DOT/FAA/AR-08/8

Air Traffic Organization
Operations Planning
Office of Aviation Research
and Development
Washington, DC 20591

A Study of the Flammability of Commercial Transport Airplane Wing Fuel Tanks

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February 2008

Final Report

U.S. Department of Transportation
Federal Aviation Administration

NOTICE

Technical Report Documentation Page

1. Report No. DOT/FAA/AR-08/8	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle

A STUDY OF THE FLAMMABILITY OF COMMERCIAL TRANSPORT AIRPLANE WING FUEL TANKS

5. Report Date

February 2008

6. Performing Organization Code

7. Author(s)

William M. Cavage and Steven Summer

8. Performing Organization Report No.

DOT/FAA/AR-07/??

9. Performing Organization Name and Address

Federal Aviation Administration
William J. Hughes Technical Center
Airport and Aircraft Safety
Research and Development Division
Fire Safety Branch
Atlantic City International Airport, NJ 08405

10. Work Unit No. (TRAIS)

11. Contract or Grant No.

12. Sponsoring Agency Name and Address

U.S. Department of Transportation
Federal Aviation Administration
Air Traffic Organization Operations Planning
Office of Aviation Research and Development
Washington, DC 20591

13. Type of Report and Period Covered

Final Report

14. Sponsoring Agency Code

ANM-112

15. Supplementary Notes

16. Abstract

The Fire Safety Team of the Airport and Aircraft Safety Research and Development Division performed tests at the Federal Aviation Administration (FAA) William J. Hughes Technical Center using the environmental chamber and the air induction facility (wind tunnel) to examine individual effects that contribute to commercial transport wing fuel tank flammability. Additionally, previously acquired wing tank flammability measurements taken during flight tests were compared with the results from the FAA Fuel Air Ratio Calculator in an effort to see if the calculations agreed with existing flight test data.

The results of the scale fuel tank testing in the environmental chamber showed that (1) fuel height in the tank had little or no effect on the flammability, (2) increasing the amount of heat on the top surface and a higher ambient temperature caused increased flammability, and (3) lower fuel flash point increased flammability greatly. Wind tunnel tests conducted with a section of a Boeing 727 wing tank showed that, under dynamic airflow conditions, change in ullage temperature was the primary mechanism affecting ullage flammability, not fuel temperature, as observed in environmental chamber tests. Other wind tunnel tests showed that the angle of attack of the fuel tank played little role in reducing fuel tank flammability, but that a cross-venting condition of the fuel tank would lead to a very rapid decrease in hydrocarbon concentration. An input temperature algorithm could be used with the FAA Fuel Air Ratio Calculator to significantly improve predictions of wing tank ullage flammability, based on tests that showed in-flight changes of ullage flammability in a wing tank are driven largely by the ullage temperature. This is very different from what had been shown with a center wing fuel tank, in which fuel temperature continues to be the main driver of flammability even during flight.

17. Key Words

Fuel, Fuel tank, Wing, Wing tank, Flammability, Hydrocarbon

18. Distribution Statement

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19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 30	22. Price

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LIST OF ACRONYMS

CWT	Center wing tank
FAA	Federal Aviation Administration
FAR	Fuel Air Ratio
NASA	National Aeronautics and Space Administration
THC	Total hydrocarbon concentration

EXECUTIVE SUMMARY

In response to potential fuel tank safety issues highlighted by the TWA Flight 800 accident in 1996, the Federal Aviation Administration (FAA) has developed a demonstration fuel tank inerting system and has proposed new regulations limiting the flammability of vulnerable fuel tanks on commercial transport airplanes. The FAA proposed to limit the flammability exposure time of the more vulnerable center wing and body-style fuel tanks to that of the fleet average wing fuel tank flammability exposure time. Although the FAA has studied center wing fuel tank flammability in detail, many assumptions regarding the understanding of commercial transport wing tank flammability remain to be validated. Simple calculation models used by the FAA have not been completely validated and could be modified, with additional comparison data. The Fire Safety Team of the Airport and Aircraft Safety Research and Development Division performed tests at the Federal FAA William J. Hughes Technical Center using the environmental chamber and the air induction facility (wind tunnel) to examine individual effects that contribute to commercial transport wing fuel tank flammability. Additionally, previously acquired wing tank flammability measurements taken during flight tests were compared with the results from the FAA Fuel Air Ratio Calculator in an effort to see if the calculations agreed with existing flight test data.

The results of the scale fuel tank testing in the environmental chamber illustrated three things. First, fuel height in the tank had little or no effect on the flammability progression during ground heating tests. Second, increasing the amount of top heat used caused the flammability to increase twice as much. Also, reducing ambient temperature not only decreased the absolute flammability of an ullage, but also limited the ability of the ullage flammability to grow. Flammability for these tests decreased on average 37 percent during the length of the test going from a hot day to a warm day. Third, the testing illustrated that a decreased fuel flash point increased flammability greatly. Wind tunnel tests conducted with a section of a Boeing 727 wing tank showed two different tests, one heated from the top and the other from the bottom, gave the same resulting flammability progression regardless of the bulk fuel temperature. In the top-heated test, with a relatively low starting fuel temperature, a rapid decrease in ullage and surface temperatures was observed, while the fuel temperature changed slowly. In the bottom-heated test, with a relatively high starting fuel temperature, the fuel temperature was shown to have decayed in a similar manner as the ullage and surface temperatures. As the flammability was similar in each test, this shows that the rapid decrease in ullage temperature is the driving force for the reduction of tank flammability while in flight, due to increased condensation within the tank ullage. Other wind tunnel tests showed that the angle of attack of the fuel tank played little role in reducing fuel tank flammability, but that a cross-venting condition of the fuel tank would lead to a very rapid decrease in hydrocarbon concentration.

The data from wing tank flammability flight tests were compared to calculations with the FAA Fuel Air Ratio (FAR) Calculator. It was demonstrated that the FAR calculator, when used with modified temperature data, provided significantly improved predictions of wing tank ullage flammability. This modified temperature was the absolute fuel temperature at takeoff modified by the change in ullage temperature at each time step.

It is evident from all the tests and modeling work that in-flight changes of ullage flammability in a wing tank are driven largely by the ullage temperature. This behavior is very different from what had been shown with a center wing fuel tank, in which fuel temperature continues to be the main driver of flammability even when in flight.

1. INTRODUCTION.

1.1 BACKGROUND.

In response to potential fuel tank safety issues highlighted by the TWA Flight 800 accident in 1996, the Federal Aviation Administration (FAA) has developed a demonstration fuel tank inerting system and has proposed new regulations limiting the flammability of vulnerable fuel tanks on commercial transport airplanes. The FAA proposed to limit the flammability exposure time of vulnerable center wing and body-style fuel tanks to that of the fleet wing fuel tank flammability exposure time. Although the FAA has studied center wing fuel tank flammability in detail, many assumptions regarding the understanding of commercial transport wing tank flammability remain to be validated. Simple calculation models used by the FAA have not been completely validated and could be modified, with additional comparison data. Research is needed to illustrate the potential effect of numerous parameters on the overall flammability exposure of the fuel tank ullage.

1.2 PREVIOUS RESEARCH.

In the 1980s, the Department of Defense did an extensive study of fuel tank ullage flammability centered around the use of an onboard inert gas generation system, fuel scrubbing [1], and the validated ullage composition predictions with a ground test article. The tests evaluated tanks with JP-4 fuels at varying altitude and temperature and concluded that the experimental data agreed well with the ullage composition model predictions.

Previous FAA fuel tank flammability experiments include a study of the effect of condensation due to cold temperatures on fuel tank ullage vapor concentrations [2] and mass loading effects on ullage fuel vapor concentrations [3]. Flammability of a Boeing 747 center wing and inboard wing fuel tank were measured during flight tests with the FAA demonstration inerting system on the National Aeronautics and Space Administration (NASA)-operated 747 SCA [4]. The flight tests had extensive instrumentation to monitor temperatures, pressure, and total hydrocarbon concentration (THC) in both the center and inboard wing fuel tanks as well as oxygen concentration variations in the inerted center wing tank. This report illustrated that equilibrium hydrocarbon levels in the center wing tank could be correlated with simple calculation models used by the FAA.

Additionally, the FAA developed a model to predict the ullage hydrocarbon concentration based on the principals of evaporation and condensation [5]. This model uses a generic fuel composition, developed during previous research, based on flash points and was capable of predicting resulting flammability with reasonable accuracy, and could even illustrate time progression of flammability, although altitude results gave large discrepancies with measured data.

1.3 SCOPE.

Tests were performed at the FAA William J. Hughes Technical Center by the Fire Safety Branch of the Airport and Aircraft Research and Development Division using an environmental chamber and an air induction facility (wind tunnel) to examine individual effects that contribute to commercial transport wing fuel tank flammability. Additionally, previously acquired wing tank flammability measurements made during flight testing were compared with results from the FAA fuel air ratio (FAR) Calculator in an effort to see if the calculations agreed with existing flight test data.

2. EQUIPMENT AND PROCEDURES.

2.1 EQUIPMENT.

Three test articles were used to acquire wing tank flammability data for analysis: the scale fuel tank test article in the Fire Safety environmental chamber, the wing fuel tank test article in the Fire Safety wind tunnel, and the NASA-operated 747 SCA.

2.1.1 Scale Fuel Tank Test Article.

The scale fuel tank test article was a 128-gallon capacity, welded, rectangular aluminum tank, roughly 3 by 3 by 2 feet with a drain at the bottom. The top of the tank has a capped fuel port, a vent, a removable instrument panel, and a pressure-relief hole. The capped port is used for refueling, defueling, and checking the fuel quantity. The vent is a 2-inch hole capped by a duck-bill check valve with an adjacent small hole. This allows for large quantities of air to escape the tank when necessary while limiting the amount of air that can enter the tank. The removable instrumentation panel is a 16- by 16-inch piece of aluminum that was fitted with various bulkhead fittings. The fittings allow access for gas sample tubing and thermocouples and also allow for the deposit of air and nitrogen for test and fire protection purposes. The pressure-relief hole, which is normally closed, is 12 by 8 inches. It has a sheet of thick aluminum foil sandwiched between the rim of the rectangular hole and a retaining plate. The hole provides pressure relief in the event of a reaction in the flammable fuel tank ullage, which would cause a failure.

To simulate flight conditions, the scale fuel tank test article was tested in a 72- by 71- by 93-inch environmental chamber at reduced ambient pressure and varying temperatures. 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 to control the absolute pressure. A manual temperature controller was used to control chamber temperature.

The primary instruments that were integrated with the scale fuel tank test article were temperature sensors that determined the various fuel tank temperatures. Ten K-type thermocouples were employed to determine the temperatures of the fuel and ullage as well as the top, bottom, and sides of the scale fuel tank test article. An additional thermocouple measured the ambient temperature of the environmental chamber. Also, an absolute pressure transducer measured the pressure altitude of the environmental chamber.

A J.U.M. Engineering THC analyzer was used to determine the flammability of the ullage during the proposed testing. The THC analyzer is a fully automated flame ionization detector analyzer that uses an internal pump to sample from a fuel tank ullage. The THC analyzer was used with a boost pump to provide data during simulated flight conditions (reduced pressures). The ullage was not sampled continuously, as continued sampling has a drastic effect on test results by consistently drafting hydrocarbons out of the fuel tank and adding air to the ullage. The hydrocarbon analyzer was calibrated with a propane mixture calibration gas allowing it to give THC results as propane.

All instruments were monitored by a computer data acquisition system. This system allowed for the real-time visualization of data as well as data storage. Figure 1 shows a block diagram of the scale fuel tank test equipment.

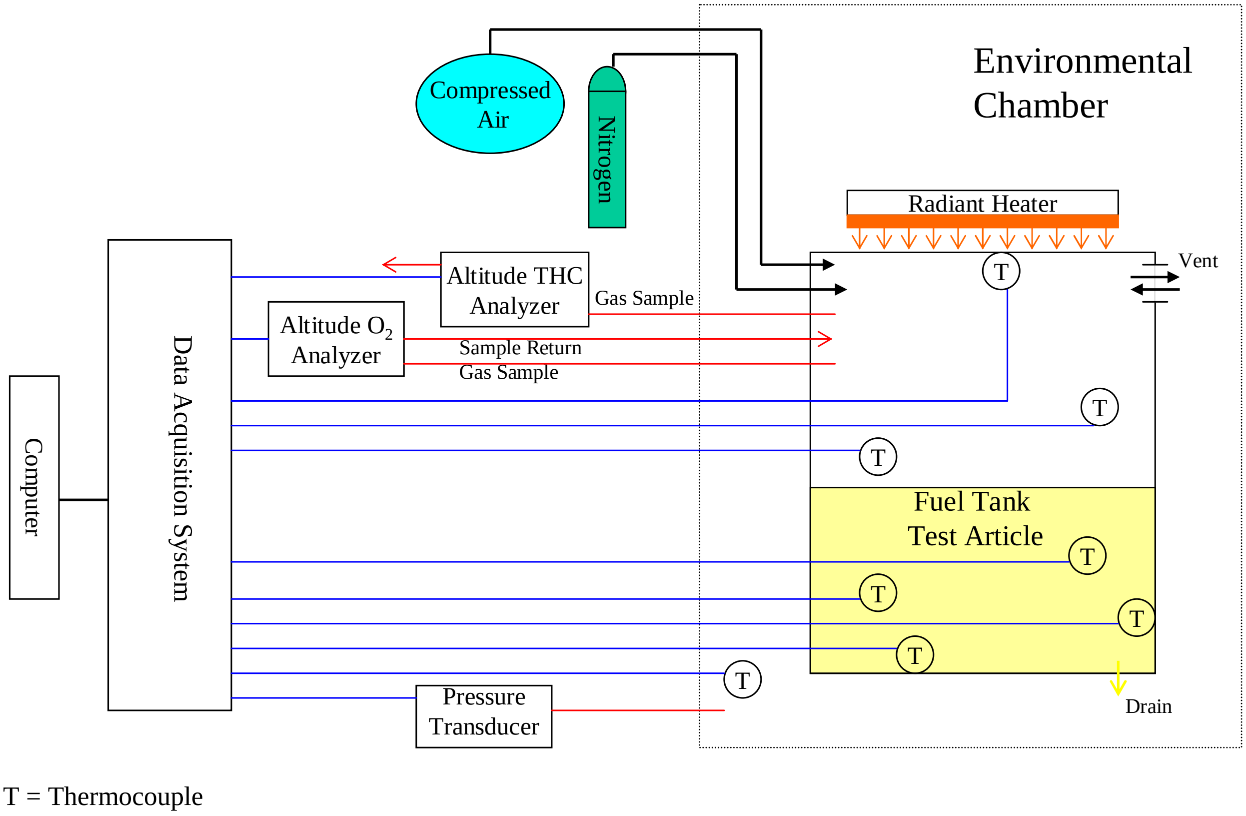


Figure 1. Block Diagram of the Scale Fuel Tank Test Article and Instrumentation

2.1.2 Wing Fuel Tank Test Article.

The wing fuel tank test article was made from the surge tank of the FAA Fire Safety Branch's Boeing 727 ground test article by removing the last 8 feet of the right wing, and is shown in figure 2. The surge tank with its current configuration has a capacity of approximately 36.5 gallons. It contains two vent ducts, which, for the purposes of testing, were sealed to create a single bay wing tank. The tank section was mounted in the low-speed portion of the Fire Safety Branch's Air Induction Test Facility (herein called the wind tunnel), as shown in figure 2. The tank was mounted so tests could be performed at both a 0° and 15° angle of attack relative to the airspeed direction.

The wind tunnel is an induction-type nonreturn wind tunnel with a 5-foot diameter, high-speed test section and a 9.5-foot, octagonal, low-speed test section. The air induction is provided by two Pratt & Whitney J-57 turbine engines exhausting into the diffuser cone. The high-speed exhaust from the two engines provides the primary flow that induces a secondary flow through the test sections. The nonreturn design of the wind tunnel allows for the testing of a flammable fuel tank in either test section without potentially flammable vapors building up in the wind tunnel. This testing employed the low-speed test section, in which the wing was mounted horizontally, giving a maximum airspeed of approximately 90 miles per hour. The wing was mounted on a pivoting axis to allow for variation of the wing's angle of attack.

Figure 2. Wing Fuel Tank Test Article Installed in the Wind Tunnel

The primary instrumentation integrated with the test article consisted of 12 K-type thermocouples to record the fuel, ullage, and surface temperatures within the tank. These temperature sensors consisted of one thermocouple on each surface of the tank, three located within the liquid fuel, two in the open ullage space, and one attached to a device that kept it floating in an attempt to determine the temperature of the top film layer of fuel. The THC analyzer used in the scale fuel tank experiments was employed to measure the flammability in the ullage space. Additionally, wind speed and temperature within the wind tunnel were monitored.

2.1.3 The NASA 747 SCA Flight Test Aircraft.

To better understand the dynamics of center wing and wing fuel tank flammability in flight, a series of flight tests were performed on the modified NASA 747 SCA (figure 3) during simulated commercial transport airplane operations with a center wing tank (CWT) inerting system. Measurements were made to characterize the inert gas distribution in the CWT as well as flammability of both the center wing and inboard wing fuel tanks. Oxygen concentration measurements were made at multiple locations in the CWT and multiple temperatures, and THC measurements were made both in the CWT and inboard wing fuel tank. A more complete description of the test article is given in reference 4.

Figure 3. NASA 747 SCA During FAA Fuel Tank Inerting Tests

2.2 TEST PROCEDURES.

Three different test procedures were used for the subject work: the scale fuel tank in the environmental chamber, the wing fuel tank, and the NASA 747 fuel tank.

2.2.1 Scale Fuel Tank Tests.

For a typical scale fuel tank test, the fuel tank test article was filled to the specified test fuel level. It was then allowed to sit overnight in the environmental chamber at the specified starting ambient temperature to allow for isothermal conditions at the start of the test. When the test began, the data recorder was started to capture the isothermal temperature conditions and measure the initial ullage flammability. Radiant heaters were then used to heat the top of the tank over an extended period of time to measure the time progression of flammability along with the tank surface, fuel, and ullage temperatures. The ambient temperature of the chamber was controlled manually to maintain a constant heat-rejection environment as the tank became hotter. After the desired heating time was complete, the radiant heat was removed, and the fuel tank test article was brought to high-altitude, low-temperature conditions, while the progression of flammability was measured with the associated fuel tank temperatures.

The testing involved varying the fuel level, the ambient test article temperature, and the top heat intensity. Also, the flash point of the fuel varied throughout the testing series and gave an approximation of the effect of this rarely studied parameter.

2.2.2 Wing Fuel Tank Tests.

The wing fuel tank test article was installed in the low-speed test section of the FAA wind tunnel. Fuel was preconditioned to an initial temperature of 90°F at sea level pressure. The fuel was then transferred to the wing tank test article through the vent. Radiant heaters were used to heat the top surface of the tank for an extended period of time. After the desired temperatures and ullage flammability were achieved, the radiant heaters were removed, and airflow through the wind tunnel commenced. On a typical test, the time duration between the removal of the heaters and the startup of the wind tunnel was approximately 10 minutes. Additionally, the time from when the wind tunnel was started to the time it reached maximum airspeed was approximately 10 minutes. Maximum airspeed through the low-speed section of the wind tunnel was about 90 mph. The progression of flammability and the cooling effects on the tank were monitored and measured throughout the tests.

Throughout testing, fuel load levels were maintained at 80% capacity, and experiments were conducted with the tank at a 0° or 15° angle of attack relative to the air speed direction. Tests in which the heat load was exposed to the bottom surface of the tank were also conducted in a similar manner and with corresponding test conditions to the top surface-heated tests. Comparison of the bottom- and top-heated tests gave an indication of the variance in heat transfer effects on the fuel load and the impact on the ullage flammability between a center wing and outboard wing tank, respectively.

2.2.3 The NASA 747 SCA Flight Tests.

The FAA flight tests performed on the NASA 747 SCA consisted of a series of flights at different cruise and descent times to evaluate a number of inerting system operational methodologies and to observe the progression of flammability in the aircraft CWT both with and without fuel tank inerting. Additionally, wing tank flammability was measured during long ground operations as well as during all phases of flight.

Typically, the aircraft was fueled in the morning, and fuel tank flammability was measured during an extended ground operation. Notes were made of the ambient temperature and the amount of sunlight during the ground operations, and fuel samples were acquired to allow for flash point evaluation. A more complete description of the test procedures is given in reference 4.

3. FLAMMABILITY CALCULATIONS.

The FAR calculator is a tool developed by the FAA that uses fuel flash point and distillation data and basic inputs, such as fuel temperature, pressure, fuel type, and fuel load, to compute the FAR for an isothermal tank (based on fuel temperature). It is a static model that calculates the FAR for a single given point in time using fuel vapor concentration predictions based on fuel component vapor pressure, given ambient pressure and temperature, assuming the fuel is at ambient temperature. A copy of the FAR calculator can be found on the FAA Fire Safety Branch's website at http://www.fire.tc.faa.gov/systems/fueltank/downloads.stm. To compare results from the FAR calculator with the flight test data, temperature and atmospheric pressure data were input into the model at 5-minute increments to obtain independent calculations of FAR.

4. DISCUSSION OF RESULTS.

4.1 SCALE FUEL TANK TEST RESULTS.

The results of the scale fuel tank flammability experiments are given for the following parameters: fuel height, heat intensity, ambient temperature, and flash point.

4.1.1 Effect of Fuel Height.

Two tests with the same top heat intensity were compared to determine the effect of the height of the fuel on the generation of flammable vapors. Figure 4 shows both tests, which had the same starting ambient temperature of 90°F and used the same fuel with identical flash point. Although the fuel load for the 60% test was twice as far from the top of the tank as the 80% full test, both ullage and fuel temperatures progressed nearly identically over time. This resulted in virtually the same progression of ullage flammability during the simulation of a parked aircraft being heated by the sun. The THC started just above 1%, with the isothermal tank at 90°F, and progressed to about 1.6%. This illustrates that the mechanism for flammability growth is the conduction of heat into the ullage from the top surface of the tank. Both tests illustrate nearly identical fuel and ullage temperature progressions, which explains why flammability is nearly the same for both tests.

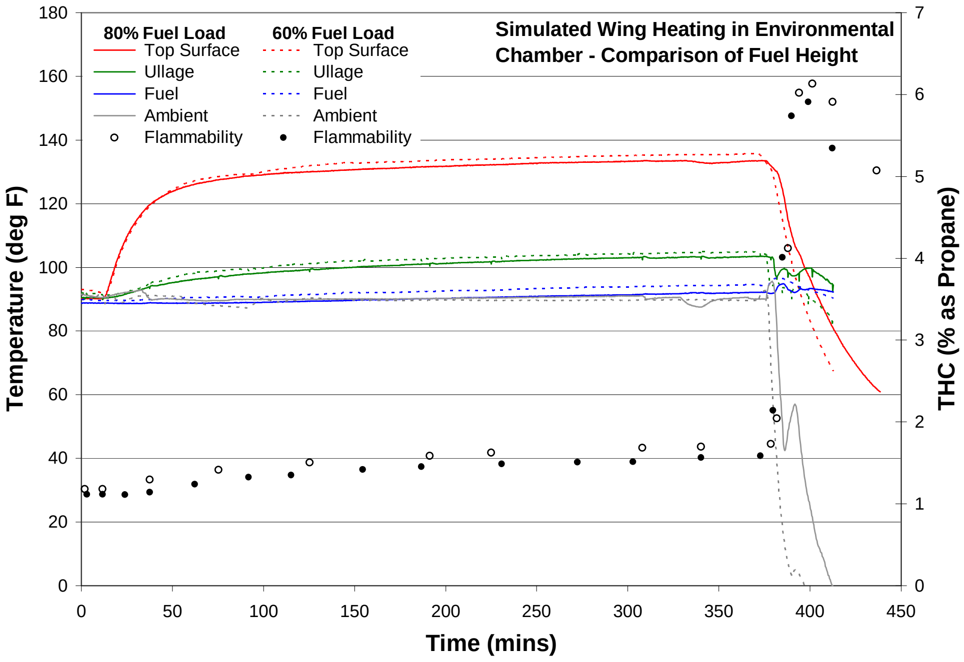


Figure 4. Comparison of Simulated Wing Tank Heating Flammability Tests for Two Different Fuel Load Heights

Both THCs peaked at about 6% when the fuel tank was subjected to reduced ambient pressure equivalent to approximately 35,000 feet pressure altitude. The ambient temperature in the environmental chamber was subjected to maximum cooling during the time of ascent. The drastic decrease in pressure accounts for the large increase in THC. These results do not illustrate the THC expected in an aircraft wing tank, as the test article was not subjected to the flight conditions that a wing fuel tank would be, but rather gives a measure of the potential for flammability to grow after takeoff. It should be noted that the percentage increase in THC for this test (and most others) is comparable to observed increases of center wing flammability during flight testing. This is expected, given that the cooling mechanism for this experiment is conduction of heat from the tank to the cold surrounding air, which is how center wing fuel tanks cool. All tests illustrate the same flammability progression when the pressure and temperature is decreased in the environmental chamber. The THC illustrates a rapid increase, peaks just after the pressure stabilizes, and then begins to decrease as fuel tank temperatures decrease. This same progression of flammability is observed in virtually all available CWT flight test data after takeoff [4].

4.1.2 Effect of Heat Intensity.

The effect of heat intensity on the ullage flammability is illustrated in figure 5, which compares two different tests with different radiant heater settings with the same ambient temperature, fuel load quantity, and fuel flash point. As expected, the greater heat intensity gave higher ullage and fuel temperatures, which resulted in a higher THC. After approximately 5 hours, the increase in THC was twice as great for the test with high top heat. It is not clear how these two top heat intensity tests compare with the amount of heat absorbed by a commercial transport airplane wing in the sun, but wing tank top surface internal temperatures have never been measured in excess of 140°F, although anecdotal information implies they can be much higher.

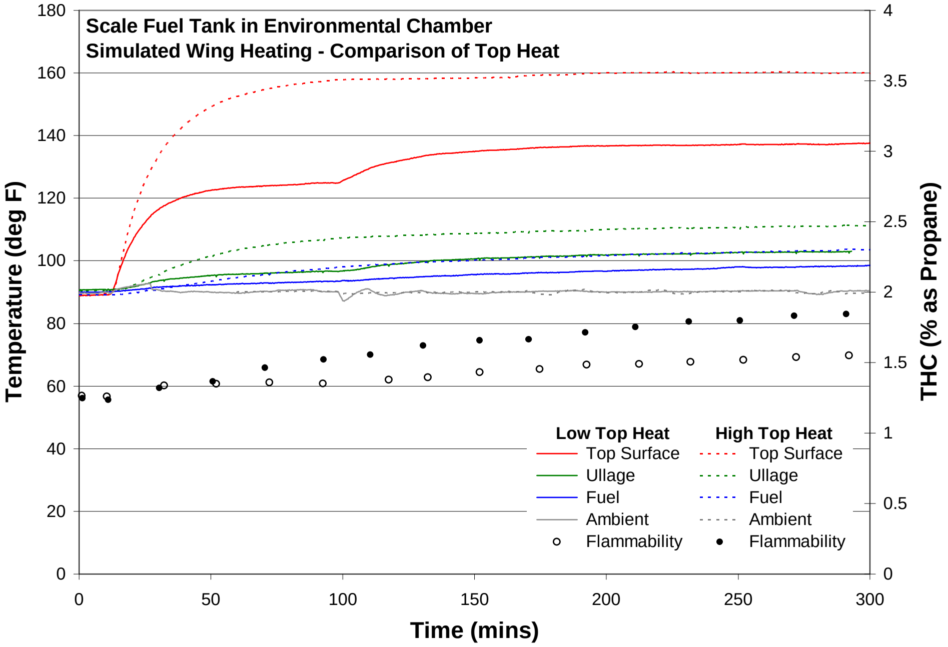


Figure 5. Comparison of Simulated Wing Tank Heating Flammability Tests for Two Different Top Heat Intensities

4.1.3 Effect of Ambient Temperature.

The effect of the ambient temperature on the ullage flammability is illustrated in figure 6, which compares two different tests with different ambient temperatures with the same top radiant heat, fuel load quantity, and fuel flash point. As expected, the higher ambient temperature gave higher ullage and fuel temperatures. For this particular comparison, both cases remained below the lower flammability limit (2% THC as propane) for the entire test, with the THC for the lower ambient temperature being consistently 36-38 percent below the higher ambient temperature test. It is easy to see that a lower fuel flash point, or greater heat intensity for both scenarios, could easily have created flammable conditions for a sustained period of time in the ullage of the higher ambient temperature test, but not the lower ambient test. The effect of the greater ambient temperature on ullage flammability is two fold: a higher ambient temperature allows for a greater THC at the start of test, and the decreased heat rejection of a higher ambient temperature allows for greater ullage and fuel temperatures. Both tests used an average fuel flash point. Thus, ambient temperature surrounding a wing fuel tank has a profound effect on the overall time flammability exposure.

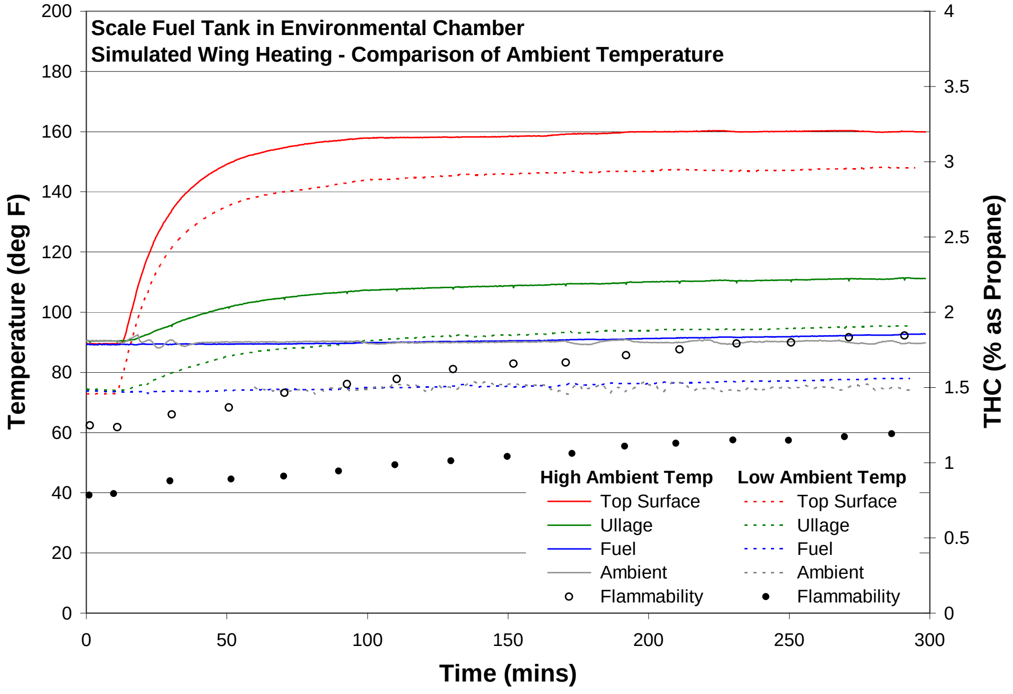
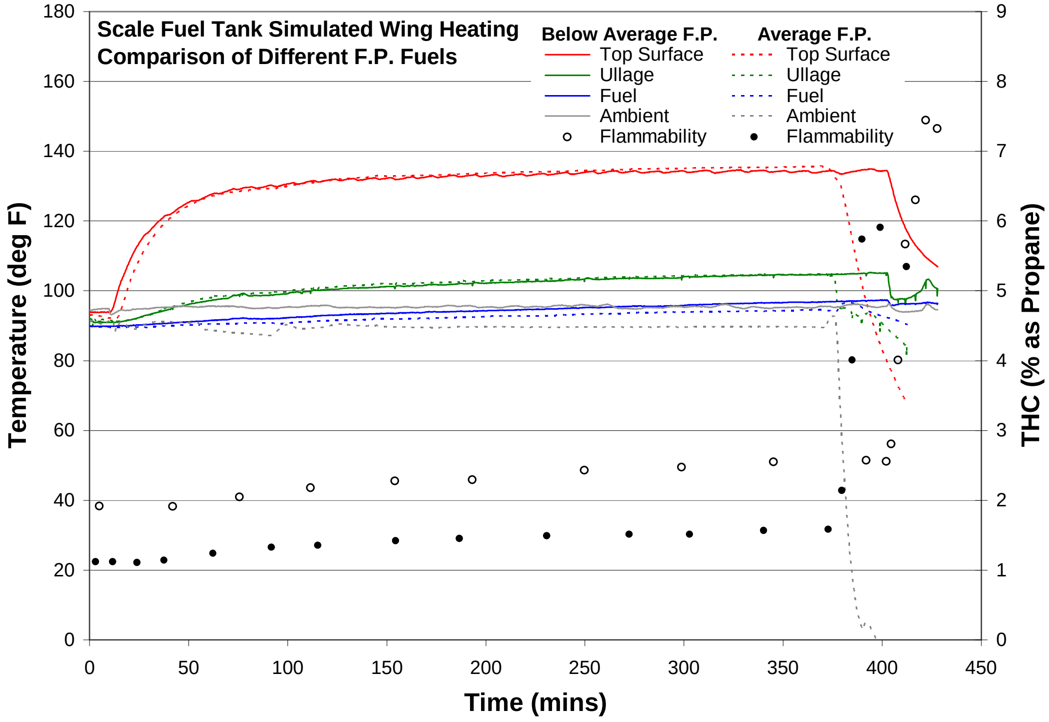


Figure 6. Comparison of Simulated Wing Tank Heating Flammability Tests for Two Different Ambient Temperatures

4.1.4 Effect of Flash Point.

The effect of the fuel flash point on the ullage flammability is illustrated in figure 7, which compares two different tests with different fuel flash points with the same top radiant heat, fuel load quantity, and ambient temperature. As expected, the higher fuel flash point gave higher THCs throughout the entire test at equivalent ullage and fuel temperatures. It is apparent the flash point can have a great effect on the overall time flammability exposure of a wing fuel tank ullage. It remains to be seen to what extent flash point varies in the commercial transport fleet fuel supply, and if the 125°F fuel flash point stated is truly average.



F.P. = Flash point

Figure 7. Comparison of Simulated Wing Tank Heating Flammability Tests for Two Different Fuel Load Flash Points

4.2 WING FUEL TANK TEST RESULTS.

The results of the wing fuel tank flammability experiments are given in three different areas. Results are shown for the effect of varying the type of heating by heating the tank from the top or bottom surface (i.e., heating the ullage versus heating the fuel), the effect of the wing's angle of attack relative to the wind direction, and the effect of cross-venting of the tank. The two vertical red lines in each graph depicting these results indicate the times when airflow through the wind tunnel was initiated and when the airflow reached full airspeed. The approximate time duration between these two events in all of the tests is 10 minutes. Hydrocarbon concentration readings were taken just prior to the start of airflow through the wind tunnel, just after the wind tunnel reached maximum velocity, and at approximate 5-minute intervals after that.

4.2.1 Effect of Heating Type.

The effect of the two different types of heating are shown in figures 8 and 9, which display the results for two different tests conducted under similar conditions. The main difference in these tests is that figure 8 shows the tank heated from the top (hot-ullage test), and figure 9 shows the tank heated from the bottom (hot-fuel test). Additionally, there was a slight difference in the ambient temperature of each test. The recorded ambient temperature for the hot-ullage test was 55°F and for the hot-fuel test was 62°F. The maximum THC measured in both tests was approximately 2.9%, occurring in both just prior to initiation of the wind tunnel. The THC where the tunnel reached maximum velocity was 2.7% and 2.5% THC in the hot-ullage and hot-fuel tests, respectively. From this point on, the THC decayed in a very similar fashion in each test, reaching a concentration of 1.25% approximately 30 minutes after full speed was reached in both tests.

The major difference between the two tests was the method by which the ullage, surface, and fuel temperatures decay. In the hot-ullage test, the ullage and top surface temperatures decayed quite rapidly, while the bulk fuel temperature only changed by approximately 20°F throughout the test. The dynamics of the hot-fuel test, as expected, are quite different. Here, the fuel starts at a much higher temperature and, therefore, decays in a similar manner as both the ullage and top surface temperatures. It appears that the rapid decrease in ullage temperature is the driving effect on tank flammability. The temperature change observed caused a significant amount of condensation within the ullage, which reduced the vapor concentration. As the effects of condensation start to dominate, the fuel temperature plays a very small role in the change in flammability.

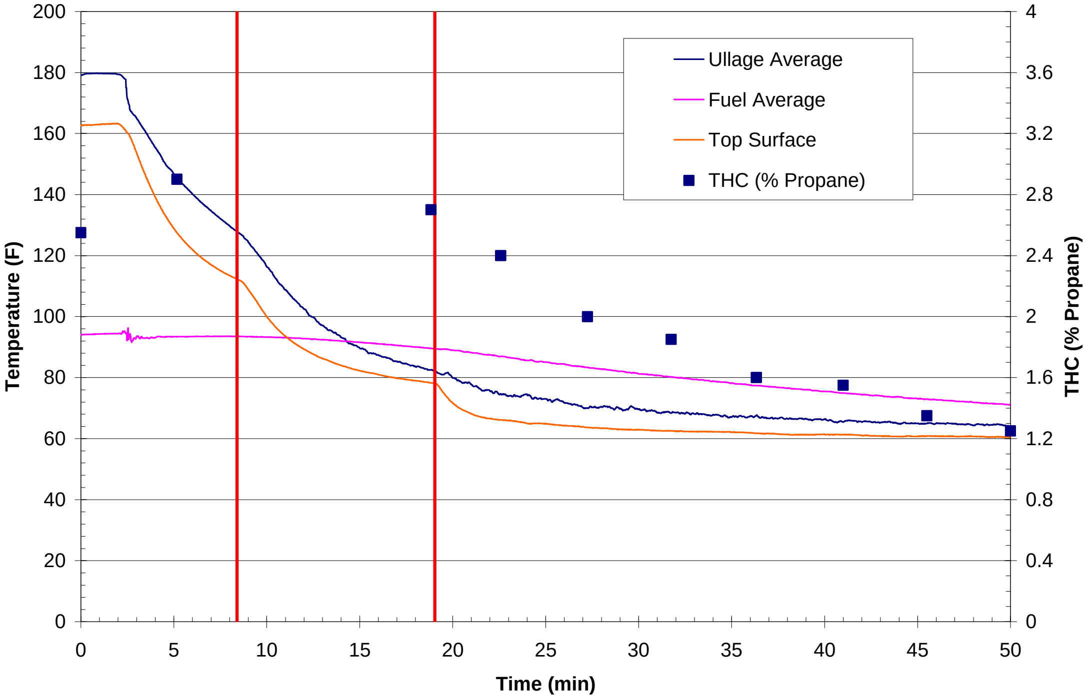


Figure 8. Results of the Hot-Ullage Wind Tunnel Wing Tank Test

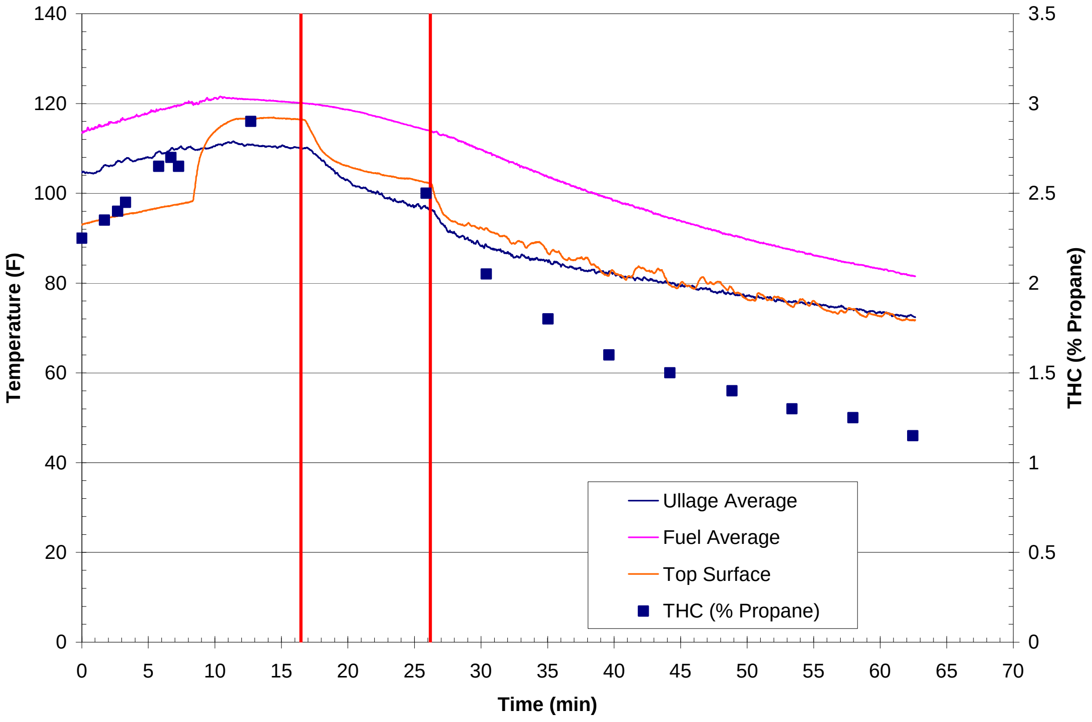


Figure 9. Results of the Hot-Fuel Wind Tunnel Wing Tank Test

4.2.2 Effect of Angle of Attack.

Tests were conducted with the wing at a 0° and 15° angle of attack relative to the air stream in the wind tunnel to determine if there was any effect of the wing's angle of attack on the change in flammability while in flight. The results of two of these tests are shown in figures 10 and 11, both of which were hot-fuel tests (i.e., heated from the bottom).

Figure 10 shows the temperature and THC measurements taken from the test with the wing at a 0° angle of attack. Figure 11 shows the measurements for the test in which the wing was pitched at a 15° angle of attack. The THC reading prior to the start-up of the wind tunnel in each test was 3.4% and 3.9%, and the ambient temperature at the time of each test was 64° and 51°F, respectively. When the wind tunnel reached maximum velocity, the THC in the 0° test was approximately 2.8%, while in the 15° test, it dropped to approximately 3.3%. From this point on, the THC decayed in a very similar fashion in each of the tests, reaching a concentration of approximately 1.5% to 1.6% about 30 minutes after full speed was reached in both tests. Temperature changes in each test also follow a very similar trend. Thus, the angle of attack where the fuel tank is placed relative to the direction of the airspeed appears to have little to no effect on the cooling of—and condensation of—the fuel vapor within the tank.

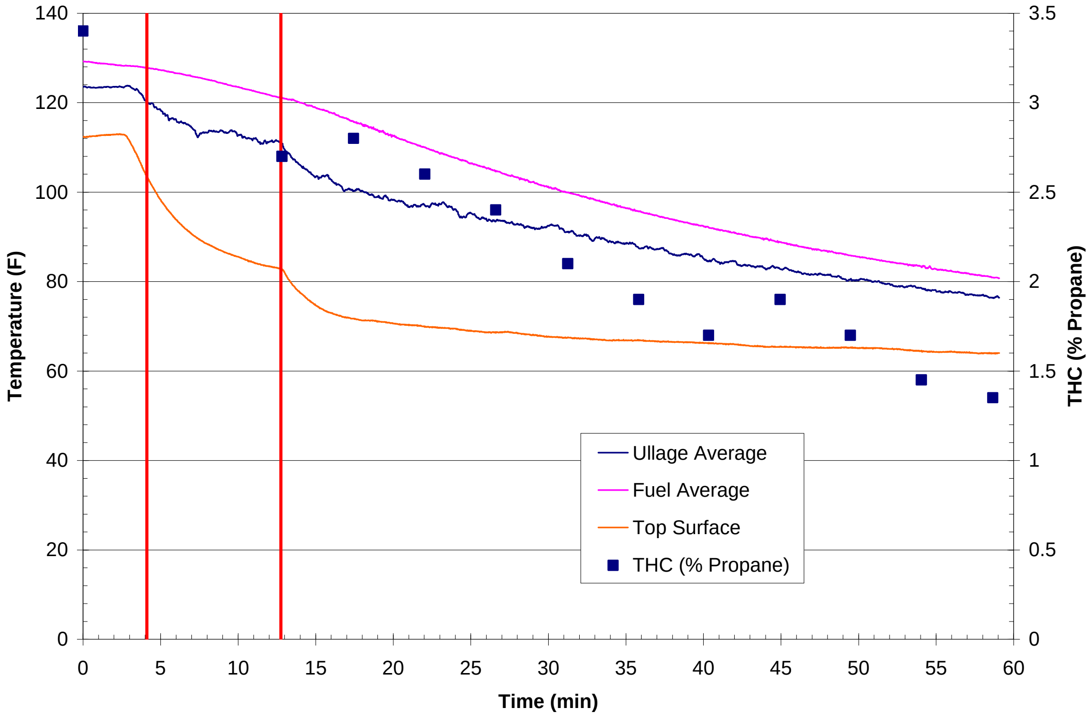


Figure 10. Results of the Hot-Fuel Wind Tunnel Wing Tank Test at 0° Angle of Attack

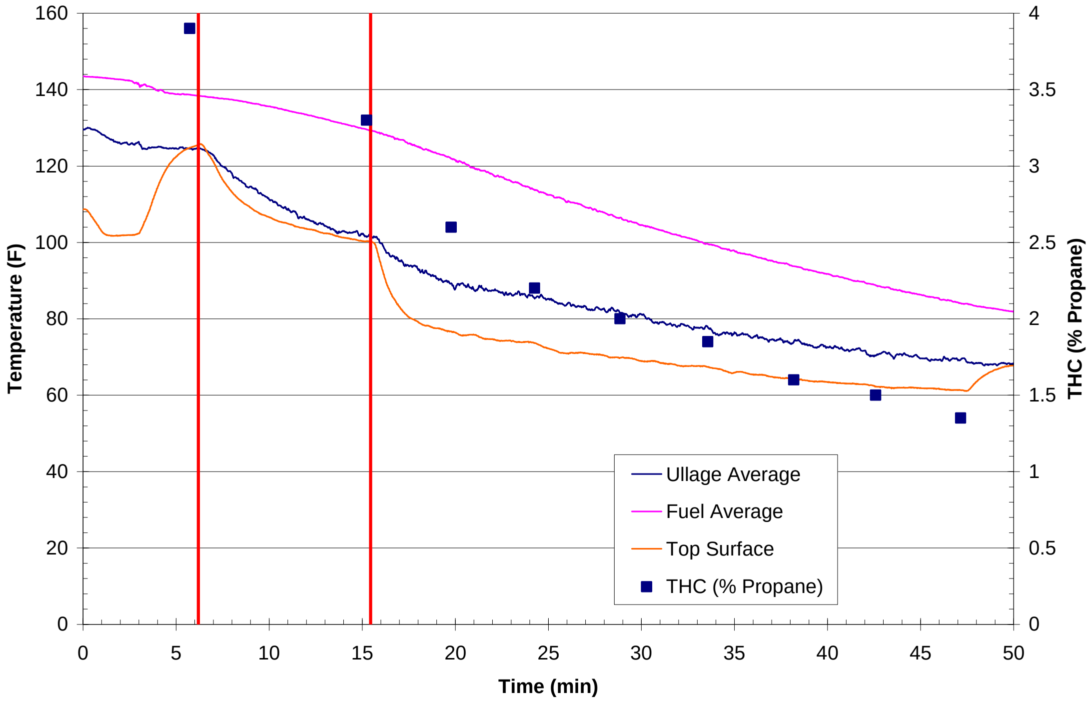


Figure 11. Results of the Hot-Fuel Wind Tunnel Wing Tank Test at 15° Angle of Attack

4.2.3 Effect of Cross-Venting.

A test was performed in which the tank vent was left open and routed externally to the wind tunnel in an effort to examine the effect air flowing through the tank vents would have on flammability. With the wind tunnel in operation, this configuration created a cross-venting effect across the fuel tank ullage. The results of this test, which was a hot-ullage test conducted with an ambient temperature of 50°F, is shown in figure 12. Comparing these results to those shown previously, it is evident that cross-venting of the tank causes a significantly more rapid decrease in THC. The maximum THC measured in this test was 3.1%. In the 10 minutes that it took the wind tunnel to reach maximum velocity, this concentration dropped to 2.1%, and from this point, it took another 15 minutes for the concentration to reach 1.25%. This decrease in THC is much greater than the results that were shown in figures 8 through 11.

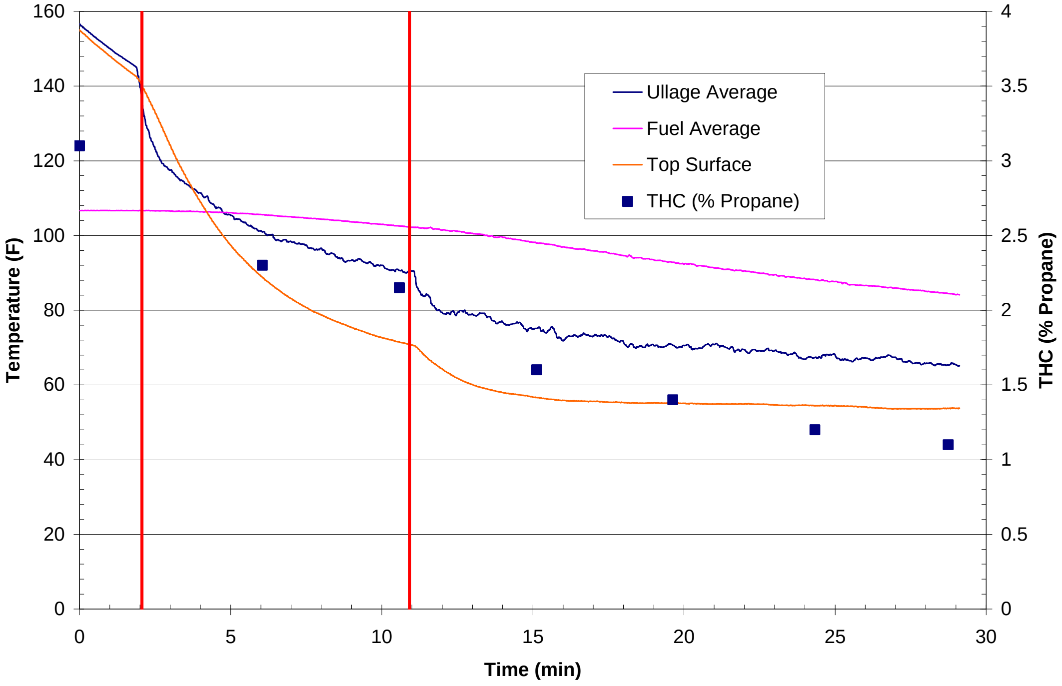


Figure 12. Results for a Hot-Ullage Test With Cross-Venting of the Tank

4.3 FLIGHT TEST DATA MODEL COMPARISONS.

Wing tank data from flight tests conducted on the NASA 747 SCA were analyzed and compared to results given by the FAA FAR calculator to model wing tank flammability. Figure 13 shows a comparison of the model results with the NASA 747 SCA flight test data for the first hour of flight using fuel temperature as the input. It is observed that this method provides reasonable results for the duration that the aircraft is on the ground. In flight, however, because condensation plays such a large role, calculations show this approach to be inadequate. Figure 14 shows the same comparison for that flight while using the ullage temperature as an input into the model. Here, it is observed that, while there is a large error during ground time, the ullage temperature input provides significantly better results when in flight. During flight, the ullage temperature changes rapidly due to changes in ambient temperature. This temperature change results in a large amount of condensation. This condensation is the main driver of flammability changes while in flight.

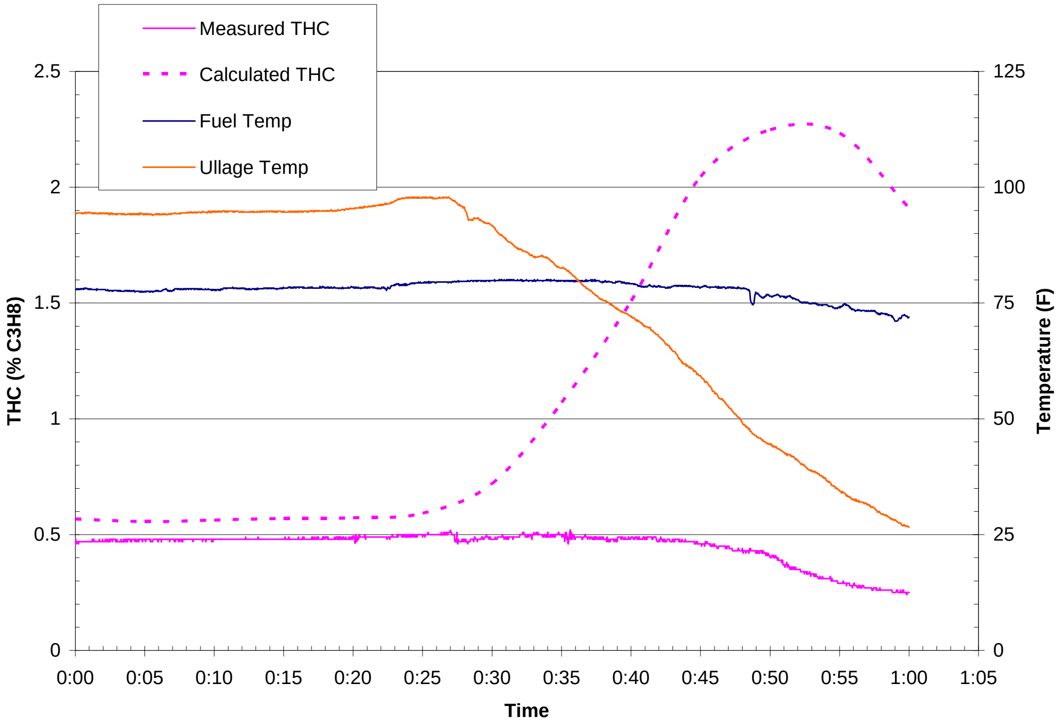


Figure 13. Comparison of Measured and Calculated Wing Tank Flammability for the First Hour of Flight Using Fuel Temperature Inputs

Based on the results of these two computations and the knowledge gained from the various tests performed in the altitude chamber and air induction facility, two assumptions can be made:

- On the ground, the fuel temperature drives flammability and causes evaporation of the liquid fuel with no condensation effects.

- In flight, fuel temperature changes slowly due to its large mass, but ullage temperature changes quickly. This rapid temperature change, along with the ambient pressure, is what drives flammability while in flight.

If these assumptions are made, then the inputs to the FAR are fuel temperature and ambient pressure while on the ground. In flight, the fuel temperature is modified by the equivalent change in ullage temperature at each time step, and this is used as the temperature input.

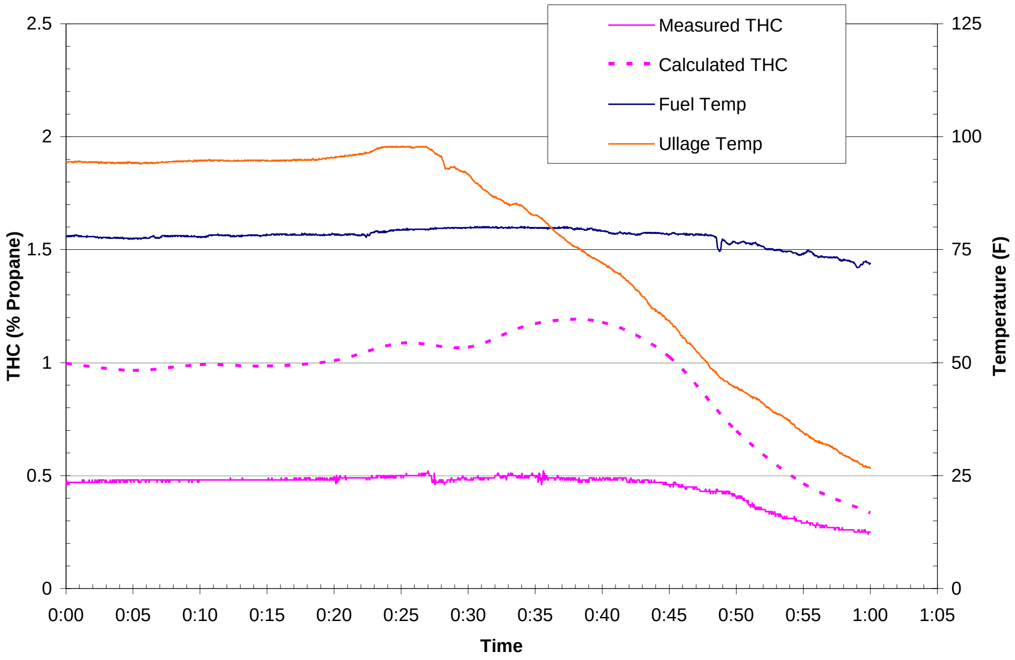


Figure 14. Comparison of Measured and Calculated Wing Tank Flammability for the First Hour of Flight Using Ullage Temperature Inputs

Figures 15 through 19 show the results of using this input temperature algorithm in the FAR calculator for comparison with data from five different flight tests. Each figure depicts the THC and fuel and ullage temperatures. In addition, the modified temperature, which was used as an input into the model and the computed THC, is shown.

While the absolute error at certain points within these graphs may be somewhat high, the tendency of the fuel vapor concentration to track the change in ullage temperature is evident. This is another indication that the ullage temperature is what drives wing fuel tank flammability when in flight, rather than the bulk fuel temperature. Further modification of the input temperature algorithm could provide a further improvement of the ability to predict wing tank flammability.

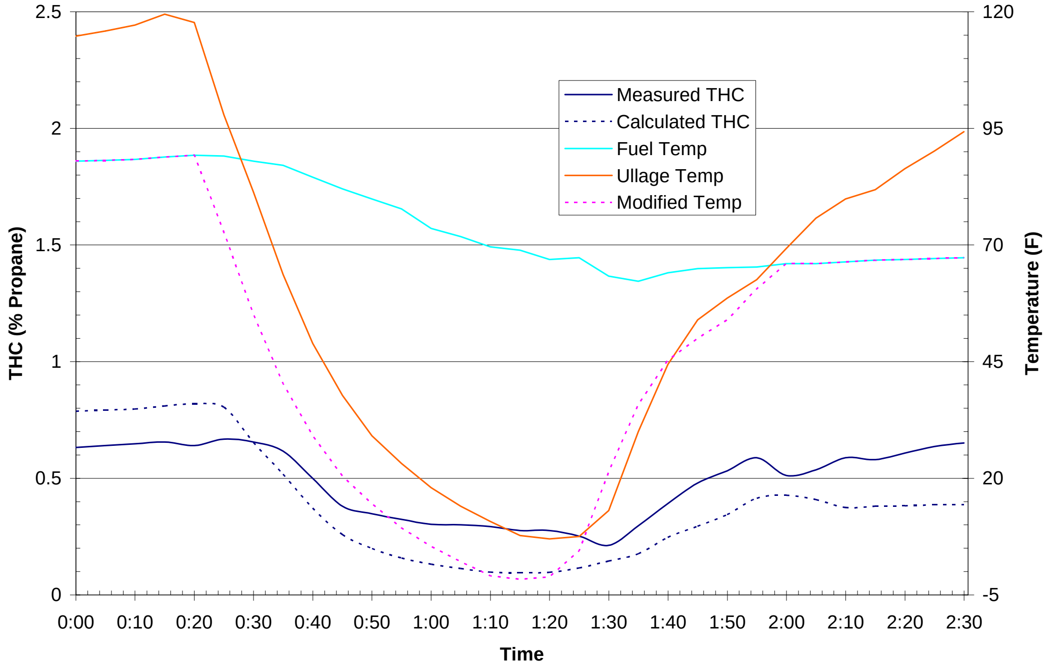


Figure 15. Comparison of Measured and Calculated Wing Tank Flammability for Flight Test 1

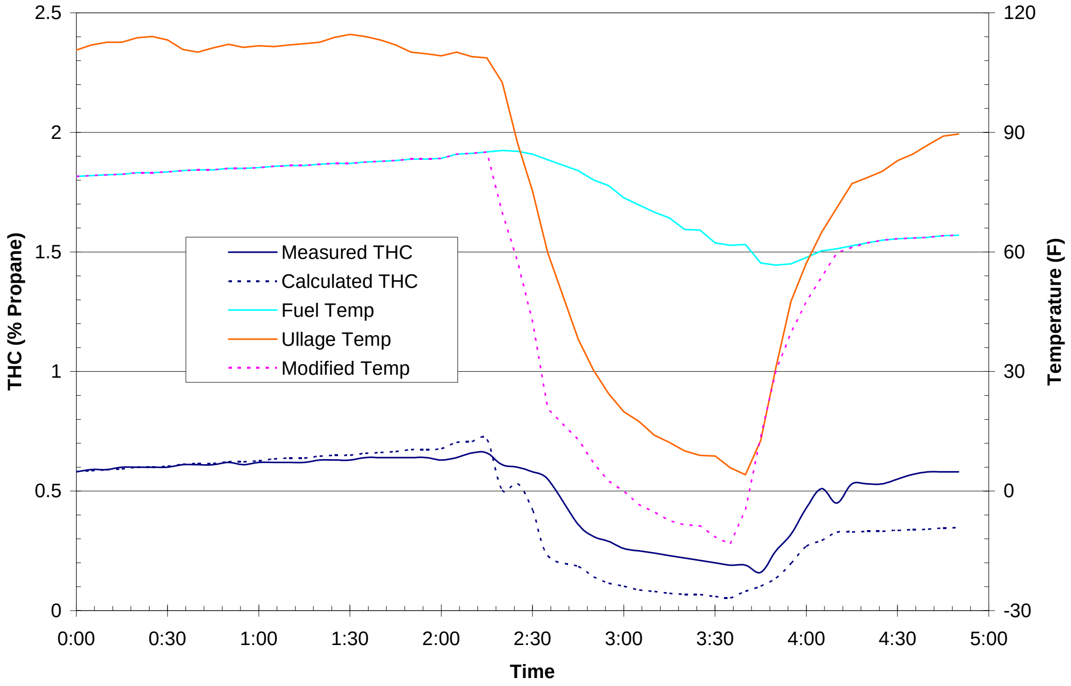


Figure 16. Comparison of Measured and Calculated Wing Tank Flammability for Flight Test 2

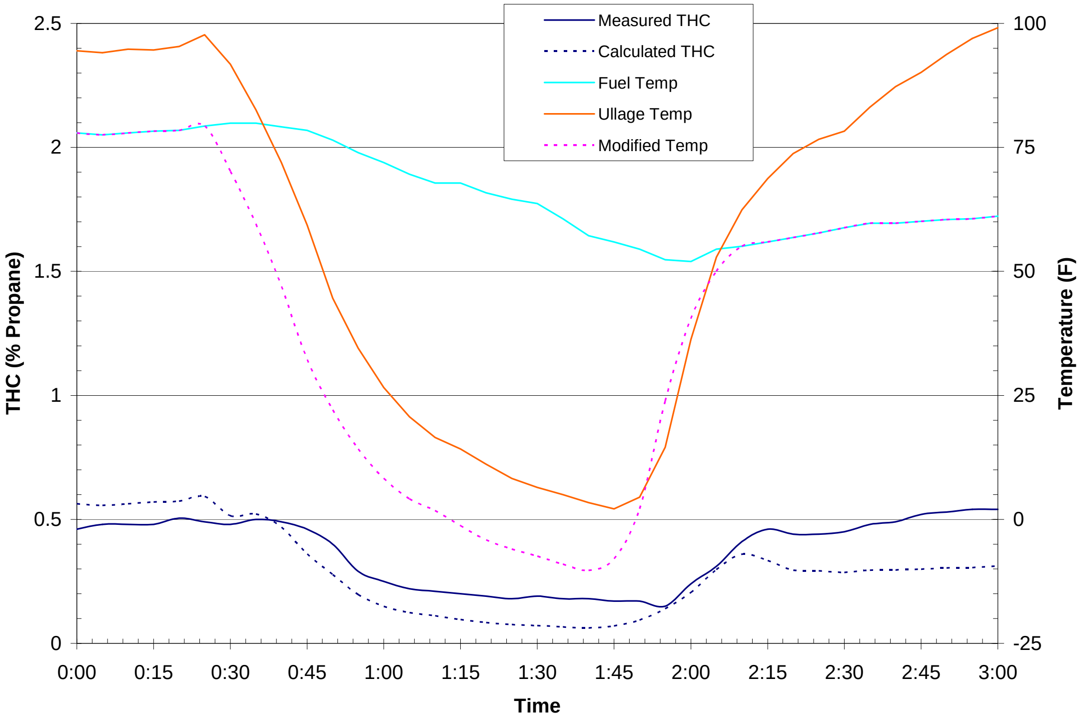


Figure 17. Comparison of Measured and Calculated Wing Tank Flammability for Flight Test 3

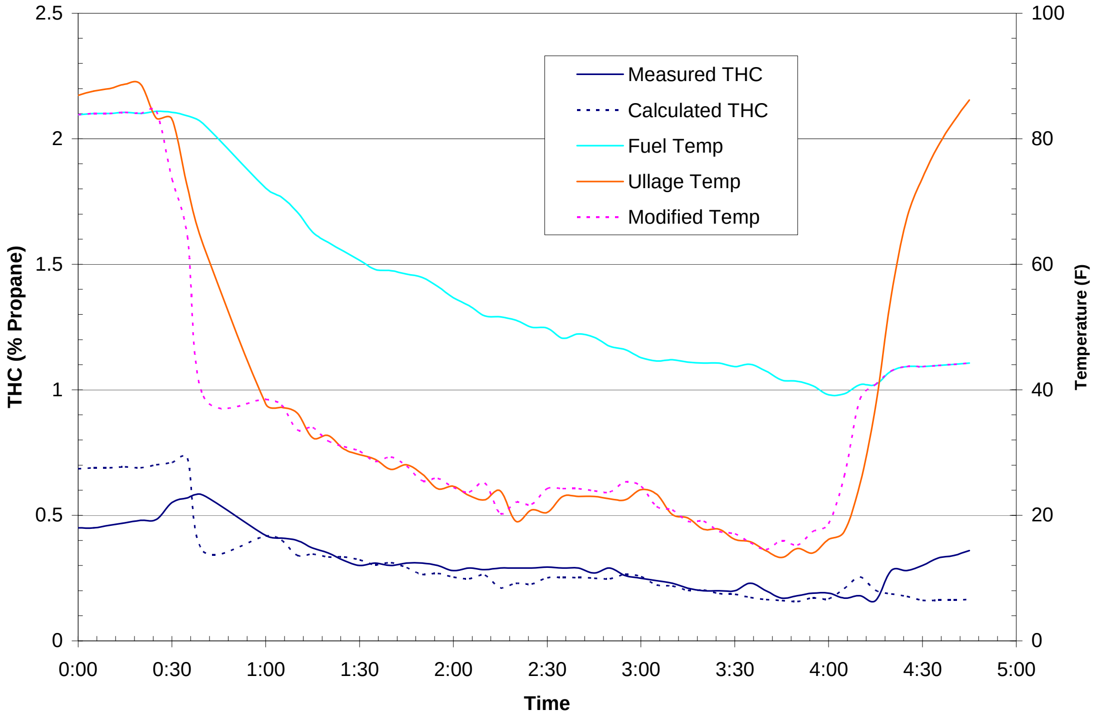


Figure 18. Comparison of Measured and Calculated Wing Tank Flammability for Flight Test 4

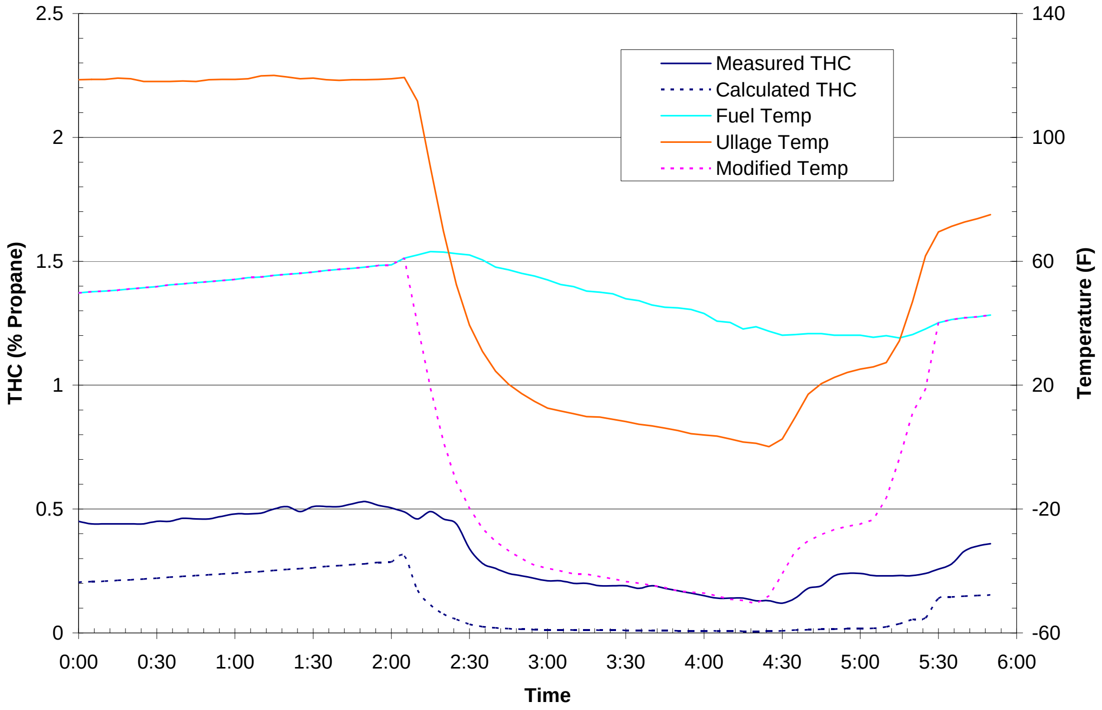


Figure 19. Comparison of Measured and Calculated Wing Tank Flammability for Flight Test 5

5. SUMMARY OF RESULTS.

Tests were performed at the William J. Hughes Technical Center by the Fire Safety Branch of the Airport and Aircraft Safety Research and Development Division in an environmental chamber as well as an air induction facility (wind tunnel) to examine individual effects that contribute to commercial transport wing fuel tank flammability. Additionally, previously acquired wing tank flammability measurements made during flight testing were compared with results from the FAA FAR Calculator in an effort to see if the calculations agreed with existing flight test data.

The results of the scale fuel tank testing in the environmental chamber illustrated that fuel height in the tank had little or no effect on the flammability progression during simulated ground heating tests. Increasing the amount of top surface heating doubled the measured THC. Reducing ambient temperature not only decreased the absolute flammability of an ullage, but also limited the ability of the ullage flammability to grow due to increased heat rejection of the fuel tank. Flammability for these tests decreased on average 37 percent during the length of the test going from a hot day to a warm day. Decreasing flash point has the ability to increase flammability greatly, but more work is needed to evaluate different fuel flash points under similar conditions.

Wind tunnel tests conducted with a section of a 727 wing tank showed that the difference in a top-heated tank versus a bottom-heated tank was not in how the ullage THC decreased under dynamic airflow conditions, but rather the mechanism by which the decrease occurs. In the top-heated test, a rapid decrease in ullage and surface temperatures was observed, while the fuel temperature changed slowly due to the large mass of liquid fuel. In the bottom-heated test,

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however, the fuel temperature was shown to have decayed in a similar manner as the ullage and surface temperatures. As the THC reacted the same in each test, this shows that the rapid decrease in ullage temperature is the driving force for the reduction of tank flammability while in flight due to increased condensation within the tank ullage. Additional tests in the wind tunnel showed that the angle of attack of the fuel tank relative to wind direction played little role in reducing fuel tank flammability, but when the fuel was subjected to a cross-venting condition, THC decreased more rapidly.

Using the FAA FAR calculator to predict ullage THCs in a series of flight tests that had been conducted by the FAA on the NASA 747 SCA showed that an input temperature algorithm could be used with the model to provide significantly improved flammability predictions in an aircraft wing tank. The algorithm reduces the input fuel temperature by the change in ullage temperature at each time step. Further modification of the input temperature algorithm, along with additional test data, could provide further improvement in the models ability to predict wing tank flammability.

6. REFERENCES.

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