Paper Number

Ground-Based Inerting of a Boeing 737 Center Wing Fuel Tank

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ABSTRACT

A series of aircraft flight and ground tests were performed by the Federal Aviation Administration and the Boeing Company to evaluate the effectiveness of ground-based inerting (GBI) as a means of reducing the flammability of center wing fuel tanks (CWTs) in the commercial transport fleet. Boeing made available a Boeing 737-800 for modification and testing. The fuel tank was instrumented with gas sample tubing and thermocouples and tests were performed inerting the CWT to 8 percent oxygen to allow for a measurement of fuel tank inerting and heating. Results showed that under quiescent conditions the oxygen concentration in the fuel tank remained somewhat constant, keeping the CWT inert (below 10- to 12-percent oxygen by volume) for relatively long periods of time. Certain wind conditions and flight conditions created cross venting within the CWT that allowed for significant increases in the oxygen. A modification to the vent system created a significant increase in the benefit of the GBI even at low to moderate fuel loads.

INTRODUCTION

Significant emphasis has been placed on fuel tank safety since the TWA flight 800 accident in July 1996. Fuel tank inerting has been studied as a method of reducing the likelihood of an explosion within a commercial transport fuel tank [1]. Recently, a fuel tank inerting working group was formed by the Aviation Rulemaking Advisory Committee (ARAC) in response to a task assigned by the FAA. The task was to evaluate a rule change that would require a reduction in commercial transport airplane fuel tank flammability with an emphasis on center wing and body style tanks. A previous ARAC working group has stated that the most potentially cost-effective method of fuel tank flammability reduction is ground-based inerting (GBI) [2]. Ground-based Inerting or GBI is defined as inerting fuel tanks during ground operations. This protection is believed to extend into ground and flight operations, depending on fuel load and flight profile. Although significant research has been performed to quantify the ability of nitrogen or nitrogen-enriched air (NEA) to inert a commercial transport fuel tank, ground- based inerting has never been attempted in an operational aircraft.

EQUIPMENT AND PROCEDURES

The testing was performed in conjunction with the Boeing Company utilizing a production aircraft. Boeing personnel provided all aircraft engineering, modification, support personnel, and equipment. The primary responsibility of the Federal Aviation Administration (FAA) was to develop a test plan with the Boeing Company and to provide the instrumentation to measure oxygen concentration at eight locations in the center wing tank (CWT) throughout the pressure and temperature regime of the testing.

TEST ARTICLE

For the testing, a Boeing 737-800 was provided by the Boeing Company prior to its delivery. The center wing tank has a capacity of 28,803 pounds of fuel (4,299 gals). It is contained in the center wing section of the aircraft, within the body and the inner sections of the wing root, often referred to as the cheek section. The empty CWT ullage volume is 598 normal cubic feet for the purpose of inerting the tank with NEA. The main tanks each hold 17,258 lbs of fuel (2,576 gals) and are contained entirely within the wings. The test aircraft CWT was modified with an NEA distribution manifold, consisting of aluminum tubing with flexible tubing used for connections from section to section. Each section of tubing had several nozzles designed to distribute the NEA in the different bays of the CWT.

To instrument the aircraft, Boeing personnel installed thermocouples and gas sample tubing in the CWT. As mentioned, the tank is divided into three major sections (center section, left cheek, and right cheek) with each section being separated into several bays. Figure 1 gives a top diagram of the CWT with numbers illustrating the locations of the eight sample ports. Thermocouples were located near each sample port as well as throughout the CWT and below the tank in the area of the air cycle machines (pack bay). These air cycle machines generate large quantities of heat during operation, increasing the temperature of the CWT, and contributing to fuel tank flammability. The FAA developed a system to allow for the continuous measurement of oxygen concentration at the eight identified locations in the center wing tank [3]. The system consisted of a regulated sample train with flow through oxygen sensors in line and ancillary equipment. Two identical four-channel systems were developed. Each four-channel system was self-contained in a standard 19-inch half rack designed to meet the Boeing flight test airworthiness requirements. Each system had four independent sample trains that draw an ullage sample from the fuel tank, regulate the sample pressure, expose the sample to the oxygen sensor, and redeposit the sample back in the fuel tank. The data acquisition system used was designed, built, and certified by Boeing for the purposes of flight test and evaluation. It was a multiplexed data system that uses data modulation to create a data stream for storage or discrimination. The system was integrated with the aircraft ARINC bus to obtain aircraft data in parallel with all installed sensors. Also, weather data was made available during the ground testing.

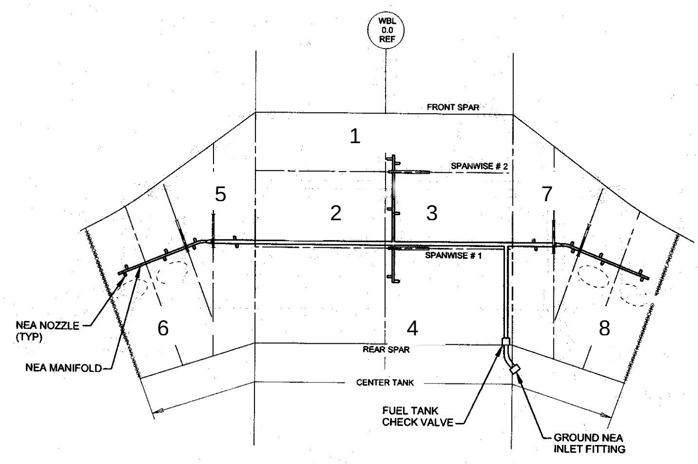

Figure 1. Boeing 737-800 CWT Plan View

The industrial gas generator used to provide NEA to the airplane CWT was a general-purpose, off-the-shelf HFM gas separator with a skid-mounted compressor. The unit contained five gas separation modules, each 6 inches in diameter, allowing the unit to generate as much as 125 cubic feet per minute (CFM) of 95-percent NEA (5-percent oxygen by volume). The purity of the NEA gas (oxygen concentration) can be adjusted to values from 14-percent oxygen by volume (NEA 86 percent) to less than 1-percent oxygen by volume (NEA 99 percent or greater). The NEA was supplied through a flow meter mounted on a cart with two pressure regulators. This equipment allowed for the output of the NEA machine (125 CFM at 100 psig on a 1-inch line) to be regulated to about 95 CFM on a 2-inch line with less then 2.5 psig back pressure during deposit. This allowed for safe deposit of the NEA in the fuel tank via the inerting manifold inlet.

TEST PROCEDURES

All tests were performed at King County International Airport in Seattle, Washington. The testing consisted of five ground tests and five flight tests. Before each test the NEA generator was reconfigured to supply air to the aircraft fuel tank, allowing the tank to be purged and ensuring a consistent initial oxygen concentration (approximately 20.9% oxygen by volume). At the start of each test the data acquisition system was started and the NEA was directed into the tank. The tank was considered ready for testing when all sensors read approximately 8% oxygen concentration by volume. Next, the auxiliary power unit (APU) was started, ground power was switched off, and the air cycle machines were started. Lastly, the aircraft was operated in accordance with the test plan.

Ground Testing

The ground testing portion of the test plan required several tests under different fuel loads and wind conditions. Due to the limitations in the test schedule and logistics, the existing wind conditions were utilized and noted instead of seeking out the ideal wind conditions. In one case, a fan directing air across one vent scoop simulated the effect of wind with one vent blocked by a building, loading bridge, or similar related support equipment. Table 1 gives a list of tests with fuel load, wind condition, and test duration.

TABLE 1. Summary of Ground Tests

Test	Fuel Load	Wind Condition	Duration
1	0%	Calm Winds	2 Hours
2	0%	Simulated Winds	2 Hours
3	80%	High Natural Winds	2 Hours
4	80%	High Natural Winds	2 Hours
5	20%	Simulated Calm Winds	2 Hours

Flight Testing

The focus of the flight testing was to determine the effect of the fuel load on the inert ullage space and to determine how long the CWT would remain inert in flight. An effort was made to keep the tests as consistent as possible from test to test to allow for fair comparison. The exception to this was the duration of the ground operation portion of the test to the flight portion. This was varied to illustrate the effect of blocking a tank vent on the test results. After the first flight test, one vent was blocked to prevent cross flow within the CWT. To prevent repeating some or all of the ground tests, the worst case (test 5, 80% fuel load) was extended to include a 2-hour ground duration period. Table 2 gives a listing of flight tests with fuel load, ground duration, and flight duration.

TABLE 2. SUMMARY OF FLIGHT TESTS

Test	Fuel Load	Ground	Flight
1	0%	20 Minutes	2 Hours
2	0%	20 Minutes	2 Hours
3	20%	30 Minutes	2 Hours
4	40%	30 Minutes	2 Hours
5	80%	2 Hours	2 Hours

ANALYSIS

NONDIMENSIONAL ANALYSIS

Much of the data is presented in a nondimensional format to allow for comparison of the aircraft inerting data with data collected in the lab, as well as to allow numbers to be easily applied to any ullage-washing scenario.

It is advantageous to present the data in a manner which is easily applied to all fuel tanks and all NEA flow rates. It can be hypothesized that the volume of NEA deposited within the tank dictates how quickly or slowly a vented fuel tank becomes inert. It also follows that this volume of gas divided by the total volume of the tank would be constant, given a purity of gas deposited and consistent mixing. Using this information, the time scale of the data was nondimensionalized by applying the flow rate and fuel tank volume, giving what has become known as the volumetric tank exchange.

$$Volumetric\ Tank\ Exchange \quad = \quad \frac{Time * Volume\ Flow\ Rate}{Fuel\ Tank\ Volume}$$

In an effort to verify that the physical mechanisms at work do, in fact, largely dictate ullage washing of a vented fuel tank, it was desired to present the inerting data by nondimensionalizing the measured tank oxygen concentration in terms of inerting gas purity. The described theory states that the tank oxygen concentration is brought to the purity of the inerting gas over time by simply displacing the ullage space gas. This implies that the ratio of the difference between the oxygen concentration of air (ambient conditions) and the ullage in time and air and the NEA gas purity being added to the tank have a constant relationship, given a fixed volume of gas deposited. This can be described by the following relationship for the nondimensional factor referred to as the tank inerting ratio.

$$Tank\ Inerting\ Ratio \quad = \quad \frac{[O_{2\,Amb}] - [O_{2\,ullage}]}{[O_{2\,Amb}] - [O_{2\,NEA}]}$$

With:

$O_{2\,Amb}$ = Oxygen concentration of ambient air

$O_{2\,NEA}$ = Oxygen concentration of inerting gas (NEA)

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

INERTING SOLUTIONS

An exact solution to fuel tank inerting was created by using a perfect mixing model to develop an equation in terms of the rate of change of ullage oxygen concentration with respect to time. Application of this concept gives the following simplification.

$$-\frac{1}{x}dx \quad = \quad \frac{\dot{Q}}{V_{Tank}}dt$$

With: $x = [O_2\ NEA] - [O2]$

The solution of this equation can be manipulated to allow for comparison of the exact solution to existing nondimensional experimental data. This was determined to be the following:

$$\frac{O_{2\,Amb} - O_2(t)}{O_{2\,Amb} - O_{2\,NEA}} \quad = \quad 1 - e^{-Qt/V_{Tank}}$$

The complete solution is given in an appendix in reference 4.

The nondimensional methods described in section 3.1 allow for the creation of an empirical curve based on previously acquired inerting data for different purities and flow rates of NEA. An empirical relationship between volumetric tank exchange and inerting ratio had been developed with previous ullage-washing experiments performed by the FAA. These experiments quantified the amount of NEA needed at a given purity level (oxygen concentration) to inert a rectangular tank, with one NEA nozzle and one vent, of any volume. This empirical relationship assumes a fourth order polynomial curve fit [4]. The equation is given below.

Tank Inerting Ratio =
$$-0.0145x^4 + 0.1345x^3 - 0.5275x^2 + 1.0873x - 0.0121$$

In this equation x is the volumetric tank exchange.

RESULTS

The data is generally presented in terms of an average of the three primary areas of the CWT, the center body section, the left cheek, and the right cheek. The center body section of the center wing fuel tank is the area of the tank contained within the fuselage area of the aircraft that has three spanwise bays with a total of four sample ports. One sample port within the center body section was considered redundant (port 2) as it resided very close to a second sample port (port 3); therefore, three ports were used when calculating the average oxygen concentration of the center bay area of the CWT. The left and right cheek areas are areas of the CWT that are within the wing hub area. Each cheek area contains five bays of differing orientation to the wing cord with two sample ports used to calculate the average oxygen concentration. These areas consistently exhibited different behaviors indicating very little ullage gas interaction between the areas, while the sample ports within these areas consistently behaved similarly to one another. For this reason, the data is presented in terms of the average oxygen concentration in the three areas described.

TANK INERTING

Figure 2 shows a plot of average oxygen concentration versus time during ground test 1. This graph also has a line of constant 8% oxygen concentration highlighting when each tank area reached the desired inert level. This case was for an empty tank (0% fuel), and 95% NEA at a flow rate of 90 CFM. This data was non-dimensionalized in the manner previously outlined to give figure 3. This graph also compares the exact and empirical solutions discussed. Figure 3 illustrates a volumetric tank exchange (VTE) of 1.75 required to achieve the desired inerting ratio, which is slightly greater than the theoretical value given by the exact solution of 1.7 and significantly greater than the empirical relationship that results in a VTE of 1.5.

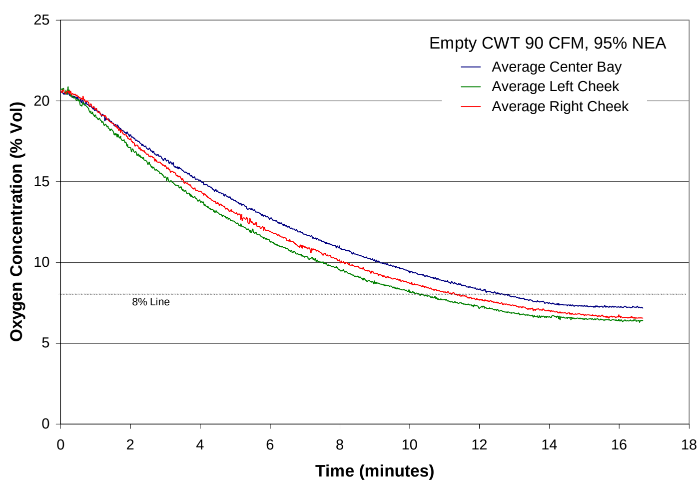

Figure 2. Ground Test 1 Ullage-Washing Average Oxygen Concentration Data

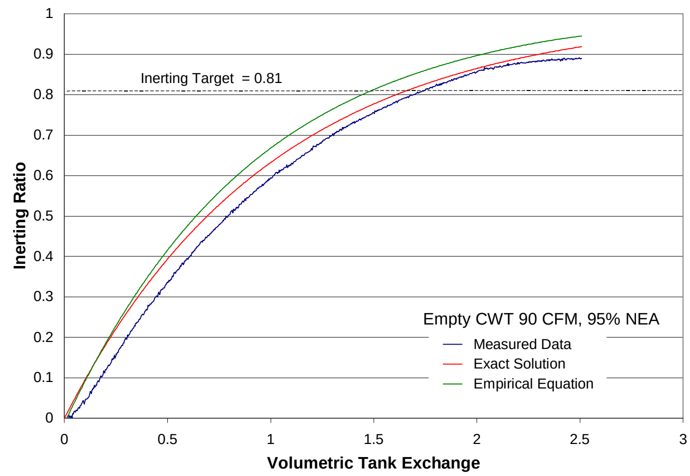

Figure 3. Ground Test 1 Nondimenstional Ullage-Washing Data

Figure 2 illustrates that the manifold was not completely balanced given the flow conditions of the test. The oxygen concentration of the cheeks decreased at a faster rate, resulting in an uneven distribution of NEA. The outflow of the tank is through the vent system ports which are located in each cheek area. This had the effect of decreasing the efficiency of the inerting process by a small factor from the theoretical solution. The FAA empirical data illustrates a greater efficiency of inerting. This is most likely due to the accuracy of the oxygen analyzer used for the testing, but more information is needed to validate or refute the FAA empirical data illustrating a VTE of 1.5 is required to inert a fuel tank ullage to an 8% oxygen concentration with NEA 95%.

WIND EFFECTS

To examine the effect of wind on the ability of the CWT to remain inert, the tank was inerted on two different occasions with zero fuel load and allowed to sit on condition for 2 hours. As previously discussed, the condition consisted of remaining parked at the test location with the air cycle machines running for 2 hours. One test was with quiescent wind conditions while the other test had a fan blowing over the right wing vent only to simulate a crosswind affecting only that vent. This created a differential pressure between the CWT wing vents to determine the effect on the ullage oxygen concentration.

The results of the quiescent and simulated crosswind tests are seen in figures 4 and 5, respectively. These illustrate that under quiescent conditions the NEA dispersed very little (not measurable); however, the simulated crosswind had a profound effect on the average oxygen concentration of the left cheek area, which is where the right wing vent opens to the CWT. The average oxygen concentration in the left cheek reached 10% in less then 20 minutes, illustrating a need to limit cross venting of a CWT under some conditions of GBI for aircraft with cross-vented fuel tanks. Figure 6 compares the overall average CWT oxygen concentration for both wind conditions, illustrating the profound effect of the simulated crosswind.

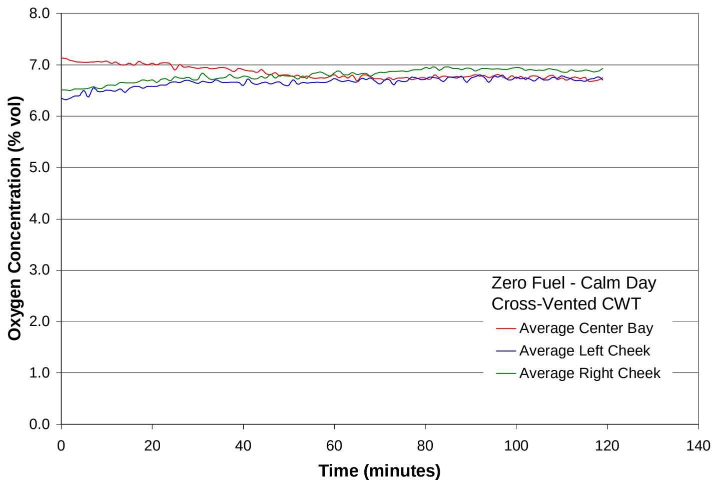

Figure 4. Calm Winds CWT NEA Dispersion Data

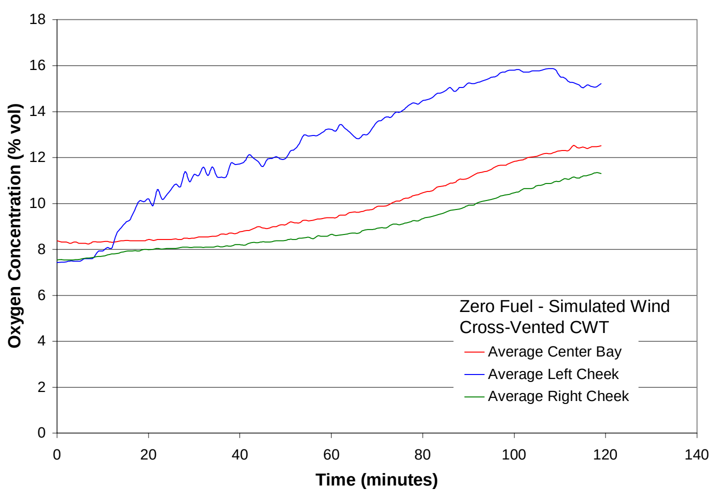

Figure 5. Simulated High Winds CWT NEA Dispersion Average Bay Data

GROUND FUEL EFFECTS

To determine the effect of fuel loads on an inert ullage during ground operations, the CWT was inerted twice to 8-percent oxygen concentration and then loaded with fuel to 20 and 80 percent, respectively. The aircraft remained on condition (packs running) for 1.5 to 2 hours. The average oxygen concentration for the three CWT areas is presented for the 20- and 80-percent fuel case in figures 7 and 8, respectively.

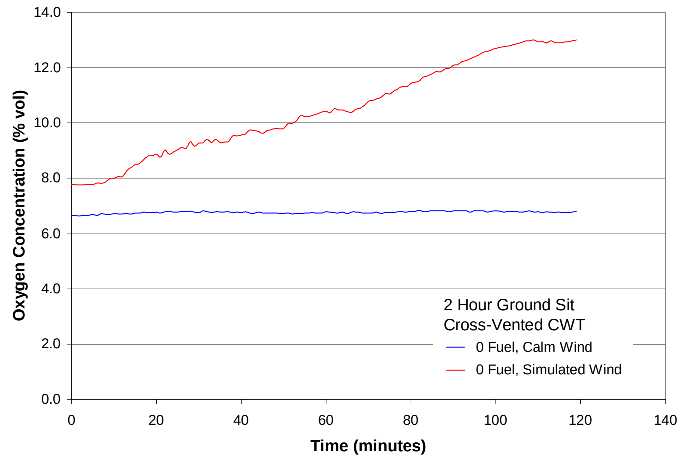

Figure 6. Comparison of NEA Dispersion for Two Wind Conditions

The effect of fueling on the inert ullage space was substantial but did not cause the average oxygen concentration in any of the three main areas of the tank to increase significantly above 10-percent oxygen by volume. The 80-percent fuel case had the highest increase in oxygen concentration with the 20-percent fuel case having about half the effect. The increase in oxygen concentration was attributed to dissolved gases being released from the fuel due to atomizing and frothing at the exit points of the fueling manifold in the tank, but more information and testing is needed to validate this hypothesis.

The 20-percent fuel load case illustrates no significant effect of the fuel on the ullage oxygen concentration after refueling. The effect of the higher fuel load on the inert ullage for the 80-percent fuel case cannot be determined, as high winds caused a rapid increase in oxygen concentration that would far overshadow any effect the fuel would have displayed.

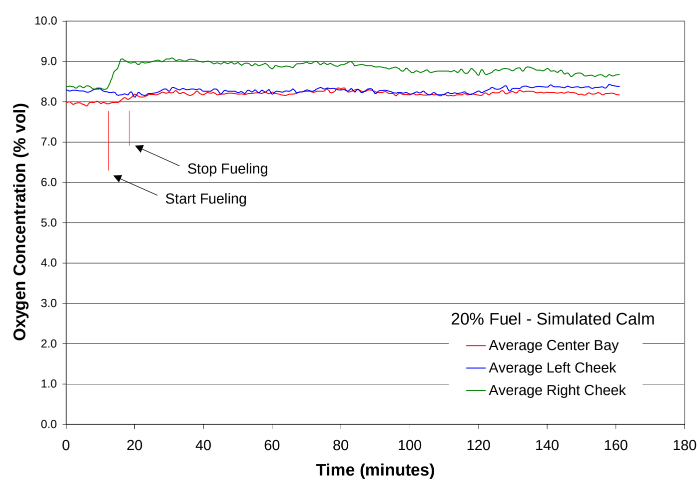

Figure 7. Twenty-Percent Fuel Load NEA Dispersion Data-Fuel After Inerting

Figure 8. Eighty-Percent Fuel Load NEA Dispersion Data-Fuel After Inerting

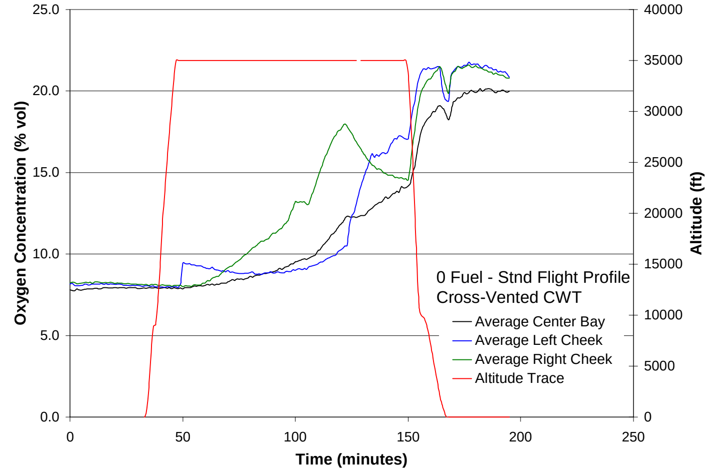

Figure 9. Zero Fuel Load Flight Test NEA Dispersion Data With Cross Venting Configuration

CENTER WING TANK CROSS-VENTING EFFECT

The effect of the cross-venting configuration on the dispersion of NEA in the CWT of the aircraft was also examined in a flight test. The aircraft CWT was inerted to 8%, and after a brief settling period, the air-cycle machines were operated for 20 minutes on the ground. The aircraft then briefly taxied to a runway and took off. The aircraft proceeded to an altitude of 35,000 feet as prescribed by air-traffic control, and then did several standard maneuvers at altitude. Figure 9 illustrates the profound effect of these maneuvers. During the test, the pilot also trimmed the aircraft in an intentional side-slip to maximize the effect of the cross-vented tank. This data illustrates that the three primary CWT areas had an average oxygen concentration of less then 10% for only approximately 40-50 minutes at cruise altitude.

This data was repeated after an aircraft modification was performed to prevent cross venting of the CWT by blocking one vent channel (figure 10). The pilot repeated the flight profile and test procedures as best as possible. The average oxygen concentration in each bay remained below 10 percent for virtually the entire flight until descent. During descent, the oxygen concentration of the tank rose sharply as expected, as outside air rushed in the vents to equalize pressure between outside and inside of the CWT. Figure 11 compares the overall oxygen concentration of the CWT for both tests shown in figures 9 and 10 and illustrates the profound difference of eliminating cross venting on the ability of the tank to remain inert during normal flight operations.

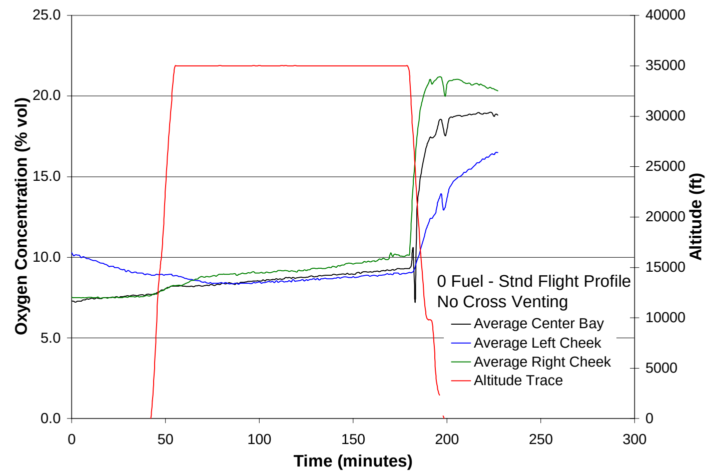

Figure 10. Zero Fuel Load Flight Test NEA Dispersion Data Without Cross Venting

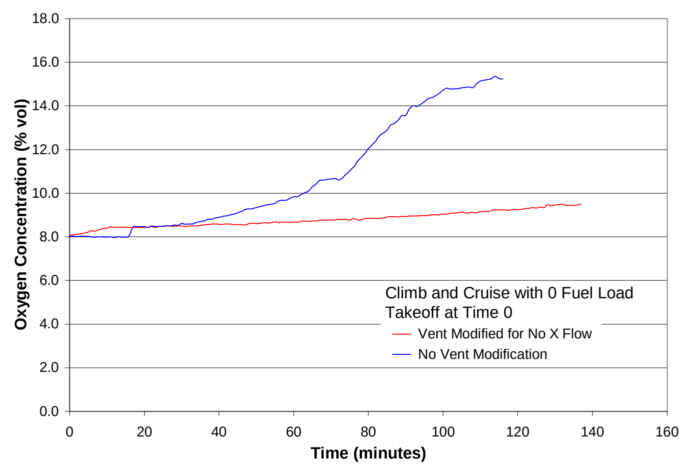

Figure 11. Comparison of NEA Dispersion for Two Venting Configurations

FUEL EFFECTS AT ALTITUDE

To study the effect of fuel load on an inert ullage, figure 10 was employed to establish a baseline of NEA dispersion without cross venting and no fuel in the CWT. The CWT average oxygen concentration increased approximately 1.5 percent during the ascent and 2-hour cruise. The three remaining flight tests each utilize the same basic flight profile with three different fuel loads.

To compare the effects of fuel load as it pertains to flight operations, the increase in overall average CWT oxygen concentration was plotted for the four fuel load flight tests. Figure 12 gives the increase in average CWT oxygen concentration at each fuel load tested with no cross venting, excluding the decent portion of flight. This illustrates the effect of fuel load on the increase in ullage oxygen concentration for the flight profile previously discussed. As expected, the greater the fuel load, the greater the effect on the ullage oxygen concentration. As more fuel is used, more air enters the fuel tank and raises the oxygen concentration.

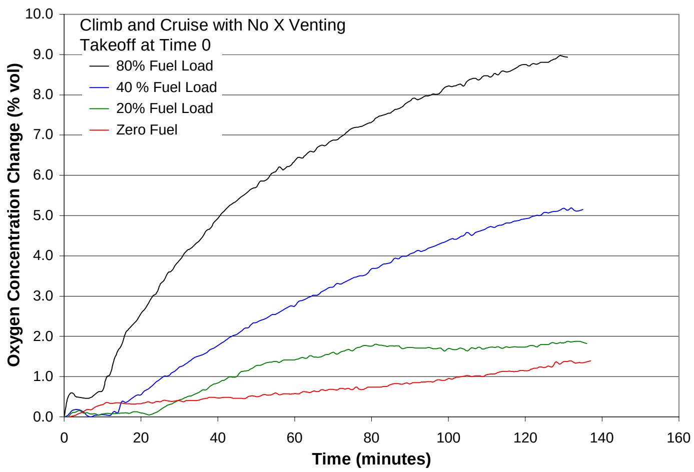

Figure 12. Average CWT O_2 Concentration Increase Comparison Plot for Different Fuel Loads

To illustrate the effect of fuel on the ullage, oxygen concentration was plotted against fuel load (figure 13). Examining figure 13, it can be seen that both the 40- and the 80-percent fuel load tests burned the same fuel quantity at altitude (30% of the fuel load), but the 80-percent fuel case oxygen concentration during the 80% fuel load test rose on average 1.5% more. This is the combined effect of the larger fuel load having a greater amount of dissolved oxygen being liberated due to altitude pressure changes and a smaller ullage to affect. It is presumed that the primary effect is due to the smaller ullage, but further tests and analysis are required to quantify the effect of the fuel alone on the ullage oxygen concentration. The 1.5% difference accounts for less then half of the difference in the total increase in average ullage oxygen concentration between the 40- and 80-percent fuel load tests. The cruise portion of the 80-percent fuel load test started with the oxygen concentration being 2.5% greater than the cruise portion of the 40-percent fuel load test.

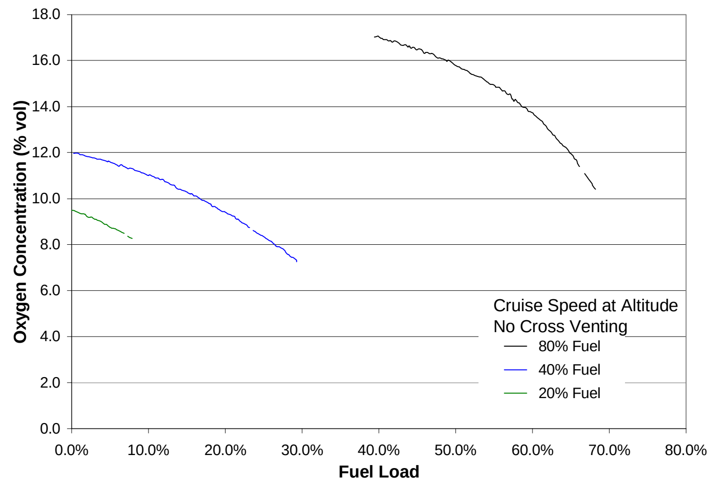

Figure 13. Change in Average CWT O_2 Concentration Comparison Plot for Different Fuel Loads During Cruise

Figure 14 gives the oxygen concentration with respect to altitude during the climb portion of the 0-, 20-, 40-, and 80-percent fuel load tests. The 40- and 80-percent fuel load cases illustrate a similar behavior; however, the 80-percent fuel case has a marked increase in oxygen concentration during the last 5 to 10 thousand feet of climb even though both tests used a similar amount of fuel load during climb (10 percent). This also was presumed to be due to the larger fuel load liberating a greater amount of oxygen during climb, and affecting a smaller space.

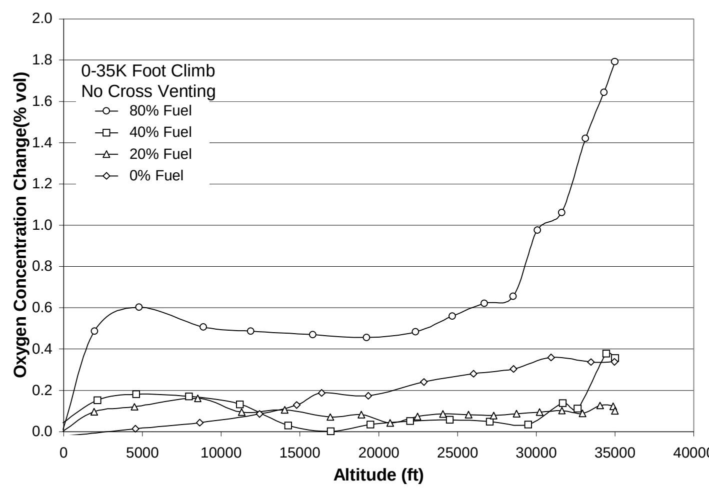

Figure 14. Change in Average CWT O_2 Concentration Comparison Plot for Different Fuel Loads During Climb

CONCLUSION

Ground-based inerting was successfully executed on a Boeing 737 in a flight test environment. The center wing tank was inerted with 95% nitrogen-enriched air, using approximately 1.8 tank volume exchanges of inerting gas, also known as the volumetric tank exchange (VTE). During quiescent wind ground tests and the ground test without CWT cross venting, the ullage oxygen concentration was relatively stable. These tests would have allowed the oxygen concentration to remain below 10 percent on the ground for over 4 hours, even with a fuel load of 80 percent. Simulated and real-wind conditions created rapid increases in oxygen concentration in the CWT. However, with the installation of a device to prevent cross venting of the tank, the wind effects were significantly reduced. Flight tests with and without cross venting highlights this profound effect on an inert fuel tank ullage in flight. During a flight test with a cross vented center wing tank, the average ullage oxygen concentration remained below 10 percent for about 1 hour of flight. With cross venting eliminated, under the same test scenario, the average oxygen concentration was maintained below 10 percent for the entire cruise portion of the flight. As expected, during descent, air entering the center wing tank to equalize pressure created large and immediate increases in ullage oxygen concentration.

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3. “Ground and Flight Testing of a B-737 Center Wing Fuel Tank with Nitrogen-Enriched Air,” Burns, Michael and Cavage, William M., DOT/FAA/AR-01/63, August 2001.

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