DOT/FAA/TC-14/23

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—GLARE

August 2014

Final Report

This document is available to the U.S. public through the National Technical Information Services (NTIS), Springfield, Virginia 22161.

This document is also available from the Federal Aviation Administration William J. Hughes Technical Center at actlibrary.tc.faa.gov.

U.S. Department of Transportation
Federal Aviation Administration

NOTICE

This document is disseminated under the sponsorship of the U.S. Department of Transportation in the interest of information exchange. The United States Government assumes no liability for the contents or use thereof. The United States Government does not endorse products or manufacturers. Trade or manufacturer's names appear herein solely because they are considered essential to the objective of this report. The findings and conclusions in this report are those of the author(s) and do not necessarily represent the views of the funding agency. This document does not constitute FAA policy. Consult the FAA sponsoring organization listed on the Technical Documentation page as to its use.

This report is available at the Federal Aviation Administration William J. Hughes Technical Center's Full-Text Technical Reports page: actlibrary.tc.faa.gov in Adobe Acrobat portable document format (PDF).

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT/FAA/TC-14/23		

4. Title and Subtitle	5. Report Date
DEVELOPMENT OF A FIREFIGHTING AGENT APPLICATION TEST PROTOCOL FOR AIRCRAFT FUSELAGE COMPOSITES, PHASE I—GLARE	August 2014
	6. Performing Organization Code
7. Author(s) John C. Hode and William Doig	8. Performing Organization Report No.
9. Performing Organization Name and Address SRA International 1201 New Road, Suite 242 Linwood, NJ 08221	10. Work Unit No. (TRAIS) 11. Contract or Grant No. DTFACT-10-D-00008
12. Sponsoring Agency Name and Address Federal Aviation Administration Airport Safety and Operation (AAS-300) 800 Independence Avenue SW Washington, DC 20591	13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code AAS-300

15. Supplementary Notes

The Federal Aviation Administration Airport Technology Research & Development Branch COR was Keith Bagot.

16. Abstract

A research effort is underway to develop a standardized test method to determine the amount of firefighting agent needed to extinguish fires involving aircraft built with advanced composite materials. These tests focus on evaluating the behavior of GLAss-REinforced aluminum laminate (GLARE) when exposed to a simulated aviation fuel-fed pool fire. This test is a continuation of previous carbon fiber-reinforced plastic fire tests reported in DOT/FAA/TC-12/6, "Development of a Firefighting Agent Application Test Protocol for Aircraft Fuselage Composites, Phase I—Carbon Fiber."

This series of tests assessed the fire behavior of GLARE samples that are representative of aircraft skin applications. These tests focused on determining (1) if the temperature transfers through the sample, (2) if burnthrough or post-exposure burning occurs, (3) if a smoldering condition exists after fire exposure, (4) the amount of time it takes for the sample to naturally cool below 300°F (149°C) after the fire source is removed, and (5) if there are any physical indicators that would help firefighters determine if the sample has cooled sufficiently to prevent re-ignition.

The Federal Aviation Administration NextGen 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. Twelve tests were conducted using GLARE 3-5/4-0.3, with a total thickness of 2.5 mm (0.098 in.). Nine of these tests used a 12- by 18-inch sample positioned flat, with the face of the sample in front of the fire source. The remaining three tests used the same size sample cut into four equal pieces layered 0.75 inch apart and set with the edges of the long side facing the fire source. The samples were subjected to different fire exposure times. Temperature measurements and infrared images were collected during the tests.

The nine flat panel tests measured the temperature on both sides of the sample, and the temperature measured on the back of the sample was less than half of the burner side temperature. Burnthrough did not occur during any of these tests. In each test, the outer layer of aluminum that faced the burner melted away, but the glass layers below remained mostly intact. There was some amount of post-exposure flame in all tests performed. Despite the exposure duration, the post-exposure flame lasted approximately 1 minute. The recorded times for the flat panel test samples to cool below 300°F (149°C) were not consistent. However, for the layered tests, the recorded times were consistent with an average time of 11 minutes 36 seconds. There were no visual indications that the samples had cooled below 300°F (149°C).

17. Key Words	18. Distribution Statement
Aircraft composites, GLARE, fire test method, NextGen oil burner, Forward-Looking Infrared, Aircraft Rescue and Firefighting	This document is available to the U.S. public through the National Technical Information Service (NTIS), Springfield, Virginia 22161. This document is also available from the Federal Aviation Administration William J. Hughes Technical Center at actlibrary.tc.faa.gov.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	44	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

ARFF	Aircraft Rescue and Firefighting
CFR	Code of Federal Regulations
CFRP	Carbon Fiber-Reinforced Plastic
FAA	Federal Aviation Administration
FLIR	Forward-Looking Infrared
GLARE	GLAss-REinforced aluminum laminate
TC	Thermocouple

EXECUTIVE SUMMARY

Historically, composite materials have been used in commercial aircraft in nonstructural parts throughout the aircraft; however, their use in the fuselage has been limited. Currently, two particular advanced composite materials have been used significantly in construction of commercial aircraft fuselages, carbon fiber-reinforced plastic (CFRP) and GLAss-REinforced (GLARE) aluminum laminate.

Research is underway to develop a standardized test method to determine the amount of firefighting agent needed to extinguish fires involving aircraft built with these advanced composite materials. This series of tests focused on evaluating the behavior of GLARE when exposed to a simulated aviation fuel pool fire. These tests are a continuation of previous CFRP fire tests documented in DOT/FAA/TC-12/6, "Development of a Firefighting Agent Application Test Protocol for Aircraft Fuselage Composites, Phase I—Carbon Fiber."

This series of tests focused on determining (1) if the temperature transfers through the sample, (2) if burnthrough or post-exposure burning occurs, (3) if a smoldering condition exists after fire exposure, (4) the amount of time the sample takes to naturally cool below 300°F (149°C) after the fire source has been removed, and (5) if there are any physical indicators that would help firefighters determine if the sample had cooled sufficiently to prevent re-ignition.

Twelve tests were conducted using GLARE 3-5/4-0.3, with a total thickness of 2.5 mm (0.098 in.). Nine of these tests used a 12- by 18-inch flat panel configuration with the sample face in front of the fire source. The remaining three tests used the same size sample cut into four equal pieces in a layered configuration 0.75 inch apart and set with the edges of the long side facing the fire source. 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. The samples were subjected to different fire exposure times. Temperature measurements and infrared images were collected during the tests.

The flat panel tests measured the temperature on both sides of the sample. For the nine flat panel test conducted, the temperature measured on the back of the sample was less than half of the burner side temperature. Burnthrough did not occur during any of these tests. In each test, the outer layer of aluminum that faced the burner melted away, but the glass layers below remained mostly intact. There was some post-exposure flame in all the tests. Despite the exposure duration, the post-exposure flame lasted approximately 1 minute. The recorded times for the flat panel test samples to cool below 300°F (149°C) were not consistent. However, in the layered tests, the recorded times were consistent, with an average time of 11 minutes 36 seconds. There were no visible indicatons that the samples had cooled below 300°F (149°C) to prevent re-ignition.

1. INTRODUCTION.

Using composite materials in commercial aircraft construction is not a new concept; however, commercial aircraft manufacturers have only recently started incorporating advanced composites into the pressurized fuselage or aircraft primary structure. Currently, commercial aircraft manufacturers use two advanced composite materials to construct certain fuselages: carbon fiber-reinforced plastic (CFRP) and GLAss-REinforced aluminum laminate (GLARE). Designs by both Boeing and Airbus for new wide-body aircraft have pushed the use of composites to 50% or more [1 and 2]. Boeing's 787 Dreamliner is the first commercial aircraft with a CFRP fuselage and wings [1]. Airbus is developing the A350, a primarily CFRP aircraft using about 50% composites, similar to Boeing's 787 [2]. The Airbus A380 is the world's largest passenger aircraft. It is unique in commercial aviation not only because of its size and double-deck design but also because GLARE is used in two large sections of the pressurized fuselage. The upper deck floor beams are also constructed of CFRP [3].

The Federal Aviation Administration (FAA) is developing a standardized test method to determine the amount of firefighting agent needed to extinguish fires involving aircraft fuselages built with advanced composites. Researchers have taken a two-phased approach toward the development of this test method. Phase I assesses the fire behavior of aircraft fuselages built using composite materials and has two parts. The first part of Phase I, involving CFRP, has already been conducted and the findings are published in an FAA report [4]. The GLARE tests described here comprise the second part of Phase I. The Phase II tests will entail determining the amount of firefighting agent needed to extinguish and cool aircraft composites.

1.1 BACKGROUND.

GLARE is a fiber-metal-laminate composite material comprised of layers of aluminum alloy and unidirectional fiberglass. GLARE comes in a number of variations. For example, GLARE 3-3/2-0.4 breaks down as follows: the first number (3) defines the grade, 3/2 specifies the number of respective aluminum and glass layers, and 0.4 is the aluminum thickness in millimeters. Table 1 shows the standard GLARE grades [5]. GLARE uses FM94 adhesive with symmetric plies of unidirectional S-glass fiber, usually aligned along or across the rolling direction of the aluminum, known as the respective 0° and 90° directions. In GLARE 3 and GLARE 6, the fiberglass in each fiber ply is in a cross-layup, with an outer-to-inner 0/90 configuration for GLARE 3 and a ±45 or ∓45 configuration for GLARE 6. GLARE 3 and GLARE 6 are made with an uneven number of fiberglass plies. During the manufacturing process, the center ply is laid down first in the 0° (or +45°) direction then the 90° (or -45°) direction.

Table 1. Standard GLARE Grades

GLARE Grade		Metal Thickness and Alloy	Fiber Orientation (each ply)
GLARE 1		0.3-0.4 mm, 7475-T761	0,0
GLARE 2	GLARE 2A	0.2-0.5 mm, 2024-T3	0,0
	GLARE 2B		90,90
GLARE 3			0,90
GLARE 4	GLARE 4A		0,90,0
	GLARE 4B		90,0,90
GLARE 5			0,90,90,0
GLARE 6	GLARE 6A		+45,-45
	GLARE 6B		-45,+45

1.1.1 Use of GLARE in Commercial Aircraft.

Airbus has used GLARE in two sections of the A380's fuselage, shown as green in figure 1 [6]. (The yellow and purple represent aluminum and carbon fiber materials, which are not the main focus of this report.) The forward section of GLARE stretches from behind the first main deck door to just past the first upper deck door. The rear section of GLARE starts just behind the middle upper deck door and continues to the empennage. Vertically, both of these GLARE sections reach across the aircraft crown, starting below the main deck passenger windows.

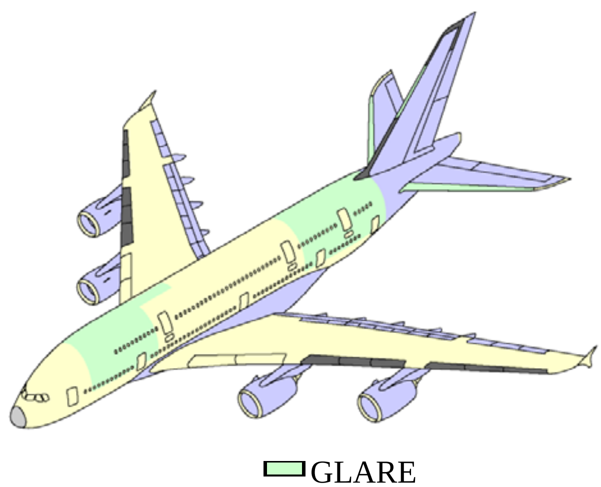


Figure 1. Location of GLARE Fuselage Sections of the Airbus A380

Separately, the aluminum and fiberglass layers within GLARE pose no new challenge to Aircraft Rescue and Firefighting (ARFF) operations. The glass fibers, while essentially inert, can be somewhat degraded by fire, but the resin portion of the fiberglass is combustible. Therefore, the amount of resin in the material dictates the potential for flammability and smoke. Published flammability properties of GLARE [7] have described it as having very good resistance to burnthrough. Roebroeks [8] discussed fire resistance tests conducted by Boeing, which found that GLARE was able to resist burnthrough for over 15 minutes while exposed to temperatures up to 2012°F (1100°C). This prolonged resistance to burnthrough was attributed to the fire-resistant glass layers and the added insulation created by charring of the resin. Roebroeks noted that the back aluminum temperature measured during the tests did not exceed 572°F (300°C), emphasizing the insulation properties of GLARE. Roebroeks also notes that the outermost aluminum layer burns away quickly, and the resin in the affected area burns away in a maximum of 30 seconds, leaving a layer of fiberglass between the burner and the rest of the material. Roebroeks further notes that the delamination that occurs helps insulate the intact layers from the fire. Zhu et al. [9] show that thermal decomposition of the GLARE resins can occur at temperatures near 490°F (255°C), and this decomposition results in delamination. Hagenbeek [7] calculated and discussed thermal conductivity of GLARE: 0.74-0.95 W/m-C° in-plane and 0.43-0.53 W/m-C° transverse. This shows that GLARE is better at spreading heat across the material rather than through the material.

1.1.2 Previous GLARE Fire Tests.

As requested by Structural Laminates Company, several GLARE configurations underwent flammability testing between 1994 and 2001, with the results provided, in part, in appendix A. The GLARE samples were exposed to the Oil Burner Test for Cargo Liners (Boeing BSS 7323); the 60-second vertical Bunsen burner test (Boeing BSS 7230, Method F1); and the 30-second 45-degree Bunsen burner test (Boeing BSS 7230, Test Method D). Based on the available documentation, Boeing's test methods are the same as the methods described in the "Aircraft Materials Fire Test Handbook" [10]. This Handbook describes all FAA standard fire test methods that comply with the Code of Federal Regulations (CFR) for aircraft certification.

The Oil Burner Test for Cargo Liners was used on GLARE samples manufactured to the Boeing BMS 7-326A Revision A (2/19/93) test method in the following configurations: 3-2/1-0.026, 4-2/1-0.031, 5-2/1-0.036, 3-3/2-0.044, and 4-3/2-0.054. The oil burner test requires that the material prevent flame penetration during a 5-minute burner exposure. The temperature, measured 4 inches above the back of the material, must not exceed 400°F (205°C) to pass. Not once did flames penetrate the sample. Recorded temperatures from the back of the samples never went above 156°F (69°C). Appendix A shows a chart of the back temperature data from these tests.

The 60-second vertical Bunsen burner test showed no dripping, but slightly different burn lengths: 0.4 inch on average for GLARE 3-3/2 and 1.13 inches for GLARE 5-2/1. Despite the difference in burn length, both were well within the allowable length of 6 inches. The 30-second 45-degree Bunsen burner tests on these two GLARE configurations demonstrated no afterglow (smoldering) or flame penetration (burnthrough).

Testing in accordance with FAA Advisory Circular 20-135 [11] showed GLARE 3-2/1, GLARE 3-2/3, and GLARE 4-2/1 met the requirements of a fireproof material suitable for use for powerplant (engine) fire. To meet that definition, the material must perform "as well as or better than steel" by withstanding "a 2000°F flame for 15 minutes minimum" [11].

1.1.3 Cessna GLARE Fire Tests.

In 1991, Structural Laminates Company completed several cargo liner tests that used GLARE edge/corner components. Only videos of the tests were available for review. These tests used the Oil Burner Test for Cargo Liners method, which uses the Park Oil burner in a vertical configuration with a 2-gallon-per-hour fuel spray nozzle. The videos show the test beginning when the burner slides into the test frame after a 2-minute preburn. The test ran for 5 minutes. The corners were made of either GLARE 3-3/2 or GLARE 1-3/2, with a smooth 90° bend. An unknown thickness and brand of conventional phenolic cargo liner was fastened to the inside surface of the corner to make the top and side panels. Screw fasteners held the cargo liner to the corner. Figure 2 shows the test setup. There was no temperature data available from these tests, as they were pass/fail burnthrough tests.

Figure 2. Cessna GLARE Cargo Liner Corner Test Setup

Table 2 shows the observed times of events from the test videos. In all but one test, the sample and the off-gassed vapors ignited. In Test 3 of GLARE 1-3/2, the off-gas and sample ignited quickly, involving the entire sample in the fire. Generally, the samples began smoking and buckling within 30 seconds of fire exposure. Sample buckling is when there was an observable warping. The times shown in table 2 indicate when buckling started.

Table 2. Times of Observed Events During the Cessna GLARE Cargo Liner Corner Tests

	GLARE 3-3/2			GLARE 1-3/2		
	Test 1	Test 2	Test 3	Test 1	Test 2	Test 3
Smoke	00:25	00:20	00:24	00:23	00:20	00:20
Buckle	00:25	00:27	00:37	00:24	00:22	00:22
Ignition	01:16	01:20	00:31	none	00:29	00:49
Burner off	01:23	05:04	05:02	06:07	05:09	02:05
Flame out	01:51	02:53	02:17	none	01:49	02:16

Note: Time shown in minutes and seconds (MM:SS.)

Figure 3 shows a series of screen captures from the GLARE 3-3/2 Test 2 video, showing the test start, buckling and smoking, and sample ignition.

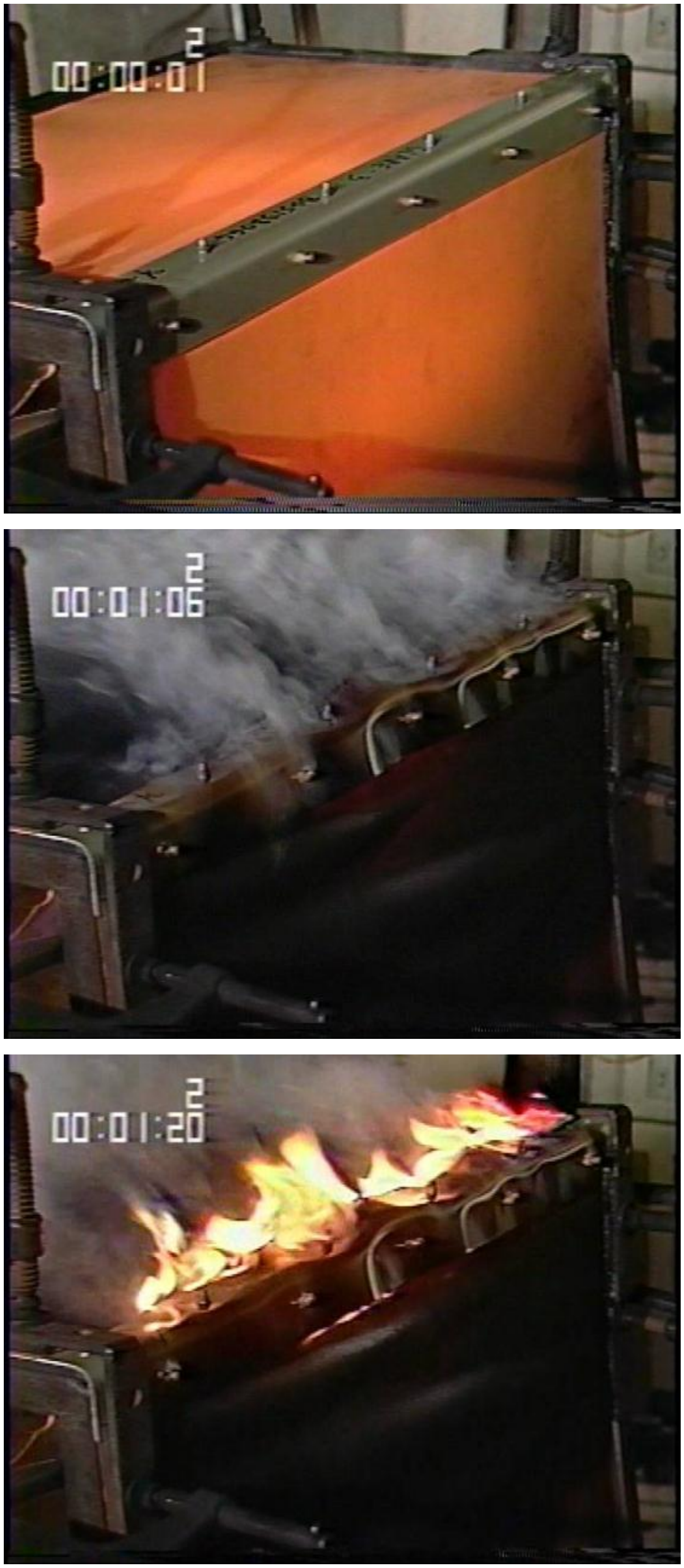


Figure 3. Cargo Liner Corner Test 2 of GLARE 3-3/2

1.2 OBJECTIVES.

The flat panel and layered test objectives were to

- characterize the heat transferred through the sample using infrared images and thermocouple (TC) measurements.
- determine if burnthrough or post-exposure burning occurred by analyzing the video images and temperature measurements.
- determine if a smoldering condition exists after fire exposure by analyzing the video images and temperature measurements.
- determine the amount of time it takes the sample to naturally cool below 300°F (149°C) after removing the fire source.
- document any visible indications that the material has cooled below 300°F (149°C) by laboratory observations and analyzing the video and infrared images.

2. TEST SETUP.

For a test to accurately assess if a fuel-fed pool fire under and around an aircraft will cause advanced composite skin material to burn through or cause self-sustained burning or smoldering, it is important that the test correctly represents that conditions being encountered. The only laboratory-scale FAA test method available that represents an external fuel-fed pool fire is a kerosene-fired oil burner test. This test method was developed to determine a fuselage's resistance to fire penetration due to an external fuel-fed pool fire. It shows compliance with the burnthrough resistance standard for thermal/acoustic insulation [12]. The details of the test method and apparatus are described in 14 CFR Part 25.856 [12].

In 2008, after finding that the oil burner originally specified for the test was out of production, a new burner design was adopted and is referred to as the FAA NextGen Burner hereafter. Figure 4 shows the FAA NextGen Burner, located at the FAA Component Fire Test Facility [13].

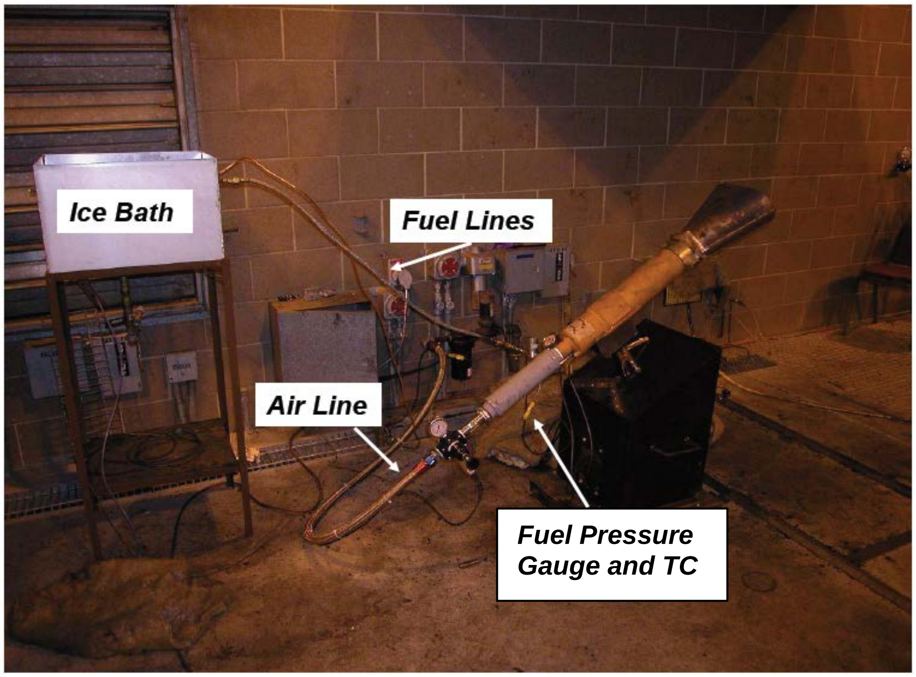


Figure 4. The FAA NextGen Burner Test Apparatus

2.1 SAMPLE MATERIAL.

The tests used 12- by 18-inch GLARE 3-5/4-0.3 samples, with a total thickness of 2.5 mm (0.098 in.). Each test used one sample. The flat panel tests used the samples directly, while the layered tests each used one panel cut into four 12- by 4.5-inch strips.

GLARE 3-5/4-0.3 has five layers of 0.3-mm-thick 2024-T3 aluminum sheets alternating with four layers of S2 fiberglass. Each fiberglass layer consists of unidirectional fiberglass plies oriented in a 0/90-degree layup. Cytec Industries Inc. FM 94-27% resin with 248°F (120°C) cure was used in the pre-impregnated fiberglass sheets. This thickness and configuration is representative of the average thickness and configuration of GLARE found in the A380 fuselage skin.

2.2 FLAT PANEL TEST SETUP.

Figure 5 shows the relationship of the "picture frame" material holder (used in the flat panel tests), to the kerosene-fired FAA NextGen Burner [14]. After ignition, the FAA NextGen Burner runs for 2 minutes to allow it to come up to temperature. The cart-mounted material holder is rolled in front of the FAA NextGen Burner after the 2-minute preburn. The material holder positions the sample 1 inch above the FAA NextGen Burner cone's centerline and 4 inches from the cone's face.

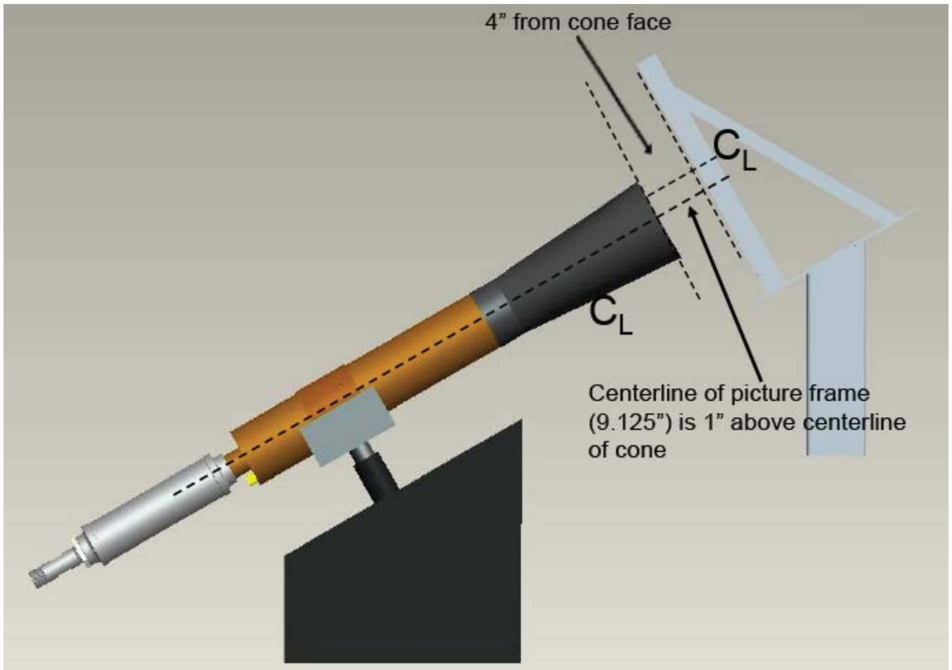


Figure 5. The FAA NextGen Burner Test Apparatus and Material Holder Setup

Two layers of 18- by 32-inch Thermal Ceramics Kaowool™ M ceramic insulation boards framed the GLARE samples to hold the sample in place and avoid any flame wrap-around on the sample edges. The insulation board closest to the FAA NextGen Burner had a centered opening smaller than the GLARE sample by 1 inch on all sides. The rear insulation board had the same 12- by 18-inch centered opening as the sample. Figure 6 shows an exploded view of the assembly.

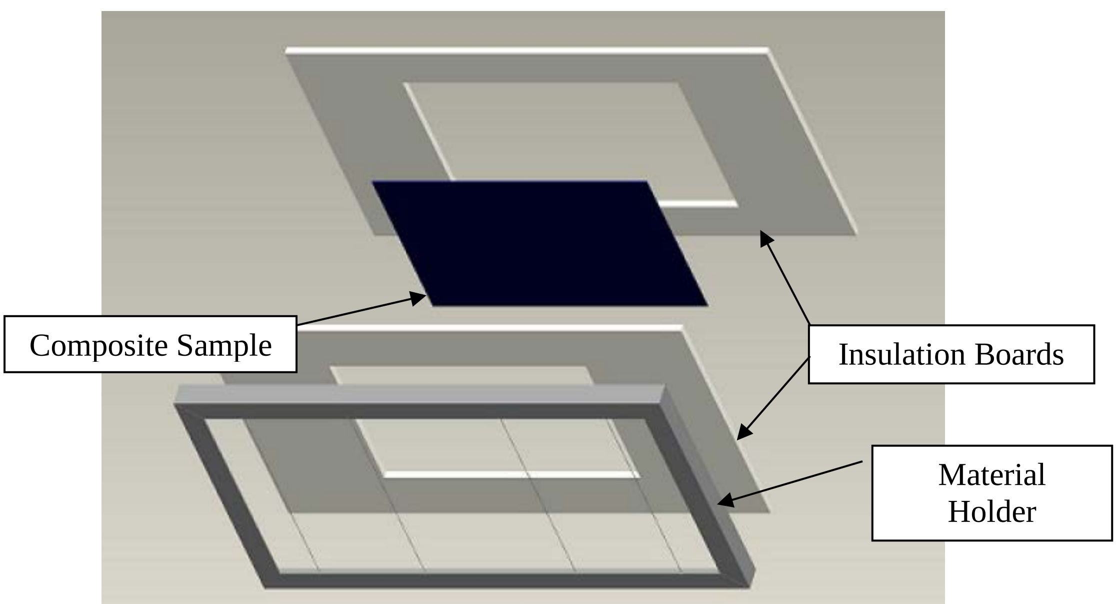


Figure 6. Exploded View of Composite Sample, Insulation Boards, and Material Holder

Instrumentation consisted of five 32-gauge K-type, Kapton® polyimide insulated TCs positioned on the back of the sample. Thermocouples, numbered 1, 2, 4, and 5, were fixed to the corners of the sample with 2-inch-square pieces of insulation board and small pieces of fiberglass-backed tape. The insulation boards were secured with pressure from screws threaded through the angle iron posts that ran across the back of the panel. The TC wires were placed under the pad so they would not be underneath the front insulation board. Figure 7 shows a cross section of the corner TC placement.

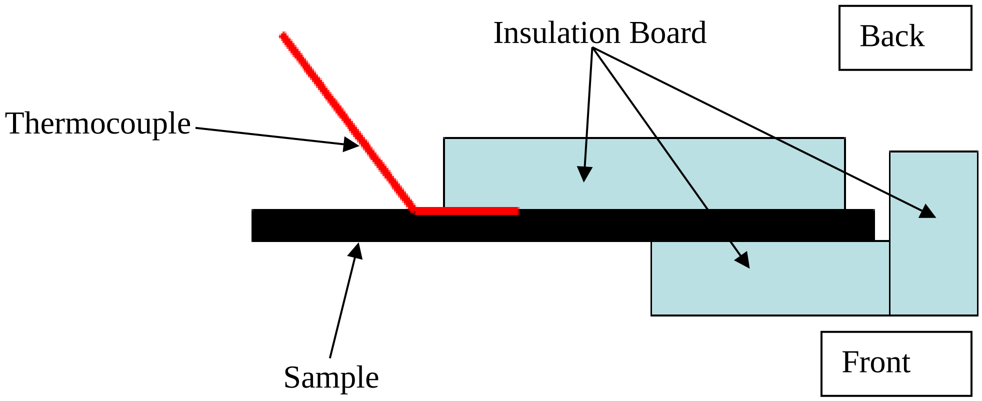


Figure 7. Cross-Section View of the Corner TC Placement

The fifth TC (TC3) measured the sample temperature at the center of the back. A small piece of fiberglass-backed tape held it in place. All TCs were positioned to relieve tension on the TC wire. Figure 8 shows the TC placement.

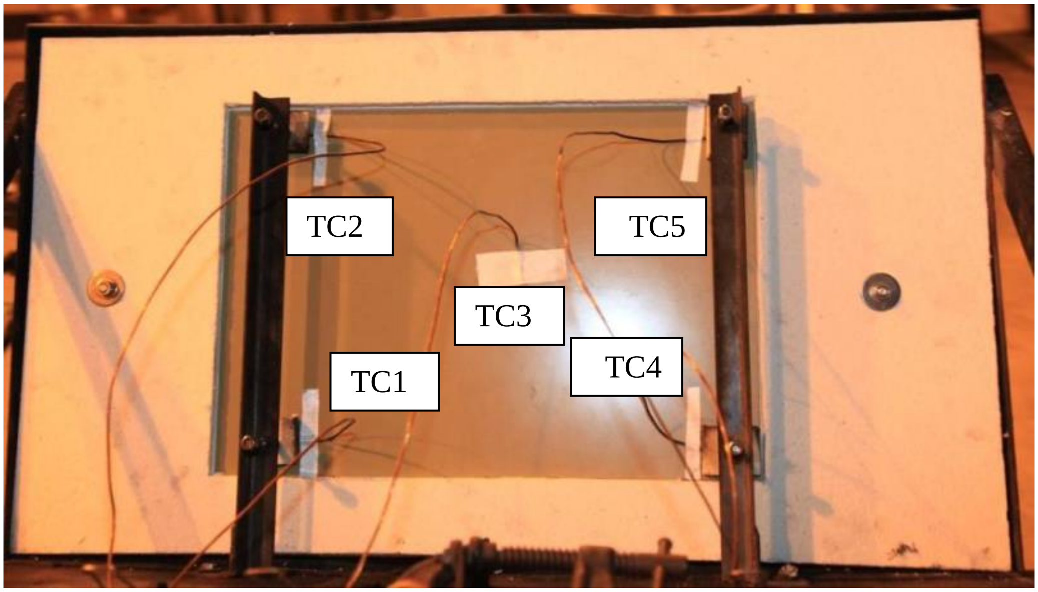


Figure 8. Thermocouple Placement

Three video cameras recorded the tests. One forward-looking infrared (FLIR) video camera (FLIR Systems, Inc. model P660) provided a thermal image of the sample's back. That camera's spot tool displayed a calculated apparent temperature that correlates to TC3. FLIR temperature measurements were manually recorded while reviewing the video because the FLIR model P660 camera did not record thermographic data. Temperatures were manually recorded every second for the first 10 seconds, then every 5 seconds after that. One color video camera captured a close-up view of the sample's front from approximately a 45° angle. A second color video camera captured a close-up view of the sample's back. Figure 9 shows the positions of the cameras in the laboratory.

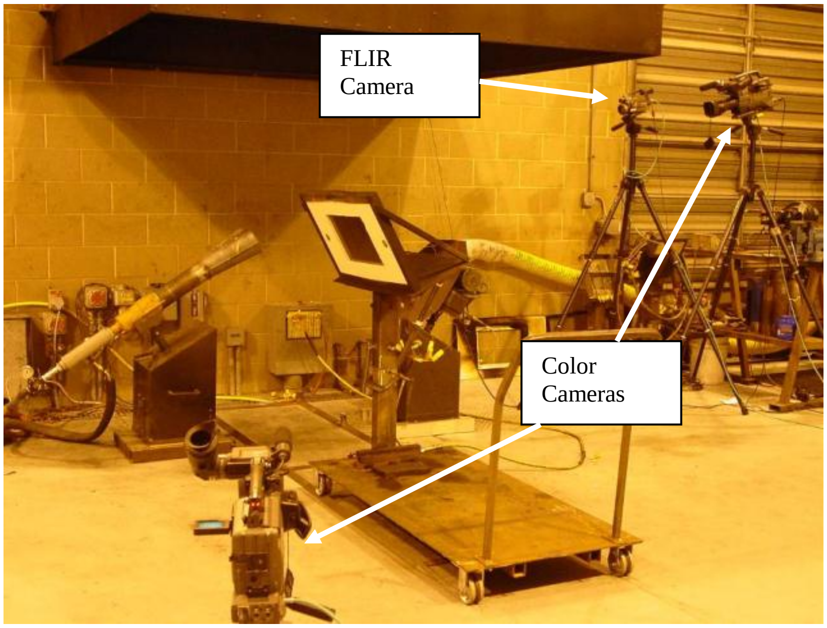


Figure 9. Laboratory Camera Positions

The nine flat panel configuration tests were divided into 8-, 5-, and 1-minute exposure duration scenarios. These exposure durations were selected based on findings from the Phase I CFRP tests [4]. The goal of the 8-minute exposures was to run the test long enough to see if burnthrough could occur but not so long as to risk warping the FAA NextGen Burner cone. The 5-minute exposures represented a hypothetical scenario of a 2-minute fire plus the 3 minutes needed for the ARFF to arrive at the scene. The 1-minute exposures were designed to heat the sample enough for combustion to occur but not enough to burn off too much resin. This was thought to give the best opportunity for post-exposure burning.

Tests 1 through 3 were 8-minute exposures; however, Test 1 stopped after 2 minutes 5 seconds because, during the test, the sample's back and edges burned significantly and too much of the sample had burned to continue. Test 1 was the only unsuccessful test and was not repeated due to a limited amount of sample material. Tests 4 through 6 were 5-minute exposures, and tests 7 through 9 were 1-minute exposures.

2.3 LAYERED TEST SETUP.

The layered test configuration used in Tests 10 through 12 was designed to assess the potential of post-exposure, re-radiative-effects to induce smoldering with GLARE. In this configuration, four 12- by 4.5-inch-long GLARE samples were stacked with a 0.75-inch space between the layers. Holes were drilled approximately 1 inch from each 4.5-inch edge so the samples could be mounted on pillars made from threaded rod. The 0.75-inch space between the pieces was maintained using nuts and washers. Figure 10 shows the layered test configuration.

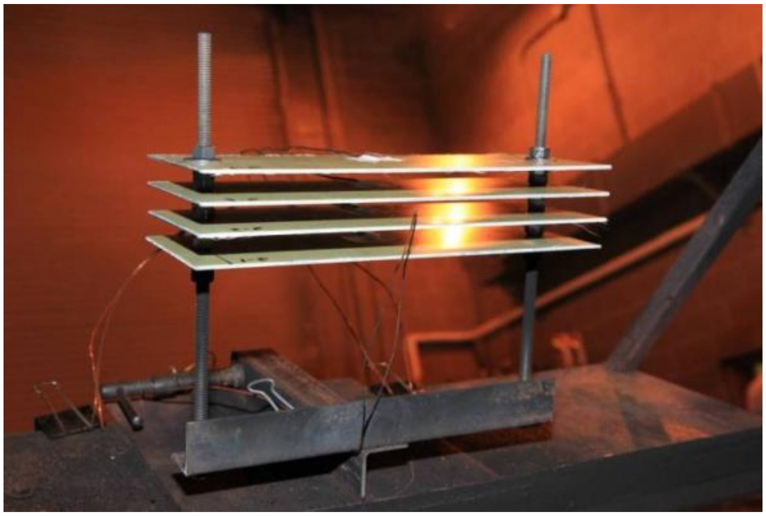


Figure 10. Layered Test Configuration

The mount for the threaded rod was attached to a plate on the base of the material holder, which attached to the pedestal on the cart. The layered samples were centered to the FAA NextGen Burner both vertically and horizontally. Figure 11 shows the layered test setup and its relationship to the FAA NextGen Burner.

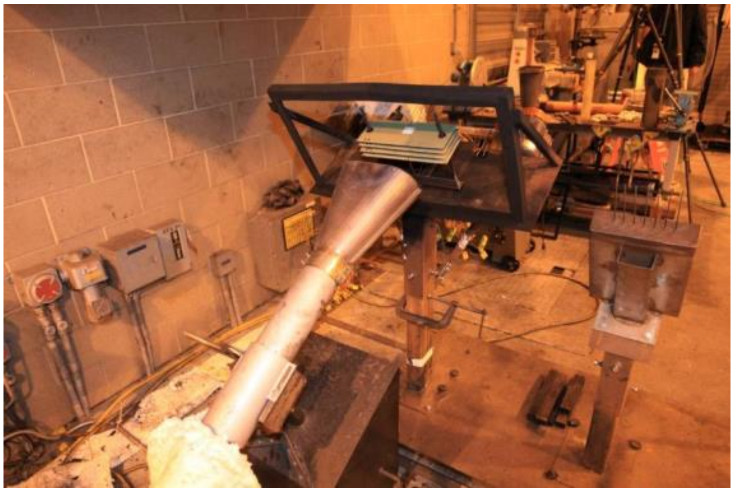


Figure 11. Layered Test Setup

The thermocouples used to monitor temperature in each layer were numbered 1 through 4 from the top down. Each TC laid flat on the surface of the sample with the TC bead approximately 1 inch in from the rear edge and secured in place with a small piece of fiberglass-backed tape. A fifth TC was positioned approximately center and slightly in front of the layers to measure the FAA NextGen Burner temperature. Figure 12 shows a close-up of the layered configuration and TCs. Tests 10 through 12 used this configuration for a 1-minute fire exposure time.

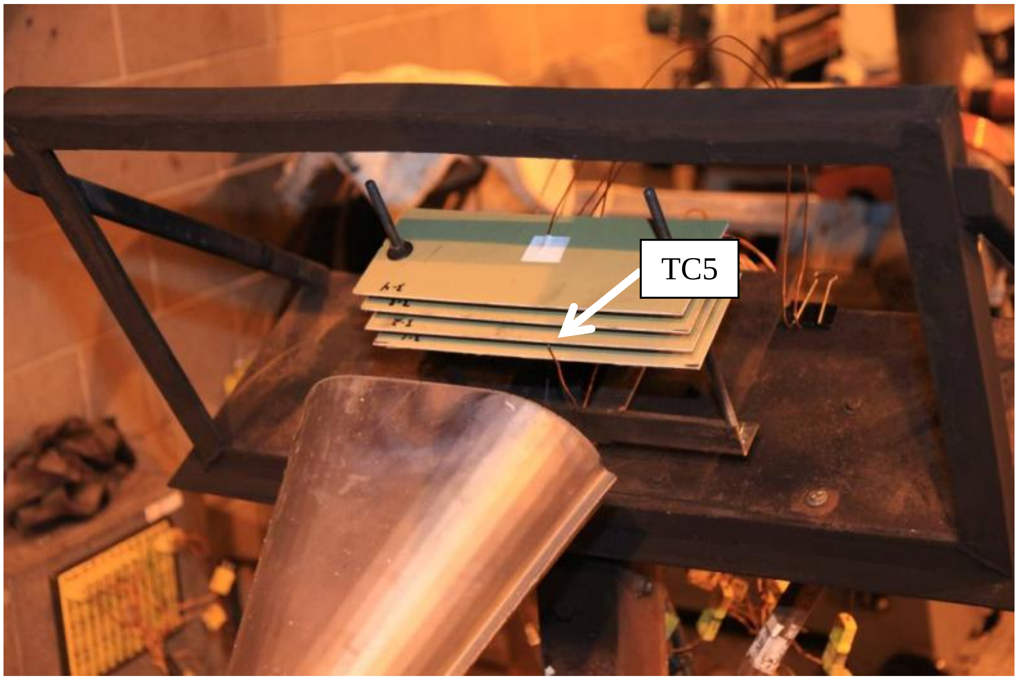


Figure 12. Close-up of Layered Test Configuration

The camera setup used to document the layered test was similar to the setup used for the flat panel tests. The thermal camera's spot temperature tool was centered on the stack.

3. RESULTS.

The test analyses included a review of the TC data, FLIR and color videos, and posttest inspections of each sample. These analyses also included identifying cues to assess if the sample cooled below 300°F (149°C), the temperature recommended by the United States Air Force [15 and 16].

3.1 MASS LOSS.

In previous testing, the sample weights before and after fire exposure were recorded to give an indication of sample resin loss [4]. CFRP consists of only fibers and resin, and since test temperatures were nowhere near high enough for the carbon fibers to burn off, the mass loss in the sample was directly indicative of the mass loss of the resin.

GLARE consists of aluminum sheets, fiberglass, and resin. Test temperatures were high enough that in addition to resin burn off, some aluminum would melt and drip. This meant that the change in sample mass could not be attributed to resin loss. Therefore, mass loss of the sample was unable to directly indicate resin loss, and other factors indicating sample condition were noted.

Figure 13 shows a GLARE sample following a 1-minute fire exposure for Test 9. The samples completely delaminated and fell apart. Glass plies and aluminum sheets simply came apart while removing the samples from the frame, and some of the aluminum had melted between the insulation boards and dripped onto the floor.

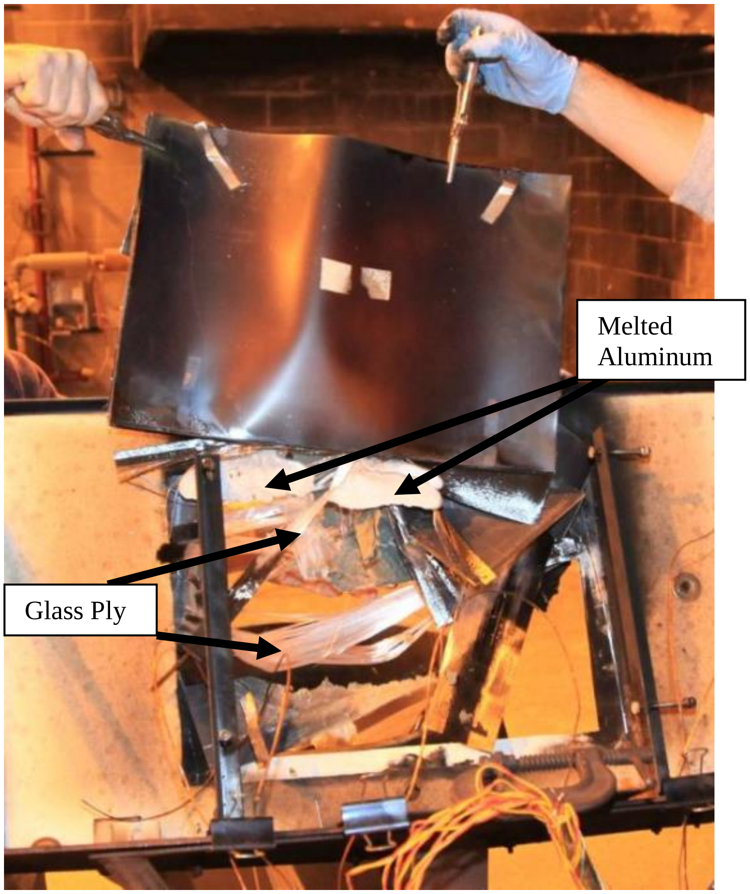


Figure 13. Test 9—GLARE Sample After a 1-Minute Exposure

3.2 SAMPLE TEMPERATURES.

Data collected during calibration of the FAA NextGen Burner prior to testing showed flame temperatures averaged 1847°F (1008.3°C) across the face of the burner. Sample temperatures were gauged using TC3, which was placed in the center of the panel's back. Table 3 provides the maximum temperatures measured by TC3. The overall average for the maximum back temperature for all exposures was 611.2°F (321.8°C).

Table 3. Maximum Sample Temperature for Each Exposure Duration

Test Numbers and Exposure Times	Maximum Sample Temperature (°F) Exposure 1	Exposure 2	Exposure 3	Average Maximum (°F)
Tests 1-3 (8 min.)	1062.5	583.2	670.1	771.9
Tests 4-6 (5 min.)	581.6	543	505	543.2
Tests 7-9 (1 min.)	395.4	444	609.5	483

As expected, maximum sample temperatures for the flat panel tests all occurred close to or shortly after the FAA NextGen Burner was turned off, indicating the material had little thermal inertia. Figure 14 shows the times that the samples reached maximum TC3 temperature, relative to both the start of the test and to turning off the FAA NextGen Burner.

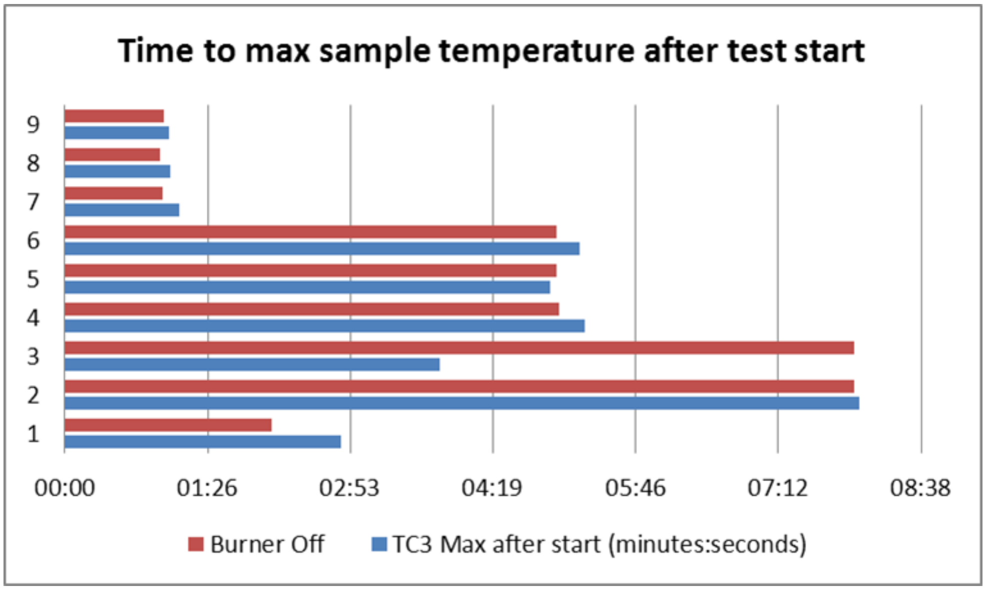


Figure 14. Tests 1-9 Maximum Sample Temperature Times

Burning on the back of the sample skewed the maximum temperatures for Tests 1 and 3. The spike in TC3's temperature was due to ignition of the fiberglass-backed tape. In Test 1, the temperature continued to rise until it reached its maximum temperature at 2 minutes 47 seconds. Figure 15 shows the continued rise in sample temperature after turning off the FAA NextGen Burner in Test 1.

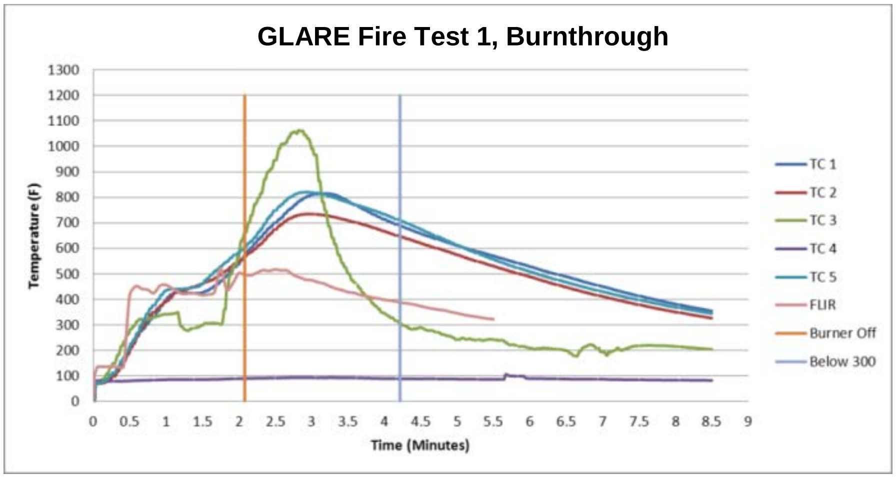


Figure 15. Continued Rise in Sample Temperature due to Burning—Test 1

The thermal camera captured apparent sample temperatures while recording infrared images of the test. Generally, the temperatures measured by the camera agreed with the TC3 measurements, except in some cases when flames obscured the surface. The camera temperature range selected for these tests was -32°F (-35.5°C) to 680°F (360°C). Other temperature ranges were available, but they did not offer the ability to observe the necessary detail at 300°F (149°C) and below while allowing a high maximum temperature. Figure 16 shows a FLIR image taken during Test 8 (1-minute exposure).

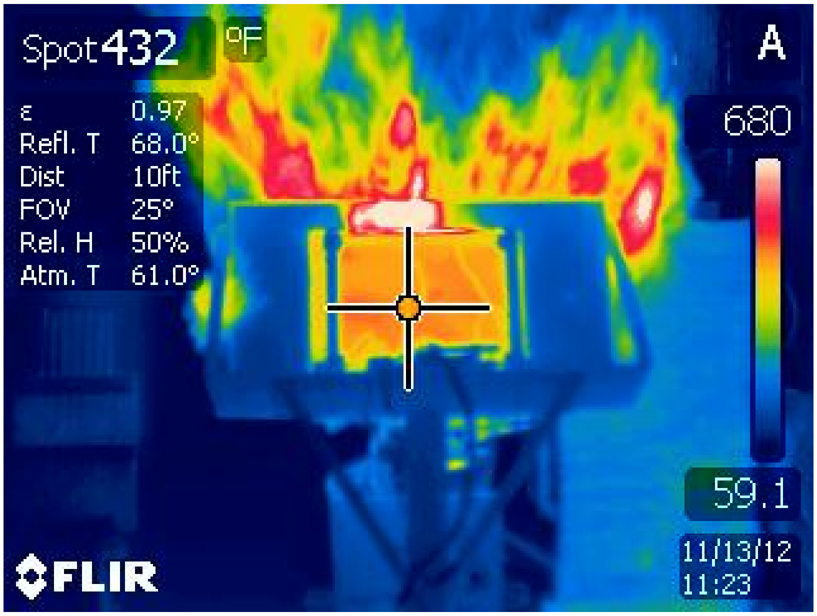


Figure 16. A FLIR Image From Test 8

Figure 17 shows TC and FLIR measurements for Test 8, which is typical for all flat panel tests. Appendix B shows all the test data.

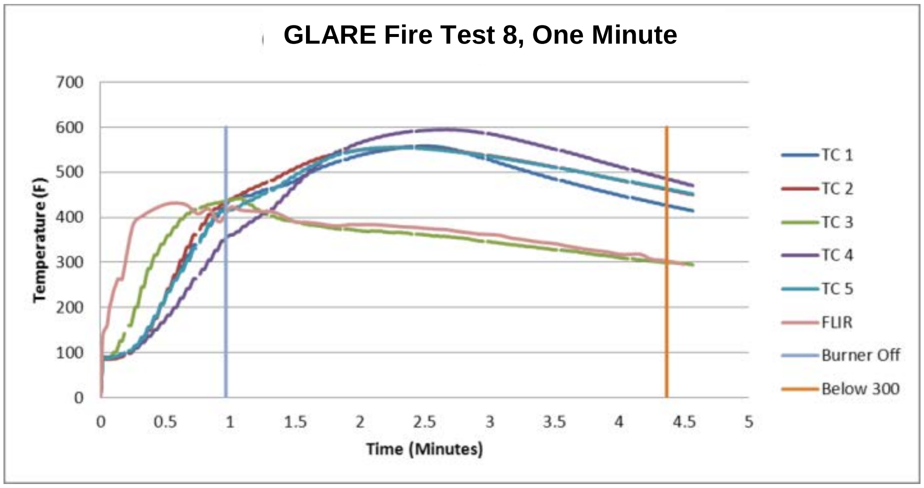


Figure 17. The TC and FLIR Measurements for Test 8

The sample's back temperature was far less than the FAA NextGen Burner temperature. Thermal conductivity of constituent GLARE materials plays a role in the low through-thickness heat transfer, while delamination further reduces heat transfer. Each sample tested delaminated significantly, as discussed in section 3.1. This created gaps that helped insulate the sample's back from heat penetration. Though much less than the FAA NextGen Burner temperature, longer fire exposures slowly increased the back temperatures until the FAA NextGen Burner was turned off. Charts for Tests 2, 4, 5, and 6 (in appendix B) show the gradual increase in TC3 temperature prior to turning off the FAA NextGen Burner. Figure 18 shows this continued heating measured at TC3 in the Test 2, 8-minute exposure.

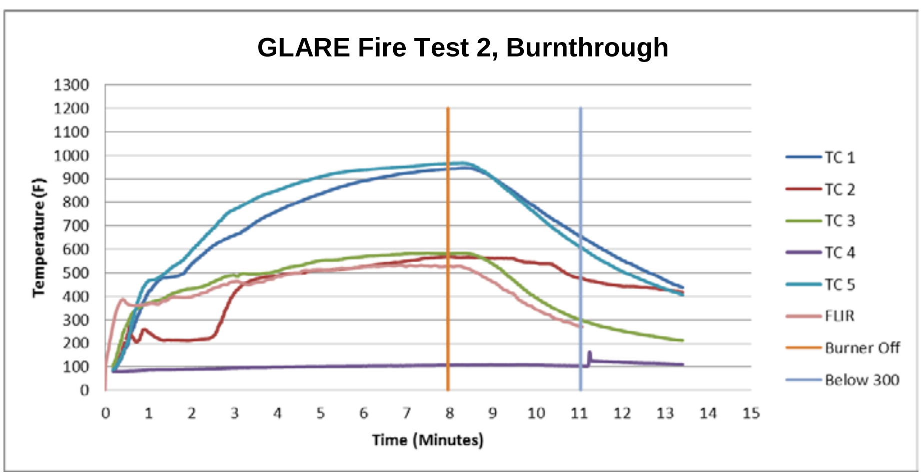


Figure 18. Continued Sample Heating in Test 2 After Delamination

3.3 BURNTHROUGH.

None of the flat panel tests achieved sample burnthrough. There was smoke ignition and resin off-gassing on the back during each 8-minute burnthrough test. Test 1 was stopped after 2 minutes 5 seconds due to severe burning of the sample. The sample ignited 43 seconds after the test began. The flame stopped for 9 seconds at approximately the 1-minute mark before reigniting. Figure 19 shows the amount of free burning 1 second after the FAA NextGen Burner was turned off. After Test 1, the decision was made that the remaining two burnthrough tests would not be stopped early despite how much back burning occurred.

Figure 19. Test 1—1 Second After FAA NextGen Burner was Turned off

Each sample tested in the flat panel configuration had a similar appearance after the test. The outer layer of aluminum facing the FAA NextGen Burner either completely or mostly burned or melted away. The fiberglass underneath remained intact, but the resin was burned away. In some cases, especially after the 8-minute exposures, the fibers were very brittle and broke easily when handled. In Test 2, several glass fibers near the top of the sample had melted ends. This was not observed in other tests. Figure 20 shows the sample from Test 2 after exposure to the FAA NextGen Burner.

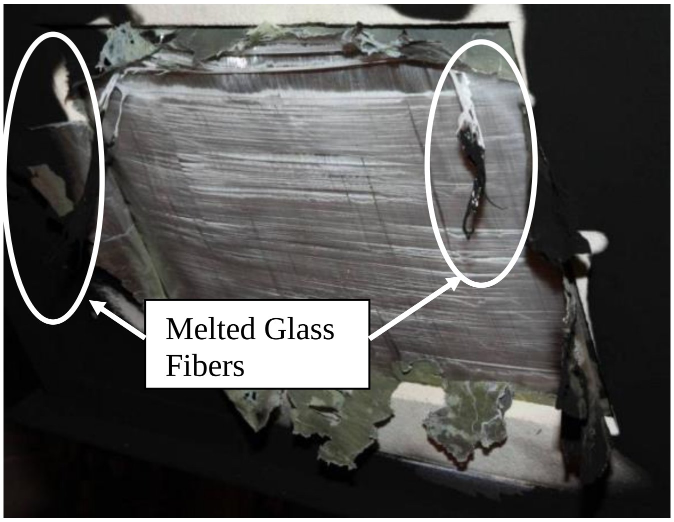


Figure 20. Post-Exposure Sample—Test 2

3.4 POST-EXPOSURE FLAME.

In both flat panel and layered configurations, every sample had smoke ignition and flaming combustion. Figure 21 shows the duration of flaming combustion once the FAA NextGen Burner was turned off. The duration of post-exposure flame appears relatively consistent and independent of configuration and exposure duration.

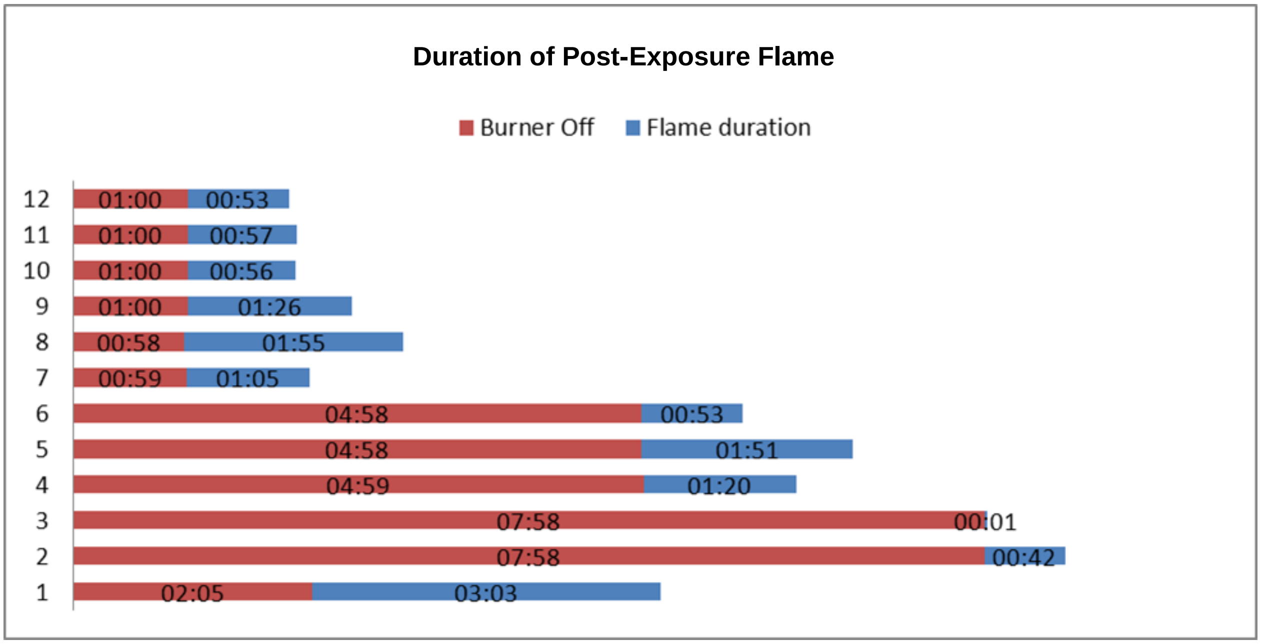


Figure 21. Tests 1-12 Duration of Post-Exposure Flame

3.5 FIRST-MINUTE EVENTS.

Several events consistently occurred within the first minute of every flat panel test. These events may explain the back burning and similar after-flame times. Light smoking began almost immediately after the sample was exposed to the FAA NextGen Burner. The external light smoke start time ranged from immediately to 5 seconds. The TC3 temperatures, at onset, ranged from 76.2°F (58.3°C) to 137°F (58.3°C). The sample was observed to delaminate with a pop within approximately 30 seconds, indicated by either visible sample movement or the TC wires wiggling, followed by an onset of heavy smoke that was closely followed by smoke ignition. Ignition of the smoke started when it contacted the FAA NextGen Burner flame on the front side. Figure 22 compares these first-minute events for the nine flat panel tests. The average times of these events are shown in figure 23.

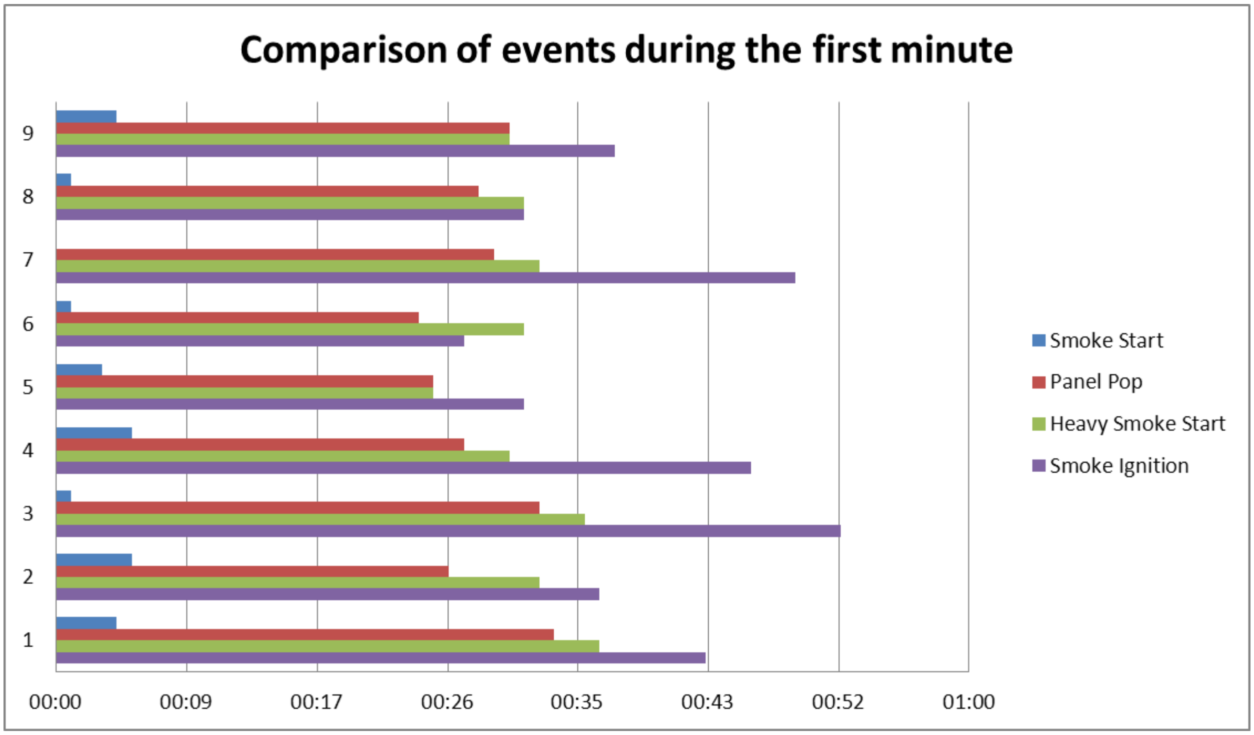


Figure 22. Tests 1-9 Comparison of First-Minute Events

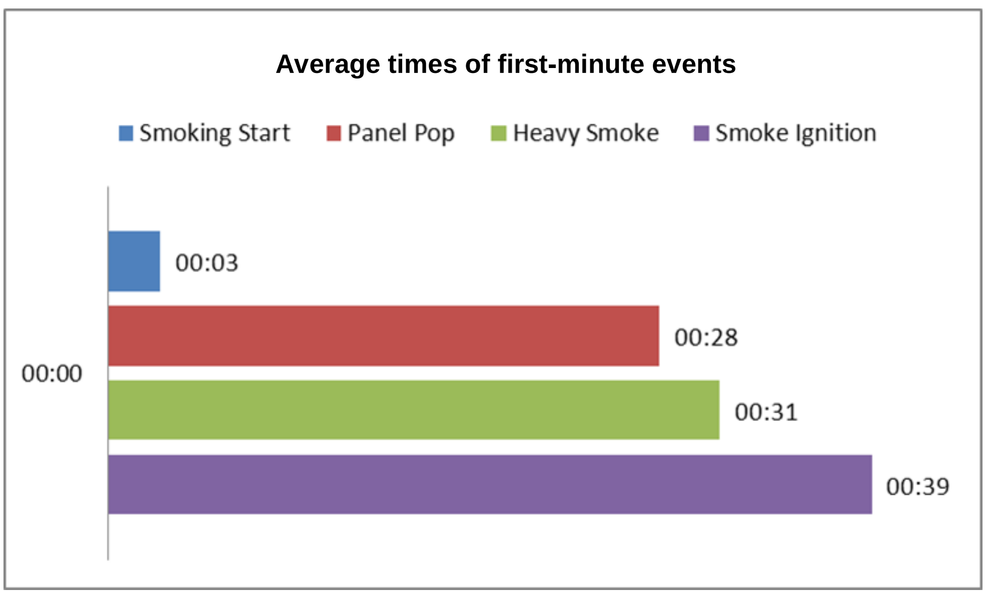


Figure 23. Average Times of First-Minute Events

Temperature and exposure duration at the time of the pop, shown in figures 24 and 25, may show the threshold of significant GLARE delamination. It took between 24 and 33 seconds for the pop to occur. The TC3 temperatures ranged from 261°F (127.2°C) to 356.8°F (180.4°C). Further investigation would require additional testing, but these tests make it clear that a significant event happens when the pop occurs. Whether caused by a build-up of internal off-gas pressure, loss of resin adhesion and subsequent layer separation, or some combination, the onset of heavy smoke occurred immediately after the pop. The smoke produced is combustible, and in almost all the color videos, there is smoke ignition when it contacts the front side flame.

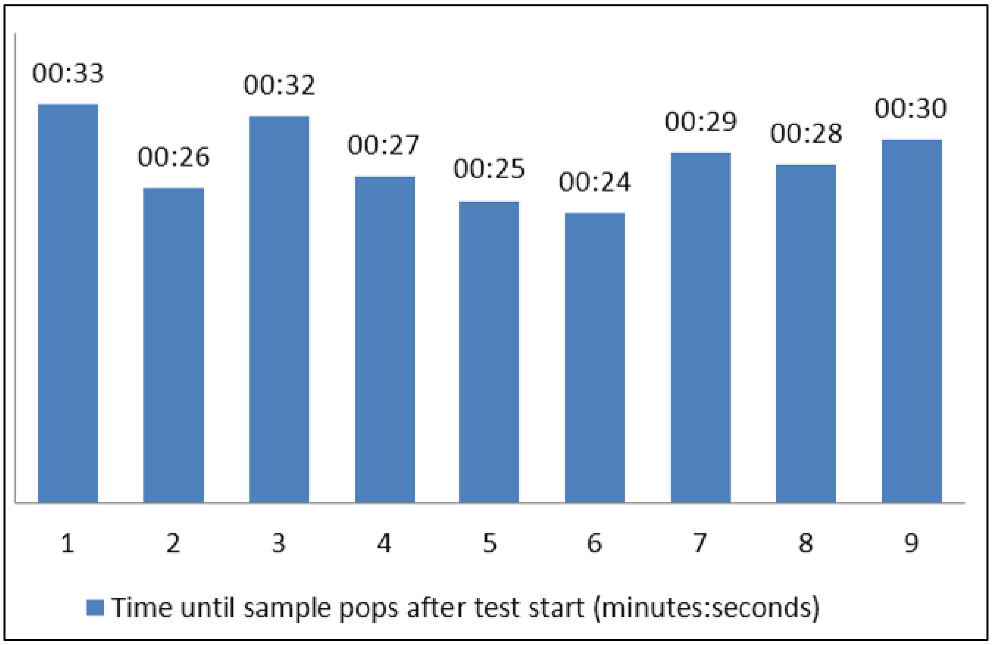


Figure 24. Time to Sample Pop

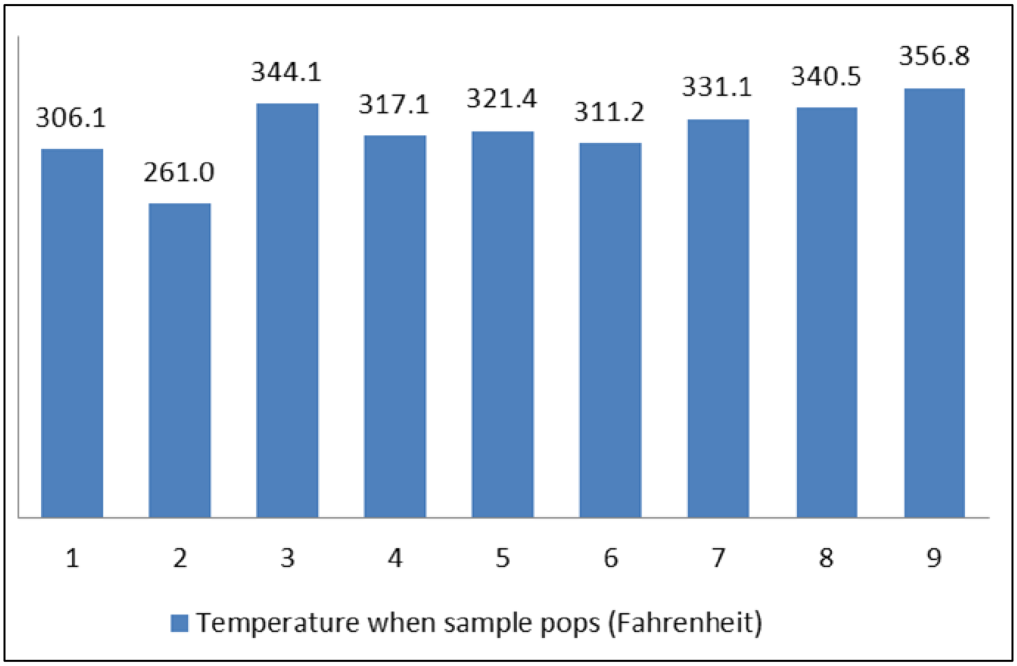


Figure 25. Temperature of TC3 When Sample Pops

Each sample bowed in the center, generally creating a chimney-like effect. Figure 26 shows the chimney effect created after the pop during Test 6. Burning continued at the chimney opening in Test 6 for 53 seconds after turning off the FAA NextGen Burner.

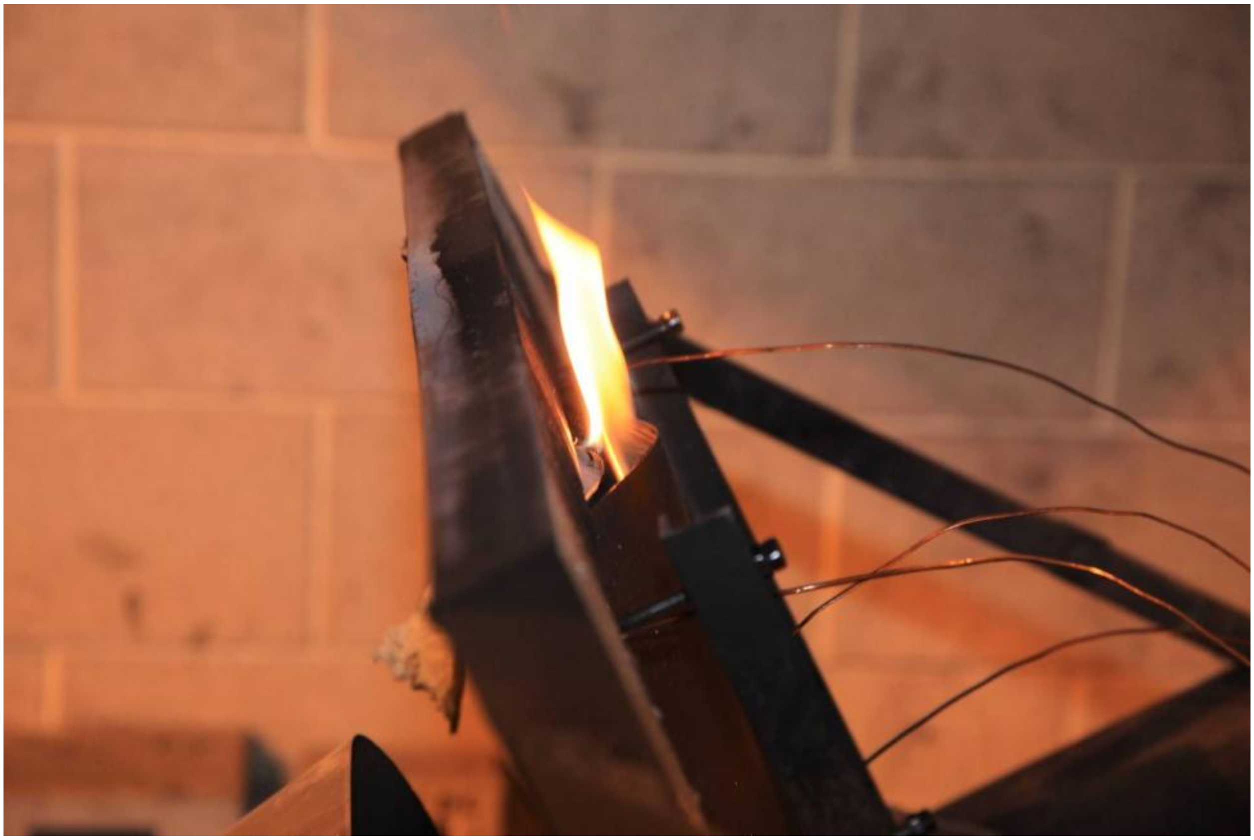


Figure 26. Chimney Effect in Test 6

After the panel popped in Test 9, there was a vigorous smoke flame. The sample bowed in the middle, but more so at the bottom, displacing slightly to the rear, which allowed heat in from the front. The sample popped at 30 seconds, followed immediately by heavy smoke production, then a smoke puff from the bottom at 37 seconds. Figure 27 shows the progression in Test 9.

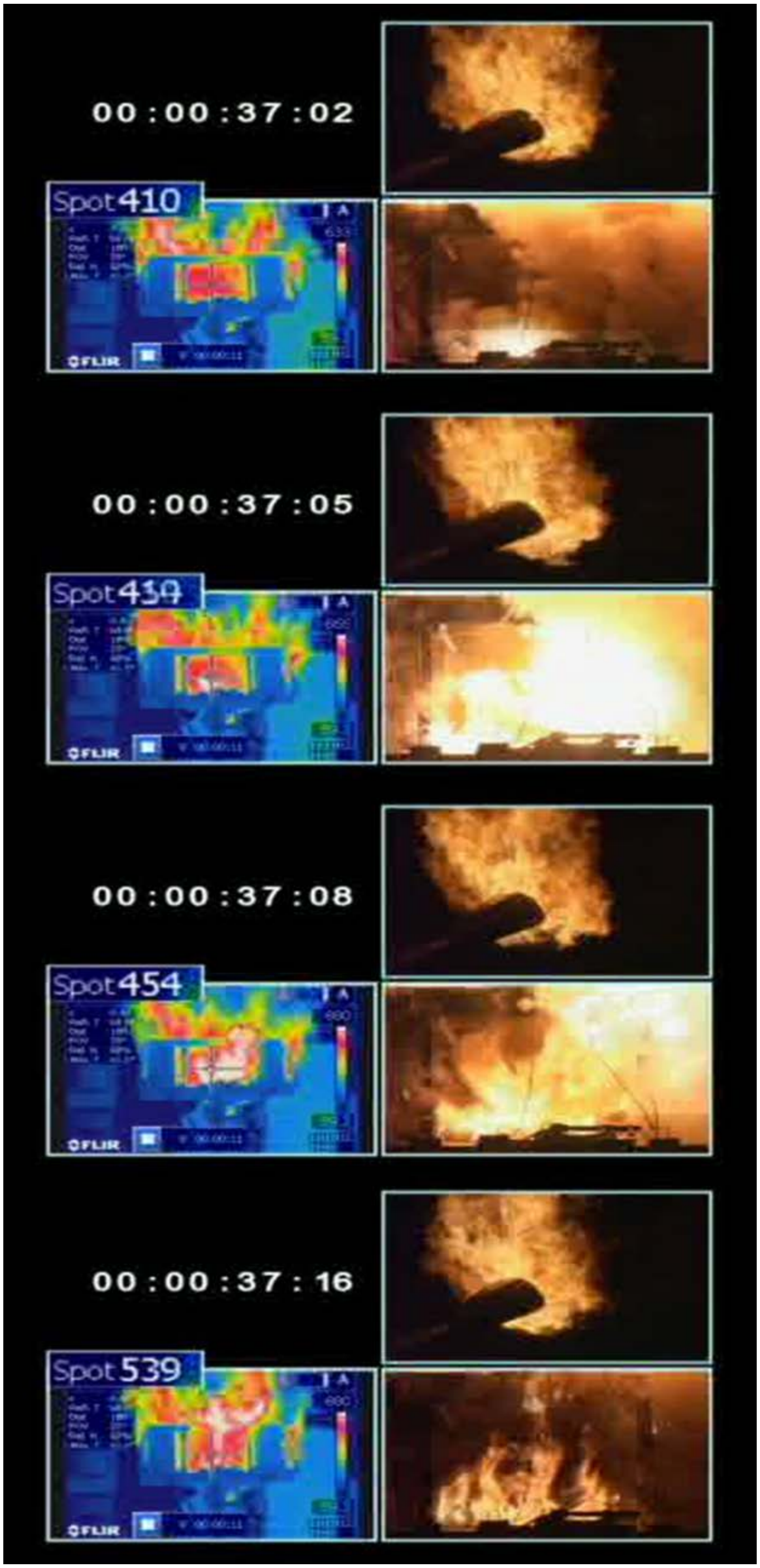


Figure 27. Smoke Ignition—Test 9

3.6 HIDDEN AREAS.

The insulation pads covering the corner TCs in the flat panel tests also served to simulate hidden or insulated areas of the aircraft. While the ceramic insulation used differed from that used in aircraft, it withstood repeated fire exposure and was desirable for these tests. These insulated areas offered the greatest chance of observing smoldering conditions since heat could not readily escape. In all nine flat panel tests, TC temperatures in the corners were generally higher than the TC3 center temperature. Maximum corner temperatures during the 8- and 5-minute tests happened within seconds or very shortly after the TC3 maximum temperature was reached. However, during the 1-minute exposure tests, the corners reached peak temperatures more than 1 minute after the TC3 peak temperature. Figure 28 shows the delayed peak of corner temperatures for Test 7. Sample cooling in these areas was also slow. Each chart for Tests 1 through 9 (appendix B) shows the corner temperatures were higher than 300°F (148.9°C) while the TC3 temperatures were cooler. The cooling slope for the corners, shown in figure 29, was similar to the cooling slope for the center in each test. This seems to indicate that the cooling mechanism for GLARE is uniform, but the insulation keeps the hidden areas hotter.

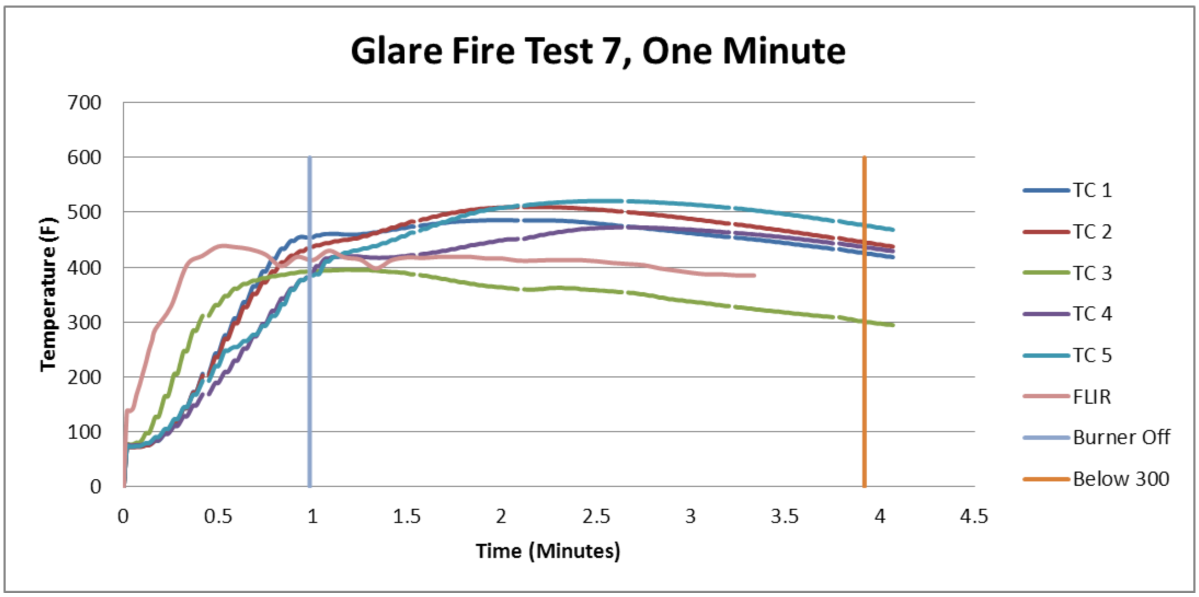


Figure 28. Delayed Corner Heating in Test 7

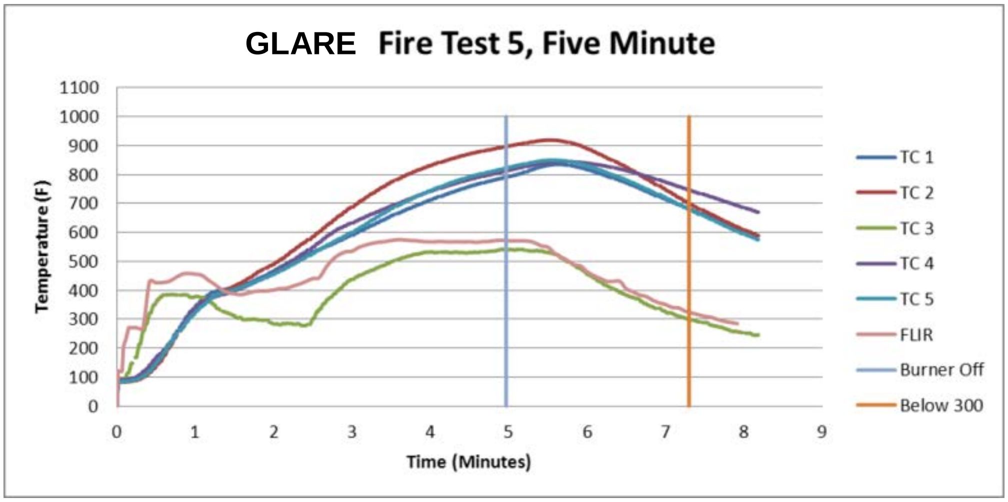


Figure 29. Rapid Corner Cooling in Test 5

3.7 LAYERED TESTS.

The layered tests expanded the assessment of smoldering by creating a configuration that gave the best opportunity to radiate heat between layers. The CFRP tests showed that some smoldering occurred, mainly in the corners, but very high-temperature smoldering occurred during the layered tests [4]. The GLARE tests did not exhibit smoldering. Tests 10 through 12 exposed the GLARE for 1 minute. After exposure, all four pieces in the layered configuration were completely delaminated. Even the flat panel tests had completely come apart, as discussed in section 5.1. Figure 30 shows the delaminated sample after Test 11.

Figure 30. Delaminated Sample After Test 11

In each layered test, the sample burned significantly following flame exposure, but for less than 1 minute. The after-flame durations are shown in figure 21. Figure 31 shows post-exposure burning immediately following removal of the FAA NextGen Burner for Test 12. This was the typical amount of post-exposure burning observed during each layered test.

Figure 31. Post-Exposure Burning During Test 12

Although no smoldering was observed during the layered tests, it took a long time for the layers to cool below 300°F (148.9°C) compared to the flat panel tests. The times to cool below that point for Tests 10, 11, and 12 were 11 minutes 43 seconds, 10 minutes 58 seconds, and 12 minutes 8 seconds, respectively, for an average time of 11 minutes 36 seconds. Figure 32 shows the measured temperatures for Test 12 and illustrates the long delay to cool below 300°F (148.9°C).

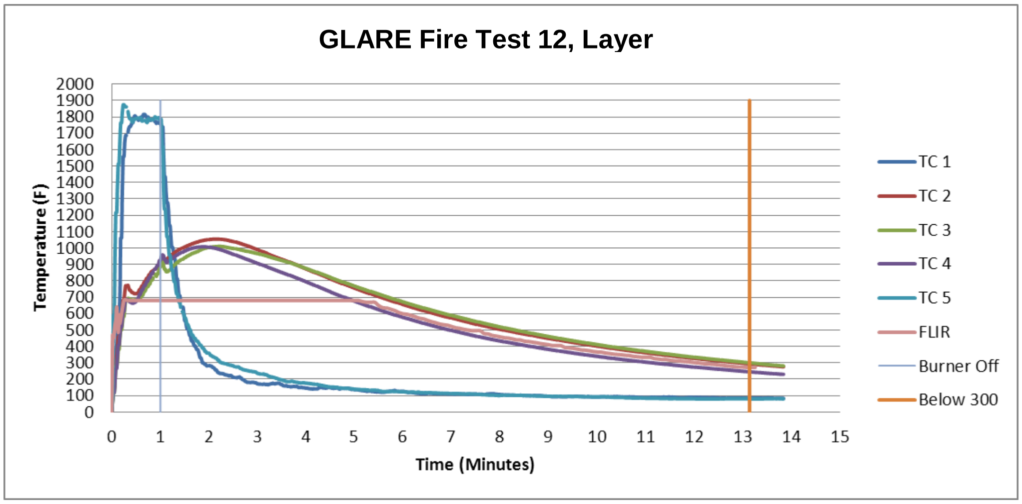


Figure 32. Measured Temperatures for Test 12

It is important to note that the FLIR camera apparent temperature display range peaked at 680°F (360°C). That is why the FLIR measurements plateaued at 680°F (360°C). During Test 10, the thermal camera spot tool was inadvertently set below the center of the layers instead of at the center of the stack. During the test, the issue was discovered, and the camera was adjusted to move the spot tool. The chart for Test 10, shown in figure 33, notes a notch in the thermal camera line at approximately the 4.5- to 5-minute mark, which is this adjustment. After the adjustment, the temperature reading from the thermal camera matched closely with those from the TCs. This issue only affected Test 10.

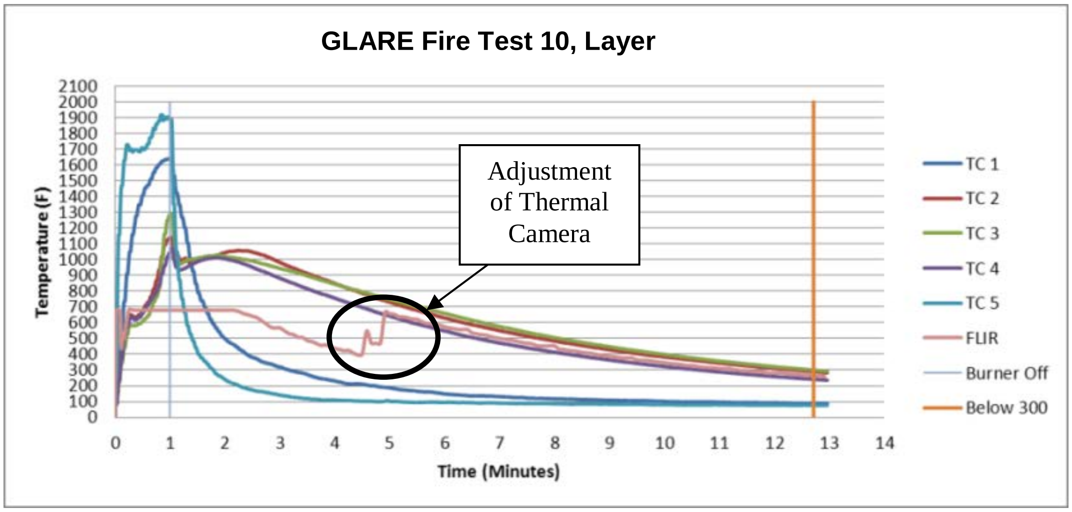


Figure 33. Test 10 Chart Showing FLIR Camera Adjustment

3.8 COOLING BELOW 300°F (149°C).

The time it took each sample to naturally cool below 300°F (149°C) for Tests 1 through 9 did not offer any consistent results. There were no similarities between exposure durations. Figure 34 shows the time each sample took to cool below 300°F (149°C) after turning off the FAA NextGen Burner.

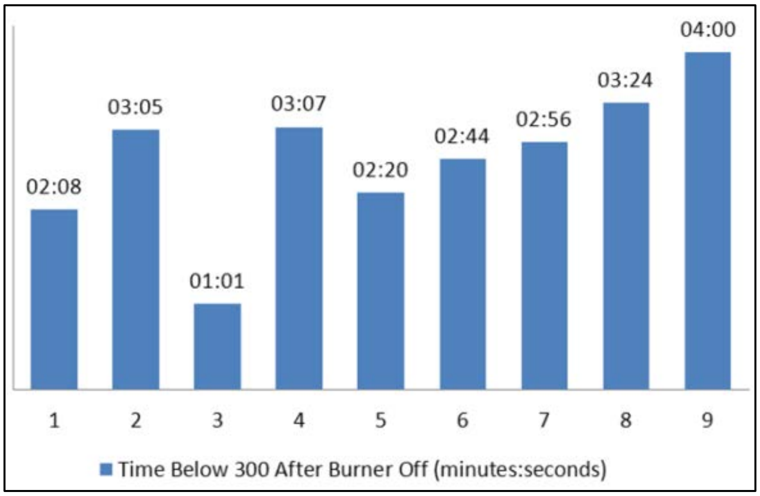


Figure 34. Time for Sample to Cool Below 300°F (149°C)—Tests 1-9

Numerous tests will be required to come to any conclusions concerning the amount of time GLARE takes to cool below the 300°F (149°C) threshold in this configuration. However, for the layered tests, the recorded times were consistent with an average time of 11 minutes 36 seconds.

There was no glowing or smoldering observed that would provide visible indicators to help ARFF determine if the GLARE had cooled below 300°F (149°C). Observation of light smoke continued even after the samples cooled sufficiently. Because of this, ARFF should rely on thermal imaging to look for hot spots and ensure sufficient cooling. Caution should be taken because these tests showed the temperature transferred through these samples was less than half of the FAA NextGen Burner temperature on the other side. This indicates the remaining GLARE structures may obstruct other burning areas from thermal imaging.

4. SUMMARY.

Twelve tests were conducted using GLARE 3-5/4 0.3, with a total thickness of 2.5 mm (0.098 in.). Nine of the tests used a 12- by 18-inch sample positioned flat, with the face of the sample in front of the FAA NextGen Burner. The remaining three tests used the same size sample cut into four equal pieces layered 0.75 inches apart and set with the edges of the long side facing the FAA NextGen Burner. The test objectives were to determine (1) if the temperature transferred through the sample, (2) if burnthrough or post-exposure burning occurred, (3) if a smoldering condition existed after fire exposure, and (4) the amount of time it took for the sample to naturally cool below 300°F (149°C) after removal of the fire source. Observation and video analysis sought to document visible indications that the material had cooled below 300°F (149°C) to help provide firefighters with a means to determine if the burning GLARE had cooled sufficiently to prevent re-ignition.

For the nine flat panel tests, the temperature measured on the back of the sample was less than half of the FAA NextGen Burner side temperature. Burner calibration showed that the flame averaged approximately 1850°F (1010°C), while maximum temperatures on the back of the sample were 483°F (251°C), 543°F (284°C), and 772°F (411°C) for the 1-, 5-, and 8-minute exposures, respectively. Maximum temperatures were observed close to the time when the FAA NextGen Burner was stopped. The temperature measurements indicated that the material had little thermal inertia.

Burnthrough did not occur during any of the tests. In each test, the outer layer of aluminum facing the FAA NextGen Burner melted away but the glass layers below remained mostly intact. There was some post-exposure flame in all the tests. Despite the duration of exposure, the post-exposure flame lasted approximately 1 minute.

The recorded times for the flat panel test samples to cool below 300°F (149°C) were not consistent. However, in the layered tests, the recorded times were consistent, with an average time of 11 minutes 36 seconds. Further testing would be required to investigate this further.

There were no visible indications that any of the samples cooled below 300°F (149°C). As a result, firefighters will have to rely on other methods to determine if the material has cooled to safe temperatures. For example, thermal cameras may be able to determine temperature by pointing the camera's spot temperature tool at the delaminated edges or other voids or pockets.

5. REFRENCES.

1. Griffiths, B., "Boeing Sets Pace for Composite Usage in Large Civil Aircraft," *Composites World*, May 1, 2012.
   Available at http://www.compositesworld.com/articles/boeing-sets-pace-for-composite-usage-in-large-civil-aircraft.aspx. (date last visited 6/6/14).

2. Hunter, B., "Looking Forward to A350 XWB's Maiden Flight," *Innovation in Textiles*, March 25, 2013.
   Available at http://www.innovationintextiles.com/composites/looking-forward-to-a350-xwbs-maiden-flight/. (date last visited 6/6/14).

3. Pora, J., "Advanced Materials and Technologies for A380 Structure," *FAST 32*, pp. 3-8, July 2003. Available at http://www.airbus.com/support/publications/?eID=dam_frontend_push&docID=17447. (date last visited 6/6/14).

4. Hode, J., "Development of a Firefighting Agent Application Test Protocol for Aircraft Fuselage Composites, Phase I—Carbon Fiber," FAA report DOT/FAA/TC-12/6, June 2012.

5. Vlot, A. and Gunnink, J., eds., "Fibre Metal Laminates: An Introduction," *Dordrecht: Kluwer*, 2001.

6. Airbus S.A.S., "A380 Aircraft Rescue and Fire Fighting Chart," *Airbus S.A.S.*, France, March 1, 2007.

7. Hagenbeek, Michiel, "Characterisation of Fibre Metal Laminates Under Thermo-mechanical Loadings," TU Delft Thesis, November 15, 2005.
   Available at http://repository.tudelft.nl/assets/uuid:2c91c8bd-b0a4-4c3b-86ee-f5ad8f1ea24e/ae_hagenbeek_20051115.pdf. (date last visited 6/12/14).

8. Roebroeks, G.H.J.J., "GLARE, A Structural Material for Fire Resistant Aircraft Fuselages," *Aircraft Fire Safety*, *AGARD Conference Proceedings*, 587, October 1996, pp. 26-1 – 26-13.

9. Guo-liang Zhu, Yan-ping Xiao, Yong-xiang Yang, et al., "Recycling of Aluminum From Fibre Metal Laminates," *Journal of Shanghai Jiaotong University (Science)*, Vol. 17, No. 3, June 1, 2012, pp. 263-267.

10. Horner, A., "Aircraft Materials Fire Test Handbook," FAA report DOT/FAA/AR-00/12, April 2000.

11. Federal Aviation Administration Advisory Circular 20-135, “Powerplant Installation and Propulsion System Component Fire Protection Test Methods, Standards, and Criteria,” February 6, 1990.

12. Title 14 Code of Federal Regulations Part 25.856, Appendix F Part VII, “Test Method to Determine the Burnthrough Resistance of Thermal/Acoustic Insulation Materials,” September 2, 2003.

13. Ochs, R.I., “Burnthrough Test Method for Aircraft Thermal/Acoustic Insulation, NexGen Burner Update,” *International Aircraft Materials Fire Test Working Group*, Paris, France, June 27, 2007.

14. Marker, T.R., “Full-Scale Test Evaluation of Aircraft Fuel Fire Burnthrough Resistance Improvements,” FAA report DOT/FAA/AR-98/52, January 1999.

15. Olson, J.M., “Mishap Risk Control Guidelines for Advanced Aerospace Materials; Environmental, Safety, and Health Concerns for Advanced Composites,” U.S. Air Force Advanced Composites Program Office, October 28, 1993.

16. United States Air Force, Technical Order 00-105E-9, “Aerospace Emergency Rescue and Mishap Response Information,” Revision 14, December 31, 2008.

APPENDIX A—STRUCTURAL LAMINATES COMPANY TESTING

The following document is an excerpted data sample regarding 1994-2001 test results. The tests were performed by Boeing Technology Services for Structural Laminates Company. Additional tests were performed by OCM Test Laboratories for Aviation Equipment Structure, Inc.

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION

STATEMENT OF COMPLIANCE WITH THE FEDERAL AVIATION REGULATIONS

DATE: March 28, 1994

AIRCRAFT OR AIRCRAFT COMPONENT IDENTIFICATION

MAKE	MODEL NO.	TYPE (Airplane, Radio, Helicopter, etc.)	NAME OF APPLICANT
Boeing	All	Airplane	Structural Laminates Company

LIST OF DATA

IDENTIFICATION | TITLE

BMT Work Request 94-00716

Oil Burner Cargo Liner Test

Description	Flame Penetration	Peak Temp.
.026 2/1 Glare D1221A470	No	187°F
.031 2/1 Glare D1221C472	No	188°F
.036 2/1 Glare D1221B471	No	174°F
.044 3/2 Glare D1221D473	No	171°F
.054 3/2 Glare D1221E474	No	161°F

PURPOSE OF DATA

To show compliance with the burn through requirements for cargo liner materials

APPLICABLE REQUIREMENTS (List specific sections)

FAR 25.855(c) Amendment 72

CERTIFICATION - Under authority vested by direction of the Administrator and in accordance with conditions and limitations of appointment under Part 183 of the Federal Aviation Regulations, data listed above and on attached sheets numbered ______ ______ have been examined in accordance with established procedures and found to comply with applicable requirements of the Federal Aviation Regulations.

I (We) Therefore

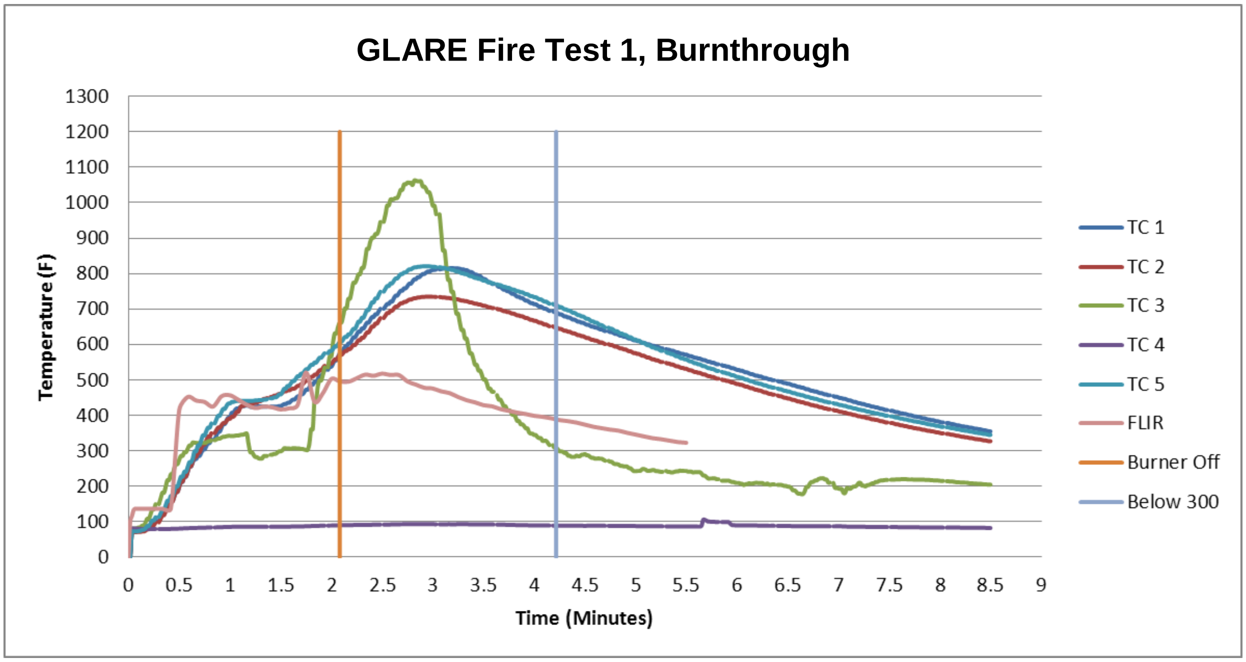
- [ ] Recommend approval of these data
- [x] Approve these data

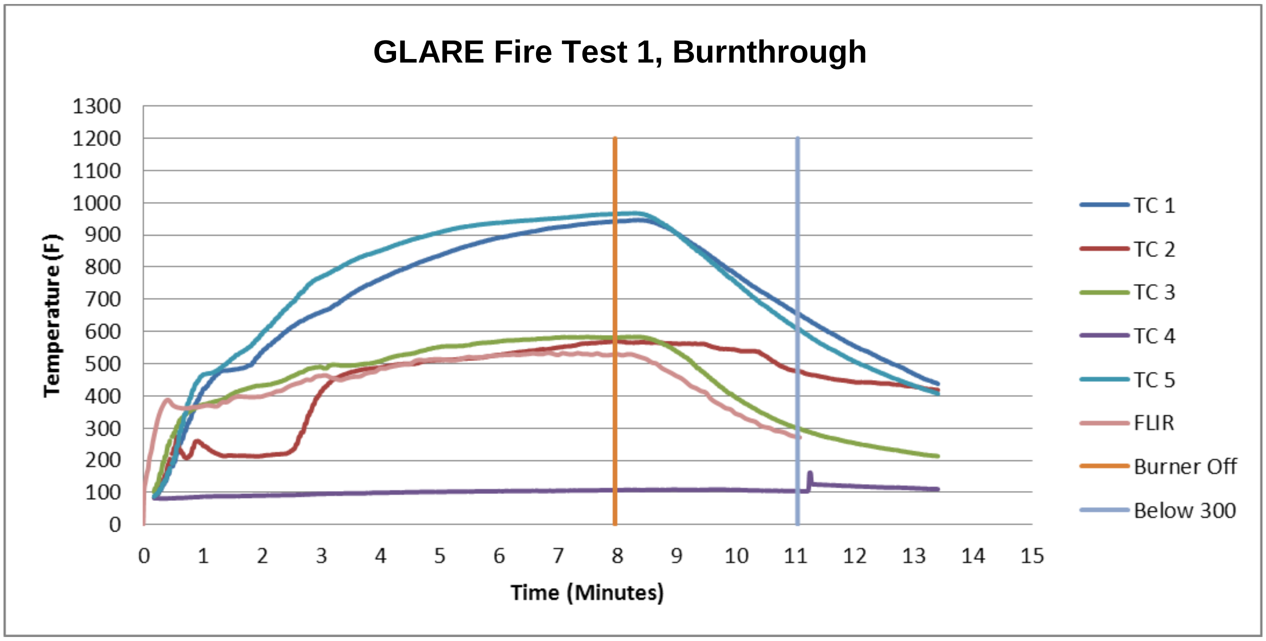
SIGNATURE(S) OF DESIGNATED ENGINEERING REPRESENTATIVE(S)	DESIGNATION NUMBER(S)	CLASSIFICATION(S)
R Rydberg	NM-1539	Interior Materials Flammability

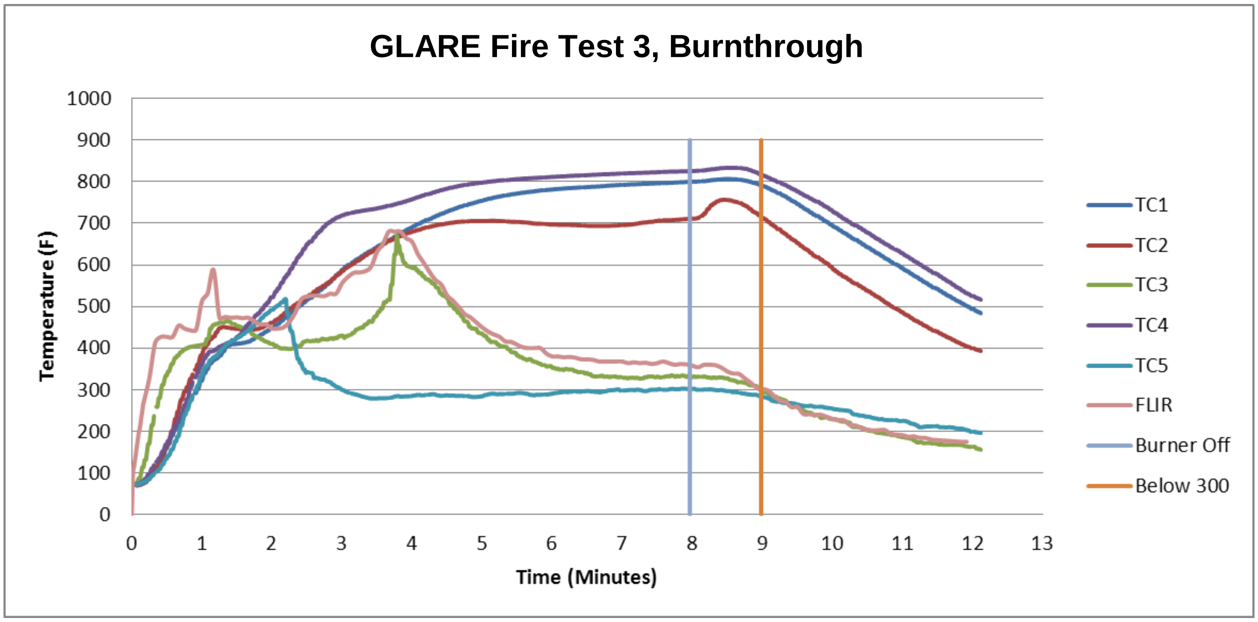
FAA Form 8110-3 (1-70) SUPERSEDES PREVIOUS EDITION

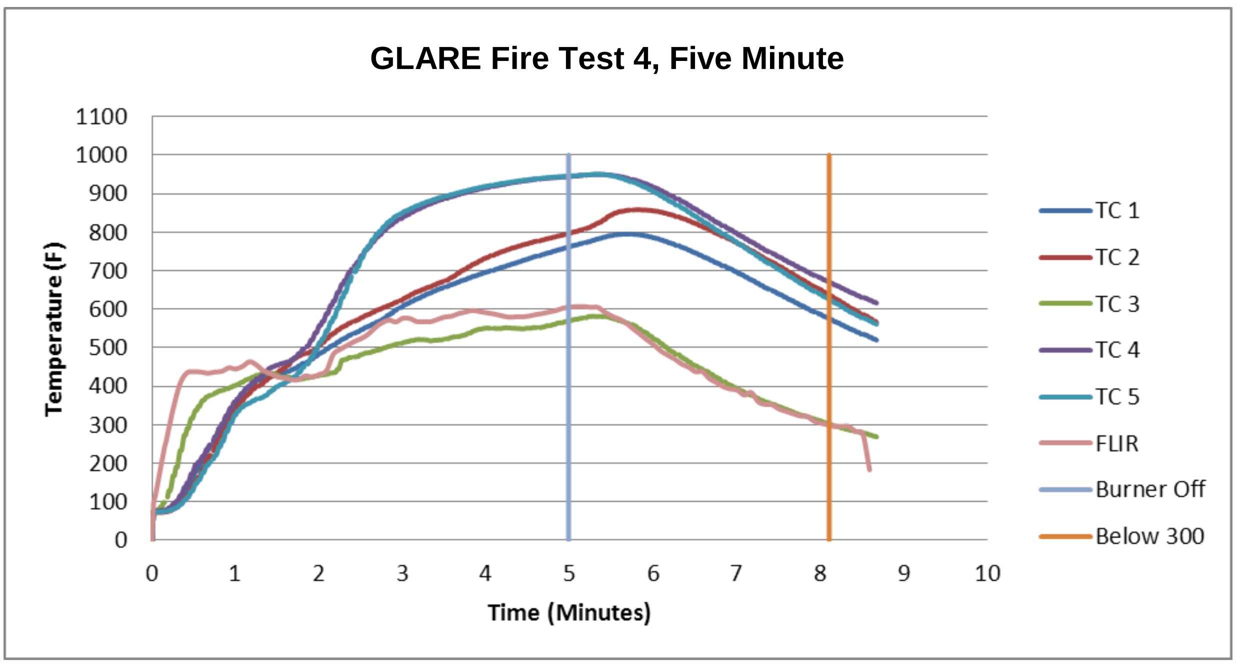
GPO

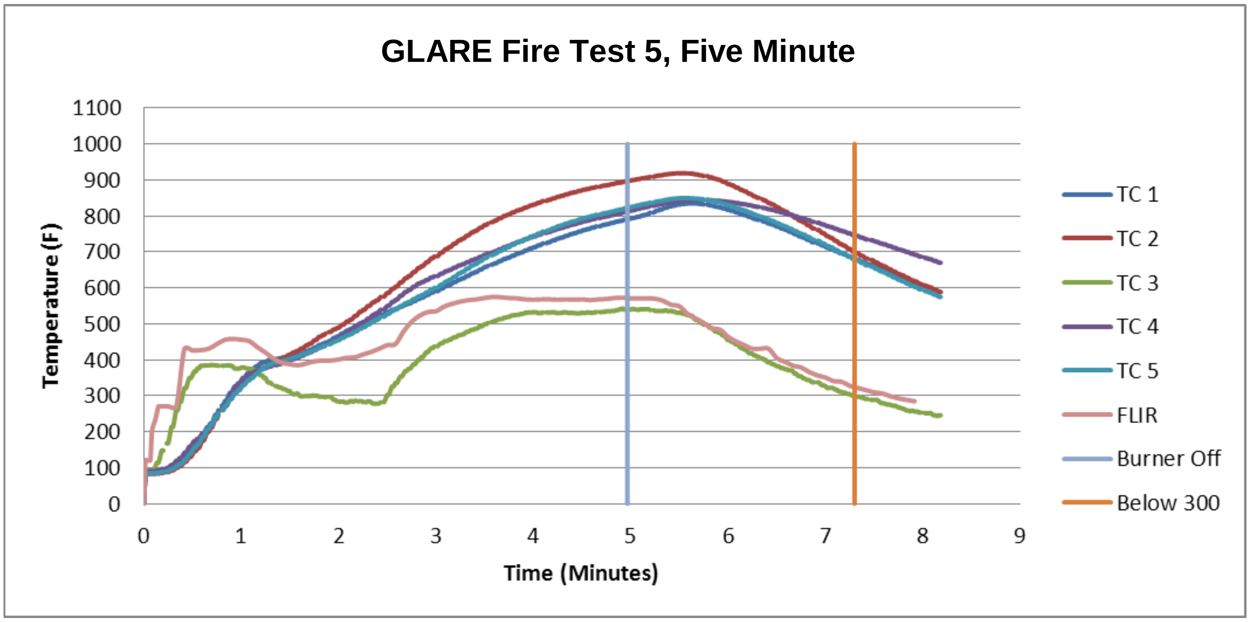
APPENDIX B—TEST CHART DATA

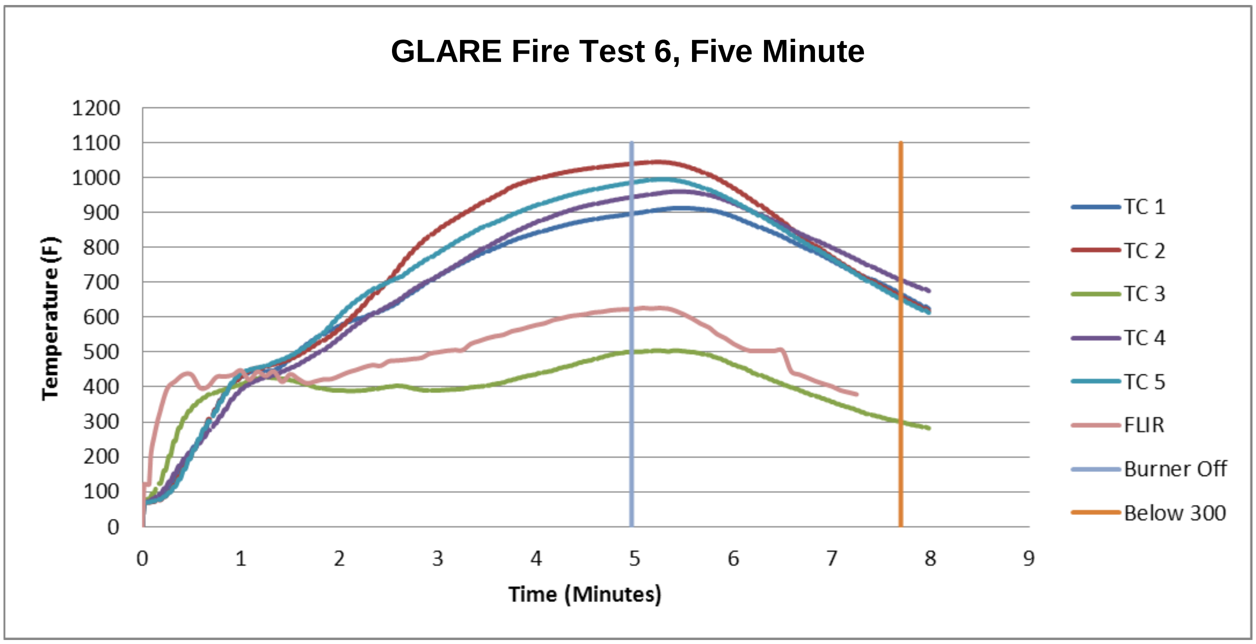


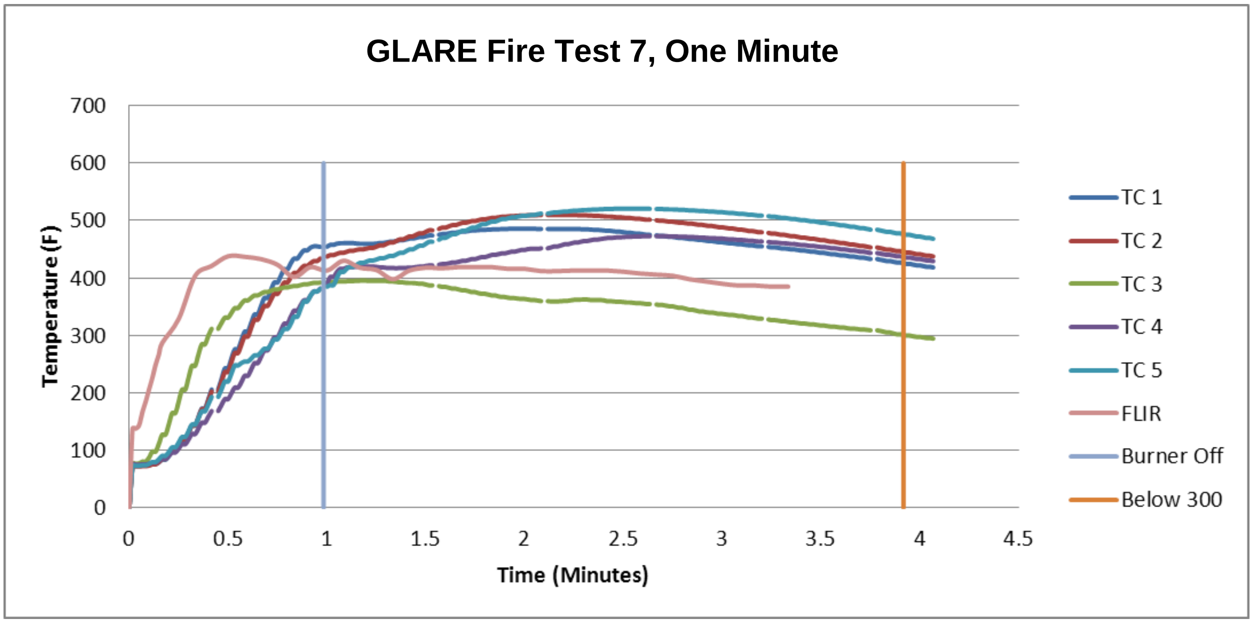


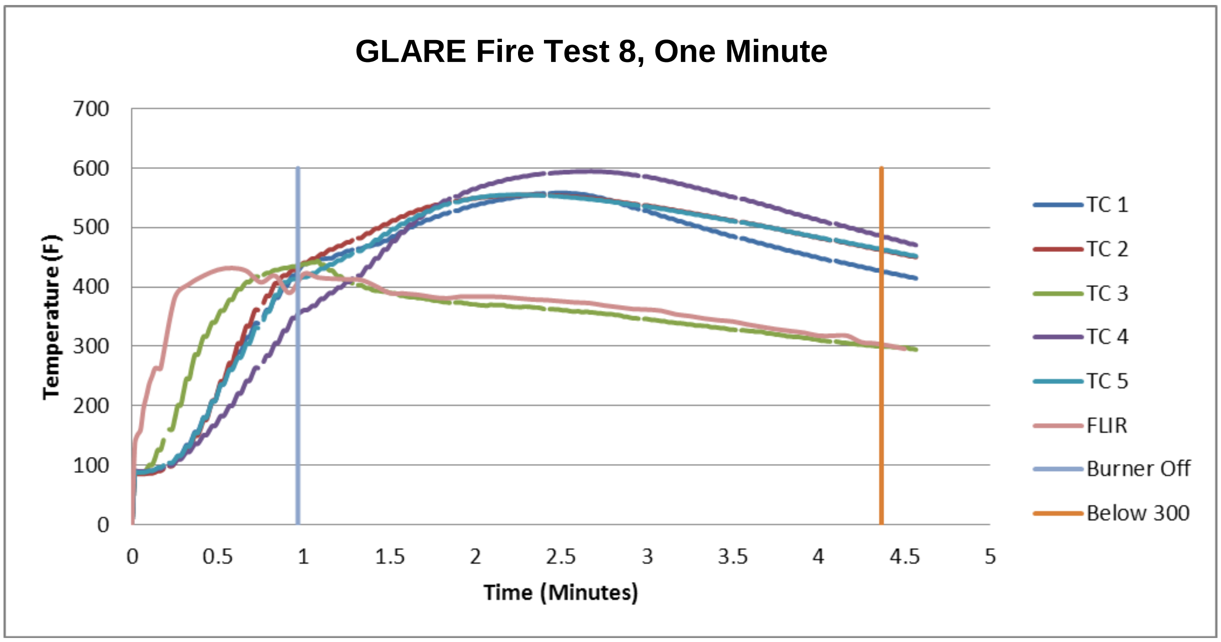

GLARE Fire Test 3, Burnthrough
Temperature (F)
1000
900
800
700
600
500
400
300
200
100
0
0
1
2
3
4
5
6
7
8
9
10
11
12
13
Time (Minutes)
TC1
TC2
TC3
TC4
TC5
FLIR
Burner Off
Below 300

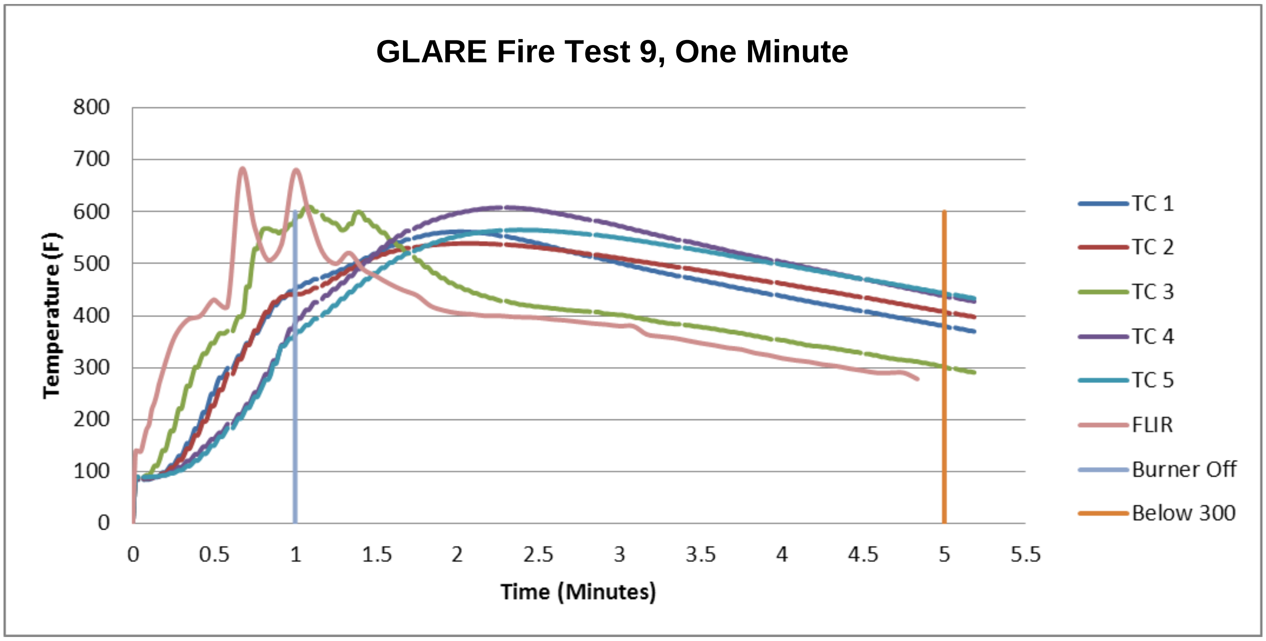

GLARE Fire Test 4, Five Minute
Temperature (F)
1100
1000
900
800
700
600
500
400
300
200
100
0
0
1
2
3
4
5
6
7
8
9
10
Time (Minutes)
TC 1
TC 2
TC 3
TC 4
TC 5
FLIR
Burner Off
Below 300

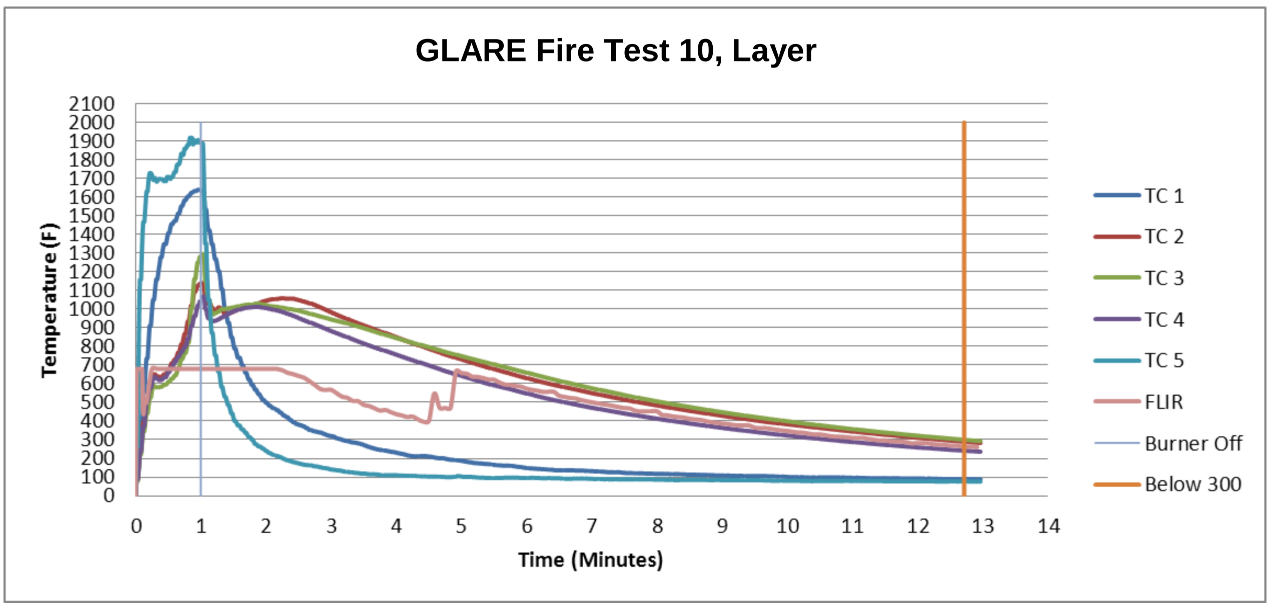

GLARE Fire Test 5, Five Minute
Temperature (F)
1100
1000
900
800
700
600
500
400
300
200
100
0
0
1
2
3
4
5
6
7
8
9
Time (Minutes)
TC 1
TC 2
TC 3
TC 4
TC 5
FLIR
Burner Off
Below 300

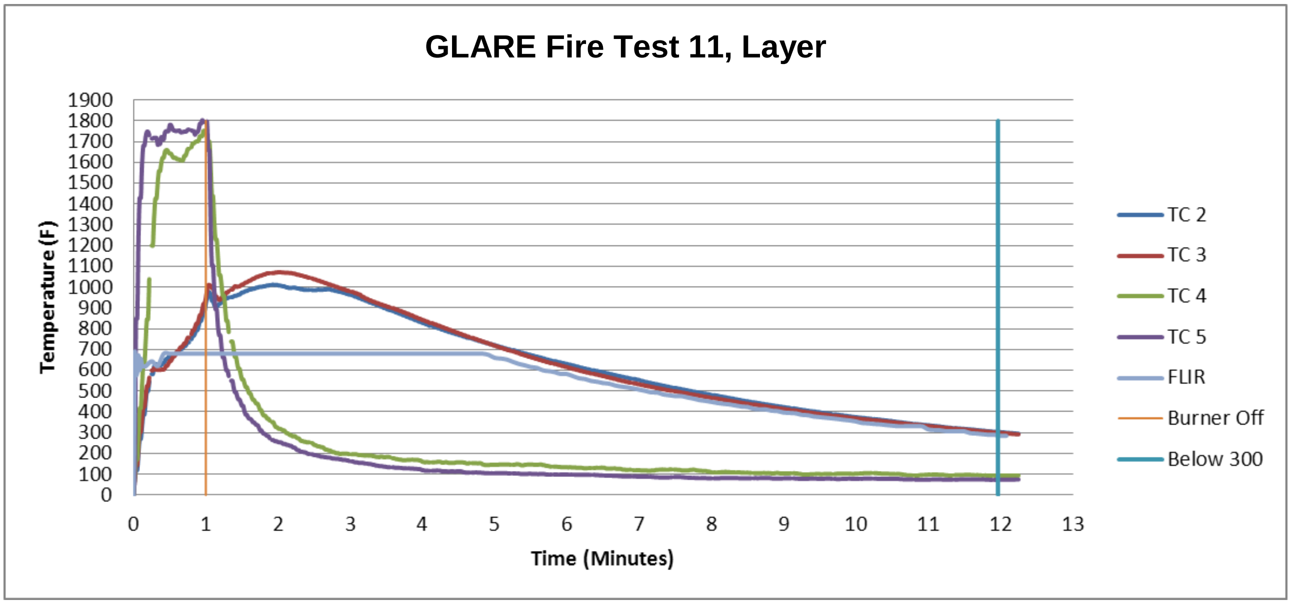

GLARE Fire Test 6, Five Minute
Temperature (F)
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
0
1
2
3
4
5
6
7
8
9
Time (Minutes)
TC 1
TC 2
TC 3
TC 4
TC 5
FLIR
Burner Off
Below 300

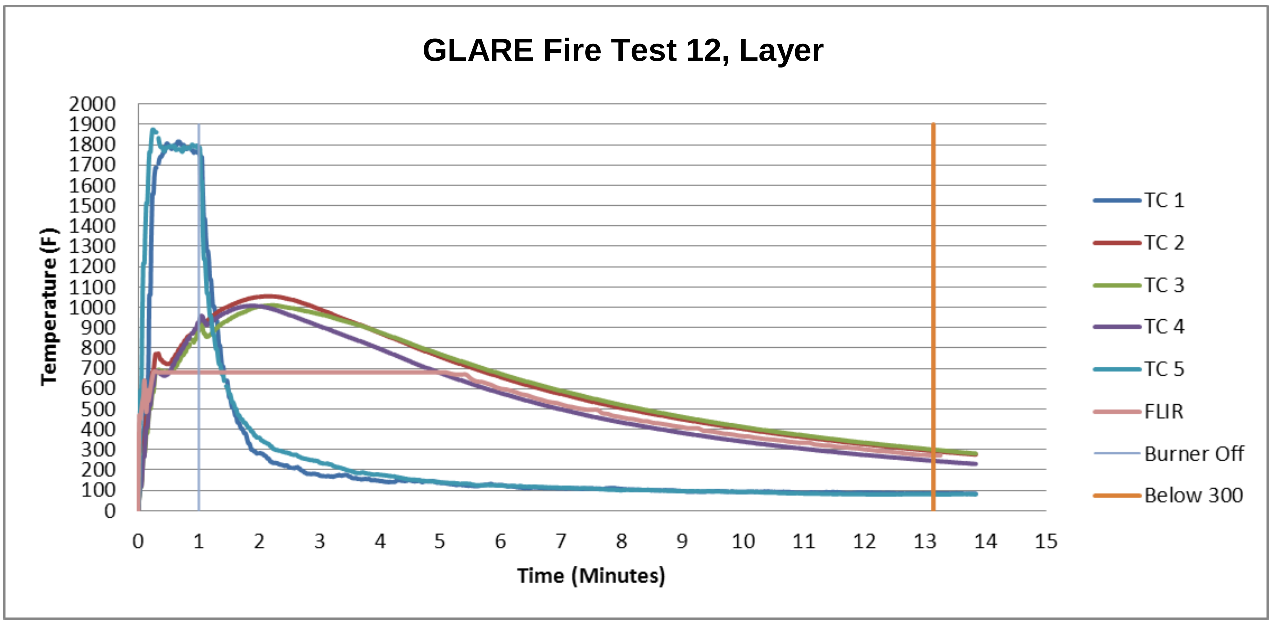

GLARE Fire Test 7, One Minute
700
600
500
400
300
200
100
0
Temperature (F)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
Time (Minutes)
TC 1
TC 2
TC 3
TC 4
TC 5
FLIR
Burner Off
Below 300


GLARE Fire Test 8, One Minute
700
600
500
400
300
200
100
0
Temperature (F)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (Minutes)
TC 1
TC 2
TC 3
TC 4
TC 5
FLIR
Burner Off
Below 300


GLARE Fire Test 9, One Minute
Temperature (F)
800
700
600
500
400
300
200
100
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
Time (Minutes)
TC 1
TC 2
TC 3
TC 4
TC 5
FLIR
Burner Off
Below 300


GLARE Fire Test 10, Layer
Temperature (F)
2100
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
Time (Minutes)
TC 1
TC 2
TC 3
TC 4
TC 5
FLIR
Burner Off
Below 300


GLARE Fire Test 11, Layer
Temperature (F)
Time (Minutes)
TC 2
TC 3
TC 4
TC 5
FLIR
Burner Off
Below 300


GLARE Fire Test 12, Layer
Temperature (F)
Time (Minutes)
TC 1
TC 2
TC 3
TC 4
TC 5
FLIR
Burner Off
Below 300