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Federal Aviation Administration
William J. Hughes Technical Center
Aviation Research Division
Atlantic City International Airport
New Jersey 08405

Development of a Firefighting Agent Application Test Protocol for Aircraft Fuselage Composites, Phase I—Carbon Fiber

June 2012

Final Report

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16. Abstract
This project was initiated to develop a live fire test protocol that could determine if the amounts of fire extinguishing agent currently carried on Aircraft Rescue and Fire Fighting vehicles are sufficient to extinguish fires involving aircraft built with advanced composite material fuselages. Currently two advanced composite materials are used in construction of commercial aircraft fuselages; GLAss-REinforced Fiber Metal Laminate, commonly called GLARE, and carbon fiber composite. The objective of this series of tests was to assess the fire behavior of carbon fiber composites. These tests focused on the following specific fire behaviors: (1) if either self-sustained burning or smoldering exist after fire exposure, (2) the extent of heat propagation through the carbon fiber composite, (3) how long it takes for the carbon fiber composite to naturally cool below 300°F (150°C), and (4) if there are any physical indicators that would help firefighters determine that the carbon fiber composite had cooled sufficiently to prevent reignition. These tests comprise the first phase of a two-phase approach to assess the fire behavior of aircraft fuselage advanced composite materials. The second phase will determine the amount of firefighting agent needed to extinguish and cool the composite.

Twenty-three tests were conducted on 0.08-inch-thick, laminate-type carbon fiber composite samples sized 18 by 12 inches. The fiber content of the samples was 60%, which is typical for carbon fiber composite used in aircraft fuselages. The samples were mounted on a small platform at a 45° angle. The Federal Aviation Administration NextGen oil burner was used as the fire source. It generates temperatures just over 1800°F (990°C), which are similar to that of an aviation fuel-fed pool fire. Samples were subjected to different fire exposure times. Temperature measurements and infrared images were collected during the tests. In several instances, the initial weight of the sample was compared to the postexposure weight to determine the amount of resin consumed in the test.

The tests showed that flaming combustion, smoldering, and smoking occur in various degrees of severity during and after fire exposure. Given the temperatures that can be achieved in an aviation fuel-fed pool fire, sufficient heat is available to raise the carbon fiber composite temperature to briefly sustain both flaming and smoldering after the pool fire is extinguished. Forward-looking infrared images and thermocouple measurements indicated laminate-type carbon fiber composite absorbs heat unevenly across its surface. Natural cooling of the samples below 300°F (150°C) happened quickly in areas that were open to the air and free to dissipate heat. The fastest time was almost 90 seconds for the uncovered sample center. Smoking was the only reliable visible indicator that could be used by firefighters to identify areas that still require continued application of agent.

17. Key Words
Carbon fiber, Advanced composite material, Fire tests, Smoking, Smoldering, NextGen burner

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LIST OF ACRONYMS

ACO	United States Air Force Advanced Composites Office
ARFF	Aircraft Rescue and Fire Fighting
FAA	Federal Aviation Administration
FLIR	Forward Looking Infrared
GLARE	GLAss-REinforced Fiber Metal Laminate
IR	Infrared
OSU	Ohio State University
TC	Thermocouple
USAF	United States Air Force

EXECUTIVE SUMMARY

Certificated airports that are required to have Aircraft Rescue and Fire Fighting (ARFF) service must have specific minimum amounts of extinguishing agent on hand, based on the airport index. The airport index is determined by the length and average daily departures of air carrier aircraft. There are five index levels, each having a specific requirement for the amount of firefighting agent and number of firefighting vehicles available at the airport during operations. The current required amounts of extinguishing agents are the focus of this study, in regard to their sufficiency for aircraft fuselages built with significant amounts of advanced composite material.

Currently two advanced composite materials are used in construction of commercial aircraft fuselages; GLAss-REinforced Fiber Metal Laminate (commonly called GLARE) and carbon fiber composite. The objective of this series of tests was to assess the fire behavior of carbon fiber composite. These tests focused on these specific fire behaviors: (1) if either self-sustained burning or smoldering exist after fire exposure, (2) the extent of heat propagation through the carbon fiber composite, (3) how long it takes for the carbon fiber composite to naturally cool below 300°F (150°C), and (4) if there are any physical indicators that would help fire fighters determine that the carbon fiber composite had cooled sufficiently to prevent reignition. These tests comprise the first phase of a two-phase approach to assess the fire behavior of aircraft fuselage advanced composite materials; the second phase will determine the amount of firefighting agent needed to extinguish and cool the composite.

Twenty-three tests were conducted on 0.08-inch-thick, laminate-type carbon fiber composite samples sized 18 by 12 inches. The fiber content of the samples was 60%, which is typical for carbon fiber composite used in aircraft fuselages. The samples were mounted on a small platform at a 45° angle. The Federal Aviation Administration NextGen oil burner was used as the fire source. It generates temperatures just over 1800°F (990°C), which are similar to that of an aviation fuel-fed pool fire. Samples were subjected to different fire exposure times. Temperature measurements and infrared images were collected during the tests. In several instances, the initial weight of the sample was compared to the postexposure weight to determine the amount of resin consumed in the test.

These tests have shown that flaming combustion, smoldering, and smoking occur in various degrees of severity during and after fire exposure. Given the temperatures that can be achieved in an aviation fuel-fed pool fire, approximately 1800°F (990°C), sufficient heat is available to raise the carbon fiber composite temperature to a level that could sustain both flaming and smoldering after the pool fire is extinguished. Wind and radiant heating between two carbon fiber composite structures can intensify fire conditions. Resin and the residual amount of resin after fire exposure is the determining factor in the flame amount that can be achieved. Longer fire exposures burn off more resin than shorter exposures. However, smoldering conditions seem to be independent of resin content and are driven by sufficient heating of the carbon fibers themselves. After longer fire exposures, there was evidence of oxidized carbon fibers.

Forward-looking infrared images and thermocouple measurements indicated carbon fiber composite absorbs heat unevenly across its surface. Natural cooling of the samples below 300°F

(150°C) happened quickly in areas that were open to the air and free to dissipate heat. The fastest time for the sample to cool below 300°F (150°C) was almost 90 seconds for the uncovered sample center. Smoking was the only reliable indicator that fire fighters could use to identify areas that still require continued application of agent. To identify changes in the material temperature, fire fighters can use thermal imaging and sensory cues. Mechanical failures identified in this report warrant further consideration to fully explore their impact on the overall fire environment. Based on the results of these tests, some conditions warrant an application of firefighting agent to sufficiently cool the carbon fiber composite.

1. INTRODUCTION.

The introduction of new commercial aircraft that are constructed primarily of advanced composite materials has raised concerns within the Aircraft Rescue and Fire Fighting (ARFF) community as to whether the current equipment and fire extinguishing agents are adequate for this type of aircraft construction. The United States Air Force (USAF) identified the possibility that carbon fiber composite aircraft present a more persistent fire scenario. The USAF reported that the postcrash fire of a mainly carbon fiber composite aircraft, a B-2, took significantly more extinguishing agent and time than expected to fully extinguish the fire [1]. Carbon fiber composites' propensity to burn and other technical measures of burning for a particular carbon fiber composite composition is discussed in a Federal Aviation Administration (FAA) report [2]. The report established degradation temperatures that cause burning in composites range between 572° and 932°F (300° and 500°C). In a postcrash fuel-fed pool fire the temperatures can be approximately 1800°F (990°C).

Certificated airports that are required to have ARFF service must have specific minimum amounts of extinguishing agent on hand based on the airport index. The airport index is determined by the length and average daily departures of air carrier aircraft. There are five index levels, each having a specific requirement for the amount of firefighting agent and vehicles, available at the airport during operations. The current required amounts of extinguishing agents are the focus of this study, in regard to their sufficiency for aircraft fuselages built with significant amounts of advanced composite material. This study was initiated to develop a live fire test protocol that could determine if the amounts of fire extinguishing agent currently carried on ARFF vehicles are sufficient to extinguish fires involving aircraft built with composite fuselages. Currently two advanced composite materials are used in construction of commercial aircraft fuselages; GLAss-REinforced Fiber Metal Laminate (commonly called GLARE) and carbon fiber composite. The objective of this series of tests was to assess the fire behavior of carbon fiber composite. The tests focused on these specific fire behaviors: (1) if either self-sustained burning or smoldering exist after fire exposure, (2) the extent of heat propagation through the carbon fiber composite, (3) how long it takes for the carbon fiber composite to naturally cool below 300°F (150°C), and (4) if there are any physical indicators that would help fire fighters determine that the carbon fiber composite had cooled sufficiently to prevent reignition. These tests comprise the first phase of a two-phase approach to assess the fire behavior of aircraft fuselage advanced composite materials; the second phase will determine the amount of firefighting agent needed to extinguish and cool the composite.

1.1 OBJECTIVE.

The objectives of these tests were to

- determine, through observation and temperature measurements, if either self-sustained burning or smoldering exist after fire exposure.
- show the extent of heat transfer through the carbon fiber composite or lateral flame propagation with infrared (IR) analysis and surface temperature readings.

- document the amount of time necessary for the carbon fiber composite to naturally cool below 300°F (150°C) after removing the fire source.

- demonstrate any physical indications that could help fire fighters visually determine if the carbon fiber composite has cooled sufficiently to prevent reignition.

These tests were conducted to determine if a persistent, self-sustaining fire condition that would warrant application of fire extinguishing agent can occur in aircraft fuselage carbon fiber composites. Results from these tests will determine if phase II tests are necessary.

1.2 EVALUATION APPROACH.

To accurately assess if an aircraft with a carbon fiber composite fuselage burns or smolders after extinguishment of an impinging fuel-fed pool fire, it is important to use a test methodology that correctly represents that fire condition. Most standard laboratory-scale fire tests currently used by aircraft manufacturers and regulators focus on the simulation of internal fire conditions. For example, the cone calorimeter was used in concert with the Ohio State University (OSU) fire calorimeter test apparatus to provide data in reference 2. The cone calorimeter, although shown to be an accurate determinate of a materials' fire properties, simulates a compartment fire condition where radiant heating is the dominant transfer mechanism [3]. Because of this, neither the cone calorimeter nor the OSU apparatus was chosen for this study.

The FAA kerosene-fired NextGen burner was chosen as the fire source for these tests as it closely represents an impinging external fuel-fed pool fire on an aircraft fuselage. It is the required burner to establish compliance with the new 4-minute burnthrough resistance standard for thermal-acoustic insulation. Title 14 Code of Federal Regulations (CFR) Part 25.856 [4] describes this laboratory-scale apparatus in detail. The NextGen burner is an updated version of burner that replaces the Park Oil Burner due to unavailability of parts.

A total of 23 tests were conducted. A primary configuration was used for testing; however, two other configurations were also explored for specific purposes in tests 9, 22, and 23, which are discussed in section 3. Where appropriate, certain results from these tests, such as smoldering or postexposure flaming, are included with the discussion of the primary test configuration results. Section 1.4 describes the primary test configuration in detail. Exposure times were varied between 1, 3, 5, and 10 minutes, with at least three tests attempted for each.

1.3 MATERIALS.

The carbon fiber composite used for these tests was provided by the USAF Advanced Composites Office (ACO) at Hill Air Force Base, Utah. Other materials, such as GLARE, different aircraft carbon fiber laminates, or nonaerospace materials, may be tested as part of this project but were not included here. The carbon fiber composite samples were fabricated by the Ogden Air Logistics Center for use in composite repair training. These are standard samples that were built to a USAF specification without any intentional flaws. According to the specification, all surfaces must be wrinkle free with no seams or butt joints, with vacuum bag and debulking after every four plies. The prepreg used was T-300/5208. The design thickness of the sample was 0.08 inch (2.032 mm) with an overall dimension of 18 inches (45.72 cm) by 12 inches (30.48 cm). Sample construction was a quasi-isotropic lay-up [0, 90, +45, -45] S2 of 16 plies, with the 0 ply in the 18-inch direction.

Two samples were tested for resin/fiber content. One was tested by ACO, using ASTM D 3171-09, and the other by Cytec Engineered Materials using an undisclosed method. Cytec Engineered Materials is a manufacturer of the resin used in aircraft fuselage composite materials. The fiber content measured by these laboratories was 61.2% by weight and 59.97% by volume, respectively. The Cytec analysis included an average thickness, measuring 0.0971 inch (2.47 mm).

<u>1.4 TEST CONFIGURATION</u>.

External fire impinging on an aircraft is normally the result of a fuel spill. The current firefighting procedure is to immediately attack the external fire to facilitate evacuation and protect the fuselage skin from burnthrough. With traditional aluminum aircraft, burnthrough can occur within 1 minute [5 and 6]. The FAA developed and adopted the NextGen oil burner to simulate an aviation fuel-fed pool fire for burnthrough testing.

The NextGen burner is an updated version of the Park Oil Burner [7]. Average temperatures generated by the NextGen burner are just over 1800°F (990°C). For these tests, it was mounted on a small platform at a 45° angle as shown in figure 1, just as it is configured for thermo-acoustic insulation tests.

Figure 1. Kerosene-Fired FAA NextGen Burner and Sample Frame

Because the samples were smaller than the width of the flame generated by the burner, the samples were protected to eliminate the potential for the flame to wrap around the edge. Two ThermalCeramics Kaowool™ M-board ceramic insulation boards were used to frame the sample; one cut to the size of the sample, the other cut smaller than the sample by 1 inch on all sides, as shown in figure 2. The boards were then secured together to ensure no flame could slip between them. The sample also needed to be secured so that it would not displace to the rear, which would allow flame to directly wrap around the edges. Two posts (see figure 3) were fabricated from 1-inch angle iron with two long screws threaded through them to firmly press each corner of the sample against the front Kaowool board.

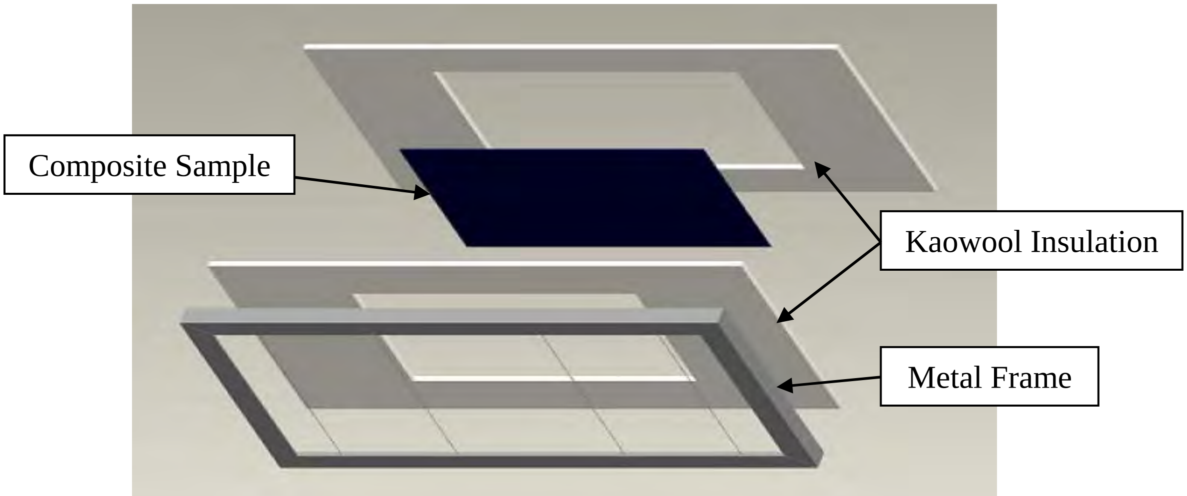

Figure 2. Exploded View of Sample Frame

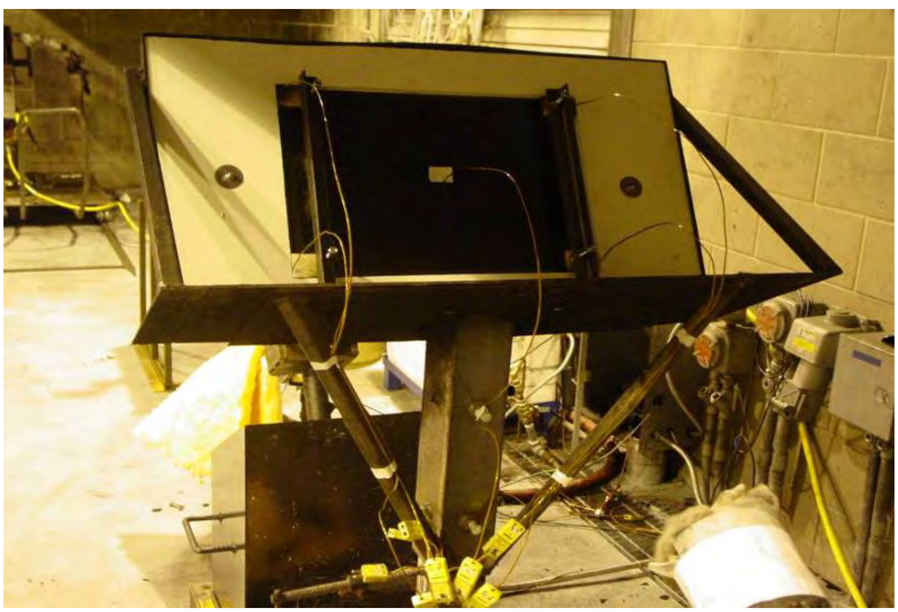

Figure 3. View of Thermocouple Placement and Angle Iron Posts

To define the aspects of the sample and for clarity in this report, the side of the sample that faced the burner was considered the front. The opposite side where the thermocouples (TC) were placed is the back. Further references to the sample will use the front or back description.

Temperature measurements, recorded in Fahrenheit and converted to Celsius to include both scales in this report, were taken from the back of the sample by Omega Type-K, 30-gauge TCs, set in five positions, as shown in figure 4 and is shown set-up in the laboratory in figure 3. Corner TCs were secured in place using small Kaowool pads held in place by the pressure of the securing post screws. The center TC was held in place with fiberglass tape. During the first several tests, the center TC would occasionally spring out of place due to the tape adhesive softening from the conducted heat. It was discovered that the TC wire was in tension in the opposite direction of the sample. The TC wires were repositioned so that the tension was relieved. At times, additional TCs were used to check or verify the measurements of the standard five TCs.

Figure 4. Numbering Sequence of TCs on the Sample

Another set of temperature measurements, along with IR images of the sample, were collected using a Forward-Looking Infrared (FLIR®) Systems, Inc. IR video camera. This specialized camera not only captures IR video but can also be set to capture color and IR still images at regular time intervals. The camera was set to record both IR and color still images every 20 seconds along with the running IR video.

Color video cameras were positioned to capture both front and back views. The backside video camera positioned behind the sample frame allowed for a side-by-side comparison of the color and FLIR videos. In later tests, the color camera view was zoomed in on the sample for closer examination of conditions that may not be visible from a wider view. The second color video camera was positioned approximately 45º to the front of the sample frame. Actual positions of the FLIR and two color video cameras are shown in figure 5.

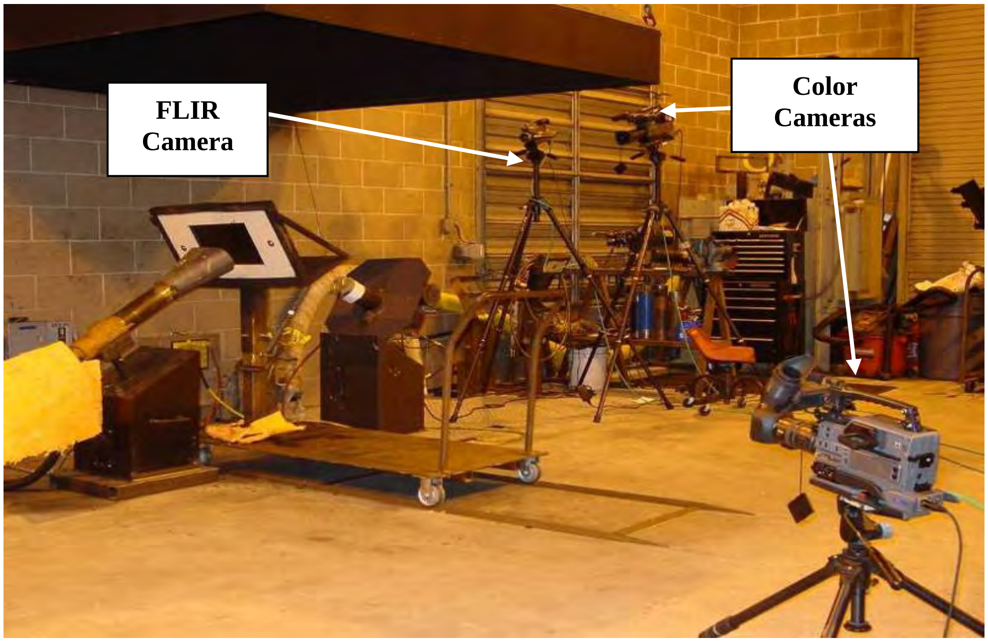

Figure 5. Test Configuration

2. RESULTS.

Analysis of the tests included a review of the TC data, FLIR and color videos, and posttest visual inspections of each sample. This analysis includes cues to assess if the sample cooled sufficiently to prevent reignition.

2.1 SAMPLE WEIGHTS.

Recording pre and postexposure weights was not considered until after testing had begun and, therefore, was not documented for all tests. Of ten test samples where weights were recorded both before and after testing, four samples were exposed for 1 minute, one sample was exposed for 3 minutes, and the last five samples were exposed for 10 minutes. Six samples were weighed only after exposure but are included for postexposure weight comparison. Table 1 shows the recorded weights before and after exposure.

Table 1. Recorded Initial and Postexposure Sample Weights

Exposure Time (minutes)	Test Number	Initial Weight (g)	Postexposure Weight (g)	% of Initial Weight
1	12	530.89	447.22	84.2
1	16	531.23	438.86	82.6
1	17	529.41	447.23	84.5
1 (with fan)	18	528.88	445.26	84.2
3	6	unknown	406.72	unknown
3	7	unknown	411.56	unknown
3	10	533.70	415.92	77.9
5	1b	unknown	408.10	unknown
5	2	unknown	404.16	unknown
5	3	unknown	407.79	unknown
10	5	unknown	379.65	unknown
10	13	531.80	364.15	68.5
10	14	529.75	364.69	68.8
10	15	531.29	374.83	70.6
10 (with fan)	19	527.58	369.27	70.0
10 (with fan)	21	529.02	346.50	65.5

Note: Tests are grouped by exposure duration.

When comparing each sample's initial weight to the postexposure weight, it is clear that the duration of exposure has a direct effect on the amount of remaining resin and fiber. On average, one minute exposures left 83.9% of the initial weight and 10-minute exposures left 68.7% of the initial weight. Longer exposures, particularly 10 minutes, regularly caused severe damage to the front of the sample, localized to the center in a general outline of the burner cone. In these exposures, a rough hole was made in the outer plies. The depth of penetration into each 10-minute sample varied slightly but in most cases, as in figure 6, taken from test 5, the ±45º plies were visible. The edges of the rough hole had jagged, soft-fiber ends and there were fibers loosely hanging from the sample.

Figure 6. Postexposure Damage, 10-Minute Exposure

On the outer plies, soft bunches of hair-like carbon fibers, called fiber clusters, hung from the sample edges. The loose fiber clusters were released during the longer exposure, which accounts for some of the missing fibers and weight. Notably, some carbon fibers had light-gray colored ends, especially in tests 13, 14, 15, and 21, around the border of the hole (see figure 7).

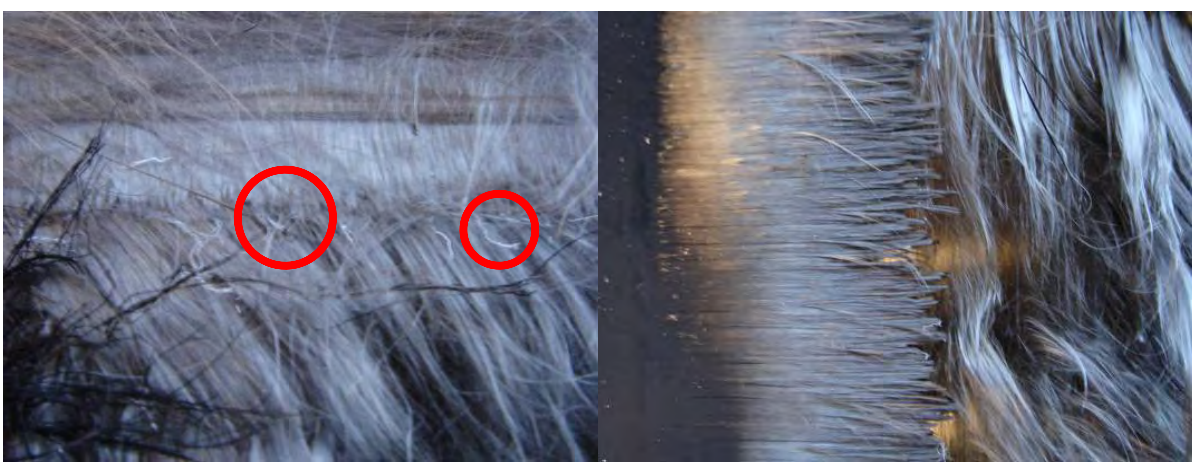

Figure 7. Close-Up of Gray, Jagged Fiber Ends From Test 15

Although a more detailed assessment of the gray ends was not part of this assessment, Quintiere [2] documented that oxidation will occur at sufficiently high temperatures. Gandhi and Lyon [8] found that fire significantly reduced fiber size, in part due to oxidation. Gandhi further documented that oxidation at temperatures above 1640°F (900°C) in an oxygen-rich environment will completely consume carbon fibers. Considering the NextGen burner can reach 1800°F (990°C) or more, it is possible that these gray fiber ends were oxidized carbon fibers and the jagged fibers resulted from fiber ends that had been oxidized and reduced to dust.

2.2 SAMPLE TEMPERATURES.

TCs and a FLIR camera were used to measure sample temperatures. The TC in the center of the sample was labeled TC 3. The FLIR camera measures the temperatures at one specific spot, shown on the screen as a crosshair. The FLIR spot was always positioned on the sample as close to TC 3 without being focused on the thermocouple, but the distance from TC 3 was not always the same. One of the first observations noted was that TC 3 and FLIR temperatures did not match. A feature of the FLIR camera software allows for additional crosshairs to be added to IR still images. The preset crosshair is blue, and the additional crosshairs are white. When additional crosshairs were added to one of the images, it revealed clear temperature variations, as shown in figure 8. It was observed in the FLIR images that the samples had clear color variations across the surface during exposure indicating that the samples did not heat uniformly. Therefore, temperature measurements, even in close proximity, should not be expected to match.

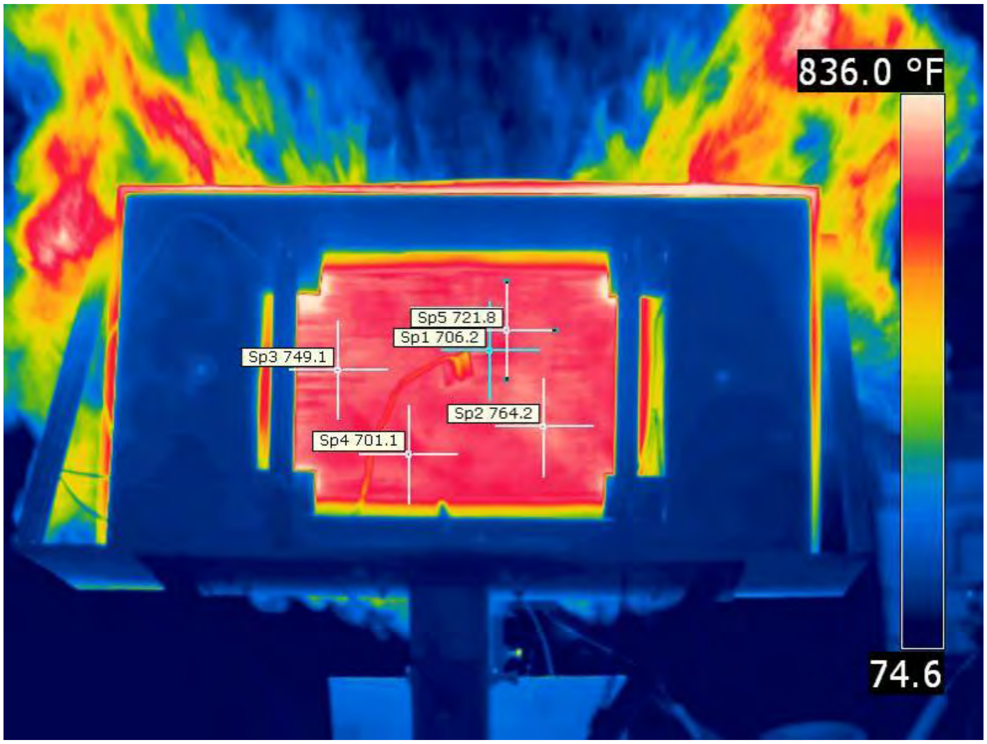

Figure 8. Sample Temperature Variations

Given that laminate-type carbon fiber composites are a buildup of fiber sheets, or plies, that are held together by a resin, they will delaminate when damaged. Delamination occurs when one fiber sheet separates from an adjacent sheet. This will occur under fire conditions as the sample temperature increases and begins to degrade and volatize the resin. As the resin loses its ability to hold the plies together, they separate, creating an air space between them. That air space provides a level of insulation from heat transfer deeper into or through the laminate. The fiber plies themselves also offer insulation from further heat penetration. Despite the limited insulation offered by the air spaces and fiber, as the fire exposure continues, heat continues to travel through the panel, increasing the temperature on the unexposed side. For tests with less than 10 minutes of exposure, the average maximum TC 3 readings were approximately 700°F (374°C). For 10-minute exposures, the average maximum sample temperature measured at TC 3 was 822°F (442°C).

Figure 9 shows a typical tracing chart of the TC and FLIR measurements. All tests showed similar tracings. The sample heats very rapidly at the onset; after approximately 4 minutes, the temperature trend flattens but continues to increase gradually and slowly until the exposing flame is removed. For shorter exposure durations, this is not as apparent in the charts; however, all charts show that the maximum temperatures were all reached near the point when the burner was removed. Figure 10 shows an example of the tracing from a shorter exposure.

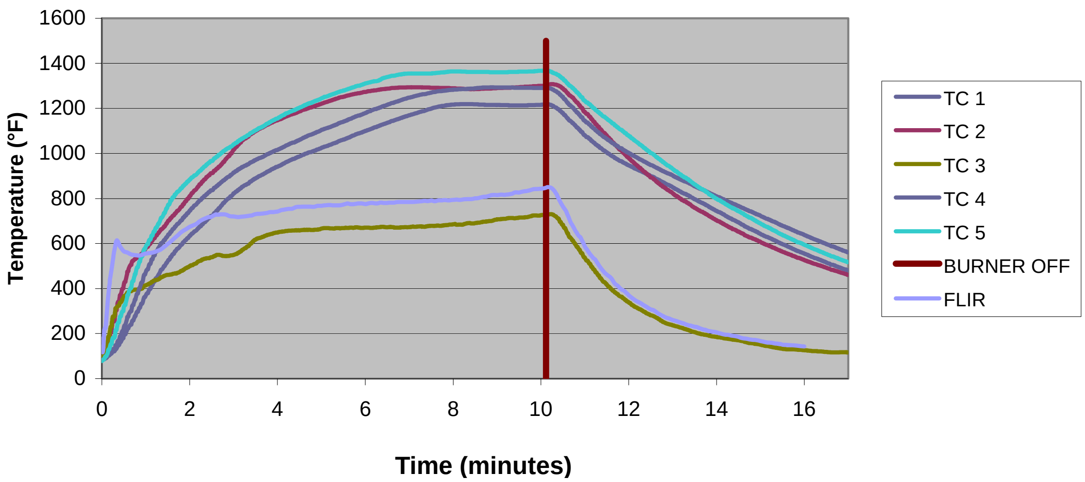

Figure 9. Test 14, TC and FLIR Data

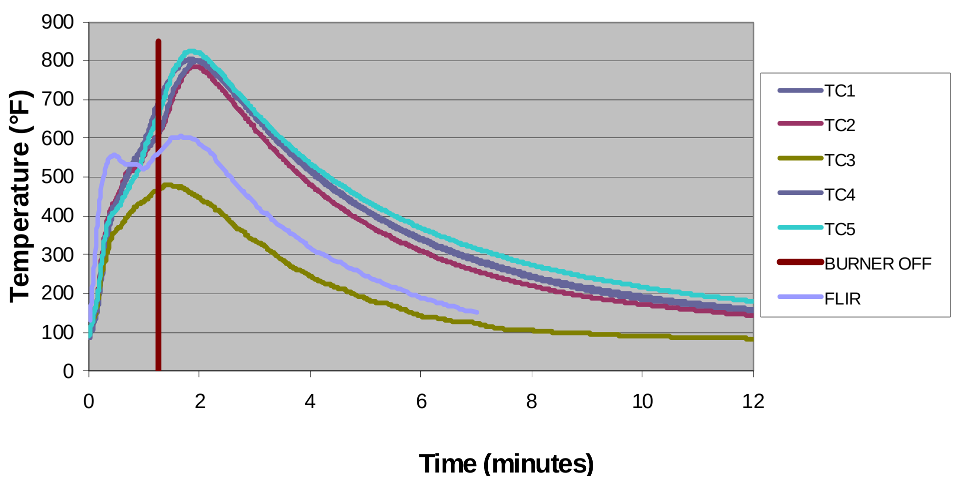

Figure 10. Test 16, TC and FLIR Data

An additional thermocouple, TC 6, was added for tests 18 to 21 to check the readings from TC 3. For all tests, TC 3 was positioned against the sample so that the solder bead on the tip was in contact with the sample. When TC 6 was added, it was positioned so that not only the tip of the TC contacted the sample, but also about 1 to 1.5 inches (25.4 to 38.1 mm) of the wire. Increasing the amount of TC wire in contact with the sample was based on prior experience s by personnel from the FAA chemistry laboratory. It was assumed that this change would prevent heat sink from the wire to air. This slight adjustment showed TC 6 measurements more closely aligned with FLIR measurements. Figure 11 shows the TC 6 and FLIR measurements are virtually the same.

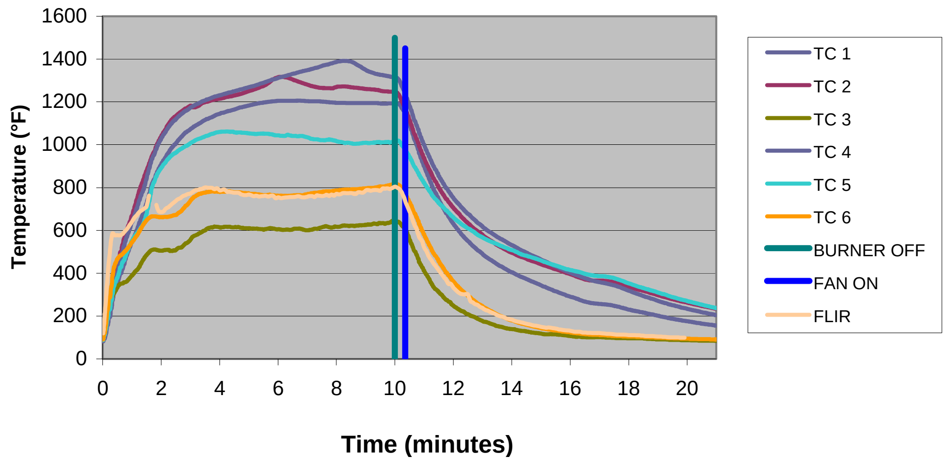

Figure 11. Test 19, TC and FLIR Data

Although the TC 6 and FLIR measurements are similar in test 19, there was still significant difference in other tests, as shown in figure 12. TC 3 and FLIR measurements more closely agreed in some tests, as shown in figure 13. The reason for these differences could not be identified. To maintain consistency in the analysis of this test data TC 3 measurements are used as the representative sample temperature.

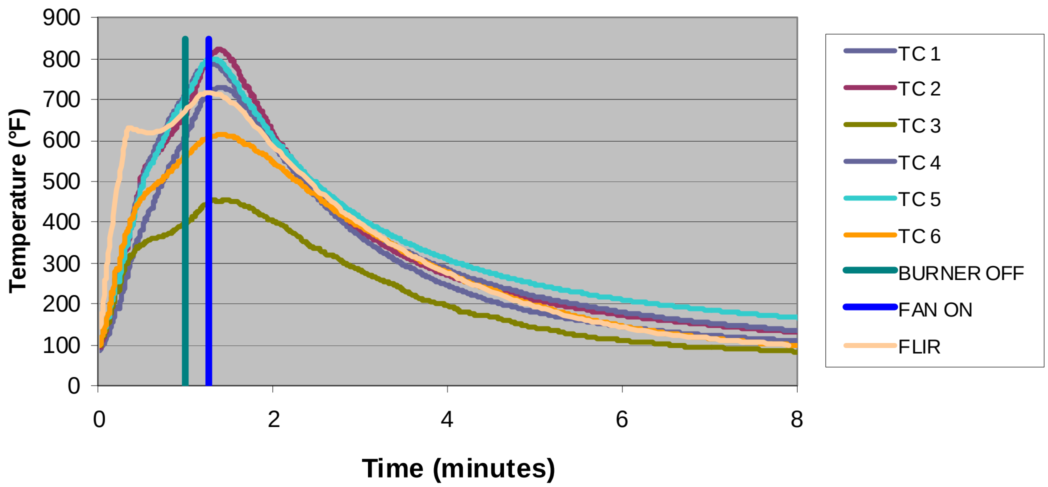

Figure 12. Test 18, TC and FLIR Data

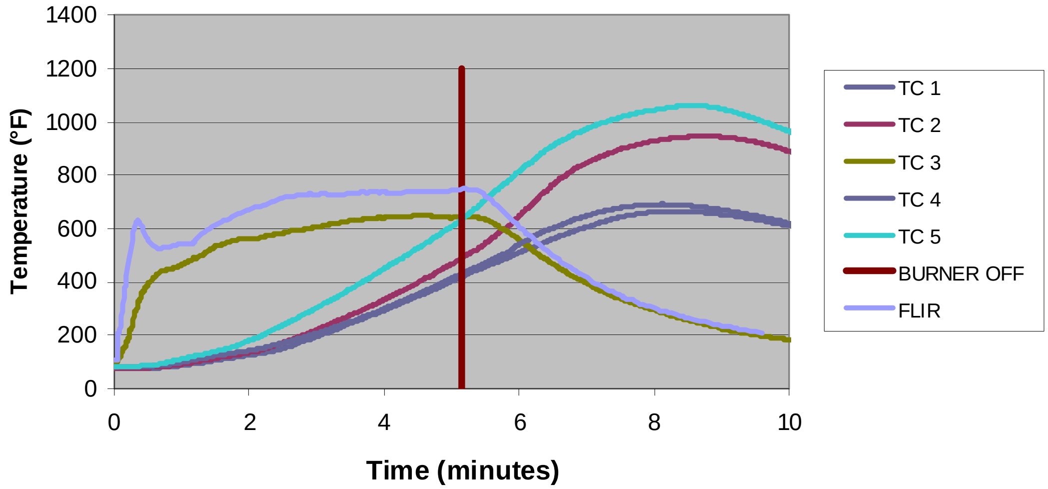

Figure 13. Test 2, TC and FLIR Data

As previously mentioned, maximum sample temperatures were reached near the time of burner removal. Both TC and FLIR measurements agree on the average time to reach the maximum temperature in each exposure time category. Table 2 shows the time to maximum sample temperature as grouped by exposure time.

For shorter exposures, the maximum temperatures were generally reached after the burner was removed. The averages of the longer exposures showed maximum temperatures were reached shortly before burner removal. Exposures longer than 10 minutes were not explored because (1) the severe damage inflicted on the samples at 10 minutes did not seem to leave much resin and (2) the amount of fiber clusters released. Limiting the release of fibers was determined to be an important and appropriate safety measure.

The time for the composite sample to naturally cool below 300°F (150°C) was recorded. This specific temperature was chosen because it was recommended by the USAF [9 and 10]. By ensuring the composite cools below 300°F (150°C), a margin of safety is realized over the auto-ignition temperatures of common aviation fuels [11].

It took between 1 minute 27 seconds and 11 minutes 31 seconds for the TC 3 temperature to naturally fall below 300°F (150°C) for all of the primary test configurations. A better representation of the data set is the median, which occurred at 2 minutes 13 seconds. As a point of comparison, the sample heated to 300°F (150°C) in the first few seconds of exposure.

As the sample cooled, it produced a crackling sound. It was assumed that the fibers were readjusting as pressure and temperature decreased. The precise temperatures were not recorded while this sound occurred. However, the sound may offer an indication of the sample's temperature because it stopped after cooling. There was no visual change in the appearance of the sample that would indicate its temperature.

Table 2. Time to Maximum Sample Temperatures

Test	Exposure Time (minutes)	FLIR Maximum Sample Temperature	FLIR Time to Maximum Temperature	FLIR Time to Maximum Temperature (seconds)	Average Time to Maximum Temperature (seconds)	TC Maximum Sample Temperature	Time to Maximum Sample Temperature	Time to Maximum Sample Temperature (seconds)	Average Time to Maximum Temperature (seconds)
12	1	701	1:15	75	67	602.3	1:25	85	84
16	1	605	1:40	100		482.0	1:26	86	
17	1	568	0:25	25		369.1	1:22	82	
11	2	729	1:50	110		616.2	2:19	139	
20	2.5 (with fan)	759	2:45	165		549.2	2:57	177	
6	3	739	2:50	170	185	691.8	3:16	196	197
7	3	735	3:10	190		650.6	3:17	197	
10	3	717	3:15	195		720.8	3:18	198	
1b	5	Data error	Data error	Data error	305	620.9	5:11	310	295
2	5	749	5:00	300		652.1	4:30	270	
3	5	771	5:10	310		657.2	5:07	306	
13	10	800	9:45	585	597	656.9	8:36	516	576
14	10	850	10:10	610		730.0	10:13	613	
15	10	836	9:55	595		605.8	9:58	598	

2.3 HIDDEN AREAS.

As described in section 1.4, this test configuration incorporated a 1-inch (25.4-mm) border of Kaowool insulation around the front face. Each of the back corners was covered by small Kaowool pads, measuring approximately 2 square inches (50.8 square mm), which were used to hold TCs in place. This technique created four small hidden areas that were insulated on both sides. The hidden areas may simulate areas on an actual aircraft where the composite is fitted into metal or some other construction with the composite sandwiched between materials. These insulated areas may also offer some insight into what differences thermal-acoustic insulation installed against the aircraft skin makes.

Initially, in tests 1-8 and 10, TCs were set under the Kaowool pad with the wire leading out between the pad and the border, as shown in figure 14. A schematic of the initial corner TC placement in figure 15 shows the Kaowool in blue, the composite sample in black, and the TC in red.

This placement consistently showed that temperatures in the insulated corners (TCs 1, 2, 4, and 5) did not initially rise as rapidly as the unprotected sample center (TC 3). Then, once the burner was removed, temperatures continued to rise significantly. The corner that reached the highest temperature was used to determine the maximum hidden area temperature and the time necessary to reach that temperature.

Seven of the first ten tests had valid measurements for this analysis. Analysis of the data clearly shows that all the corners reached maximum temperatures up to several minutes after burner removal. Figures 13, 16, and 17 show delayed heating in the corners, reaching maximum temperatures well after the burner was removed and cooling more slowly than the uncovered area. The figures show that this pattern was independent of the exposure duration.

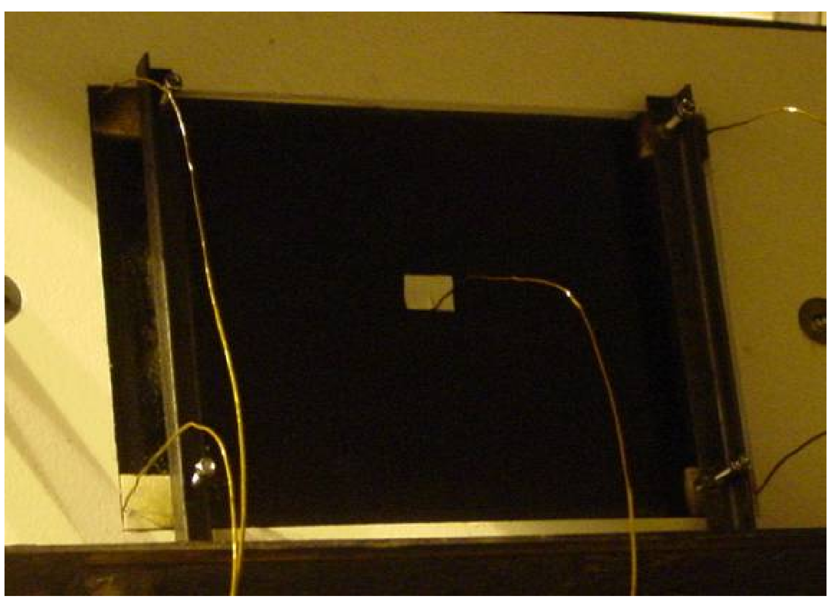

Figure 14. Initial Corner TC Placement

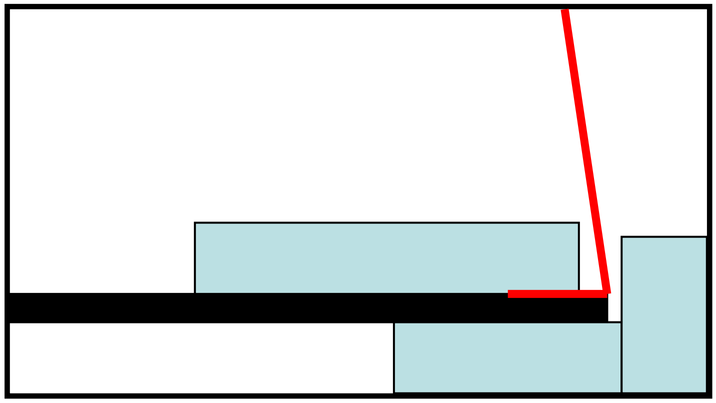

Figure 15. Cut-Away View of Initial Corner TC Placement

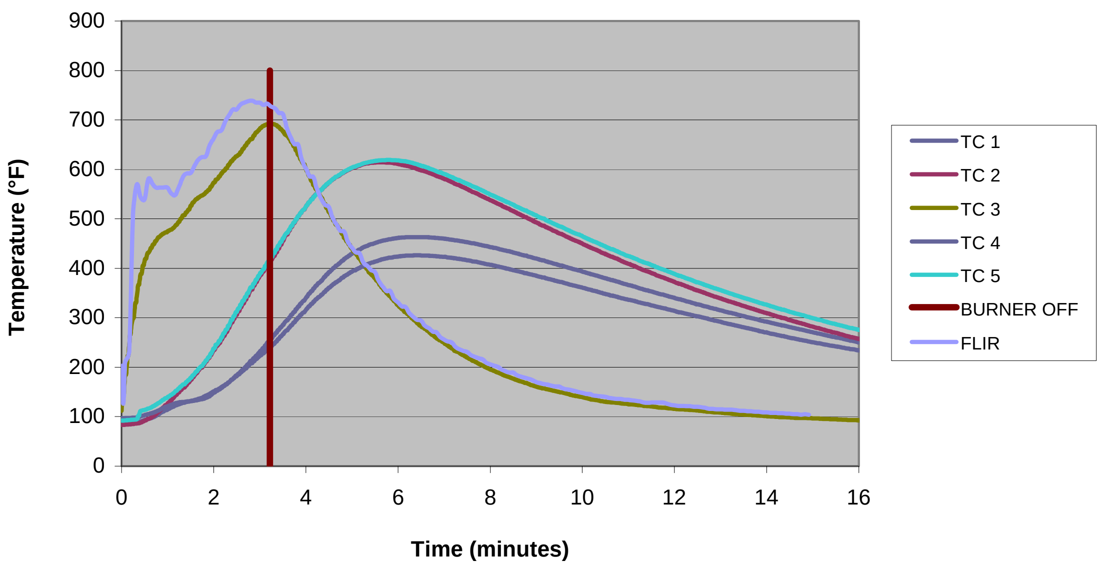

Figure 16. Test 6, TC and FLIR Data

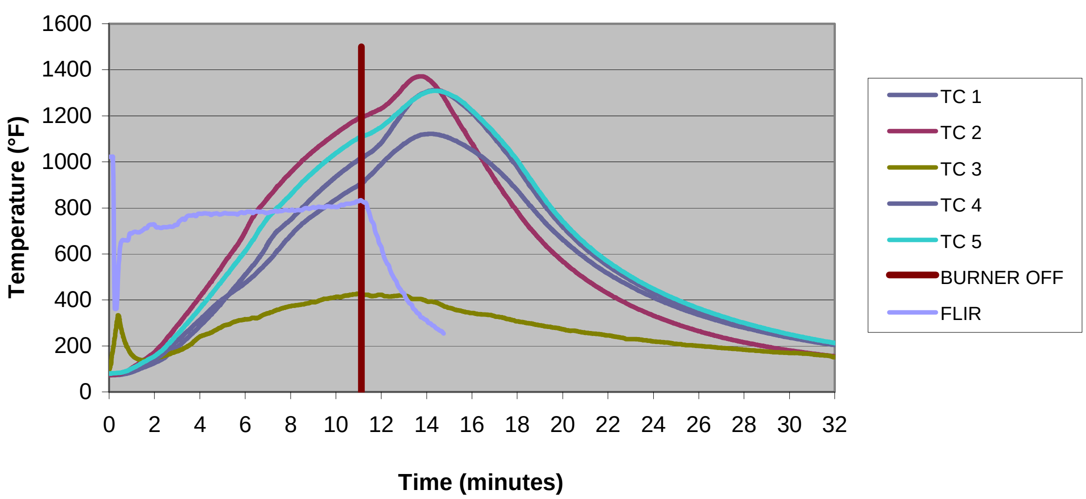

Figure 17. Test 5, TC and FLIR Data

The insulation protected the corners during fire exposure. Then during cool-down, it prevented the heat from being carried away by convection. To look more closely at the temperatures in the corners, an additional TC was added to the upper left corner of the sample, close to where TC 2 is located. It was labeled TC 7 and was positioned just below and in line with the right edge of the Kaowool pad. Figure 18 is an IR image from test 12 that clearly indicates the position of TC 7.

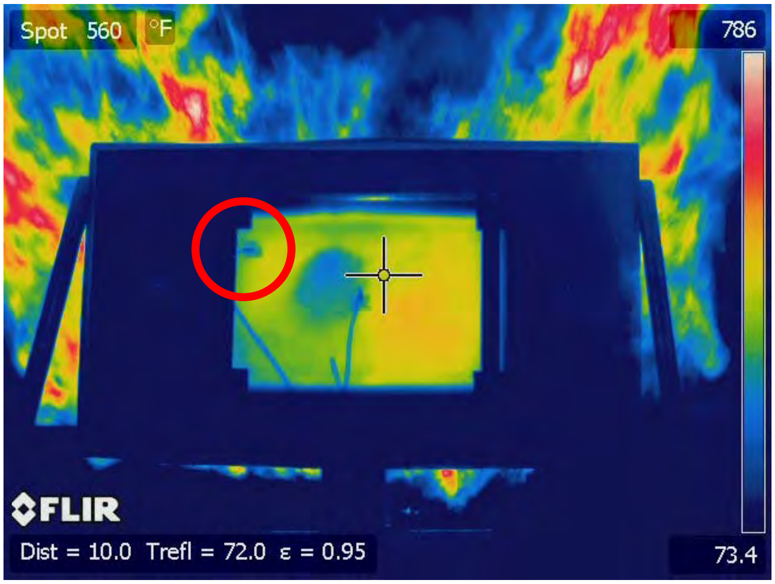

Figure 18. Test 12, TC 7 Position

In comparison, the TC 7 temperatures agreed well with TC 3, indicating that the insulation affected the sample heat transfer, as expected. This also identified limitations in heat transfer in a laminate-type carbon fiber composite. Although TC 7 was very close to the corner's higher temperatures, it agreed more with TC 3, which was in the center of the sample.

Thereafter, the corner TCs were repositioned so that they contacted the sample in an area that the front Kaowool board did not cover. Figure 19 shows the revised position of the corner TCs. Again, the Kaowool is in blue, the TC is red, and the sample is black.

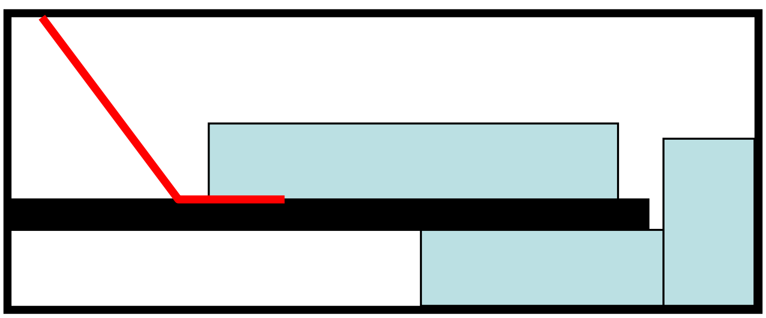

Figure 19. Cut-Away View of Revised Corner TC Placement

This adjustment offered a simulation of aircraft skin with thermal insulation behind it. After the modification to the test method, corner TC measurements reached maximum temperatures when the NextGen burner was removed, just as TC 3 showed for the uncovered sample. The data still showed that the corners reached significantly higher temperatures than the rest of the sample. In 10-minute exposures, the corners reliably reached temperatures at or above 1200°F (654°C). For 1- or 3-minute exposures, the maximum temperatures were, on average, about 200°F (93.3°C) above the measured TC 3 temperatures. These maximum corner temperatures were similar to those measured before the TC adjustment, but they were being reached much sooner.

2.4 MECHANICAL FAILURE.

During the test, an unexpected event occurred: the sudden mechanical failure of some samples during the early moments of fire exposure. Seven of the twenty tests that used the primary test configuration suffered sudden buckling at the center of the 18-inch edge of the sample. The frequency of buckling between the top or bottom edge was split, indicating that orientation of the sample did not factor into the failure. The time until failure ranged from 23 to 42 seconds, with an average of 30 seconds. Quintiere [2] discussed how vaporization of the resin creates pressure within the laminate-type carbon fiber composite as the vapor tries to escape, which causes swelling. During this series of tests, the videos show that, in all cases, smoke escaped from the edges of the sample, not the face. In fact, vigorous smoke was observed pouring out from the edges. All the samples swelled during exposure, although the amount of swelling was not always the same. The front overlap of Kaowool protected the outside border of the sample face, leaving it mostly intact, which retained swelling to the middle.

A clear border of less damage around the entire sample, with hardened bubbles of resin char in some areas, was obvious during the postexposure inspection, as shown in figures 20 and 21. In test 17, the sample buckled at the center of the top edge, cracking the front Kaowool board after 41 seconds of fire exposure. The sample started to smoke at 16 seconds, with heavy smoke at 20 seconds. At approximately 27 seconds, the amount of smoke reduced. This reduction in smoke was more obvious just prior to the mechanical failure. Once the failure occurred, a surge of heavy smoke came from the top edge. Ignition of the heavy smoke occurred at 42 seconds.

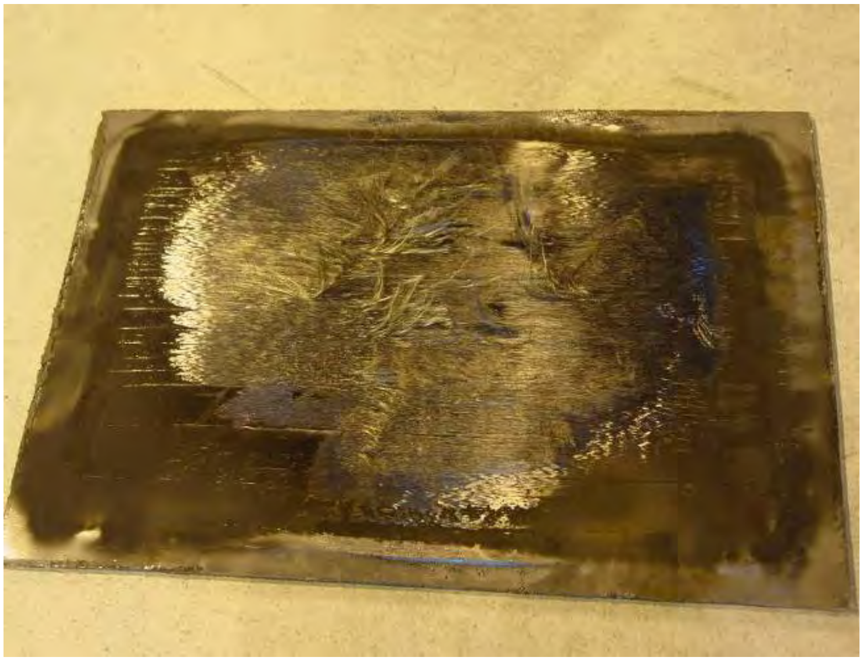

Figure 20. Front of Sample From Test 1B Postexposure

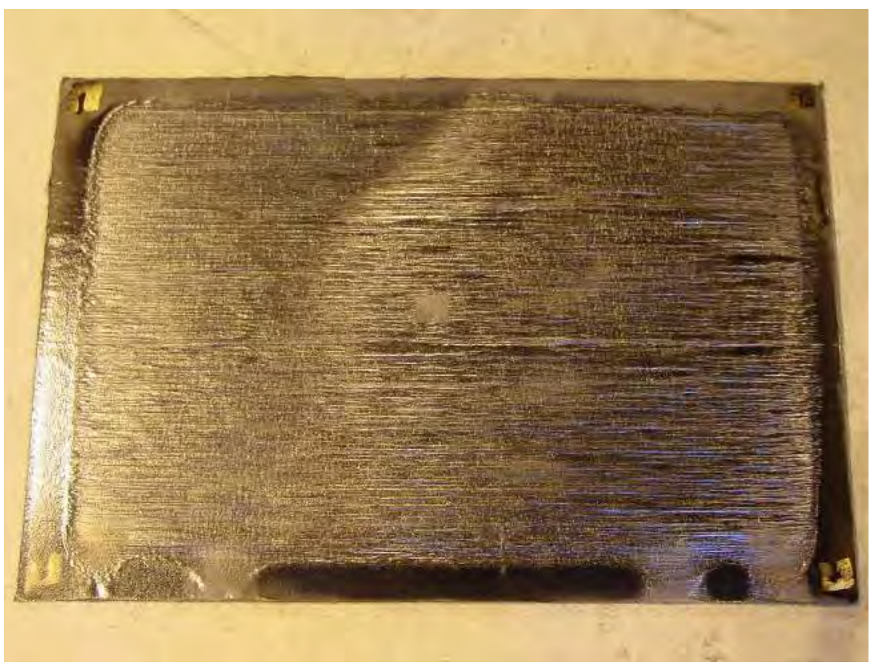

Figure 21. Back of Sample From Test 1B Postexposure

During the other tests where a sudden failure of the sample occurred, the sudden burst of fire from the back was the only indication of a mechanical failure. A postexposure inspection confirmed that the sample buckled. The mechanical failure from test 4 is shown in figure 22.

Figure 22. Buckled Sample From Test 4

After the first several failures, the ACO was contacted to inquire if the samples were built with flaws or if the fabrication process was somehow different than that used for actual aircraft parts. According to the ACO, all samples were prepared from the same batch of materials and were autoclave-cured using F-16 process specifications [12]. As part of the effort to prevent flame wrap around, the samples were fitted as tightly as possible into the back Kaowool board. It is possible that the back Kaowool board restricted the escape of smoke from the edges and may have created a back pressure. These failures appear to be a rupture related to the internal pressurization; however it remains unclear why only some of the samples failed in this way.

2.5 SMOKING.

Each sample emitted smoke during exposure and continued to produce smoke after burner removal. Since smoke production was present in each test configuration, all tests have been included in the results. The smoke was not analyzed as part of this study but has been investigated elsewhere [13]. Similarly, the combustibility of the smoke was not measured, but was clearly observed. In some tests, heavy smoke ignited when contacted by flame. Those instances of ignition are discussed in section 2.6. The time of onset of smoke production ranged from 2 to 31 seconds, with an average time of 15 seconds. The onset of heavy smoke ranged from 13 to 39 seconds, with an average of 24 seconds. After burner removal, the smoke ceased in as little as 16 seconds or as much as 5 minutes 58 seconds.

Smoke may be a good indicator of the materials' temperature. The smoke started at an average temperature of 254°F (124°C), but the measured range was between 111°F (44°C) and 392°F (202°C), which is too wide a range to definitively state that smoke will start and stop at a certain temperature. FLIR temperatures at the onset of smoking had similar variations. The average

FLIR temperature at the onset of smoke was 447°F (232°C), ranging from 139°F (60°C) to 621°F (330°C). The data show that the smoke did not occur below 110°F (43.3°C).

2.6 REAR FLAME.

As discussed in section 2.5, there were clear instances when the heavy smoke contacted with an ignition source. In tests 4 and 21, a mechanical failure of the sample led to smoke ignition, which led to complete fire involvement of the back side. Figure 23 shows the amount of backside flame for test 4. Figure 24 shows backside flame during test 21. Test 4 suffered the mechanical failure at 35 seconds, as indicated by a burst of thick smoke and a color change in the IR image. Full involvement of the back occurred at 53 seconds. For test 21, the results were nearly identical: failure at 23 seconds with full flame involvement at 49 seconds.

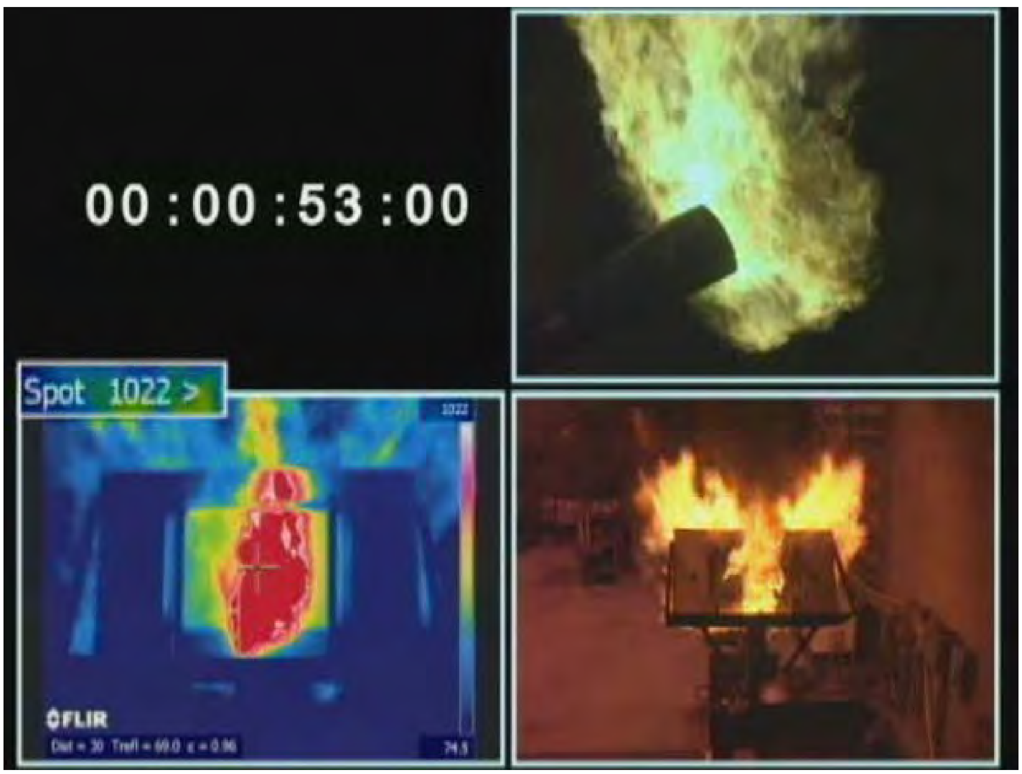

Figure 23. Backside Flame Involvement in Test 4

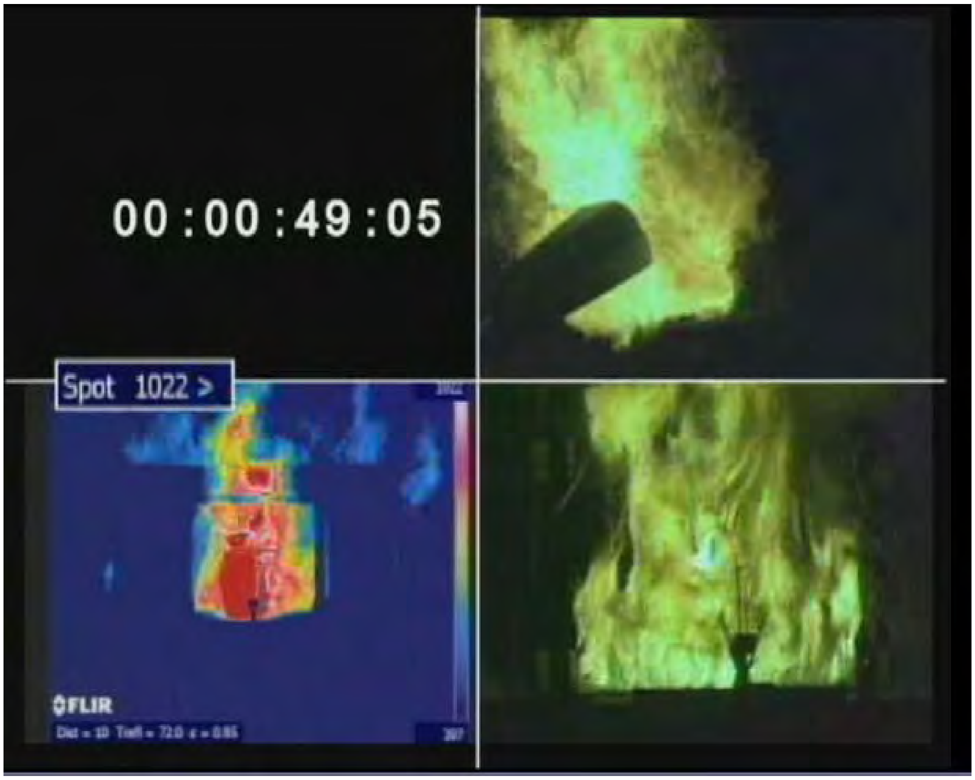

Figure 24. Backside Flame Involvement in Test 21

In test 18, the smoke ignited 1 second after the burner was removed, as the smoke column from the back top edge contacted the flame from the front face. The video clearly showed that the flame traced down to the sample then across the top edge. Figure 25 shows a series of screen-captured images from the test 18 video. Of the 23 tests, 8 had postexposure flaming on both sides of the sample that lasted 1 minute 20 seconds on average compared to all other instances of postexposure flaming that averaged 30 seconds.

The smoke ignition was not particular to test 18, but also identified in three other tests. Test 19 had two instances where the smoke ignited during the test; tests 4 and 17, the smoke clearly ignited when it contacted the flame.

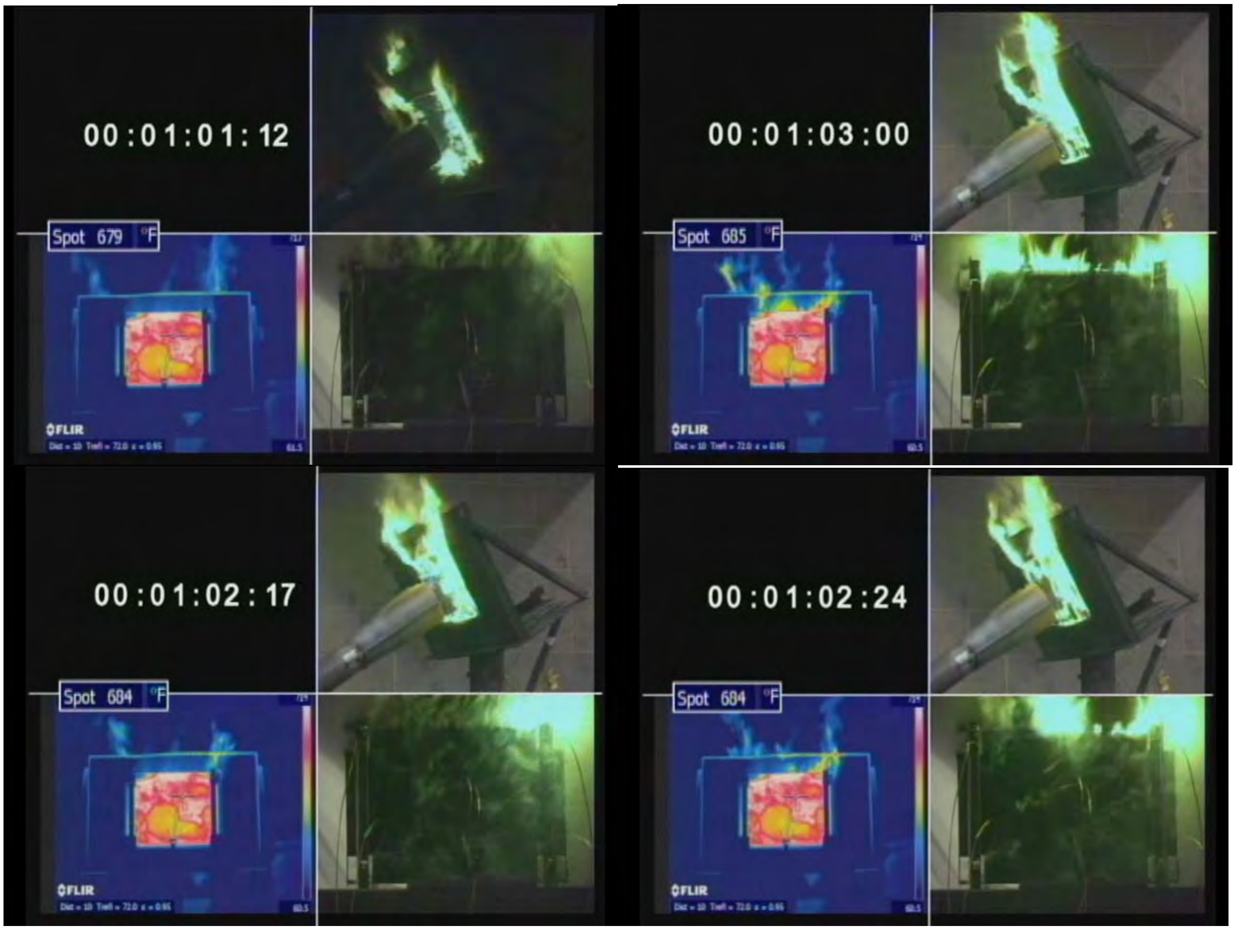

Figure 25. Postexposure Backside Smoke Ignition, Test 18

2.7 POSTEXPOSURE FLAMING.

Once the NextGen burner was removed, flaming continued after every test, regardless of test configuration, for as little as 1 second to nearly 3 minutes. The average time for total flame extinction was 47 seconds.

In some instances, as in the 1-second flame duration from test 13, the flames were very small, and scattered about the front, or the front edges. In other instances, flickers of flame were observed inside the sample, through gaps in the delaminated outer fiber plies, as in tests 6 and 16. Tests 16 through 18 were 1-minute tests in which, after removal of the burner, the entire front was enveloped by flame, as shown in figure 26.

Figure 26. Postexposure Flaming Combustion, Test 16

Reviewing the times in which the flames self-extinguished after burner removal provides a clear difference between exposure durations. This may indicate that greater amounts of remaining resin (fuel) allow for longer, self-sustained flaming (chemical reaction) until the sample temperature cools sufficiently (heat) or the resin is burned away. Median postexposure flaming times grouped by exposure duration are shown in table 3.

Table 3. Postexposure Flaming Durations

Exposure Time (minutes)	Test	Front or Back Flaming	Time to Self-Extinguish After Burner Off	Duration (seconds)	Average Time (seconds)	Median Time (seconds)
1	9	Edge	0:09	9	54	75
1	12	Both	1:17	77		
1	16	Front	0:31	31		
1	17	Both	1:18	78		
1 (with fan)	18	Both	1:15	75		
2	11	Front	0:26	26	38	38
2.5 (with fan)	20	Both	0:49	49		

Table 3. Postexposure Flaming Durations (Continued)

Exposure Time (minutes)	Test	Front or Back Flaming	Time to Self-Extinguish After Burner Off	Duration (seconds)	Average Time (seconds)	Median Time (seconds)
3	6	Both	1:07	67	47	50
3	7	Both	0:50	50		
3	10	Front	0:24	24		
5	1b	Front	0:58	58	30	25
5	2	Front	0:12	12		
5	3	Front	0:29	29		
4.5	4	Front	0:21	21		
8	1	Back	2:22	142	-	-
10	5	Front	0:18	18	48	17
10	13	Front	0:01	1		
10	14	Front	0:15	15		
10	15	Both	0:38	38		
10 (with fan)	19	Both	2:58	208		
10 (with fan)	21	Front	0:09	9		

2.8 POSTEXPOSURE SMOLDERING.

Postexposure smoldering became a condition of particular interest after it was observed during the video analysis of the initial 12 tests. Prior to the tests, it was decided that the color camera view should match the FLIR camera view to allow a matching side-by-side picture that could be used for demonstration. Therefore during these tests, the color camera view of the sample's backside was not a close-up. This made it difficult to view the subtle glow that can indicate a smoldering condition. The remaining tests used a closer view of the sample for better observation of any conditions the sample may display.

No smoldering was observed for any of the 5-minute exposures, although in shorter and longer exposures some smoldering was observed. Of the 23 tests conducted, 14 had at least one location on the sample where smoldering occurred. Not all smoldering was observable immediately after the burner was removed. In several cases, smoldering did not present for up to several minutes after exposure. For this analysis, each separate location was considered as a separate occurrence. Some tests had two or more separate locations that smoldered.

The onset of smoldering ranged from immediately to 2 minutes 33 seconds after exposure, with an average initiating time of 46 seconds, as presented in table 4. Smoldering continued, on average, for 2 minutes 28 seconds, ranging from 42 seconds to 5 minutes 13 seconds. More often, smoldering conditions occurred in the corners. During test 16, smoldering was observed in the center of the sample and in seven other tests on the top edge. One test smoldered on the left edge, but this occurred during test 1 when the sample became unsecured on the left edge and flame wrapped around that edge.

In tests where sufficient data were available, the temperatures in the smoldering areas were documented at the time of onset and cessation and compared with the TC 3 temperature for the same time. The average and median values are shown in table 5. The average and median values both indicate that the temperatures within the smoldering areas reduced by 30% from onset to cessation, while the temperature of the sample decreased more than 50%.

Beginning with test 18, a small floor fan was used to determine if simulated airfield wind conditions would reveal or aggravate any smoldering. A Kestrel® 4500 Pocket Weather Tracker was used to measure the wind speed of the fan, which was 7-8 mph (11.3-12.9 kph) at a 4-foot (1.22-m) distance. The fan was used in tests 18 through 22. In tests 18 and 20, the fan did not seem to make any difference in the duration or intensity of smoldering compared to other similar exposure times, except that in test 18 the smoldering began after almost 1 minute 30 seconds. Tests 19 through 21 showed very bright, robust smoldering. The fan appeared to enhance the smoldering but did not affect the measured temperatures. A comparison between wind-driven and non-wind-driven smoldering is shown in tests 22 and 23, and is discussed in section 3.2.

Table 4. Occurrences of Smoldering

Exposure Time (minutes)	Test	Postexposure Smoldering	Front or Back	Location	Initiating Time After Burner Removal	Initiating Time After Burner Removal (seconds)	Time to Cessation	Time to Cessation (seconds)
1	12	Y	Back	Top edge	0:00	0	2:32	152
1	16	Y	Back	Center	0:00	0	1:40	100
1 (with fan)	18	Y	Back	Top edge	1:28	92	1:32	92
2.5 (with fan)	20	Y	Back	Top edge	0:00	0	1:53	113
3	6	Y	Back	Top edge	0:00	0	1:27	87
8	1	Y	Back	Top edge	0:00	0	2:22	142
	1	Y	Back	Left edge	0:00	0	2:22	142
10	5	Y	Back	Left top corner	1:01	61	2:41	161
	5	Y	Back	Right top corner	1:54	114	0:56	56
10	13	Y	Back	Top edge	0:00	0	1:04	64
	13	Y	Back	Left bottom corner	2:24	144	2:53	173
10	14	Y	Back	Right top corner	0:00	0	2:42	162
10	15	Y	Back	Right bottom corner	2:00	120	1:22	82
	15	Y	Back	Right top corner	2:00	120	3:02	182
10 (with fan)	19	Y	Back	Top edge	0:00	0	2:38	158
	19	Y	Back	Right top corner	1:33	93	5:13	313
	19	Y	Back	Right bottom corner	1:37	97	2:09	129
	19	Y	Back	Left top corner	2:33	153	3:06	186
10 (with fan)	21	Y	Back	Right top corner	0:00	0	3:12	196
	21	Y	Back	Right bottom corner	0:23	23	0:42	42
	21	Y	Back	Left top corner	0:34	34	1:50	110
1 (with fan)	22	Y	N/A	N/A	0:00	0	5:03	303
1	23	Y	N/A	N/A	0:00	0	4:11	251

N/A =Not applicable

Table 5. Average and Median Data of Smoldering Condition

	Time to Begin After Burner Off (seconds)	Onset Temp (°F)	Onset Temp (°C)	Sample Temp (°F)	Sample Temp (°C)	Time to Cessation After Begin (seconds)	Stop Temp (°F)	Stop Temp (°C)	Sample Temp (°F)	Sample Temp (°C)
Average	90	940	509	434	225	155	665	354	205	97
Median	95	916	495	434	225	159	668	356	198	93
Maximum	153	1367	748	727	389	313	957	518	419	217
Minimum	0	629	334	231	112	42	390	200	113	45

Temp = Temperature

2.9 REIGNITION.

The potential for reignition is a primary concern for fire fighters on an aircraft incident because of the amounts of fuel that could be present. Training and practice dictate that a blanket of firefighting foam must be maintained to prevent reignition.

Three of the primary configuration tests had some amount of reignition after burner removal. During test 10, the flame flickered for less than 1 second. Test 19 had a flame initiate after 1 minute 4 seconds; the flame then stopped and started again for 2 minutes 58 seconds, which could be attributed to the addition of the fan. Test 20 had flames reignite from the left and top edges of the sample. They both occurred after 23 seconds; the left edge only lasted 9 seconds, the top edge lasted 26 seconds. However, for test 20, the flames reignited at the same location they occurred during fire exposure. They had extinguished 1 second prior to the reignition so this may not have been a reignition but a persistent fire. Both tests 19 and 20 included wind-driven conditions, which lends to the conclusion that wind may not only create a more robust smoldering but can cause reignition.

3. OTHER TEST CONFIGURATIONS.

3.1 TEST 9.

Test 9 was conducted to determine if immersing an edge of the sample into the burner flame, on a downward angle, would inflict a more severe postexposure flaming or even flame propagation. The sample was fixed on the same frame used for the primary configuration, but the sample was held vertically with the 12-inch edge facing into the burner flame. Figure 27 shows the sample orientation.

Figure 27. Sample Orientation for Test 9

Five TCs were positioned toward the rear of the sample, as shown in figure 28. The maximum temperature measured by the TCs was 777°F (417°C), reached in 59 seconds at TC 2. The FLIR camera measured 819°F (441°C) maximum at 1 minute. It took the sample 1 minute 55 seconds to cool below 300°F (150°C) at TC 2. All the measurements are consistent with those of the primary configuration tests. However, it is important to state that TC 2 and TC 3 were either in the path of the flame or at the border of it. The crosshair of the FLIR camera was pointed at the center of the sample, which was also along the flame border. The other three TCs measured temperatures below 400°F (206°C), with the lowest maximum temperature at TC 4 of 280°F (139°C).

Figure 28. Test 9, TC Numbering Sequence

There was some flame along the forward top edge of the sample after burner removal, but it only lasted for 5 seconds. A brief flicker of flame emanated from the bottom edge at 9 seconds after burner removal. The sample was only exposed for 1 minute 10 seconds.

3.2 TESTS 22 AND 23.

The samples used in tests 22 and 23 were cut into four equal pieces that were layered with 3/4-inch (76.2-mm) gaps between each piece. Figure 29 shows the sample orientation after test 23. These tests were conducted to determine how radiant heating between the layers changed the postexposure conditions, particularly the amount and severity of any smoldering.

The Fire Protection Handbook [14] states:

> "When two bodies face each other and one body is hotter than the other, a net flow of radiant energy from the hotter body to the cooler body will ensue until thermal equilibrium is achieved. … The ability of the cooler body to absorb radiant heat depends on the nature of the surface. If the receiving surface is shiny or polished, it will reflect most of the radiant heat away, whereas if it is black or dark in color, it is likely to absorb most of the heat."

The emissivity of the carbon fiber composite sample was determined to be 0.95, which is very close to the maximum value of 1.0. This means that carbon fiber composite readily absorbs heat, and in turn, reflects very little of the radiant heat.

Figure 29. Sample Orientation for Tests 22 and 23

Exposure times were limited to 1 minute. A fan was introduced in test 22. Once the burner was removed, some self-sustained flames persisted but the most dramatic result was a very bright, hot smoldering on all the interior surfaces, as shown in figure 30. This result was exactly the same for both tests.

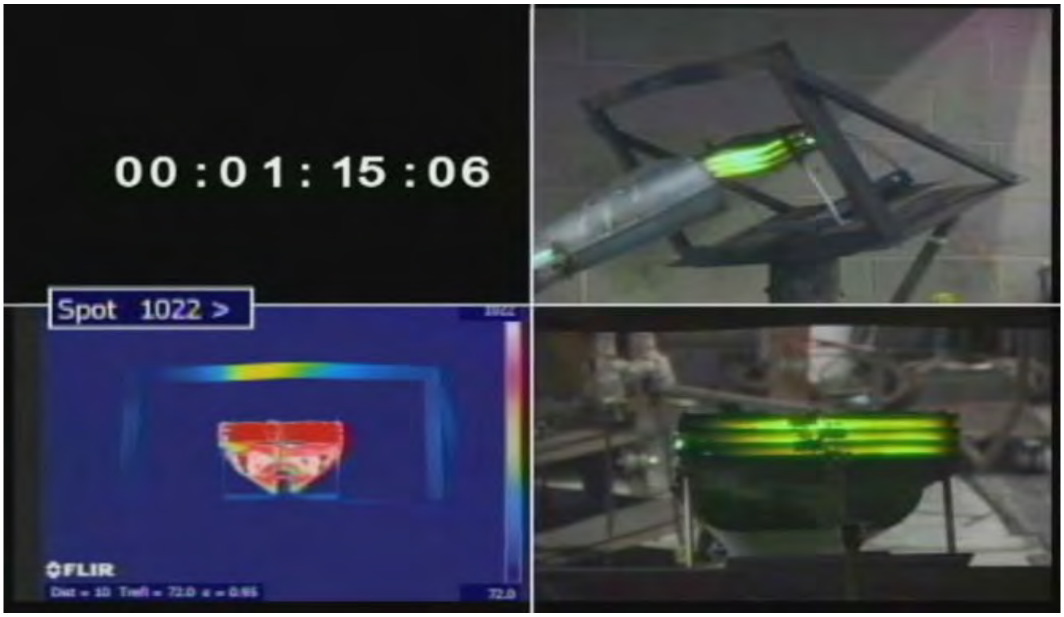

Figure 30. Smoldering in Test 23

TCs were positioned on the top surface of each layer, numbered 1-4 from the top to the bottom. Temperatures measured by TCs showed maximum temperatures in the vicinity of 1750°F (962°C). While this configuration does not necessarily simulate any typical aircraft construction, there are many locations where aircraft structures could radiate heat to each other, as in locations where composite framing and stringers meet the skin.

Wind does seem to have had a small effect on the duration of the smoldering condition. A fan was introduced following removal of the burner in test 22, which caused the smoldering to last 52 seconds longer than in test 23.

As the layers continued to smolder, plies of fiber fell from the layers. As the layers were taken apart for disposal, they mostly fell apart, indicating that most of the resin had burned away.

4. SUMMARY.

This series of tests showed that flaming combustion, smoldering, and smoking will occur in various degrees of severity during and after fire exposure. Given the temperatures that can be achieved in an aviation fuel-fed pool fire, around 1800°F (990°C), sufficient heat is available to raise the temperature of carbon fiber composite to briefly sustain flaming and smoldering, even after the extinguishment of the fuel-fed pool fire.

During this study, a thin, flat, laminate-type carbon fiber composite sample exhibited some postexposure flaming and smoldering. Areas where Kaowool™ insulation covered one side of the sample, temperatures were approximately 500°F (262°C) above those measured on the uncovered area, indicating that aircraft thermal-acoustic insulation and areas of structural joining may have an effect on the fire condition and increase the potential for persistent smoldering. Additionally, simulated airfield wind conditions enhanced and prolonged the smoldering condition. Since the thickness of the samples was only representative of fuselage skin, the response of a much thicker or stiffened sample under similar conditions is unknown. Results from tests 22 and 23 indicate that areas where two carbon fiber composite structures are close enough to radiate heat to each other have the potential to reach extremely high temperatures, similar to those of an external fuel-fed pool fire.

It was shown that backside sample temperatures sometimes varied even when measured in close proximity to each other. It is possible that these temperature variations indicate an inherent protective mechanism that would prevent flame spread to the larger area outside the fire exposure. In these tests, the sample was completely covered by flames, which makes any assessment of propagation impossible without being able to consider a sample that extends beyond the fire area.

The amount of resin available for combustion is an important factor concerning how much postexposure flaming can occur. The longer the fire exposure, the more resin will burn away, and the more damage will be sustained through the composite delaminating and outer fiber plies breaking away. However, smoldering conditions seem to be independent of resin content and driven by heating the fibers. Internal pressurization always caused swelling of the samples, despite that smoke was escaping from the edges. In some tests, an edge of the sample suffered mechanical failure that appears to be a rupture caused by the internal pressurization.

FLIR images and TC measurements indicated laminate-type carbon fiber composites absorb heat unevenly across their surface, possibly due to delamination. For the fire service, these variations do not make a difference because hot areas must always be addressed to achieve total extinguishment. Thermal-imaging cameras should be used to check for hot spots just as in any other fire. In all the tests, the FLIR measured the surface temperature of the carbon fiber composite, which does not provide a clear indication of the temperature inside thick composite or even behind thin composite. Every maximum FLIR temperature measured was less than half the temperature emitting from the burner, indicating that while the fire may be extreme, the opposite surface temperature is not. A study of the effects of composite thickness on infrared imaging and temperature measurements may better define the effectiveness of thermal imaging.

Cooling the samples to below 300°F (150°C) (to eliminate the reignition hazard) happened quickly in areas that were open to the air and free to dissipate heat. Areas covered on one side by the Kaowool insulation normally took several minutes to cool. This could be due to the large difference in peak temperatures between those two areas. A higher peak temperature may require a longer time to cool. Regardless of the reason, the composite must be cooled below 300°F (150°C). The fastest cool-down time was almost 90 seconds for the uncovered sample center. As previously discussed, thicker composite, stiffened areas, and thermal-acoustic insulation may cause higher temperatures like those in tests 22 and 23. Based on the results of this study, there are conditions that warrant further investigation to determine if firefighting agents need to be applied to mitigate the hazard.

Smoking was the only reliable visual indicator identified during the tests that could be used by fire fighters to identify areas that still required continued application of agent for cooling. It was determined that smoke was not produced at temperatures under 110°F (43.3°C). Fire service thermal-imaging cameras should be used; however, it should be noted that temperatures measured on a composite structure may mask higher temperatures behind it. These tests consistently showed temperatures measured on the samples that were less than half of the fire temperature on the opposite side.

5. CONCLUSIONS.

The tests conducted in this study rendered the following conclusions.

- Flaming combustion, smoldering, and smoking will occur in various degrees of severity during and after fire exposure, depending on the duration of fire exposure.

- Lateral propagation could not be assessed because the flame completely covered the sample.

- It was shown that back side sample temperatures varied somewhat even when measured in close proximity.

- Cooling the samples below 300°F (150°C) happened relatively quickly in areas that were open to the air and free to dissipate heat but slowly in areas covered with insulation. The fastest time measured for this to occur was almost 90 seconds for the uncovered sample center.

- Thermal-imaging cameras should be used to check for hot spots just as in any other fire situation. Smoking was the only reliable visual indicator identified during testing that could be used by fire fighters to identify areas that still required continued cooling.

- Some test results showed that composite samples can continue to burn or smolder after fire exposure. In those tests, the residual fire that remained after burner removal was small, and therefore, did not require agent application. In all cases, the residual fire quickly self-extinguished. High-temperature smoldering after fire exposure was found when samples were oriented closely together. Further tests are necessary to develop a fire test protocol that will generate a robust postexposure fire to require application of firefighting agent to extinguish the fire.

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