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Aviation Research Division
Atlantic City International Airport
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The Effects of Topcoat Color and Material Thickness on the Flammability Characteristics of Composite and Aluminum Wing Fuel Tanks

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16. Abstract

The Airport and Aircraft Safety Research and Development Group Fire Safety Team performed tests at the FAA William J. Hughes Technical Center to examine the variation in flammability exposure of fuel tanks comprised of a composite material skin and a traditional aluminum skin. The variation in topcoat color of the aluminum material was analyzed, as was the variation in thickness of the composite material.

Tests examining the effects of topcoat color of the aluminum fuel tank were consistent. These tests showed that while the bare composite material transmits radiant heat into the fuel tank much more readily than the bare aluminum material, once aviation grade primer and a topcoat (regardless of color) are applied, the aluminum skin behaves in a similar manner to the composite. The application of both white and black topcoat colors to the aluminum panels resulted in the aluminum tank temperatures and total hydrocarbon concentration (THC) measurements being consistent with the composite tank test results, which is evidence that a difference in material properties is not what leads to differences in temperatures and THC measurements. Instead, it was thought that the reflective behavior of the bare aluminum material, causing much of the radiant heat to be reflected off the tank, resulted in lower fuel tank temperatures and, therefore, lower THC measurements. However, additional testing with the composite material, with a reflective aluminum epoxy applied to it, did not exhibit the anticipated impact to the internal tank temperatures and flammability measurements. As a result, the testing conducted was inconclusive as to the cause of the fuel tank behavior.
Panel heat tests with the composite materials of varying thicknesses showed a correlation between panel thickness and temperature on the bottom surface of the panel. However, tests showed that when these panels are installed on a fuel tank, the difference in thickness provides little variance in resulting tank temperatures and THC measurements. These tests, however, did once again confirm the strong correlation between ullage temperature and THC within a fuel tank when heated from above.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF ACRONYMS

BMS	Boeing Materials Specification
CWT	Center wing tank
THC	Total hydrocarbon concentration

EXECUTIVE SUMMARY

In response to potential fuel tank safety issues highlighted by the Trans World Airlines Flight 800 accident in 1996, the FAA has conducted a significant amount of research on the flammability of traditional aluminum fuel tanks. This research, along with the development and demonstration of a fuel tank inerting system, has led to regulations requiring the reduction of flammability within high-risk fuel tanks. Fuel tanks located in the wing of an aircraft are traditionally considered to be of low flammability because of the absence of external heat sources and the rapid cooling that occurs in flight because of the high thermal conductivity of the aluminum skin of the aircraft. However, there have been recent advances in composite materials, and these advanced materials are increasingly being used in the construction of aircraft. Research was conducted to determine how the lower thermal conductivity of composite materials could impact fuel tank flammability. The research included investigation of how the topcoat finish color of these materials and their aluminum counterparts may affect heat transfer into the fuel tank, and therefore the resulting flammability of the tank. In addition, the impact of variations in the thickness of a composite wing tank skin thickness on heat transfer into the fuel tank was investigated.

The Fire Safety Branch performed tests at the FAA William J. Hughes Technical Center to examine the variation in flammability exposure of fuel tanks comprised of a composite material skin and a traditional aluminum skin. The variation in topcoat color of the aluminum material and the thickness of the composite material were analyzed.

Tests aimed at examining the effects of topcoat color of the aluminum fuel tank were all extremely consistent. The panel heat tests under static conditions, air induction facility tests, and tests comparing two identical 727 wing tanks all showed that although the bare composite material transmits radiant heat into the fuel tank much more readily than the bare aluminum material, the aluminum skin behaves in a similar manner to the composite once aviation grade primer and a topcoat, regardless of color, is applied. Throughout the air induction facility tests, large increases in both ullage temperature and total hydrocarbon concentration (THC) measurements were observed for both sets of material, whereas there were only slight increases in the average fuel temperatures. In addition, once airspeed through the wind tunnel was initiated, significant and almost immediate decreases in ullage temperature and hydrocarbon concentration were observed. This is consistent with previous findings showing that for a wing tank heated from above, ullage temperature changes are the driving force behind in-flight flammability. In comparison, a center wing tank heated from below has the bulk average fuel temperature as the main driving force.

The application of white topcoat to the aluminum panels in these tests and black topcoat in previous tests both resulted in the aluminum tank temperatures and THC measurements being consistent with the composite tank test results. These results were initially regarded as evidence that it was not a difference in material properties that led to increased temperatures and THC measurements in the composite panel tests. Instead, it was thought that the reflective behavior of the bare aluminum material, causing much of the radiant heat to be reflected off the tank, resulted in lower fuel tank temperatures and, therefore, lower THC measurements. However, additional testing with the composite material, with a reflective aluminum epoxy applied to it, did not exhibit the anticipated impact to the internal tank temperatures and flammability measurements. As a result, the testing conducted was inconclusive as to the cause of the fuel tank behavior.

Panel heat tests under static conditions with composite panels of 1/4″, 1/2″, and 3/4″ thickness showed that thinner composite material transmits heat more readily. Similarly, the thinner the panel, the faster it cools toward ambient during the cool-down period of each of the panels. Based on these results, it was expected, with the various thickness panels installed on the fuel tank, that the thinner panels would lead to higher internal tank temperatures, and higher THC measurements. However, once installed on the tank, there was more variation in the test results. In some of the tests, the tank temperatures and THC measurements were similar, regardless of the skin thickness. Moreover, the 3/4″ thick panel actually resulted in the highest average ullage temperatures and the highest THC measurements of the three panels.

In summary, while under static conditions consistent with airplane ground operations, a correlation between composite panel thickness and temperature was shown. However, when these fuel tank panels were tested in a wind tunnel simulating in flight conditions with airflow around the tank, the difference in thickness provides little if any variation in resulting tank temperatures and THC measurements. These tests however, re-confirmed the strong correlation between ullage temperature and THC within a fuel tank when heated from above, simulating sun exposure during airplane ground operations.

1. INTRODUCTION

1.1 BACKGROUND

In response to potential fuel tank safety issues highlighted by the Trans World Airlines Flight 800 accident in 1996, the FAA has conducted a significant amount of research on the flammability of traditional aluminum fuel tanks. This research, along with the development and demonstration of a fuel tank inerting system, has led to regulations requiring the reduction of flammability within high-risk fuel tanks. Fuel tanks located in the wing of an aircraft are traditionally considered to be of low flammability because of the absence of external heat sources and the rapid cooling that occurs in flight due to the high conductivity of the aluminum skin of the aircraft. However, composite materials are increasingly being used in the construction of aircraft. Research is required regarding how the topcoat finish color of these materials and their aluminum counterparts may affect heat transfer into the fuel tank and the resulting flammability of the tank. In addition, as the thickness of a composite wing varies throughout the structure, information is also needed on how this variation in thickness may affect heat transfer into the fuel tank.

1.2 PREVIOUS RESEARCH

Previous FAA fuel tank flammability experiments included studies of condensation, due to cold ambient temperatures, on fuel tank ullage vapor concentrations [1] and mass loading effects on ullage fuel vapor concentrations [2]. Flammability of a Boeing 747 center wing tank (CWT) was studied during flight tests with the FAA inerting system on the NASA-operated 747 Shuttle Carrier Aircraft [3]. This project had extensive instrumentation to monitor temperatures, pressure, and total hydrocarbon concentration (THC) in the center and inboard wing fuel tanks and oxygen concentration variations in the inerted CWT.

Studies have also been conducted to examine the effects of pressure and temperature variation (as observed in flight) on a traditional aluminum wing fuel tank [4]. These tests showed that the flammability drivers of a wing fuel tank vary greatly from a CWT. For a CWT located within the fuselage section of the aircraft, flammability is driven by the bulk average fuel temperature. Fuel is evaporated as fuel temperature is increased because of heating from ductwork or systems located under the fuel tank, As the aircraft takes off, decreased pressure causes further fuel evaporation. At the same time, some condensation takes place because of cooling from decreased ambient temperatures.

The heating in a wing fuel tank does not take place from beneath the fuel tank but from radiant heating of the top skin and ullage by the sun. The hot ullage heats the top layer of fuel within the fuel tank, causing fuel evaporation. The bulk average fuel temperature, however, remains relatively low. As the aircraft takes off, cooling and condensation from changes in the outside environment are much more significant, as the entire fuel tank surface is subjected to cold air at a high speed.

Recent testing [5] has examined the variation in flammability exposure of a fuel tank comprised of composite material skin versus a traditional aluminum skin. Tests conducted with the bare, uncoated materials used as the top and bottom skin surfaces of a fuel tank showed that the composite fuel tank had the potential to result in a significant increase in flammability exposure. This was because the composite material transmits radiant solar heat into the fuel tank much more readily than the aluminum skin. Further testing showed that the topcoat color of the composite skin had little effect on the resulting fuel tank temperatures and flammability levels. However, bare aluminum reflected much of the radiant solar heat, resulting in a smaller increase in fuel tank temperature than a comparable composite fuel tank. When the aluminum skin was coated with an aviation grade primer and black-colored paint, a drastic increase in tank temperatures and flammability levels was recorded. Thus, under the right conditions, it was observed that a traditional aluminum fuel tank could behave similar to a composite fuel tank in terms of temperature and flammability profiles during ground staging conditions with solar heating present.

1.3 SCOPE

Tests were performed at the FAA William J. Hughes Technical Center to examine the variation in flammability exposure of fuel tanks comprised of composite material skin and a traditional aluminum skin. The effect of the variation in topcoat color of the aluminum material was analyzed, as was the variation in thickness of the composite material.

2. TEST EQUIPMENT

2.1 FUEL TANK TEST ARTICLE

The fuel tank test article used in these experiments measured 3' x 3' square with a depth of 1', with aerodynamic leading and trailing edges. It was instrumented with 12 K-type thermocouples and a sample port for THC measurement. Thermocouples were placed in the liquid fuel and vapor space at depths of 2″, 4″, 6″, and 8″. Two thermocouples were also placed in the ullage toward the top of the fuel tank to ensure that ullage measurements were captured during high fuel load cases. Surface thermocouples were placed at the center of each of the six sides of the fuel tank.

A THC analyzer, a fully automated flame ionization detector analyzer that uses an internal pump to sample the fuel tank ullage, was used to measure the flammability levels of the ullage space during the tests. The THC analyzer was used with a boost pump to acquire accurate data at reduced pressures. All sample lines leading from the fuel tank to the analyzer inlet were heated to a minimum of 200°F to eliminate any effects of fuel vapor condensation along the sample line. The ullage was not sampled continuously because continued sampling has a drastic effect on test results by consistently drafting ullage gas out of the fuel tank head space and replacing it with air. The THC analyzer was calibrated with a propane (C_3H_8) mixture calibration gas, allowing it to give THC results as a propane equivalent.

A set of three radiant panel heaters was situated approximately 12″ from the top of the fuel tank for the heating portion of the test. Each of these heaters had two heating elements of 750 watts each, and when run on the low-heat setting, only one of the heater elements would operate. Thus, each heater had an output capacity of 750 watts on the low-heat setting and 1500 watts on the high-heat setting. These values are on the order of the energy density of solar radiation observed at the earth's surface, which is approximately 1.4 kW/m2 [6].

The fuel tank was constructed so that the top and bottom surfaces of the aluminum and composite panels could be interchanged. The remainder of the fuel tank was insulated to minimize any thermal effects from other sources. Aerodynamic nose and tailpieces were constructed and attached to the fuel tank for the wind-tunnel tests. For the initial tests aimed at evaluating the effect of topcoat color, 1/4″ thick aluminum panels and 3/8″ thick composite panels were used in an attempt to be consistent with typical aircraft wing structures.

The composite panels used to evaluate the effect of topcoat color were fabricated by Integrated Technologies, Inc. from material supplied by Toray Composites (America) that was qualified to Boeing Materials Specification (BMS) 8-276. The composite panels were fabricated by stacking the BMS 8-276 pre-preg tape in a repeating orientation sequence of -45, 0, 45, and 90 degrees with respect to the reference direction and symmetric with respect to the mid-plane of the panel to provide a final composite having uniform strength and stiffness in the fiber plane after curing. In the present panels, the (-45, 0, 45, 90) sequence was repeated 12 times for a total of 48 layers, resulting in a total thickness of 0.36″. Thermal, combustion, and flammability properties of this composite material have been reported [7].

The BMS 8-276 material was not attainable for subsequent tests; therefore, for the tests aimed at evaluating the effects of material thickness and for the 727 wing tank test article, a similar aerospace grade resin system (i.e., HexPly 8552) supplied by Hexcel Corporation was used. This material was laid up by S.A. Robotics in a similar fashion to the BMS 8-276 pre-preg tape to provide test panels of 1/4″, 1/2″, and 3/4″ for the top and bottom surfaces of the fuel tank.

2.2 AIR INDUCTION FACILITY

The air induction facility is an induction-type, non-return wind tunnel with a 5′ diameter, high-speed test section and a 9.5′ 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 non-return design of the wind tunnel allows for flammable fuel tank tests in either test section without potentially flammable vapors building up in the wind tunnel. The tests for this research used the high-speed section.

A typical pressure profile from one of the fuel tank tests within the air induction facility is shown in figure 1. As the engines are started and run at the idle position, a pressure drop within the fuel tank of approximately 0.36 psi (approximate equivalent altitude of 625') is observed. When running at this initial throttle position, air speeds passing through the wind tunnel were recorded at approximately 0.14 mach. As the engines were taken to 90% of full throttle, a further pressure drop of 3.2 psi (approximate equivalent altitude of 6650') was observed. Running at this throttle position, with the fuel tank installed in the test section, produced air speeds of approximately 0.4 mach.

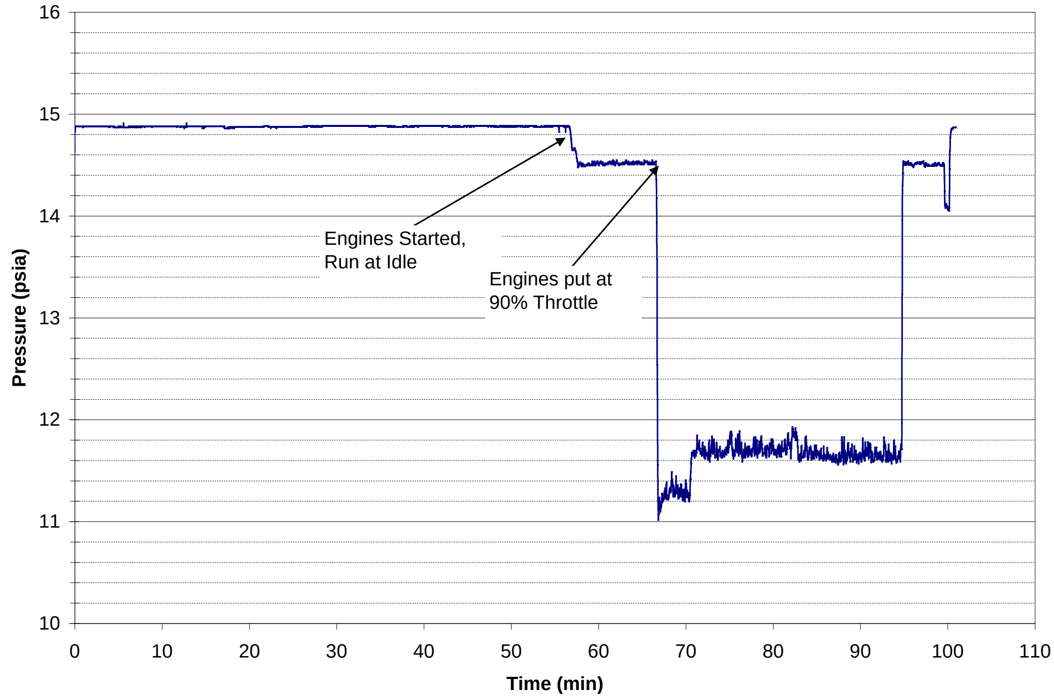

Figure 1. Typical pressure profile of fuel tank during wind tunnel operations

<u>2.3 727 WING TANK TEST ARTICLES</u>

The 727 wing tank test articles were made from the surge tanks of the FAA Fire Safety Branch's Boeing 727 ground test article by removing the last 8' of each wing. These test articles are shown in figure 2. Each surge tank, under the resulting configuration, has a capacity of approximately 36.5 gallons. Each contains two vent ducts, which were sealed to create a single bay wing tank for the purposes of testing. The upper panel that covered the entire surge tank of one of the wings was removed, and it was re-skinned with a 1/8″ thick piece of composite material. This composite was constructed from the HexPly 8552 resin system and laid up in a repeating orientation sequence of -45, 0, 45, and 90 degrees with respect to the reference direction and was symmetric to the mid-plane of the panel. The panel was constructed to be 1/8″ thick to be consistent with the adjoining material on the remainder of the wing section.

Figure 2. 727 wing tank test articles

The two fuel tank test articles were situated next to each other, adjacent to an instrumentation trailer in a location that received direct sunlight for the majority of the day. Instrumentation in each of the test articles was identical and consisted of 12 K-type thermocouples to record the fuel, ullage, and surface temperatures within the tanks. These temperature sensors consisted of one thermocouple on each tank surface, 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. In addition, a sample line to monitor the THC concentration of each of the tanks was routed to an analyzer within the instrumentation trailer. These sample lines were run through a series of automated solenoid valves that were set so for a 20-second sample to be taken from each tank at alternating 5-minute intervals throughout the test.

3. TEST PROCEDURES

3.1 PANEL HEAT TESTS

The panel heat tests were a series of tests conducted under static conditions to examine the heat transfer through each panel. The 42″ x 42″ panels were individually tested with the heaters placed approximately 12″ above them in the high-heat setting. Each panel was heated for a full 20 minutes, followed by a 25-minute cool-down period. The temperature at the center point of the bottom surface of the panel was recorded throughout, using a K-type thermocouple. An image of the setup for these panel heat tests is shown in figure 3.

Figure 3. Photo of panel heat test setup

3.2 AIR INDUCTION FACILITY TESTS

The fuel tank test article was mounted in the high-speed section of the air-induction facility. An aerodynamic nose and tailpiece were constructed of aluminum and installed on the fuel tank. Foam insulation was also installed on all sides of the fuel tank to allow heating and cooling through the top and bottom surfaces. Three radiant heaters were used to heat the top surface of the fuel tank for 1 hour. After the initial hour had passed, fuel that had been preconditioned to a temperature of 90ºF was transferred into the fuel tank. Heating of the fuel tank continued for another full hour, at which point the heaters were removed and air flow through the wind tunnel was initiated. After an initial engine warmup time of approximately 5–10 minutes, the wind tunnel was taken to 90% of capacity and was maintained at that level for 30 minutes. Throughout the tests, temperatures in the fuel tank and pressure changes were monitored and recorded. Hydrocarbons were not sampled continuously because continued sampling has a drastic effect on test results by consistently drafting hydrocarbons out of the fuel tank and adding air to the ullage. As such, discrete hydrocarbon sample points were taken every 15 minutes during the hour that the fueled tank was being heated. Additionally, samples were taken just prior to engine startup, prior to the engines being taken to 90% capacity, and every 5 minutes thereafter. The tests to evaluate the effects of topcoat color were conducted at fuel loads of 40%, 60%, and 80% with both aluminum and composite top and bottom skins. Subsequent tests to evaluate the effects of the thickness of the composite panels were conducted only at fuel loads of 40% and 80%. Heater settings for each fuel load were varied from the low (750 watts per heater) to the high setting (1500 watts per heater).

3.3 727 WING TANK TESTS

The two 727 wing tank test articles were situated next to each other, adjacent to an instrumentation trailer in a location that received direct sunlight through the majority of the day. Each tank was filled with 25 gallons of JP-8 fuel, and was allowed to heat and cool according to the ambient conditions of the day. Temperature and THC readings were recorded throughout the testing. In the case of THC measurements, heated sample lines from each tank were routed to a series of automated solenoid valves that were set so that a 20-second sample was taken from each tank at alternating 5-minute intervals throughout the test.

4. DISCUSSION OF RESULTS

4.1 PANEL HEAT TEST RESULTS

The results of the panel heat tests for the bare and painted composite and aluminum panels is shown in figure 4. This figure depicts the center-point temperature on the bottom surface of each of the panels. The difference in thermal properties of the bare composite and aluminum panels is evident [3], as the composite panel peaked at temperatures of approximately 240ºF, whereas the aluminum panel peaked at approximately 110ºF. It is also observed that the aviation-grade primer and white paint applied to the composite panel had very little impact on the heat transfer through the panel, which had a very similar temperature profile and a peak temperature of approximately 225ºF. Conversely, the aviation-grade primer and paint, both black and white, had tremendous effects on the results, making the aluminum panel behave more like the composite panel. The black-painted aluminum had a peak temperature of approximately 240ºF, whereas the white-painted aluminum had a peak temperature of approximately 205ºF. The cool-down period of all of the panels, with the exception of the bare aluminum, followed very similar trends as well.

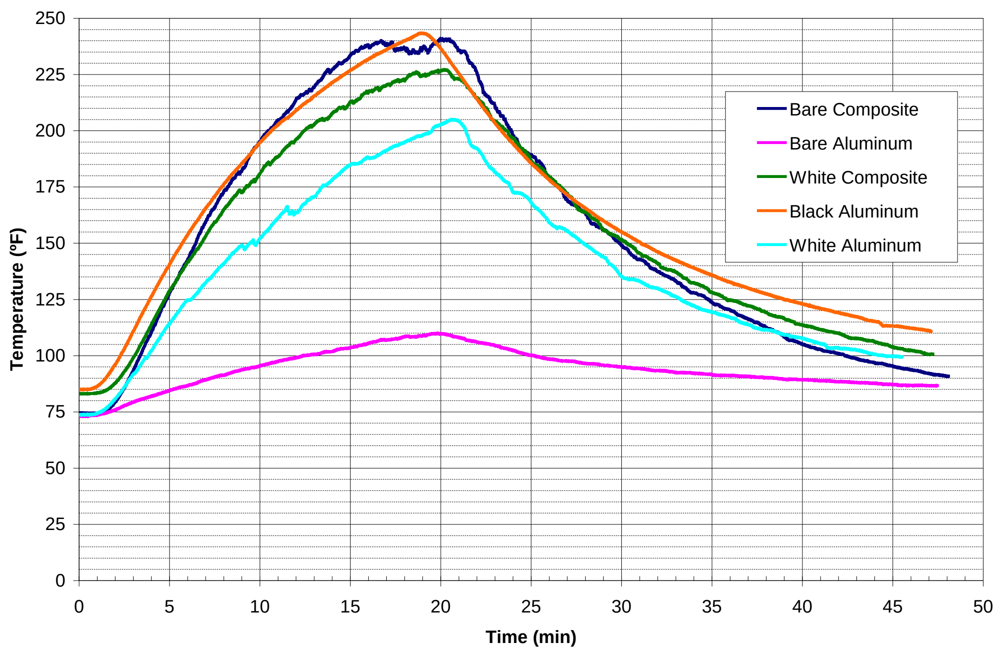

Figure 4. Comparison of center-point temperature for the bare and painted composite and aluminum materials during panel-heating test

The fact that both topcoat colors on the aluminum panel resulted in significant increases in panel temperatures indicated that a difference in material properties was not what led to increased temperatures and THC measurements in the composite panel tests [3]. Rather, it was the reflective behavior of the bare aluminum material that was causing much of the radiant heat to be reflected off of the tank, resulting in lower fuel tank temperatures and lower THC measurements.

The results of the panel heat tests for the composite panels of varying thickness are shown in figure 5. These panels were all left uncoated because it was previously shown that the topcoat color of the composite panels did not affect results. As expected, the results show that the thinner the composite material, the more readily heat transmits through it. The 1/4″ thick composite panel reached a peak temperature of approximately 205ºF, the 1/2″ panel reached approximately 185ºF, and the 3/4″ panel reached approximately 160ºF. Similarly, during the cool-down period, the thinner the panel, the faster it cools towards ambient. Based on these results, it is expected that with the various thickness panels installed on the fuel tank, the thinner panels will lead to higher internal tank temperatures and higher THC measurements.

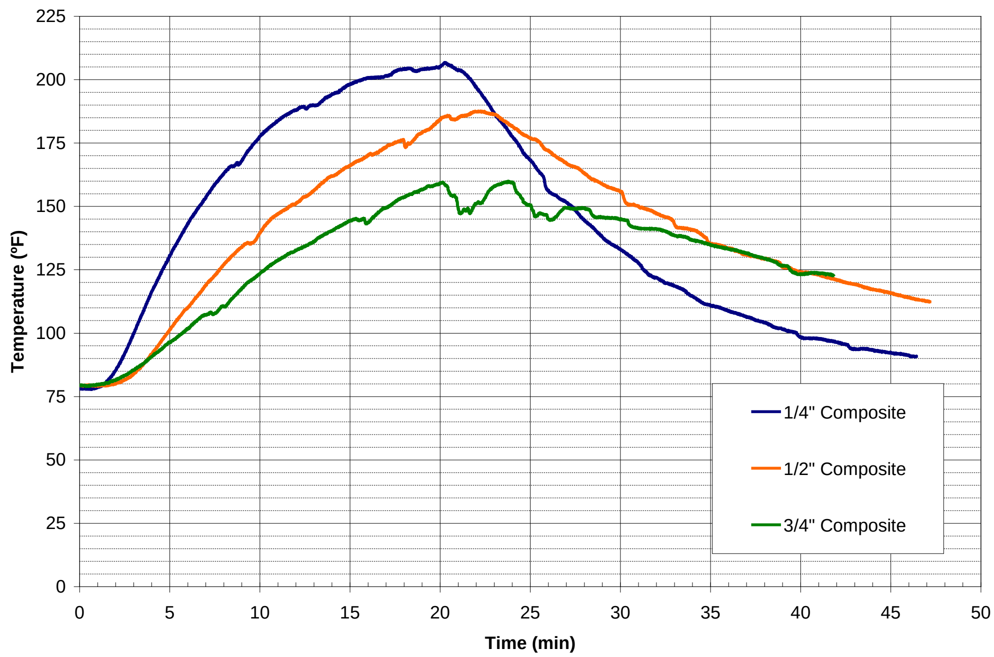

Figure 5. Comparison of center-point temperature for the various thickness composite materials during panel heating test

4.2 AIR INDUCTION FACILITY TEST RESULTS

Previous test results evaluating the bare aluminum and bare composite panels were reported in detail in reference 3. In addition to the bare material results, this report also discusses results of testing with the composite material painted white and the aluminum material painted black. These topcoat colors were initially evaluated to determine if a light-colored paint might make the composite material retain heat similar to the bare aluminum material and if a darker color might cause the aluminum panel to behave more like the composite. These tests showed that although the topcoat color did not affect the heat transfer behavior of the composite material, there was a drastic effect on the aluminum material. Based on these results, additional tests were conducted, with the aluminum panel painted white so the full effect of topcoat color could be evaluated. The results of these white-painted aluminum fuel tank tests are discussed in section 4.2.1 of this report. For simplicity, the results are provided in comparison to the bare composite material results from the previous testing [5], with the knowledge that both the white-painted composite and black-painted aluminum tests previously conducted [5] showed similar behavior to this bare composite material.

The results of the testing conducted to evaluate the effect of the thickness of the composite material is discussed in section 4.2.3 of this report.

4.2.1 White-Painted Aluminum Test Results

Figures 6–11 display the air-induction test facility results comparing the white-painted aluminum with the bare composite material. Figures 6–8 consist of the low-heat-setting test results, whereas figures 9–11 consist of the high-heat-setting test results. For each heat setting, results are shown for the 40%, 60%, and 80% fuel-load tests, respectively, and consist of average fuel temperature, average ullage temperature, and fuel vapor flammability measurements. The initial point at which airflow through the wind tunnel was started is shown in figures 6–11 as the ullage temperature immediately begins to drop. The vertical, dashed lines in these figures indicate the approximate time at which the engines were shifted to the 90% throttle position. It should be noted that in the 60% fuel load, high-heat composite panel test, the first 21 minutes of data were lost because of a malfunction of the data-acquisition system.

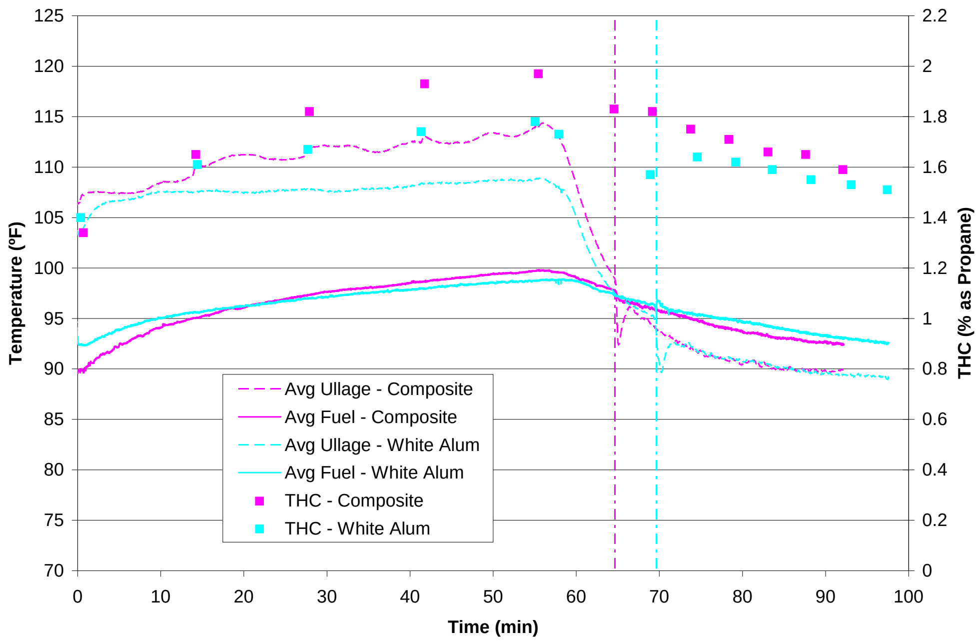

Figure 6. Comparison of white-painted aluminum and bare composite material fuel tank results for a 40% fuel load under the low-heat setting

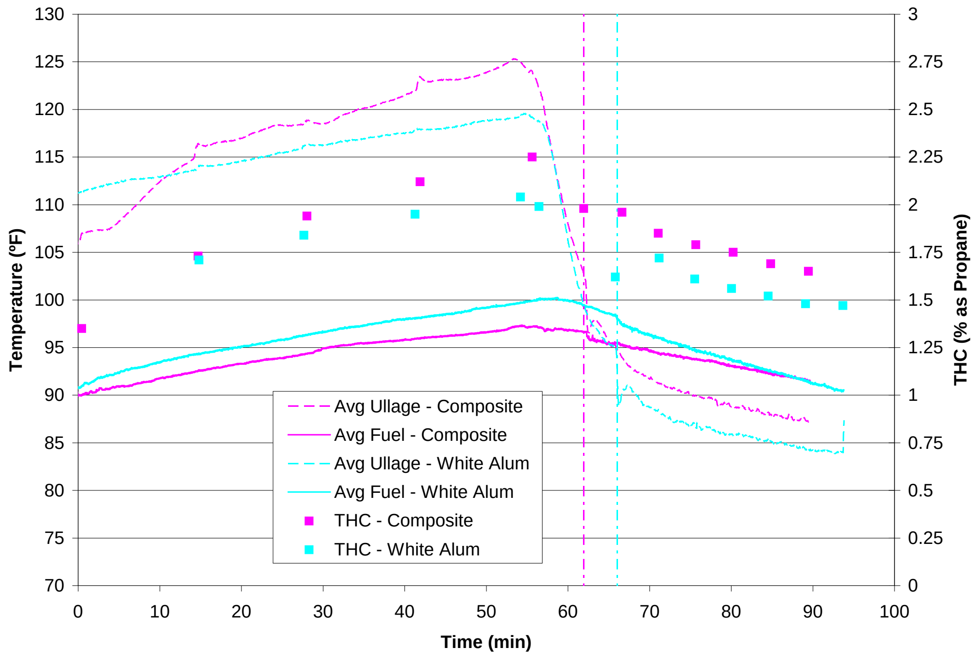

Figure 7. Comparison of white-painted aluminum and bare composite material fuel tank results for a 60% fuel load under the low-heat setting

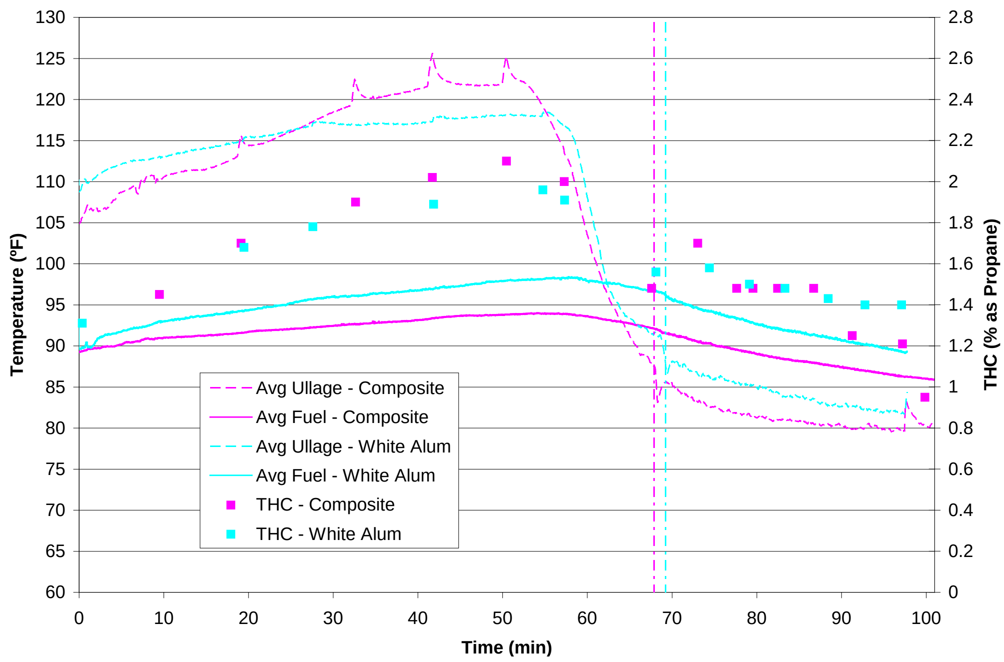

Figure 8. Comparison of white-painted aluminum and bare composite material fuel tank results for an 80% fuel load under the low-heat setting

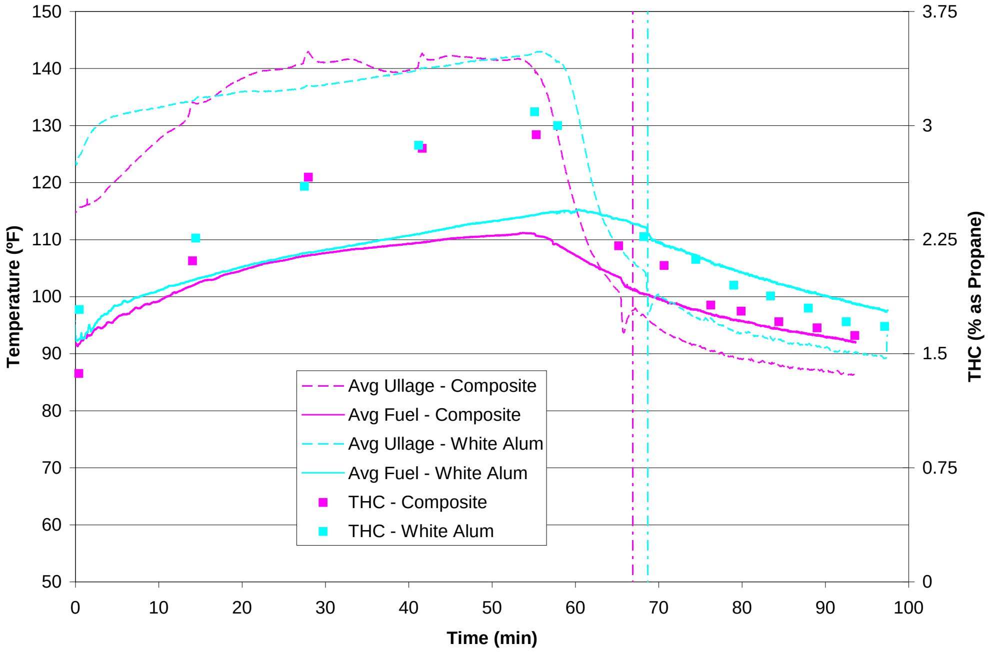

Figure 9. Comparison of white-painted aluminum and bare composite material fuel tank results for a 40% fuel load under the high-heat setting

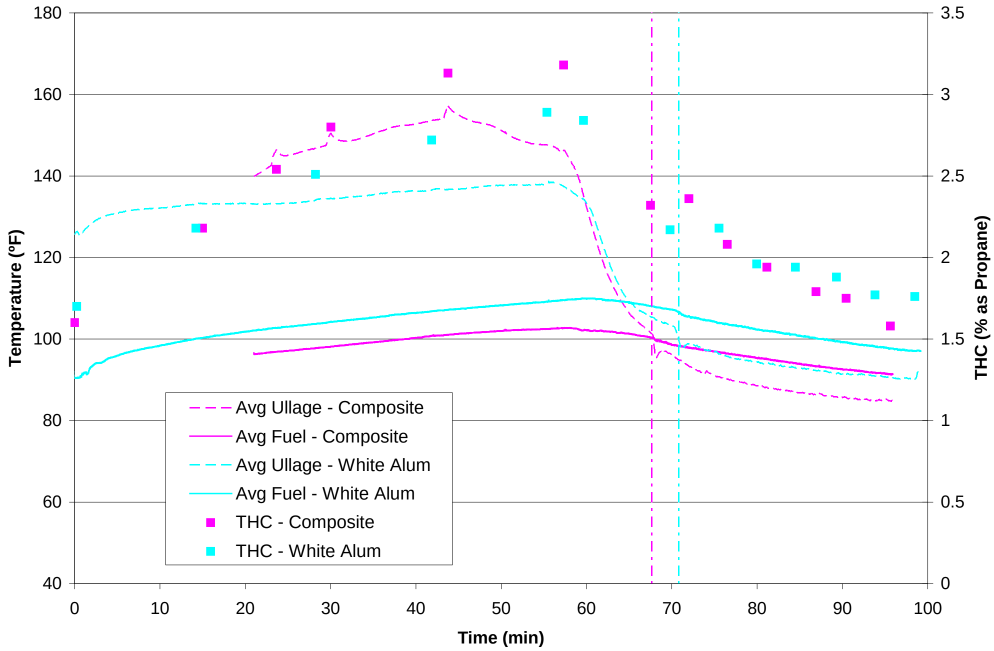

Figure 10. Comparison of white-painted aluminum and bare composite material fuel tank results for a 60% fuel load under the high-heat setting

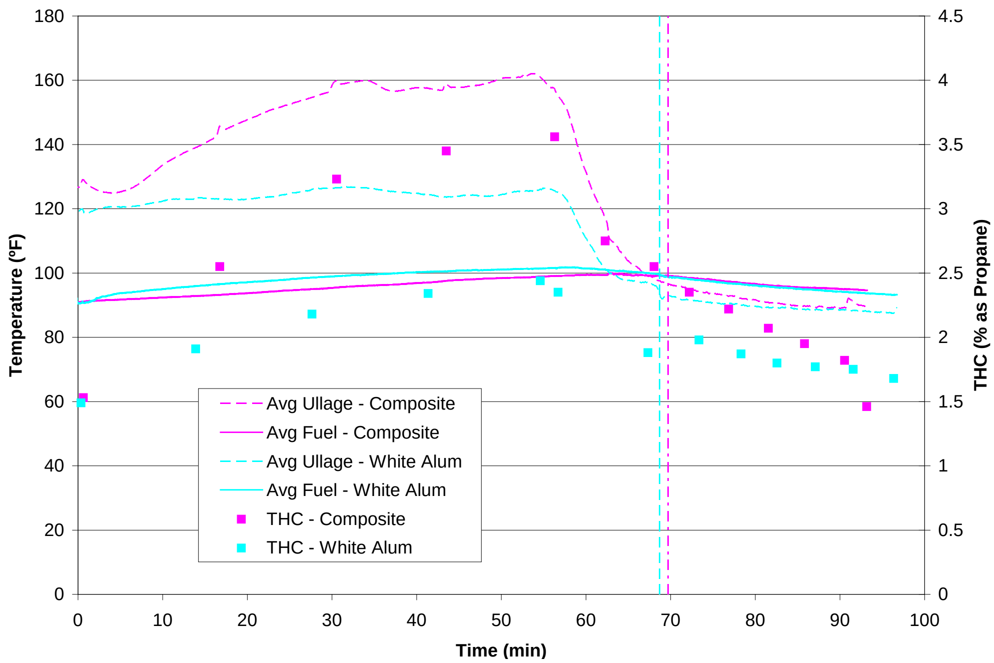

Figure 11. Comparison of white-painted aluminum and bare composite material fuel tank results for an 80% fuel load under the high-heat setting

These results clearly show that the white-painted aluminum tank behaves similarly to the bare composite tank. With the exception of the 80% high-heat test, the average ullage temperatures, fuel temperatures, and THC measurements all closely follow each other, with the temperatures being within just a few degrees of one another, and the THC measurements being almost indistinguishable from each other. Large increases in both ullage temperature and THC measurements are observed for both sets of material, which is in contrast to the bare aluminum tests that were previously conducted [5]. Similar to the previous tests [5], only slight increases in the average fuel temperatures are observed throughout. This clearly depicts a correlation between high THC measurements and high ullage temperature increases, as was previously observed in references 4 and 5. Therefore, in contrast to a CWT, which is heated from below, with the bulk average fuel temperature being the main driver behind flammability, it is observed that ullage temperature changes are the driving force behind in-flight flammability of wing fuel tanks that are heated from above.

As airspeed through the wind tunnel is initiated, significant and almost immediate decreases in ullage temperature are observed in both the white-painted aluminum and the bare composite fuel tanks. The fuel temperature also decreases, but at a much slower rate than the ullage temperatures. A decrease in the THC measurements is also observed in both tanks, and again follows the trend of the decreasing ullage temperatures. This trend of decreasing ullage temperature and THC measurements is much more pronounced in the high-heat tests because the temperature difference relative to ambient air is much higher, therefore allowing for a larger decrease in ullage temperature, and in THC measurements. Even with this rapid decrease in temperature and THC, however, the fuel tanks of both the white-painted aluminum and the bare composite material remained in the flammable region, greater than roughly 2% C_3H_8, for some time after airflow was started.

The 80% fuel load, high-heat scenario is the only condition at which the previously described trends were not observed. The bare composite fuel tank under these conditions resulted in average ullage temperatures roughly 40ºF higher than those in the white-painted aluminum tank, resulting in corresponding increased THC measurements within the bare composite tank as well. It is unknown why this discrepancy exists for this test case. Nevertheless, the previously observed correlation between THC and ullage temperature was also evidenced under these conditions.

4.2.2 Test Results of Composite Panels Coated With High-Reflectivity Aluminum Epoxy

Following the testing of the bare composite and coated aluminum panels, it was believed that the variation in tank temperatures and hydrocarbon concentrations was due largely to the reflective nature of the bare aluminum material as opposed to material property differences. To test this hypothesis, additional testing was conducted with a high-reflectivity aluminum epoxy applied to the 1/4″ composite panels. A photograph of the test article with this coating applied is shown in figure 12. This testing was conducted only at 40% and 80% fuel loading under both the low- and high-heat setting.

Figure 12. Photograph of tank with high-reflectivity aluminum epoxy applied to composite material

The results of these four tests can be seen in figures 13–16. These figures compare the high-reflectivity epoxy results to the bare composite material. The resulting fuel temperature and hydrocarbon concentration exhibited in these figures, however, do not corroborate the proposed hypothesis because there is no discernible, consistent impact on the results due to the application of the epoxy.

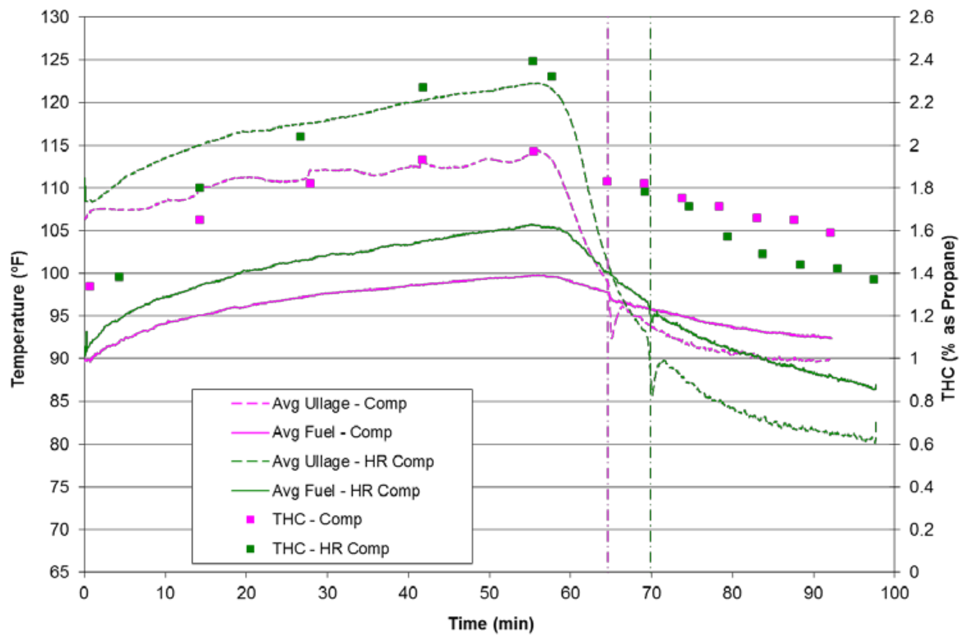

Figure 13. Comparison of high-reflectivity and bare composite material fuel tank results for a 40% fuel load under the low-heat setting

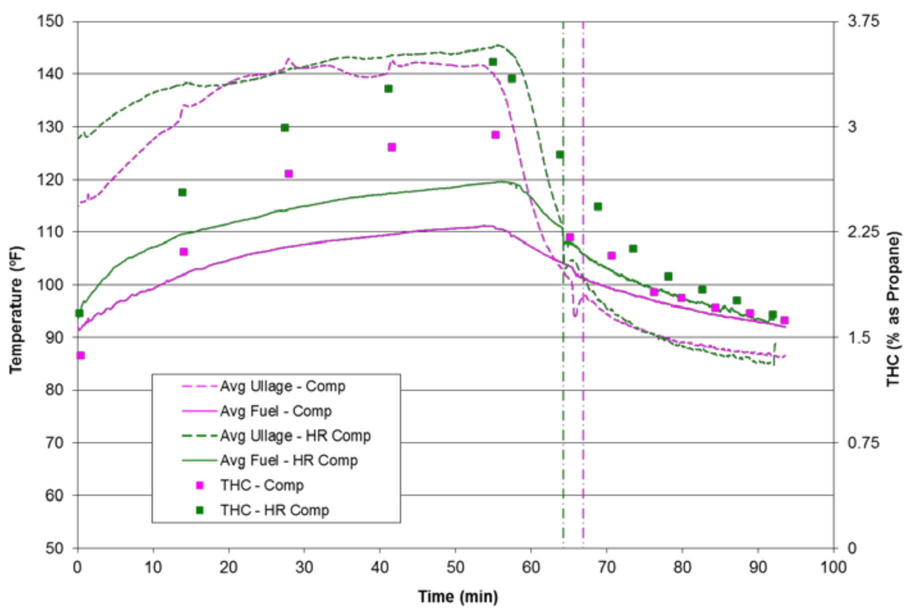

Figure 14. Comparison of high-reflectivity and bare composite material fuel tank results for a 40% fuel load under the high-heat setting

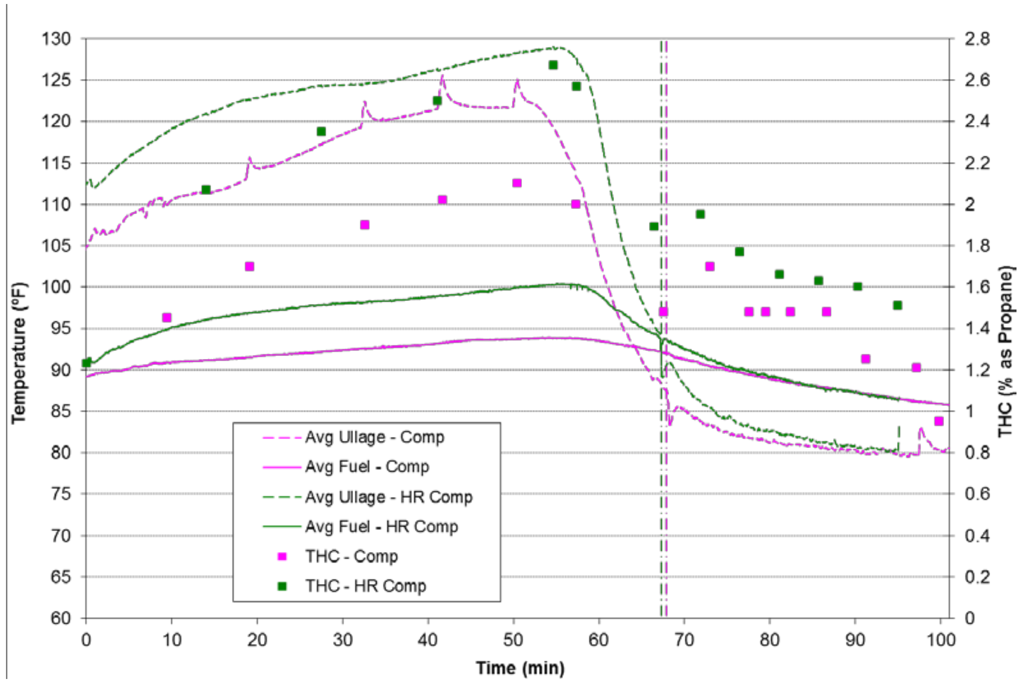

Figure 15. Comparison of high-reflectivity and bare composite material fuel tank results for an 80% fuel load under the low-heat setting

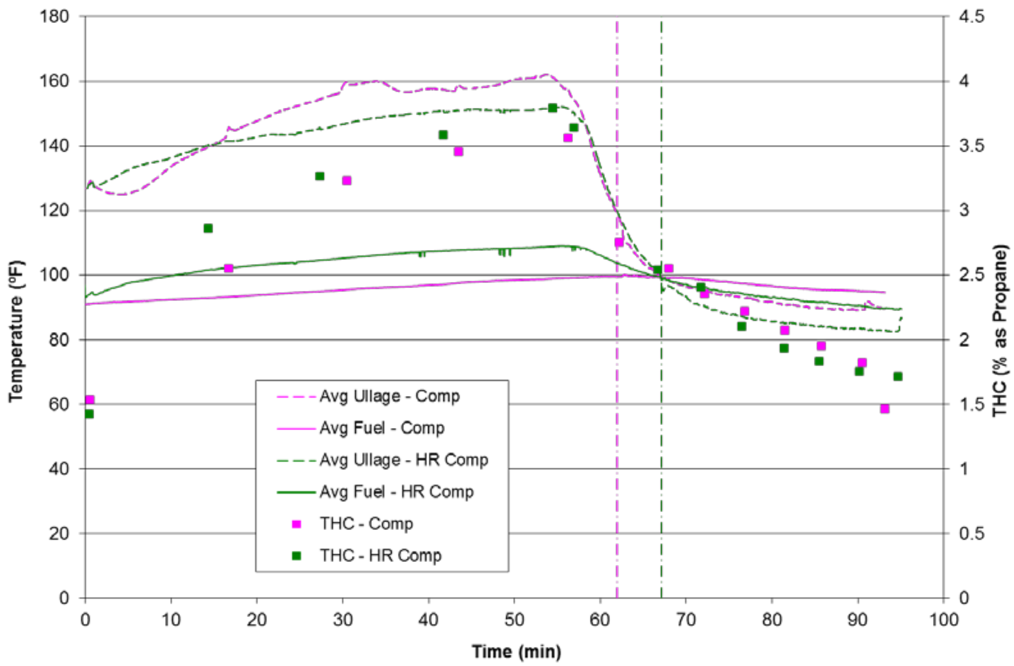

Figure 16. Comparison of high-reflectivity and bare composite material fuel tank results for an 80% fuel load under the high-heat setting

4.2.3 Composite Thickness Test Results

Figures 17–20 show the results of the low- and high-heat 40% and 80% fuel load test conditions of the composite panels of varying thickness. Based on the panel heat tests discussed in section 4.1 of this report, it is expected that the thickness of the material would correlate directly with fuel tank temperature and THC measurements. However, as seen in these figures, there is considerable variability in the test results, and the expected dependency on panel thickness was not apparent. In some of the tests, such as the 40%, low-heat setting case, the tank temperatures and THC measurements correlate as expected. In others, such as in the 40% and 80% high-heat setting cases, the 3/4″ thick panel actually resulted in the highest average ullage temperatures and the highest THC measurements of the three panels. This finding is in direct contradiction with the panel heat test results, which showed that the thinner the composite material is, the more readily heat transmits through it.

Although a correlation between panel thickness and temperature was shown under static conditions, these tests show that the expected inverse relationship between tank temperatures and THC measurements did not occur. These tests, however, consistently confirmed the strong correlation between ullage temperature and THC within a fuel tank when heated from above.

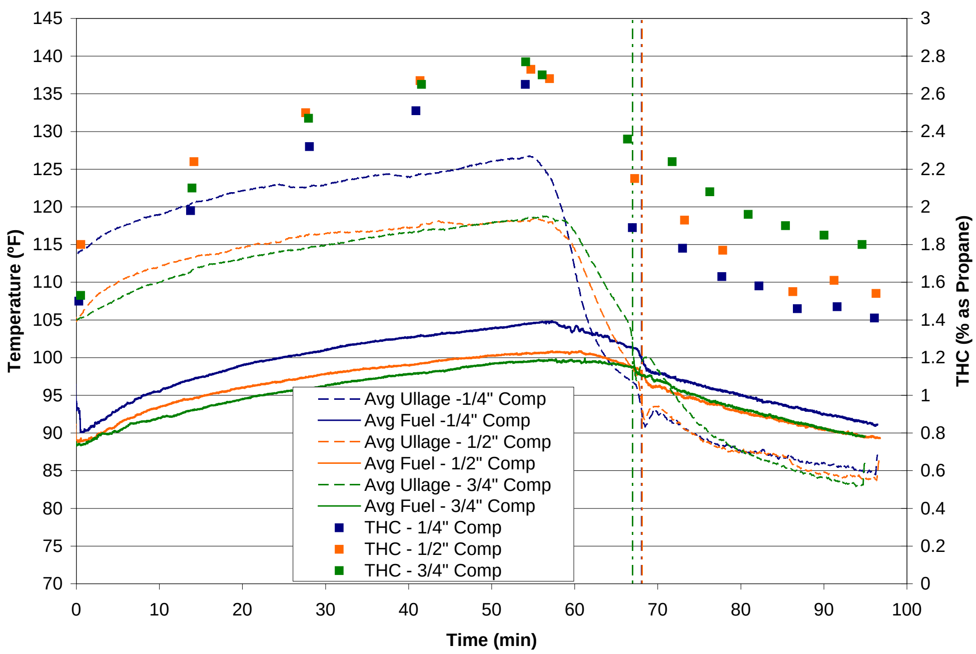

Figure 17. Comparison of various thickness composite material fuel tank results for a 40% fuel load under the low-heat setting

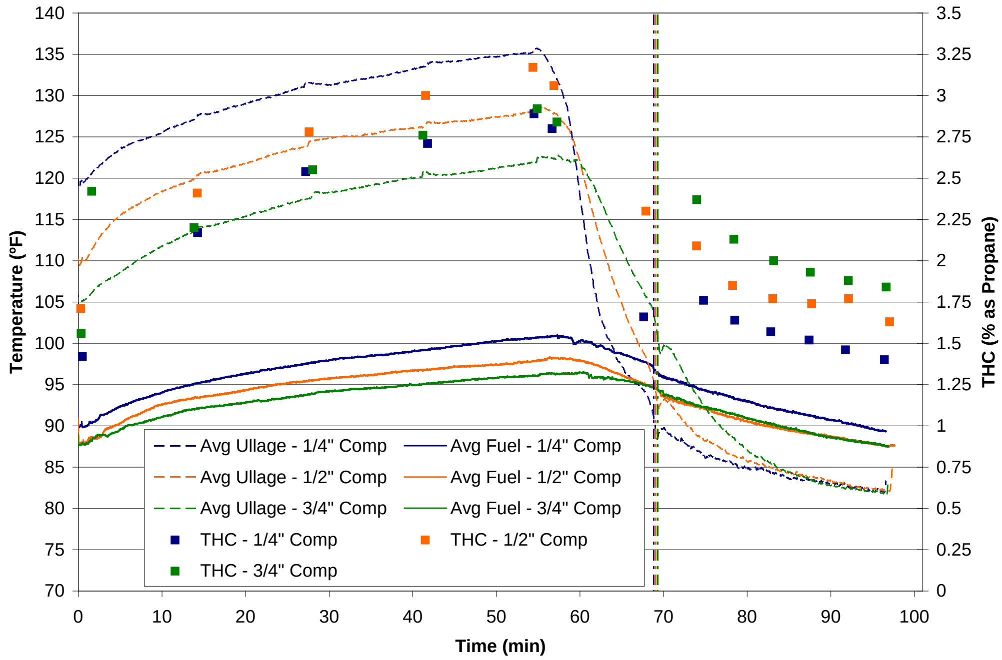

Figure 18. Comparison of various thickness composite material fuel tank results for an 80% fuel load under the low-heat setting

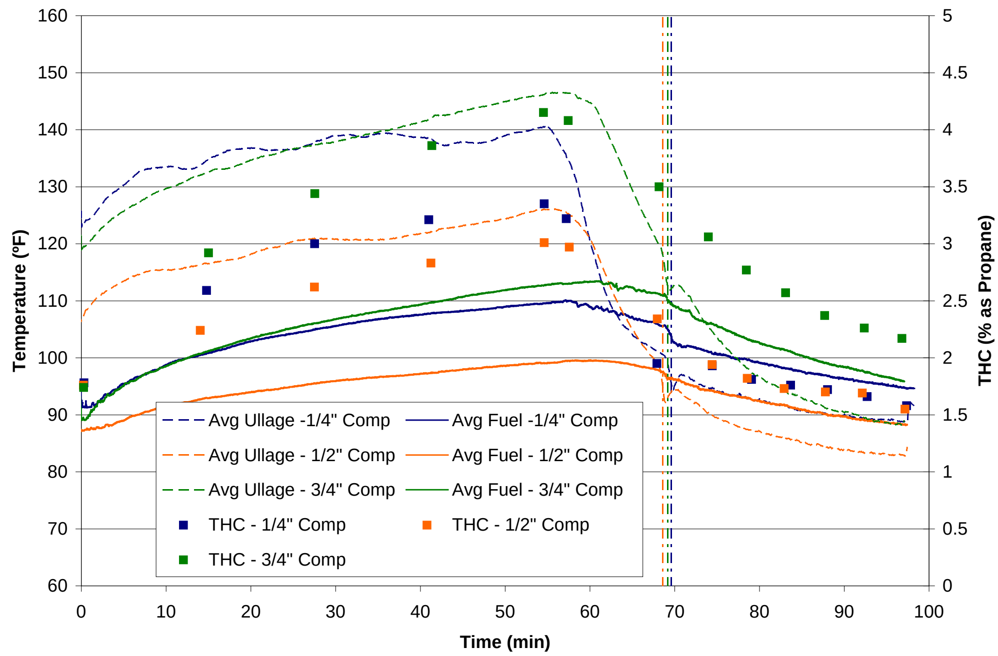

Figure 19. Comparison of various thickness composite material fuel tank results for a 40% fuel load under the high-heat setting

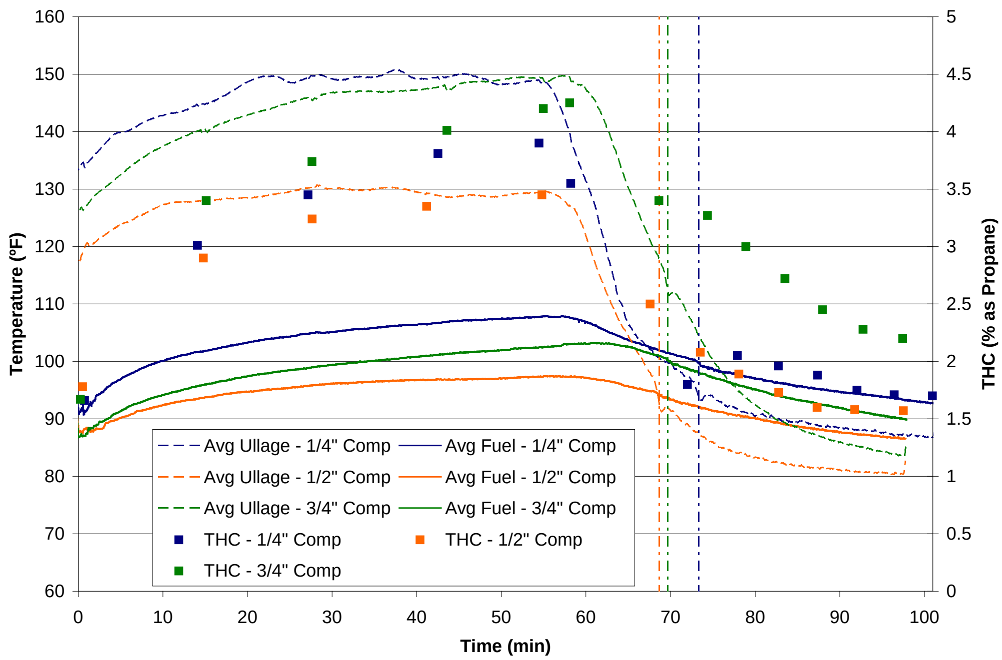

Figure 20. Comparison of various thickness composite material fuel tank results for an 80% fuel load under the high-heat setting

4.3 727 WING TANK TEST RESULTS

Figures 21–24 show the results from the 727 wing tank tests. Each figure shows ambient temperature, average ullage temperatures, and THC measurements for both tanks. Figure 16 depicts results from a test that was started early in the day, in which the fuel tanks were allowed to warm up as the ambient temperature increased throughout the day from approximately 75ºF to between 85ºF and 90ºF. During this test, average ullage temperatures increased from approximately 80ºF to 120ºF for the aluminum tank and 130ºF for the composite fuel tank. The THC measurements followed a very similar trend to the ullage temperatures, increasing from 0.6% C_3H_8 to approximately 1.6% C_3H_8.

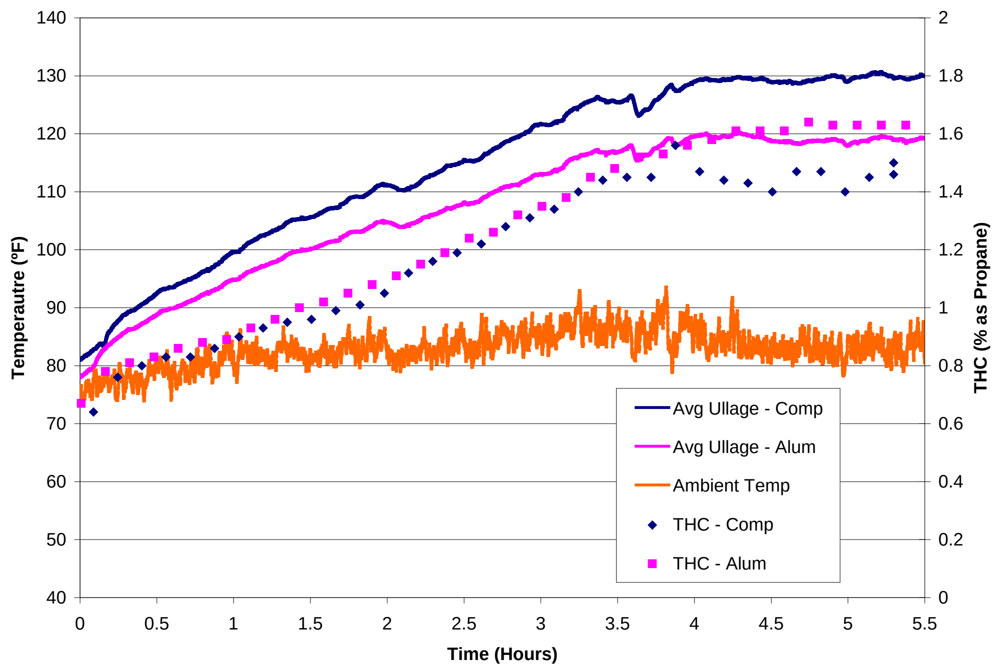

Figure 21. 727 wing tank test results for a 5.5-hour test started in early morning

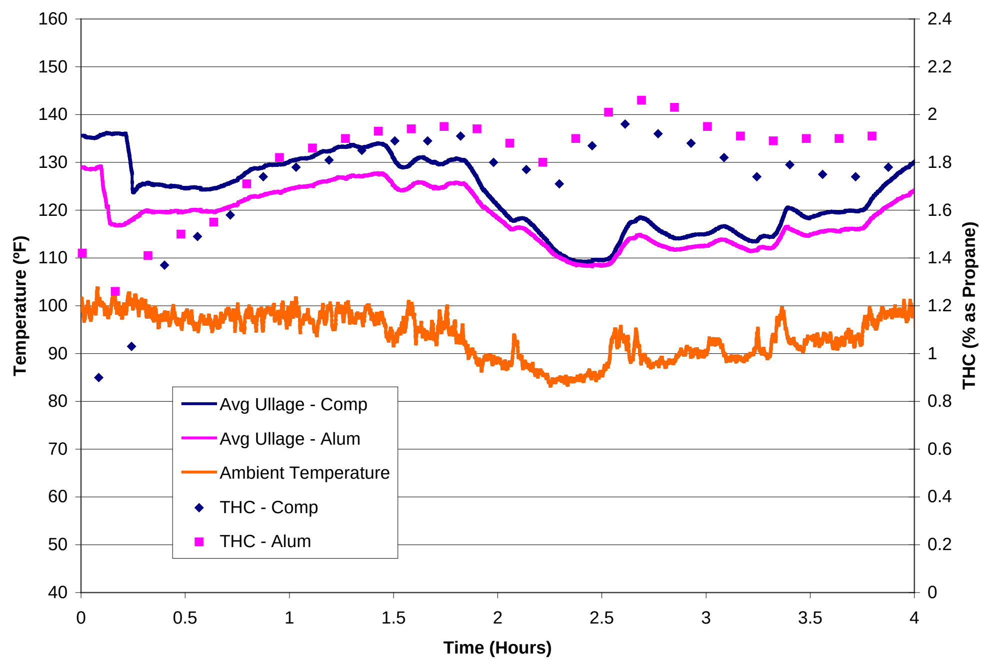

Figure 22. 727 wing tank test results for a 4-hour test started mid-morning

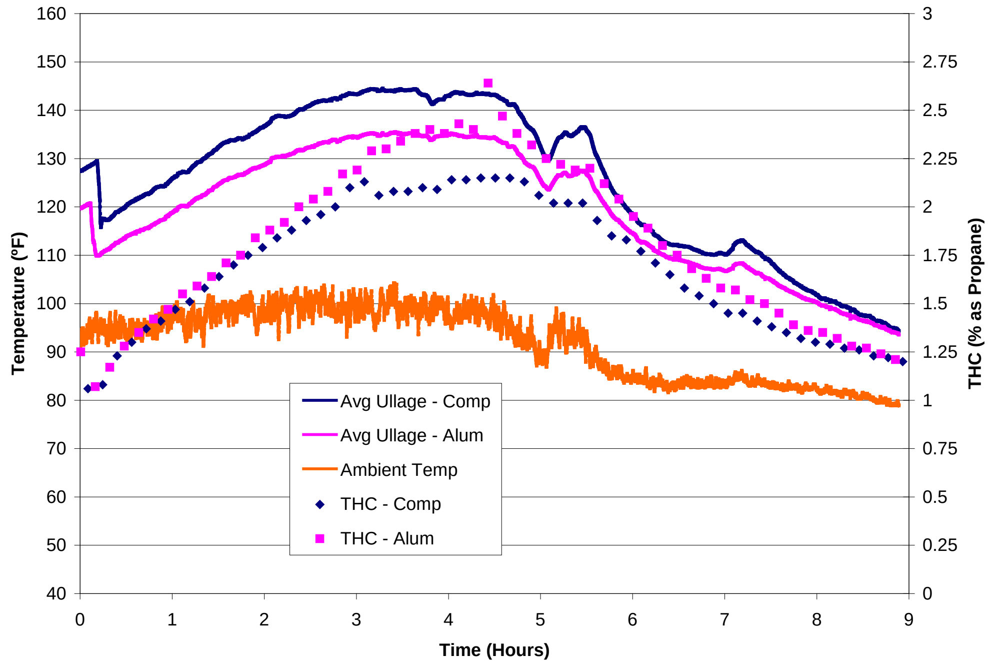

Figure 23. 727 wing tank test results for a 9-hour test started mid-morning

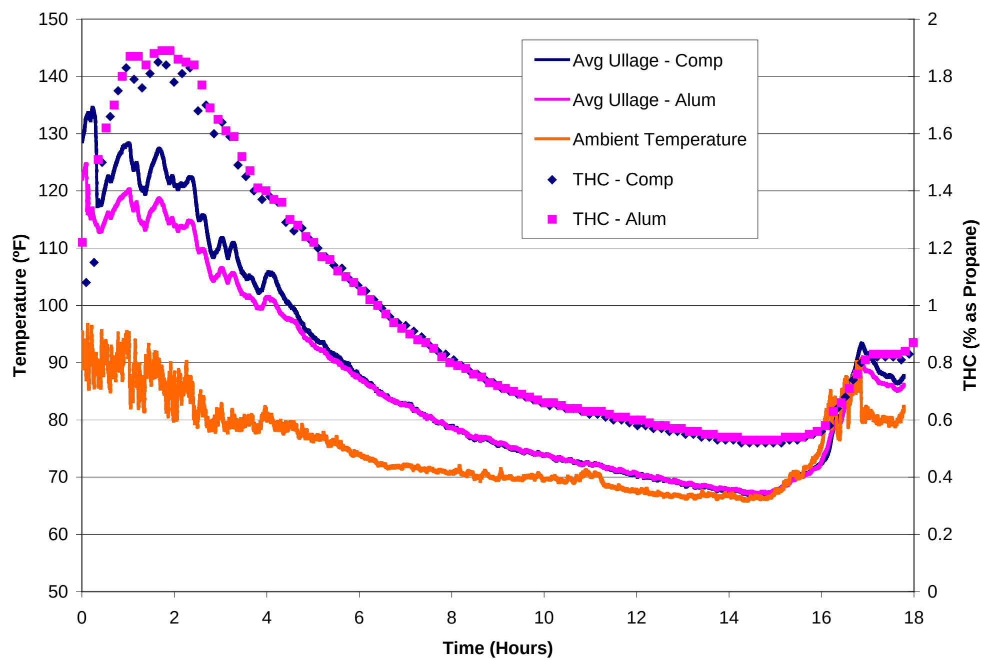

Figure 24. 727 wing tank test results for an 18-hour test started early afternoon

The tests in figure 22–23 were both started in mid-morning, when the ambient temperature had already had time to climb to close to 100ºF. In the case of figure 22, this ambient temperature held pretty consistent throughout the length of the test. During the scenario of figure 23, however, the test was allowed to go for a full 9 hours. This provided some detail on the cool-down period of the tank because the ambient temperature cooled to approximately 80ºF during the evening hours. In both tests, a strong dependence of THC measurements on ullage temperatures was observed. Both tests also showed that the THC measurements in both tanks increased steadily during warmup and exceeded the lower limit of flammability of approximately 2% C_3H_8 almost 3 hours after they were fueled. In the case of figure 18, as the ambient temperature decreases, the tank ullage temperatures and resulting THC measurements exhibited a similar decrease.

The test in figure 24 was initiated at approximately 2:00 pm and was allowed to run for a full 18 hours, overnight and into the morning hours of the next day. Ambient temperature at the start of the test was approximately 90ºF and cooled to less than 70ºF during the overnight hours. As the morning hours were reached, the ambient temperature again began to increase, reading more than 80ºF at the end of the test. Average ullage temperatures in both tanks correlated closely, starting out at between 120ºF–130ºF and cooling to just less than 80ºF before climbing again to more than 90ºF in the morning hours. The THC measurements in both tanks were nearly identical throughout the test and, as in previous tests, closely followed a similar trend in ullage temperatures. Two hours into the test, the lower limit of flammability (approximately 2% C_3H_8) was approached, but was never reached, before cool down. As ullage temperatures decreased, the THC measurements decreased to approximately 0.5%, before climbing again to more than 0.8% at completion of the test.

As discussed in sections 4.2.1, 4.2.2, and 4.2.3 of this report, all of these tests exhibit a very strong correlation between ullage temperature and THC measurements. There is also a striking similarity between the tank ullage temperatures and the THC measurements in both the aluminum and composite fuel tanks. In fact, through much of the testing, the data between the two are indistinguishable.

5. SUMMARY OF RESULTS

Tests were conducted to examine the variation in temperature and fuel vapor flammability of fuel tanks comprised of a composite material skin and a traditional aluminum skin when heated from above. The effect of topcoat color of the aluminum material and the variation in thickness of the composite material were analyzed.

Tests examining the effects of topcoat color of the aluminum fuel tank were all extremely consistent. The panel heat tests under static conditions, air induction facility tests, and tests comparing two identical 727 wing tanks all showed that although the bare composite material transmitted radiant heat into the fuel tank much more readily than the bare aluminum material, the application of aviation-grade primer and a topcoat, regardless of color, resulted in the aluminum skin behaving similarly to the composite. Throughout the-air induction facility tests, large increases in both ullage temperature and THC measurements were observed for both sets of material, whereas there were only slight increases in the average fuel temperatures. In addition, once airspeed through the wind tunnel was initiated, significant and almost immediate decreases in ullage temperature and hydrocarbon concentration were observed. This is consistent with previous findings [4, 5] showing that, for a wing tank heated from above, ullage temperature changes are the driving force behind in-flight flammability. In comparison, a CWT, heated from below, is driven primarily by the bulk average fuel temperature.

The application of white topcoat to the aluminum panels in these tests and black topcoat in previous tests [5] both resulted in the aluminum tank temperatures and THC measurements being consistent with the composite tank test results. These results were initially regarded as evidence that it was not a difference in material properties that led to increased temperatures and THC measurements in the composite panel tests [3]. Instead, it was thought that the reflective behavior of the bare aluminum material, causing much of the radiant heat to be reflected off of the tank, resulted in lower fuel tank temperatures and lower THC measurements. However, additional testing with the composite material, which had a reflective aluminum epoxy applied to it, did not exhibit the anticipated impact to the internal tank temperatures and flammability measurements. As a result, the testing conducted was inconclusive as to the cause of the fuel tank behavior.

Panel heat tests under static conditions with composite panels of 1/4″, 1/2″, and 3/4″ thickness showed that heat transmits readily throughout thinner composite material. Similarly, the thinner the panel, the faster it cools toward ambient during the cool-down period of each of the panels. Based on these results, it was expected that, with the various thickness of the panels installed on the fuel tank, the thinner panels would lead to higher internal tank temperatures and, therefore, higher THC measurements. However, once installed on the tank, there was relatively more variation in the test results. In some of the tests, the tank temperatures and THC measurements were similar, regardless of the skin thickness. Moreover, the 3/4″ thick panel actually resulted in the highest average ullage temperatures and the highest THC measurements of the three panels.

In summary, there is a correlation between panel thickness and temperature while under static conditions. Conversely, when these panels were tested on a fuel tank, the difference in thickness provided little variance in resulting tank temperatures and THC measurements. These tests, however, did reconfirm the strong correlation between ullage temperature and THC within a fuel tank when heated from above.

6. REFERENCES

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