

Cold Ambient Temperature Effects on Heated Fuel Tank Vapor Concentrations

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16. Abstract Experiments were conducted within a simulated aircraft center wing fuel tank (CWT) to qualitatively analyze the effects of decreased ambient temperatures, such as might occur at increased altitudes, on the vapor concentrations found in a typical CWT ullage. A small quantity of fuel in the CWT test article was heated to 125°F for two hours, corresponding to a temperature of approximately 10°F above the flashpoint of the fuel. The tests were conducted at sea level (14.7 psia), however, the wall temperature of the tank was cooled to a temperature corresponding to a given altitude. The following real-life scenarios were simulated. <ol style="list-style-type: none"> 1. BASELINE TEST: The environmental conditioning system (ECS) packs are run for two hours while the aircraft is on the ground. After some time, the packs are turned off, and the aircraft remains on the ground. 2. LOW-ALTITUDE TEST: The aircraft, after running its ECS packs, takes off and climbs to a low altitude, of approximately 9,000 ft, cooling the CWT to approximately 55°F. 3. INTERMEDIATE-ALTITUDE TEST: The aircraft, after running its ECS packs, takes off and climbs to an intermediate altitude of approximately 22,000 ft, cooling the CWT to 15°F. 4. HIGH-ALTITUDE TEST: The aircraft, after running its ECS packs, takes off and climbs to a full altitude of approximately 30,000 ft, cooling the CWT to -20°F. <p>From these tests, it was determined that the ambient temperature does indeed have a significant effect on the vapor concentrations formed in the fuel tank ullage at small fuel mass loadings. When allowed to cool naturally to the room's ambient temperature (~75°F), the fuel-air ratio decreased at an average rate of $1.07 \times 10^{-5} \text{ min}^{-1}$ for the low-altitude test, it decreased at an average rate of $7.50 \times 10^{-5} \text{ min}^{-1}$, and for intermediate- and high-altitude scenarios, it decreased at an average rate of $1.58 \times 10^{-4} \text{ min}^{-1}$ and $2.08 \times 10^{-4} \text{ min}^{-1}$, respectively. Thus, as the ambient temperature is decreased, the rate of decrease in the fuel-air ratio increases.</p>					
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1. INTRODUCTION.

1.1 PURPOSE.

This technical note describes experiments designed to determine and qualitatively analyze the effects of a decrease in the ambient temperature, such as might occur at increased altitude, on the fuel vapor concentrations formed in a heated aircraft fuel tank.

1.2 BACKGROUND.

Although the occurrence of an aircraft fuel tank explosion is quite rare compared with the amount of hours flown, the flammability of the fuel tank vapors is currently a topic of much concern. This interest largely stems from the crash of TWA flight 800 in July of 1996 over East Moriches, NY. Since this accident, a number of research activities have been undertaken, in an attempt to better characterize and understand the flammability characteristics of Jet-A fuel and how the conditions existing within the center wing fuel tank (CWT) affect these characteristics.

1.2.1 The Center Wing Fuel Tank and Environmental Conditioning System.

Passenger aircraft typically use the wing structures as their main fuel tanks, where the fuel is in direct contact with the outside skin. Since larger aircraft (B-737s, B-747s, etc.) have a need for greater quantities of fuel, the structural wing box within the fuselage is also used to store fuel [1]. This fuel tank is referred to as the CWT. In the case of a B-747, this tank is divided into seven bays with a total volume of approximately 2300 ft³. Figure 1, as taken from reference 2, shows a schematic of the B-747 CWT.

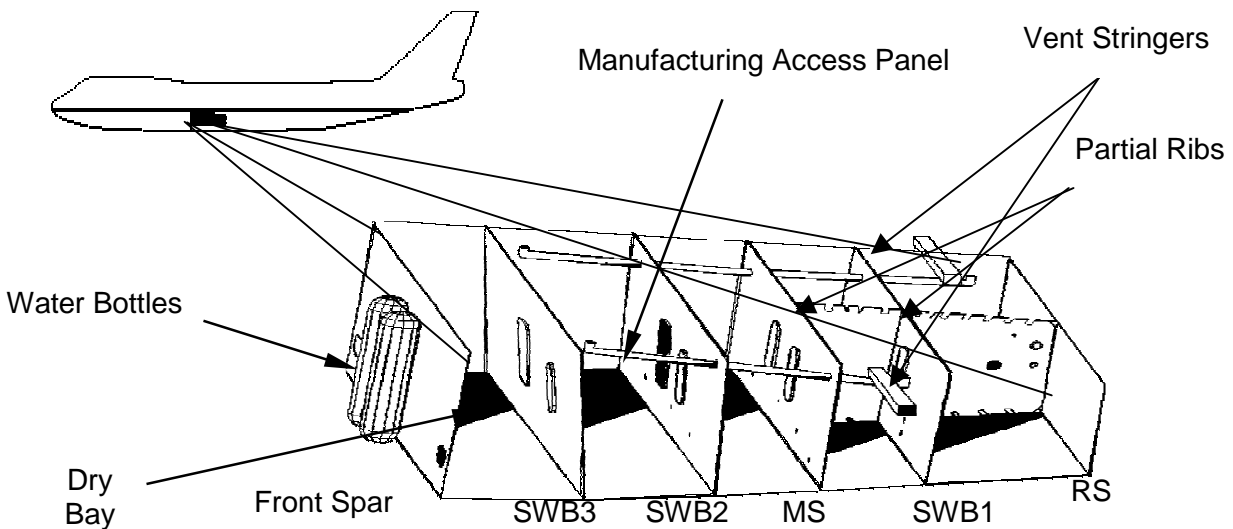


FIGURE 1. SCHEMATIC OF A CENTER WING FUEL TANK

Many of these larger aircraft have environmental conditioning system (ECS) packs located directly under the CWT. Each of these packs “receives regulated bleed air from the engine compressors, removes heat from the bleed air with a primary and a secondary heat exchanger, and exhausts the excess heat beneath the airplane” [3]. The cooled bleed air is then used to pressurize the cabin. Heat transfer from the ECS packs can lead to a significant increase in the fuel temperatures in the CWT.

These packs are used to condition the cabin while the aircraft is on the ground before take off. The increase in fuel temperature, therefore, depends greatly on how long the packs are operating on the ground. The TWA 800 emulation flight data [4] show that the fuel temperature could increase from 80°F to approximately 125°F in 2 1/2 hours of ground time.

This elevation in temperature may create a flammable mixture in the ullage. In fact, the Aviation Rulemaking Advisory Council’s (ARAC) Fuel Tank Harmonization Working Group [5] has determined that heated CWTs are at risk of having a potentially flammable mixture in the ullage 30% of the total flight time as compared to only 5% in CWTs without adjacent heat sources.

The potential risk imposed by heated center wing fuel tanks depends on a variety of parameters such as the fuel flash point, mass loading, vapor pressure, and others. Another factor is the impact of a decrease in the ambient temperature such as might occur at increased altitude, on ullage flammability.

The following is a brief discussion of the more important aforementioned parameters affecting the ullage flammability.

1.3 OVERVIEW OF ULLAGE FLAMMABILITY PARAMETERS.

1.3.1 The Fuel Flash Point.

The flash point is an estimate of the minimum temperature, at atmospheric pressure, at which sufficient vapor is released by the fuel to form a flammable fuel-air environment [6]. For Jet-A fuel, the minimum specified allowable flash point is 100°F. While the flash point is a good measure of flammability relative to other fuels, for multicomponent fuels it is difficult to determine a precise relationship between the flash point and the mixture flammability. This stems from the fact that the flash point depends on the vapor concentration, which for multicomponent fuels varies as a function of temperature for the various components of the liquid fuel.

1.3.2 The Fuel Mass Loading.

The fuel mass loading of the tank is defined as the mass of fuel per unit volume of the tank holding it. In other words, for a full tank, the mass loading is equal to the density of the fuel (approximately 800 kg/m³), for a half-full tank, it is equivalent to half of the density and so on [1]. In the case of TWA 800, the tank had a capacity of 13,200 gallons and only contained 50 gallons of fuel. This corresponds to a fuel mass loading of approximately 3 kg/m³. The mass loading has a bearing on both the fuel temperature (heat transfer) and ullage vapor concentration.

1.3.3 The Fuel Vapor Pressure.

In a partially filled fuel tank, the hydrocarbon molecules are evaporated into the vapor space above the liquid fuel. If the temperature remains constant and there is no turbulence, this evaporation will continue until the number of fuel molecules leaving the liquid equals the number of molecules returning to the liquid surface. The vapor pressure is defined as the pressure exerted in the ullage (i.e., the vapor space) by the fuel molecules [1]. Therefore, if the vapor pressure at a given temperature is known, through calculations, in principle, one can determine the amount of fuel existing in the ullage at equilibrium, and therefore, the fuel-air ratio. It has also been determined in prior research [7], that a significant decrease in the fuel-air ratio occurs at extremely low mass loadings of approximately 0.08 and 0.15 kg/m³.

2. DISCUSSION OF TESTS AND RESULTS.

2.1 EXPERIMENTAL SETUP.

The tests discussed in this technical note were conducted in an aluminum tank test article with an internal volume of 88.21 ft³. This tank was surrounded by a 3" thick shell on the left, right, and rear walls as shown in figure 2. Carbon dioxide was plumbed into this shell in order to cool the fuel tank walls, simulating lower ambient temperatures at elevated altitudes. On the bottom of the tank, a thermostatically controlled hot plate was located directly beneath the fuel. The tank was instrumented with 11 K-type thermocouples as shown in table 1.

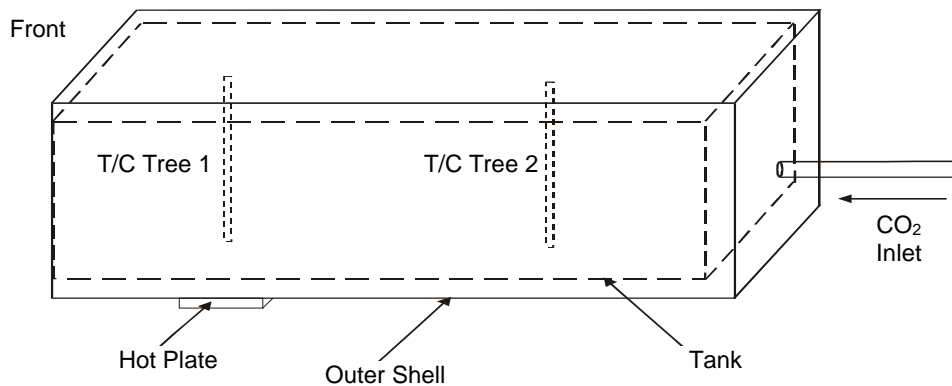


FIGURE 2. EXPERIMENTAL SETUP

TABLE 1. THERMOCOUPLE LOCATIONS

T/C No.	Location Inside Tank	T/C No.	Location Inside Tank
0	T/C Tree 2: Lower	6	Left Ceiling
1	T/C Tree 2: Middle	7	Right Ceiling
2	T/C Tree 2: Upper	8	Right Wall
3	Placed in Fuel	9	Rear Wall
4	T/C Tree 1: Middle	10	Left Wall
5	T/C Tree 1: Upper		

In addition, fuel vapor was collected through two sample lines, one mounted high and the other low, which were easily switched via a three-way electronic ball valve. The fuel vapor concentration was measured with a J.U.M. Model VE7 total hydrocarbon analyzer. Preliminary tests have shown that both ports read the same value, indicating that stratification of the vapor was negligible, and the mixture in the tank could be treated as homogeneous.

The analyzer uses a flame ionization detector burner that was calibrated using a mixture of 4 percent propane in nitrogen. The readings were given in parts per million of propane (ppm C₃H₈) on a scale of 0 to 100,000, corresponding to 0 to 10 volts DC, respectively. These readings were then converted to the more familiar and useful fuel-to-air-mass ratio (kg fuel/kg air) using the following equation:

$$\frac{Mass_{FuelVap}}{Mass_{Air}} = \frac{(ppm\ C_3H_8)(CR)(MW_{FuelVap})}{MW_{Air}} (10^{-6})$$

In this formula, the molecular weight of air (MW_{Air}) used was 28.84 g/mol. The carbon ratio (CR) and the fuel vapor's molecular weight ($MW_{FuelVap}$) used were 3/9.58 and 132.4 g/mol, respectively, as determined by Sagebiel in his research for the National Transportation Safety Board [8]. It should be noted, however, that this molecular weight is only an estimate, as Jet-A is an extremely difficult fuel to characterize with properties varying from batch to batch. Therefore, this is not an accurate calculation of the fuel-to-air ratio. Its primary purpose is to approximately locate the mixture within the flammability envelope to determine the *relative* differences in fuel-to-air-mass ratios resulting from heating/cooling the fuel.

2.2 EXPERIMENTAL PROCEDURE.

Experiments were conducted to simulate the following real-life scenarios.

1. **BASELINE TEST:** The environmental conditioning system (ECS) packs are run for two hours while the aircraft is on the ground. After some time, the packs are turned off and the aircraft remains on the ground.
2. **LOW-ALTITUDE TEST:** The aircraft, after running its ECS packs, takes off and climbs to a low altitude, of approximately 9,000 ft, cooling the CWT to approximately 55°F.
3. **INTERMEDIATE-ALTITUDE TEST:** The aircraft, after running its ECS packs, takes off and climbs to an intermediate altitude of approximately 22,000 ft, cooling the CWT to 15°F.
4. **HIGH-ALTITUDE TEST:** The aircraft, after running its ECS packs, takes off and climbs to a high altitude of approximately 30,000 ft, cooling the CWT to -20°F.

For all tests, 1.5 gallons of fuel was used, corresponding to a mass loading of 1.82 kg/m³. The fuel was heated and maintained at 125°F, corresponding to approximately 10°F above the fuel's flash point. The total time of heating for all tests was kept constant at 2 hours. After this time passed, the hot plate was turned off and the CO₂ was injected into the fuel tank's shell (with the

exception of the baseline test in which no CO₂ was used and the tank was allowed to naturally cool to room ambient temperature).

The amount of CO₂ injected was thermostatically controlled to maintain the three cooled walls at an average temperature corresponding to 30°F above the ambient temperature of the desired altitude. For instance, an altitude of 9,000 ft. corresponds to an ambient temperature of approximately 25°F, so the low-altitude test was performed by maintaining the fuel tank walls at approximately 55°F. It should be noted that the set tank wall temperatures do not simulate an actual aircraft. In fact, in the case of the 747 CWT, the tank wall temperatures are somewhat higher and are location dependent.

The injection of the CO₂ was continued until it was clear that there was a significant decrease in the hydrocarbon count. In the case of the baseline test, the tank was allowed to cool to the room's normal ambient temperature for the maximum amount of time allowed by the data acquisition system.

2.3 EXPERIMENTAL RESULTS.

The results from the experiments are shown in figures 3 through 5. Figures 3 and 4 show plots of the fuel and wall temperature histories, respectively; while figure 5 shows the fuel-air ratio variation with time.

As is seen in figure 3, the wall temperatures rose slightly during the heating of the fuel and then cooled, either naturally or by injection of the CO₂, to the desired ambient temperature. The fuel temperature profiles followed a similar pattern, being held constant at 125°F for the aforementioned 2 hours. After this time, the fuel temperature drops off asymptotically toward the ambient temperature. At small fuel mass loadings, it is evident that the fuel temperature decreased dramatically when subjected to cooler ambient air.

The fuel-air ratio reached a maximum of approximately 0.0145 for all four tests at the end of the 2-hour heating process. After this point, we see a large variation in the fuel-air ratio of the four different cases. For the baseline test with no cooling, it takes a full 6 hours for the fuel-air ratio to decrease to approximately 0.01. On the other hand, when the tank walls are cooled, we see a much more rapid decrease in the fuel-air ratio. When cooled to 55°F, a value of approximately 0.0115 is reached 40 minutes after the start of the cooling process; when cooled to 15°F, a value of 0.005 is reached 60 minutes after; and when cooled to -20°F, a value of 0.002 is reached just 60 minutes into the cooling process.

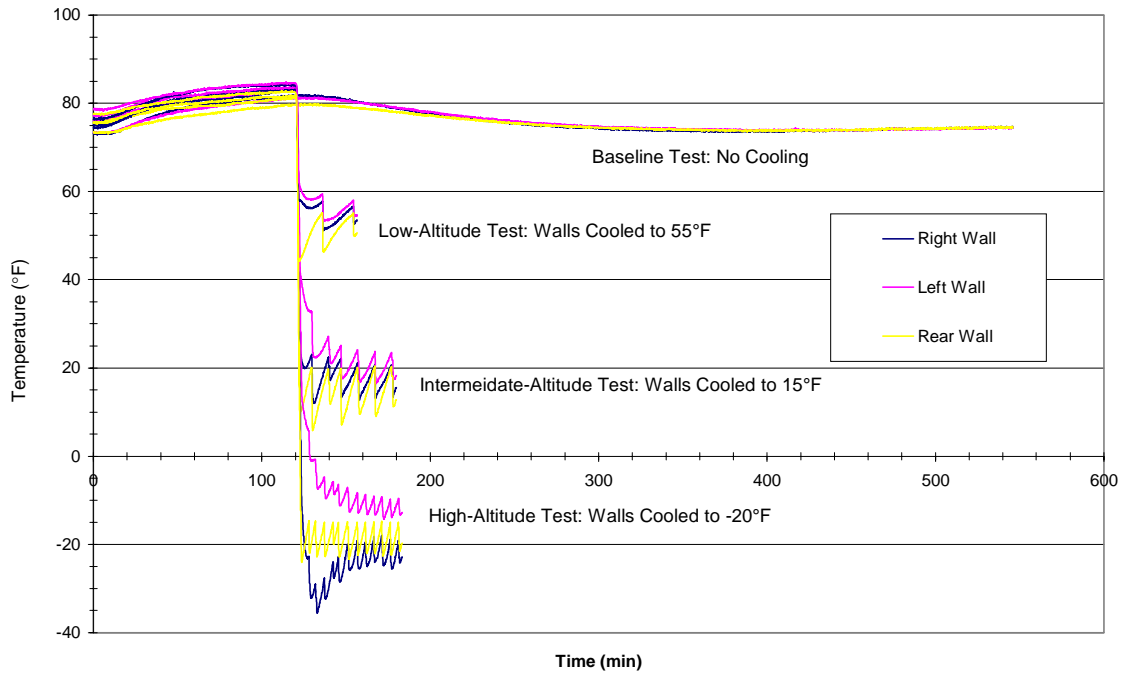


FIGURE 3. TANK WALL TEMPERATURES (°F) AS A FUNCTION OF TIME

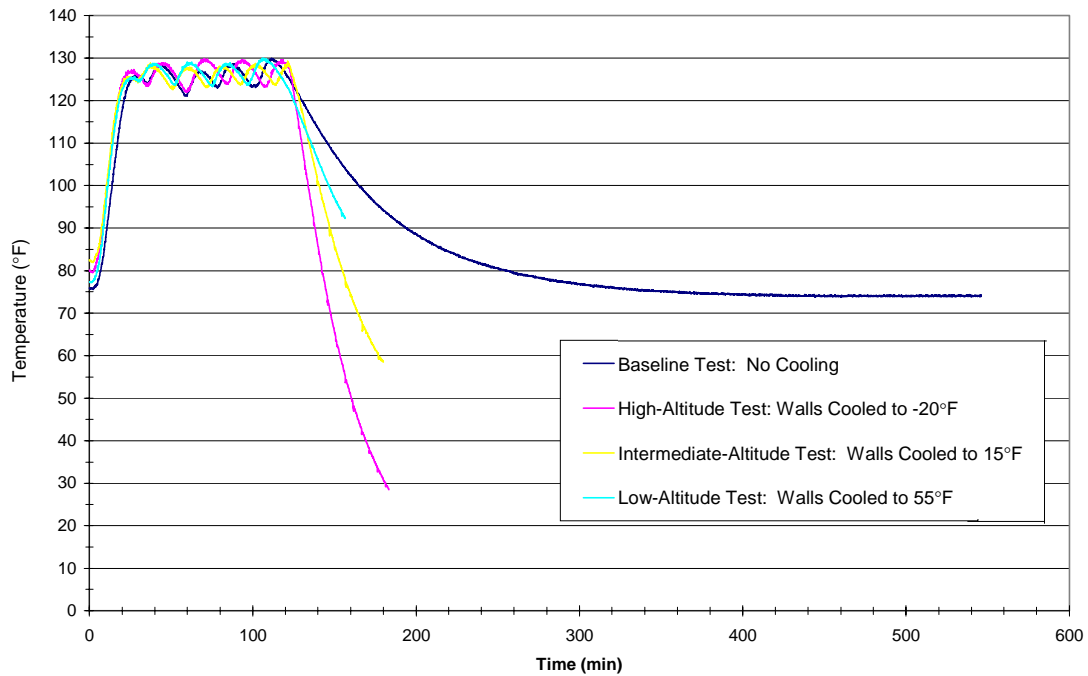


FIGURE 4. FUEL TEMPERATURE (°F) AS A FUNCTION OF TIME

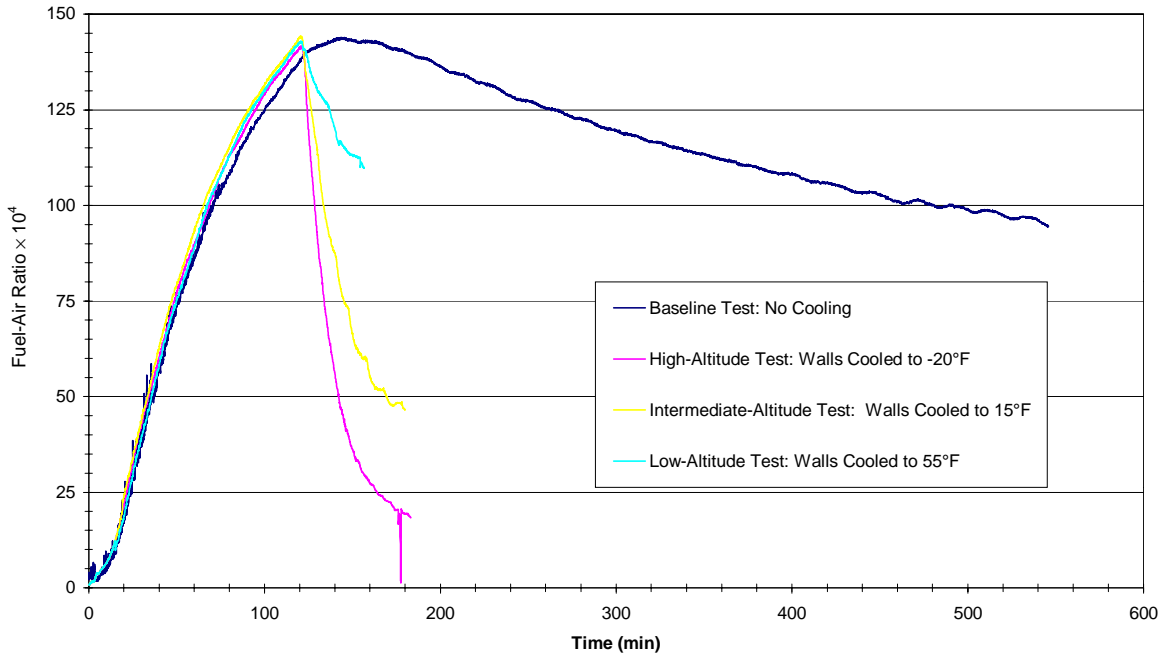


FIGURE 5. FUEL-AIR RATIO AS A FUNCTION OF TIME

2.4 CONCLUSIONS.

Experiments were conducted in a simulated fuel tank to qualitatively determine the effects of a decrease in the ambient temperature, such as might occur at increased altitude, on the fuel vapor concentrations formed in a heated CWT ullage at low fuel mass loadings. From these experiments, it can be concluded that as the ambient temperature is decreased, the fuel-air ratio decreases at an increasing rate. At a fuel mass loading of 1.82 kg/m^3 , when allowed to cool naturally to the room's ambient temperature ($\sim 75^\circ\text{F}$), the fuel-air ratio decreased at an average rate of $1.07 \times 10^{-5} \text{ min}^{-1}$; when cooled to 55°F , it decreased at an average rate of $7.50 \times 10^{-5} \text{ min}^{-1}$; and for the cases of 15°F and -20°F , it decreased at an average rate of $1.58 \times 10^{-4} \text{ min}^{-1}$ and $2.08 \times 10^{-4} \text{ min}^{-1}$, respectively. Or, at an ambient temperature of -20°F , the rate of decrease of the fuel-air-mass ratio is about 20 times greater than when the fuel is allowed to cool naturally to a standard ambient temperature.

3. REFERENCES.

1. Fuel Flammability Task Group, "A Review of the Flammability Hazard of Jet A Fuel Vapor in Civil Transport Aircraft Fuel Tanks," DOT/FAA/AR-98/26, June 1998.
2. Birky, M. M., "Flammability Program for TWA 800 Accident Investigation," Presentation given at The International Fire and Cabin Safety Research Conference, Atlantic City, NJ, November 16 - 20, 1998.
3. Bower, D. R., "Flight Test Group Chairman's Factual Report of Investigation," NTSB Docket No. SA-516, Exhibit No. 23A, 1997.
4. National Transportation Safety Board, "Flight Test Results: TWA 800 Emulation Flight," NTSB Docket No. SA-516, Exhibit No. 23F.
5. Fuel Tank Harmonization Working Group, "Fuel Tank Harmonization Working Group: Final Report," Aviation Rulemaking Advisory Committee, July 1998.
6. Nestor, L., "Investigation of Turbine Fuel Flammability Within Aircraft Fuel Tanks," Naval Air Propulsion Test Center Report DS-67-7, 1967.
7. Summer, S. M., "Mass Loading Effects on Fuel Vapor Concentrations in an Aircraft Fuel Tank Ullage," DOT/FAA/AR-TN99/65, September 1999.
8. Sagebiel, John C., "Sampling and Analysis of Vapors From the Center Wing Tank of a Test Boeing 747-100 Aircraft," DRI Energy and Environmental Engineering Center Report, NTSB Docket No. SA-516, Exhibit No. 20G, November 1997.