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Evaluation of Carbon Fiber Composite Flammability: Effect of Sample Thickness and External Ambient Conditions on Inboard Surface Flame Propagation

Robert I. Ochs

January 2015

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16. Abstract

A series of tests was performed to determine the relative effect of test sample thickness and external ambient conditions on the flame propagation potential of carbon fiber-reinforced epoxy airplane fuselage materials. A test rig was used to simulate an inaccessible cabin area, with a fire source placed at the bottom and thermocouples positioned along the length of the test panel. The test rig could vary the ambient conditions of the external, non-fire side of the sample. A scenario of minimal heat loss was simulated by placing a 1/2-inch thick ceramic fiberboard insulation panel directly on the exterior surface, whereas a scenario of high heat loss was simulated by flowing water along the exterior surface of the panel. Different solid laminate sample thicknesses and one sandwich panel with four plies on each side of a 1-inch thick honeycomb core were tested. Post-test burn length and width measurements were made to assess the level of flame propagation. Test results indicated that the relative flammability of a composite material is dependent upon the rate of heat dissipation from the flame-impinged surface, which varies depending on the panel thickness and the heat dissipation rate at the outboard surface. Thin panels (0.04- to 0.1-inch thick) were found to propagate flames under static ambient conditions, and were also more heavily influenced by the heat transfer at the outboard surface. Thicker panels (0.13- to 0.37-inch thick) were found to have enough thermal mass between the flame-impinged surface and the outboard surface to not propagate flames under static ambient conditions, and were relatively unaffected by the heat transfer at the outboard surface. The sandwich panel was found to behave like a thin composite panel fitted with an insulated outboard surface and was entirely unaffected by the heat dissipation rate at the outboard surface.

17. Key Words
Composite, Flammability, Flame propagation, Inaccessible area, In-Flight, Hidden fire, Carbon fiber

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Al	Aluminum
FAA	Federal Aviation Administration
CFB	Ceramic fiberboard
ACF	Aerospace carbon fiber
BTU	British Thermal Unit

EXECUTIVE SUMMARY

The increasing use of composites as primary and secondary structures in commercial airplanes presents unique certification challenges for the Federal Aviation Administration (FAA). Traditional metallic structures do not react with fires and, therefore, have not been required to meet any of the FAA's cabin interior fire test requirements, which have increased in severity in recent years to protect against fires in inaccessible areas after the fatal in-flight fire of Swissair 111 in September 1998. The FAA imposes Special Conditions to certify composite fuselage airplanes for flammability. A standardized lab-scale test method is currently being refined for more general implementation. This study was conducted to determine the effect of composite panel thickness and external heat loss on inboard flame propagation when exposed to a hidden fire.

A variety of composite samples were evaluated, all produced from the same unidirectional carbon epoxy prepregs with toughened 350°F epoxy systems. The samples ranged from 0.044 inch to 0.3675 inch in thickness; one honeycomb sandwich panel measured 1.088 inches in thickness. An intermediate-scale test apparatus was constructed with the ability to simulate the narrow insulated spaces in an inaccessible area of an airplane cabin. The apparatus held a test panel measuring 18 inches wide by 48 inches long at a 30-degree angle from the horizontal plane. A urethane foam block, 4 inches square by 9 inches tall, was the fire source, producing a flame that directly impinged on the inboard surface of the test panel. Inboard panel temperatures were measured with 8 thermocouples and video was recorded during the test. Post-test burn length and width measurements were taken to evaluate the level of flame propagation. Three different heat-dissipation rate scenarios were evaluated at the outboard surface: static ambient air, insulated surface with ceramic fiberboard, and enhanced cooling with water flowing on the outboard surface.

The results from this test series indicate that the relative flammability of a composite material is dependent on the rate of heat dissipation from the flame-impinged surface. This varies depending on several factors, including the panel thickness and the heat dissipation rate at the outboard surface. Thin panels (0.04-inch to 0.1-inch thick) were found to propagate flames under static ambient conditions, and were also more heavily influenced by the heat transfer at the outboard surface. Thicker panels (0.13-inch to 0.37-inch thick) were found to have enough thermal mass between the flame-impinged surface and the outboard surface to not propagate flames under static ambient conditions, and were relatively unaffected by the heat transfer at the outboard surface. The sandwich panel was found to behave like a thin composite panel with an insulated outboard surface, and was entirely unaffected by the heat dissipation rate at the outboard surface. These results can be used as general knowledge for assessing the in-flight fire threat for composite fuselage airplanes. Actual composite airplane configurations will have varying thicknesses because the composite skin in some areas may be thinner than the structural members, such as stringers and frames. These components also have varying levels of contact with the external ambient conditions; the outboard surface of the skin is in direct contact with the external air flow, but the stringers and frames do not have direct contact, resulting in different levels of heat conduction from a hidden fire. Consideration must be given to these factors when performing an analysis of in-flight composite material flammability.

INTRODUCTION

BACKGROUND

Modern transport airplanes have increasing quantities of nonmetallic composite materials throughout the airframe, including the fuselage skin and structural components. Substitution of metallic, nonflammable components with potentially flammable composite materials introduces certification challenges because traditional airframes are constructed of metallic materials, which do not require an evaluation for flammability. The use of Special Conditions is currently the only method of certifying these nontraditional composite airplanes for flammability [1]. The Federal Aviation Administration must ensure that the flammability evaluation by the applicant, either by test or analysis, adequately demonstrates that the composite structure provides a level of safety equivalent to or better than traditional aluminum (Al) constructions. This report describes tests conducted to study the effect of sample thickness and external heat loss on flame propagation from a hidden fire.

OBJECTIVE

The aim of this work is to develop a general understanding of the effect of sample thickness and external heat loss on flame propagation on composite aircraft fuselage skin when exposed to a hidden fire source.

EXPERIMENTAL CONFIGURATIONS

TEST SAMPLES

The various composite samples procured for this test series are listed in table 1. The samples were constructed of unidirectional carbon tape prepregs with a toughened 350°F epoxy system, and are referred to as aerospace carbon fiber #1 (ACF1) in this report. All samples measured 18 inches wide by 48 inches long. Five different thickness panels were tested, as well as one sandwich panel, which consisted of the ACF1-4 material bonded to each side of a 1-inch-thick meta-aramid honeycomb core.

Table 1. Composite Sample Configurations

Sample ID	# Plies	Thickness (in)	Thickness (mm)	Layup
ACF1-4	4	0.044	1.1176	(0,90,90,0)
ACF1-8	8	0.1005	2.5527	(0,45,-45,90)s
ACF1-16	16	0.1325	3.3655	(0,45,-45,90)2s
ACF1-24	24	0.2775	7.0485	(0,45,90,-45,90,0)2s
ACF1-32	32	0.3675	9.3345	(0,45,-45,90)4s
ACF1-HC	4-HC-4	1.088	27.6352	(0,90,90,0)

TEST APPARATUS

A sample holder, shown in figure 1, was constructed to simulate an inaccessible area in an aircraft cabin. The sample was 18-inch wide by 48-inch long and was placed in a frame constructed from 1-inch angle stock. The inboard side of the panel was enclosed with an insulated sheet metal shroud to simulate the insulation and backside of the cabin sidewall. The distance from the inboard face of the test panel to the insulated shroud was 1 inch. The outboard side of the test sample was exposed to ambient conditions in the laboratory. A small, insulated enclosure on the bottom of the test rig housed the fire source, a 4″ by 4″ by 9″ untreated urethane foam block with 0.61 cubic inches (10 milliliters) of heptane soaked into the bottom to promote uniform burning. The foam block was placed on a 4-inch square pan with a spike in the center to hold it in place. A semicircular sheet metal shroud insulated with fiberglass batting was placed around the foam block to prevent heat loss and to direct heat towards the test panel. The panel was oriented at an angle of 30 degrees from the horizontal plane. Panel temperatures were measured during the test with open bead K-type thermocouples placed within 1/8 inch of the inboard panel surface, 3 inches on either side of the vertical centerline of the panel, and spaced at the intervals defined in figure 2. Video was recorded during the test for analysis of burning behavior.

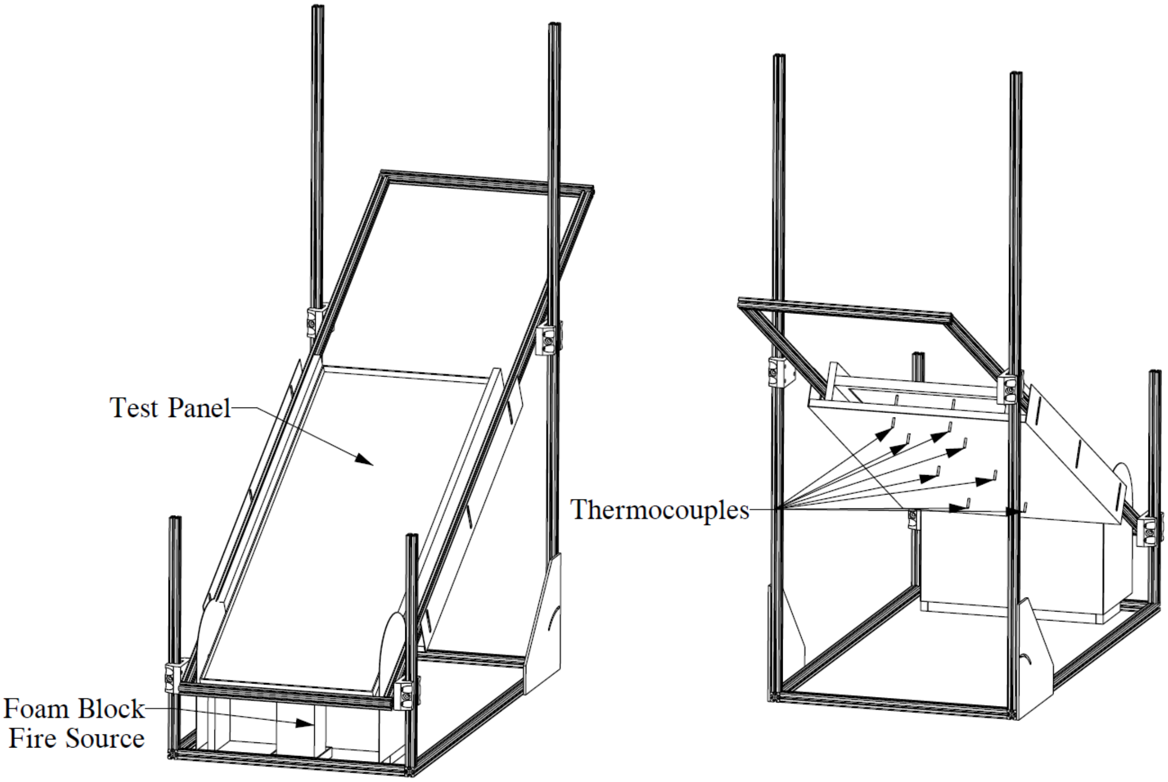

Figure 1. The Test Apparatus, Front and Back View

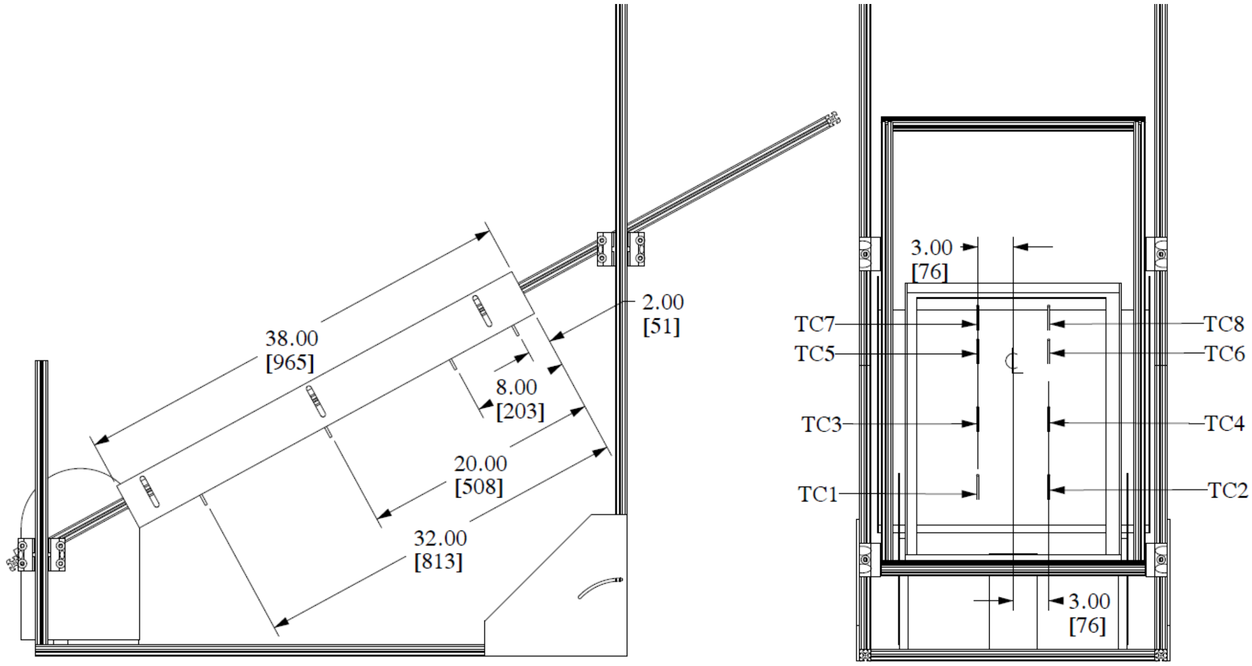

Figure 2. Location of Thermocouples on the Test Apparatus

<u>External Ambient Conditions.</u> The external, backside heat loss rate of the panel was controlled by one of two methods. In the first method, the insulated panel tests were conducted by placing a 1/2-inch thick (12.7 mm) ceramic fiberboard (CFB), measuring 18-inches wide by 48-inches long (457.2 mm by 1219.2 mm), directly on the outer surface of the test panel. For the second method, the enhanced cooling tests were conducted by flowing thin streams of water along the back surface of the panel. A 3/8-inch (9.525 mm) diameter, 18-inch long (457.2 mm) copper pipe was installed near the top of the test panel holder. One end of the pipe was closed off and the other was connected to a shutoff valve and a water supply line. Twenty-four 1/16-inch diameter holes were made in the copper pipe to allow thin streams of water to flow out and down along the back surface of the test panel. A water catch rail and drain were made at the bottom of the sample frame to ensure no water entered the inside of the test rig.

<u>TEST PROCEDURE</u>

All tests were performed in a 26′ by 52′ lab with a 20-foot ceiling and relatively constant temperature in the range of 60°F–80°F (15.5°C–26.6°C). The foam block fire source was prepared by measuring out 0.61 cubic inches (10 milliliters) of heptane in a graduated cylinder. The heptane was poured into a shallow pan and the bottom of the foam block (the 4-inch square side) was used to soak up the heptane from the pan. The foam block was then pierced in the center by the spike in the foam block holder and pushed down so that the heptane-soaked end of the foam block was flush with the surface of the foam block holder. The foam block holder was then placed into the fire box end of the test apparatus, aligned horizontally on the centerline of the test rig. A flat piece of sheet metal, 18-inches wide by 12-inches long (457.2 mm by 304.8 mm), was placed in the test panel frame to determine the distance from the test panel to the top-back edge of the foam block, as displayed in figure 3. The top-back edge made contact with the inside surface of the sheet metal. The sheet metal was then removed, and the panel to be tested was placed in the frame. Small clamps were used to hold the panel in place in the event of flexing during heating. The foam block was ignited with a handheld lighter, after which personnel exited the room to observe the test remotely. The test was considered complete when no visible smoke was seen emanating from the test apparatus. The lab was then evacuated with exhaust fans, and personnel re-entered the room to remove the test panel. The burn length and width were measured once the panel had cooled. Burned areas were considered to be those that had shown evidence of resin depletion and exposed carbon fibers on the surface. Sooted or discolored areas were cleaned with a mild detergent and were not considered in the measured burn length.

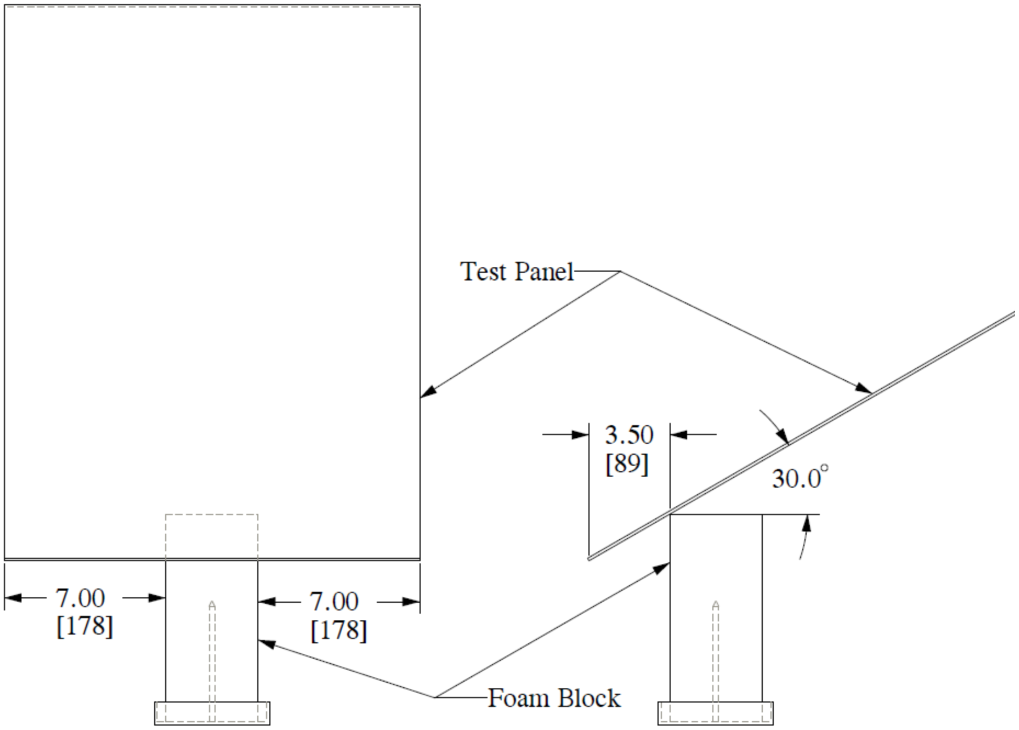

Figure 3. Placement of the Foam Block Relative to the Test Panel

RESULTS

BASELINE TESTS

A baseline test series was performed to evaluate the temperature profile near the sample surface during foam block flame impingement for materials with different thermal conductivities that do not burn. An Al sheet, 1/16-inch (1.59 mm) thick with a thermal conductivity of 1160 British Thermal Units (BTUs)·in/hr·ft^2·°F (167 W/m·K), and a CFB panel, 1/2-inch thick with a thermal conductivity of 0.80 BTU·in/hr·ft^2·°F (0.11 W/m·K), were chosen for this series. The temperature profile from the Al sheet is displayed in figure 4, whereas the temperature profile from the CFB is displayed in figure 5. The peak measured temperature, time to peak temperature, and the temperature profile width are listed in table 2. The peak temperature is defined as the highest measured value of all 8 thermocouples during the test, and the profile width is defined as the width of the temperature pulse at half the maximum value. The widths of both temperature profiles are similar and provide an estimate for the foam block fire source active burn time, approximately 40–60 seconds to the peak and 100 seconds total. The peak temperature, however, differs significantly because of the different thermal conductivities of the test panels. Because neither of the materials burn, but both have drastically different peak temperatures, the peak measured temperature cannot be used solely to indicate test severity; it is a function of heat loss through the test panel. The temperature profile width, combined with the peak, can indicate extended burning beyond that from the foam block fire source.

Table 2. Temperature Profile Information for Baseline Tests

Sample ID	Peak Temperature (°F)	Time to Peak (sec)	Profile Width (sec)
Al	835	53	98
CFB	1356	42	93

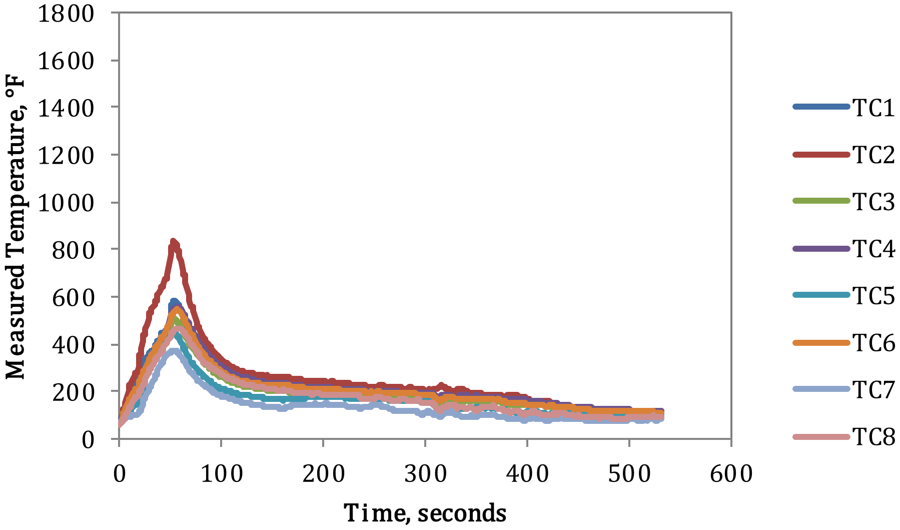

Figure 4. Measured Panel Temperatures for 1/16-Inch Thick Al Sheet

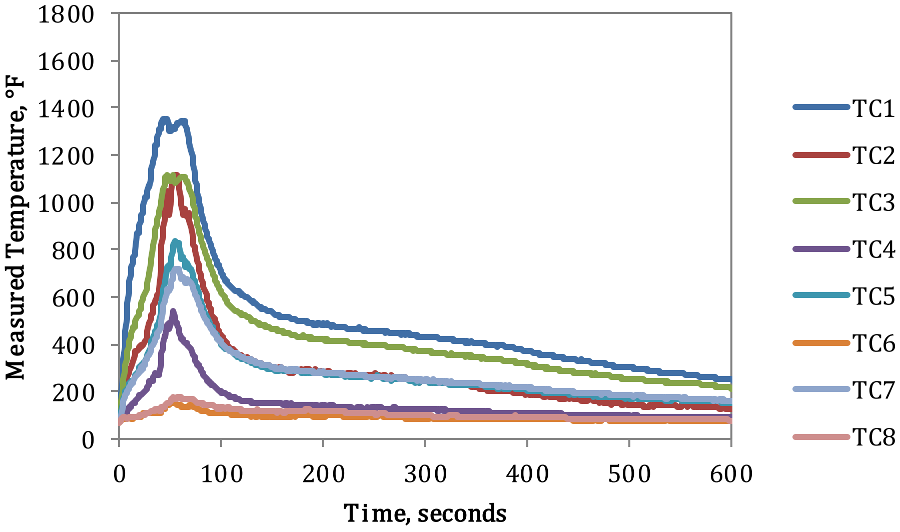

Figure 5. Measured Panel Temperatures for CFB

PANEL THICKNESS TESTS

The post-test measured burn lengths and widths for the panels of differing thicknesses are listed in table 3; the measured burn lengths are displayed graphically in figure 6. The data suggest that for solid laminates, thicker panels are less likely to propagate flames from a hidden fire source. However, thin panels in the range of 0.04-inch to 0.1-inch thick (1.12 mm to 2.55 mm) are likely to propagate flames under these static ambient conditions. The 8-ply panel was found to have a burn length nearly double that of the 4-ply panel, suggesting that the surface of the thinner 4-ply panel is more directly connected to the external surface, removing heat from the surface quickly enough to prevent sustained combustion and propagation. Thickness alone cannot be used to make judgments on the flame propagation potential of a panel; the ACF1-HC sandwich panel was found to have the longest burn length, despite being the thickest panel overall. This is because of the construction of the panel. The heat is retained in the inboard 4-ply face and the honeycomb core is mostly air, a relatively poor heat conductor. The resulting energy balance dictates that the heat remains in the surface plies rather than conducted away, increasing epoxy vaporization rates and providing sufficient fuel to sustain combustion and full-length propagation.

Table 3. Measured Burn Length and Width for Various Panel Thicknesses

Sample ID	Thickness (in)	Burn Length (in)	Burn Width (in)
ACF1-4	0.044	11.25	9.63
ACF1-8	0.101	21.25	10.5
ACF1-16	0.133	5	4
ACF1-24	0.278	0	0
ACF1-32	0.368	0	0
ACF1-HC	1.088	44.75	12.25

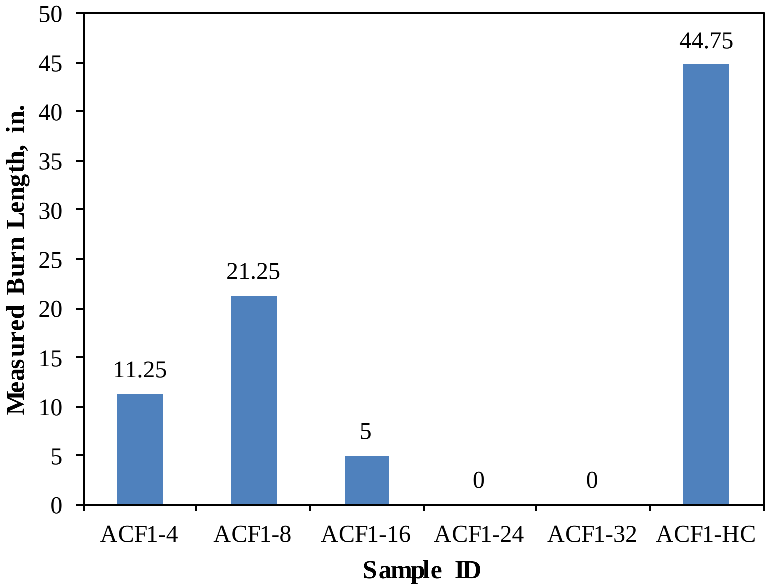

Figure 6. Measured Burn Length for Various Panel Thicknesses

The peak measured temperatures, time to peak, and peak width are listed in table 4, and a correlation between profile width and measured burn length is displayed in figure 7. The measured temperature profiles from these tests are displayed in figures 8 through 13. Note that in figure 8, a data acquisition system malfunction resulted in one thermocouple being recorded on all 8 channels. The profiles and burn lengths reveal the level of involvement of each panel beyond the foam block fire source. A general trend is observed that panels with longer burn lengths typically have greater temperature profile widths. The ACF1-8, with the longest burn length of the solid laminate panels, has the widest profile and a high peak temperature. The ACF1-4 has a narrower temperature profile than the foam block fire source, indicating that the panel was able to transfer heat readily to the outside air and self-extinguished once the fire source was no longer impinging. The 16-, 24-, and 32-ply panels demonstrated relatively narrow temperature profiles and lower peak temperatures, although the 32-ply panel showed some activity toward the end of the profile, possibly indicating some release of volatiles from the panel but not significant enough to reveal any measureable flame propagation. The ACF1-HC temperature profile indicates extended burning beyond the foam block fire source with a temperature profile width of 219 seconds and the highest peak temperature. Figure 14 displays screenshots from the test video of ACF1-HC at 1, 2, 3, and 4 minutes from foam block ignition, showing flames emitting from the top of the fixture, which was observed for 2 minutes and 30 seconds starting at 1 minute and 41 seconds from foam block ignition. For the static ambient tests, ACF1-HC was the only sample that had flames emitting from the apparatus.

Table 4. Temperature Profile Information for Panel Thickness Tests

Sample ID	Peak Temperature (°F)	Time to Peak (sec)	Profile Width (sec)
ACF1-4	1311	38	66
ACF1-8	1284	77	150
ACF1-16	1170	23	71
ACF1-24	889	28	76
ACF1-32	1248	66	76
ACF1-HC	1547	223	219

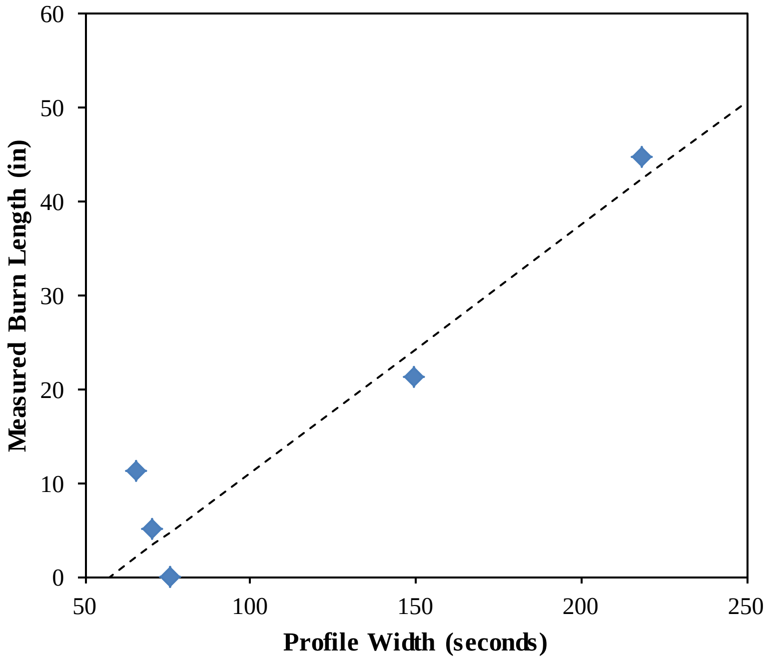

Figure 7. Correlation Between Measured Burn Length and Temperature Profile Width

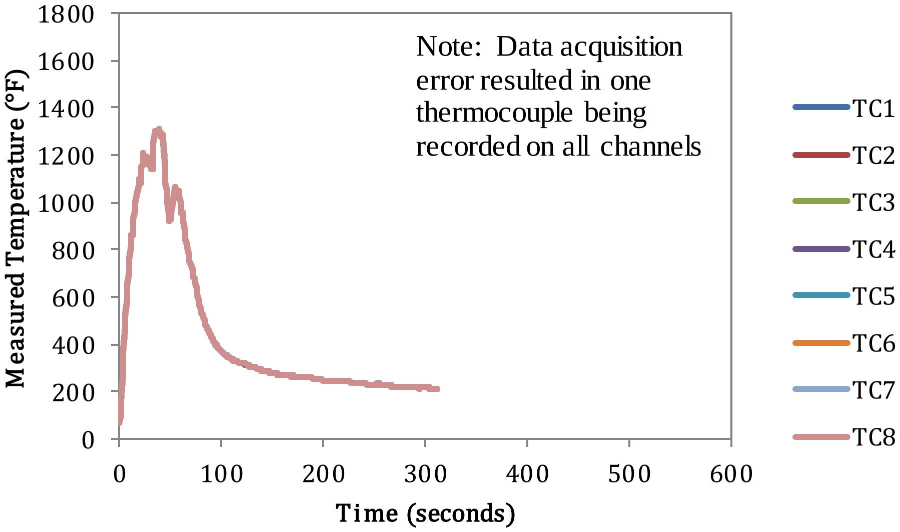

Figure 8. Measured Panel Temperatures for ACF1-4

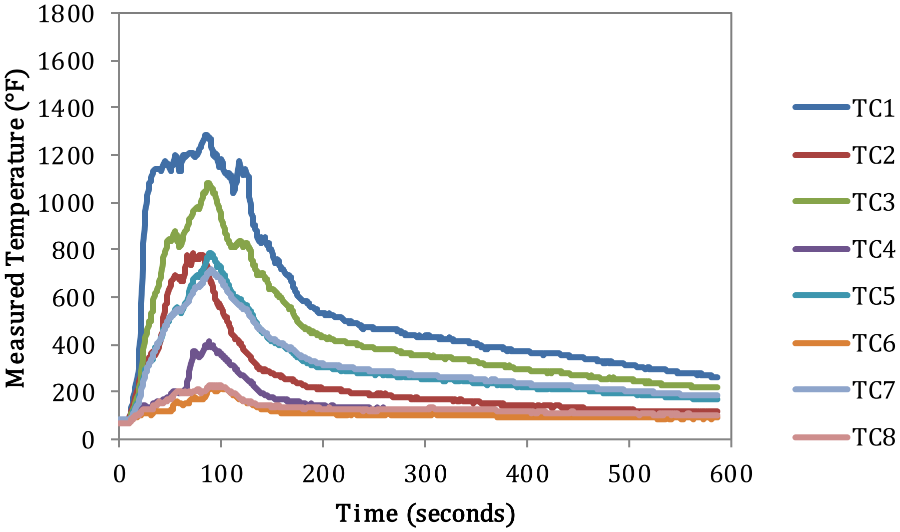

Figure 9. Measured Panel Temperatures for ACF1-8

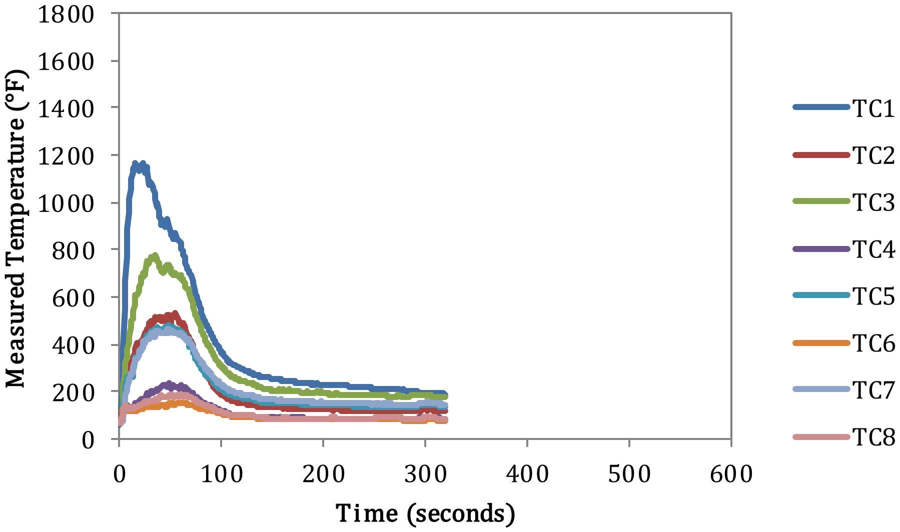

Figure 10. Measured Panel Temperatures for ACF1-16

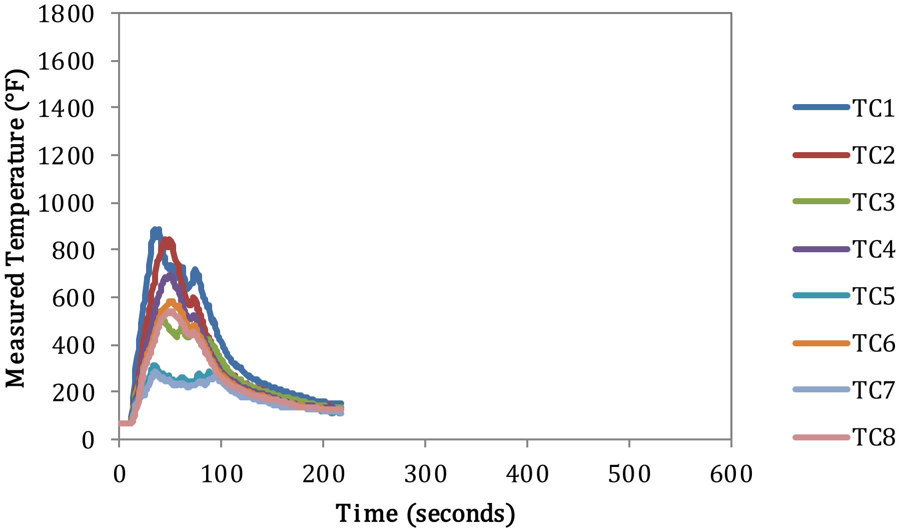

Figure 11. Measured Panel Temperatures for ACF1-24

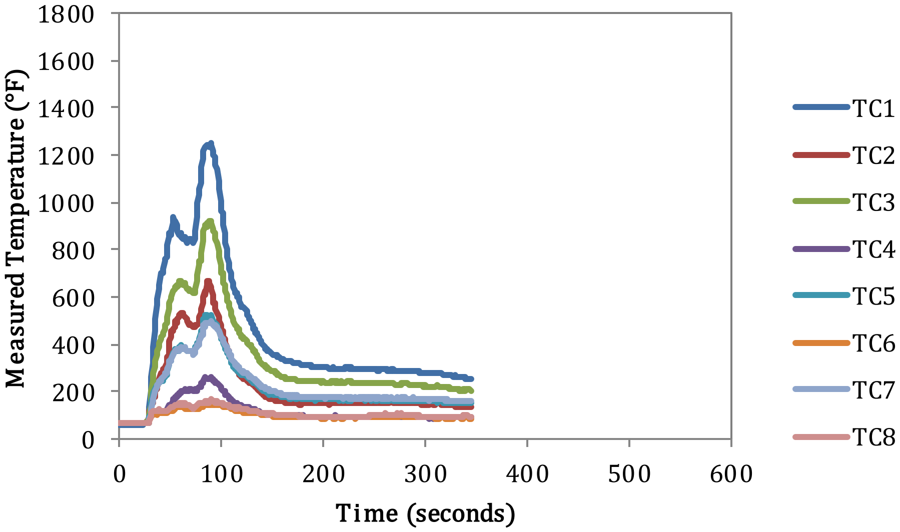

Figure 12. Measured Panel Temperatures for ACF1-32

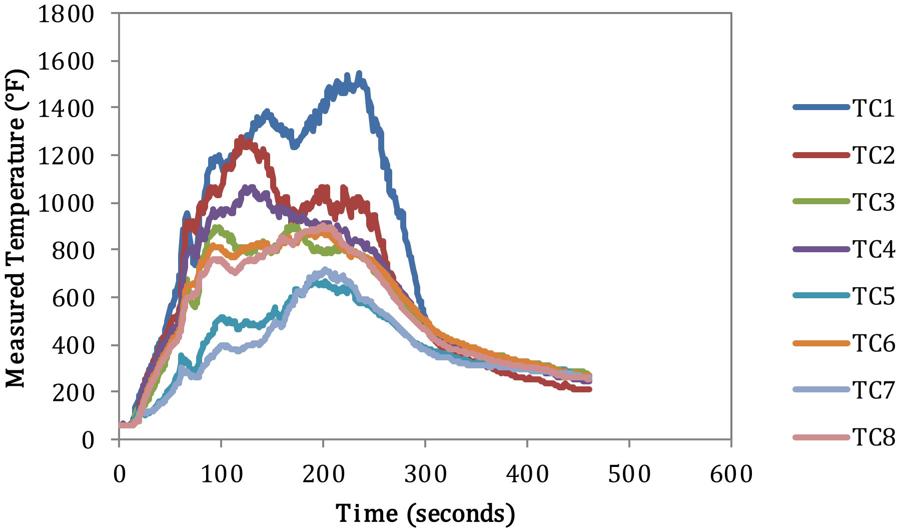

Figure 13. Measured Panel Temperatures for ACF1-HC

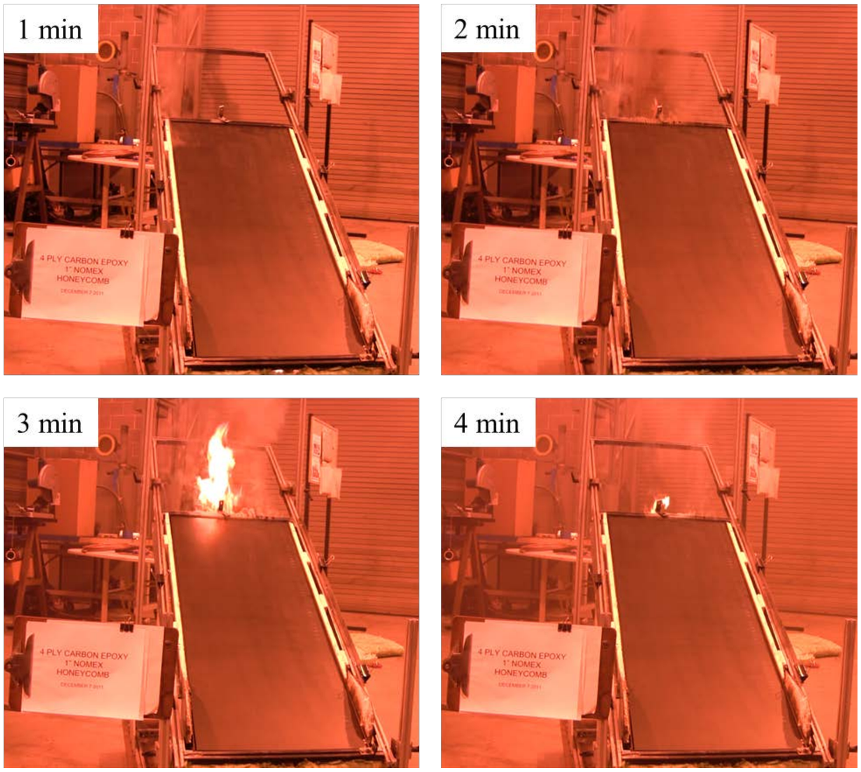

Figure 14. Screen Shots From Test Video of ACF1-HC

INSULATED PANEL TESTS

The next series of tests were conducted by placing the CFB directly on the outboard side of the test panel to significantly reduce the heat loss by convection at the outboard surface. The test results are listed in table 5 and displayed graphically in figure 15. The peak measured temperatures, time to peak, and peak width are listed in table 6, and a correlation between temperature profile width and measured burn length is displayed in figure 16. The measured temperature profiles from these tests are displayed in figures 17 through 21. The influence of the reduced convective heat loss is apparent, as both ACF1-4 and ACF1-8 have drastically increased burn lengths, behaving similarly to the ACF1-HC panel, demonstrating that the honeycomb core acts as an insulator like the CFB. Both the 4- and 8-ply panel tests exhibited flames emitting from the top of the test apparatus similar to the ACF1-HC under static ambient conditions. The burn length for the insulated 16-ply panel was similar to the uninsulated 16-ply panel test. Beyond the 16-ply, the influence of the reduced convective heat loss becomes insignificant, as evidenced by the similar test results for the 24- and 32-ply panels. This indicates that thicker panels have sufficient thermal mass to conduct heat from the area of impingement through the panel thickness and across the inboard surface to maintain surface temperatures low enough to preclude epoxy vaporization and flame propagation.

Table 5. Measured Burn Length and Width for Insulated Panel Tests

Sample ID	Thickness (in)	Burn Length (in)	Burn Width (in)
ACF1-4	0.044	45.375	13.125
ACF1-8	0.101	42.25	8.875
ACF1-16	0.133	5.875	7.875
ACF1-24	0.278	0	0
ACF1-32	0.368	0	0

Table 6. Temperature Profile Information for Insulated Panel Tests

Sample ID	Peak Temperature (°F)	Time to Peak (sec)	Profile Width (sec)
ACF1-4	1491	84	213
ACF1-8	1412	111	271
ACF1-16	1215	57	64
ACF1-24	939	46	62
ACF1-32	827	80	60

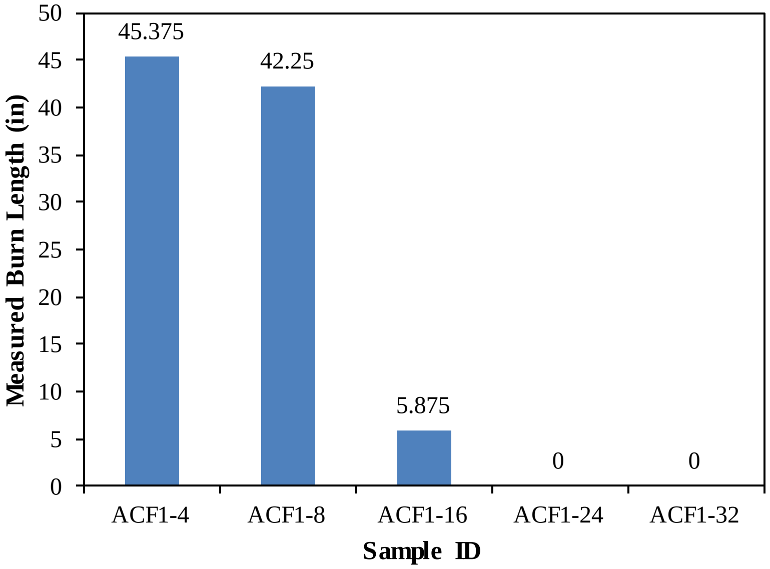

Figure 15. Measured Burn Length for Various Panel Thicknesses With Insulated Backside

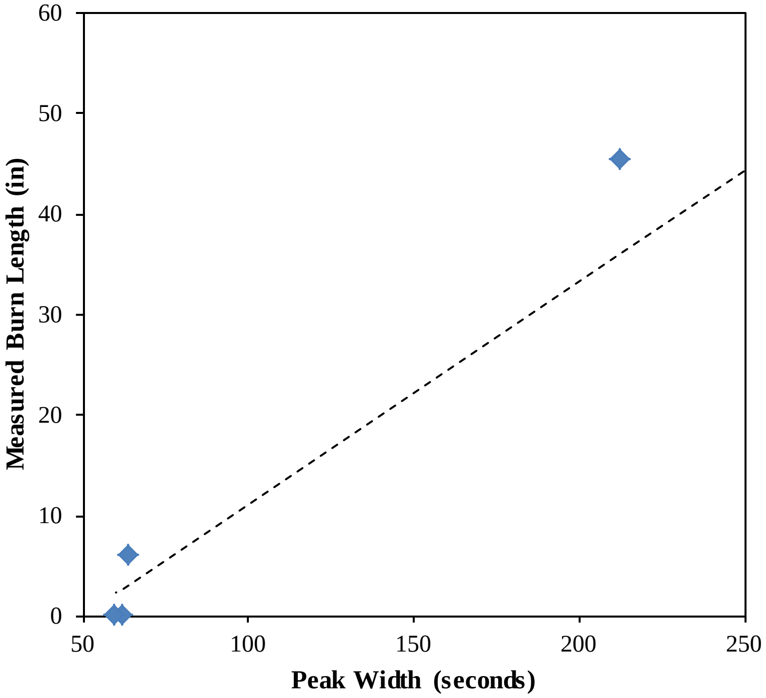

Figure 16. Correlation Between Measured Burn Length and Temperature Profile Width

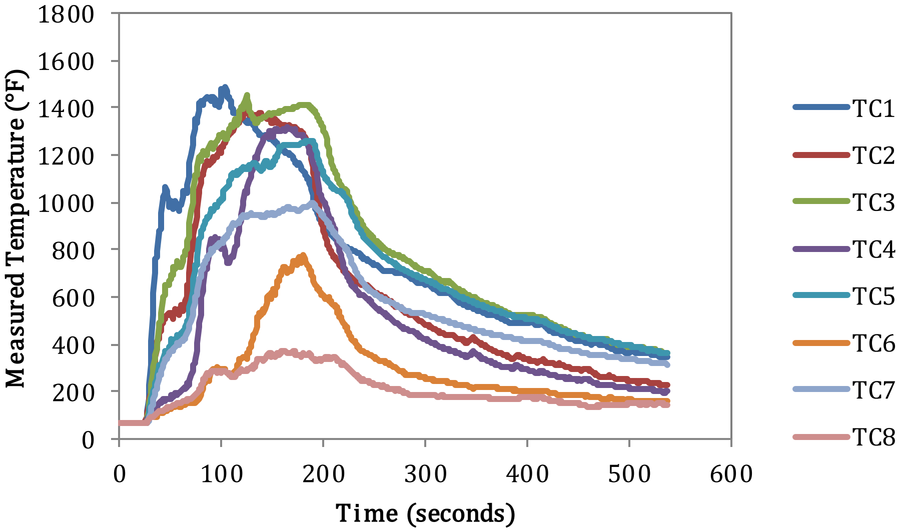

Figure 17. Measured Panel Temperatures for Insulated ACF1-4

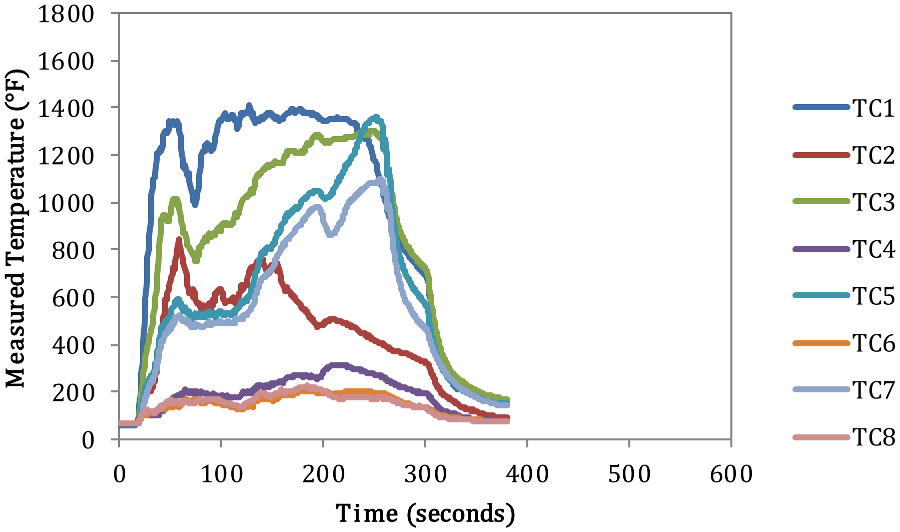

Figure 18. Measured Panel Temperatures for Insulated ACF1-8

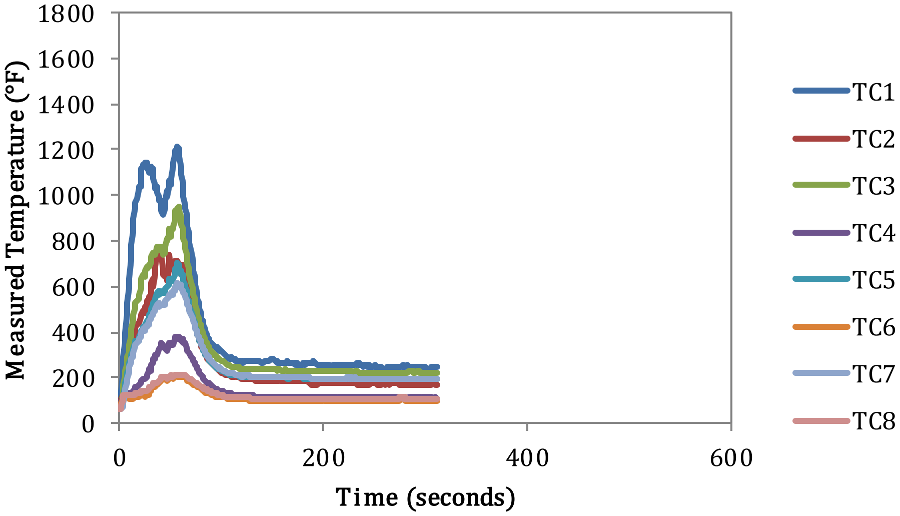

Figure 19. Measured Panel Temperatures for Insulated ACF1-16

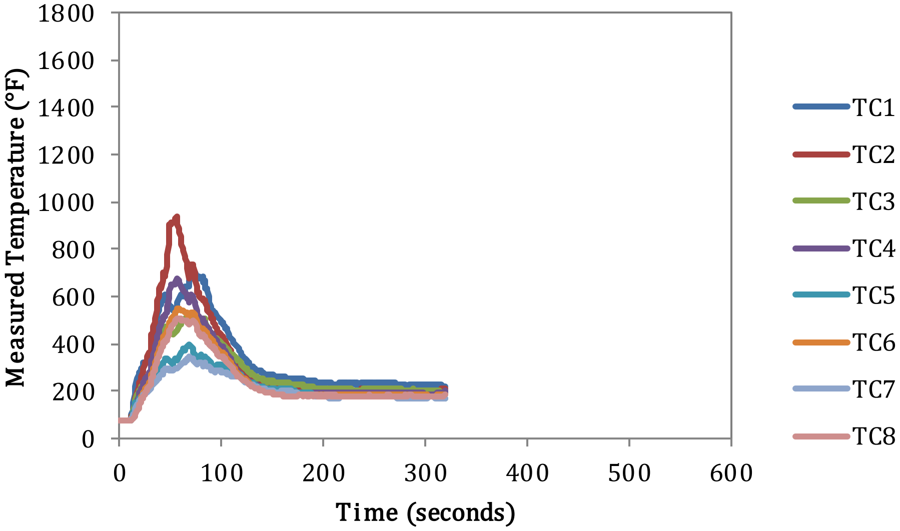

Figure 20. Measured Panel Temperatures for Insulated ACF1-24

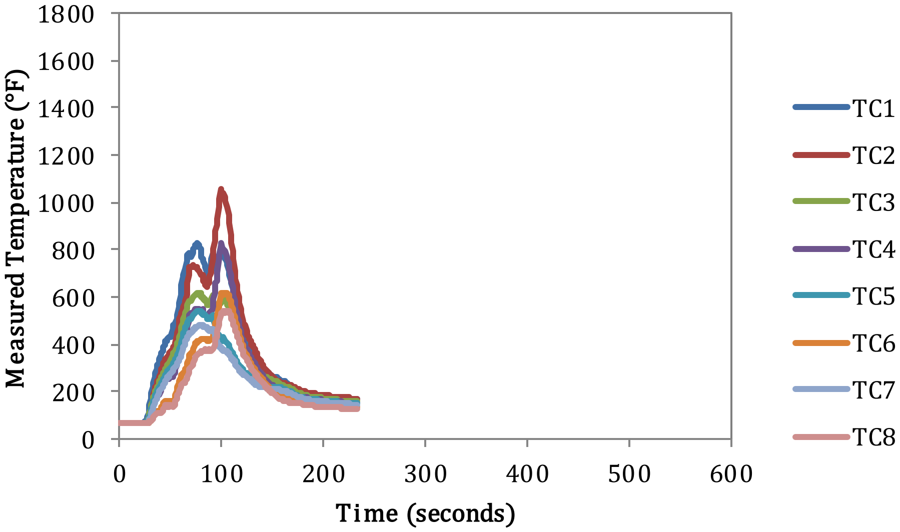

Figure 21. Measured Panel Temperatures for Insulated ACF1-32

ENHANCED COOLING TESTS

The final test series used water to increase the heat transfer from the external surface of the test panel. Only ACF1-4 and ACF1-HC were tested because of limited availability of test panels. The test results are listed in table 7 and are displayed graphically in figure 22. The peak measured temperatures, time to peak, and peak width are listed in table 8, and the correlation between temperature profile width and measured burn length is displayed in figure 23. The measured temperature profiles from these tests are displayed in figures 24 and 25. The results indicate that the increased heat loss significantly impacts the burn length of the thin ACF1-4 panel, but has no effect on the thicker sandwich panel ACF1-HC. The increased heat loss at the outboard surface of the ACF1-4 is enough to maintain panel temperatures below that for significant epoxy vaporization. The inboard surface of ACF1-HC, however, remains isolated from the external cooling effects because of the insulating honeycomb layer. A comparison between the baseline, insulated panel, and enhanced cooling test for the ACF1-4 and ACF1-HC is displayed in figure 26, showing the difference in reaction to outboard surface heat dissipation rates for the two panel types.

Table 7. Measured Burn Length and Width for Enhanced Cooling Tests

Sample ID	Thickness (in)	Burn Length (in)	Burn Width (in)
ACF1-4	0.044	0	0
ACF1-HC	1.088	45.5	15

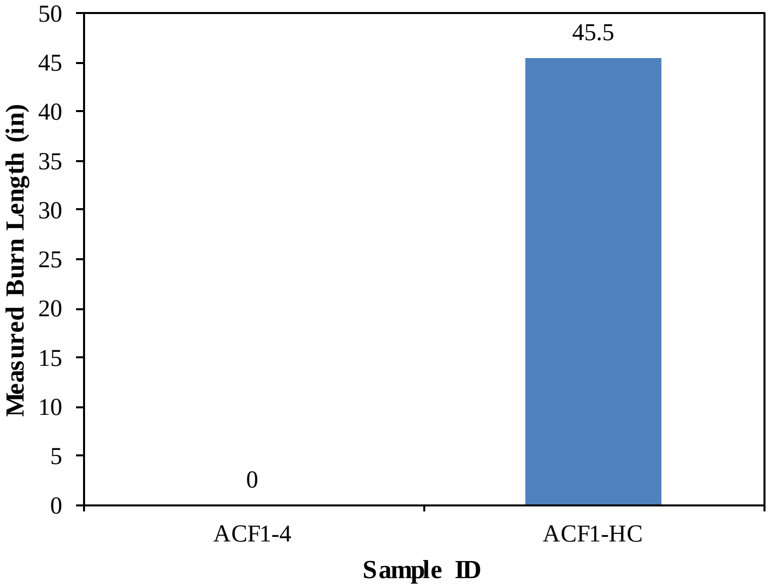

Figure 22. Measured Burn Length for Various Panel Thicknesses With Increased Heat Transfer

Table 8. Temperature Profile Information for Enhanced Cooling Tests

Sample ID	Peak Temperature (°F)	Time to Peak (sec)	Profile Width (sec)
ACF1-4	1094	46	56
ACF1-HC	1784	128	181

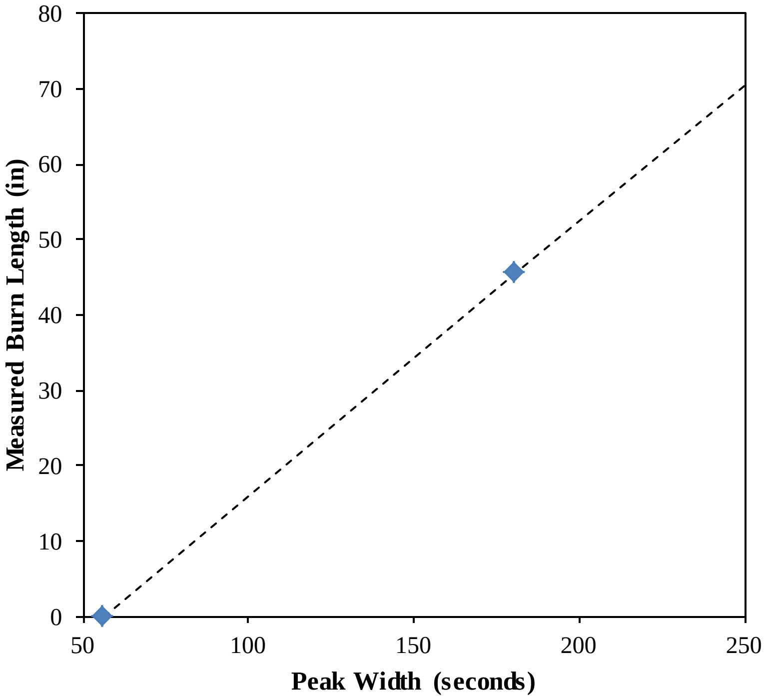

Figure 23. Correlation Between Measured Burn Length and Temperature Profile Width

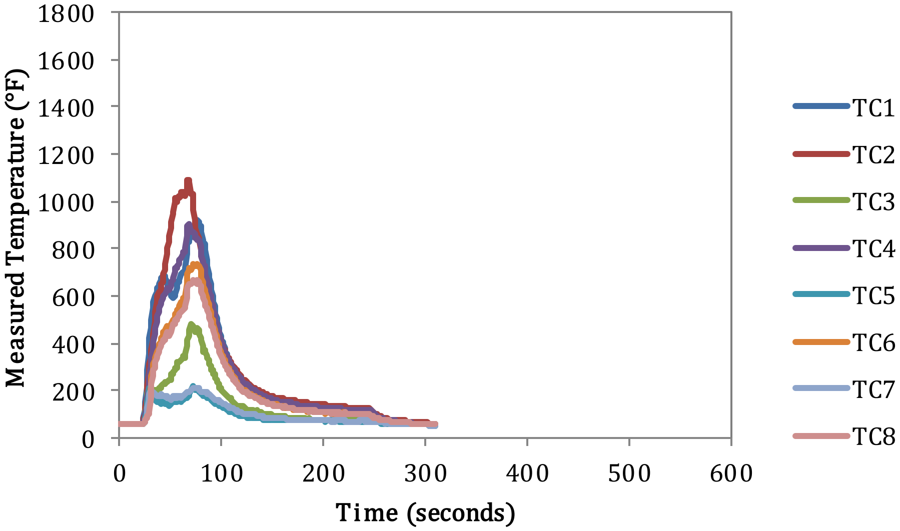

Figure 24. Measured Panel Temperatures for ACF1-4 With Enhanced Cooling

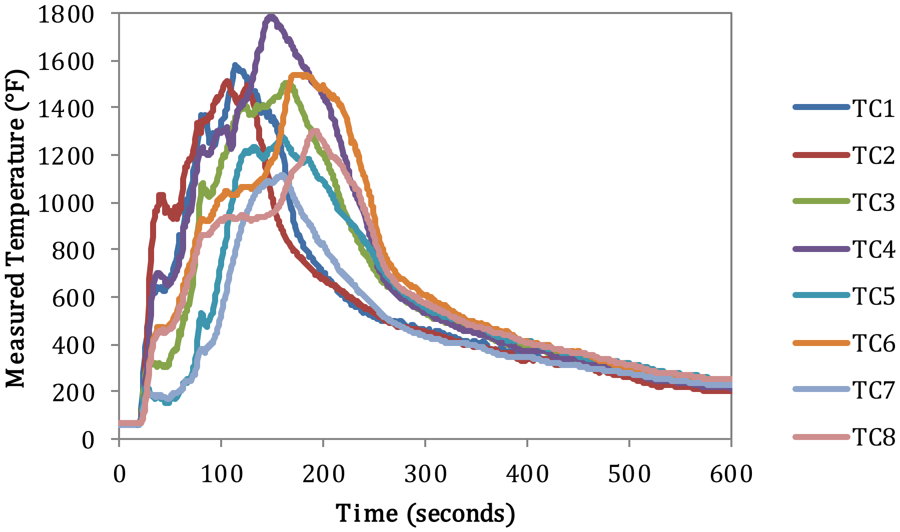

Figure 25. Measured Panel Temperatures for ACF1-HC With Enhanced Cooling

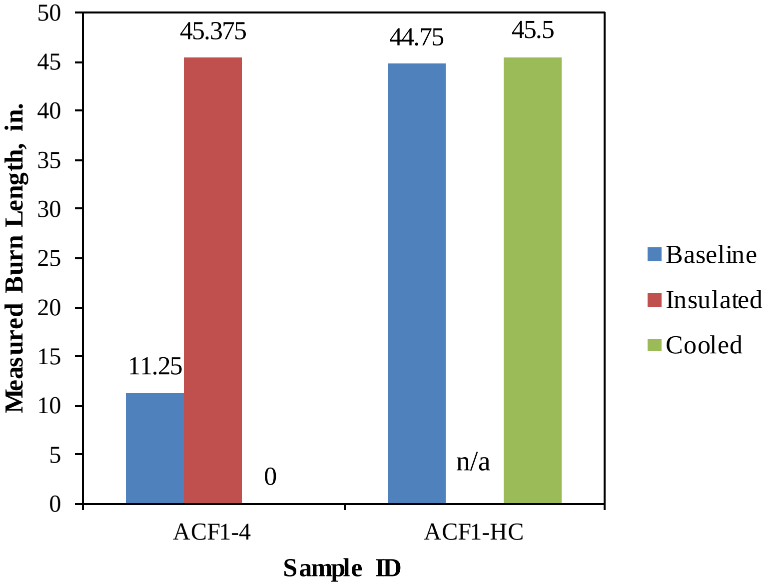

Figure 26. Comparison of Three Heat Transfer Conditions for ACF1-4 and ACF1-HC

SUMMARY

The results from this test series indicate that the relative flammability of a composite material is dependent upon the rate of heat dissipation from the flame-impinged surface. This varies depending on several factors, including the panel thickness and the heat dissipation rate at the outboard surface. Thin panels (0.04- to 0.1-inch thick) were found to propagate flames under static ambient conditions, and were also more heavily influenced by the heat transfer at the outboard surface. Thicker panels (0.13- to 0.37-inch thick) were found to have enough thermal mass between the flame-impinged surface and the outboard surface to prevent flame propagation under static ambient conditions, and were relatively unaffected by the heat transfer at the outboard surface. The honeycomb core sandwich panel was found to behave like a thin composite panel and was unaffected by the heat dissipation rate at the outboard surface.

These results can be used as general knowledge for assessing the in-flight fire threat for composite fuselage airplanes. Actual composite airplane configurations will encompass varying thicknesses because the composite skin in some areas may be thinner than the structural members, such as stringers and frames. These components also have varying levels of contact with the external ambient conditions; the outboard surface of the skin is in direct contact with the external flow, but the stringers and frames do not have direct contact, resulting in different levels of heat conduction from a hidden fire. Consideration must be given to these factors when performing an analysis of in-flight composite material flammability and the effects of forced convective heating by the external high-speed cold airstream.

REFERENCES

1. "Special Conditions: Boeing Model 787-8 Airplane; Composite Fuselage In-Flight Fire/Flammability Resistance," Federal Aviation Administration, Renton, Washington, 2007.