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A Comparison of 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 Federal Aviation Administration William J. Hughes Technical Center using the environmental chamber and the Air Induction Facility (wind tunnel) to examine the variation in flammability exposure of a fuel tank composed of a composite material skin and a traditional aluminum skin. Tests were also conducted to examine the impact of material topcoat color on fuel tank temperature and hydrocarbon concentrations.

The correlation between high total hydrocarbon concentration measurements and high ullage temperature increases in all tests provided further indication that ullage temperature changes were the driving force behind in-flight flammability for fuel tanks when heated from above. This is contrary to what had been found for a heated center wing fuel tank in which the average bulk fuel temperature is the main driver behind fuel tank flammability.

The tests showed that composite panels, regardless of topcoat color, have the potential to result in a significant increase in flammability exposure because they transmit radiant heat into the fuel tank much more readily than a traditional aluminum fuel tank. However, the results also showed that under the right conditions, either through additional heat input or a change in material topcoat color, an aluminum fuel tank could behave similar to a composite fuel tank.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF ACRONYMS

C_3H_8	Propane
BMS	Boeing Material Specification
CWT	Center wing tank
FAA	Federal Aviation 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 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 recent regulations requiring the reduction of flammability within high-risk fuel tanks. Traditionally, fuel tanks located in the wing of an aircraft are considered to have low flammability due to the absence of external heat sources and the rapid cooling that occurs in flight because of the high 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. As such, research is required on fuel tanks made of new composite materials to determine the potential effect they have on the flammability exposure of aircraft wing fuel tanks.

The Fire Safety Team performed tests at the FAA William J. Hughes Technical Center, using the environmental chamber and the Air Induction Facility (wind tunnel), to examine the variation in flammability exposure of a fuel tank comprised of composite material skin versus a traditional aluminum skin.

The results from the tests in the environmental chamber showed that the top skin temperature for the composite fuel tank reached much higher temperatures when subjected to the same radiant heat source. This increased skin temperature caused the internal ullage and fuel temperatures to be much higher for the composite skin fuel tank and resulted in significantly higher total hydrocarbon concentration (THC) measurements. The aluminum fuel tank never reached the accepted lower flammability limit of approximately 2.0% during the entire 5-hour heating cycle. In contrast, the fuel tank with composite skin reached the flammability limit within approximately 45 minutes of heating and reached a peak THC of more than twice the aluminum fuel tank.

Tests in the air induction test facility showed similar changes in initial temperature and THC profiles. In each high-heat test with bare materials, the ullage temperature in the composite fuel tank was between 40°-60°F higher than the aluminum fuel tank tests. The average fuel temperatures, however, varied by only 10°F and showed much less of a temperature increase than the ullage. THC measurements in each aluminum fuel tank test varied only slightly throughout the full length of the test, whereas extremely large increases were observed in the composite fuel tank tests. These measurements peaked between 3% and 3.5% propane (C_3H_8) for the composite fuel tank, whereas peak readings of approximately 1.5% C_3H_8 were observed for each aluminum fuel tank test. As airspeed through the wind tunnel was initiated, decreases in both ullage and fuel temperature were observed. The largest decrease was observed in the ullage temperature of the composite skin fuel tank as this had the largest temperature differential relative to ambient temperature. THC measurements in the aluminum fuel tank tests showed minimal change, while measurements in the composite fuel tank tests showed a significant decrease corresponding to the large decrease in ullage temperature. Even with this rapid decrease in THC, the composite fuel tank remained in the flammable region for a significant amount of time, up to 25 minutes after the 90% throttle position of the wind tunnel was reached.

The low-heat tests with bare materials displayed similar behavior, although, due to the lower heat input, the temperatures and corresponding THC measurements were not as elevated as in the high-heat tests. In each of these tests, the average ullage temperature in the composite fuel tank was between 15°-30ºF higher than those from the aluminum fuel tank tests. The average fuel temperatures varied by approximately 10ºF. The composite fuel tank tests showed THC measurements that peaked between 2% and 2.25% C_3H_8, whereas the aluminum fuel tank tests peaked at readings between 1.2% and 1.4% C_3H_8.

A single test was conducted with the bare aluminum material and a 60% fuel load in which the fuel tank was heated so that ullage temperatures were generated similar to the bare composite fuel tank. This test showed that given the proper conditions, an aluminum fuel tank could result in temperatures and THC measurements that resembled the composite fuel tank.

Tests were also conducted to examine the impact of material topcoat color on fuel tank temperature and THC concentrations. Aviation-grade primer and white paint were applied to the composite panels to determine if a light-colored paint might affect the material's heat retention, causing it to behave more like the bare aluminum material. Similarly, aviation-grade primer and black paint were applied to the aluminum panels to determine if a darker color might cause the temperature and THC measurements to be similar to the bare composite material, which was black in color. These tests showed that the topcoat color on the composite panels had essentially no effect on the resulting ullage temperatures and THC measurements. However, results from the painted aluminum fuel tank tests showed a drastic effect, making the fuel tank behave similar to the composite fuel tank tests than the bare aluminum fuel tank tests. The ullage and fuel temperature profiles, as well as THC measurements of the painted aluminum fuel tank, matched very closely to the painted composite fuel tank.

The correlation between high THC measurements and high ullage temperature increases that were observed in all the tests was further indication that ullage temperature changes are the driving force behind in-flight flammability for fuel tanks when heated from above. This is contrary to what had been found for a center wing fuel tank that is heated from below in which the bulk average fuel temperature is the main driver behind fuel tank flammability.

The tests showed that composite fuel tanks, regardless of topcoat color, are significantly more flammable than traditional aluminum fuel tanks because they pass radiant heat into the fuel tank much more readily. However, the results also showed that under the right conditions, either through additional heat input or a change in topcoat color, an aluminum fuel tank could behave similarly to a composite fuel tank.

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 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 recent regulations requiring the reduction of flammability within high-risk fuel tanks. Traditionally, fuel tanks located in the wing of an aircraft are considered to be low flammability due to the absence of external heat sources and the rapid cooling that occurs in flight because of the high conductivity of the aluminum skin of the aircraft. There have, however, been recent advances in composite materials, and these advanced materials are increasingly being used in the construction of aircraft. As such, research is required on fuel tanks consisting of these new composite materials to determine the potential effect they may have on the flammability exposure of aircraft wing fuel tanks.

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 fuel tank (CWT) was studied during flight tests with the FAA inerting system on the National Aeronautics and Space Administration-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, as well as oxygen concentration variations in the inerted CWT.

Recent 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. As fuel temperature is increased, due to heating from ductwork and/or systems located under the fuel tank, fuel is evaporated. As the aircraft takes off, decreased pressure causes further evaporation of the fuel. At the same time however, some condensation takes place due to cooling from decreased ambient temperatures.

A wing fuel tank differs in that the heating does not take place from beneath the fuel tank, but rather 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 thus condensation) from changes in the outside environment are much more significant as the entire fuel tank surface is subjected to cold air at high speed.

1.3 SCOPE.

Tests were performed at the FAA William J. Hughes Technical Center using the environmental chamber and the Air Induction Facility (wind tunnel) to examine the variation in flammability exposure of a fuel tank comprised of a composite material skin and a traditional aluminum skin. Tests were conducted with composite and aluminum panels as bare material and with different topcoat colors applied to examine the impact that the topcoat colors might have on heat transfer into the fuel tank.

2. TEST EQUIPMENT.

2.1 FUEL TANK TEST ARTICLE.

The fuel tank test article used in these experiments measured 3- by 3-ft square by 1-ft deep, with aerodynamic leading and trailing edges, and was instrumented with 12 thermocouples as well as a sample port for THC measurement. Thermocouples were placed in the liquid fuel and vapor at depths of 2, 4, 6, and 8 inches. Additionally, two thermocouples were 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 was used to measure the flammability levels of the ullage space during the tests. The THC analyzer is a fully automated flame ionization detector analyzer that uses an internal pump to sample the fuel tank ullage. 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, as 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.

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.

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. In an attempt to be consistent with typical aircraft wing structures, the aluminum panels were 1/4″ thick, and the composite panels were approximately 3/8″ thick.

The composite panels were fabricated by a composite manufacturer (Integrated Technologies, Inc.) from material supplied by Toray Composites (America) that was qualified as 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 inch. Thermal, combustion, and flammability properties of this composite material have been reported [5].

2.2 ENVIRONMENTAL CHAMBER.

Initial testing of the scale fuel tank test article was conducted at reduced ambient pressure and varying temperatures in the FAA Fire Safety Environmental Chamber Facility. The scale fuel tank was placed in the environmental chamber, which measured 72 by 71 by 93 inches. The environmental chamber pressure and temperature was controlled manually. A radiant heater was mounted above the fuel tank test article. Figure 1 shows a block diagram of the fuel tank test article in the environmental chamber.

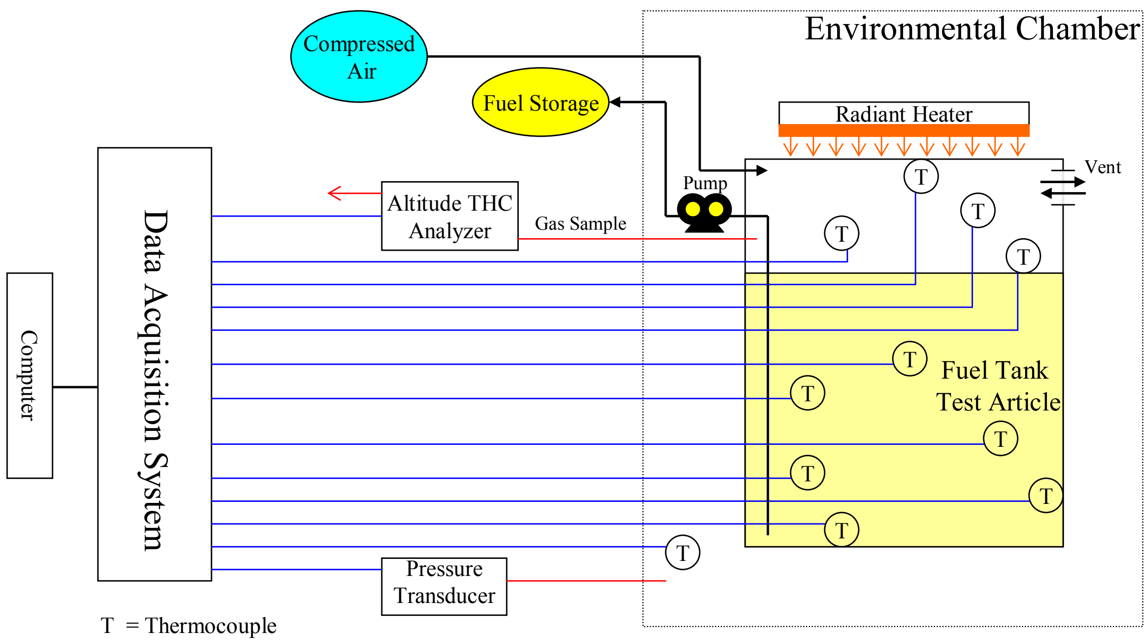

Figure 1. The Scale Fuel Tank Test Article and Instrumentation in the Environmental Chamber

2.3 AIR INDUCTION FACILITY.

The Air Induction Facility 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 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 2. 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 ft) 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 ft) was observed. Running at this throttle position produced air speeds of approximately 0.4 mach.

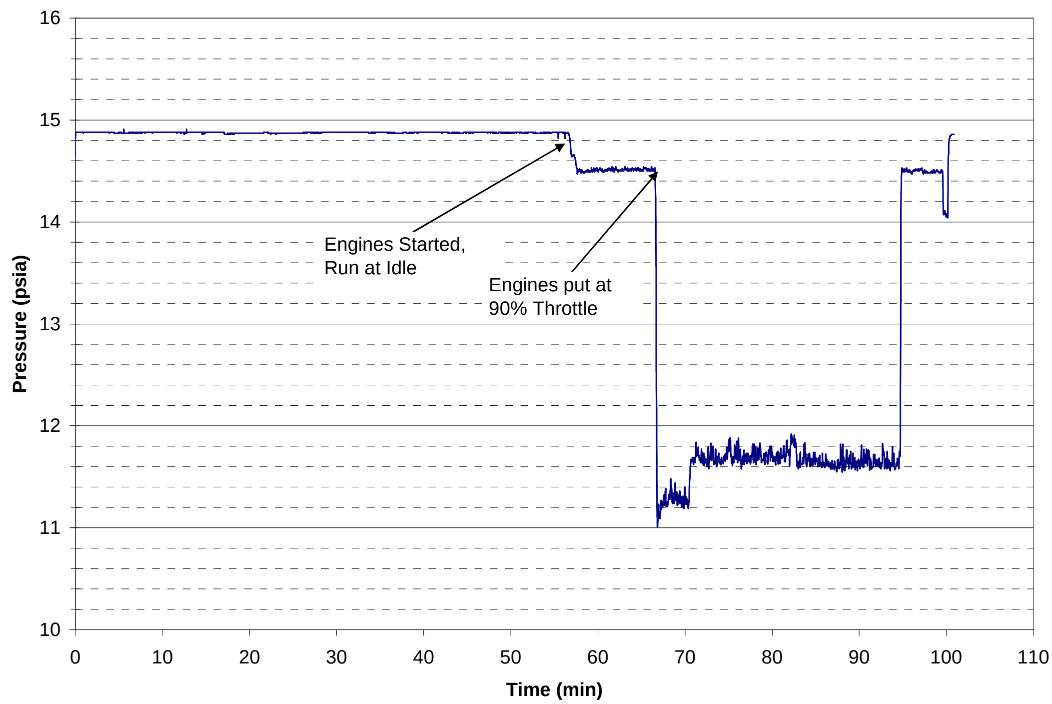

Figure 2. Typical Pressure Profile of Fuel Tank During Wind Tunnel Operations

3. TEST PROCEDURES.

3.1 ENVIRONMENTAL CHAMBER TESTS.

To examine the effect of radiant heating of a fuel tank from above on the progression of ullage flammability for both skin materials in a controlled environment, the fuel tank test article was tested in an environmental chamber. The fuel tank with each skin material was subjected to the same radiant heat source on the top skin for approximately 300 minutes in two separate tests. The fuel tank was first allowed to sit overnight in the environmental chamber with a 60% fuel load at 90°F ambient temperature to obtain a stable THC at the start of the test. After data illustrating the temperature stability and consistency was acquired for 20 minutes, the radiant heat source was switched on and the progression of temperature and flammability was monitored. Gas samples to measure THC were acquired approximately every 20 minutes.

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. Additionally, foam insulation was installed on all sides of the fuel tank to allow heating and cooling of the fuel tank only through the top and bottom surfaces. 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 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, 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. 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 start-up, prior to the engines being taken to 90% capacity, and every 5 minutes thereafter. Tests were conducted at fuel loads of 40%, 60%, and 80% with both aluminum and composite top and bottom skins. Heater settings were varied from a low to a high setting for each test condition. During the composite and aluminum comparative tests, all other variables, including heat input to the fuel tank, were maintained constant throughout the test interval.

Additionally, tests were conducted to examine the impact of material topcoat color on fuel tank temperature and THC concentrations. Aviation-grade primer and white paint were applied to the composite panels to determine if a light-colored paint might affect the material's heat retention, making it behave more like the bare aluminum material. Similarly, aviation-grade primer and black paint were applied to the aluminum panels to determine if a darker color causes the temperature and THC measurements to be similar to bare composite material, which was black in color.

4. DISCUSSION OF RESULTS.

4.1 ENVIRONMENTAL CHAMBER TEST RESULTS.

The progression of ullage flammability for both skin materials during identical radiant heating from above are compared in figure 3. Clearly, the top skin temperature of the composite fuel tank reached much higher temperatures when subjected to the same radiant heat source. This caused internal ullage and fuel temperatures to be much greater for the composite skin fuel tank, resulting in a significantly more flammable fuel tank. The environmental chamber temperature was held constant at 90°F. It was unclear how much the increase in flammability was due to the absorption of heat (because of the black color of the composite skin) or due to the lack of internal heat rejection (because the composite skin is a poor heat conductor). The aluminum fuel tank never reached the accepted lower flammability limit of approximately 2.0% during the entire 5-hour heating cycle. In contrast, the composite fuel tank reached the flammability limit within approximately 45 minutes of heating and reached a peak THC of more than twice the aluminum fuel tank.

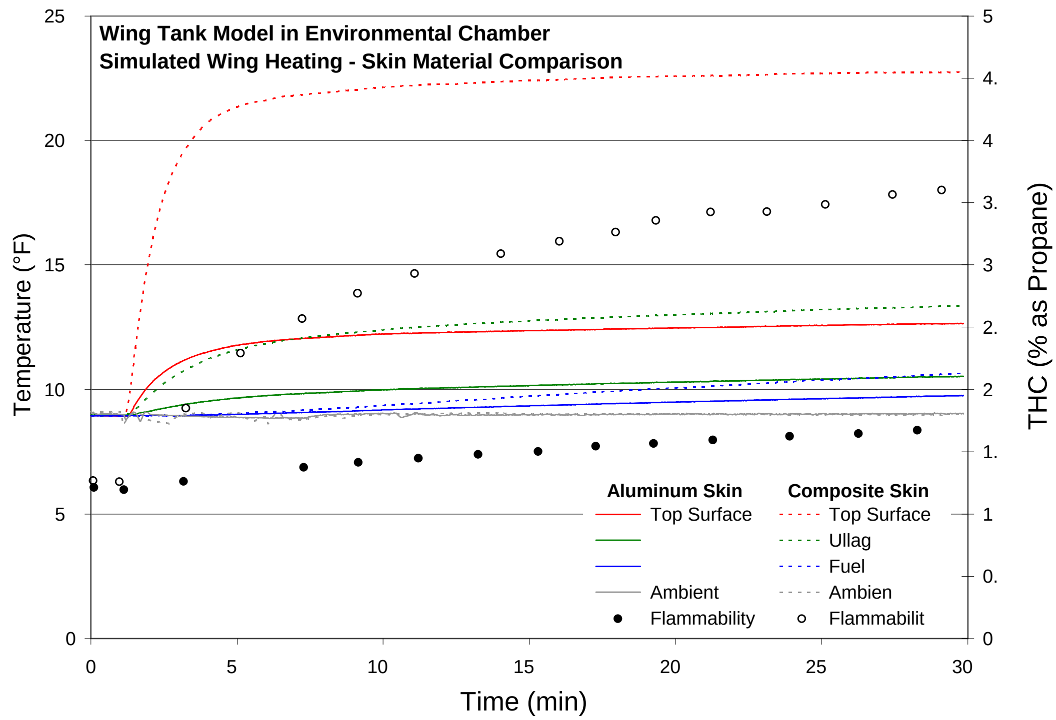

Figure 3. Comparison of Ground Heating Events for the Fuel Tank Test Article With Aluminum and Composite Skins

4.2 AIR INDUCTION FACILITY TEST RESULTS.

4.2.1 Panel Heat Test Results.

A series of initial tests were conducted to examine heat transfer through each panel prior to testing the panels installed on the fuel tank in the wind tunnel. Each panel was heated from above with the heaters in the high-heat setting with a single thermocouple placed at the center point on the inner surface of each panel. Heating continued for a full 20 minutes, followed by a 25-minute cool-down period. This test was conducted with the bare aluminum and composite panels and with the black-painted aluminum and white-painted composite panels.

The results of these tests are shown in figure 4. The difference in thermal properties of the bare composite and aluminum panels is evident, as the composite panel peaked at temperatures of approximately 240ºF; the aluminum panel peaked at a much lower temperature of approximately 110ºF. The white-painted 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. The black-painted aluminum panel, however, had a tremendous effect on the results, making the aluminum panel behave more like the composite panel. The temperature profile of the painted aluminum closely matched the bare and painted composite panels, with a peak temperature of approximately 240ºF. The cool-down period of the painted aluminum, the bare composite, and the painted composite panels also followed very similar trends.

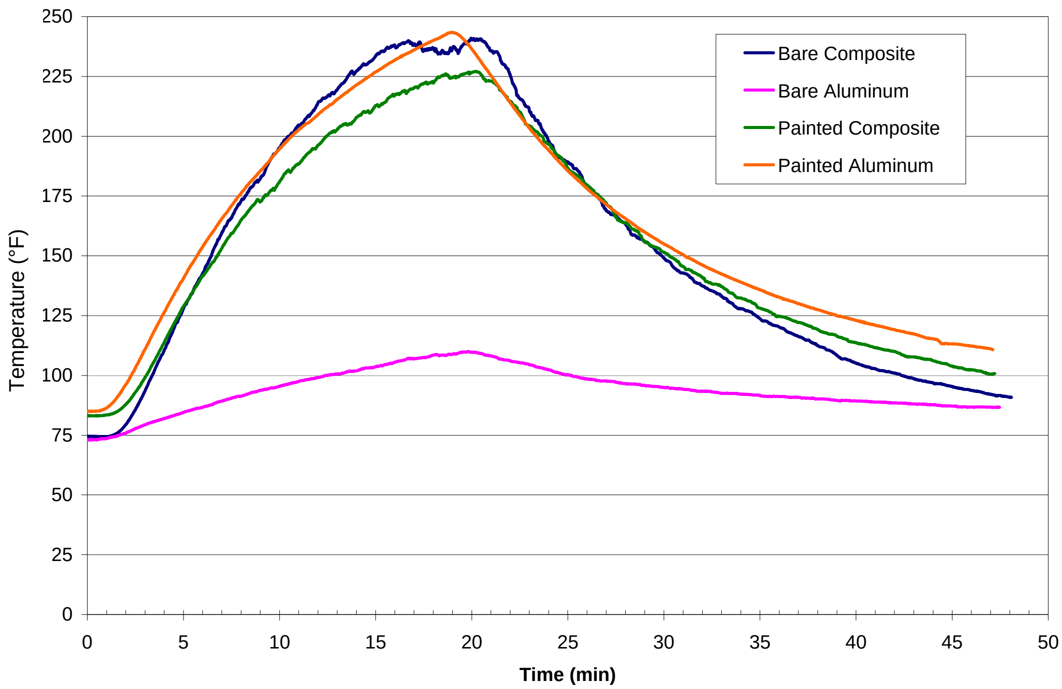

Figure 4. Comparison of Center-Point Temperature for all Materials During Panel Heating Test

4.2.2 Bare Material Test Results—High-Heat Setting.

Figures 5 through 7 display the results for the high-heat setting tests with the bare composite and aluminum panels. These figures consist of fuel temperature, ullage temperature, and flammability measurement results for the 40%, 60%, and 80% fuel load tests, respectively. The initial point at which airflow through the wind tunnel was started is shown in these figures 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 composite panel test, the first 21 minutes of data was lost due to a malfunction of the data acquisition system.

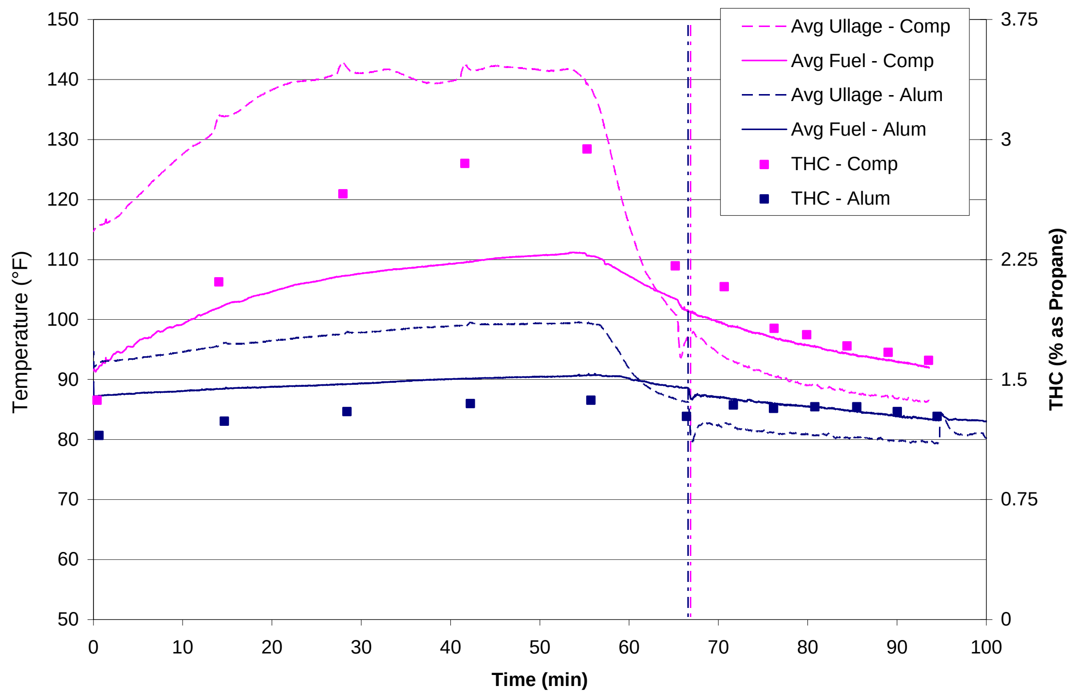

Figure 5. Comparison of Aluminum and Composite Fuel Tank Results for a 40% Fuel Load Under the High-Heat Setting

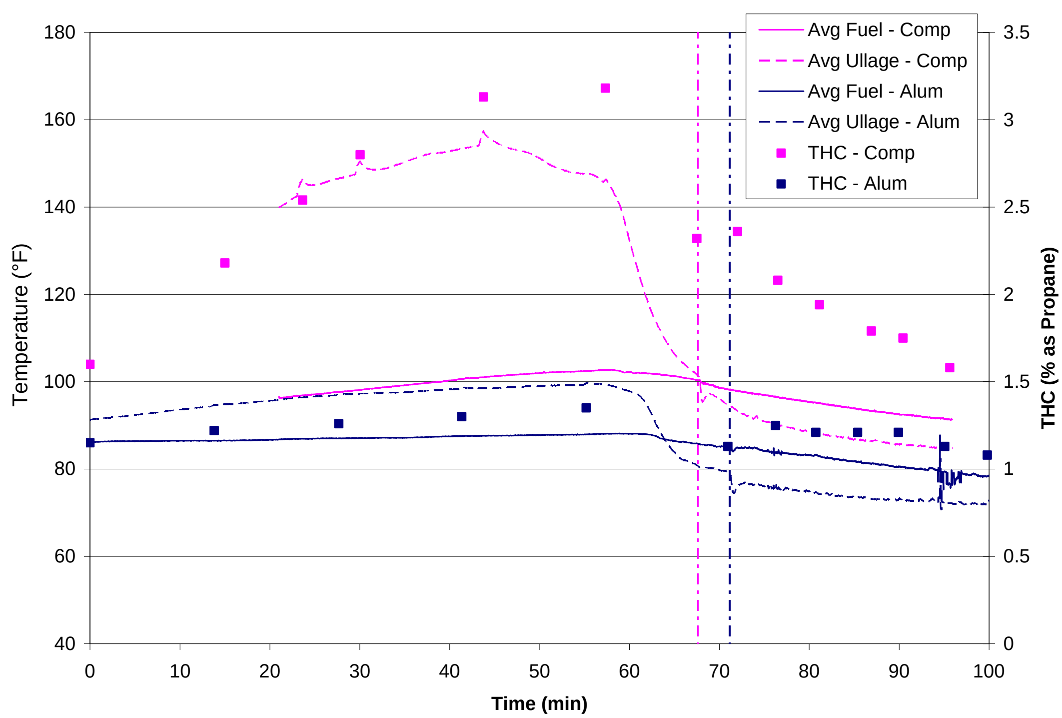

Figure 6. Comparison of Aluminum and Composite Fuel Tank Results for a 60% Fuel Load Under the High-Heat Setting

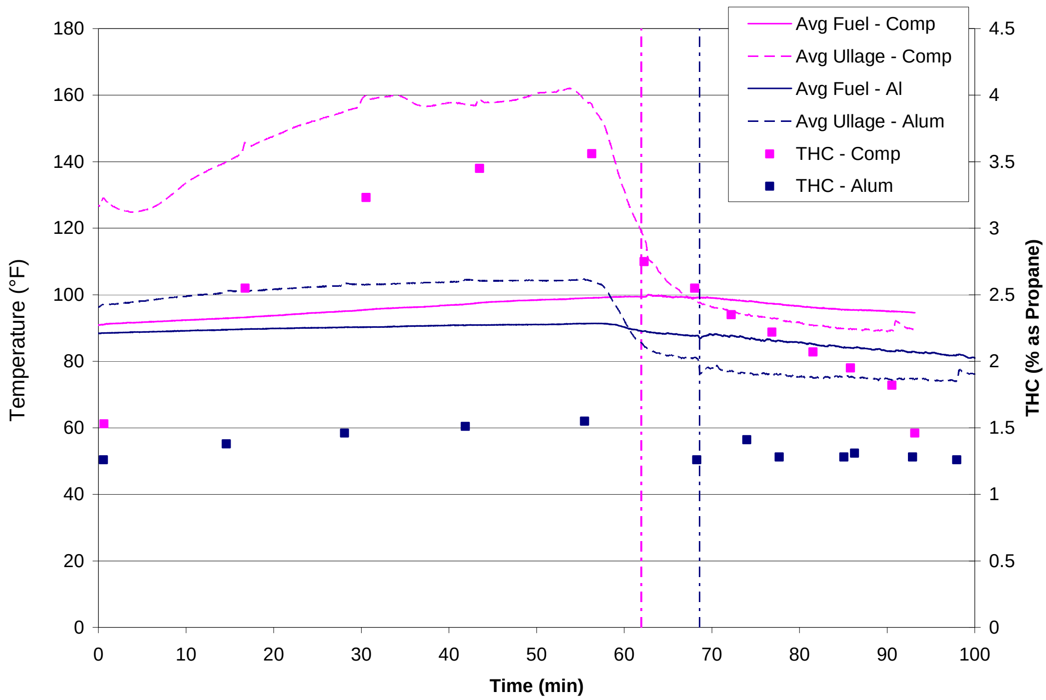

Figure 7. Comparison of Aluminum and Composite Fuel Tank Results for an 80% Fuel Load Under the High-Heat Setting

As observed in the environmental chamber test results, significantly higher ullage temperatures are evident in each composite tank test. In each test, the ullage temperature in the composite fuel tank is between 40°-60°F higher than those from the aluminum fuel tank tests. The average fuel temperatures, however, vary by only 10°F and show much less of a temperature increase than the ullage. THC measurements in each of the aluminum fuel tank tests vary only slightly throughout the full length of the test, whereas extremely large increases can be observed in the composite fuel tank tests.

The correlation between high THC measurements and high ullage temperature increases is further indication, as shown in reference 4, that ullage temperature changes are the driving force behind in-flight flammability of wing fuel tanks that are heated from above. This contrasts the CWT (which is heated from below) in which the bulk average fuel temperature is the main driver behind fuel tank flammability.

As airspeed through the wind tunnel was initiated, significant and almost immediate decreases in ullage temperature were observed in both the aluminum and composite fuel tanks. These changes for the aluminum fuel tank, however, are quite reduced, as the temperature difference relative to ambient is much less than in the composite fuel tank tests. Fuel temperature changes in both the composite and aluminum fuel tanks show little change throughout the operation of the wind tunnel. Again, this is due to the low difference between the fuel and ambient temperature. THC measurements in the aluminum fuel tank tests showed minimal change, while measurements in the composite fuel tank tests showed a significant decrease corresponding to the large decrease in ullage temperature. Even with this rapid decrease in THC, however, the fuel tank remained in the flammable region, greater than roughly 2% C_3H_8, for some time after airflow was started. In the 80% fuel load case, the fuel tank remained in the flammable region for close to 25 minutes after the 90% throttle setting was reached.

4.2.3 Bare Material Test Results—Low-Heat Setting.

Figures 8 through 10 display the results for the low-heat setting tests with the bare composite and aluminum panels. Similar to the high-heat test results, higher ullage temperatures were observed in each composite fuel tank test. As expected, however, due to the lower amount of heat input to the fuel tank, the temperatures were not as elevated as in the high-heat tests. In each test, the ullage temperature in the composite fuel tank was between 15°-30°F higher than those from the aluminum fuel tank tests. The average fuel temperatures, however, varied by approximately 10°F and showed much less of a temperature increase than the ullage. As airspeed through the wind tunnel was initiated, the fuel tanks behaved very similarly to what was observed in the high-heat tests of both bare materials; however, the ullage temperature decreases in both fuel tanks was less severe, as the initial temperatures were significantly reduced due to the lower-heat setting.

The THC profiles show similar trends as well. The composite fuel tank tests showed somewhat significant increases in THC measurements, though not nearly as severe as in the high-heat tests. In each test, the composite tank peaked between 2% and 2.25% C_3H_8 and then decreased as airspeed through the wind tunnel was initiated. The aluminum fuel tank tests peaked between 1.2% and 1.4% C_3H_8 and remained relatively steady throughout the remainder of the test.

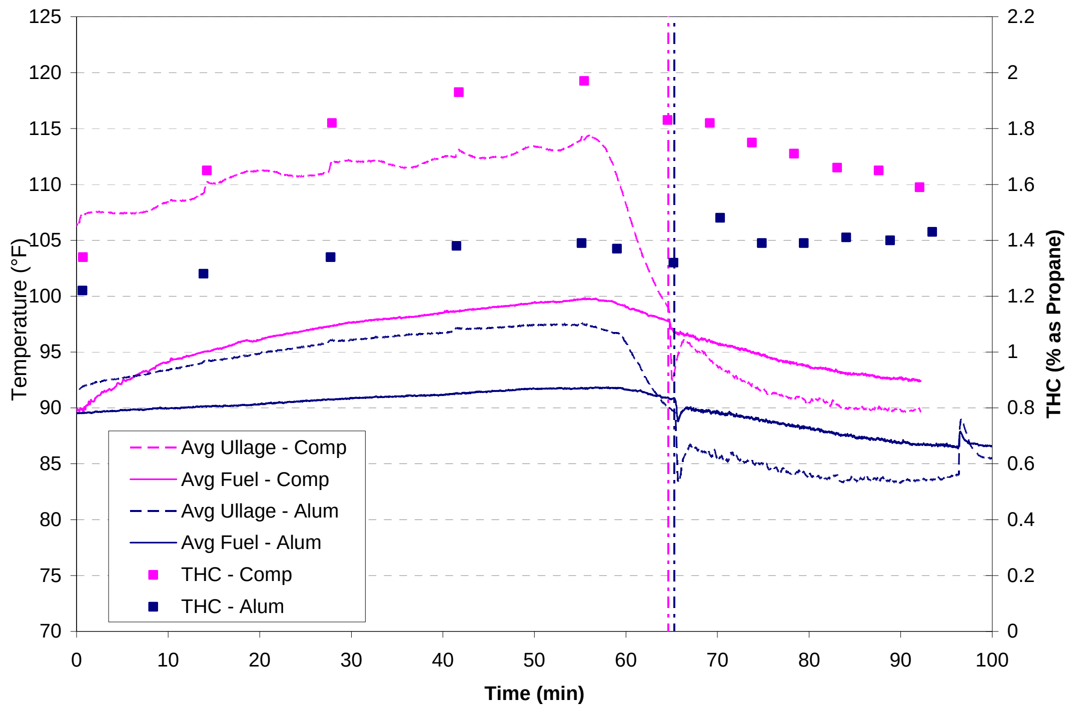

Figure 8. Comparison of Aluminum and Composite Fuel Tank Results for a 40% Fuel Load Under the Low-Heat Setting

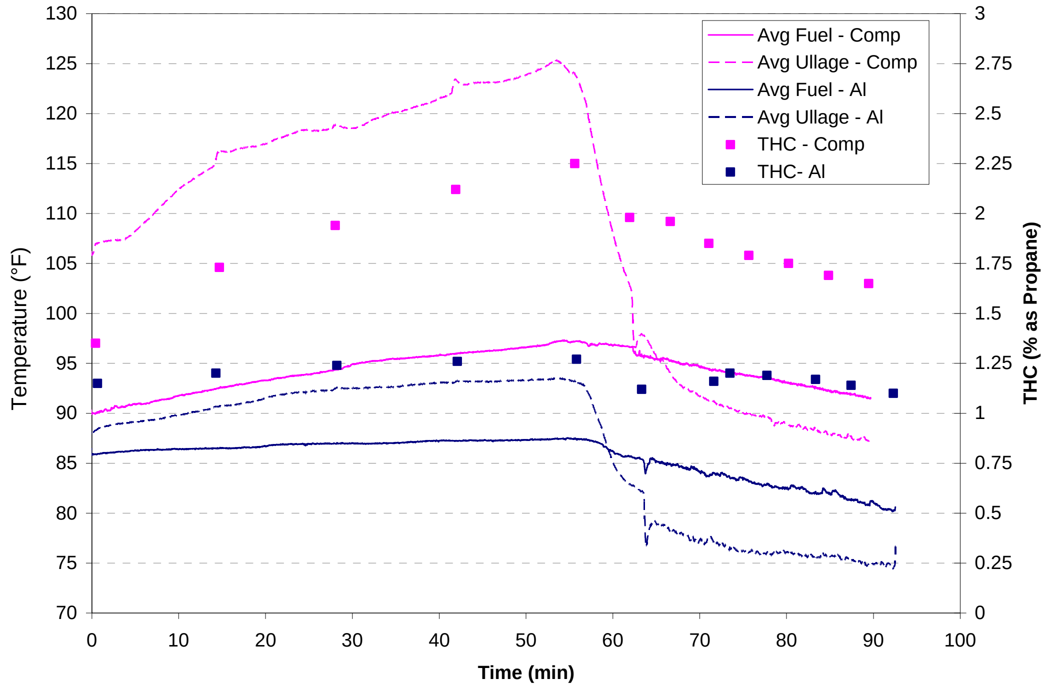

Figure 9. Comparison of Aluminum and Composite Fuel Tank Results for a 60% Fuel Load Under the Low-Heat Setting

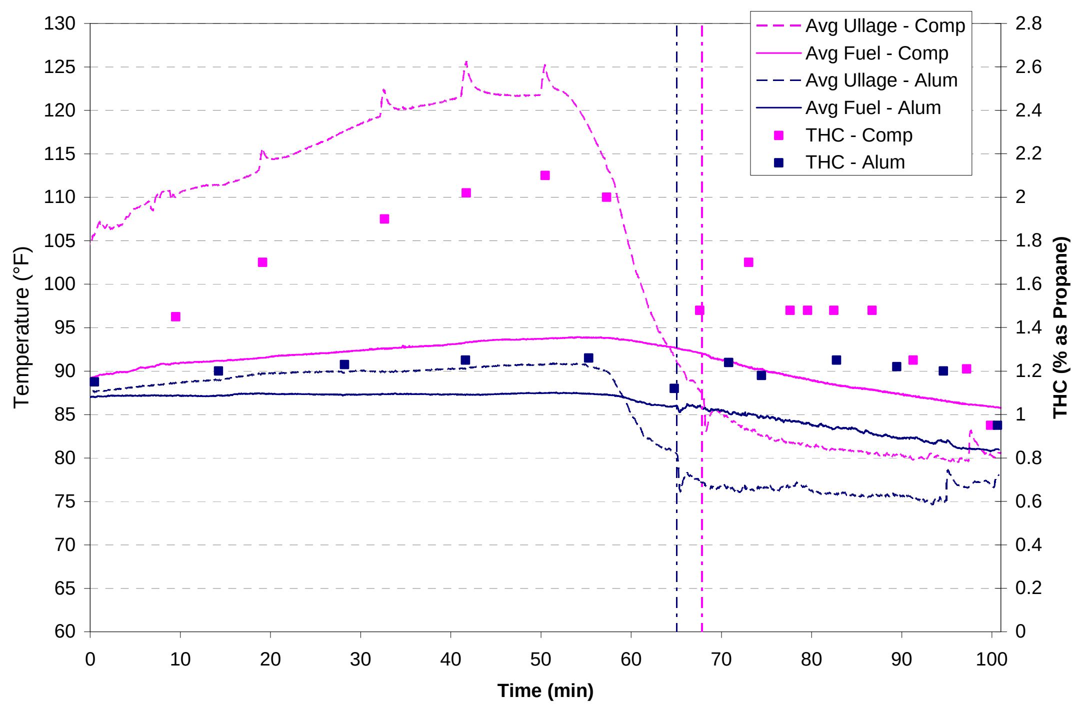

Figure 10. Comparison of Aluminum and Composite Fuel Tank Results for an 80% Fuel Load Under the Low-Heat Setting

4.2.4 Superheated Aluminum Test Results.

A single test was conducted with the bare aluminum material and a 60% fuel load in which the fuel tank was heated in a manner that generated ullage temperatures similar to what was observed in the bare composite fuel tank test. This was done to determine the behavior of an aluminum fuel tank during wind tunnel operation, when heated sufficiently so as to generate ullage temperatures and THC measurements similar to a composite fuel tank.

The results from this test and the comparable composite fuel tank test are shown in figure 11. Although ullage and fuel temperatures matched quite closely with both material fuel tanks, the aluminum fuel tank THC concentration never quite reached the same level as the composite fuel tank. The aluminum fuel tank peaked at approximately 2.6% C_3H_8, whereas the composite fuel tank peaked at approximately 3.2% C_3H_8. When airflow through the wind tunnel was initiated, however, it was observed that both the fuel tank ullage temperatures and the THC profiles behaved similarly for both materials.

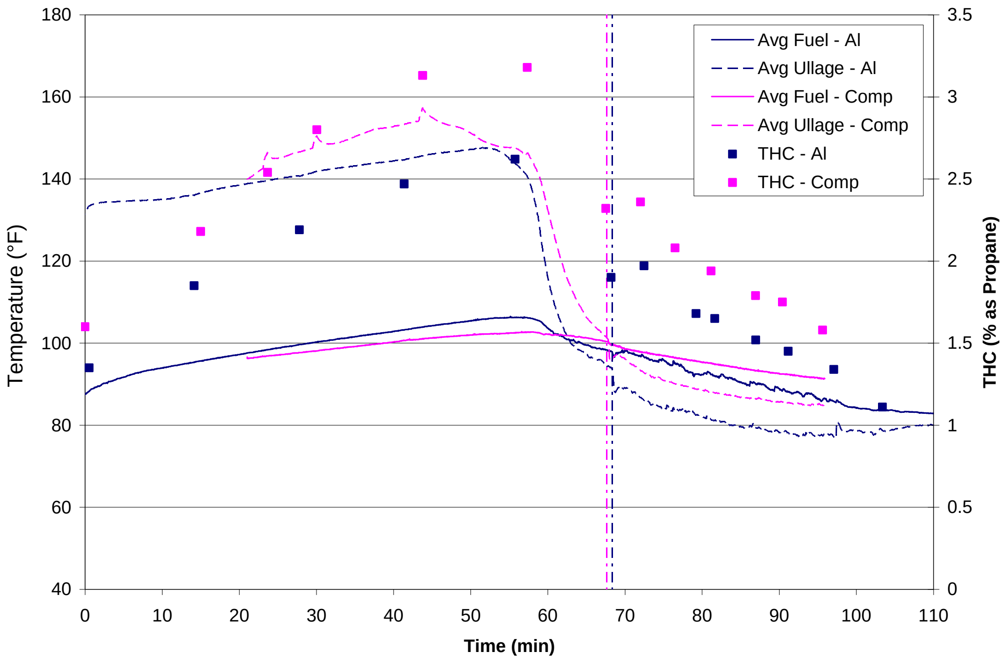

Figure 11. Comparison of Superheated Aluminum and Composite High-Heat Setting Fuel Tank Results for a 60% Fuel Load

4.2.5 Painted Material Test Results.

Additional tests were conducted to examine the impact of painted material topcoat color on fuel tank temperature and THC concentrations. Primer and white paint were applied to the composite panels to determine if a light-colored paint affected the material's heat retention, making it behave more like the bare aluminum material. Similarly, primer and black paint were applied to the aluminum panels to determine if a darker color caused the temperature and THC measurements to be similar to the bare composite material, which was black in color.

Figures 12 and 13 show a comparison of the painted and bare composite materials for the 40% and 60% fuel loads under the high-heat setting. It is evident from these figures that the painted panels had essentially no effect on the resulting ullage temperatures and THC measurements. These ullage temperature and THC measurements were virtually identical throughout the full length of both tests. Fuel temperature in the 60% fuel load test showed some variation, with the painted composite material resulting in a slightly higher fuel temperature of approximately 15ºF throughout the test.

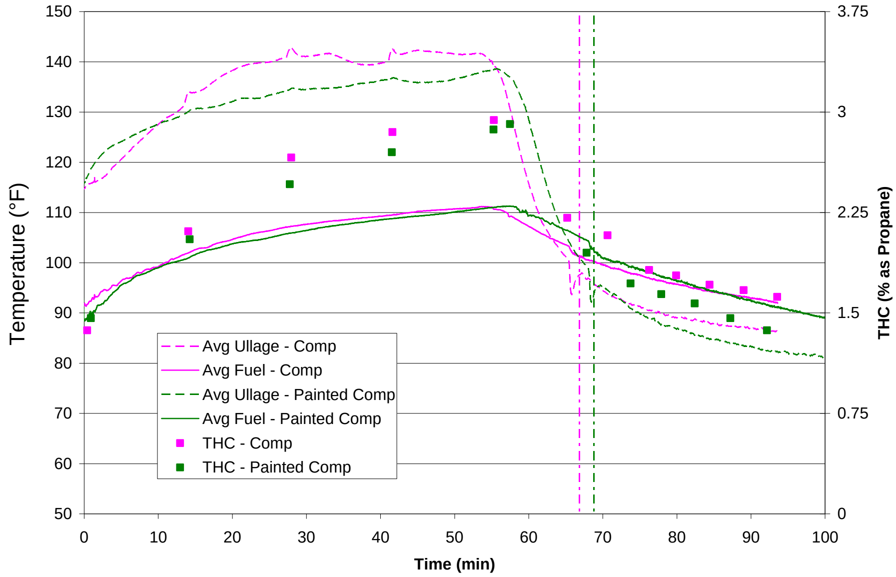

Figure 12. Comparison of Painted and Bare Composite Material Fuel Tank Results for a 40% Fuel Load Under the High-Heat Setting

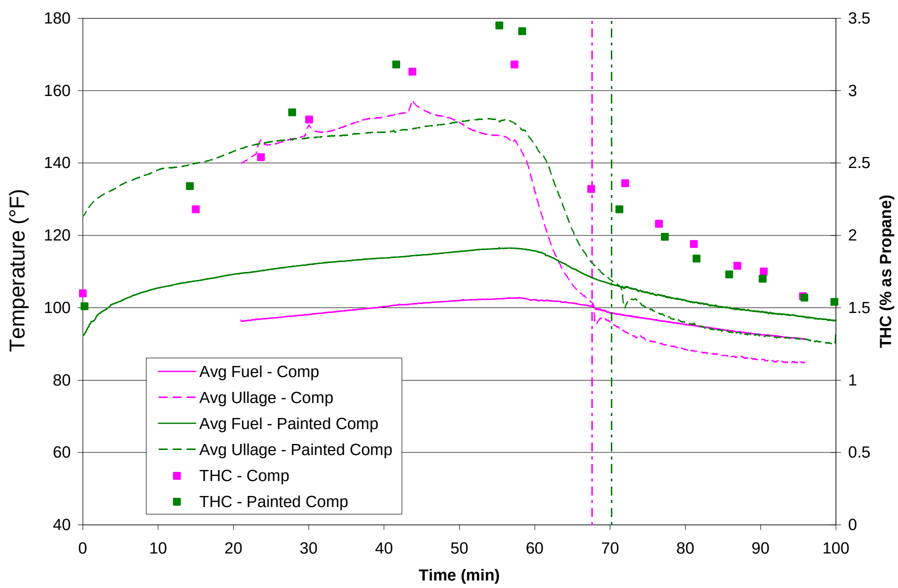

Figure 13. Comparison of Painted and Bare Composite Material Fuel Tank Results for a 60% Fuel Load Under the High-Heat Setting

Figures 14 and 15 show a comparison of the painted aluminum and composite materials for the 40% and 60% fuel loads under the high-heat setting. The results were as expected, based on the results of the panel heat tests and superheated aluminum panel tests discussed in sections 4.2.1 and 4.2.4 of this report, respectively. Ullage and fuel temperature profiles of the two fuel tanks match very closely in both cases, just as in the panel heat tests. Similarly, as observed in the superheated aluminum fuel tank tests, the THC profiles showed similar trends, although the painted aluminum fuel tank never quite reached the peak values that were observed with the composite fuel tank. Due to the increased ullage temperatures, however, the THC measurements were quite elevated from what was observed with the bare aluminum material. On the cooling side, as airflow through the wind tunnel was initiated, both fuel tanks behaved similarly in terms of temperature and THC profiles.

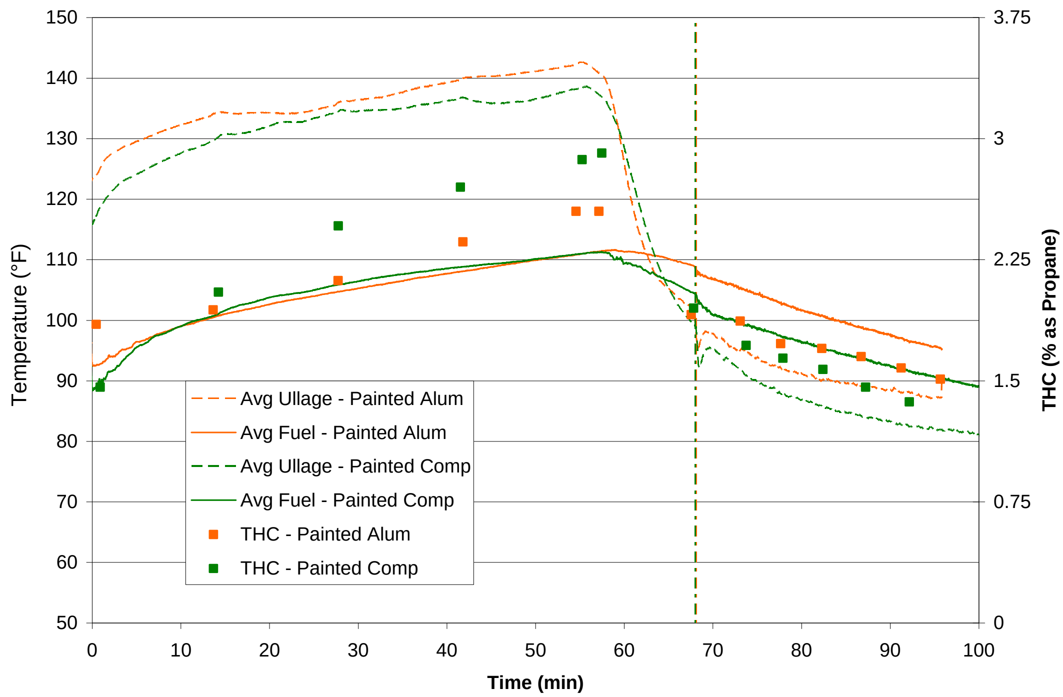

Figure 14. Comparison of Painted Aluminum and Composite Material Fuel Tank Results for a 40% Fuel Load Under the High-Heat Setting

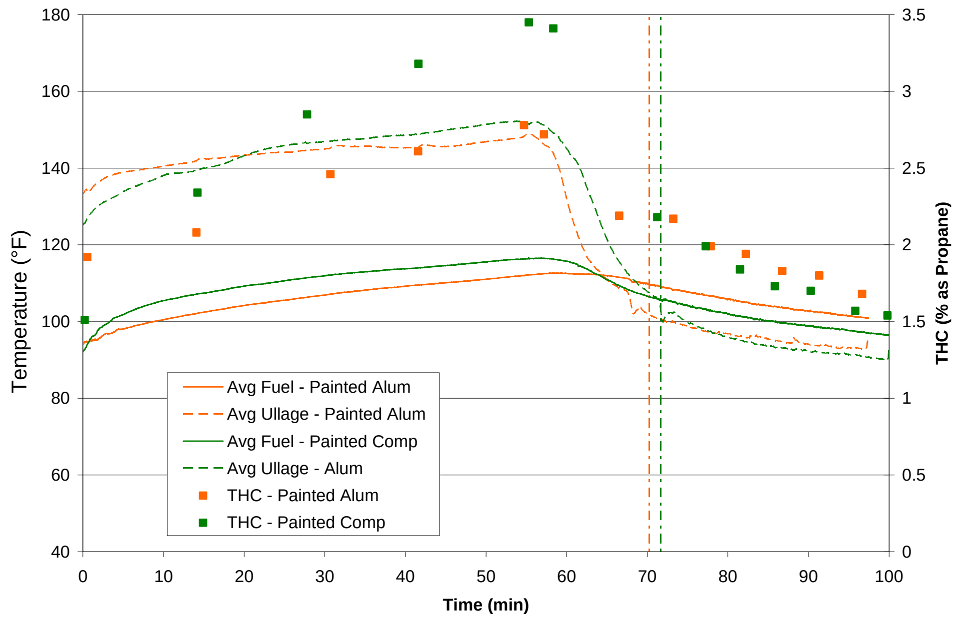

Figure 15. Comparison of Painted Aluminum and Composite Material Fuel Tank Results for a 60% Fuel Load Under the High-Heat Setting

5. SUMMARY OF RESULTS.

Tests were conducted in the environmental chamber and the Air Induction Facility (wind tunnel) to examine the variation in flammability exposure of a fuel tank comprised of a composite material skin and a traditional aluminum skin.

The results from the environmental chamber tests showed that the outer surface skin temperature for the composite fuel tank reached much higher temperatures when subjected to the same radiant heat source. This higher skin temperature caused the internal ullage temperature to be much higher for the composite skin fuel tank and resulted in significantly higher THC measurements. The aluminum fuel tank never reached the accepted lower flammability limit of approximately 2.0% during the entire 5-hour heating cycle. In contrast, the composite fuel tank reached the flammable limit within approximately 45 minutes of heating and reached a peak THC of more than twice that of the aluminum fuel tank.

Air induction test facility tests showed similar changes in initial temperature and THC profiles following radiant heating of the skin from above. In each high-heat test with bare materials, the ullage temperature in the composite fuel tank was between 40°-60°F higher than the aluminum fuel tank tests. The average fuel temperatures, however, varied by only 10°F and showed much less of a temperature increase than the ullage. THC measurements in each bare aluminum fuel tank test varied only very slightly throughout the full length of the test, whereas extremely large increases were observed in the composite fuel tank tests during heating. These measurements peaked at between 3% and 3.5% C_3H_8 for the composite fuel tank, whereas peak readings of approximately 1.5% C_3H_8 were observed for each aluminum fuel tank test. When the wind tunnel was initiated, a decrease in ullage temperature was observed. The largest ullage temperature decrease occurred in the composite fuel tank as this had the largest temperature differential relative to ambient. THC in the aluminum fuel tank tests showed minimal change, whereas measurements in the composite fuel tank tests showed a significant decrease, which closely tracked the large decrease in ullage temperature. Even with this rapid decrease in THC, the composite fuel tank remained in the flammable region for a significant amount of time, up to 25 minutes at the 90% throttle position of the wind tunnel.

The low-heat tests with bare materials displayed similar behavior, although the temperatures and corresponding THC were not as elevated as in the high-heat tests due to the lower amount of heat input. In each test, the average ullage temperature in the composite fuel tank was between 15°-30ºF higher than in the aluminum fuel tank. The average fuel temperatures varied by approximately 10ºF. The composite fuel tank tests showed THC, which peaked between 2% and 2.25% C_3H_8, whereas the aluminum fuel tank tests peaked between 1.2% and 1.4% C_3H_8.

A single test was conducted with the bare aluminum material and a 60% fuel load in which the fuel tank was heated in such a manner as to generate ullage temperatures similar to what was observed in the bare composite fuel tank before wind tunnel operations. This test showed that given the proper conditions, an aluminum fuel tank could result in temperatures and THC measurements that resembled a composite fuel tank during fuel tank cooling under simulated flight conditions.

Additionally, tests were conducted to examine the impact of painted material topcoat color on fuel tank temperature and THC concentrations. Primer and white paint were applied to the composite panels to determine if a light-colored paint affected the material's heat retention, making it behave more like the bare aluminum material. Similarly, primer and black paint were applied to the aluminum panels to determine if a darker color causes the temperature and THC to be more similar to the bare composite material, which was black. These tests showed that the painted composite panels had essentially no effect on the resulting ullage temperatures and THC. However, results from the painted aluminum fuel tank test showed a drastic effect, making the fuel tank behave more similarly to the composite fuel tank than the bare aluminum fuel tank. The ullage and fuel temperature profiles, as well as THC measurements of the painted aluminum fuel tank, matched very closely to the painted composite fuel tank.

The correlation between THC and ullage temperature that was observed in all tests corroborated previous findings, as shown in reference 4, that ullage temperature changes are the driving force behind in-flight flammability of fuel tanks initially heated from above. This is contrary to what had been found for a CWT heated from below, in which the bulk fuel temperature is the main driver behind fuel tank flammability.

The tests showed that composite fuel tanks, regardless of topcoat color, are significantly more flammable than traditional aluminum fuel tanks when heated from above because they transfer heat into the fuel tank much more readily. However, the results also showed that under the right conditions, either through additional heat input or a change in topcoat color, an aluminum fuel tank could behave in a similar manner to a composite fuel tank.

6. REFERENCES.

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