Modeling of In-flight Fuel Tank Inerting for FAA OBIGGS Research

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ABSTRACT

Extensive development and analysis has illustrated that fuel tank inerting could potentially be cost-effective using air separation modules in an efficient manner. To support the development of the FAA inerting system, analytical and scale replica models of two different commercial transport center wing fuel tanks (CWT) were developed and tested to gage the ability of these relatively simple modeling methods to predict the ullage oxygen concentration of a specific fuel tank, given a flight cycle and system performance. The analytical model predicted ullage oxygen concentration of the single bay Airbus A320 CWT using the measured system performance and time versus altitude data; however, the agreement was not as good for the peak and resulting ullage oxygen concentration values measured in a compartmentalized Boeing 747 CWT during flight testing. The plywood scale replica tested in an environmental chamber inerted with a scaled flow also duplicated the measured A320 flight test data well, while the scale 747 CWT data acquired has not been validated, with qualitative analysis illustrating significant discrepancies between model peak bay values and those measured on the NASA 747 SCA flight test.

INTRODUCTION

Background. The Federal Aviation Administration (FAA) has placed significant emphasis on fuel tank safety since the TWA Flight 800 accident in July 1996. Extensive development and analysis has shown that fuel tank inerting could potentially be cost-effective if air separation modules (ASM), based on hollow-fiber membrane technology, could be used in an efficient manner to produce inert gas. To illustrate this, the FAA, with the assistance of several aviation-oriented companies, developed an onboard inert gas generation system (OBIGGS) with ASMs that uses aircraft bleed air to generate nitrogen-enriched air (NEA) at varying flow and purity during a commercial airplane flight cycle.

To support this research, the FAA's Fire Safety Branch has developed two modeling methods to predict ullage oxygen concentration, given a set of inerting conditions and a flight profile. The first uses analytical calculations, based on the perfect mixing equation, to calculate the mass of oxygen in a generic ullage of a specified volume at any time step, given a flight cycle and system performance. The second employs a scale fuel tank replica in an altitude chamber, which can be inerted with a scaled flow from a small NEA generator. The ullage oxygen concentration of the tank is monitored with an oxygen analyzer capable of measuring oxygen concentration at the reduced pressures of altitude.

Previous Research. Previous fuel tank ullage modeling work was primarily performed by the United States Department of Defense to study the survivability of military aircraft. The most well known of these studies culminated in an extensive model of ullage gas composition, given a wide range of mission data, fuel data, and OBIGGS performance [1]. This model was validated with a wide range of test data generated in a ground test facility designed to simulate an aircraft fuel tank ullage during various military aircraft flight profiles. The focus of the modeling research was to study ullage flammability and air evolution from fuel during particular military missions, and included the effect of tank slosh and vibration.

Early FAA inerting research focused on quantifying the amount and purity of NEA needed to inert a rectangular aircraft fuel tank test article in support of the FAA research into ground-based inerting. This research was complimented by the development of an analytical model to calculate the effect of adding NEA to an ullage, given a constant flow and purity assuming perfect mixing [2]. Additional research was performed to study the inerting of multiple-bay compartmentalized fuel tanks using a scale 747 plywood model built and instrumented to be inerted in a variety of ways. This scale inerting research validated that those tanks could be inerted in the same manner as single-bay rectangular tanks by distributing the gas throughout the tank somewhat evenly. This study also illustrated that by depositing all the inert gas in a single location, strategically away from the vent system, a more simplistic deposit system could actually improve the efficiency of the inerting process, allowing for a lower average ullage oxygen concentration, given the same quantity of inert gas deposited [3].

The FAA also developed a multiple bay analytical model for ground-based inerting, using the previously developed analytical model discussed in reference 2, to study the capabilities and limitations of that very rudimentary method. Comparisons of both the scale 747 model and the multiple bay analytical model data were made with full-scale ground inerting measurements and also with a computational fluid dynamics model developed by Boeing Phantom Works [4]. This reference illustrates the excellent agreement between ground inerting data on a 747SP ground test article and data obtained with the scale 747 plywood model, as compared to the multiple bay analytical model, and gives the results of a mock trade study to illustrate the usefulness of both FAA-developed modeling methods.

ANALYTICAL MODEL

Analytical In-Flight Inerting Model. To better understand the inerting process for a wider range of flight scenarios and system methodologies, an analytical model was developed to calculate the average tank ullage oxygen concentration, given a specific tank volume, starting oxygen concentration, and system performance schedule. This performance schedule gives a mission time and altitude with the system volume flow rate and purity (oxygen concentration). The tank ullage temperature is also included, and the model makes the assumption that the pressure inside the tank is equal to ambient pressure outside the aircraft.

The model calculates the mass of oxygen in the tank at the start of the mission, given the tank volume and starting oxygen concentration, and tracks the change in mass of oxygen due to the addition of inert gas and ventilation of ullage gas. 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 (pressure P) and temperature (T), to calculate density using the equation of state with the universal gas constant for air (R).

$$P \quad = \quad r\,RT \tag{1}$$

The mass of oxygen is calculated by multiplying the NEA volume flow rate by the time step (delta t), the NEA oxygen fraction, and density. The mass of oxygen removed from the tank due to inerting and altitude change is obtained by multiplying the net mass flow out of the vent by the ullage gas oxygen fraction. The net ullage gas mass out of the vent is the sum of mass of the NEA deposited during the time step and the mass of ullage gas removed due to an increase in altitude, which is obtained by multiplying the change in density during the time step by the tank volume. When the net mass out of the tank becomes negative, air enters the tank and the resulting change in mass of oxygen of the ullage is obtained by multiplying the net mass of air entering the tank by the oxygen fraction of air. The mass of oxygen calculated in the tank at each time step is divided by the tank gas mass to obtain oxygen concentration at that time. The following equation illustrates the model process by giving the calculation of mass of oxygen at any time t.

$$m_{O_2}(t) \;=\; m_{O_2}(t-1) \;+\; \dot{m}*IGOF \;-\; \dot{m}*UGOF(t-1) \;-\; (\Delta r*V_{Tank})*UGOF(t-1) \;+\; (\Delta r*V_{Tank})*0.21 \tag{2}$$

In this equation, *UGOF*(*t*-1) is the fraction of oxygen in the ullage gas. It is calculated by dividing the mass of oxygen in the tank at *t*-1 by the mass of gas in the tank ullage or:

$$UGOF(t-1) \quad = \quad m_{O_2}(t-1)/m_{Tank}(t-1) \tag{3}$$

Where: $m_{O_2}(t)$ = Mass of oxygen in tank at time t
$\dot{m}$ = Mass flow rate of inerting gas (in terms of t)
$IGOF$ = Fraction of oxygen in inerting gas
Δr = Change in ullage density due to altitude change
V_{Tank} = Volume of tank ullage
m_{Tank} = Mass of gas in tank

TEST ARTICLES

Scale A320 Center Wing Tank. The FAA constructed a model of an A320 CWT to evaluate the FAA inerting system and inert gas deposit methods in a single compartment tank during flight operations. The A320 scale tank model was constructed from plywood, based on drawings obtained from the original equipment manufacturer to ½ length scale (figure 1). The longitudinal bracing and vent system was simulated using PVC tubing, and the deposit nozzle is made from copper tubing. It is supported by a plywood stand and has an instrumentation panel that contains eight oxygen analysis ports, one sample return port, and one thermocouple port. The tank has four access panels on the top surface to change the deposit, venting, or instrumentation configuration of the tank if necessary. NEA was made from bottled nitrogen and shop air with a mixer attached to an oxygen analyzer and dispensed to the tank with a mass flow controller. The tank model was placed in an environmental chamber that can simulate the temperature and pressure environment of a commercial transport airplane. The altitude profile was controlled by an operator by allowing more or less air to vent into the chamber while the vacuum pump continuously operated.

Figure 1: Scale A320 CWT Plywood Model

The model tank was instrumented with thermocouples and sample tubing for oxygen analysis. The primary measurements taken during the tests were the oxygen concentration in the tank (single location) as well as the oxygen concentration and flow rate of the NEA deposited. The scale tank ullage temperature was monitored as was the chamber pressure, which was converted to altitude. These parameters were recorded with an off-the-shelf data acquisition system that acquired data and stored it on a computer.

Airbus A320. Flight tests of the FAA inerting system were performed in conjunction with Airbus to both validate the OBIGGS performance through a typical commercial transport flight cycle and to determine the effect of several operational considerations on the ability of the system to inert the aircraft's CWT. The aircraft has a basic operating weight of 93,079 lb with a gross takeoff weight of 162,040 lb. It has a 112-foot wing span and is 123 feet long. The maximum cruise speed of the aircraft is 487 knots at an altitude of 28,000 feet with a ceiling of 43,000 feet. The CWT has an 8200-liter capacity (2165 gal) and is located below the floor and in between the wings, within the fuselage of the aircraft. The CWT has a single NEA deposit and a single vent opening with a total ullage volume, when the tank is empty, of 289 normal cubic feet. Figure 2 shows a side view of the Airbus A320 CWT.

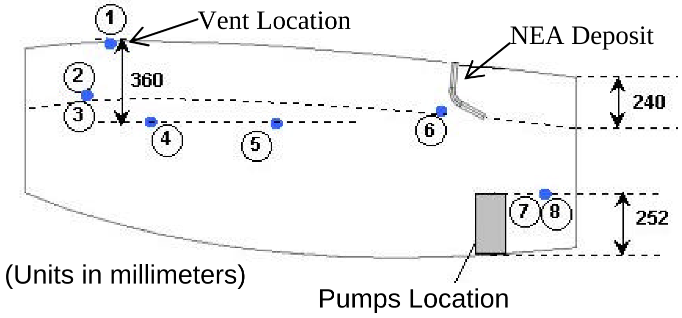

Figure 2: Side View of A320 CWT Showing the Eight Oxygen Sample Locations

The primary instrumentation employed for the flight test centered on the gas sample tubing in the CWT that allowed continuous oxygen concentration measurements at eight locations in the tank during each flight test (figure 2) using the FAA-developed Onboard Oxygen Analysis System (OBOAS). Additionally, the FAA OBIGGS was instrumented extensively to analyze the system performance for each test, including NEA flow and purity. The FAA inerting system was operated with a single ASM for all tests discussed. Flight parameters were also measured for data analysis [5].

Scale 747 Tank. To model inert gas distribution in a multiple bay fuel tank, the 24% length scale 747 CWT model discussed in reference 3 was installed in an environmental chamber and inerted with a predicted system performance over a generic flight profile. Each of the six bays had a fitting for oxygen analysis, sample return port, and a mounted thermocouple. The tank has a removable lid to change the deposit, venting, or instrumentation configuration of the tank if necessary. The scale model used the same environmental chamber as the scale A320 model, and NEA was made in the same manner as the scale A320 tests and dispensed to the tank with a mass flow controller. All instrumentation was recorded with a data acquisition system that acquired data and stored it on a computer. Figures 3 and 4 gives a cut-away view and top diagram, respectively, of the compartmentalized 747 CWT, including the bay numbering convention.

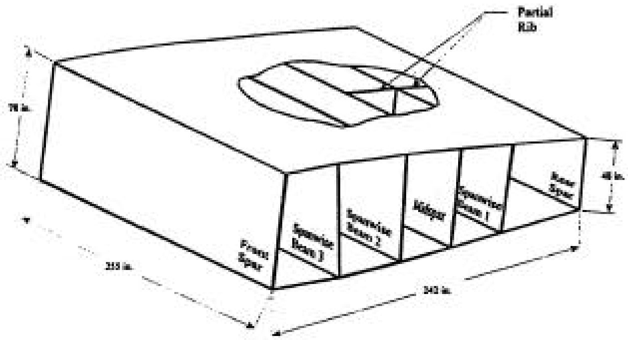

Figure 3: Boeing 747 Center Wing Tank Cut-Away View

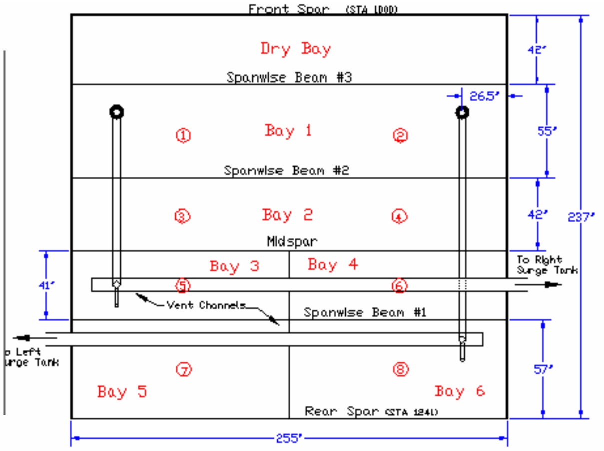

Figure 4: Top Diagram of the Boeing 747 CWT

NASA 747 SCA. Flight tests of the FAA inerting system were performed in conjunction with NASA on the NASA 747 SCA, which is a highly modified Boeing 747 used to carry the Space Shuttle Orbiter, to study the OBIGGS performance through various flight conditions and validate existing inerting models. The FAA OBIGGS was installed in the test aircraft pack bay area, and the inert gas from the system was deposited in bay 6 of the aircraft CWT. The primary instrumentation employed for the test was the gas sample tubing in the CWT that allowed continuous oxygen concentration measurements at eight locations in the tank (see figure 4) during each flight test using the FAA OBOAS. Additionally, the FAA OBIGGS was instrumented extensively, including NEA flow and purity, to analyze the system performance for each test. Additionally, atmospheric pressure was collected to analyze the inerting process during the flight tests [6].

RESULTS

Comparison With A320 Flight Test Data. Both modeling methods were compared to measured ullage oxygen concentration data acquired during testing of the FAA OBIGGS on an Airbus A320 test aircraft. Figures 5 and 6 illustrate that both models compared well to the average ullage oxygen concentration measured on the flight test, particularly the trends of the change in oxygen concentration that consistently change with the flight test data. Any small differences can be explained by the longer ullage oxygen concentration measurement lag from the flight tests compared to the scale model tests, while the analytical model has no inherent delay in the result. The oscillating data trend observed in the scale model data is the result of slight oscillations in the descent rate, which deviate from a more consistent flight test descent rate.

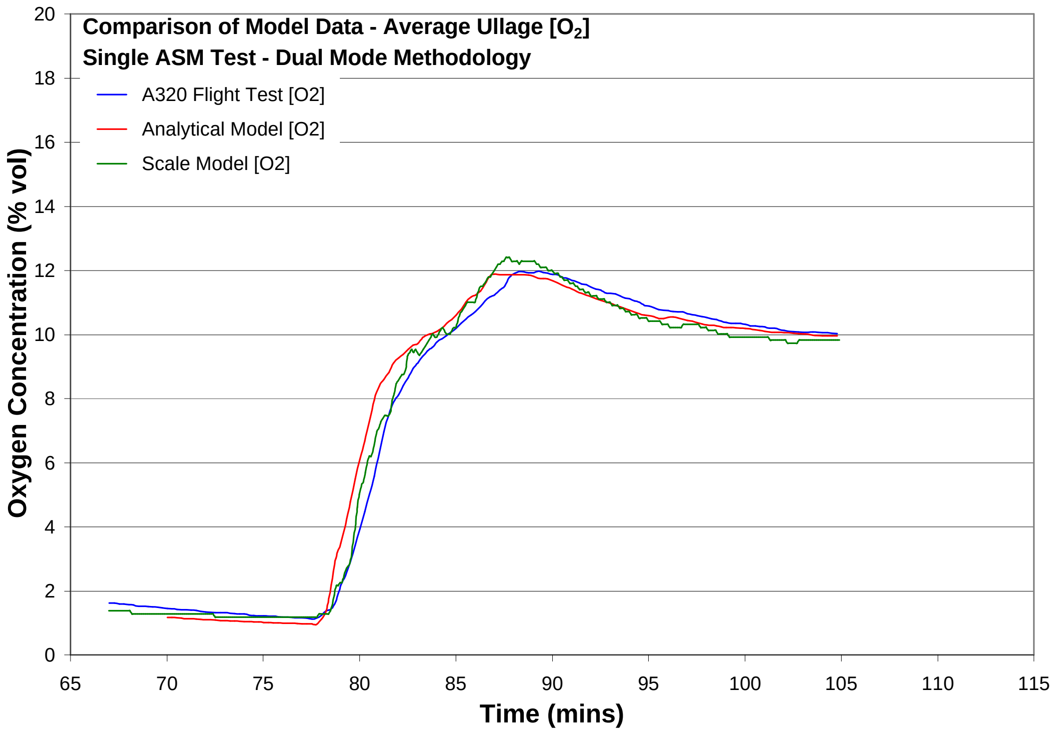

Figure 5: Comparison of Ullage Oxygen Concentration Modeling Methods With Measured A320 Flight Test Data for the Descent Phase of an OBIGGS Test Operated in the Dual-Flow Methodology

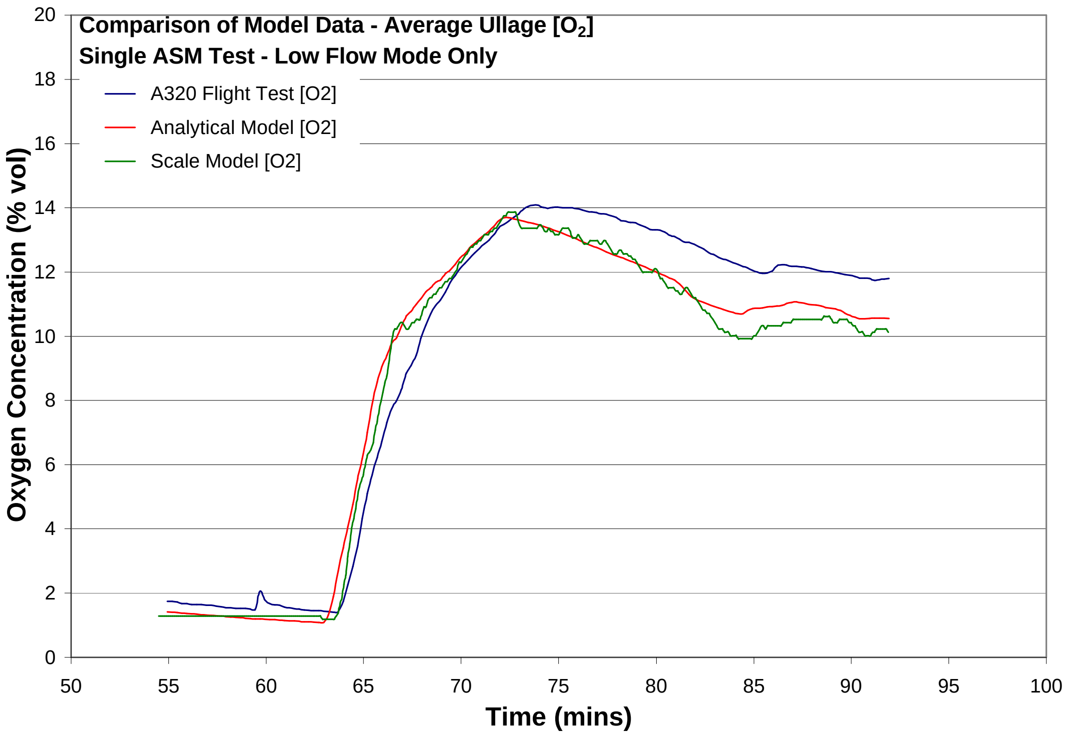

Figure 6: Comparison of Ullage Oxygen Concentration Modeling Methods With Measured A320 Flight Test Data for the Descent Phase of an OBIGGS Test Operated in the Low-Flow Mode Only

The comparison of the peak and resulting ullage oxygen concentrations for the two model methods to the flight test data shown in figure 5 illustrates excellent agreement with all peaks being within 0.5% oxygen concentration difference. The large deviations in ullage oxygen concentration between 78 and 82.5 minutes are again due to the large time lag in the measurement of ullage oxygen concentration during the flight test. Figure 6 illustrates the same comparison for an Airbus flight test that did not employ the high-flow mode during descent. The data again illustrates good agreement during the majority of the descent, but after the peak ullage oxygen concentration of approximately 14%, the measured flight test oxygen concentration deviates significantly from both modeling methods, giving a resulting oxygen concentration with approximately 1.5% difference.

To examine the ability of the scale model to duplicate localized ullage oxygen concentration behavior observed during flight testing, oxygen concentration measurements made close to the vent in the scale model were compared to the measurements made near the vent system of the A320 flight test aircraft (location 1, figure 2). Figure 7 shows the similarities between the local oxygen concentration measurements made near the vent system in the scale tank and the flight test aircraft for the descent phase of the flight test given in figure 5. These measurements show a marked difference when compared to the average ullage oxygen concentration results observed in figure 5, which, for the flight test data, was obtained by averaging all eight sample locations, while the scale model average data was a single measurement near the center of the scale test article. Although the peak differs by approximately 1% oxygen concentration, the similarities in the data trends show some consistency between the scale model and the flight test tank in terms of mixing air into the tank from the vent system.

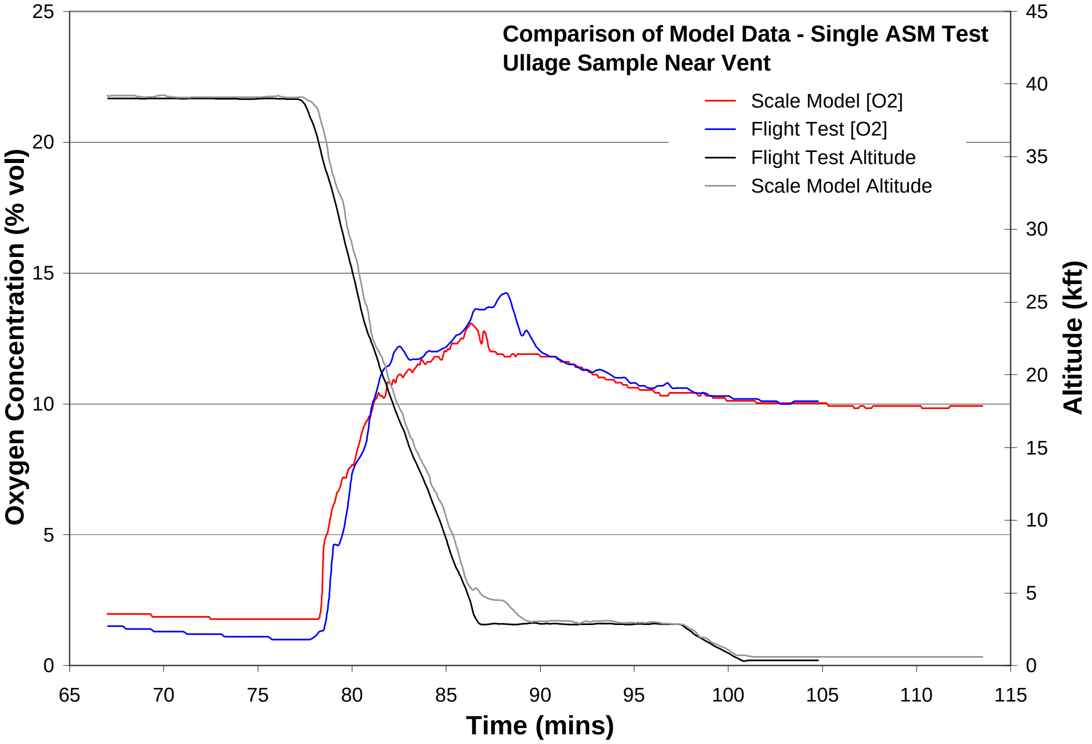

Figure 7: Comparison of Ullage Oxygen Concentration Measured Near the Vent for the Scale Model and the A320 Flight Test for the Descent Phase of Airbus Flight Test v1972

<u>Comparison of Modeling Methods</u>. To gage the ability of both models to accurately predict ullage oxygen concentration, given a specified flight cycle and system performance, the mission profile from the Airbus v1972 test using the system in the dual-flow methodology was modified to reflect a descent profile more typical of a commercial transport descent and landing. The system performance for this descent profile was

made by using the flow and oxygen concentration measured during the Airbus flight test. This fictitious descent had the same total descent time of 23.5 minutes from 39,000 feet that the above-mentioned Airbus test had, and was modeled using both the analytical and scale model methods and compared for consistency (figure 8). As in the case of model comparisons with flight test data, the models exhibit very similar trends with the scale model having some unexpected oscillations. The line corresponding to the scale model atmospheric pressure shows small discrepancies compared to the analytical pressure data, which tend to correlate to these oscillations. Although the scale model-predicted peak for this test is approximately 0.7% oxygen concentration greater than the analytical model, the predicted resulting oxygen concentration differs by only 0.2%.

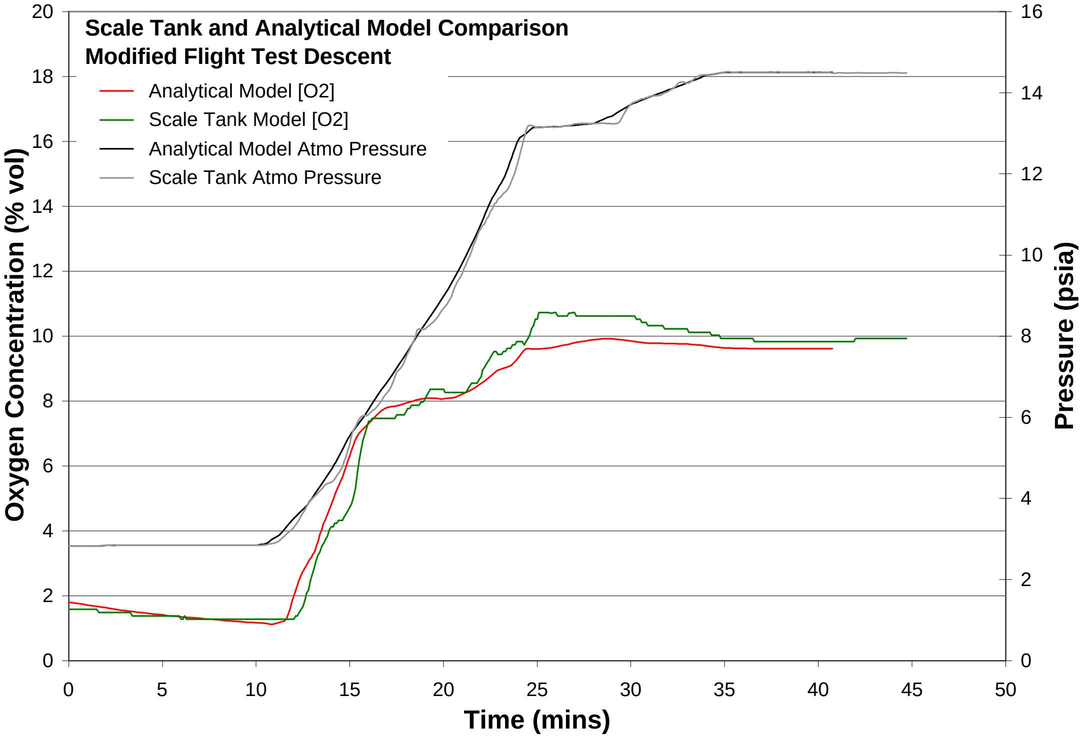

Figure 8: Comparison of Ullage Oxygen Concentration Model Results With Atmospheric Pressure for a Fictitious Descent Using a Single ASM OBIGGS Operated in the Dual-Flow Methodology

To examine the capability of the modeling methods to be used for parametric studies, both modeling methods were used to predict the ullage oxygen concentration for an Airbus flight test using smaller inerting systems. Both modeling methods were used to simulate the Airbus v1972 test descent starting with the same initial oxygen concentration, but with an OBIGGS that had 75% of the flow as the single ASM OBIGGS on the referenced flight test and also one that had 50% of the flow of that OBIGGS. Figures 9 and 10 give the results of the study for the scale and analytical models respectively. Both modeling methods exhibit the expected trends and agree well when comparing peak and resulting oxygen concentration values. Although one peak value has a discrepancy of 0.8% oxygen concentration, all other compared values are less than 0.5% oxygen concentration difference. Table 1 gives the peak and resulting ullage oxygen concentration values for both the scale and analytical model data obtained from the study as well as the Airbus v1972-measured flight test results. Both models predict that an OBIGGS with 75% of the flow of the OBIGGS employed on the Airbus v1972 test would have a resulting oxygen concentration of approximately 11% oxygen after the high descent rate employed in that test and would give a peak ullage oxygen concentration between 13 and 14 percent oxygen by volume.

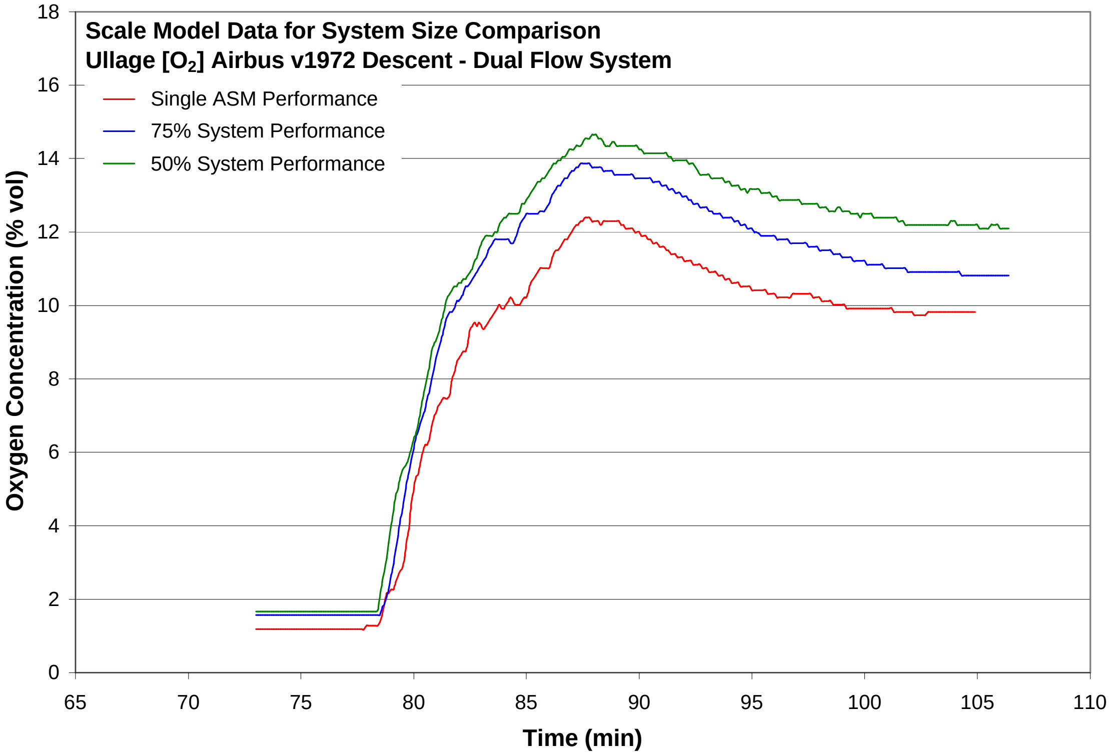

Figure 9: Comparison of Ullage Oxygen Concentration Scale Model Results for Single ASM, 75%, and 50% Flow With the OBIGGS Operated in the Dual-Flow Methodology

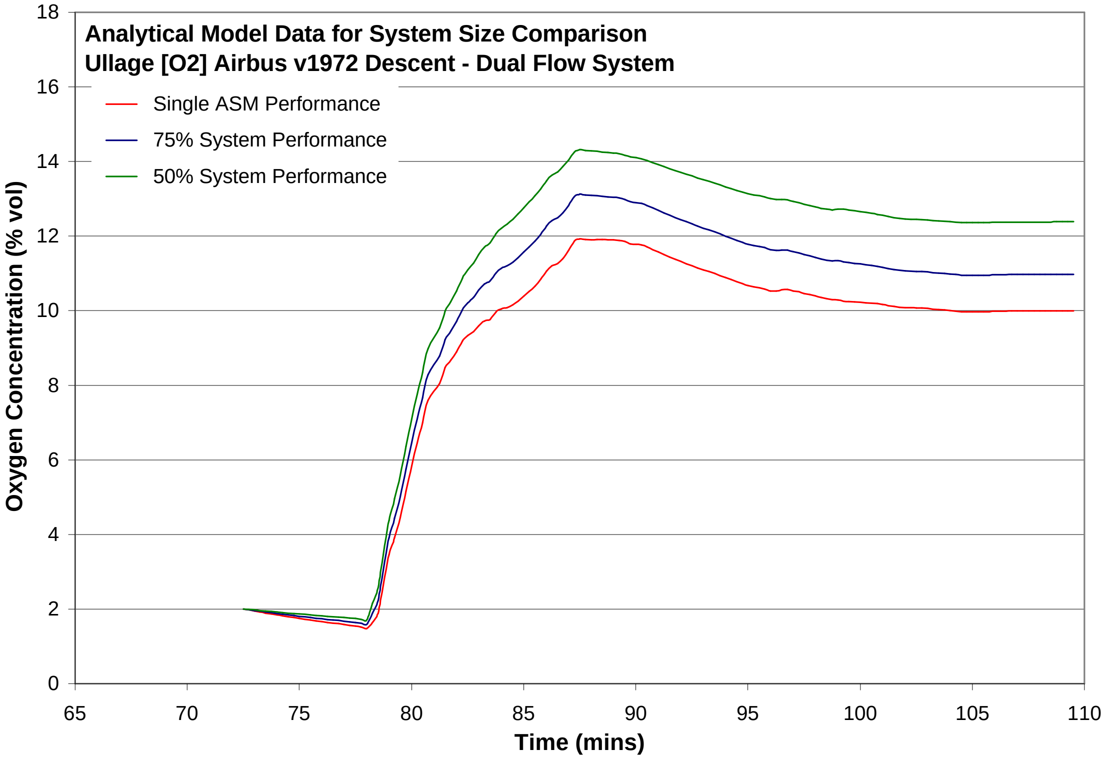

Figure 10: Comparison of Ullage Oxygen Concentration Analytical Model Results for Single ASM, 75%, and 50% Flow With the OBIGGS Operated in the Dual-Flow Methodology

Table 1. Table of Predicted Ullage Oxygen Concentration Values for Three Different OBIGGS Sizes Employed for the Airbus v1972 Flight Test Descent

Case	Analytical Model Peak [O_2]	 Resulting [O_2]	Scale Model Tests Peak [O_2]	 Resulting [O_2]	Flight Test Peak [O_2]	 Resulting [O_2]
Single ASM	11.9	10	12.3	9.8	12	10
75% System Flow	13.1	11	13.9	10.8		
50% System Flow	14.3	12.4	14.6	12.1		

747 Model Data. To gage the ability of the analytical model to predict average ullage oxygen concentration of an inerted multiple-bay fuel tank with a single deposit point, the analytical model was applied to the mission profile and system performance measured on the NASA 747 SCA flight test. Figure 11 gives the bulk average ullage oxygen concentration calculated from individual bay measurements compared with the results of the analytical model. A comparison of the data shows good agreement with the data trends, with significant disagreements between the model and the measured data during most of the test. The model overpredicts the maximum and minimum values by approximately 1 percent oxygen, with some discrepancy between the times at which the peaks occur and the resulting oxygen concentration differs by approximately 1.5% oxygen by volume. Any deviation in peak times can be explained by the long delay in the OBOAS sample system, which takes as much as 2-3 minutes to completely respond to rapid changes in the ullage oxygen concentration. The differences in peak values can be explained by the efficiency of the inerting process when comparing inerting a six bay tank with a single deposit to a single bay generic tank shape with a single deposit, which the model is representing. Previous studies of inerting compartmentalized fuel tank models on the ground exhibited an increase in inerting efficiency when using single-deposit methods [3]. The increased efficiency would manifest itself as a lower oxygen concentration achieved for the same amount of inert gas deposited, similar to what is observed in figure 11.

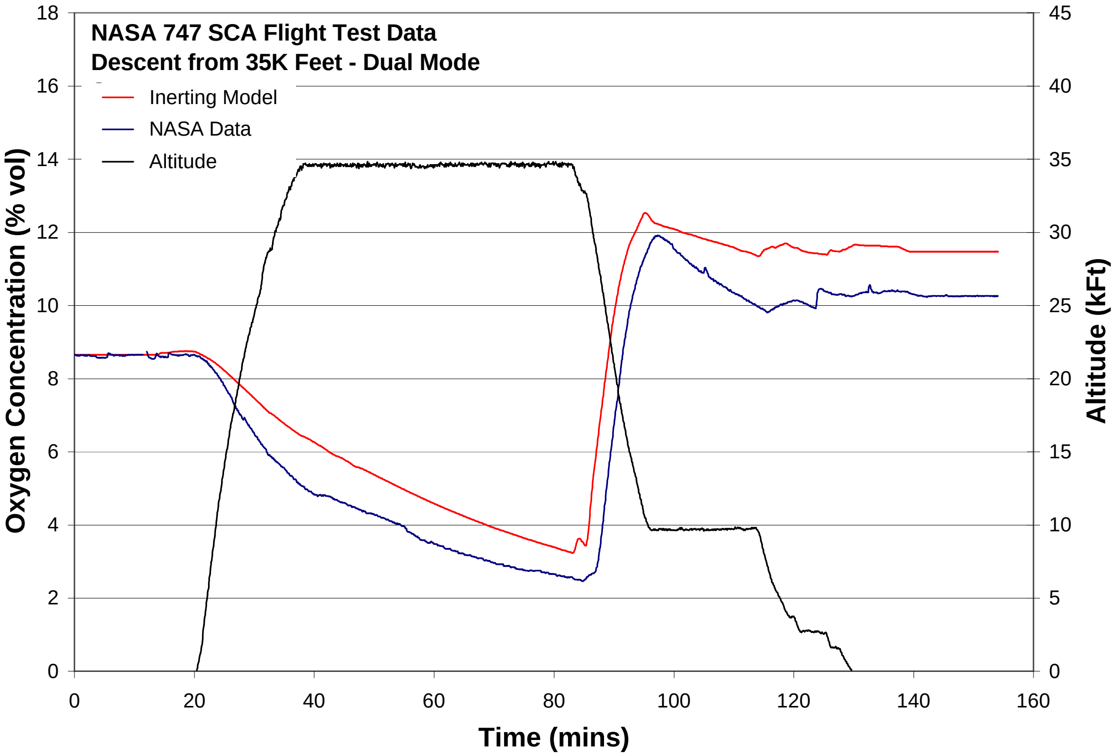

Figure 11: Comparison of Measured Average Ullage Oxygen Concentration With Analytical Model Data

The oxygen concentration distribution was measured using the scale 747 plywood tank during testing in the FAA Fire Safety Branch environmental chamber. Figure 12 illustrates the expected trends of inert gas distribution during descent as air enters the tank via vent tubing in bays 1 and 3. The predicted system performance used does not reflect measured flight test performance closely enough to allow for a valid comparison with existing NASA 747 SCA flight test data. It is apparent, however, that the distribution of air into the tank through the vent system in the model data is not representative of what was observed in the flight test data, as bay 1 tended to peak much higher and quicker than bay 3, which is the opposite of what is observed in figure 12.

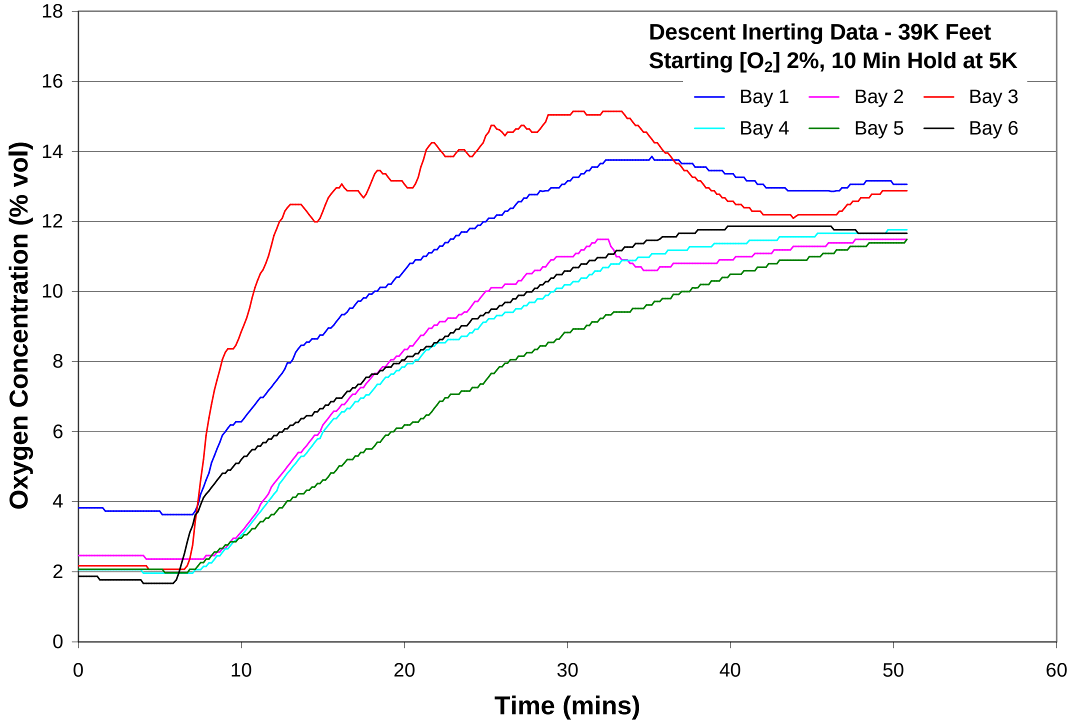

Figure 12: Ullage Oxygen Concentration Distribution Measured in the 747 Scale Model During a Simulated Descent

SUMMARY

The FAA has developed two methods of modeling in-flight ullage oxygen concentration, given a measured OBIGGS performance during a flight cycle. Both the analytical calculation model and the scale replica model methods have demonstrated the ability to predict ullage oxygen concentration measured during flight tests in a single bay center wing fuel tank with one deposit and one external vent with local oxygen concentration measurements in the scale model illustrating some similarities to local measurements on the full-scale aircraft. Additional work is required to better understand the limitations in using scale models to examine localized mixing of air and inert gas within a fuel tank ullage. Both modeling methods demonstrated the ability to take a modified flight profile or system performance data and produce meaningful, consistent results. When the single bay analytical model was used to predict average ullage oxygen concentration in a multiple bay tank, the data trends showed good agreement, but had significant discrepancies in the peak and resulting oxygen concentrations. Additional work is needed to perfect and validate the multiple bay scale modeling method.

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