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An Analysis of Factors Effecting Cargo Bay Fire Suppression Using a Fuel Tank Inerting System

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16. Abstract

Adding the capability of inert gas generation for fuel tank inerting to a commercial transport airplane has the potential to improve fire safety and reduce the weight and complexity of existing cargo bay fire suppression systems. To determine the effectiveness of a potential fuel tank inerting system for use as a cargo bay fire suppression metered system, a single air separation module (ASM) was tested to obtain specific performance points relevant to cargo bay fire suppression. These performance points were then used to calculate the time required to inert a single cargo bay with that inerting system and also to calculate how much time the cargo bay would not be inert using the Onboard Inert Gas Generation System (OBIGGS) with a discharge of halon. The acquired ASM performance data illustrated that an ASM based OBIGGS used for fuel tank inerting would be consistent with the requirements for a cargo bay fire suppression metered agent system. The nitrogen-enriched air (NEA) flow was very sensitive to ASM feed pressure (bleed air pressure) and the NEA flow from the ASM decreases as the static permeate pressure increases (aircraft altitude decreases). As expected, it is easier to inert the cargo bay as pressure altitude increases due to the decrease of gas mass in the compartment. The results of modeling the oxygen concentration with a halon discharge and representative air leakage into the bay to determine time not inert for given conditions illustrated the same date trends. This means that the same parameters that decreased the calculated times to inert also reduced or eliminated the calculated times not inert. When observing the sensitivity of the time not inert, results to decreasing the air leakage rate and increasing the size of the halon shot both decreased calculated time not inert values, although both values are also very sensitive to the ASM feed pressure. The time not inert values calculated were not that sensitive to cargo bay size with the same size OBIGGS provided that the leakage rate was the same and the cargo bay had the same relative size halon discharge. Increasing cargo bay density (fullness) decreased large positive time not inert results.

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LIST OF ACRONYMS

Δ_p	Pressure change
ASM	Air separation module
FAA	Federal Aviation Administration
NASA	National Aeronautics and Space Administration
NEA	Nitrogen-enriched air
OBIGG	Onboard Inert Gas Generation System
psia	Pounds per square inch absolute
SCFM	Standard cubic feet per minute

EXECUTIVE SUMMARY

In response to potential fuel tank safety issues highlighted by the TWA Flight 800 accident in 1996, the Federal Aviation Administration (FAA) has developed a fuel tank inerting system and has been seeking to enact new regulations limiting the flammability of some kinds of fuel tanks on most commercial transport airplanes. In doing this, the FAA would be encouraging many aircraft operators to install Onboard Inert Gas Generation Systems (OBIGGS), which generate a continuous flow of nitrogen-enriched air (NEA) at some flow rate depending on a variety of aircraft conditions. Adding this capability to a commercial transport airplane has the potential to improve fire safety and reduce the weight and complexity of existing fire suppression systems. One such system is the cargo bay fire suppression system. Cargo bay fire suppression is often accomplished in two phases with an initial discharge of agent into the bay to extinguish open flaming and a second continuous discharge of agent to maintain an inert concentration in the bay. One such application for a potential commercial aircraft OBIGGS would be to replace this metered agent (second discharge).

To determine the effectiveness of a potential fuel tank inerting system for use as a cargo bay fire suppression metered agent system, a single air separation module (ASM) was tested to obtain specific performance points relevant to cargo bay fire suppression. These performance points were then used to determine the time required to inert a single cargo bay with an inerting system previously sized for the center wing fuel tank of a classic-type Boeing 747. This data was validated with a full-scale inerting test on the FAA's Boeing 747SP ground test article aft cargo bay. Calculations were then made to determine how much time, if any, the cargo bay would not be inert using this OBIGGS with a discharge of halon and air leakage into a bay, given the inerting halon concentration of 3% and inerting oxygen concentrations of both 12% and 15%.

The acquired ASM performance data illustrated that an ASM-based OBIGGS used for fuel tank inerting would be consistent with the requirements for a cargo bay fire suppression metered agent system. ASM mass flow rate at a set of given conditions is independent of the static pressure at which the NEA is deposited (i.e., cargo bay altitude). The NEA flow was very sensitive to ASM feed pressure. For example, the time to reach 12% oxygen in the cargo bay with 5% NEA was 5 times slower at 30 pounds per square inch absolute (psia) feed pressure than at 45 psia. There is also decreasing performance of the ASM as the static permeate pressure increases (aircraft altitude decreases), as the time to reach 12% oxygen in the cargo bay is 2.5 times greater at 8,000-foot altitude than at 30,000-foot altitude with the cargo bay at 5,000-foot altitude. As expected, it is easier to inert the cargo bay as pressure altitude increases. The results of modeling the oxygen concentration with a halon discharge and representative air leakage into the bay to determine "time not inert" for given conditions illustrated the same trends observed in the "time to inert" results. When observing the sensitivity of the time not inert results to decreasing the air leakage rate and increasing the size of the halon shot both decreased calculated time not inert values, although both values are also very sensitive to the ASM feed pressure. The time not inert values calculated were not that sensitive to cargo bay size with the

same size OBIGGS. There is less than 1.5 minutes difference in the time not inert for the 2600-cubic-foot cargo bay than for the 4600-cubic-foot cargo bay provided that the leakage rate was the same and cargo bay had the same relative size halon discharge. Increased cargo density (fullness) drastically decreased the resulting time not inert data. Additional work is needed to establish specific aircraft requirements and capabilities as well as understanding any synergetic effects of halon and oxygen deficient atmospheres.

1. INTRODUCTION.

1.1 BACKGROUND.

In response to potential fuel tank safety issues highlighted by the TWA Flight 800 accident in 1996, the Federal Aviation Administration (FAA) has developed a demonstration fuel tank inerting system and has proposed new regulations limiting the flammability of some kinds of fuel tanks on most commercial transport airplanes. In doing this, the FAA would be encouraging many aircraft operators to install Onboard Inert Gas Generation Systems (OBIGGS), similar to the one developed by the FAA Airport and Aircraft Safety Research and Development Division, Fire Safety Branch. These systems generate a continuous flow of inert gas in the form of nitrogen-enriched air (NEA) at a given flow rate depending on a variety of aircraft conditions and design requirements. Adding this capability to a commercial transport airplane has the potential to improve fire safety and reduce the weight and complexity of existing fire suppression systems. One such system is the cargo bay fire suppression system.

Cargo bay fire suppression is often accomplished in two phases. After the indication of a cargo bay fire, a single quick discharge bottle containing Halon 1301 is released into the identified bay to obtain a concentration above that which is needed to extinguish visible flames. After a sufficient amount of time has passed, a second discharge of Halon 1301 is released, referred to as the metered bottle, which continuously delivers a small amount of agent to maintain an inert concentration in the bay, given some previously determined leakage rate, for the extent of the aircraft's diversion time. One such application for a potential commercial aircraft OBIGGS would be to replace this metered fire suppressant. If the fuel tank inerting system were diverted to the affected cargo bay just after the indication of a cargo bay fire, it could reduce the oxygen concentration of the bay to below inerting levels before the initial fire suppression discharge has dissipated. It remains to be seen if an inerting system sized to keep a center wing fuel tank inert during a commercial transport flight cycle would be able to keep a single cargo bay from the same aircraft inert.

NEA or nitrogen is used to suppress fires by displacing the already present oxygen in the air around a fire. It is generally accepted that an atmosphere of 15% oxygen is required for combustion to occur. Previous research performed by Department of Defense studied suppressing fires with several agents including NEA generated by an OBIGGS and determined that generating an atmosphere consisting of 12.4% oxygen by volume would suppress the worst fire scenario studied [1].

Previous FAA fuel tank inerting experiments include the development of a fuel tank inerting system designed to maintain an inert oxygen concentration in the center wing fuel tank of a classic-style Boeing 747 (-100, -200, SP) using air separation modules. An air separation module (ASM) is a device that uses tiny hair-sized hollow fibers to separate air into a nitrogen rich gas stream and a waste gas affluent using the properties of permeation. The OBIGGS was designed by the FAA with help from industry representatives and was built by a company to meet basic aviation requirements. The system had a dual flow methodology and was tested on a Boeing 747SP ground test aircraft [2]. The system was also flight tested on a modified Boeing 747 operated by the National Aeronautics and Space Administration (NASA) [3].

NASA Fire Safety researchers performed a study with the Boeing Company to try and determine what fire suppression systems could be enhanced or replaced using OBIGGS. The report on the first part of this extensive research project examined uses for nitrogen and oxygen on a commercial transport aircraft in lieu of stored bottles of oxygen and fire suppressant. The report examined many aspects of gas use, including fire suppression, and performed some calculations of nitrogen requirements, particularly for cargo bay fire protection [4].

1.2 SCOPE.

To determine the effectiveness of a potential fuel tank inerting system for use as a cargo bay fire suppression metered system, a single ASM was tested to obtain specific performance points relevant to cargo bay fire suppression. This gives the precise amount of NEA flow the test ASM will produce under specific conditions. These performance points were then used to determine the time required to inert a single cargo bay with an inerting system previously sized for the center wing fuel tank of a classic-type Boeing 747. This data was validated with a full-scale inerting test on the FAA Boeing 747SP ground test article aft cargo bay used by the FAA Airport and Aircraft Safety Research and Development Division, Fire Safety Branch. Calculations were then made to determine how much time, if any, the cargo bay would not be inert using this OBIGGS given the inerting halon concentration of 3% and inerting oxygen concentrations of both 12% and 15%. These calculations were made varying the parameters of system feed pressure (bleed air pressure), system permeate pressure (altitude), and cargo bay pressure. The effect of the initial halon discharge must be factored into the analysis of NEA available from an appropriately sized fuel tank inerting system in the context of replacing the sustained cargo bay suppression agent (metered bottle).

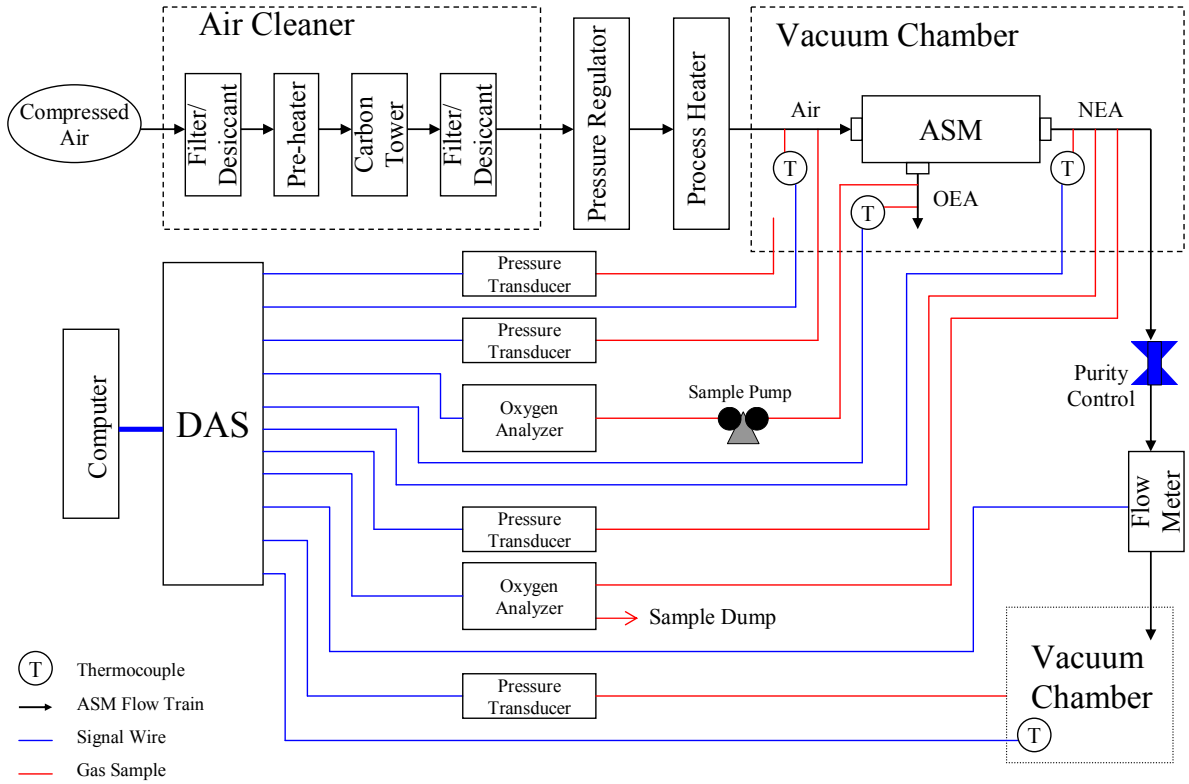
2. EQUIPMENT AND PROCEDURES.

2.1 EQUIPMENT.

Two pieces of equipment used for the testing discussed in this report are the ASM performance test article and the full-scale 747SP ground test article.

2.1.1 The ASM Performance Test Article and Instrumentation.

The ASM performance test article consists of a single MEDAL D-640 ASM in an environmental chamber plumbed with a clean air supply and the associated instrumentation. NEA generated by the ASM was deposited into a separate smaller environmental chamber to allow for the simulation of reduced cargo bay pressures. Figure 1 shows a block diagram illustrating the main components of the ASM performance testing as well as the component connectivity with the associated instrumentation.



DAS=Data Acquisition System

Figure 1. Block Diagram of ASM Performance Test Article With Instrumentation

2.1.1.1 The ASM Performance Test Article.

A single MEDAL D-640 ASM was mounted on a stand and tested inside of the FAA Airport and Aircraft Safety Research and Development Division, Fire Safety Branch Environmental Chamber. Compressed air was plumbed to the ASM through bulkhead fittings on the side of the environmental chamber. The compressed air was first passed through a pressure regulator to control the ASM feed air pressure, and then through a process heater to heat the air to the optimum performance temperature of 180°F. Before being heated, the air was cleaned using the air cleaning system from an industrial NEA generator, which provides clean (filtered and desiccated) air and operates using 115 volts alternating current, single-phase power. This unit uses a carbon activation tower and multiple desiccating filters to ensure clean dry air was provided to the ASM. The output of the ASM was plumbed out of the environmental chamber through a bulkhead fitting into a needle valve (back pressure control). The NEA flow was then plumbed through a flow meter and into a vacuum chamber to allow for testing with reduced deposit pressures.

The ambient pressure the ASM is subjected to was created by the environmental chamber. The chamber vacuum pump was continuously operated to decrease pressure to the desired altitude, while valves on the side of the chamber were opened and closed to meter in air and control the absolute pressure on the ASM test article. This allowed for the necessary static pressure

conditions on the ASM permeate port. The inside dimensions of the chamber are 72 by 71 by 93 inches.

2.1.1.2 Instrumentation.

To determine the temperature of the air entering the ASM, a K-type thermocouple was installed in the air deposit line. Additional thermocouples were used to measure the temperatures of the permeate (ventilation waste), NEA, and environmental chamber.

Pressure transducers were used to measure the absolute pressure of the air being fed into the ASM as well as the NEA generated by the ASM. Pressure transducers were also used to measure the atmospheric pressure in the environmental chamber that housed the ASM experiment as well as measure the pressure in the vacuum chamber receiving the NEA. The sensors used were static, diaphragm-type pressure transducers.

The flow meter used to measure the flow of NEA from the ASM at sea level was a 0-20 SCFM roto-type flow meter. A small group of data points required a flow meter with either a scale of 0-50 SCFM or 0-4 SCFM. To measure NEA flow at reduced pressures (increased altitude) a totalized flow meter was employed. This instrument uses the energy required to drive two thermopiles in wake of a shedding vortex to measure flow over a variety of pressures and temperatures, and contains both total pressure and temperature measurements and digital data processor to control sensor output. A more complete description of the totalizing flow meter is given in reference 3.

The NEA oxygen concentration was measured with an oxygen analyzer, which uses a remote galvanic cell-type sensor calibrated with air. The sample was pressure fed from the NEA output of the ASM to the sensor with a small rotometer to control sample flow. To measure the permeate oxygen concentration, a paramagnetic-type oxygen analyzer was employed. A pump drafted a sample from the waste port and provided the necessary flow to a pressure regulator and flow meter, which was tuned from test to test to provide a constant sample back pressure to the analyzer.

A computer data acquisition system continuously monitored the specified instruments during each test. This unit had a software package capable of programming the unit to acquire data as well as displaying the necessary data in a variety of ways.

2.1.2 The 747SP Ground Test Article.

The 747SP ground test article was developed to study the integration of aircraft systems with fire safety equipment and contains the FAA fuel tank inerting system developed for the purposes of research and evaluation. A more complete description of the ground test article and the FAA fuel tank inerting system can be found in reference 2.

The cargo bay of the 747SP ground test article was instrumented with eight gas sample lines plumbed to eight oxygen analyzers. This allowed eight different continuous oxygen measurements in the cargo bay. The flow rate and oxygen concentration of the NEA was measured, as stated in reference 2. The OBIGGS was operated prior to depositing the NEA in

the cargo bay to allow for proper warmup and calibration of the various instruments. Figure 2 shows the eight cargo bay gas sample locations.

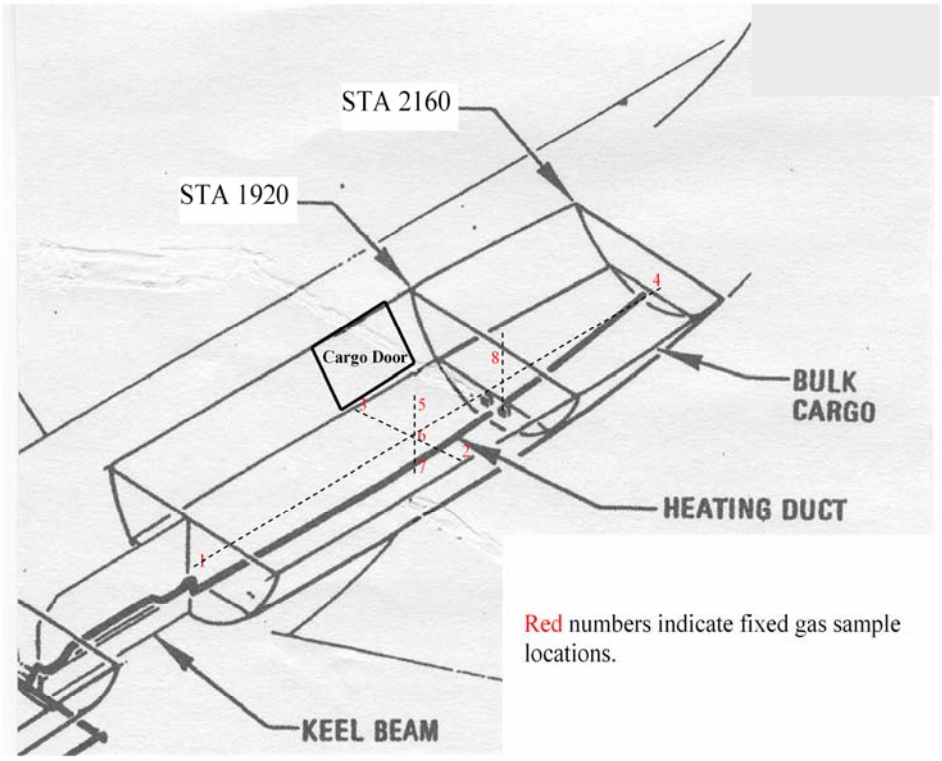


Figure 2. Diagram of the Aft Cargo Bay of the 747SP Ground Test Article With Gas Sample Locations

2.2 TEST PROCEDURES.

Two different test procedures were used for the subject work: the ASM performance test procedures and the full-scale cargo bay inerting procedure.

2.2.1 The ASM Performance Test Procedure.

The ASM performance test procedures were designed to determine the NEA flow generated by a MEDAL D-640 ASM under specific conditions. The conditions that determine the ASM performance are the ASM feed air pressure, the ASM feed air temperature, the ASM permeate pressure, the back pressure on the ASM (purity control), and the bay deposit pressure. The ASM feed air temperature was held constant for these tests at 180 degrees Fahrenheit, which has been identified by the manufacturer as the optimal performance temperature. This gives the following four variable parameters used for the ASM performance testing: ASM feed air pressure, ASM permeate pressure, NEA oxygen concentration, and bay deposit pressure. Table 1 shows the four variable parameters with the measured units and the range of values tested relevant to the described test sequence.

Table 1. Variable Parameter for the ASM Performance Test

Parameter	Units	Range
ASM feed pressure	psia	30-60
ASM permeate pressure	psia	4.37-14.72 (30,000 ft to 0 ft)
NEA oxygen concentration	% volume	2-10
Bay deposit pressure	psia	10.92-14.72 (8,000 ft to 0 ft)

psia = Pounds per square inch absolute

To obtain the desired performance data, all instrumentation was operated for 12-24 hours prior to all testing to ensure stability and repeatability. The ASM test article was first operated at the set operating temperature for approximately 2 hours until the performance (product volume flow) became stable at the given input conditions. This is accomplished by turning on the M750 NEA generator and then diverting air from the air cleaning system to the regulator and process heater on the test apparatus.

When the ASM performance had stabilized at the target temperature, the ASM feed pressure was adjusted using the apparatus regulator while the permeate was adjusted by closing and opening the throttling valve on the side of the environmental chamber. The NEA oxygen concentration was adjusted by turning the purity control needle valve on the product side of the ASM. When it was necessary, the deposit pressure was adjusted with a needle valve on the vacuum chamber with a series of adjacent fittings that could have the caps removed or replaced. These three or four adjustments were made repeatedly and consecutively until the conditions became stable enough to get a consistent reading for all four parameters for an extended period of time. When the readings for the data were stable the NEA flow numbers were recorded by hand from the flow meter or readout on the data acquisition system data display. Most performance points were acquired in 15-30 minutes provided the ASM was already stable, but some points could take as much as 60 minutes.

2.2.2 Full-Scale Cargo Bay Inerting Procedure.

To obtain data to validate the calculations of oxygen concentration in an aircraft cargo bay, the 747SP ground test article was used in conjunction with the FAA fuel tank inerting system. Data was obtained on oxygen concentration reduction in a cargo bay with a fuel tank inerting system as well as on inert gas distribution and cargo bay air leakage rates.

Each test was accomplished by first allowing all instrumentation and data acquisition equipment sufficient time to warmup and stabilize. The cargo bay was ventilated with fresh air using a large fan to ensure an ambient (21%) oxygen concentration after which the cargo door was closed and secured. The inerting system was operated for approximately 1 hour to simulate a stable operating condition indicative of normal in flight operation. At the start of the test, the inerting system flow was diverted to the cargo bay and the oxygen concentration was monitored.

Good mixing was ensured by using a small fan inside the sealed cargo bay. This allowed for better adherence of the experimental data to the cargo bay inerting model.

3. ANALYSIS.

The primary calculations performed to determine the effectiveness of a fuel tank inerting system for use in cargo bay fire suppression is the cargo bay oxygen concentration and halon concentration given a set of inerting conditions. The parameters used to make these calculations are the amount of NEA and halon deposited in the cargo bay during a given time frame. The cargo bay pressure and temperature are also used to make these calculations. The amount of NEA deposited is a function of the permeate altitude and the ASM feed pressure as well as the oxygen concentration of the NEA.

3.1 CALCULATION OF CARGO BAY OXYGEN CONCENTRATION.

To better understand and predict the inerting process and the factors effecting it for different scenarios and OBIGGS performance cases, an analytical model was developed to calculate an average bay ullage oxygen concentration, given a specific bay volume, starting oxygen concentration, and a variable system performance (NEA flow and purity). Bay temperature and pressure are also used to calculate the oxygen concentration. This model is very similar to the one used to calculate oxygen in a single-bay fuel tank ullage, given a range of inerting parameters [5]. The model that was used to calculate the oxygen concentration was modified to include an assumed air leakage rate (into the bay), which is input by the user. This is typical of observed cargo bay dynamics in previous studies [6]. This calculation assumes the net air leakage is the assumed air leakage minus the mass of NEA entering the bay. This assumption allows for zero air leakage when NEA flow becomes great enough.

The model calculates the mass of oxygen in the bay at the start of the mission, given the bay volume and starting oxygen concentration, and tracks the change in mass of oxygen due to the addition of inert gas and air leakage. First, the model converts the NEA volume flow and purity at each time step to a mass of oxygen deposited in the tank, given the altitude and temperature, to calculate density using the equation of state. Then, the model calculates the mass of air entering the bay due to a decrease in altitude (increase in pressure) and, given the mass of NEA being deposited and mass of air leakage, calculates the net air into (or out of) the tank by subtracting the two.

3.2 CALCULATION OF CARGO BAY HALON CONCENTRATION.

The cargo bay inerting model was modified to include a calculation of halon concentration. Halon was treated as an inert gas deposited into the cargo bay to obtain some concentration. In conjunction with calculating the oxygen concentration, the model calculates the moles of halon deposited and vented at every time step, assuming perfect mixing, and updates the moles of halon in the bay in accordance with the following general equation.

$$M_{\text{Halon}_{Bay}}(t) \quad = \quad M_{\text{Halon}_{Bay}}(t-1) + \Delta M_{\text{Halon}_{Bay}} \tag{1}$$

where:

t = Time
$\Delta M_{\text{Halon}_{Bay}}$ = Change in moles of halon in the bay
$M_{\text{Halon}_{Bay}}$ = Moles of halon in the bay

The concentration of halon in the bay is calculated by obtaining the mole fraction of halon, which is defined by the following equation in terms of moles of halon and moles of gas in the bay.

$$F_{Halon_{Bay}}(t) = M_{Halon_{Bay}}(t) \Big/ M_{Bay}(t) \tag{2}$$

where:

F = Mole fraction
M_{Bay} = Moles of gas in bay

4. DISCUSSION OF RESULTS.

The results of the ASM performance experiments discussed in section 2 are given in section 4.1. Data illustrating time to inert a cargo bay and time not inert with a halon discharge were calculated using the methods described in sections 3.1 and 3.2, respectively and are presented in sections 4.2 and 4.3, respectively

4.1 THE ASM PERFORMANCE.

The results of the ASM performance experiments are given in three different areas for an ASM feed air temperature of 180 degrees Fahrenheit. These are the effect of the permeate altitude, the effect of the ASM feed pressure, and the effect of the cargo bay pressure altitude.

4.1.1 Effect of Permeate Altitude.

To examine the effect of permeate pressure on ASM performance, the NEA flow rate was measured at several different permeate pressures (altitudes). Generally, in aerospace applications, an ASM will be installed outside the pressurized cabin, and as the aircraft ascends this will have a profound effect on the NEA flow and purity (residual oxygen concentrations) generated. Figure 3 gives the NEA flow measured at three different atmospheric pressures corresponding to 20,000 feet, 8,000 feet, and sea level pressure altitude for purities of 2%, 5%, and 10% oxygen by volume. On average, the ASM makes more than twice as much NEA at 20,000 feet than it does at sea level. This is due to the changing properties of the ASM with permeate pressure that allows the ASM to accept more feed flow (more permeable).

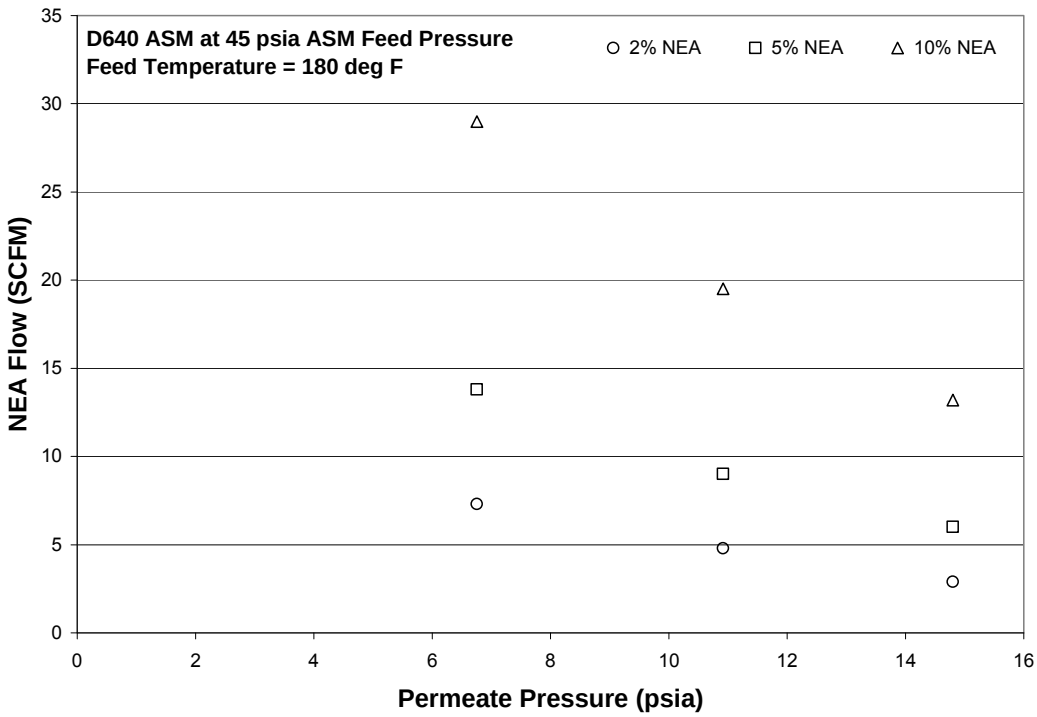


Figure 3. The ASM Performance Data Illustrating NEA Flow Generated at Various Permeate Pressure Altitudes for Different NEA Purities

4.1.2 Effect of Feed Pressure.

The effect of the ASM feed pressure on the amount of NEA flow was examined illustrating how variations in the bleed air pressure will effect the OBIGGS performance. Figure 4 gives the NEA flow generated at 30, 45, and 60 psia feed pressures for several residual oxygen concentrations. It is clear that an ASM is very sensitive to feed pressure changes because ASM feed pressure directly effects the permeability of the ASM. The values 30-45 psia represent nearly the full range of bleed air pressure observed in most common commercial transport aircraft, while the 60 psia values are indicative of conditions a system might see if it employed a boost pump for increased performance or perhaps a bleed pressure attainable on a future aircraft type. Between 30 and 45 psia feed pressure, the flow more than triples with the best performance increases for the higher residual oxygen concentration flow.

Figure 5 also gives ASM performance data showing performance changes due to increased feed pressure for different permeate altitude conditions at 5% residual oxygen concentration. It shows the compounded effect of increased feed pressure and decreased permeate pressure, which are conditions that are observed during takeoff conditions, but are not representative of descent conditions.

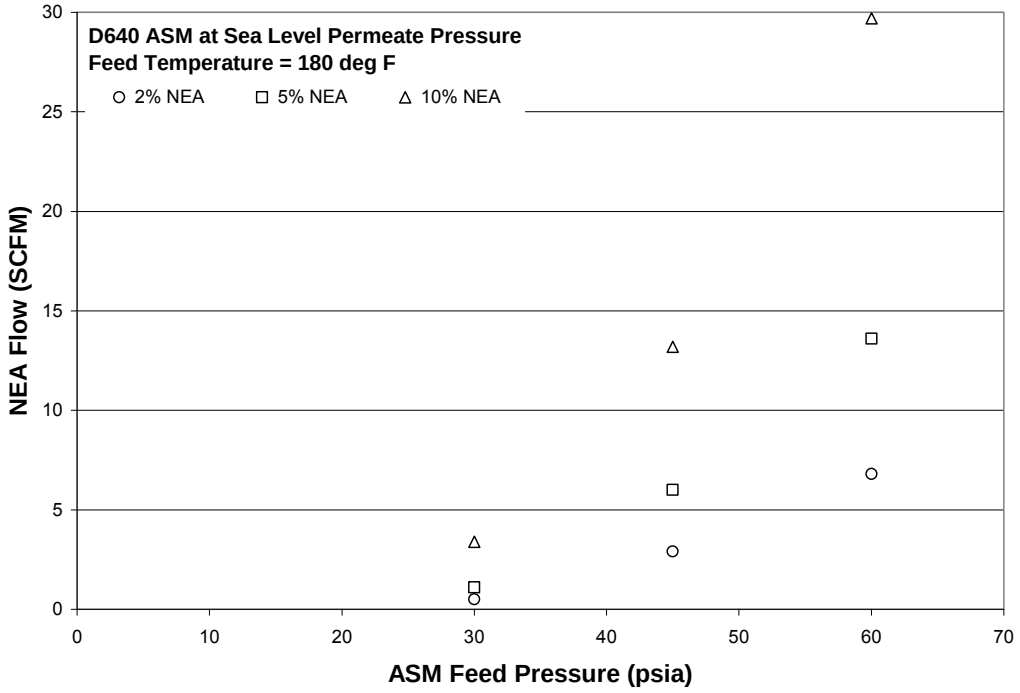


Figure 4. The ASM Performance Data Illustrating NEA Flow Generated at Various ASM Feed Pressures for Different NEA Purities

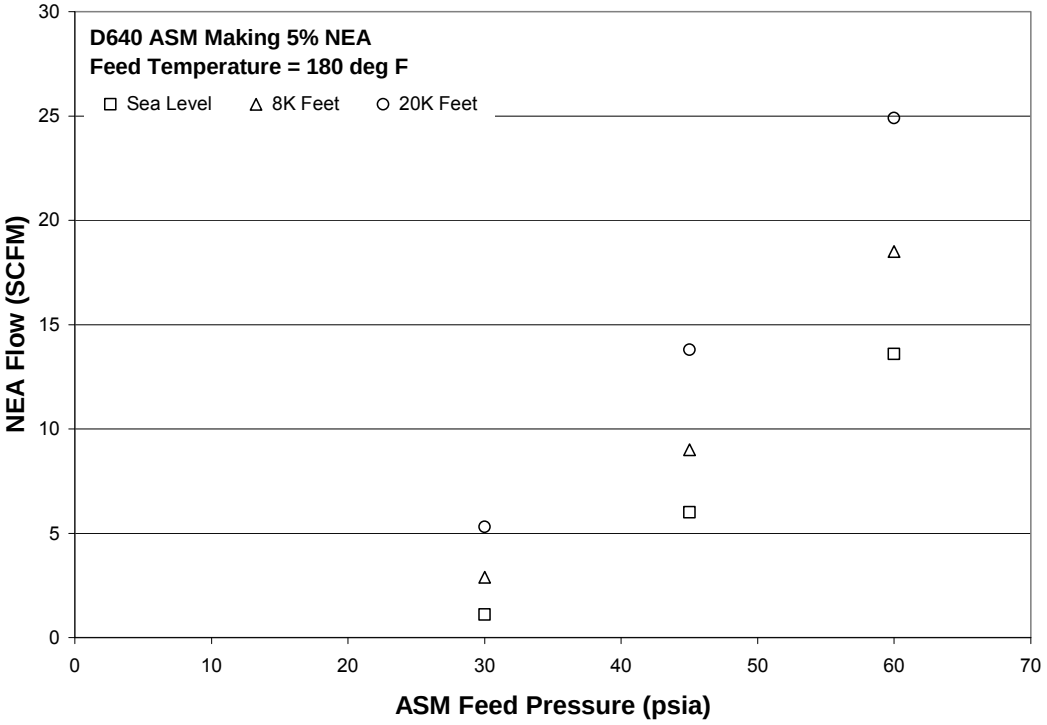


Figure 5. The ASM Performance Data Illustrating NEA Flow Generated at Various ASM Feed Pressures for Different Permeate Altitudes

4.1.3 Effect of Bay Altitude Pressure.

Most of the ASM performance data presented in the previous sections was assuming a sea level deposit pressure (14.7 psia). Many cargo bay fires occur in flight when the cargo bay has a pressure as low as 10.92 psia (or 8000-foot atmospheric pressure). ASM performance was measured for deposit pressures of sea level, 5000 feet, and 8000 feet, respectively. Permeate pressure was held constant at 6.76 psia (20,000 feet altitude) for four different data series with constant feed pressure. At each feed (pressure and permeate altitude pressure), the deposit pressure was varied. Although this changes the measured residual oxygen concentration and NEA flow rate from the NEA purity control valve (orifice), this valve was readjusted at each deposit pressure to obtain the desired NEA residual oxygen concentration for the given data series. The results of this data series are shown in figure 6. This graph appears to validate the existing assumption that deposit pressure has no measurable effect on the mass flow of NEA, but rather changes the pressure change (Δp) across the deposit orifice, which must then be adjusted to obtain the correct Δp needed. Note that the flow data is given in volume flow normalized to sea level because the actual cubic feet per minute of gas will vary with deposit altitude as per the equation of state. This is not to say that all performance points obtained at 8000-foot cargo bay pressure can then also be obtained at sea level bay pressure. For some feed pressures and permeate pressures, higher oxygen concentrations (7%-10% residual) may be obtainable at 8000-foot deposit pressure, but not obtainable at sea level due to the inability to obtain a large enough Δp across the deposit orifice.

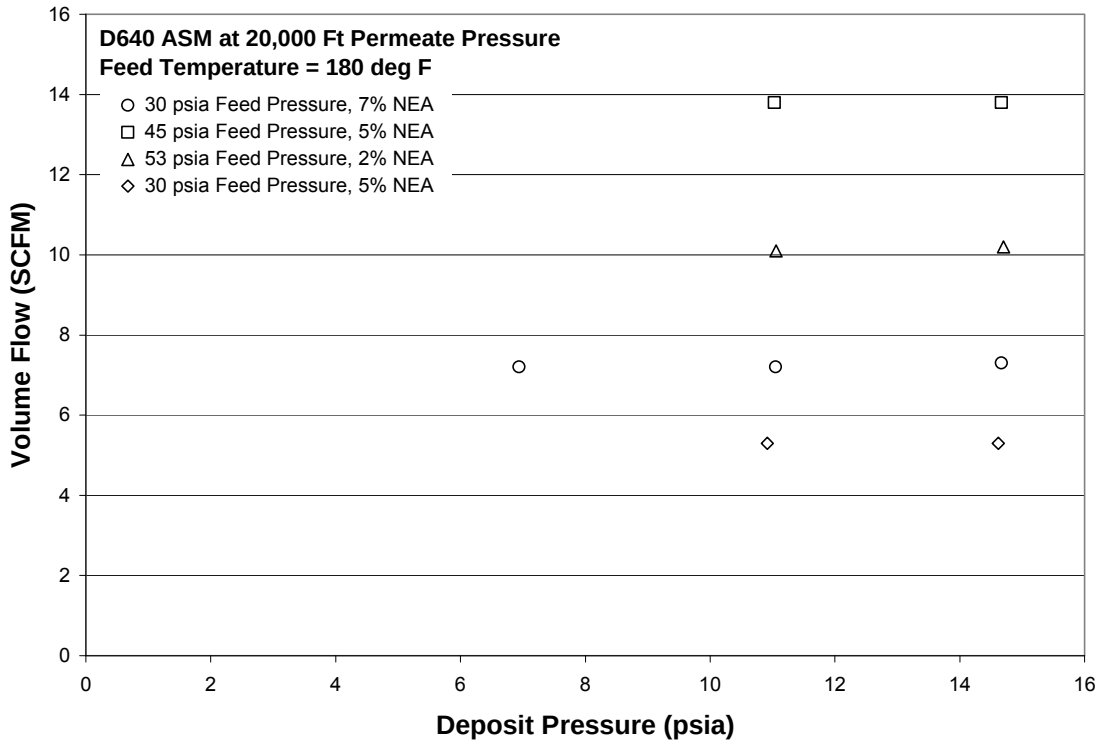


Figure 6. The ASM Performance Data Illustrating NEA Flow Generated at Various Deposit Pressures

4.2 TIME TO INERT A CARGO BAY WITH OBIGGS.

The bay inerting model was run for a variety of ASM performance points, assuming constant performance during the model time frame, to determine the time for the bay to reach 15% and 12% oxygen by volume. These different performance points are compared for three different areas. These are the effects of the permeate altitude pressure, the ASM feed pressure, and the cargo bay pressure altitude. All data presented assumes an empty 2600-cubic-foot cargo bay being inerted with 6 ASMs of the same performance, illustrated in section 4.1, with no effective air leakage. All section 4.2 data assumes that the air leakage is always less than the NEA flow. Full-scale validation of a single test result is also given, which uses an empirically derived air leakage rate.

4.2.1 Effect of ASM Feed Pressure.

Figure 7 gives the results of three different inerting model calculations for three different ASM performance points all making 10% oxygen NEA with the permeate altitude and cargo bay altitude at sea level. This graph illustrates how the time to inert data was obtained and then compiled into subsequent graphs illustrating the time for 6 ASMs to inert a 2600-foot cargo bay to suppression concentrations of 15% and 12% oxygen for different parameters and conditions.

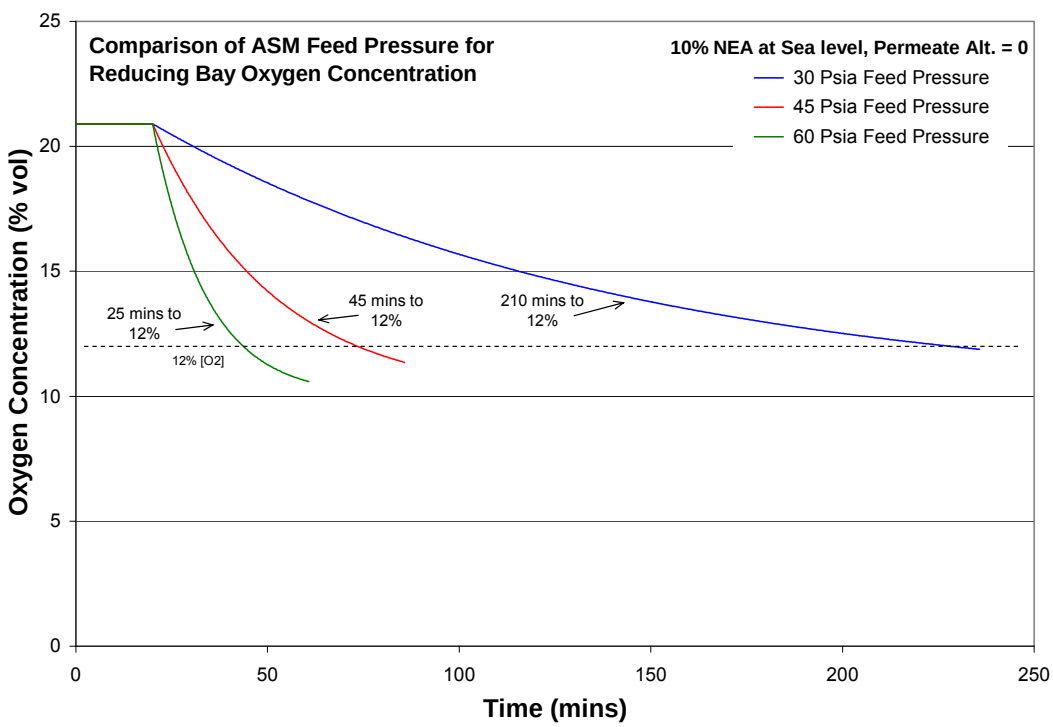


Figure 7. Inerting Model Results for Three Different Feed Pressures Illustrating the Determination of Time to Inert Results

Figure 8 gives the time to inert for three different feed pressures using both 5% and 10% NEA with the permeate pressure and the cargo bay pressure at sea level. This figure illustrates the significant advantage of increasing the ASM feed pressure from 30 to 45 psia illustrating the

cargo bay reaches 12% oxygen more than 5 times faster at the higher feed pressure using 5% NEA. Comparatively, when increasing the feed pressure to 60 psia the cargo bay only reaches 12% oxygen twice as fast as at 45 psia feed pressure. This graph also illustrates the advantage of using 10% oxygen NEA versus 5%, particularly at the lower feed air pressures.

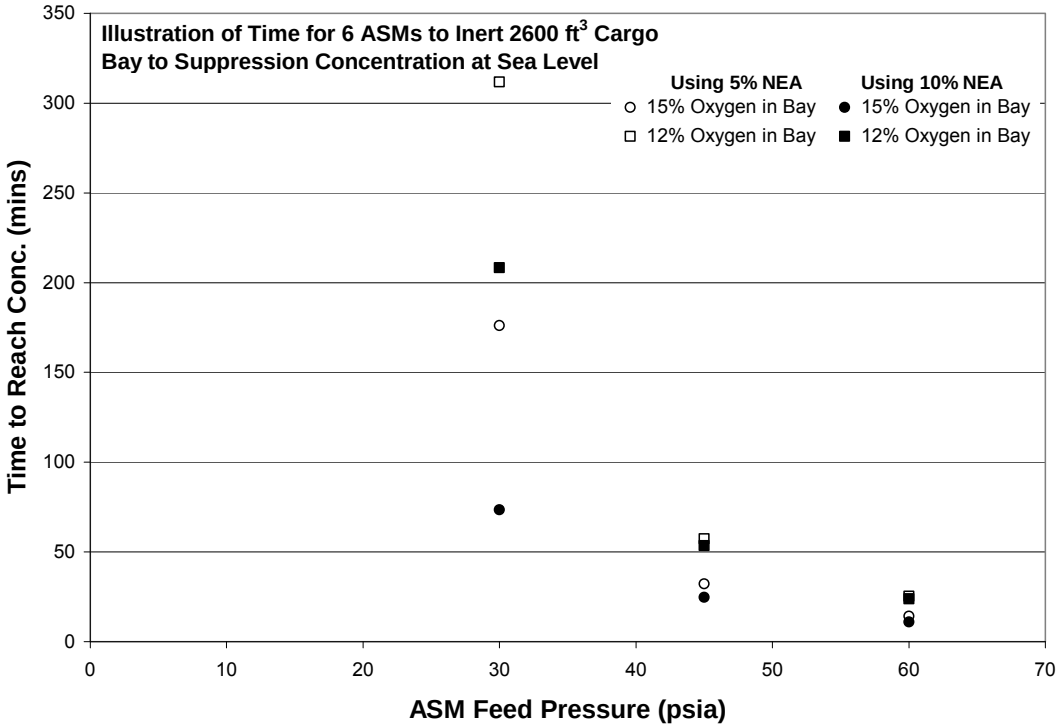


Figure 8. Time to Inert Cargo Bay Results at Sea Level Using 5% and 10% NEA Giving 15% and 12% Inerting Levels

4.2.2 Effect of Permeate Altitude Pressure.

Figure 9 gives time to inert a cargo bay data at various permeate altitude pressures for 30 psia feed pressure with a 5000-foot cargo bay pressure and 45 psia feed pressure with a sea level cargo bay. This graph shows the consistent trend of increasing permeate pressure (decreasing altitude) causes increasing time to reach inerting concentration for both the 12% and 15% levels. This graph illustrates that at 30 psia feed pressure, the cargo bay will reach 12% oxygen more than 2.5 times faster with the ASM at 30,000-foot pressure altitude than at 8,000 feet. It also illustrates slightly less advantage when considering the time to reach a 15% inerting oxygen concentration (less than 2.5 times faster). Similar relationships are illustrated by the 45 psia feed pressure data between 20,000 feet and sea level, which illustrates less than 2.5 times greater an advantage in the time to inert to 12% oxygen and more than 2 times advantage in the time to inert to 15% oxygen.

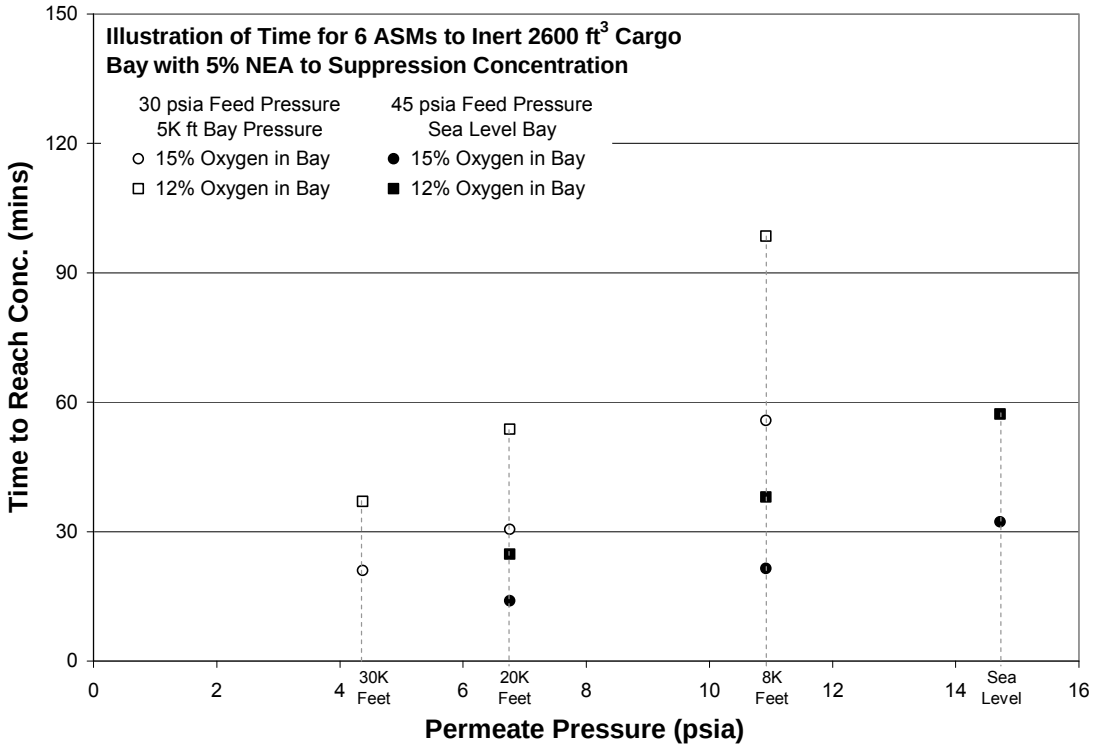


Figure 9. Time to Inert Cargo Bay Results With 5% NEA for 30 and 45 psia Feed Pressure Giving 15% and 12% Inerting Levels

4.2.3 Effect of Cargo Bay Pressure.

Figure 10 gives time to inert cargo bay results at different cargo bay pressures. As expected, the data show a consistent trend of increasing bay static pressure (decreasing altitude) causes times to inert to increase. Because the graph is for constant NEA performance for the two different feed pressures given, the observed benefit is due to the decreased pressure in the bay, which causes an increase in the actual volume flow (but constant mass flow), which in turn, increases the ventilation rate of the bay. Note that all NEA flow rate data is for SCFM, with the capital S signifying standard (normalized to sea level), which is effectively a mass flow rate. With the mass exchange needed to achieve a given oxygen concentration being constant, when the actual mass of gas in the bay decreases due to a change in pressure, the net result is that it takes less inert gas (by volume) to achieve the same inerting concentration.

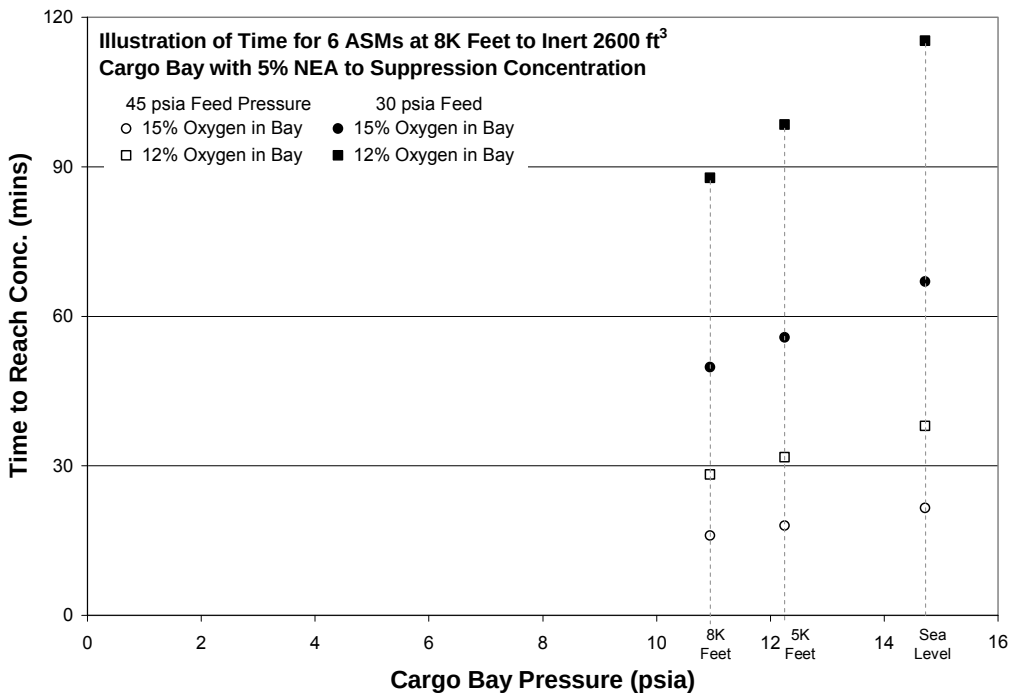


Figure 10. Time to Inert Cargo Bay Results With 5% NEA for 30 and 45 psia Feed Pressure at 8000-Foot Permeate Pressure Giving 15% and 12% Inerting Levels

4.2.4 Full-Scale Validation.

To validate the results of the inerting model, a comparison was made with a single model case with measurements of inerting the 2600-cubic-foot bay of the 747SP ground test article with six ASMs of the same model as defined by the results in section 4.1. The data illustrate good agreement with the calculations. The resulting equilibrium oxygen concentration is the oxygen concentration that would have been obtained had the experiment run until it was stable, which was estimated to be 11% for this case. This equilibrium oxygen concentration is a direct result of the estimated air leakage rate and the measured NEA flow and purity. In contrast, the shape of the curve is a function of the size of the bay as well as the NEA flow and purity. Both the precise air leakage and cargo bay size had to be estimated from other tests and information sources, while good mixing (essential to the model validity) was assured with a small fan in the bay during the test. Although it is difficult to have 100% certainty in the model validation due to the number of estimated parameters and their interconnected relationship, given a small level of uncertainty, the model is valid.

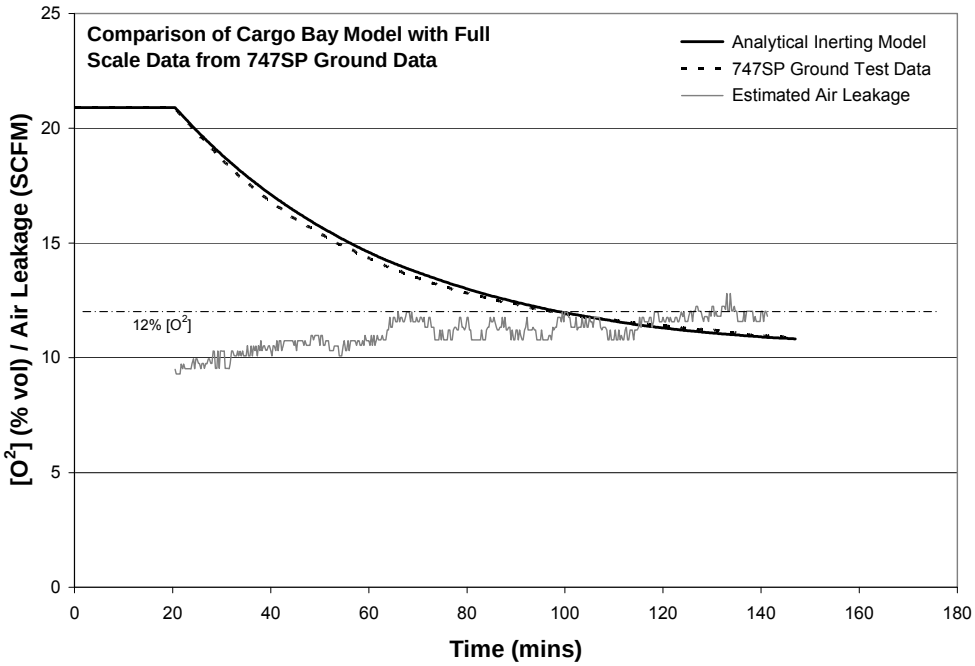


Figure 11. Comparison of Inerting Model Data With Measured Data for the 747SP Ground Test Article

4.3 TIME NOT INERT WITH HALON DISCHARGE.

The results of the time not inert calculations with a halon discharge are given in three different areas. These are the effects of (1) cargo bay altitude pressure, (2) permeate altitude pressure, and (3) ASM feed pressure. All of these calculations use the same empty 2600-cubic-foot bay, with a 50 SCFM leakage limited by the NEA flow, and the standard halon discharge that inerts the cargo bay to 5% halon in 1 minute at sea level. Section 4.3.4 will discuss the sensitivity of the calculations to these three assumptions and show the effect of cargo bay density (fullness).

Figure 12 gives the results of the halon and oxygen inerting model developed to determine any time not inert that may exist when first depositing halon in a cargo bay and then inerting the bay with NEA. This graph gives the oxygen and halon concentration for three different cargo bay pressures given a fixed ASM feed pressure and permeate pressure. The given air leakage rate will have a direct effect on displacing the halon and replacing it with air and NEA flow will decrease the bay oxygen concentration, but hasten the halon dissipation. The model assumes that NEA flow displaces the air leakage on a one-to-one basis, which is to say that an NEA flow rate of 50 SCFM or greater allows for no net leakage. Figure 12 also shows how the time not inert results are determined from these data with the time not inert for 12% and 15% inerting oxygen concentration given for the worst-case sea level data (blue lines) as Δt_{12} and Δt_{15}, respectively. At sea level, Δt_{12} is approximately 6 minutes, while Δt_{15} is approximately -5, with the negative sign indicating that this is an overlap of inerting time. All data presented in this section assumes a 3% halon inerting concentration. As an example, protection would be achieved in this case for all bay pressures assuming 15% oxygen is effective with the above stated halon inerting concentration.

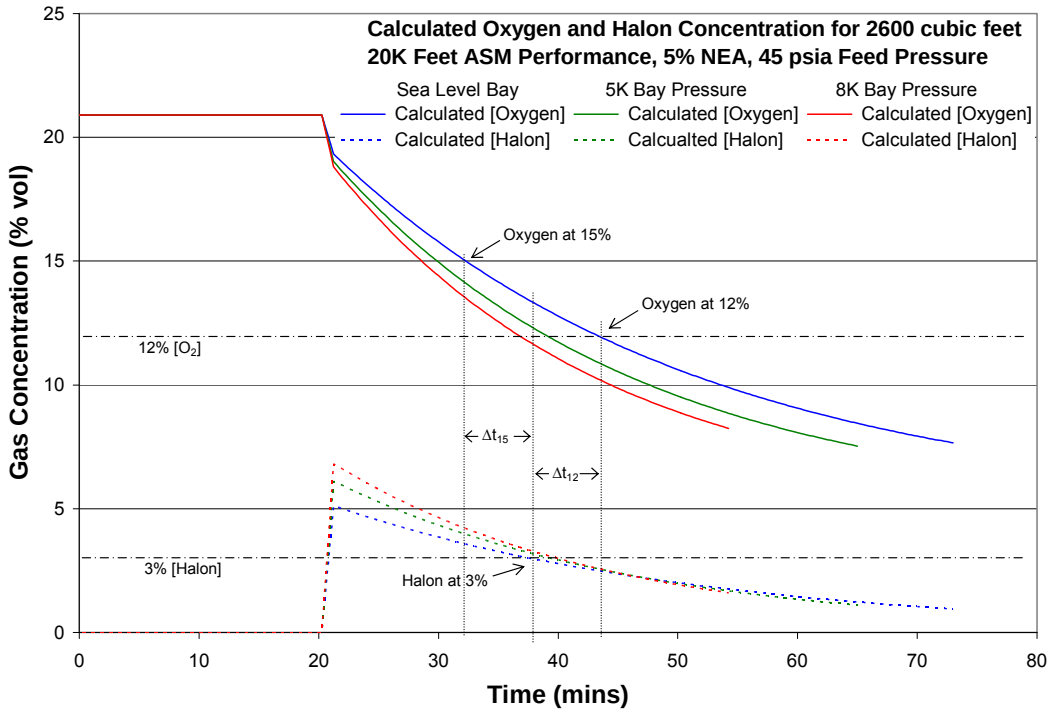


Figure 12. Inerting With Halon Model Results for Three Different Bay Pressures Illustrating the Determination of Time not Inert Results

4.3.1 Effect of Cargo Bay Altitude Pressure.

The time not inert data calculated versus cargo bay pressure for both 30 and 45 psia feed pressure at 20,000-foot permeate pressure, making 5% NEA with both 12% and 15% oxygen inerting concentrations, is given in figure 13. Again, a clear trend is observed that increasing bay pressure (decreasing bay altitude) increases the time not inert. A 30 psia feed pressure indicates large values for time not inert times for the 12% inerting concentration, while most of the other times not inert are very small or negative.

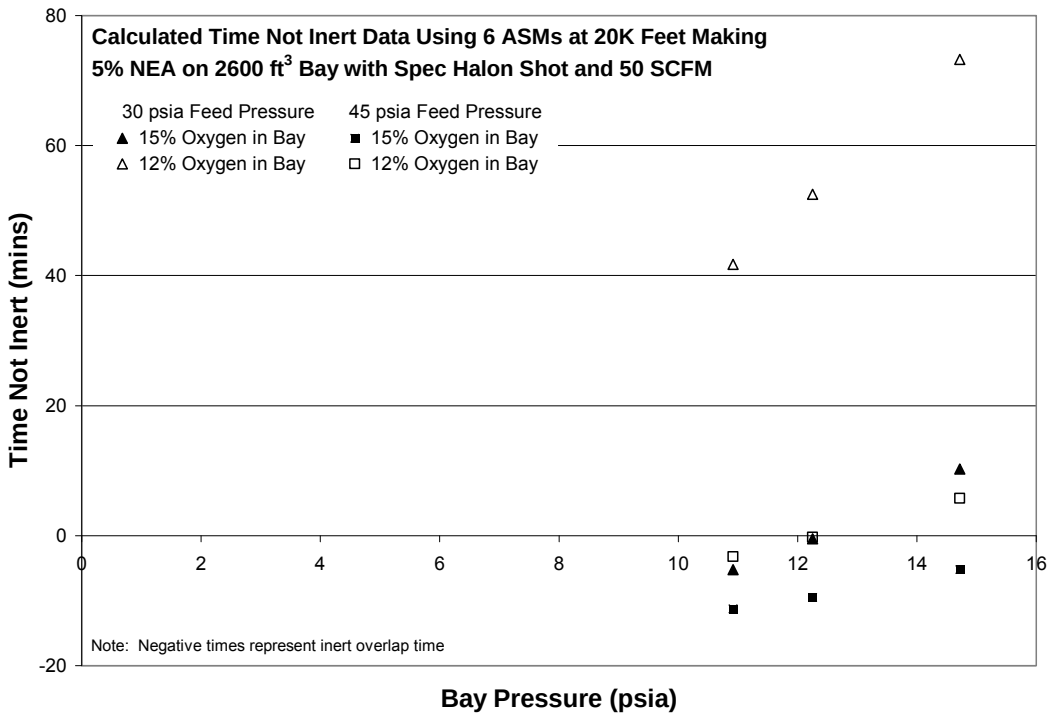


Figure 13. Cargo Bay Time not Inert Results With 5% NEA for 30 and 45 psia Feed Pressure at 20,000-Foot Permeate Pressure With 15% and 12% Inerting Levels

4.3.2 Effect of Feed Pressure.

The calculated time not inert data versus feed pressure for both 5% and 10% NEA at 8000-foot permeate pressure and 5000-foot bay pressure with both 12% and 15% oxygen inerting concentrations is given in figure 14. For the positive times not inert, the trend is as expected that increasing ASM feed pressure gives smaller not inert times. Although it was not possible to obtain any inerting concentrations with 5% NEA at 30 psia feed pressure given the other performance parameters, it is clear that there is an advantage to using 5% NEA rather than 10, because the less flow of 5% NEA decreases the ventilation of halon. This is somewhat contrary to figure 8, which states that 10% NEA gives smaller inerting times. Increasing the feed pressure above 45 psia gives diminishing returns since it does not give significantly smaller (or more negative) not inert times, although the difference for the 10% NEA inerting to 12% is noticeable. This graph illustrates, when considering figure 8, that the optimal NEA to generate will probably be a function of the feed pressure and permeate altitude.

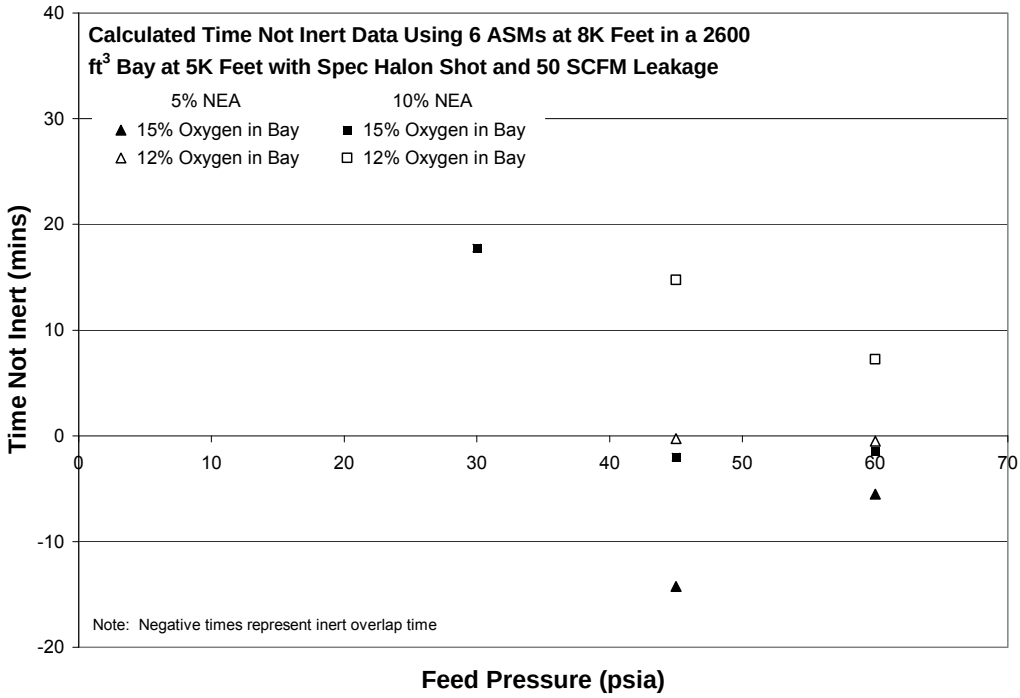


Figure 14. Cargo Bay Time not Inert Results With 8000-Foot Permeate Pressure and 5000-Foot Bay Pressure for 5% and 10% NEA Giving 15% and 12% Inerting Level Results

4.3.3 Effect of Permeate Altitude.

The calculated time not inert data versus permeate pressure for 30, 40, and 45 psia ASM feed pressure at sea level bay pressure for both 12% and 15% oxygen inerting concentrations is given in figure 15. Although the data trends are not clear as to the effect of permeate pressure in general for all the data, it is clear when examining each individual data set that the time not inert is sensitive to increased permeate pressure, with lower ASM feed pressures being most sensitive. This needs to be considered when using fuel tank inerting OBIGGS for cargo bay fire suppression. The decreasing efficiency of the inerting system during the final times before the aircraft lands and parks could allow for the cargo bay to be unprotected because feed pressures will be lowest and permeate pressure will be highest.

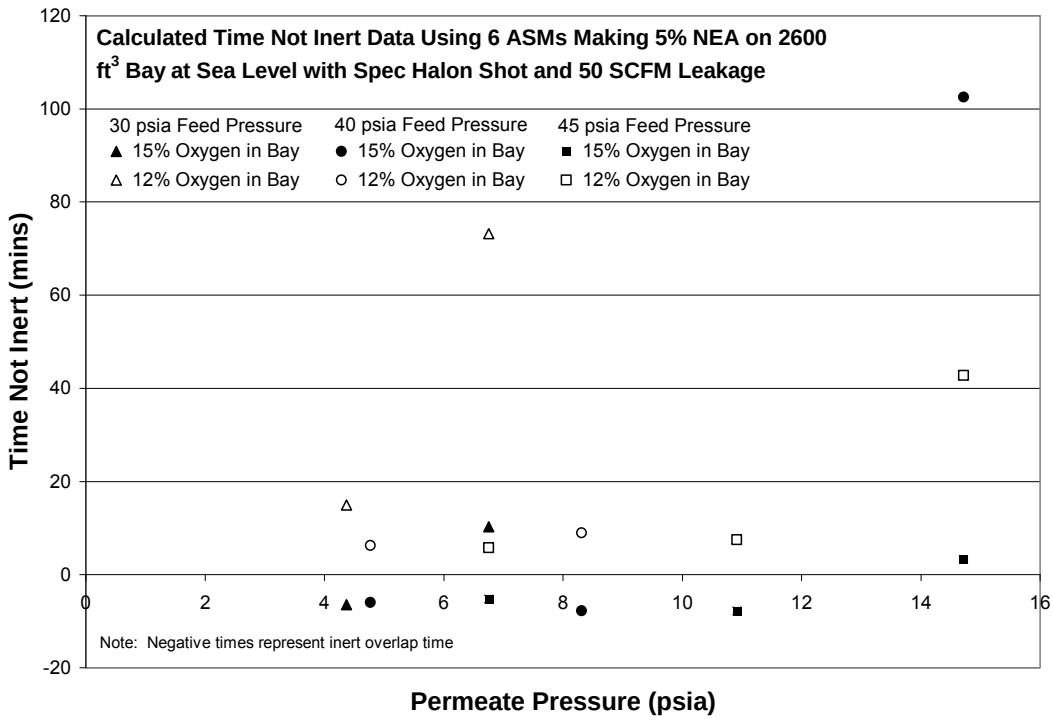


Figure 15. Cargo Bay Time not Inert Results for Different Permeate Pressures and Sea Level Bay Pressure With 5% NEA Giving 15% and 12% Inerting Level Results

4.3.4 Sensitivity of Results to Assumptions.

To examine the sensitivity of these data to the three assumptions common to the results, additional calculations were performed to vary these parameters. These parameters are cargo bay size, halon discharge amount (also called shot size), and bay leakage rate. Model calculations were performed varying these parameters with different ASM feed pressures for the case of 8000-foot permeate pressure and a 5000-foot cargo bay pressure using 5% NEA. ASM feed pressure is being examined in all of these results because it tends to be the most critical parameter for obtaining the desired bay oxygen concentration.

Figure 16 illustrates the sensitivity of the results to cargo bay size for both 45 and 60 psia feed pressures for the previously stated permeate and cargo bay pressure using the 50 SCFM leak rate and the standard halon shot (5%). Given the permeate and cargo bay pressure, the 30 psia feed pressure performance point could not achieve a 15% oxygen concentration in the bay for all bay sizes. The 12% time not inert numbers are clearly not sensitive to cargo bay size, while this graph does illustrate the sensitivity of the cargo bay inerting process to ASM feed pressure. The lack of sensitivity to the size of the cargo bay with the OBIGGS size remaining the same at first seems unusual, but not when considering that increasing the size of cargo bay also means increasing the size of the halon shot (to obtain the 5% at sea level), with the leakage rate remaining the same. This allows for effectively less ventilation of the halon with the same NEA and air flow into the bay.

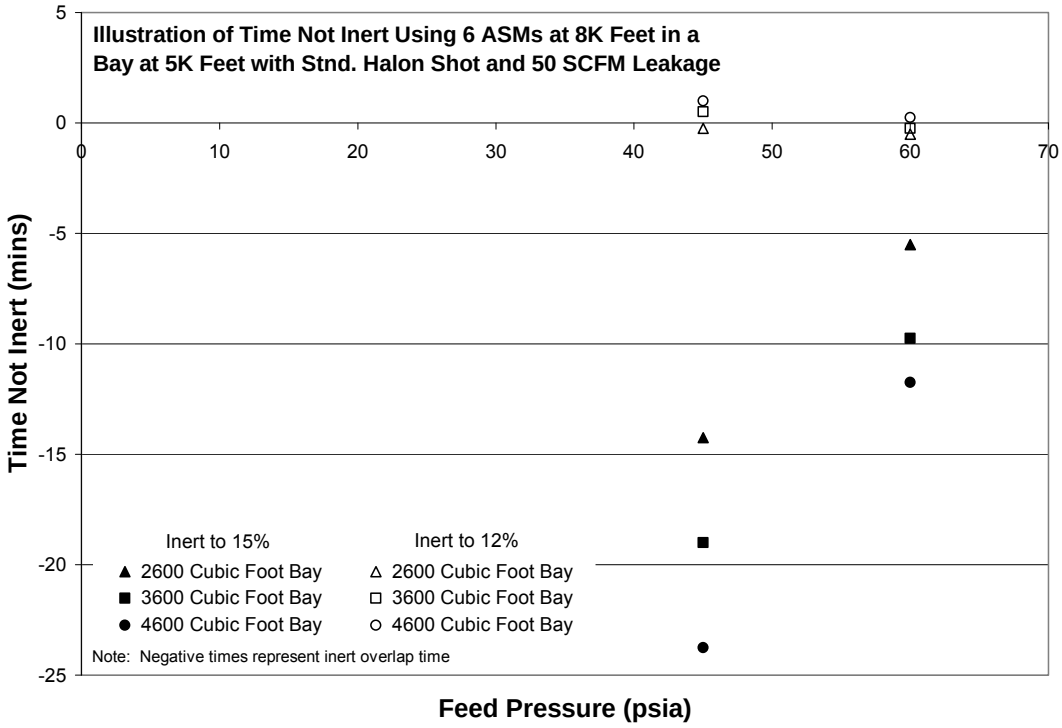


Figure 16. Cargo Bay Time Not Inert Results Versus ASM Feed Pressure for Different Cargo Bay Sizes With the 50 SCFM Leakage Rate and the Standard Halon Shot Giving 15% and 12% Inerting Level Results

Figure 17 illustrates the sensitivity of the data to halon shot size, giving the time not inert for both 45 and 60 psia feed pressures for the previously stated permeate and cargo bay pressure using the 50 SCFM leak rate and a 3600-cubic-foot cargo bay. Again, the 30 psia feed pressure performance point could not achieve a 15% oxygen concentration in the bay for any halon shot sizes, because the permeate and cargo bay pressure conditions are not adequate to do so, given the low feed pressure. When examining the 12% time not inert numbers, the standard halon shot is adequate for both ASM feed pressures presented, while the larger (6%) shot is clearly better and the smaller (4%) shot is clearly worse with some significant positive times not inert. This clearly shows, with all other things remaining the same, increasing the size of the halon shot will decrease the time not inert. The unusual trend of the inert overlap times (negative time not inert) becoming more negative when ASM feed pressure decreases is nonsensical, since as the feed pressure approaches 30 psia it becomes infinitely positive. More than likely, the 6% halon shot data for the 12% inerting concentration gives the bottom of a curve "bucket," which starts becoming more positive as ASM feed pressure continually decreases and abruptly cuts off above 30 and below 40 psia.

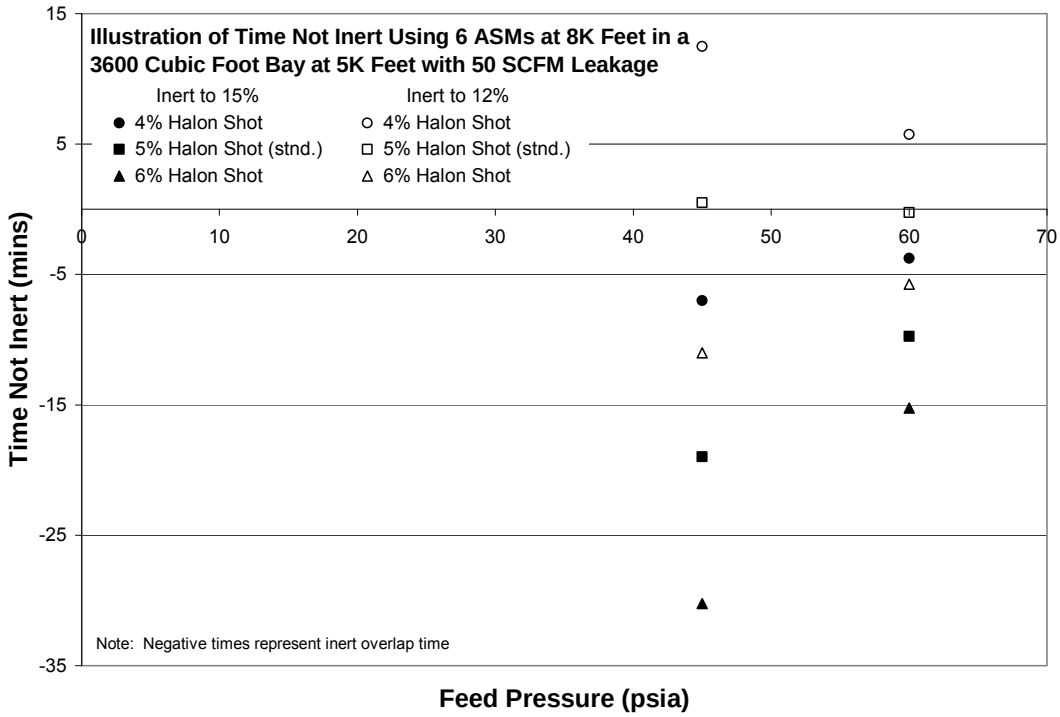


Figure 17. Cargo Bay Time Not Inert Results Versus ASM Feed Pressure for Different Halon Shot Sizes With the 50 SCFM Leakage Rate and 3600-Cubic-Foot Bay and 15% and 12% Inerting Level Results

Nowhere is this abruptness more evident than when examining figure 18, which gives: the sensitivity of the data to cargo bay air leakage rate given; the time not inert for 30, 45, and 60 psia feed pressures; the previously stated permeate and cargo bay pressure; the standard halon shot; and a 3600-cubic-foot cargo bay. With the smaller leakage rate (25 SCFM), the 30 psia feed pressure performance point was able to achieve both 15% and 12% oxygen concentration in the bay, although it was difficult with a time not inert over 90 minutes. When increasing the air leakage into the cargo bay from 50 to 75 SCFM air at 45 psia feed pressure, the time not inert to 12% oxygen goes from approximately 0 to 25 minutes. This sensitivity is expected, but still overshadowed by the effect of decreasing the ASM feed pressure by 33% (45 to 30 psia), essentially making most low-altitude performance points unable to obtain 12% or even 15% oxygen in the bay.

Adding cargo to the bay reduces the effective volume of the bay and should reduce the times not inert given in the previous sections. Although cargo is not always homogenous and contained, a cargo bay density of 25% and 50% full is not unusual in a commercial transport cargo hold. To illustrate the sensitivity of the data to the cargo bay density, the time not inert data corresponding to 30 psia feed pressure and 25 SCFM air leakage from figure 18 were compared with calculated data for a cargo hold with a 25% and 50% full cargo density. Figure 19 gives these results, indicating that cargo density has a direct result on reducing the time not inert, giving a significant reduction in the time not inert with a 50% versus a 25% cargo density.

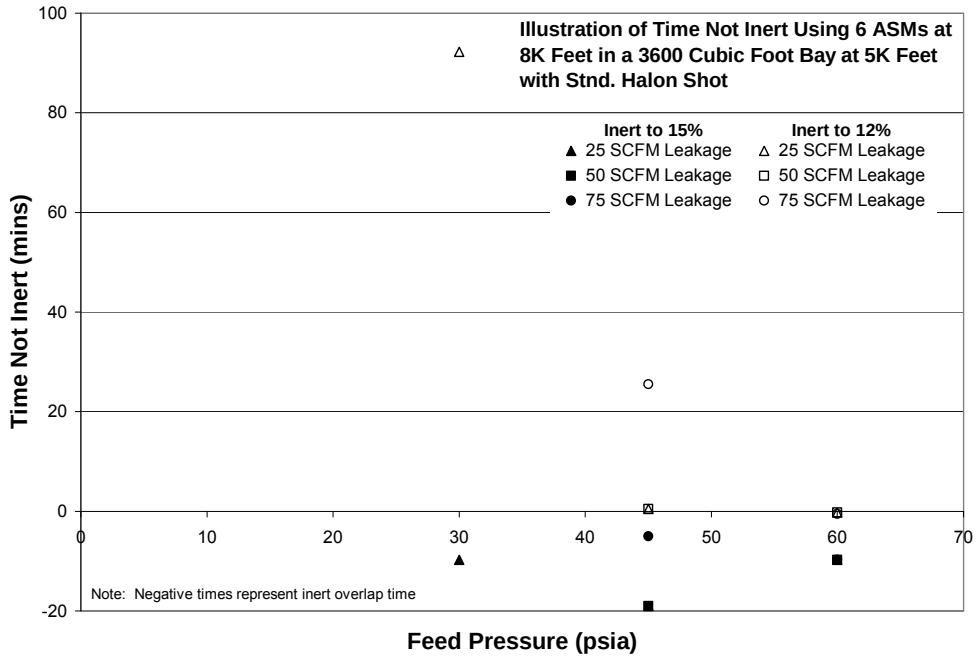


Figure 18. Cargo Bay Time not Inert Results Versus ASM Feed Pressure for Different Leakage Rates With the Standard Halon Shot and 3600-Cubic-Foot Bay at 15% and 12% Inerting Levels

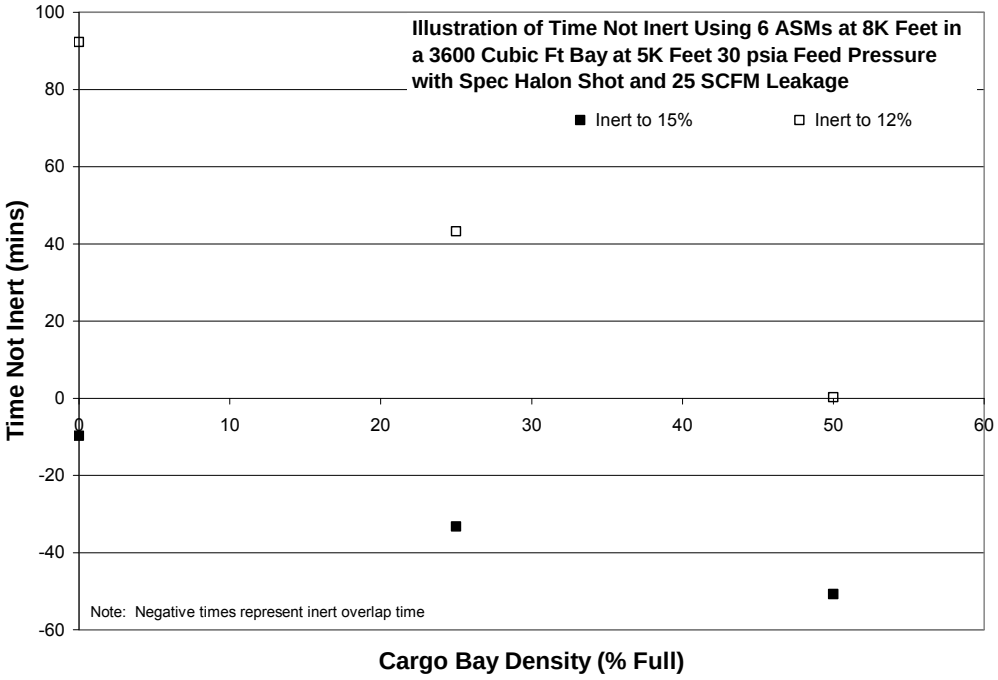


Figure 19. Cargo Bay Time not Inert Results Versus Cargo Density for 25 SCFM Leakage With the Standard Halon Shot and 3600-Cubic-Foot Bay With 30 psia Feed Pressure and 15% and 12% Inerting Levels

Additional research is required to establish, with a significant level of confidence, the oxygen depletion concentration needed to assure continued fire suppression before surmising the feasibility of using a fuel tank inerting OBIGGS for cargo bay fire suppression. Also, any combined effect of halon and oxygen depletion (i.e., 16% oxygen with 2% halon) that may offer fire suppression capability in the interim between the halon discharge and achievement of the oxygen depletion suppression concentration (i.e., 12%-15%) needs to be studied in depth to obtain a complete picture of the fire suppression coverage offered by a fuel tank inerting system.

5. SUMMARY OF RESULTS.

The acquired ASM performance data illustrated that an ASM-based OBIGGS used for fuel tank inerting would be consistent with the requirements for a cargo bay fire suppression system. The ASM mass flow rate, at a set of given conditions, is independent of the static pressure at which the NEA is deposited (i.e., cargo bay altitude), although the desired NEA oxygen concentration will change as this parameter changes, with all other parameters remaining the same. The NEA flow was very sensitive to ASM feed pressure. For example, the time to reach 12% oxygen in the cargo bay with 5% NEA was 5 times slower at 30 psia feed pressure than at 45 psia. This highlights the need to ensure the required bleed air pressure is available to give sufficient NEA flow to achieve and maintain the desired inerting concentration for the given aircraft flight scenario. This is even more important in light of the decreasing performance of the ASM as the static permeate pressure increases (aircraft altitude decreases). In one calculation, the time to reach 12% oxygen in the cargo bay is 2.5 times greater at 8,000-foot altitude than at 30,000-foot altitude with the cargo bay at 5,000-foot altitude. As expected, it is harder to inert the cargo bay as the ambient pressure increases (pressure altitude decreases), with all other parameters being constant, due to the increasing mass of gas in the bay.

The results of modeling the oxygen concentration with a halon discharge and representative air leakage into the bay to determine time not inert for given conditions illustrated the same trends observed in the results of the time to inert results. When observing the sensitivity of the time not inert results to decreasing the air leakage rate and increasing the size of the halon shot, both decreased calculated time not inert values, although these values are also very sensitive to the ASM feed pressure. The time not inert values calculated were not that sensitive to cargo bay size with the same size OBIGGS. There is less than 1.5 minutes difference in the time not inert for the 2600-cubic-foot cargo bay than for the 4600-cubic-foot cargo bay provided that the leakage rate was the same and cargo bay had the same relative size halon discharge (5% concentration in 1 minute at sea level). Increasing cargo bay density (fullness) had a large impact on reducing large positive time not inert results.

6. REFERENCES.

1. Desmarais, L.A. and Tolle, F.F., "Integrated Aircraft Fuel Tank Inerting and Compartment Fire Suppression System, Volume 2, Evaluation of Nitrogen-Enriched Air as a Fire Suppressant," AFWAL-TR-83-2021, Vol II, April 1983.

2. Cavage, William M. and Morrison, Robert, "Development and Testing of the FAA Simplified Fuel Tank Inerting System," *4th Triennial Fire and Cabin Safety Research Conference*, November 2004.

3. Burns, Michael, et al., "Evaluation of Fuel Tank Flammability and the FAA Inerting System on the NASA 747 SCA," FAA report DOT/FAA/AR-04/41, December 2004.

4. Reynolds, Thomas, et al., "Onboard Inert Gas Generation System/Onboard Oxygen Generation System (OBIGGS/OBOGS) Study, Part 1: Aircraft System Requirements," NASA/CR_2001-210903, May 2001.

5. Cavage, William M., "Modeling of In-Flight Fuel Tank Inerting for FAA OBIGGS Research," *4th Triennial Fire and Cabin Safety Research Conference*, November 2004.

6. Reinhardt, John W., "Minimum Performance Standard for Aircraft Cargo Compartment Halon Replacement Fire Suppression Systems (2nd Update)," FAA report DOT/FAA/AR-TN05/20, June 2005.