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The Effect of Fuel on an Inert Ullage in a Commercial Transport Airplane Fuel Tank

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16. Abstract

Recent Federal Aviation Administration research has illustrated that fuel tank inerting could be practical in the commercial fleet for the protection of center wing or body style tanks. The effect of pressure differences on the release of dissolved oxygen in a fuel load on an inert fuel tank ullage was studied. A test article was constructed and experiments were conducted to quantify the potential increase in oxygen concentration in an adjacent inert ullage as a result of gases in fuel during sea level stimulation, as well as at reduced atmospheric pressure. Different methods of stimulating the release of gases from the fuel were examined during laboratory experiments in an attempt to quantify the increase in oxygen concentration in an inert aircraft fuel tank ullage. This data was compared with flight test data in an attempt to gage the ability of laboratory tests and simple calculations to predict the resulting change in oxygen concentration of an inert commercial airplane fuel tank during a flight cycle.

The oxygen evolution from different fuel loads was measured to determine the resulting oxygen concentration on an adjacent ullage. At sea level, the increase in oxygen concentration can be as great as 7 percent for an ullage inerted to 6 percent with an 80 percent fuel load that was stimulated. Increasing altitude allows for an additional increase in the oxygen concentration of the ullage even if the ullage was at equilibrium at sea level. Inerting the ullage through fuel has the effect of scrubbing the fuel to some rudimentary level of protection that reduces or eliminates the increase in oxygen concentration due to fuel air evolution, depending upon fuel load. Flight test data illustrated a relatively small amount of oxygen evolving from fuel compared to the theoretical amount available. Any effect of oxygen concentration increase due to fuel tended to be obscured by the more dominant effect of air entering the vent due to fuel consumption. Oxygen concentration flight test data with consumed fuel loads and inert ullages were best duplicated in laboratory experiments by not stimulating the fuel. Calculations of oxygen concentration increase have poor agreement with flight test data, but the flight test oxygen concentrations results fall within the band of 0 and 100 percent oxygen evolution.

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LIST OF ACRONYMS

FAA	Federal Aviation Administration
NEA	Nitrogen-enriched air
OBIGGS	Onboard inert gas generation system
CWT	Center wing tank
CFM	Cubic feet per minute
VTE	Volumetric tank exchange

EXECUTIVE SUMMARY

Significant emphasis has been placed on fuel tank safety since the TWA flight 800 accident in July 1996. Recent Federal Aviation Administration (FAA) research has illustrated that fuel tank inerting could be practical in the commercial fleet if air separation modules, based on hollow-fiber membrane technology, could be applied in an effective manner. The focus of the FAA fuel tank inerting initiative is on center wing or body style tanks, which are frequently not used by the aircraft operators and are likely to be empty on most domestic flight operations. When a center wing tank has a fuel load and is inerted, what effect the fuel load has on the inert ullage needs to be studied and understood to be taken into account in the design of inerting systems. Fuel tends to trap air, which evolves from the fuel when stimulated due to the differences in partial pressures of oxygen and nitrogen. Additionally, when and aircraft ascends to altitude, the pressure in the fuel tank ullage decreases causing a further pressure discrepancy between the ullage and dissolved fuel gases. This allows for additional oxygen evolution to potentially increase the oxygen concentration of an adjacent ullage. To counteract this, some military aircraft, maintaining an inert ullage, scrub the fuel of air. This is when a device is employed, usually during fueling, that displaces most of the air from the fuel and replaces it with nitrogen-enriched air or nitrogen.

To determine the effect of fuel on an adjacent inert ullage, a test article was constructed and experiments were conducted. The focus of the test was to quantify the potential increase in oxygen concentration of an adjacent inert ullage as a result of dissolved air in fuel during sea level stimulation as well as under reduced atmospheric pressure. Different methods of stimulating the release of oxygen from the fuel during laboratory experiments were examined in an attempt to quantify the exposure of a given inert aircraft fuel tank ullage to an increase in oxygen concentration. This data was compared with flight test data in an attempt to gage the ability of laboratory tests and simple calculations to simulate the resulting change in oxygen concentration of an inert commercial airplane throughout a flight regime.

The oxygen evolution from fuel was measured to determine the resulting oxygen concentration a fuel load that is not scrubbed can have on an adjacent inert ullage. At sea level, the increase in oxygen concentration can be as great as 7 percent for an ullage inerted to 6 percent with an 80 percent fuel load that is stimulated. Increasing altitude allows for an additional increase in the oxygen concentration of the ullage even if the ullage was at equilibrium at sea level. Inerting the ullage through fuel has the effect of scrubbing the fuel to some rudimentary level of protection that reduces or eliminates the increase in oxygen concentration due to fuel air evolution. This process had the effect of reducing the increase in oxygen concentration caused by a 60 percent full fuel load on an ullage at 8 percent oxygen from 3 to 1 percent, although this fuel scrubbing method illustrated diminishing returns as the fuel load increases. Flight test data illustrated a relatively small amount of oxygen evolving from fuel compared to the theoretical amount available. Also, any effect of air evolving from fuel tended to be obscured by the more dominant effect of air entering the vent due to fuel consumption. Oxygen concentration flight test data with consumed fuel loads and inert ullages were best duplicated in laboratory experiments by not stimulating the fuel. Calculations of oxygen concentration increase have poor agreement with flight test observations, but the resulting flight test oxygen concentrations fall within a calculated band based on ambient air replacing the consumed fuel and 100 percent exchange of oxygen and nitrogen in both the ullage and fuel.

1. INTRODUCTION.

1.1 BACKGROUND.

Significant emphasis has been placed on fuel tank safety since the TWA flight 800 accident in July 1996. Since the accident, the Federal Aviation Administration (FAA) has issued numerous Airworthiness Directives, enacted a comprehensive regulation to correct potential ignition sources in fuel tanks, and conducted research into methods that could eliminate or significantly reduce the exposure of transport airplanes to flammable vapors. The latter has been in response to a new FAA policy that strives to eliminate or reduce the presence or consequences of flammable fuel tank vapors. The approach has focused on fuel tank inerting, which is commonly used by the military. Recent FAA research has illustrated that fuel tank inerting could be practical in the commercial fleet. Fuel tank inerting would be accomplished by displacing the air in the existing empty tank space above the fuel (ullage) with nitrogen or nitrogen-enriched air (NEA). This could be accomplished with a ground source of NEA or more preferably with an onboard inert gas generation system (OBIGGS). The focus of the FAA fuel tank inerting initiative is on center wing or body style tanks in the commercial transport airplane fleet. These tanks are frequently not used by the aircraft operators and are likely to be empty on most domestic flight operations. When an inert fuel tank has a fuel load, the effect of the fuel load on the ullage needs to be quantified and accounted for in the design of an inerting system.

1.1.1 Fuel Scrubbing.

Air readily dissolves in fuel. Fuel, however, has a relatively large affinity for the oxygen in air, as compared to nitrogen, as given by a solution factor known as the Ostwald coefficient, which allows fuel to contain a larger percent of oxygen by volume then air. This can result in fuel having a dramatic effect on an adjacent inert ullage, particularly at high fuel loads, if the differences in oxygen partial gas pressures can equalized via some stimulation method. Commercial transport fuel tanks are vented to atmospheric pressure to maintain equal pressure between the ullage and ambient. When an aircraft ascends to altitude, the pressure in the fuel tank ullage decreases and dissolved gases will again evolve from fuel until the partial pressures of oxygen and nitrogen between the fuel and the ullage are equal. This will again result in an increase in oxygen concentration of an inert ullage.

To counteract this effect, some military aircraft maintaining an inert ullage scrub the fuel of air. A device is employed, usually during fueling, that displaces most of the air from the fuel and replaces it with NEA or nitrogen. This scrubbing process can be accomplished by simply depositing NEA into the fuel to displace some of the dissolved air with NEA or with a more complex mixing system that displaces most of the oxygen. The resulting oxygen concentration of dissolved gases in the fuel will be dependent upon the oxygen concentration of the NEA and the thoroughness of the scrubbing process. This resulting oxygen concentration will determine the effect the fuel load will have on the adjacent inert ullage.

1.1.2 Previous Work.

Previous studies of fuel in conjunction with nitrogen inerting focused on the potential change in the oxygen concentration requirements for inerting, given a sloshing or vibrating tank [1]. This study made no mention of fuel scrubbing or the evolution of air from the fuel during sloshing, but rather focused on obtaining a reaction in a test article inert ullage after sloshing or vibrating the tank. Additionally, ullage oxygen concentration was not measured directly or tracked during testing. This is probably due to the relatively small fuel loads employed for the testing, which would have caused too little net change in ullage oxygen concentration to be tracked or measured. The Department of Defense, however, did an extensive study of OBIGGS in the 1980s during which fuel scrubbing and ullage oxygen concentration effects were studied for simulated aircraft fuel tank missions [2]. The tests evaluated tanks at high fuel loads being inerted with a specified OBIGGS with varying degrees of scrubbed fuel. The results illustrated that a significant amount of fuel scrubbing is required to keep a small ullage (mostly full tank) below 10 % oxygen concentration during climb and the first parts of cruise.

Previous FAA fuel tank inerting experiments focused on the amount of NEA gas needed to inert a commercial transport category airplane fuel tank ullage during ground operations. These experiments employed empty tanks that were simple rectangular test articles [3]. The results of these experiments illustrated that an empty tank can be inerted to 8 percent oxygen (by volume) with 1.5 volume exchanges of 5 percent NEA (5 percent oxygen). This is to say, to achieve an oxygen concentration in an ullage of 8 percent from ambient, which is 20.9 percent, a volume of 5 percent NEA equal to 1.5 times the ullage volume must be deposited in the tank. These experiments are valid for a fuel tank ullage normally vented to atmosphere and assume the tank inert gas deposit is sufficiently far from the vent to allow for adequate mixing within the ullage. This reference also gives an analytical equation developed to calculate the resulting oxygen concentration of an ullage inerted with a given purity (oxygen concentration) and flow of NEA for a fixed amount of time.

A proof of concept test of ground-based inerting was conducted by the FAA in conjunction with the Boeing company. This test was accomplished by inerting the center wing tank (CWT) of a Boeing 737-700 with NEA supplied from a ground source. The aircraft was then subjected to normal ground and flight conditions to determine the effect on the inert ullage. This test validated the inert gas requirements developed by the FAA and illustrated the change in oxygen concentration on an inert ullage due to the consumption of different fuel loads [4]. This test also examined the effects of ground fueling operations and cross-vented CWT venting systems on an inert ullage in an operational aircraft.

1.2 SCOPE.

To determine the effect of fuel on an adjacent inert ullage, a test article was constructed and experiments were conducted. The focus of the test was to quantify the potential increase in oxygen concentration of an inert ullage adjacent to a fuel load as a result of the equalization of the partial pressures of dissolved gases in fuel and ullage during sea level stimulation as well as with reduced atmospheric pressure. The inert ullage was not continually supplied with inert gas in a attempt to isolate the effect of the fuel only on the ullage oxygen concentration. Different methods of stimulating the release of gases from the fuel during laboratory experiments were examined to quantify the exposure of a given inert fuel tank ullage to an increase in oxygen concentration. Laboratory tests were performed and compared with flight test data, as well as simple calculations, to gage the ability of these tools to predict the resulting change in ullage oxygen concentration of an inert commercial airplane fuel tank ullage, due to fuel air evolution and consumption throughout a flight regime.

2. EQUIPMENT AND PROCEDURES.

2.1 EQUIPMENT.

The primary equipment used for the test was a fuel tank test article and altitude chamber with associated instrumentation.

2.1.1 Test Article.

The fuel tank test article was a welded rectangular aluminum tank roughly 3 by 3 by 2 feet high. It contained a drain at the bottom and vent on the top with an additional capped port on the top of the tank for refueling, defueling, and checking the fuel quantity. The vent in the top of the tank had a 4-inch extension with a small hole in the side and a one-way valve on top that only let ullage gas escape. When a pressure change forced ullage gas to escape, it could do so easily, but it was more difficult for chamber air to be deposited back into the ullage, with the ullage still being vented to atmosphere. Through experimentation, the fuel tank was determined to hold 128 gallons. From that fuel quantity for any percentage, the fuel load could be calculated and a graduated stick was developed to determine fuel quantity after adding fuel. Also, a 12- by 8-inch rectangular hole was installed in the top of the tank to provide pressure relief, with a sheet of thick aluminum foil sandwiched between the rim of the rectangular hole and a retaining plate, in the event of a failure, which caused a reaction in the flammable fuel tank ullage.

Additionally, an instrumentation panel was installed in the top of the tank. A 16- by 16-inch removable aluminum panel was fitted with various bulkhead fittings to allow access for gas sample tubing and thermocouples as well as allowing for the deposit of NEA and air for test purposes. Inside the tank, the NEA was directed down and away from the direction of the tank vent to maximize inert gas distribution in the ullage. Compressed air could be deposited into the tank to increase the oxygen concentration when needed. The tank also had a manifold mounted on the bottom, in the form of two U-shaped 1/4-inch tubes with small holes drilled along the length, to allow for the distribution of gas into the fuel. This could be inert gas for fuel scrubbing, air for reviving the fuel oxygen concentration to ambient conditions, or recirculated ullage gas into the fuel to equilibrate the ullage and dissolved fuel gases. Also, if necessary, fuel could be pumped out of the tank and back in through the manifold with a fuel pump to stimulate fuel air evolution.

The industrial gas generator used to provide NEA to the test article was a general purpose, off-the-shelf hollow-fiber membrane gas separator with a skid-mounted compressor. The unit required 40 amps of 230 Vac three-phase power and was equipped with an oxygen analyzer and purity alarm. It contained two gas separation modules, each 2 inches in diameter, allowing the unit to generate as much as 10 cubic feet per minute (CFM) of 95 percent NEA (5 percent oxygen by volume). The NEA generator was equipped with a galvanic cell type oxygen analyzer to determine the oxygen concentration of the NEA being produced. When specific NEA oxygen concentrations were not required, bottled nitrogen roughly of a purity of 99.9% was used for inerting to save wear and tear on the NEA generator.

2.1.2 Altitude Chamber.

To simulate flight conditions, the rectangular fuel tank test article was tested in an altitude chamber to reduce the ambient pressure to desire levels. 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 as well as the rate at which pressure changes. This allowed for not only static pressure testing to determine the effects of reduced pressure on an inert ullage adjacent to fuel, but also simulated flight profiles to compare flight test data with acquired laboratory data. The inside dimensions of the chamber are 72 by 71 by 93 inches. Figure 1 shows the fuel tank test article installed in the altitude chamber.

FIGURE 1. FUEL TANK TEST ARTICLE INSTALLED IN THE TEST ALTITUDE CHAMBER

2.1.3 Instrumentation and Data Acquisition.

The primary instrumentation integrated with the test article was an oxygen analyzer for sea level gas sampling as well as a separate analyzer that sampled for altitude (reduced pressure) tests. Additionally, thermocouples were used to measure ullage and fuel temperatures, and a flow meter was used to meter NEA into the tank for experiments. The altitude chamber had a pressure transducer that measured absolute pressure in the chamber to determine altitude. Figure 2 is a block diagram of the experimental test setup with instrumentation.

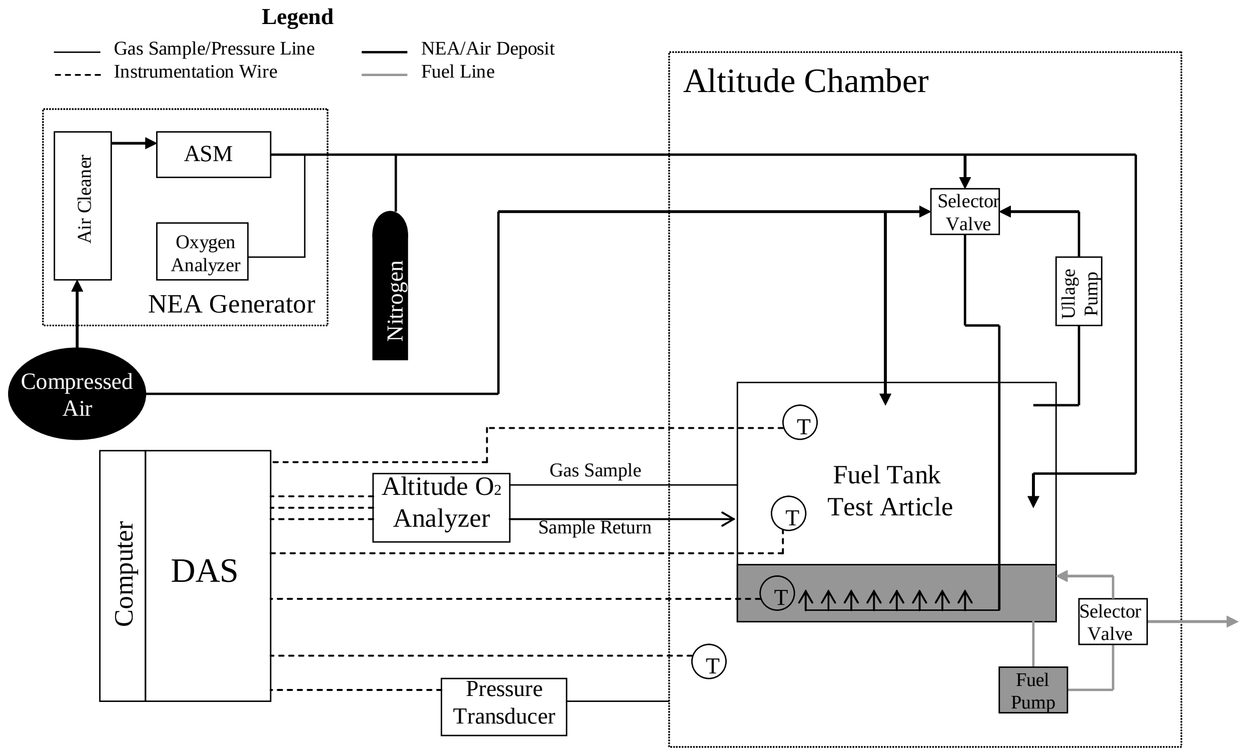

FIGURE 2. TEST ARTICLE AND INSTRUMENTATION DIAGRAM

2.1.3.1 Oxygen Analysis.

The oxygen concentration in the fuel tank ullage at sea level was measured with an oxygen analyzer that used a Polarographic™ oxygen sensor, temperature controlled sensor block, and sample flow bypass system. The sample was supplied at a flow rate between 2 and 4 liters per minute. The analyzer measured from 0 to 25 percent oxygen with a linear 0 to 5 Vdc analog output. Upscale calibration was frequently performed using 16.0 percent O_2 calibration gas. The upscale calibration provided a more accurate measurement of lower oxygen concentrations while potentially sacrificing some accuracy at full scale (21 percent). To reduce the amount of hydrocarbon vapor potentially condensing in the oxygen analyzer, a sample gas condenser was used on the ullage gas sample. This consisted of a copper sample line winding through an ice-filled box with a vertical T at the lowest point and a drain valve. This device removed fuel vapor from the gas sample, which was determined to have a negligible effect on the resulting measured oxygen concentration.

At reduced pressures (increased altitude), a laboratory-based altitude oxygen analyzer developed by the FAA was used to measure the oxygen concentration of the test article ullage during the test. This analyzer employed a galvanic cell oxygen analyzer similar to the FAA Onboard Oxygen Analysis System and used the same sample train pressure control methodology [5]. This single channel analyzer did not employ the same liquid traps and flash arrestors necessary to ensure safety on an aircraft during flight operations.

2.1.3.2 Temperature.

To detect changes in temperature during the inerting process, the test article was instrumented with three K type thermocouples. Two thermocouples were located in the ullage of the tank, and one thermocouple was located in the fuel.

2.1.3.3 Flow.

The flow meter used to measure the flow of NEA to the test article at sea level was temperature compensating with a capacity of 0.7 to 6.1 CFM of air. The accuracy of the flow meter given by the manufacturer was ± 3 percent of full scale.

2.1.3.4 Data Acquisition System.

A computer data acquisition system continuously monitored and recorded the specified instruments during each test. Data acquisition was accomplished via two analog to digital converter boards configured in a standard desktop computer. A computer program was written to acquire the signals and convert each to engineering units with a specified calibration file. Each test was saved as an ASCII file and imported into a spreadsheet where the data was reduced, analyzed, and graphed.

2.2 TEST PROCEDURES.

The fuel effects tests were performed in two primary research areas: Sea level testing and altitude testing. All tests required the same initial test procedures. The oxygen analyzer, data acquisition system, and NEA generator (when needed) were started and allowed to run for approximately 1 hour prior to testing to reach stable operating conditions. The oxygen analyzers were then calibrated before testing began. A fresh fuel load was added to the tank, as required for each test. After the fuel was added, the tank ullage was inerted to the appropriate oxygen concentration and the experiment was allowed to settle for approximately 15 minutes before starting.

2.2.1 Sea Level Tests.

Sea level tests were performed in the Aircraft Components Fire Test Facility at the William J. Hughes Technical Center, Atlantic City International Airport, New Jersey. The test apparatus was inside a climate-controlled, fire-proof test cell, allowing for consistent and relatively stable test conditions.

2.2.1.1 Stimulation Methods.

To study the most effective way of releasing excess air dissolved in fuel and equalizing the oxygen content of the fuel and ullage, several methods were applied to bring the fuel and ullage to equilibrium. The purpose of the stimulation method is to allow excess oxygen in the air dissolved in fuel to be released from the fuel into the ullage and to allow excess nitrogen in the ullage to be deposited in the fuel with little or no exchange of gases outside the fuel tank.

Three methods were studied to equalize the fuel tank gases: ullage recirculation, tank sloshing, and radiant under heating. Ullage recirculation was performed by using a small pump to draft ullage gas and deposit it into the manifold at the bottom of the tank submerged in fuel. Tank sloshing was accomplished by elevating two cattycorner legs of the tank and rocking the tank from side to side. Radiant under heat was done by attaching a hot-plate heater to the underside of the tank and heating the bottom at maximum output. In each case, the experiment was prepared as stated above with a 40 percent fuel load and inerted to 8 percent oxygen by volume. Each method was then applied to the tank.

2.2.1.2 Resulting Ullage Effects.

To study the maximum effect a fuel load could have on an adjacent inert ullage, several tests were conducted with 20, 40, 60, and 80 percent fuel loads. The tank was inerted to 6, 8, or 10 percent oxygen concentration for some or all of the fuel loads. The ullage recirculation stimulation method was applied to each experiment until the ullage oxygen concentration stabilized. The resulting ullage oxygen concentration was recorded and the increase in oxygen concentration calculated.

2.2.1.3 Effects of Inerting Through Fuel.

To study a simple way of scrubbing fuel and examine the resulting effects, several tests were conducted with 20, 40, 60, and 80 percent fuel loads. In each case, the ullage was inerted to 8 percent, using 5 percent NEA, through the manifold at the bottom of the tank under the fuel level with the volume of NEA required being measured. After a settling period, the ullage recirculation stimulation method was applied to each experiment until the ullage oxygen concentration stabilized. The resulting ullage oxygen concentration was recorded.

2.2.2 Altitude Tests.

The altitude tests were performed in the altitude chamber located in the Airflow Induction Test Facility at the William J. Hughes Technical Center.

2.2.2.1. Resulting Ullage Effects at Altitude.

To study the effect of altitude on the ability of a fuel load to effect an adjacent inert ullage, several tests were conducted using the aluminum tank test article with a 20, 40, 60, and 80 percent fuel load in the altitude chamber. As discussed in section 2.2.1.2, the experiment to determine the net ullage effect using ullage recirculation was repeated at sea level pressure for each fuel load, and the resulting ullage oxygen concentration was recorded. The chamber was then evacuated to a pressure altitude of 16,000 feet, the experiment was stabilized for approximately 10 minutes, and the ullage recirculation was repeated. After the ullage oxygen concentration stabilized, the chamber was further evacuated to 32,000 feet pressure altitude, the experiment was stabilized for approximately 10 minutes, and the ullage recirculation was repeated until the ullage oxygen concentration was stable at that altitude. The resulting oxygen concentration was noted after each stabilizing period.

2.2.2.2. Stimulation Methods.

To gage how efficient ullage recirculation releases inert gas from the fuel compared to other potential mechanisms on an existing aircraft, the results of the previous experiment measuring the net effects of fuel on an inert ullage at altitude were repeated with two other methods of stimulation. Specifically, the experiment was repeated with the 40 percent fuel load using no stimulation (altitude pressure change only), as well as using a fuel pump to draft fuel from the tank and redeposit it. The bellows type fuel pump tended to release gas from the fuel when used. The two tests with the alternate methods of stimulation were performed using the same test procedures and time line that was used for the 40 percent fuel load test with the ullage recirculation described in the previous section. This allowed for a fair comparison of the effectiveness of these methods to raise the ullage oxygen concentration.

2.2.2.3 Flight Test Simulation.

To gage how well these laboratory tests could simulate the oxygen concentration increase of an inert aircraft fuel tank ullage due to flight conditions, two tests were performed on the laboratory test article simulating two flight tests. The tank conditions (altitude, initial oxygen concentration, fuel load, and fuel consumption) observed during the FAA/Boeing ground-based inerting flight test demonstration were simulated in the test article and the resulting increased ullage oxygen concentration measured and compared to flight test data acquired. The test article was loaded with the same fuel load (volume percent), and the ullage was inerted to the same level prior to simulating the test flight profile. Fuel was pumped out of the tank at a rate that gave the same change in ullage volume percentage measured during the flight tests, and the ullage oxygen concentration was continuously measured during the test. The descent portion of the tests was not simulated and no fuel stimulation was used.

3. ANALYSIS.

The primary calculations performed for comparison with measured data were the change in oxygen concentration from air entering an inert ullage due to fuel being consumed from the tank and the increase in oxygen concentration due to air evolving from the fuel.

3.1 TANK AIR ENTRY.

The inerting equation developed in reference 3 is simply the general statement of the perfect mixing equation solved in terms of two dimensionless values known as the volumetric tank exchange (VTE) and the inerting ratio. The VTE is the exponent of the natural log function and describes the volume of gas deposited in terms of the volume of the tank. Substituting the variable parameters, this equation is stated below.

$$\frac{O_{2\,Start} - O_{2\,Ullage}}{O_{2\,Start} - O_{2\,NEA}} = 1 - e^{-Qt/V_{Tank}} \qquad (1)$$

Where: $O_{2_{Start}}$ = Oxygen Concentration of Ambient Air

$O_{2\,NEA}$ = Oxygen Concentration of Inerting Gas

$O_{2\,Ullage}$ = Oxygen Concentration of the Ullage

This equation was applied using the starting oxygen concentration as some number at or near ambient (20.9 percent oxygen by volume) and a low oxygen concentration inerting gas (NEA) was added, but the equation is valid for mixing any two gases of different oxygen concentrations in some volumetric ratio to obtain a resulting oxygen concentration.

To calculate the increase in oxygen concentration of an inert ullage due to fuel consumption, it was assumed that the fuel consumption in volumetric terms is equal to the volume of air entering the tank. The assumption is only valid for tanks that are normally vented to atmospheric pressure, as is the case with virtually all modern commercial transport airplanes. This allows the VTE to be simplified as the volume percentage of fuel consumed. Assuming the starting oxygen concentration is low and the inerting gas added is air, the following equation can be simplified.

$$O_2(t) = O_{2\,Start} - [(O_{2\,Start} - 20.9)(1 - e^{-FL\%})] \quad (2)$$

With: FL% = Tank Percentage of Fuel Consumed

This equation is valid for all size fuel tanks and assumes the fuel evolves no dissolved air that would change the oxygen concentration of the adjacent ullage. It should be noted that the percentage of fuel consumed is a percentage of the final volume of the ullage. If the final fuel load is not zero, the calculation assumes the final ullage space available is the zero percent full ullage. Also, volume inerting equations are only valid when the inert gas (or diluting gas in this case) has the same density, given the pressure altitude, as the ullage.

3.2 FUEL AIR EVOLUTION.

The effect of a fuel load on an inert ullage can be determined by considering the mass of oxygen dissolved in fuel and the mass of oxygen in the ullage as it pertains to the partial pressure of oxygen for the given medium. At some preliminary state, the partial pressure of oxygen dissolved in the fuel is higher then the partial pressure of oxygen in the inert ullage. These partial pressures can be expressed in terms of mass, given the equation of state.

$$P_{O_{U1}} V_U = m_{O_{U1}} R_O T_U$$

$$P_{O_{F1}} V_F = \frac{m_{O_{F1}} R_O T_F}{C_O}$$

These equations can be restated as follows:

$$m_{O_{U1}} = \frac{P_{O_{U1}} V_U}{R_O T_U} \quad (3)$$

$$m_{O_{F1}} = \frac{P_{O_{F1}} V_F C_O}{R_O T_F} \tag{4}$$

Given:

P_O	=	Partial Pressure of Oxygen
V	=	Volume
M_O	=	Mass of Oxygen
T	=	Temperature
R_O	=	Universal Gas Constant of Oxygen
C_O	=	Ostwald Coefficient

The subscripts *U* and *F* denote ullage and fuel, respectively, with 1 indicating the initial state. The partial pressure of oxygen is defined as the static air pressure times the volume fraction of oxygen. The Ostwald coefficient is a fractional number that describes the solubility of a gas in a fluid and varies with fluid temperature (see appendix A).

Given the mass of oxygen in the tank remains constant, the following equation is exact:

$$m_{O_{U2}} + m_{O_{F2}} = m_{O_{U1}} + m_{O_{F1}}$$

or

$$m_{O_{F2}} = (m_{O_{U1}} + m_{O_{F1}}) - m_{O_{U2}} \tag{5}$$

Given the partial pressure of oxygen between the two medium within the tank are not equal, oxygen will evolve from the higher partial pressure fuel to the lower partial pressure ullage until some equilibrium state (denoted 2) is obtained. This can be stated as follows:

$$P_{O_{U2}} = P_{O_{F2}}$$

Given the relationship between partial pressure of oxygen and mass of oxygen, this gives

$$\frac{m_{O_{U2}} R_O T_U}{V_U} = \frac{m_{O_{F2}} R_O T_F}{V_F C_O}$$

Combining with equation 5 and simplifying gives

$$m_{O_{U2}} = \frac{(m_{O_{U1}} + m_{O_{F1}}) \frac{V_U T_F}{V_F T_U C_O}}{(1 + \frac{V_U T_F}{V_F T_U C_O})} \tag{6}$$

Assuming static pressure remains constant, oxygen volume percent is calculated by determining the partial pressure of oxygen (from equation of state) and dividing by the static pressure.

$$[O_2] = \frac{P_{O_{F2}}}{P_{Atmo}} \tag{7}$$

A more complete discussion of these calculations, including the calculation of partial pressure of nitrogen and true total pressure, is given as appendix B.

4. DISCUSSION OF RESULTS.

The results of the tests discussed in section 2.2 are presented in two distinct sections. These are sea level results and results from altitude experiments.

4.1 SEA LEVEL EXPERIMENTS.

The results of the sea level experiments consisted of three areas of investigation: methods of stimulation, the resulting ullage effects, and the effects of inerting through fuel.

4.1.1 Stimulation Methods.

To examine the effect fuel evolving dissolved gases has on an adjacent inert ullage, the test article was filled with a 40 percent fuel load, and the ullage was inerted to 8 percent for three different tests. For each test, after a 10-15 minute settling period with no stimulation, the tank was stimulated with the three different methods, as discussed in section 2.2.1.1. This test was also performed with no stimulation (quiescent), during which no appreciable increase in oxygen concentration was observed during a 1-hour period. The results of the increase in oxygen concentration over time for the three different stimulation methods can be seen in figure 3. The data illustrates the superior effectiveness of the ullage recirculation method of stimulating oxygen from the fuel. Although the sloshing method illustrated some effectiveness, the consistency of the method was not as thorough as the ullage recirculation. The three distinctly different shapes of the sloshing curve are most likely due to three different people rocking the tank for different periods of time during the test. The difference from person to person is most likely due to subtle differences in the frequency and amplitude of the rocking motion. Heating the fuel from underneath did provide the release of excess air from the fuel and a resulting oxygen concentration increase in the ullage, but the method was not that effective.

It is unclear if the heating and sloshing method provides the same resulting increase in oxygen concentration as the other method, as the equations for calculating the resulting oxygen concentration increase rely on an exchange of gases between the fuel and ullage (i.e., oxygen out of and nitrogen into the fuel). This illustrates the use of the phrase oxygen evolution is a misnomer. The process is an equalization of gases in and out of the fuel and ullage. It is unknown how effective methods that do not mix the ullage and fuel together are at obtaining consistent results.

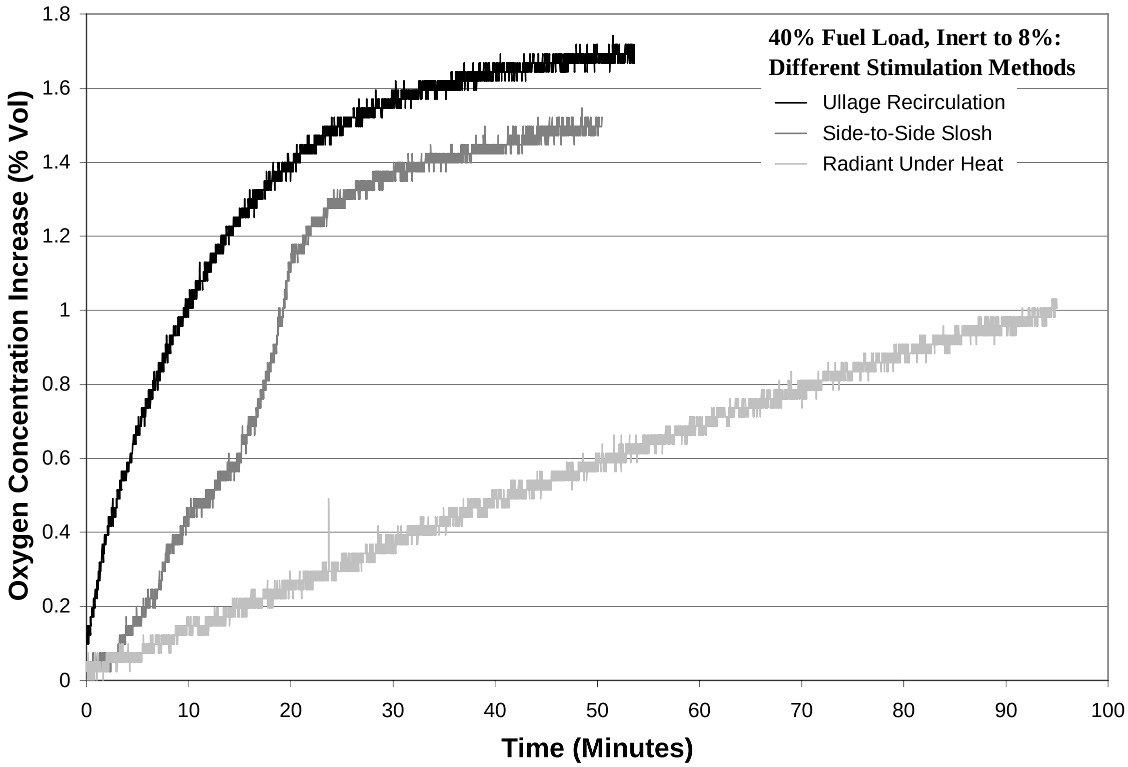

FIGURE 3. TIME-BASED RESULTS OF OXYGEN CONCENTRATION INCREASE FOR THREE DIFFERENT METHODS OF STIMULATING AIR RELEASE FROM FUEL

4.1.2 Resulting Ullage Effects.

The ullage recirculation method, illustrated in the previous test series, was repeated for different fuel loads and different starting ullage oxygen concentrations to obtain a series of curves (figure 4), giving the increase in oxygen concentration due to equalization of gases from the fuel and ullage at sea level pressure. The equations discussed in section 3.2 were used to calculate the resulting oxygen concentration given a varying fuel load. These calculations illustrate good agreement with the measured increases, although the results at 20 percent fuel load are difficult to characterize as they are less than 1 percent, near the error band of the analyzer. The resulting oxygen concentration represents an equilibrium state and illustrates a maximum increase in oxygen concentration given a fixed fuel load and ullage size at sea level in a vented tank.

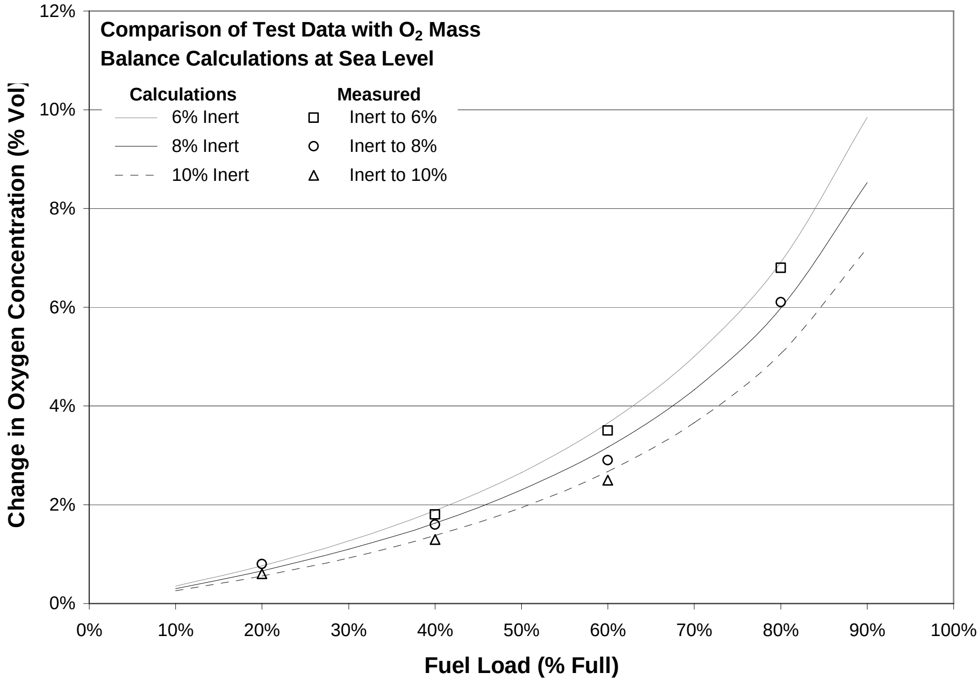

FIGURE 4. RESULTING OXYGEN CONCENTRATION INCREASES VS FUEL LOAD FOR THREE DIFFERENT STARTING INERT ULLAGES

4.1.3 Effects of Inerting Through Fuel.

To examine the effect of fuel scrubbing, several tests were done inerting the tank ullage through a manifold beneath the fuel level. This has the effect of scrubbing some of the excess oxygen from the fuel, providing some protection against ullage oxygen concentration rise during operations that could stimulate the release of excess gas from the fuel. Figure 5 gives the amount of 5 percent oxygen NEA required, in terms of VTE, to inert the ullage to 8 percent oxygen through the fuel. The horizontal line corresponding to a VTE of 1.6 represents the VTE required to inert the actual ullage volume in the normal manner (not through the fuel), which illustrates the increased amount of NEA required to inert the ullage through the fuel. Although the amount of NEA needed per volume of ullage to inert the tank to 8 percent by volume increases, as illustrated by the circles, the total volume of NEA required decreases with increasing fuel load. This is seen by the triangles which illustrate the calculated VTE using the total fuel tank volume.

Using the ullage recirculation method, each inert fuel load was stimulated to determine the resulting oxygen concentration increase as a result of inerting through the fuel. This data, given in figure 6, is compared with the 8 percent inert ullage data from figure 4. As expected, the inerting method reduced the increase in oxygen concentration of the ullage, but illustrated diminishing returns in terms of the decrease in the percentage of increase in oxygen concentration as fuel load increases. These are the fuel load cases that are the main focus of concern with large static fuel loads releasing air during operations. Although some of the measured increases seem significant, it should be noted that effect of evolving air from fuel on an ullage normally vented to atmospheric pressure would tend to be masked by the consumption of the fuel load, which has a much greater effect by allowing air to enter the ullage directly.

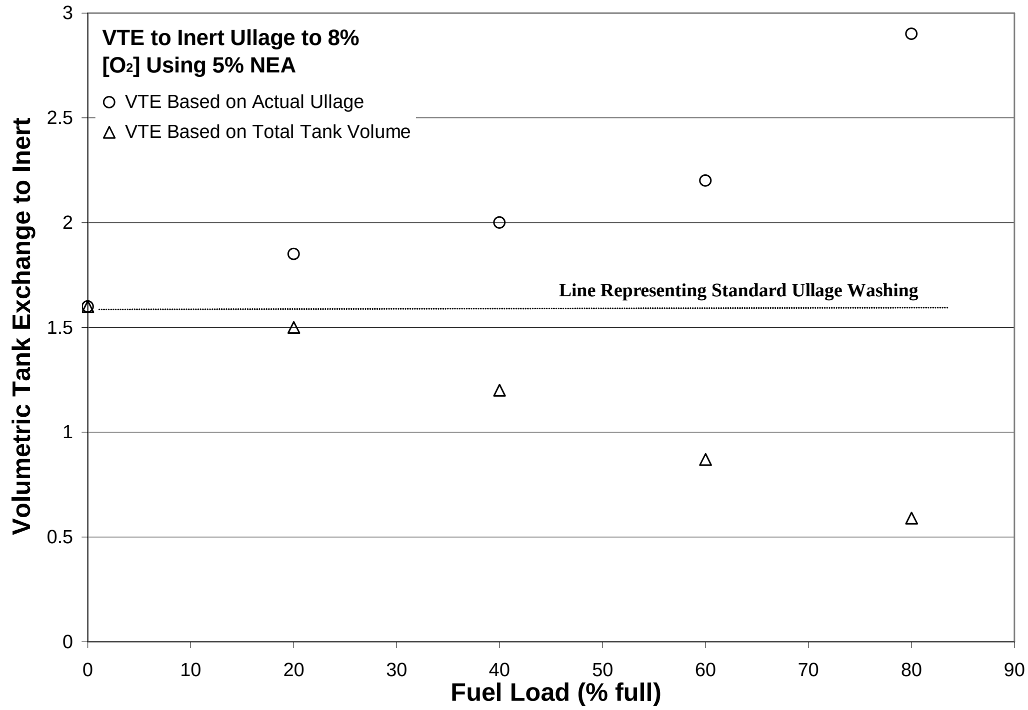

FIGURE 5. AMOUNT OF NEA REQUIRED TO INERT AN ULLAGE TO 8 PERCENT OXYGEN CONCENTRATION THROUGH THE FUEL VS FUEL LOAD

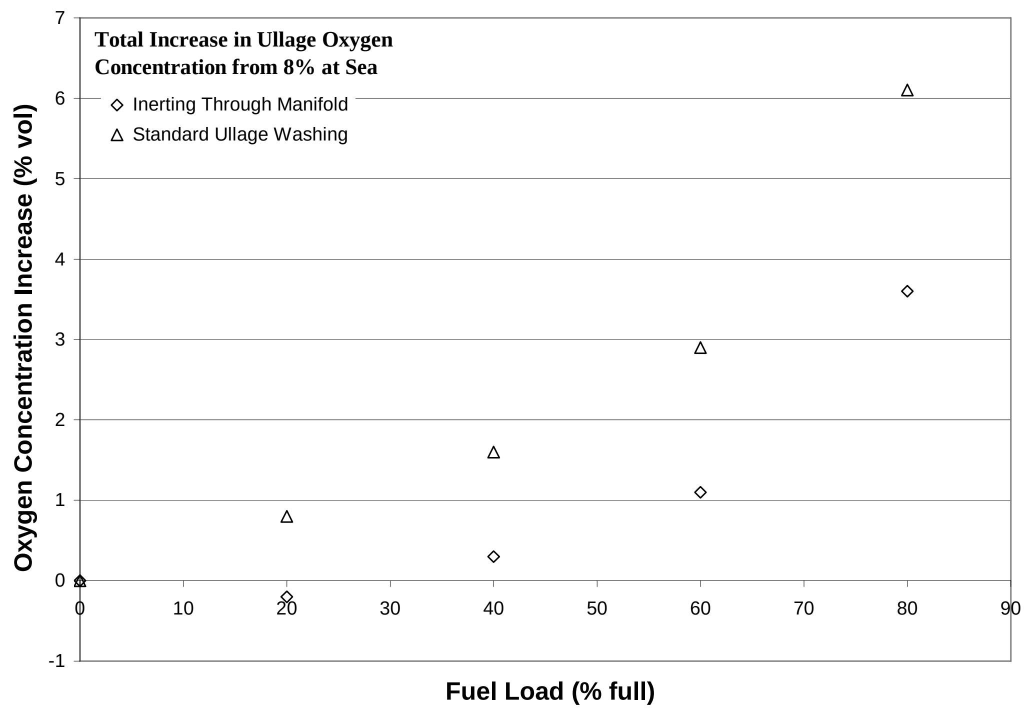

FIGURE 6. RESULTING OXYGEN CONCENTRATION INCREASE VS FUEL LOAD FOR AN 8 PERCENT ULLAGE USING REGULAR AND THROUGH FUEL INERTING

4.2 ALTITUDE EXPERIMENTS.

The results of the altitude experiments consisted of three areas of investigation: the resulting ullage effects, stimulation comparison, and the flight test simulation.

4.2.1 Resulting Ullage Effects at Altitude.

The resulting effects of a fuel load with normal air content on an adjacent inert ullage was examined at reduced air pressure to simulate the effect of altitude on an inert ullage. The procedure for equalizing the fuel and ullage by recirculation was repeated to obtain data, as discussed in section 4.1.2. The tank, which was normally vented to atmospheric pressure, was then submitted to altitude conditions and stimulated again to illustrate any additional increase in ullage oxygen concentration, as discussed in section 2.2.2.1. The results of this experiment for a 60 percent fuel load with an ullage inerted normally to 8 percent are illustrated in figure 7. All experiments are assumed to have a fuel load saturated with air. This experiment illustrates the effect of the Ostwald coefficient in that even though the ullage and fuel were at equilibrium at sea level at approximately 75 minutes into the test with an ullage oxygen concentration of 11 percent, increasing altitude to approximately 16,000 feet pressure altitude resulted in another 1 percent change in the ullage oxygen concentration after stimulation. Figure 8 gives the results of this experiment on the four fuel loads examined during the test series with the values calculated using the previously discussed theory. These values represent the maximum increase in ullage oxygen concentration a static fuel load can have at the indicated altitudes.

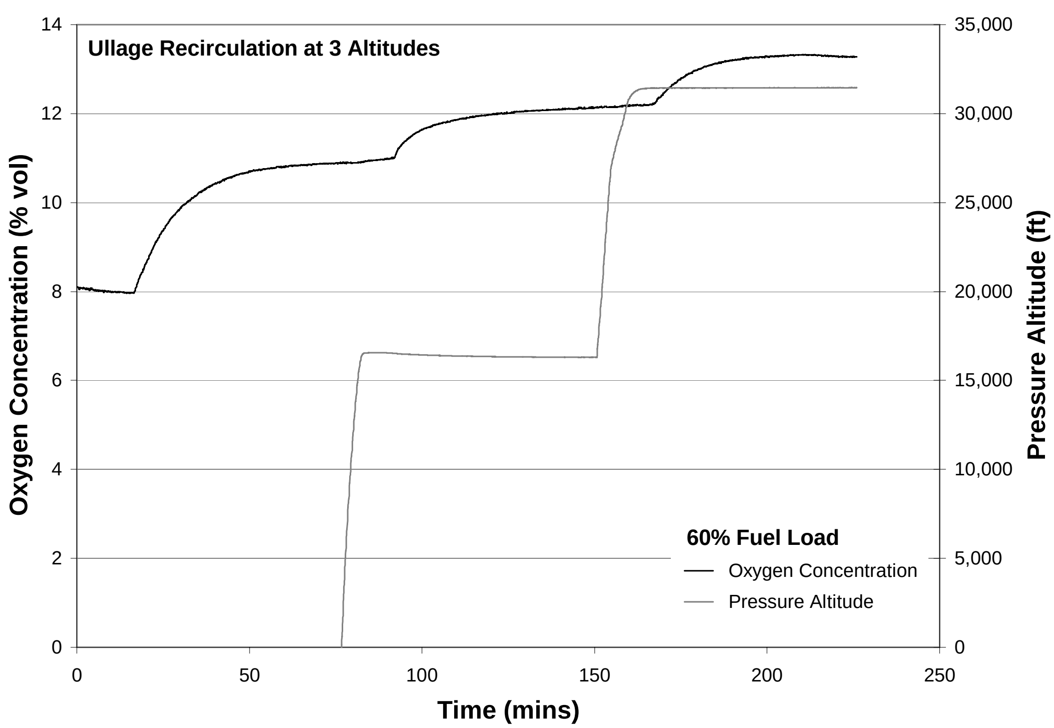

FIGURE 7. RESULTS ILLUSTRATING THE EFFECT OF A 60 PERCENT FUEL LOAD ON AN ULLAGE INERT TO 8 PERCENT USING ULLAGE RECIRCULATION AT THREE ALTITUDES

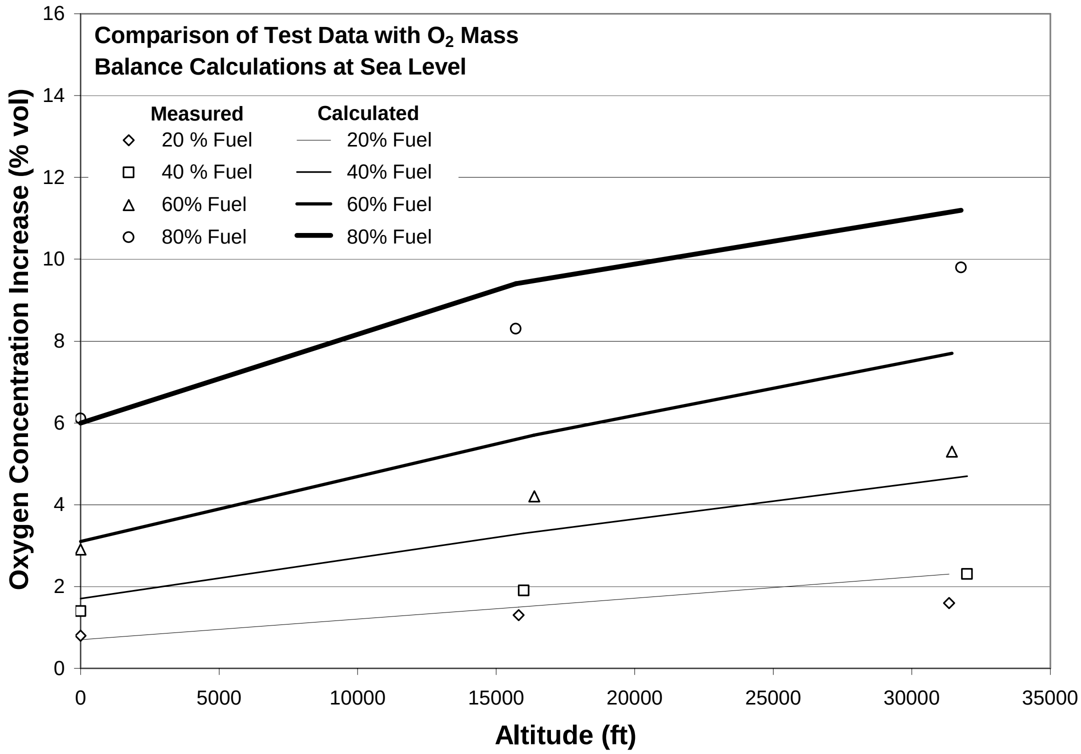

FIGURE 8. RESULTS OF ULLAGE OXYGEN CONCENTRATION INCREASE FOR FOUR DIFFERENT FUEL LOADS USING ULLAGE RECIRCULATION AT THREE ALTITUDES

The calculated values for increase in ullage [O_2] at altitude tend to have poor agreement with the measured results presented. One possible reason for this is the consistency of the initial dissolved air in the fuel, which is difficult to ensure from test to test.

4.2.2 Stimulation Comparison.

To gage the ability of excess fuel gases to increase the ullage oxygen concentration during normal conditions experienced in a commercial transport fuel tank, the 40 percent fuel load altitude test illustrated in the previous section was repeated using both fuel pump stimulation and no stimulation (quiescent). The test illustrated that the ullage recirculation was causing the fastest, most complete change in oxygen concentration as was previously discussed, although at altitude, the fuel pump became effective at releasing excess gas, and, thus, increasing the ullage oxygen concentration at altitude. Pressure changes seem to drive the rate at which gas is released for the quiescent case; however, changing pressure alone seems to be a poor stimulus for gas release.

4.2.3 Flight Test Simulation.

To judge the ability of simple scale laboratory experiments to predict the resulting oxygen concentration of an ullage, given an initial ullage oxygen concentration and a flight profile, the data in figure 9 was examined. Examining the flight test data, the quiescent fuel release had the resulting oxygen concentration that most typified the results observed, although oxygen concentration increase due to air evolution was never directly observed, as the fuel tank was constantly being consumed during each test, bringing air into the tank ullage via the vent system.

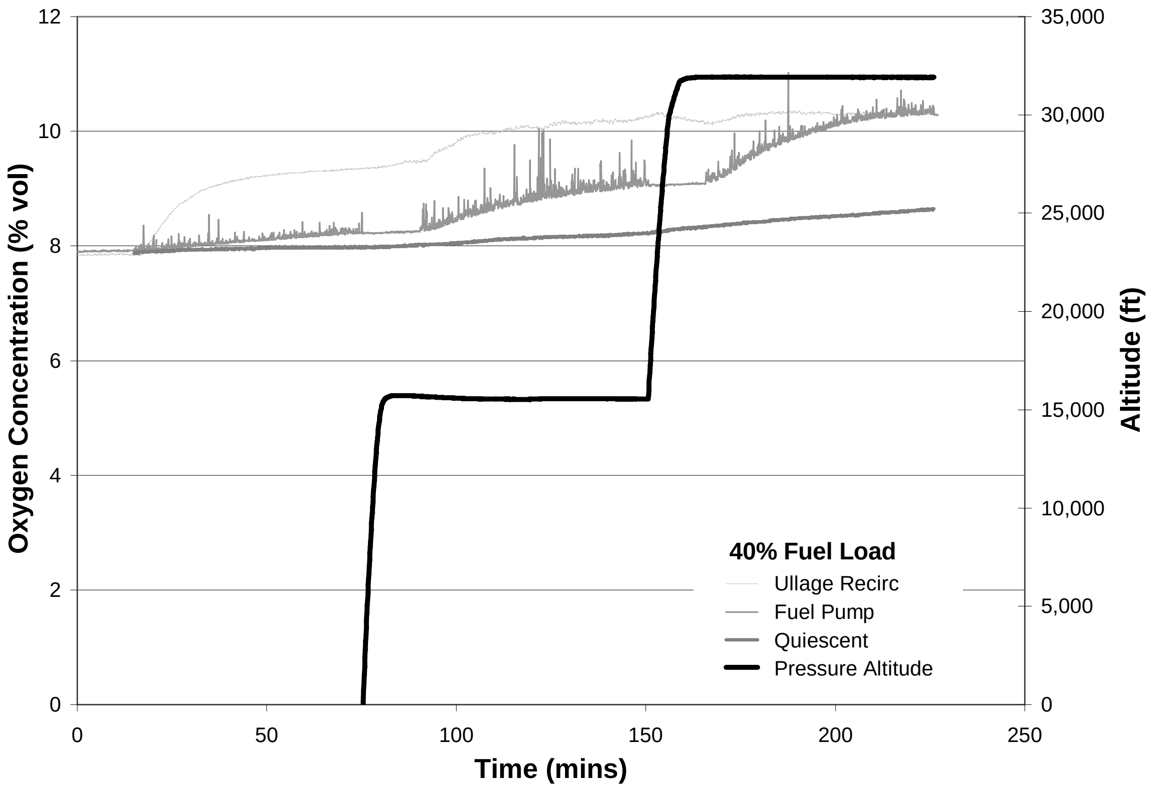

FIGURE 9. RESULTS OF ULLAGE OXYGEN CONCENTRATION INCREASE FOR A 40 PERCENT FUEL LOAD USING DIFFERENT STIMULATION METHODS AT THREE ALTITUDES

Two experiments were performed using the 17 cubic foot test article in the altitude chamber to duplicate the initial tank conditions, the fuel usage, and the flight profile of two flight tests performed in conjunction with the Boeing Company. Figures 10 and 11 illustrate ullage oxygen concentration data from the Boeing flight test [4] for the 40 and 80 percent starting fuel load, respectively, compared with flight test simulation data from the altitude chamber. The data illustrates good agreement for the taxi, takeoff, and cruise portions of the flight using only the change in pressure of the ullage as a driver for releasing excess oxygen in the fuel. For the 40 percent fuel case, the laboratory experiment predicted an ullage oxygen concentration about 0.4 percent higher than observed in the flight test or a 3 percent difference, while for the 80 percent fuel case, the laboratory experiment predicted about 1.1 percent less resulting ullage oxygen concentration or a 7 percent difference than measured in the flight test.

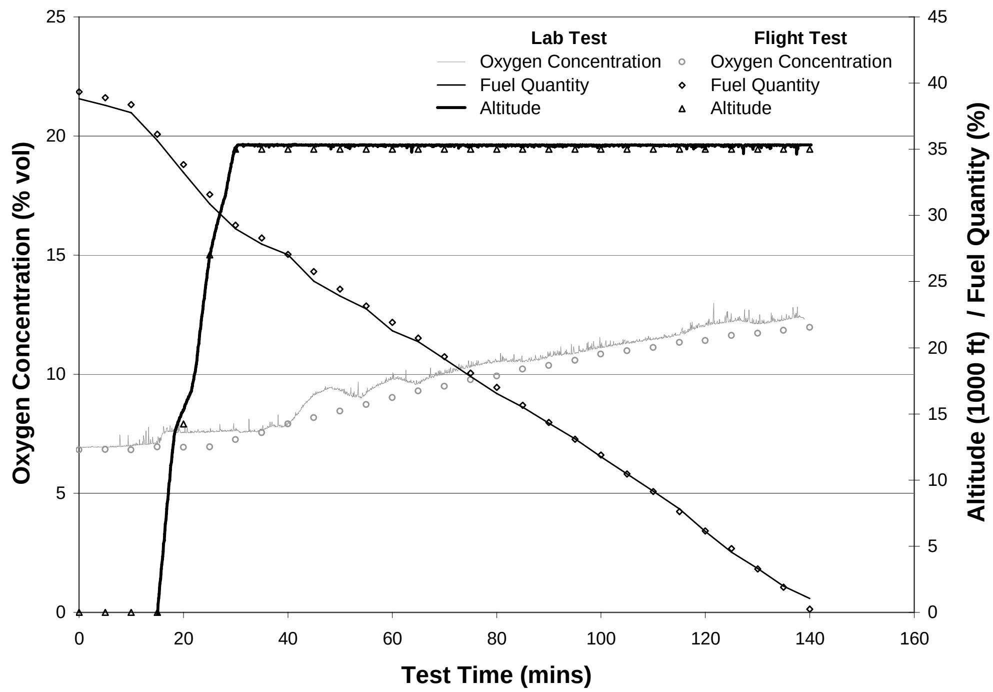

FIGURE 10. BOEING FLIGHT TEST SIMULATION ULLAGE OXYGEN CONCENTRATION DATA COMPARED TO MEASURED FLIGHT TEST DATA FOR THE STARTING 40 PERCENT FUEL LOAD TEST

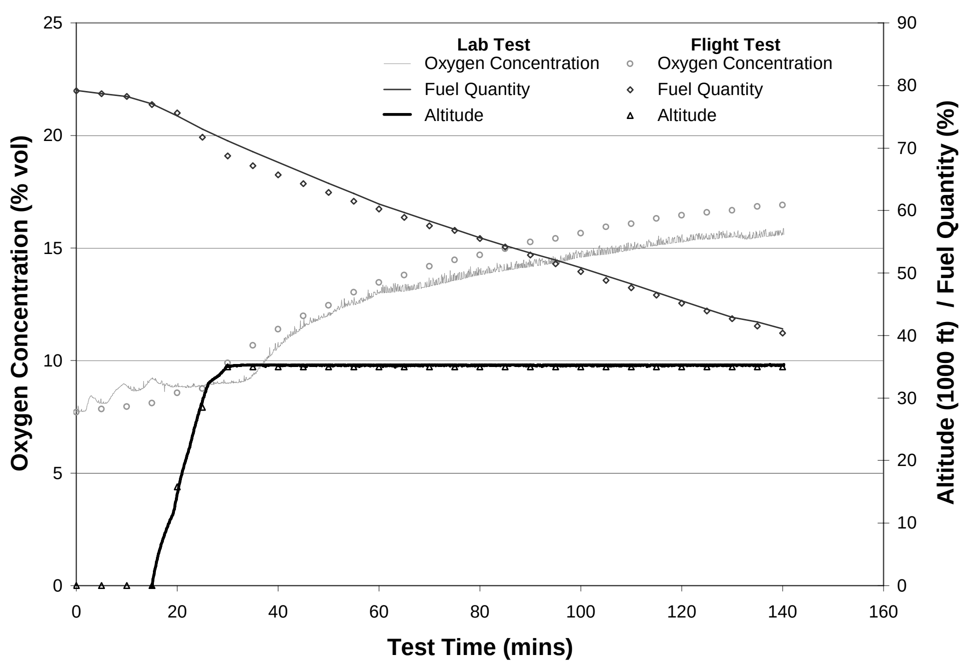

FIGURE 11. BOEING FLIGHT TEST SIMULATION ULLAGE OXYGEN CONCENTRATION DATA COMPARED TO MEASURED FLIGHT TEST DATA FOR THE STARTING 80 PERCENT FUEL LOAD TEST

The ullage oxygen concentration was calculated based on the volume of air entering the ullage being equivalent to fuel consumption. Also, the maximum increase in ullage oxygen concentration from the fuel during the tests discussed in figures 10 and 11 was calculated in terms of the equilibrium oxygen concentration in the ullage, assuming the fuel load at sea level caused the maximum increase, and the fuel load at takeoff created the maximum increase at cruise altitude. This was done using the methods described in section 3.2 and illustrated in figures 4 and 8. The resulting oxygen concentration due to air entering the vent system (fuel usage) represents the minimum increase in oxygen concentration expected during a flight test. The sum of that and the change in oxygen concentration due to air evolution from the fuel load represents the maximum increase in oxygen concentration expected during a flight test. Table 1 illustrates the results of these calculations for the two previously illustrated flight tests. The table illustrates the maximum calculated amount of ullage oxygen concentration increase is much greater than the measured flight test results.

TABLE 1. CALCULATIONS OF ULLAGE OXYGEN CONCENTRATION INCREASE FOR FUEL USAGE AND AIR EVOLUTION FOR THREE DIFFERENT FLIGHT TESTS

Item	Calculated Fuel Burn Resulting O_2	Calculated Air Evolution Change	Calculated Maximum Resulting O_2	Measured Change
40% Fuel Load Boeing Test	11.4	2.2	13.6	12.1
80% Fuel Load Boeing Test	14.1	7.5	21.6	17.0

These calculations make it possible to estimate the minimum and maximum change in oxygen concentration as a result of both fuel usage and fuel air evolution. These values can be used as a band to predict the potential change in ullage oxygen concentration of a particular flight profile and fuel usage. Figure 12 illustrates the measured ullage oxygen concentration for the two aforementioned flight tests with the predicted bands of resulting oxygen concentration. The figure illustrates that much of the oxygen in the fuel remains in the fuel even after long periods of flight at cruise with a significant amount of fuel still remaining in the tank, as is the case with the 80 percent fuel Boeing flight test. To be accurate, the calculation would need to be done in small time steps to blend the evolving gases, given some determined time constant, with the air entering the tank in the ullage to give the constantly changing ullage oxygen concentration. Currently, each separate calculation assumes the other does not exist, thus, the sum of the calculations is conservative and greater than what would result from a more accurate time-dependent simulation.

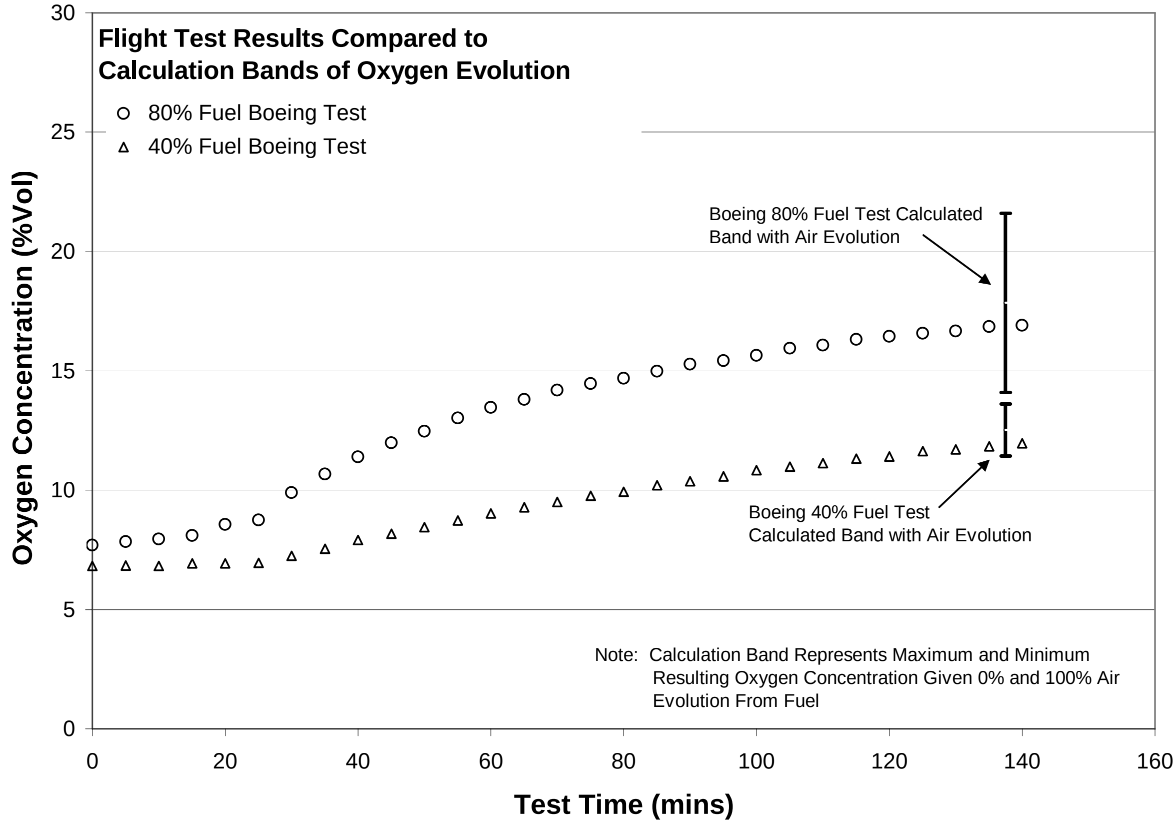

FIGURE 12. FLIGHT TEST ULLAGE OXYGEN CONCENTRATION DATA COMPARED TO CALCULATED BANDS OF OXYGEN CONCENTRATION CHANGE

5. SUMMARY OF RESULTS.

The ullage oxygen concentration will increase due to equalization of the partial pressures of dissolved oxygen in the fuel and ullage. The controlled experiments determined the resulting oxygen concentration change a fuel load can have on an adjacent ullage. At sea level, the increase in oxygen concentration can be as great as 7 percent for an ullage inerted to 6 percent with an 80 percent fuel load if the fuel is stimulated. Increasing altitude allows for an additional increase in the oxygen concentration of the ullage, even if the ullage was at equilibrium at sea level, due to the effect of the Ostwald coefficient and the reduced partial pressure of oxygen across the surface of the fuel. Inerting the ullage through fuel has the effect of scrubbing the fuel to some rudimentary level of protection that reduces or eliminates the increase in oxygen concentration due to fuel and ullage gas equalization. However, this fuel scrubbing method illustrates some significant increases in ullage oxygen concentration with higher fuel loads. Flight test data with fuel loads and inert ullages were best duplicated in laboratory experiments by not stimulating air to evolve from the fuel. Calculations of ullage and fuel gas equalization at altitude have poor agreement with presented results, but the resulting flight test oxygen concentrations fall within the calculated band based on ambient air replacement of consumed fuel and 100 percent partial pressure equalization of fuel and ullage gases.

6. REFERENCES.

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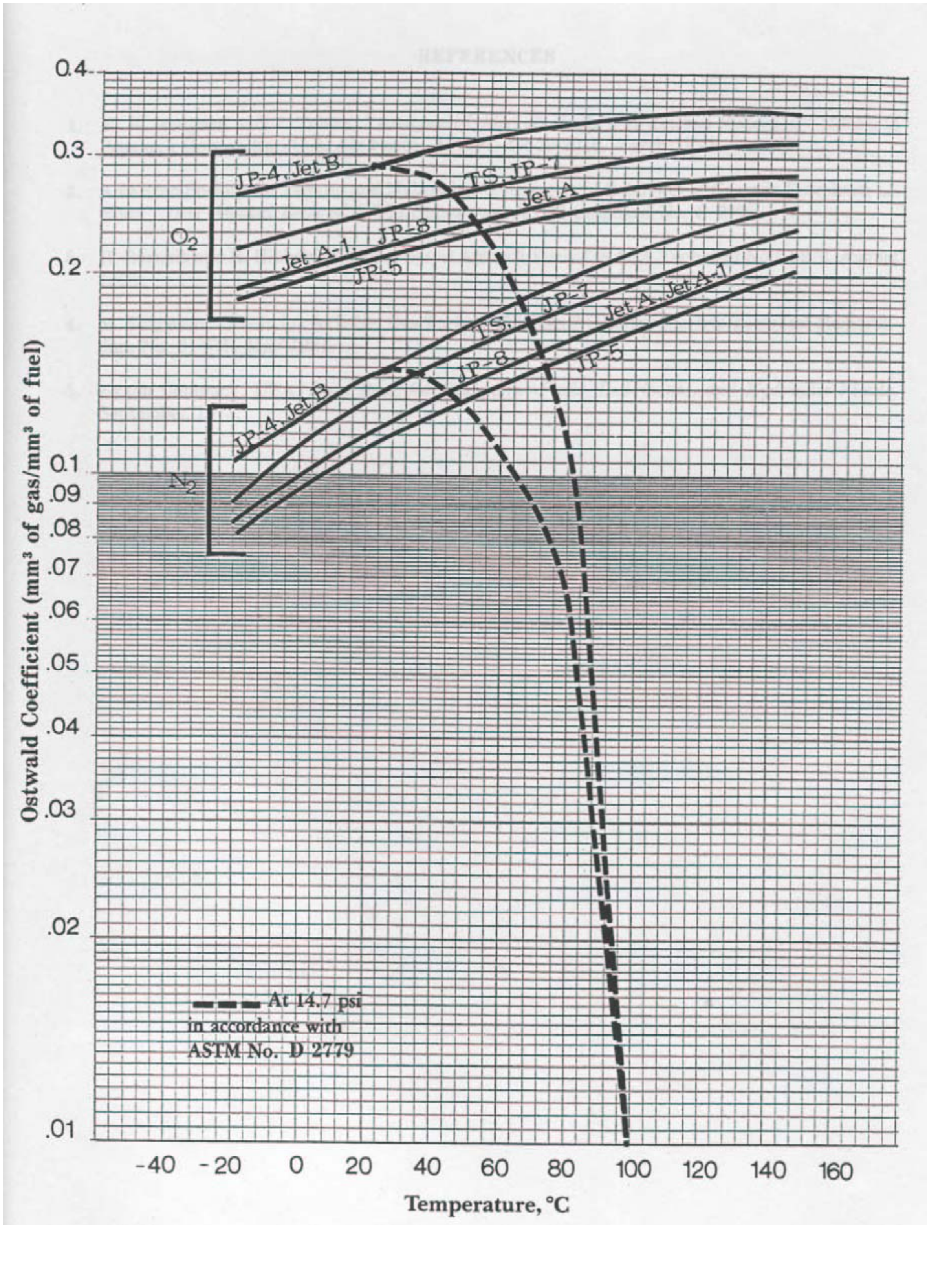
2. McConnell, P.M., Dalan, G., and Anderson, C.L., "*Vulnerability Methodology and Protective Measures for Aircraft Fire and Explosion Hazards,* Volume III Onboard Inert Gas Generation System (OBIGGS) Studies, Part 2 Fuel Scrubbing and Oxygen Evolution Tests," AFWAL-TR-85-2060, January 1986.

3. Burns, Michael and Cavage, William M., "Inerting of a Vented Aircraft Fuel Tank Test Article With Nitrogen-Enriched Air," FAA report DOT/FAA/AR-01/6, April 2001.

4. Burns, Michael and Cavage, William M., "Ground and Flight Testing of a Boeing 737 Center Wing Fuel Tank Inerted With Nitrogen-Enriched Air," FAA report DOT/FAA/AR-01/63, August 2001.

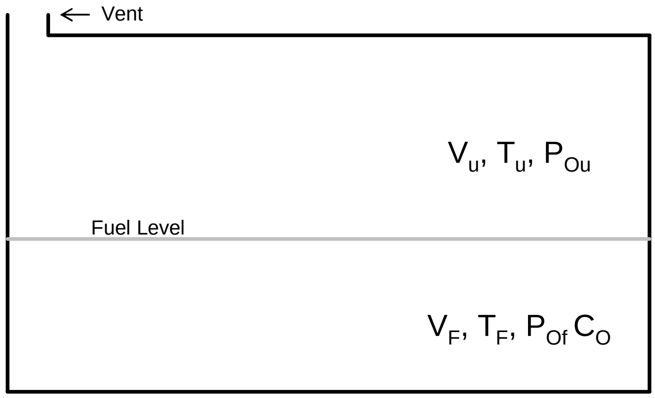
5. Burns, Michael and Cavage, William M., "A Description and Analysis of the FAA Onboard Oxygen Analysis System," FAA report DOT/FAA/AR-TN03/52, June 2003.

APPENDIX A—GRAPH OF OSTWALD COEFFICIENT FOR OXYGEN AND NITROGEN



0.4
0.3
0.2
0.1
.09
.08
.07
.06
.05
.04
.03
.02
.01
Ostwald Coefficient (mm³ of gas/mm³ of fuel)
O2
JP-4, Jet B
TS, JP-7
Jet A
Jet A-1, JP-8
JP-5
N2
JP-4, Jet B
TS, JP-7
Jet A, Jet A-1
JP-8
JP-5
At 14.7 psi in accordance with ASTM No. D 2779
-40 -20 0 20 40 60 80 100 120 140 160
Temperature, °C

APPENDIX B—CALCULATION OF ULLAGE OXYGEN CONCENTRATION CHANGE DUE TO ADJACENT FUEL LOAD



The effect of a fuel load on an inert ullage can be determined by considering the mass of oxygen dissolved in fuel and the mass of oxygen in the ullage as it pertains to the partial pressure of oxygen for the given medium. The partial pressure of oxygen is expressed in terms of the static pressure and the fraction of oxygen.

$$P_O = P_S * O_2 Fraction \qquad \text{(B-1)}$$

In the case of fuel, the partial pressure of oxygen is a function of the Ostwald coefficient, which describes the amount of oxygen dissolved in fuel given a fuel temperature.

$$P_O = C_O P_S * O_2 Fraction \qquad \text{(B-2)}$$

At some preliminary state, the partial pressure of oxygen dissolved in the fuel is higher then the partial pressure of oxygen in the inert ullage. These partial pressures can be expressed in terms of mass given the equation of state.

$$PV = mRT$$

$$P_{O_{U1}} V_U = m_{O_{U1}} R_O T_U$$

$$P_{O_{F1}} V_F = \frac{m_{O_{F1}} R_O T_F}{C_O}$$

These equations can be restated as follows:

$$m_{O_{U1}} = \frac{P_{O_{U1}} V_U}{R_O T_U} \qquad \text{(B-3)}$$

$$m_{O_{F1}} = \frac{P_{O_{F1}} V_F C_O}{R_O T_F} \qquad \text{(B-4)}$$

Given: P_O = Partial Pressure of Oxygen
V = Volume
M_O = Mass of Oxygen
T = Temperature
R_O = Universal Gas Constant of Oxygen
C_O = Ostwald Coefficient (see appendix A)

Partial pressure of oxygen is denoted by the subscript *O*, and the subscripts *U* and *F* denote ullage and fuel respectively with 1 indicating the initial state. The Ostwald coefficient is a fractional number that describes the amount of gas that is dissolved in a fluid and varies with fluid temperature.

Given the mass of oxygen in the tank remains constant, the following equation is exact.

$$m_{O_{U2}} + m_{O_{F2}} = m_{O_{U1}} + m_{O_{F1}}$$

or

$$m_{O_{F2}} = (m_{O_{U1}} + m_{O_{F1}}) - m_{O_{U2}} \tag{B-5}$$

Given the partial pressure of oxygen between the two medium within the tank are not equal, oxygen will evolve from the higher partial pressure fuel to the lower partial pressure ullage until some equilibrium state (denoted 2) is obtained. This can be stated as follows:

$$P_{O_{U2}} = P_{O_{F2}} \tag{B-6}$$

Given the relationship between partial pressure of oxygen and mass of oxygen, this gives

$$\frac{m_{O_{U2}} R_O T_U}{V_U} = \frac{m_{O_{F2}} R_O T_F}{V_F C_O}$$

Combining with equation B-5 and canceling R_O gives the following equation:

$$m_{O_{U2}} = [(m_{O_{U1}} + m_{O_{F1}}) - m_{O_{U2}}] * \frac{V_U T_F}{V_F T_U C_O}$$

or

$$m_{O_{U2}} = (m_{O_{U1}} + m_{O_{F1}}) \frac{V_U T_F}{V_F T_U C_O} - m_{O_{U2}} \frac{V_U T_F}{V_F T_U C_O}$$

Gathering M_{Ou2} Terms and simplifying gives the following relation for the resulting mass of oxygen in an ullage adjacent to a fuel load.

$$m_{O_{U2}} = \frac{(m_{O_{U1}} + m_{O_{F1}}) \frac{V_U T_F}{V_F T_U C_O}}{\left(1 + \frac{V_U T_F}{V_F T_U C_O}\right)} \tag{B-7}$$

Similarly, the equations for mass of nitrogen in the fuel and ullage can be derived with the subscript *N* denoting nitrogen in the following equations:

$$m_{N_{U1}} = \frac{P_{N_{U1}} V_U}{R_O T_U} \tag{B-8}$$

$$m_{N_{F1}} = \frac{P_{N_{F1}} V_F C_N}{R_O T_F} \tag{B-9}$$

Also the equations for the resulting mass of nitrogen in the fuel and ullage can be derived.

$$m_{N_{F2}} = (m_{N_{U1}} + m_{N_{F1}}) - m_{N_{U2}} \tag{B-10}$$

$$m_{N_{U2}} = \frac{(m_{N_{U1}} + m_{N_{F1}}) \dfrac{V_U T_F}{V_F T_U C_N}}{\left(1 + \dfrac{V_U T_F}{V_F T_U C_N}\right)} \tag{B-11}$$

The resulting partial pressures of oxygen and nitrogen in the ullage can be determined

$$P_{O_{U2}} = \frac{m_{O_{U2}} T_U R_O}{V_U} \tag{B-12}$$

$$P_{N_{U2}} = \frac{m_{N_{U2}} T_U R_N}{V_U} \tag{B-13}$$

By definition, the mole fraction of oxygen is equal to the partial pressure of oxygen divided by the resulting static pressure.

$$[O_2] = \frac{P_{O_{U2}}}{(P_{O_{U2}} + P_{N_{U2}})} \tag{B-14}$$

Assuming static pressure remains constant, oxygen volume percent is calculated by determining the partial pressure of oxygen (from equation of state) and dividing by the static pressure.

$$[O_2] = \frac{P_{O_{U2}}}{P_{Static}}$$