$31,306	$16,600	$7,269	$7,111	$5,287	$
Design	$34M	$32.7M	$31.9M	$31.8M	$31.7M	$31.9M
Installation	$3.9B	$3.3B	$18.9B	$2M	$1.5M	$1.2M
Operational						
Maintenance						
Infrastructure						
Range Lost						
Total Cost	$3.94B	$3.36B	$18.9B	Unknown	Unknown	0
# of Aircraft	1280	1092	6192	Unknown	Unknown	0
Cost per Aircraft	$3.0M	$3.1M	$3.1M	Unknown	Unknown	0

There is also a penalty to the aircraft due to the added weight of the system. In most cases, the added weight merely results in extra fuel consumed to travel the same distance. However, if the aircraft is at its maximum weight limit then some passengers cannot be carried in order to put in the extra fuel. This results in an additional penalty for lost revenue and appears in the row labeled "Long Mission" where the aircraft is the most full.

Table 10
Present Day Aircraft with Heated Body Tanks, Liquid Nitrogen Technology, Annual Recurring Costs
Due to Added System Weight

Annual Fleet Cost	Large Transport	Medium Transport	Small Transport	Regional Turbofan	Regional Turboprop	Business Jet
	$423.6M	$138.0M	$244.3M	Unknown	Unknown	$1.2M

In addition, liquid nitrogen would have to be transported to the aircraft at each refueling. This incurs costs at the airport to maintain a supply of liquid nitrogen, the means to transport it to the aircraft, and the training of personnel to handle it. For this estimate, trucks of liquid nitrogen were assumed as the means of transport for the reasons listed in Section 5.1. The Task Group was not able to define all of the cost impacts due to the limited time frame for the report, so they are left blank.

Table 11
Airport Costs for Liquid Nitrogen Technology

Non-recurring		
Nitrogen Trucks	$3.3M	Assumes 20 per airport
O2 Detectors	$16,500	Assumes 22 per airport
Annual Recurring		
Inerting Truck Fuel	$11,000	Assume 5,000 miles at 10 mpg and $1.10 per gallon
Inerting Truck Maint	???	No data at this time
Inerting Truck Operator Training	???	No data at this time
Inerting Truck Inspection	$10,000	20 trucks at $500 per inspection
O2 Detector Calibration	$2,640	Assumes 22 sensors per airport and recalibration twice per year at mechanic's rate of $60/hour
O2 Detector Training	???	No data at this time

9.2.3. Simple Hybrid System – Body (Center Tank) Only

The following costs are the estimate for a very simple system to inert the body tank only. The assumed system is a hybrid system with a distribution system in the aircraft and the inert gas supply on the ground. The distribution system consists of a quick disconnect port for hookup to the inert gas supply, a regulator to avoid damage to the tank structure, a check valve to keep fuel from flowing out of the tank to the nitrogen supply, distribution pipes in the tank, and 2 vent check valves to hold the inert gas in the tank.

Equipment must be installed on the aircraft and at the airport. The airport equipment consists of trucks carrying nitrogen in liquid or gaseous form and an oxygen detector. Although nitrogen could be provided to each aircraft by underground pipes it's virtually impossible to estimate the cost impact of installing the piping at every airport. However, it is possible to estimate the number of trucks that would be required; this task group has assumed there would be one nitrogen truck for each refueling truck at a typical airport. This follows since the inerting would occur during or immediately after the aircraft was refueled. For a "typical" airport, 20 fuel trucks were assumed which is probably much lower than the actual value. Large airports such as LAX, JFK and ORD would have many more while smaller airports may have fewer.

The oxygen detector is needed to ensure that the fuel tanks' oxygen content is safe. This would be determined by having the inerting truck operator measure the oxygen level coming out of the vent system while adding nitrogen to the tank. The operator would have to be properly trained to use the detector and the detector would require recalibration periodically.

The Task Group was not able to define all of the cost impacts due to the limited time frame for the report, so they are left blank. The system was assumed to be installed only on aircraft with heated body tanks. The Task Group was not able to determine if the Regional Turbofan and Turboprop had heated body tanks for this analysis. Therefore, the cost estimate for these aircraft is unknown. Also, the Task Group was not able to define the system weight due to limited time so the recurring cost estimate accounts only for the nitrogen used for inerting.

Table 12
Production Aircraft with Heated Body Tanks, Hybrid Inerting System, Non-Recurring Cost

Fleet Cost (US Dollars)	Large Transport	Medium Transport	Small Transport	Regional Turbofan	Regional Turboprop	Business Jet
Design	$2.3M	$2.2M	$4.3M	Unknown	Unknown	$0
Installation	$99.9M	$85.3M	$483.5M	Unknown	Unknown	$0
Operational				Unknown	Unknown	$0
Maintenance				Unknown	Unknown	$0
Infrastructure				Unknown	Unknown	$0
Range Lost				Unknown	Unknown	$0
Total Cost	$102M	$87M	$488M	Unknown	Unknown	$0
# of Aircraft	1280	1092	6192	Unknown	Unknown	0
Cost per Aircraft	$150,000	$144,000	$145,000	Unknown	Unknown	$0

Table 13
Production Aircraft with Heated Body Tanks, Hybrid Inerting System, Annual Recurring Cost
No Weight Penalty Assumed

Fleet Cost (US Dollars)	Large Transport	Medium Transport	Small Transport	Regional Turbofan	Regional Turboprop	Business Jet
Liquid Nitrogen	$92,067	$49,216	$866,770	Unknown	Unknown	$0
Cost per Aircraft	$71	$45	$140	Unknown	Unknown	$0
OR						
Gaseous Nitrogen	$36.2M	$19.3M	$35.1M	Unknown	Unknown	$0
Cost per Aircraft	$28,266	$17,711	$5,676	Unknown	Unknown	$0

Table 14
Airport Costs for Body Tank Hybrid Inerting System

Non-recurring		
Nitrogen Trucks	$3.3M	Assumes 20 per airport
O2 Detectors	$16,500	Assumes 22 per airport
Annual Recurring		
Inerting Truck Fuel	$11,000	Assume 5,000 miles at 10 mpg and $1.10 per gallon
Inerting Truck Maint	???	No data at this time
Inerting Truck Operator Training	???	No data at this time
Inerting Truck Inspection	$10,000	20 trucks at $500 per inspection
O2 Detector Calibration	$2,640	Assumes 22 sensors per airport and recalibration twice per year at mechanic's rate of $60/hour
O2 Detector Training	???	No data at this time

9.3. New Aircraft

9.3.1. Air Separation Technology – All Tanks

The following module costs are a composite of the costs estimated by various suppliers of air separation modules, assuming that all fuel tanks are inerted. The other costs are scaled from estimates made by Boeing for the industry response (July 1997) to the FAA Request for Comment. This system includes the air separator modules, precoolers, water/dust separator, shutoff valves, flow control valves, check valves, distribution pipes, pressure regulators, control orifices, pressure sensors, and climb/dive check valves.

Table 15
Future Aircraft Air Separator Technology Non-recurring Costs

Fleet Cost (US Dollars)	Large Transport	Medium Transport	Small Transport	Regional Turbofan	Regional Turboprop	Business Jet
Modules	$606,000	$304,000	$113,000	$95,000	$77,000	$125,000
Design	$34M	$32.7M	$31.9M	$31.8M	$31.7M	$31.9M
Installation	$3.9B	$3.3B	$18.9B	$2M	$1.5M	$1.2M
Operational						
Maintenance						
Infrastructure						
Range Lost						
Total Cost	$3.94B	$3.36B	$18.9B	Unknown	Unknown	0
# of Aircraft	1280	1092	6192	Unknown	Unknown	0
Cost per Aircraft	$8.3M	$4.7M	$3.4M	Unknown	Unknown	0

There is also a penalty to the aircraft due to the added weight of the system. In most cases, the added weight merely results in extra fuel consumed to travel the same distance. However, if the aircraft is at its maximum weight limit then some passengers cannot be carried in order to put in the extra fuel. This results in an additional penalty for lost revenue and appears in the row labeled "Long Mission" where the aircraft is the most full of fuel.

Table 16
Future Aircraft Air Separator Technology Recurring Costs

Annual Fleet Cost	Large Transport	Medium Transport	Small Transport	Regional Turbofan	Regional Turboprop	Business Jet
	$652.4M	$190.7M	$262.7M	Unknown	Unknown	Unknown

9.3.2. Air Separation Technology – Center Tank Only

The following module costs are a composite of the costs estimated by various suppliers of air separation modules. The other costs are scaled from estimates made by Boeing for the industry response (July 1997) to the FAA Request for Comment. This system includes the air separator modules, precoolers, water/dust separator, shutoff valves, flow control valves, check valves, distribution pipes, pressure regulators, control orifices, pressure sensors, and climb/dive check valves.

Table 17
Future Aircraft Air Separator Technology Non-recurring Costs

Fleet Cost (US Dollars)	Large Transport	Medium Transport	Small Transport	Regional Turbofan	Regional Turboprop	Business Jet
Modules	$606,000	$304,000	$113,000	$95,000	$77,000	$125,000
Design	$34M	$32.7M	$31.9M	$31.8M	$31.7M	$31.9M
Installation	$3.9B	$3.3B	$18.9B	$2M	$1.5M	$1.2M
Operational						
Maintenance						
Infrastructure						
Range Lost						
Total Cost	$3.94B	$3.36B	$18.9B	Unknown	Unknown	0
# of Aircraft	1280	1092	6192	Unknown	Unknown	0
Cost per Aircraft	$8.3M	$4.7M	$3.4M	Unknown	Unknown	0

There is also a penalty to the aircraft due to the added weight of the system. In most cases, the added weight merely results in extra fuel consumed to travel the same distance. However, if the aircraft is at its maximum weight limit then some passengers cannot be carried in order to put in the extra fuel. This results in an additional penalty for lost revenue and appears in the row labeled “Long Mission” where the aircraft is the most full.

Table 18
Future Aircraft Air Separator Technology Recurring Costs Due to Added System Weight

Annual Fleet Cost	Large Transport	Medium Transport	Small Transport	Regional Turbofan	Regional Turboprop	Business Jet
	$333.6M	$108.7M	$191.7M	Unknown	Unknown	Unknown

10. Conclusions

At this time, nitrogen appears to be the best inerting agent and there are several means of providing it to the aircraft. Ground-based ullage washing in combination with the drop in temperature within the tank reduces exposure to a flammable, non-inerted tank to approximately 1%. This is the most cost effective solution studied, with the cost over a 10-year period estimated at approximately $3-4 billion.

Present day aircraft do not have enough bleed air, in most cases, to supply an OBIGGS type system. However, OBIGGS systems can be designed into future aircraft without adverse effects for the engine.

If a full time inerting system is required for present day aircraft or retrofit aircraft then liquid or gaseous nitrogen storage could be placed aboard the aircraft. These systems tend to be a little heavier than OBIGGS and require additional airport infrastructure to support them. The overall cost for a 10-year period is similar to OBIGGS.

The following table provides a summary of the cost and benefit of each system.

Technology	**Effectiveness**	**Cost over 10 Years (US Dollars)**
On-board Liquid Nitrogen for All Tanks	100%	$35.7B
On-board Gaseous Nitrogen for All Tanks	100%	$33.9B
Air Separator Modules for All Tanks	100%	$37.3B
Air Separator Modules for the Center Tank	100%	$32.6B
Ground-based Ullage Washing with natural Fuel Cooling for Center Tank	99%	$4B with gaseous nitrogen $3B with liquid nitrogen