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Mass Loading Effects on Fuel Vapor Concentrations in an Aircraft Fuel Tank Ullage

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September 1999

DOT/FAA/AR-TN99/65

U.S. Department of Transportation
Federal Aviation Administration

NOTICE

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT/FAA/AR-TN99/65		

4. Title and Subtitle	5. Report Date
MASS LOADING EFFECTS ON FUEL VAPOR CONCENTRATIONS IN AN AIRCRAFT FUEL TANK ULLAGE	September 1999
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Steven M. Summer*	
9. Performing Organization Name and Address	10. Work Unit No. (TRAIS)
Airport and Aircraft Safety Research and Development Division Fire Safety Section Federal Aviation Administration William J. Hughes Technical Center Atlantic City International Airport, NJ 08405	
	11. Contract or Grant No.
12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
U.S. Department of Transportation Federal Aviation Administration Office of Aviation Research Washington, DC 20591	Technical Note
	14. Sponsoring Agency Code ANM-100

15. Supplementary Notes

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16. Abstract

This report discusses experiments performed within a simulated fuel tank approximately 1/20 the size of a typical B-747 center wing fuel tank (CWT). The vapors generated within the ullage of this tank were analyzed under different mass loadings in an effort to determine the effects of the mass loading and fuel distribution. It was determined from these tests that in order to have a substantial effect on the flammability of the vapor within the CWT, the mass loading would have to be somewhere between 0.08 and 0.15 kg/m^3. A substantial effect was defined as a minimum 20% decrease in the maximum hydrocarbon count when compared to the average of all tests conducted with larger mass loadings. In addition, it was found that while the distribution of the fuel has no effect on the peak flammability (vapor composition) that is reached, it does have a significant effect on how long it takes to reach the final state. The less dispersed the liquid fuel is, the longer it will take the vapor to reach its maximum flammability point.

17. Key Words	18. Distribution Statement
Fuel tank, Jet A, Flammability, Fuel vapor	This document is available to the public through the National Technical Information Service (NTIS), Springfield, Virginia 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	14	N/A

Form DOT F1700.7 (8-72) Reproduction of completed page authorized

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1. INTRODUCTION.

1.1 PURPOSE.

This paper discusses experiments designed to determine and analyze the effects of low fuel mass loadings on the fuel vapor concentrations found in a typical B-747 center wing fuel tank (CWT). Specifically, a determination was made of what conditions are necessary to significantly reduce the flammability of the fuel vapor concentration inside the CWT.

1.2 BACKGROUND.

On July 17, 1996, TWA flight 800, a Boeing 747 airplane, crashed over East Moriches, NY. The National Transportation Safety Board (NTSB) determined that this fatal accident was caused by an explosion within the CWT ullage.

The potential flammability of the ullage vapor space has long been noted, and several attempts have been made to provide protection systems against such a risk. Macdonald and Wyeth [1] discuss these briefly and explain that these attempts can be broken into four groups based upon the principle used.

1. Reducing the oxygen content below the critical value necessary for ignition.
2. The use of fire and flame suppression systems.
3. Increasing the fuel concentration above the upper flammability limit.
4. Reducing the fuel vapor concentration below the lower flammability limit.

In response to the TWA 800 accident, the NTSB "has recommended maintaining sufficient amount of fuel in the CWTs of transport aircraft to limit the liquid fuel temperature rise and evaporation, thus keeping the vapor fuel/air ratio below the explosive limit" [2]. This clearly refers to the last of the four alternatives previously described. While considering the reduction of the fuel/air ratio by means of *increasing* the mass loading (and thus reducing the vaporization of fuel due to heating), it is still necessary to look at all possible methods of reducing the fuel/air ratio. At the other end of the spectrum, by *reducing* the mass loading, there is more depletion of the lightweight, volatile hydrocarbon components of the fuel vapor, or the light ends, thus reducing the mass of the fuel vapors [2, 3].

The experiments noted here have examined the effect of the reduction of the mass loading on the ullage vapor concentration. Knowing that the effect would be seen at a relatively low mass loading, the tests used values below 6 kg/m^3.

1.3 DEFINITION OF THE FUEL MASS LOADING.

The fuel or 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/m^3), for a half-full tank, it is equivalent to half of the density and so on [2]. 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 loading of approximately 3 kg/m^3. The tank used in these experiments has a volume of 88.21 ft^3 or approximately 1/20 the volume of the CWT of a B-747. As such, a volume of 2.5 gallons of fuel in the test tank has the same mass loading as 50 gallons in TWA 800's CWT.

2. DISCUSSION OF TESTS AND RESULTS.

2.1 TEST SETUP.

The test setup, shown in figures 1 and 2, consists of the 88.21 ft^3 fuel tank, 14 K-type thermocouples, a 150,000-Btu kerosene heater, and a total hydrocarbon analyzer. The tank is constructed of 1/4″ aluminum with dimensions and thermocouple placements as shown in figure 2, with thermocouple 3 used to read the actual fuel temperature. In addition, there are two sample ports for the analyzer (shown in figure 2) which are easily switched via a three-way electronic ball valve. Preliminary tests, however, have shown that both ports read the same value, indicating that stratification of the vapor is negligible, and therefore, the mixture in the tank can be treated as homogeneous.

The analyzer, shown in figure 1, uses a FID burner and was calibrated using a mixture of 4 percent propane in nitrogen. The readings were given in parts per million of propane (ppm C_3H_8) 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 units of the fuel to air mass ratio (kg fuel/kg air) using the following equation:

$$(\text{Mass}_{\text{Fuel}}/\text{Mass}_{\text{air}}) = (\text{ppm } C_3H_8 \times 10^{-6})(\text{carbon ratio})(\text{molecular weight of fuel})(1 \text{ mol}/25 \text{ liters})$$
$$(1 \text{ liters air}/ 1.2 \text{ grams air})$$

In this formula, the carbon ratio used was 1/3, and the average molecular weight of the fuel vapor used was 132.4, as determined by Sagebiel in his research for the NTSB [4]. 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. This conversion, therefore, does not reflect the mixture flammability; its only purpose is to approximately locate the mixture within the flammability envelope. Nevertheless, this estimate should be useful for determining *relative* differences in concentration. It should also be noted that preliminary explosion tests have shown that a hydrocarbon count of approximately 14,000 ppm C_3H_8 corresponds to a flammable mixture.

Three pans were constructed for the fuel placement. They are sized 1′ × 1′, 2′ × 2′, and a much larger pan, covering the entire surface area of the tank. Initially, tests were conducted in the 2′ × 2′ pan with varying volumes of fuel in an attempt to determine the mass loading at which the flammability of the mixture will be significantly reduced. The test began with a loading of about 4.5 kg/m^3 (4.5 gallons); decreased mass loadings were employed until a notable difference was noted in the hydrocarbon count. A few of these mass loadings were also tested in the other two pans in an effort to determine the effect of the surface area of the fuel.

In addition, there were several spray tests done, in which a residual amount of the fuel was sprayed on the inner walls of the tank. This was done to determine if the left over fuel from previous flights would have an effect on the flammability.

2.2 TEST PROCEDURE.

The test procedure for these experiments is outlined below:

1. The hydrocarbon analyzer was turned on and given the proper amount of time to warm up as dictated by its specifications. It was then calibrated using the 4 percent propane mixture discussed above.

2. The fuel pan was placed in the tank, with the exception of the largest pan which covered the entire bottom surface of the tank.

3. The desired amount of fuel was carefully measured and placed in the pan.

4. Thermocouple 3 was placed inside of the fuel in such a way that it was not touching the sides or bottom of the fuel pan.

5. The door was placed on the side of the tank and sealed.

6. At this point, the data acquisition system was started, and the heater was turned on. The fuel temperature was carefully monitored and was kept as close to 125°F as possible by cycling the heater on and off as needed.

7. Throughout the test the hydrocarbon count was monitored until a steady-state concentration was reached. At this time all heating was stopped and the test was concluded.

2.3 TEST RESULTS.

Tables 1 through 3 show the results. In addition, figure 3 depicts the maximum hydrocarbon count and measured posttest flashpoint values as a function of mass loading. Figures 4 through 6 show some of the sample data.

2.3.1 Mass Loading Testing.

Table 1 shows the test results *without* the residual fuel spray for the 2′ × 2′ pan. The results indicate that there is minimal change in the hydrocarbon (HC) count for volumes between 0.25 and 3.5 gallons. However, the change between 3.5 and 4.5 gallons shows a more substantial difference in the corresponding HC counts. This is clearly the trend expected—the more fuel there is, the more fuel there is to evaporate. It is expected that further increases in fuel volume would cause the HC count to continue to rise, and eventually, the upper flammability limit would be exceeded, as suggested by option three discussed by Macdonald and Wyeth [1]. At the lower mass loadings there was a more substantial difference between the 0.25- and 0.125-gallon scenario, 12000 to 9000 ppm C_3H_8 respectively, or a 22% reduction in HC concentration compared to the average of all tests conducted at larger mass loadings. According to the criteria, this is the onset of a significant decrease in the hydrocarbon count, as suggested by option number four discussed by Macdonald and Wyeth.

It was not feasible to further lower the fuel volume tested in the 2′ × 2′ pan due to the fact that the fuel would barely cover the bottom of the pan, leaving it next to impossible to insert the thermocouple. For this reason there is only one reading in table 1, which corresponds to a 1′ × 1′ pan test. By decreasing the fuel volume once again, a significant decrease again occurred in the HC reading, giving leverage to Macdonald and Wyeth's option four.

The test results indicate that a significant reduction in the flammability of the fuel tank will occur between a mass loading of 0.15 and 0.08 kg/m^3. As is seen in the table, these mass loadings correspond to volumes of only 1.25 and 2.50 gallons of fuel in a typical B-747 CWT. Thus, in order to achieve the goal of significantly reducing the flammability of the fuel in the CWT by reducing the fuel volume, it would be necessary to purge the tank of all but 1-2 gallons of fuel.

2.3.2 Surface Area Testing.

Table 2 shows the results of different mass loading tests in the three different sized pans. Data is compared at a mass loading of 1.82 kg/m^3 (1.5 gallons) in both the 1′ × 1′ and 2′ × 2′ pans as well as a mass loading of 5.46 kg/m^3 (4.5 gallons) in both the 2′ × 2′ pan and a full bottom of the tank.

The data indicates that the maximum HC count seems to be independent of the surface area of the fuel; there is almost no change in the fuel vapor concentration with pan size. Thus, it appears that the maximum flammability of the vapors in the tank depends solely on the amount of liquid fuel in the tank and not the distribution of the fuel.

The size of the fuel pan has a significant effect on the time needed to reach the maximum fuel vapor concentration. At a fuel volume of 1.5 gallons, when the pan size was reduced from 2′ × 2′ to the 1′ × 1′, the time necessary to reach this maximum HC count more than doubled while the concentration only varied by 1500 ppm C_3H_8. Similarly, comparing the full-sized pan to the 2′ × 2′ pan, the time again doubled while the HC count stayed virtually the same.

The results are as should be expected. For a given fuel volume, using a smaller pan increases the thickness of the layer of liquid fuel in that pan. It thus takes longer to heat up the fuel to the desired temperature, which slows down the evaporation rate of the fuel. In addition, the increased fuel depth inhibits the evaporation of the light ends because they are now further from the surface. Apparently, the same processes will still occur, no matter what the duration, in achieving the same overall maximum HC count. It can be concluded that even though the flammability of the tank is independent of the dispersion of the fuel, having the fuel less dispersed throughout the tank is beneficial as it will provide more time until the mixture becomes flammable.

2.3.3 Residual Fuel Testing.

The results for the residual fuel tests are shown in table 3. Although only three tests are shown here, by comparing these tests with their counterparts in table 1, it is seen that there are virtually no differences. The maximum HC count was approximately the same, and the time duration to reach this maximum was fairly constant in each case. The fact that the maximum fuel vapor concentration remained constant leads to the conclusion that residual amounts of fuel on the walls of the tank should not have an impact on the variation of the flammability of the mixture within the tank.

2.4 CONCLUSIONS.

Tests were conducted in a simulated fuel tank approximately 1/20 the volume of a typical B-747 CWT to determine the effects on the fuel tank ullage flammability of the following factors: (1) the fuel mass loading, (2) the distribution of the liquid fuel within the tank, and (3) residual amounts of fuel on the tank walls. From these tests, it has been determined that the CWT would have to be nearly empty (a mass loading between 0.15 and 0.08 kg/m^3) in order to have a substantial effect on the flammability of the vapor. Again, it should be noted that the effect was said to be substantial if the resulting decrease in the maximum hydrocarbon count was a minimum of 20% of the average of all tests conducted with larger mass loadings. It has also been learned that while the distribution of the fuel has no effect on the maximum flammability (fuel vapor concentration) that is reached, it does have a very significant effect on how long it takes to reach the final value. The less dispersed the liquid fuel is the longer it will take the vapor to reach its maximum flammability point. In addition, it was determined that residual amounts of fuel on the side walls of the tank had little to no effect on either the maximum flammability point that was reached or the time that was necessary to reach this point.

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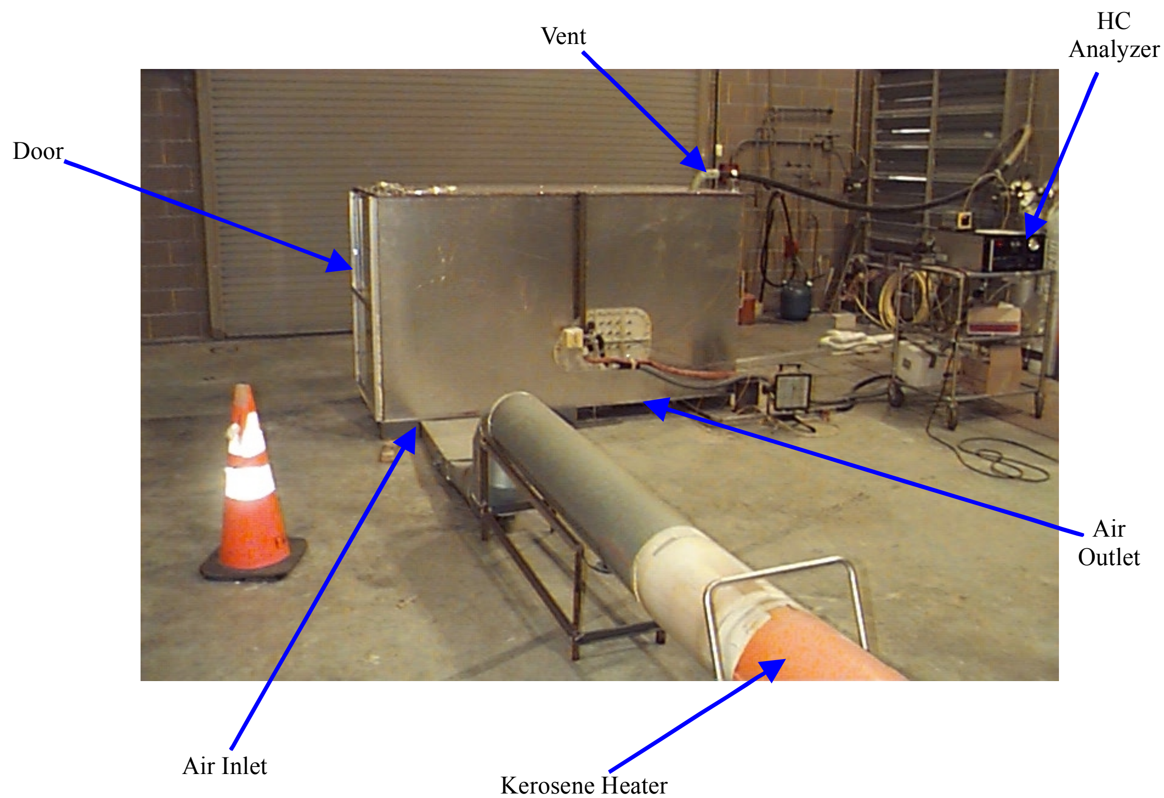

FIGURE 1. TEST SETUP

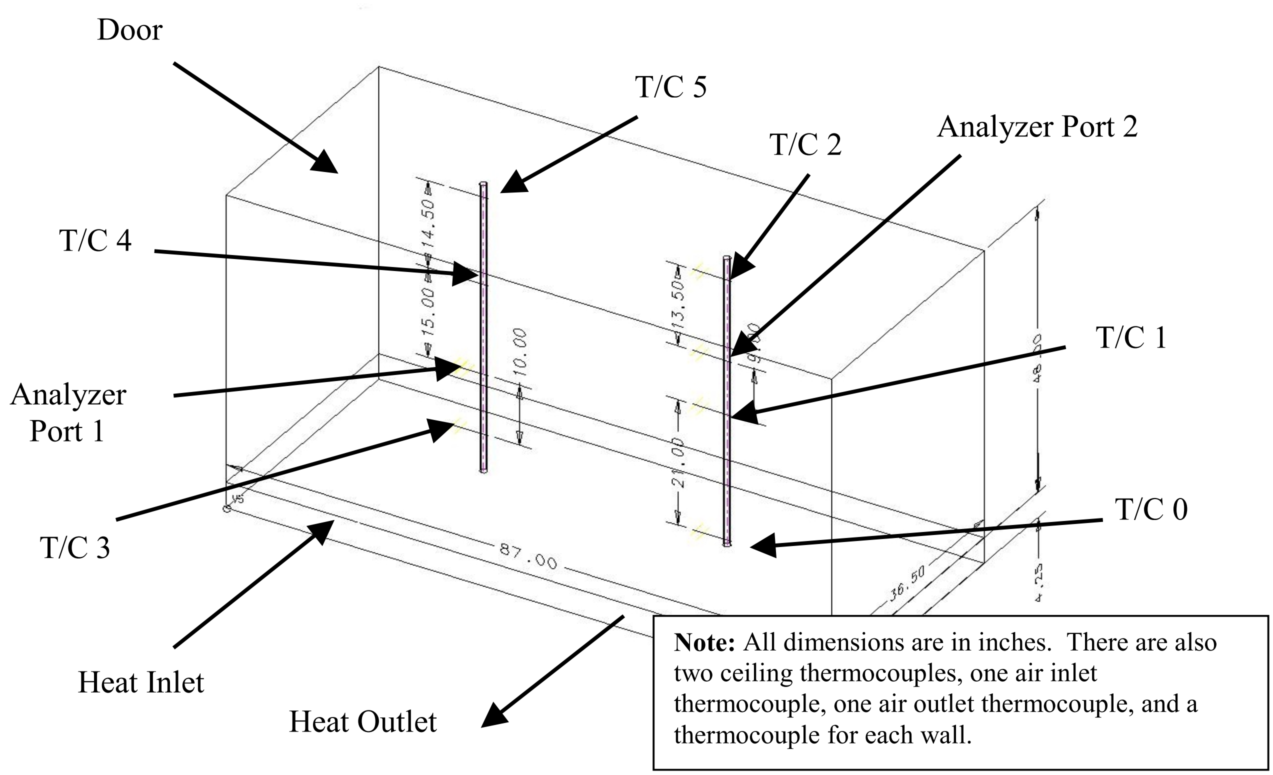

FIGURE 2. THERMOCOUPLE AND ANALYZER PORT LOCATIONS

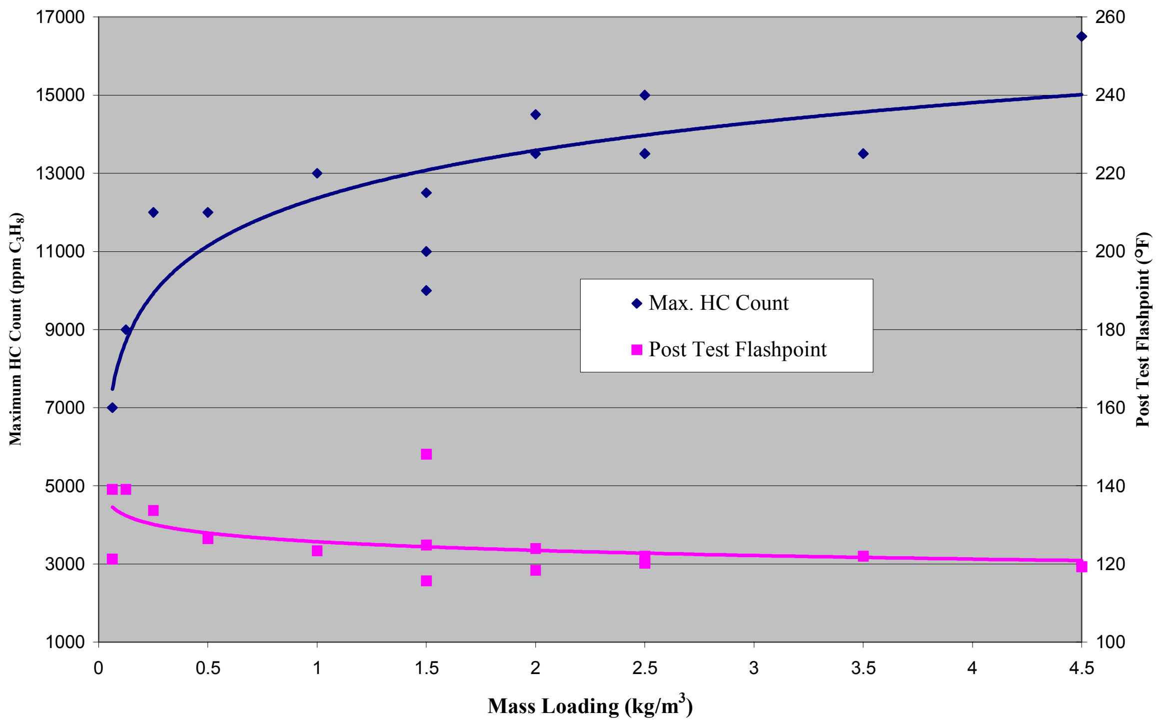

FIGURE 3. MAXIMUM HYDROCARBON COUNT (ppm C_3H_8) AND POSTTEST FLASHPOINT (°F) AS A FUNCTION OF MASS LOADING

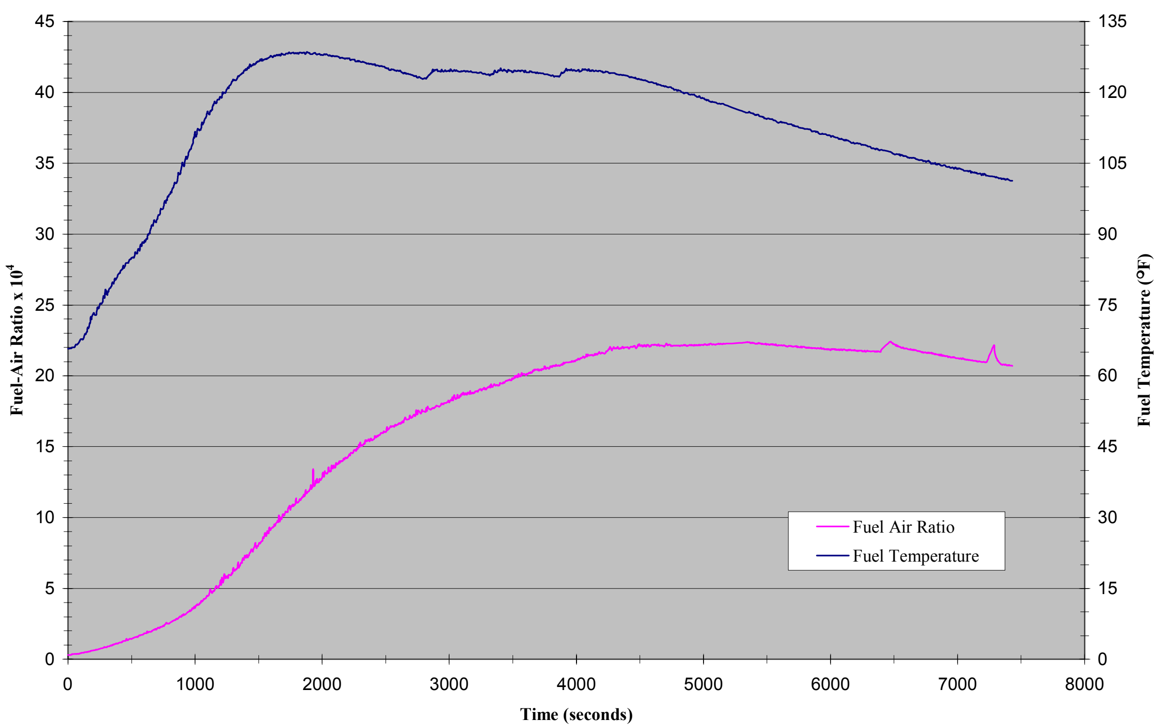

FIGURE 4. TYPICAL FUEL AIR RATIO AND FUEL TEMPERATURE (°F) PROFILES

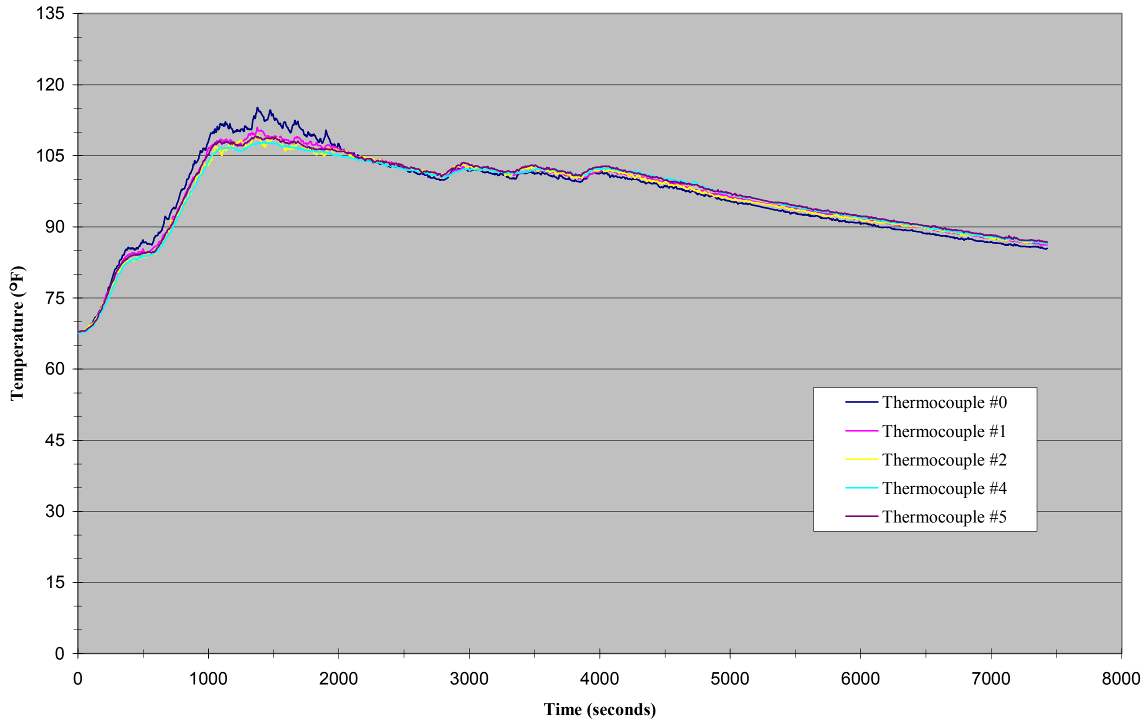

FIGURE 5. TYPICAL ULLAGE TEMPERATURE (°F) PROFILES

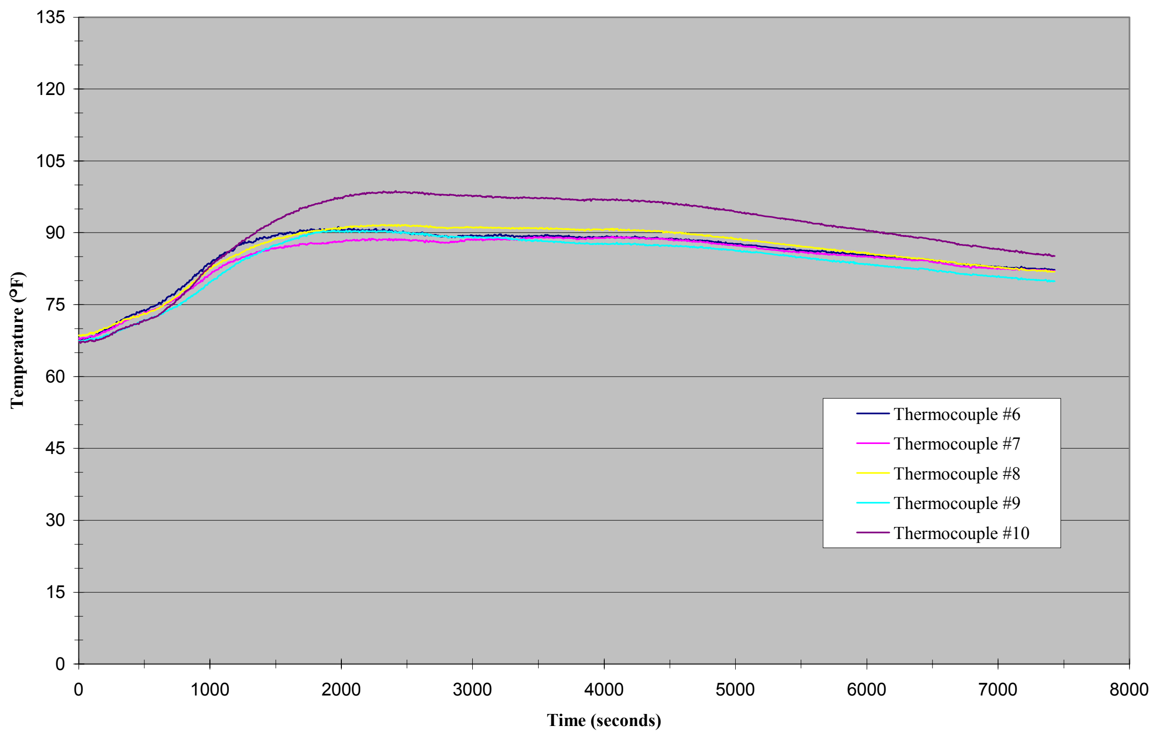

FIGURE 6. TYPICAL WALL AND CEILING TEMPERATURE (°F) PROFILES

TABLE 1. MASS LOADING TEST RESULTS

Pan Size	Volume of Fuel (gal)	Equivalent Fuel Loading (kg/m^3)	Equivalent Volume in a B-747 CWT (gal)	Maximum HC Count (ppm C_3H_8)*	Equivalent Fuel Air Ratio (kg fuel/kg air)*	Time to Reach Max. HC Count (s)*
1' × 1'	0.0625	0.08	1.25	7000	0.0103	6000
2' × 2'	0.125	0.15	2.50	9000	0.0132	5000
2' × 2'	0.25	0.30	5.00	12000	0.0177	5500
2' × 2'	0.5	0.61	10.01	12000	0.0177	5000
2' × 2'	1	1.21	20.02	13000	0.0191	4000
2' × 2'	1.5	1.82	30.03	12500	0.0184	3500
2' × 2'	2	2.42	40.03	14500	0.0213	4000
2’ × 2’	2.5	3.03	50.04	15000	0.0221	4000
2' × 2'	2.5	3.03	50.04	13500	0.0199	4500
2' × 2'	3.5	4.24	70.06	13500	0.0199	6000
2' × 2'	4.5	5.46	90.08	16500	0.0243	4000

*Approximate values only!

TABLE 2. SURFACE AREA TEST RESULTS

Pan Size	Volume of Fuel (gal)	Equivalent Fuel Loading (kg/m^3)	Equivalent Volume in a B-747 CWT (gal)	Maximum HC Count (ppm C_3H_8)*	Equivalent Fuel Air Ratio (kg fuel/kg air)*	Time to Reach Max. HC Count (s)*
2' × 2'	1.5	1.82	30.03	12500	0.0184	3500
1' × 1'	1.5	1.82	30.03	11000**	0.0162	10000
1’ × 1’	1.5	1.82	30.03	10000**	0.0147	6000
7' 3" × 3’ 0.5"	4.5	5.46	90.08	16500	0.0243	2000
2' × 2'	4.5	5.46	90.08	16500	0.0243	4000

*Approximate values only!
**Steady state was never reached.

TABLE 3. RESIDUAL FUEL TEST RESULTS

Pan Size	Volume of Fuel (gal)	Equivalent Fuel Loading (kg/m^3)	Equivalent Volume in a B-747 CWT (gal)	Maximum HC Count (ppm C_3H_8)*	Equivalent Fuel Air Ratio (kg fuel/kg air)*	Time to Reach Max. HC Count (s)*
2' × 2'	2	2.42	40.03	13500	0.0199	4000
2' × 2'	2.5	3.03	50.04	13500	0.0199	4000
1' × 1'	0.0625	0.08	1.25	7000	0.0103	6000

*Approximate values only!