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**Full-Scale Aircraft Fire Tests—A Comparison of Aluminium and Composite Burn-Through**

AEROSPACE – GROUP

NATIONAL RESEARCH COUNCIL CANADA

# **Full-Scale Aircraft Fire Tests - A Comparison of Aluminium and Composite Burn-Through**

Volume 1 of 1

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Date: May 2015

Authors : Gould, Ron, Hind, Simon, Jacquet, François



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## **A comparison of aluminium and composite burn-through**

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**List of Abbreviations**

AFFF	Aqueous Film Forming Foam
ARFF	Aircraft Rescue and FireFighting
B727	Boeing 727 aircraft
BS	Body Station
CAFS	Compressed Air Foam System
CFRP	Carbon Fibre Reinforced Plastic
DAQ	Data AcQuisition
DC	Direct Current
DOT	Department of Transportation (US)
ERS	Emergency Rescue Services
FAA	Federal Aviation Administration (US)
FML	Fibre Metal Laminate
FWD	Forward
GLARE	Glass Laminate Aluminium Reinforced Epoxy
HRET	High Reach Extendable Turret
LED	Light Emitting Diode
NNE	North, North East
NRC	National Research Council
OFS	Ottawa Firefighting Services
OIAA	Ottawa International Airport Authority
S	South
S	Stringer
SSW	South, South West
STDB	Starboard
TC	Thermocouple
TFT	Task Force Tips
TIC	Thermal Imaging Camera
UGV	Unmanned Ground Vehicle
US	United States
V	Volt

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## **1.0 INTRODUCTION**

In early 2014 the NRC was approached by Ron Gould (retired NRC staff and current guest worker) to support full scale aircraft fire tests he was planning in conjunction with Fire Chief Francois Jacquet of the Ottawa International Airport Authority Emergency Rescue Services (OIAA ERS). The tests included two separate fires: the first conducted against aluminium fuselage construction as a baseline which was followed by a second against composite fuselage construction for direct comparison. The tests were conducted on a decommissioned Boeing 727–225(F) which was previously owned by NRC and which had been used for a bomb threats against aircraft exercise in 2009<sup>1</sup> and a lithium battery cargo hold fire in 2012<sup>2</sup>. The aircraft was transferred to the OIAA ERS as a firefighter training aid in 2013.

The primary objective of the tests was to demonstrate to airport firefighters some of the differences between fires on aircraft with traditional aluminium fuselage construction versus newer fuselage structures with advanced composite materials. More specifically, fires in composite-skinned aircraft have drastically different burn-through characteristics compared to traditional aluminium-skinned structure under the same conditions and consequently higher interior temperatures and increased smoke levels persist as fires develop.

The primary objective could have been demonstrated by determining the differences in material burn-through characteristics by using a burner or flame impinging directly on relatively small test panels separately or on prepared test areas on the aircraft but since the Aircraft Rescue and FireFighting (ARFF) community is starved for real world experience, the full-scale experiments were designed to resemble real cargo aircraft fires that required co-ordinated attack and overhaul actions. The current guidance is not entirely clear on the differences between fighting aircraft fires on aluminium versus composite structures so the authors of this report devised full-scale aircraft fire tests to demonstrate the difference. A literature search did not provide an equivalent set of tests; therefore, an existing specific test procedure was not duplicated. The results of the baseline aluminium test conducted on Aug 22<sup>nd</sup> were used to determine the final configuration and test plan for the composite fire test conducted on Sept 9<sup>th</sup>. General guidance was taken from DOT/FAA/AR-00/28 primarily for the ventilation configuration of the igniter boxes (Appendix I).

Internal air temperatures and external skin temperature data were recorded using thermocouples. External skin thermal conditions were monitored using thermal imaging cameras (TIC) mounted on the airport fire trucks. The TIC camera view on the HRET-equipped truck was used to aid in selecting piercing locations for the Stinger.

<sup>1</sup> LTR-SMPL-2010-0060

<sup>2</sup> LTR-SMPL-2012-0126

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The OIAA ERS has been exploring the capabilities of the HRET and Stinger piercing tools since the 2010 arrival of a Rosenbauer Panther 6X6 equipped with a 55 foot boom. There is a need to address limitations posed by aircraft size, orientation and structural configurations that result in locations and confined spaces which cannot be accessed by the HRET and Stinger. Additionally, the OIAA ERS were recently introduced to a new firefighting tool in the form of the hand-held PyroLance® abrasive media piercing tool, during an ARFF Working Group conference in 2013. The manufacturer was invited to participate in both component tests and in the attack mounted against the onboard live fire involving composite skin structure. The aircraft-related component test results are documented in Appendix II.

Monitoring of particulates in the composite material fire smoke plume was performed with a remotely operated UGV carrying a particle monitor measuring mass concentrations of particulates in real-time. Detailed particulate measurement data are provided in Appendix III.

Although the tactics varied slightly between the two fire tests, the firefighters and their equipment were staged at pre-determined positions prior to each test being initiated.

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## **2.0 TEST CONFIGURATIONS**

The two full-scale fire tests were both conducted on-board a Boeing 727-225(F). The aircraft was located in the training area adjacent to the OIAA ERS fire hall such that equipment could approach and operate from both sides. The two fire tests were located on the main deck and set symmetrically about the over-wing exit section. The first test, the baseline aluminium structure fire in the forward fuselage will be referred to as Test 1. The composite structure fire in the aft fuselage will be referred to as Test 2. Each main deck fire zone was temporarily created by installing a flame-resistant salvage tarp on the far side of the over-wing exit, relative to the test location.

The fuselage structure had been heavily damaged from prior testing including piercing, fires and bomb blasts. It was not practical to repair all of the holes in the aircraft so it was decided to only repair the holes above the main deck floor. These holes were covered with small sheet metal panels screwed onto the fuselage skin from the outside. In an effort to make both fires as similar as possible, the air circulation to the main deck was restricted to be only through the four over-wing exit doors and from the cargo holds below via four adjacent floor grills. To equal the air moving through the skin section removed from the FWD cargo hold (Test 1) the AFT cargo door was open during Test 2.

The vast majority of the main deck cargo liner, wiring, ducts and piping were removed from the fire test locations.

The fuel package for Test 1 was centered at Body Station (BS) 700 and at BS950D for Test 2 therefore the centres of the two fires were separated by 37.4 feet (11.4 meters). With the cockpit door closed the main deck length for Test 1 was 57.9ft (17.6 m) from the cockpit bulkhead to the salvage tarp installed at BS870. The volume of this area was nominally 2766ft<sup>3</sup> (78.3m<sup>3</sup>). In Test 2 the salvage tarp was installed at BS740 leaving a distance of 46.9ft (14.3m) to the AFT pressure bulkhead and an internal volume of nominally 2239ft<sup>3</sup> (63.4m<sup>3</sup>). The Test 2 fire zone was therefore 19% smaller than that for Test 1 by 11ft (3.3m) in length and 527ft<sup>3</sup> (14.9m<sup>3</sup>) in volume. The salvage tarp was 20ft (6.2m) away from the closest side of the stack of paper-filled cardboard boxes that constituted the fuel package for both tests.

For each fire test, two thermocouple trees were installed on the main deck, one next to the fuel package and a second 100 inches (254 cm) (8.3ft/2.5m) away, to provide a profile of the internal temperatures. Each tree featured five thermocouples spaced 19.7 inches (50 cm) apart vertically with the top thermocouple located adjacent to the inner surface of the crown skin. Each test featured two external surface thermocouples in the mid-plane of the fuel package which were located at Stringer 1 and midway between stringers S5L and S6L. Both external thermocouples were covered by an insulating layer. The temperatures from the 12 thermocouples were recorded on a laptop located at

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the command post at a frequency of 1 Hertz. The data records began before the fires were started and ended just before firefighters entered the fuselage to carry out the final overhaul procedures.

The time reported for the various actions and events are calculated from the observed start of each respective fire. Each test therefore has a unique fire clock.

For each test four internal video cameras viewed the main deck. Both a TIC and a video camera were mounted on a stationary boom truck to provide an overhead exterior view of the crown. Nine cameras were used for Test 1 and ten in Test 2. Selected internal video sources were recorded both in the cameras and remotely on laptop computers in case any camera suffered fire or water damage. Only one camera remote was wireless, the remainder required cables routed out of the aircraft. The FWD interior cameras in Test 1 were aided by a floor-mounted LED light source illuminating the fuel stack so that the cameras could auto-focus in the darkened interior. The boom truck TIC video feed and one internal video camera view were routed to the incident command post. A hand-held video camera was carried by an operator traversing the site to acquire views of interest as they arose. Spectator and participant still photos and video were also collected. The stills and video from each test were composed into a compilation to summarize the set-up, fire progress and attack. These compilation videos were used to educate the three OIAA ERS firefighter platoons that were not directly involved in the tests.

Environmental conditions for both tests were daytime with cloudy skies and light winds. The aircraft was situated pointing roughly NNE in the training area at 33 deg. Test 1 was performed between 11 and 12 AM at 70.7°F (21.5°C) with winds of 8.7 mph (14 kph). The observed local wind direction at the time of the fire was from almost directly behind and moving parallel to the alignment of the aircraft (SSW at 210-220 degrees). Test 2 was performed between 1 and 2 PM at 69.8°F (21°C) with winds of 9.3 mph (15 kph). The observed local winds at the time were from the rear right to front left across the aircraft axis (S at 180-190 degrees).

The layout of the fuel package on the main deck and the camera positions for each test are shown on the side and top view CAD sketches in Figure 1. The fire trucks each had a TIC camera mounted to the top of the cab. The location of these and other thermal cameras are marked “TIC” in deference to the normal video cameras in use elsewhere. The exterior thermocouple locations are also annotated.

A closer view of the layout of the stack of boxes supplying the fuel for the fire, the airflow from the over-wing doors and cargo hold, the thermocouple positions and their numbering as well as the location of the flame resistant salvage tarp for Test 1 is shown in Figure 2. Figure 3 shows the layout of these features for Test 2.



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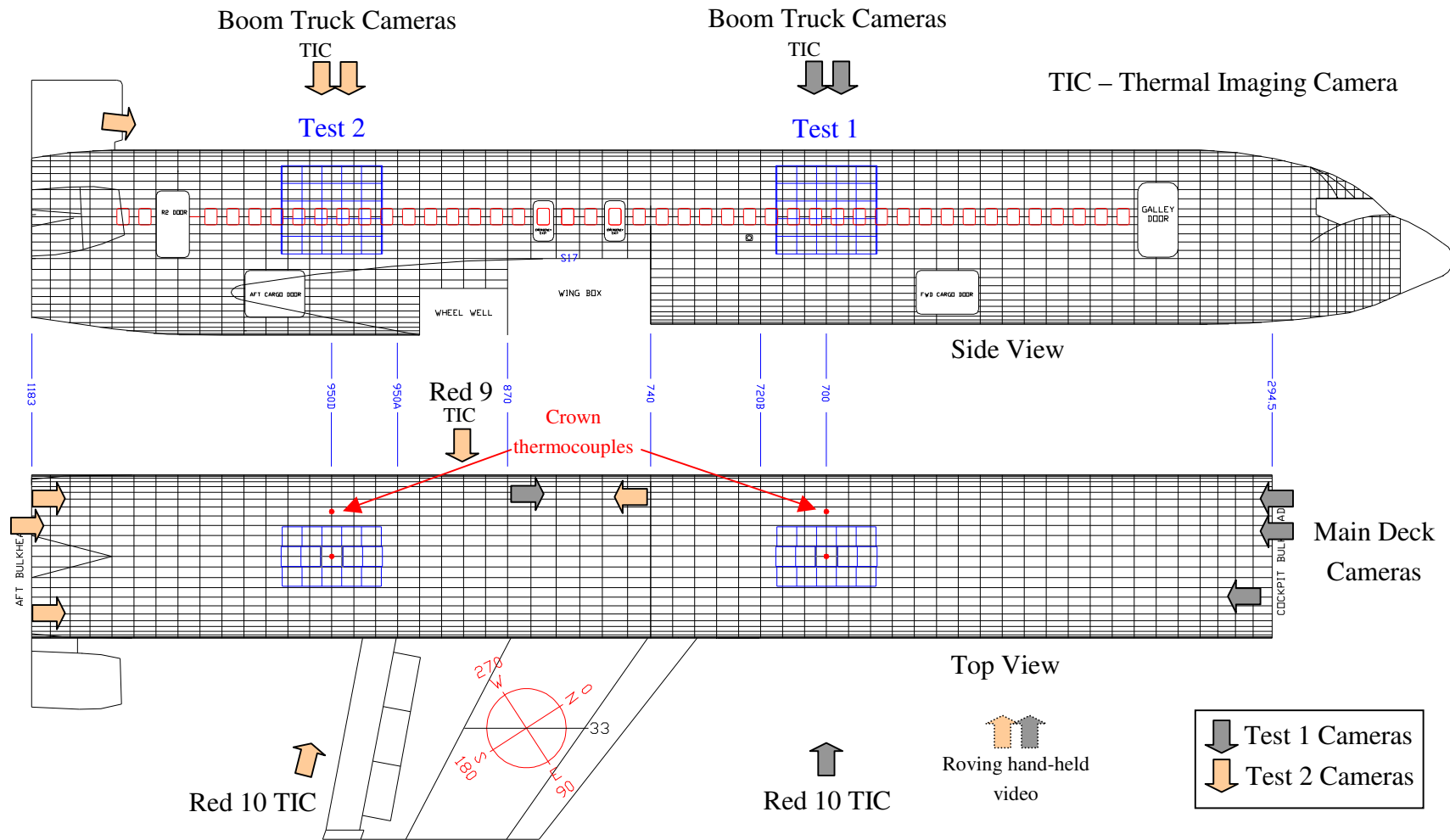


Figure 1: Top and side views of the fuel packages (blue) for both fires and their respective camera positions.

# Full-Scale Aircraft Fire Tests—A Comparison of Aluminium and Composite Burn-Through

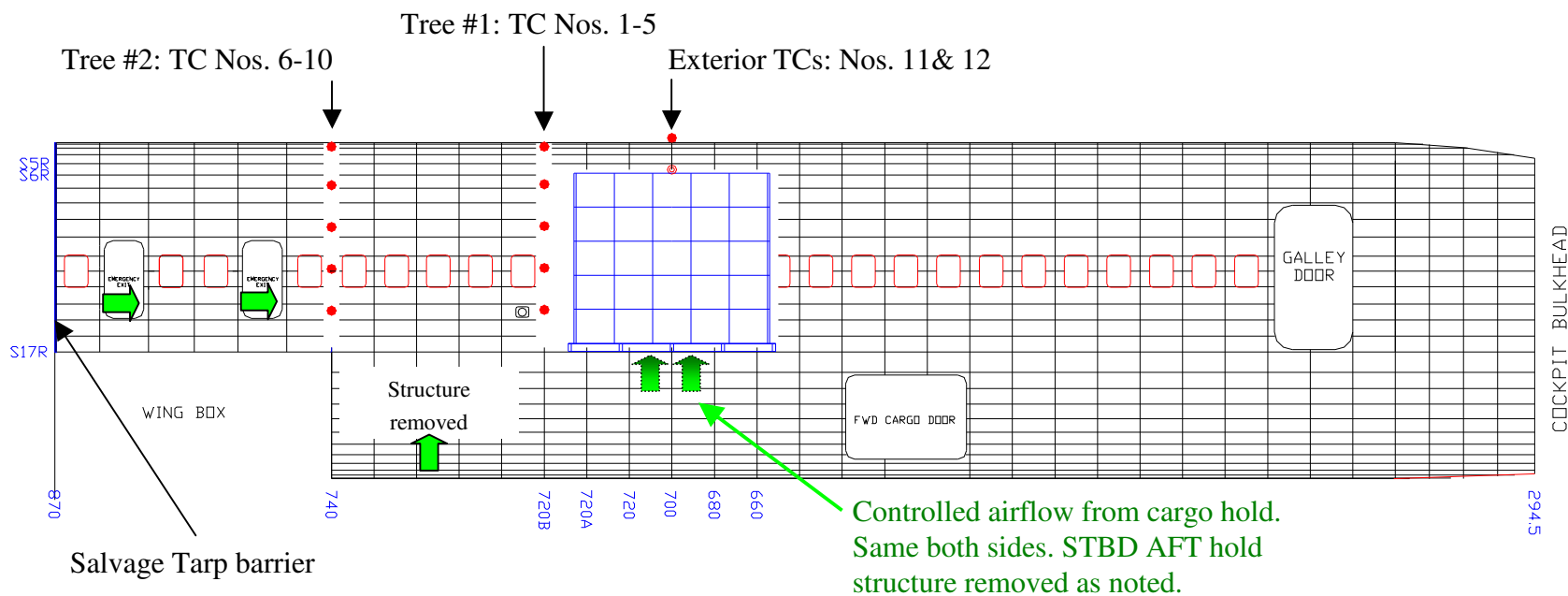


Figure 2: Test 1. Fuel Package centred at BS700. Distance to Salvage Tarp: 23.1 ft (7.3 m). Main deck length: 57.9 ft (17.7 m).

# Full-Scale Aircraft Fire Tests—A Comparison of Aluminium and Composite Burn-Through

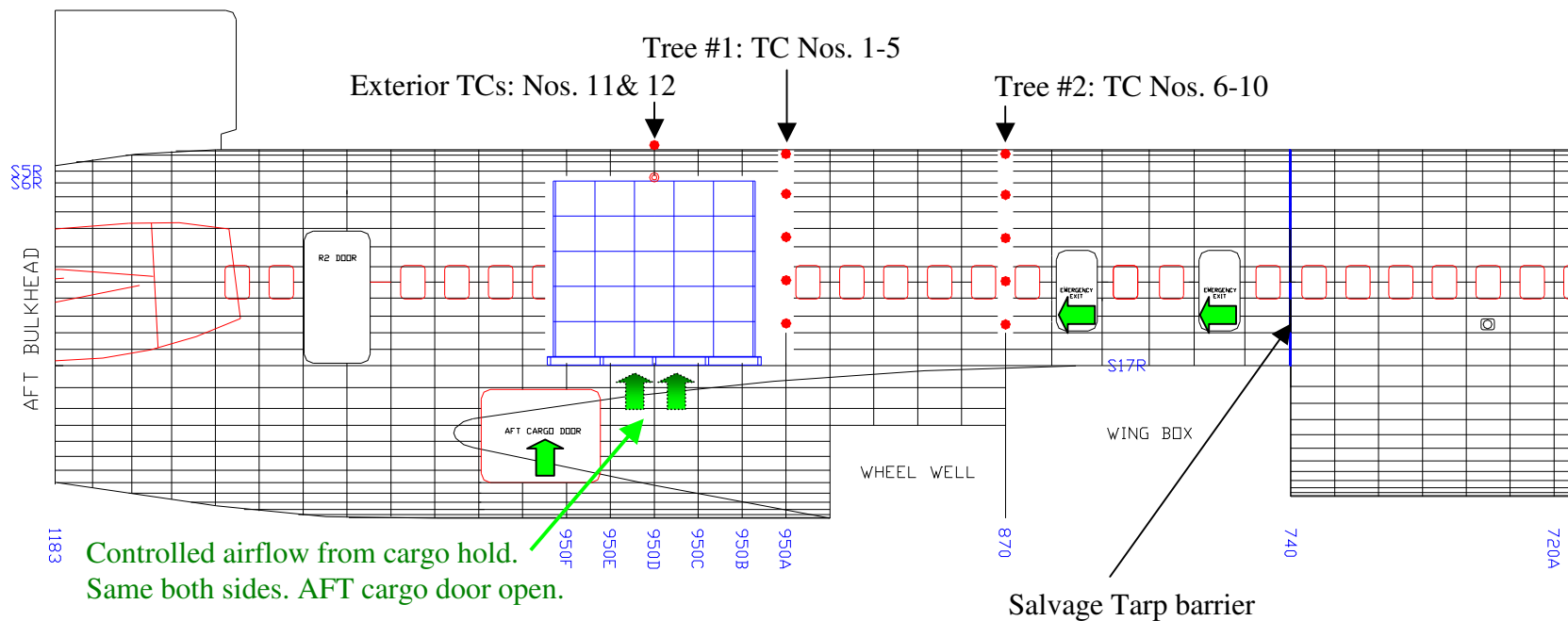


Figure 3: Test 2. Fuel Package centred at BS950D. Distance to Salvage tarp: 24.2 ft (7.4 m). Main deck length: 46.9 ft (14.3 m).

**Full-Scale Aircraft Fire Tests—A Comparison of Aluminium and Composite Burn-Through****2.1 FUEL PACKAGE**

The fuel package was designed to present the fire to the structure very early in the event by directing the energy to the crown. The design minimized heat damage to the lower sidewall areas which a shorter stack would have produced. The package was composed of a stack of 70 cardboard boxes loaded with shredded books with a light spray of diesel applied inside and out. The stack was set up on wooden pallets so that air could enter freely from the bottom. The stack comprised of four layers of three rows by five boxes capped by two rows of five, Figure 4. Narrow spaces (approximately one inch (2.54 cm), either side of the centre boxes, created two chimneys. The four lower layers of boxes were wrapped with plastic film to help secure the stack and also forced the first smoke from the fire to exit at the top of the stack where it could be viewed by the interior cameras.

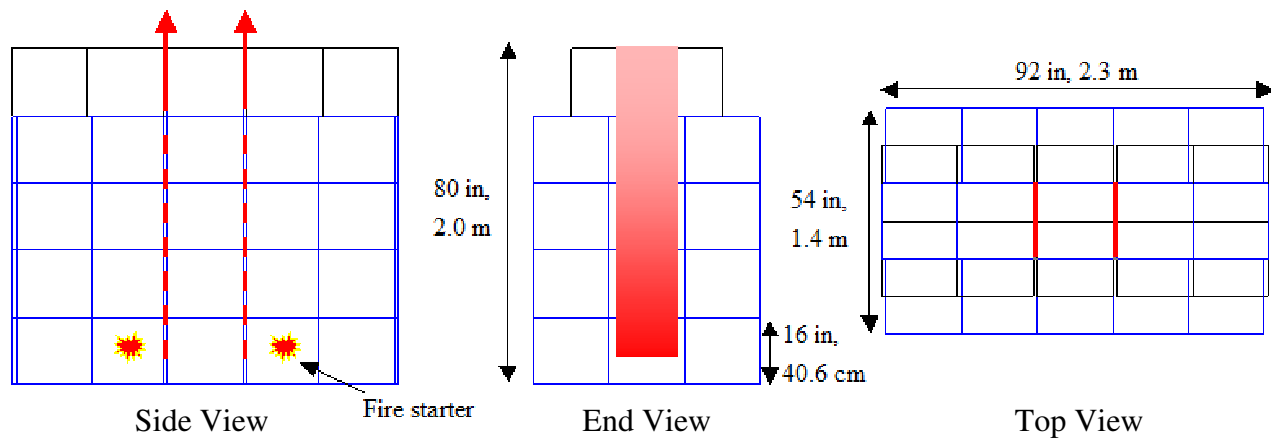


Figure 4: 70 box fuel package with two 1 inch (2.5 cm) chimneys either side of central stack.

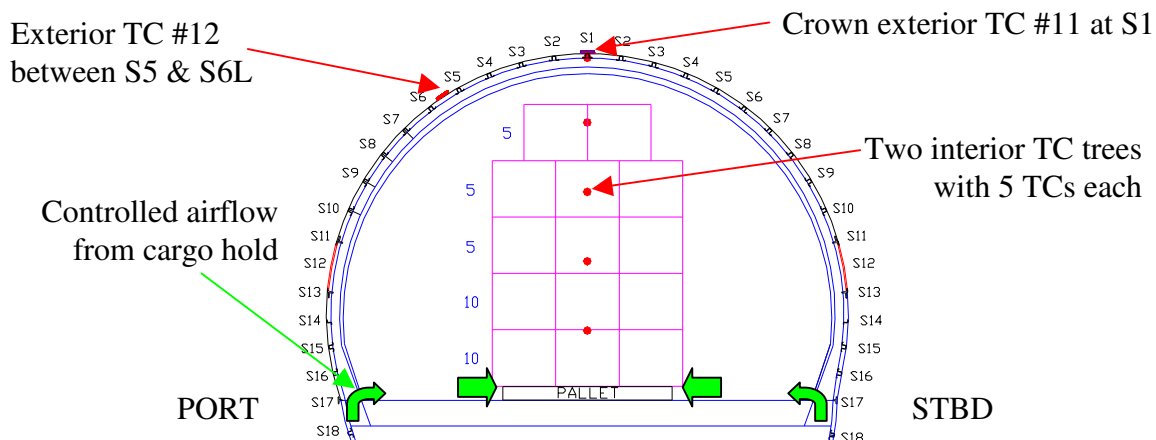


Figure 5: Cross-section view of fuel package on main deck.

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As shown in Figure 5, the boxes in the bottom two layers were each loaded (cardboard box + shredded books/magazine contents) to 10 pounds (4.5 kg) for a subtotal of 300 pounds (136 kg). The boxes in the top three layers weighed 5 pounds each (2.3 kg) for a subtotal of 200 pounds (90.7 kg). Therefore the fuel load nominally weighed 500 pounds (226.8 kg). Diesel fuel (0.18 Imp Gal, 0.8 L) was applied as an accelerant inside and on some exterior surfaces of the boxes using a hand-pump sprayer.

Although the over-wing exits were a source for incoming air to feed the combustion of the fuel package they were at the same time the initial exit for smoke generated by the fires. In Test 1 the burn-through of the crown became the principal smoke release point but the over-wing doors remained the principal exit channel in Test 2.

Airflow to the fire was supplied by having all four over-wing exit doors open. As well, air could move up from the cargo hold via the floor-level grills (Figure 5). Because of differences in size of the zones for the two fires all but two bays on either side of the stack were blocked with carpet and sand (Figure 6) to equalize the air supply available for each fire (Figure 2 and Figure 3). The AFT cargo door was opened in Test 2 to be equivalent to the FWD hold which had a large opening where a section of skin had been removed as a result of bomb damage in a previous project.



Figure 6: Carpet and sand block airflow from cargo hold to main deck.

To ignite the fire, two 12 V DC automotive cigarette lighter heating elements in metal tubes each overheated a Type 123 lithium primary battery held in each metal tube. A 12V battery was located outside the aircraft near the command post. The lithium batteries were chosen as the fire-starter because they provide both a gas flame and molten ejecta from vents at the positive terminal. The two fire-starter units were loaded into ventilated boxes located either side of the centre box in the middle row at the base of the stack in Test 1 or both in the AFT box (Test 2). The boxes were loaded with 10

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pounds of shredded paper that just covered the fire-starters. The lithium batteries took approximately two minutes to light according to trials conducted prior to the test.



a) Fire-Starter in ventilated box with shredded paper. b) Post-fire condition.

Figure 7: Lithium primary battery fire starter.

The intention had been to conduct a heat release trial of the fuel package to ensure that the fuel would generate sufficient heat for a sufficient time to melt the aluminium crown (Test 1) without penetrating an area larger than that re-skinned with advanced composites for Test 2. Unfortunately the resources were not available prior to the test dates. However, the damaged area resulting from Test 1 did not actually exceed the re-skinned area prepared for Test 2 and so no modifications were made to the fuel package between tests.

The FWD cargo hold, under Test 1, had previously been configured to permit water drainage for previous firefighting exercises. Four holes were cut in the bilge area of the AFT cargo hold, nearest the wing box, to provide similar water drainage for the composites fire in the AFT area of the main deck for Test 2.

## 2.2 TEST 1 CONFIGURATION – ALUMINIUM BASELINE FIRE

The baseline fire (Test 1) was set to determine the time to achieve and the extent of damage at initial burn-through of the original aluminium crown structure.

The crown skins in the test area were machined to taper in thickness from 0.040 to 0.047 inches (1.01-1.19 mm) between BS660 and 740.



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The internal fibreglass cargo liner, wiring bundles, air ducting and hydraulic piping runs were removed in most of the forward fuselage of the main deck area as shown in Figure 8.



a) looking FWD from over-wing exit

b) looking AFT from cockpit bulkhead

Figure 8: Views of FWD main deck prior to test.

A boom truck was positioned on the PORT side of the aircraft (Figure 9). The bucket supported a frame that carried both a thermal camera and video camera to provide exterior views of the crown of the aircraft.

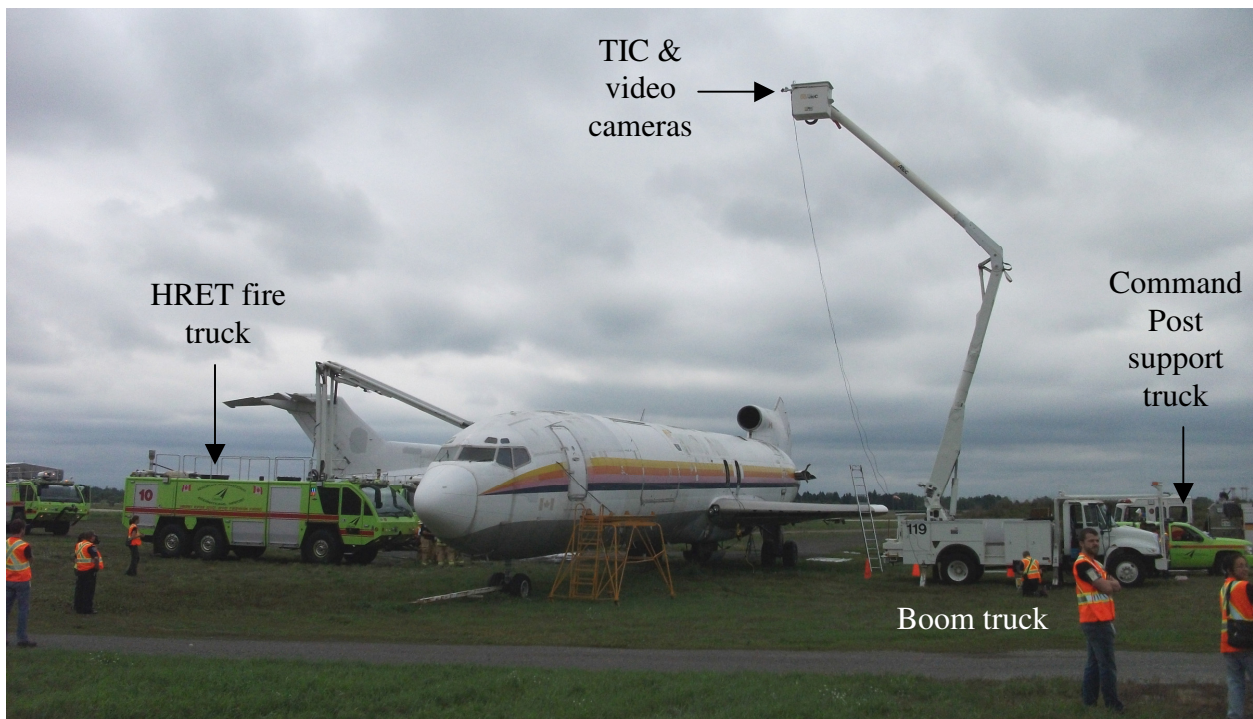


Figure 9: Boom truck positioned on PORT side perpendicular to the Test 1 fire fuel package.

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As shown in Figure 2 the fuel package extended from BS640 to BS720A. Thermocouple trees 1 and 2 were located at BS720B and BS740 respectively (100 inches, 2.5m apart). Exterior thermocouples #11 and #12 were located on the fuel package mid-plane (BS680) at the top of the crown (Stringer 1) and between Stringers 5L and 6L, respectively (60 inches, 1.52m) from tree #1. The thermocouple leads were routed from the interior trees along the floor, out the PORT FWD over-wing emergency exit door and to a vehicle parked beside the boom truck where the temperature data recording laptop computer was situated along with laptops presenting one internal and the overhead TIC views. The thermocouples were connected to a National Instruments Fieldpoint data logger which was powered by a portable generator.

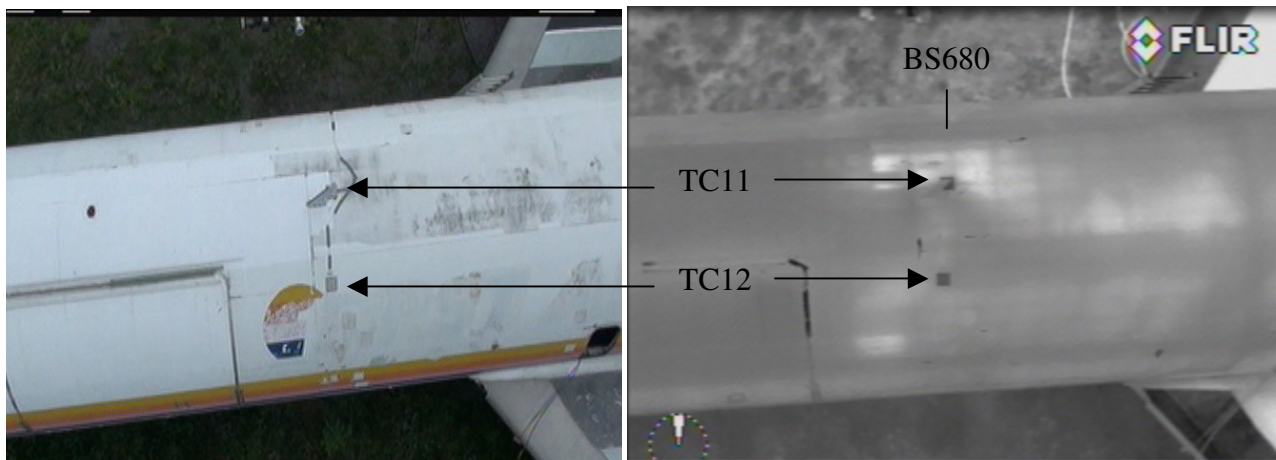


Figure 10: Exterior views from overhead video camera and TIC on boom truck prior to Test 1.

The four other internal video cameras (three looking AFT from the cockpit and one looking FWD from the over-wing exit) either recorded on internal memory cards or were backed up to laptop computers via cable connections. The internal video cameras were housed in sealed protective enclosures. The three cameras at the cockpit bulkhead wall were provided with a battery-operated LED light source shining on the fuel package so that they could establish and maintain auto-focus. The backup video recording laptops were located outside the aircraft in a separate vehicle. An operator using a hand-held video camera patrolled the exterior during the exercise to capture overall and detail views as the fire and extinguishments progressed.

### 2.3 TEST 2 CONFIGURATION – COMPOSITE FIRE

For the composite fire test, rectangular sections of the aluminium skin were cut out between frames at six bays in the crown of the aircraft (BS950A to 970) leaving narrow strips of aluminium skin to attach the replacement composite sheet material (Figure 11). Between the stated body stations the crown aluminium skin was machined to a taper in thickness from 0.060 to 0.050 (1.52 to 1.27 mm).



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The re-skinned crown area was approximately 26ft<sup>2</sup> (2.4m<sup>2</sup>). Half of the area was re-skinned with Glass Laminate Aluminium Reinforced Epoxy (GLARE) sheets and half with carbon fibre reinforced plastic (CFRP) sheets as per Figure 12, Figure 13 and Figure 14. All the composite sheets were unused test specimens from NRC with the exception of CFRP panels 4 and 5 which were harvested from the vertical stabilizer of an A320 and featured co-cured stringers. The GLARE panels were 40 to 42% thinner than the original skin they replaced except for panel 3A which was 35% thicker. The CFRP panels were either equal in thickness or, at a maximum 15% thinner than the aluminium they replaced. The composite panels were mechanically fastened to the aircraft exterior along what remained of the aluminium skin directly above the circumferential frames. External doublers of the same composite materials were added to the circumferential butt joints between the composite panels.

One-inch thick fibrous refractory ceramic insulation was installed inside the aircraft between the stringers in a perimeter around the composite panels to mitigate burn-through of the aluminium supporting the composites. The insulating material was held in place by 0.050 inch (50mm) thick sheets of fibreglass panel, salvaged from the original cargo liner, which were tucked under the stringer flanges (Figure 14).

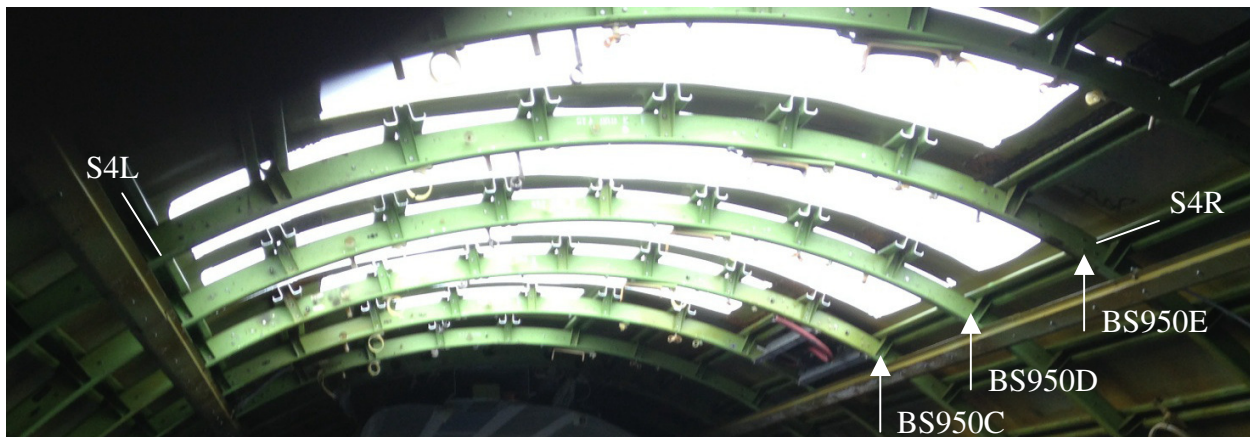


Figure 11: Skin sections and stringers removed.

The replacement panels were attached with steel bolts and nuts at the corners and steel pop rivets elsewhere. Fastener spacing was nominally 1.5 inches (3.8cm). The CFRP panels were not flat on the inner side due to various ply drop-offs which resulted in gaps when mated to the remaining aluminium skin. To seal these areas, long gaps were filled with intumescent tape and small gaps with applications of muffler cement.

The composites fire test fuel package extended from BS950A to BS970. Thermocouple trees 1 and 2 were located at BS950A and BS870 respectively (100 inches, 2.54 meters apart) as shown in Figure

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3. Exterior thermocouples 11 and 12 were located on the fuel package mid-plane (BS950D) at S1, top of the crown, and between stringers 5L and 6L, respectively. Each was covered with a pad of rigid insulation to avoid solar heating effects. TC#11 was located on top of CFRP panel 4B which lapped over the joint with GLARE panels 3 and the original aluminium skin at the crown. This configuration, with three layers of dissimilar materials under TC#11 may have insulated it or otherwise affected its sensitivity to the internal temperatures. As in Test 1, TC#11 was located on the aluminium skin between S5&6L.

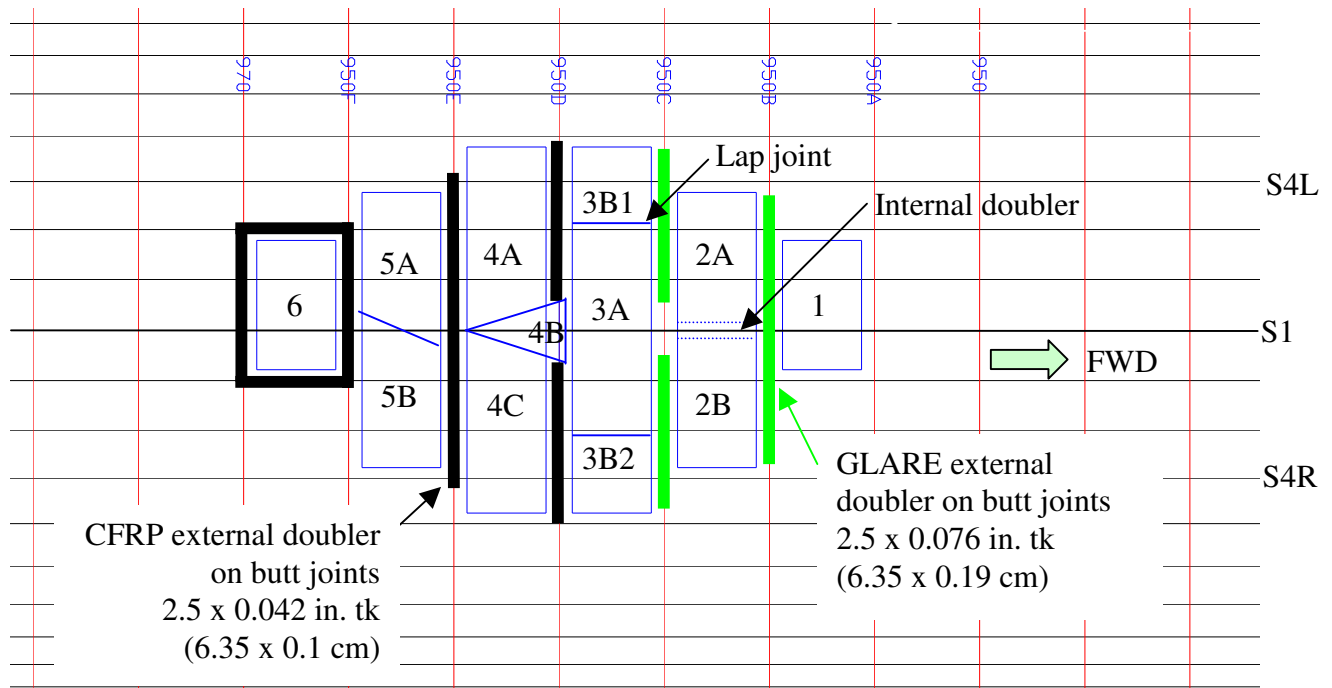


Figure 12: Schematic of replacement skin panels and external doublers.

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Table 1: Test 2 replacement skin panel materials and dimensions.

Panel	Material	Dimensions	Source	Details/Markings
1	GLARE <sup>1</sup>	19 x 24 x 0.034 in. 48.3 x 61 x 0.08 cm	NRC specimen	Exterior painted white
2A	GLARE <sup>1</sup>	19 x 28 x 0.034 in 48.3 x 71.1 x 0.08 cm	NRC specimen	Exterior painted white
2B	GLARE <sup>1</sup>	20 x 25 x 0.034 in 50.8 x 63.5 x 0.08 cm	NRC specimen	Exterior painted white
3A	GLARE <sup>2</sup>	20 x 48 x 0.076 in 50.8 x 121.9 x 0.19 cm	NRC specimen	Exterior not painted white
3B1	GLARE <sup>1</sup>	20 x 18 x 0.034 in 50.8 x 45.7 x 0.08 cm	NRC specimen	Exterior not painted white
3B2	GLARE <sup>1</sup>	20 x 18 x 0.034 in 50.8 x 45.7 x 0.08 cm	NRC specimen	Exterior painted white
4A+C	CFRP	20 x 74 x 0.042 in 50.8 x 187.9 x 0.10 cm	A320 V-stab	Painted blue. I-beam stringers
5A+B	CFRP	20 x 54 x 0.050 in 50.8 x 137.1 x 0.127 cm	A320 V-stab	Painted blue. I-beam stringers
6	CFRP	20 x 24 x 0.055 in 50.8 x 60.9 x 0.14 cm	NRC specimen	Not painted. Hat stringers

1 – 3 PLY: 2 face plies of 0.013” (0.33mm) aluminium. Core ply of 0.008” (0.2 mm) bi-axial glass fibres.

2 – 7 PLY: 4 plies of 0.013” (0.33mm) aluminium. 3 plies of 0.008” (0.2 mm) bi-axial glass fibres.

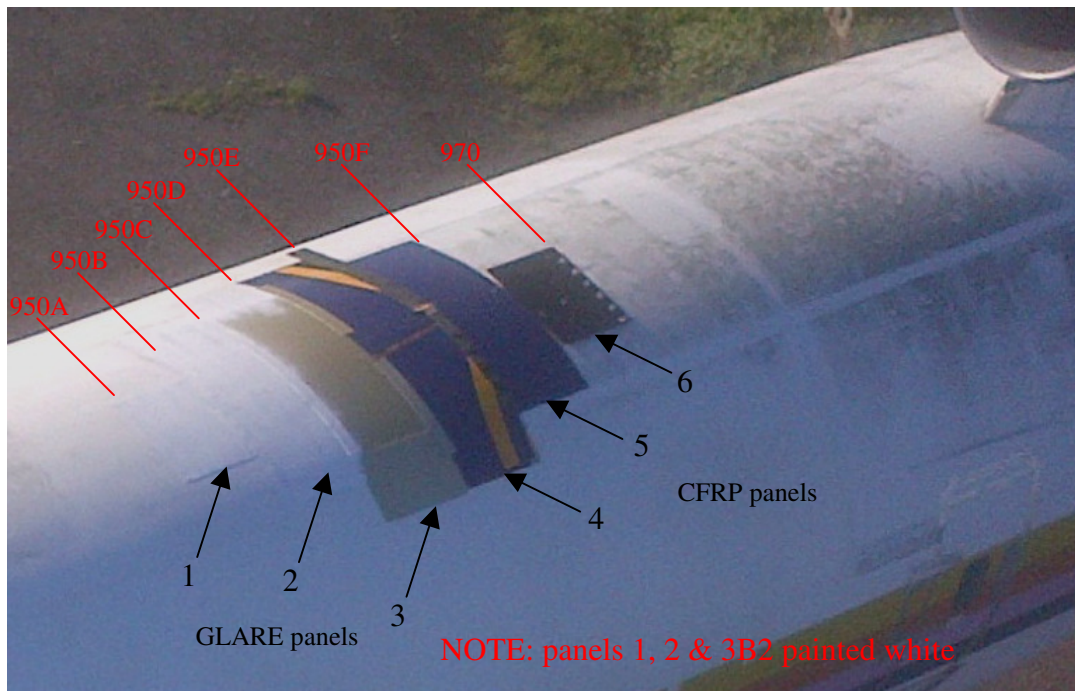


Figure 13: Exterior view of completed composite skin section.

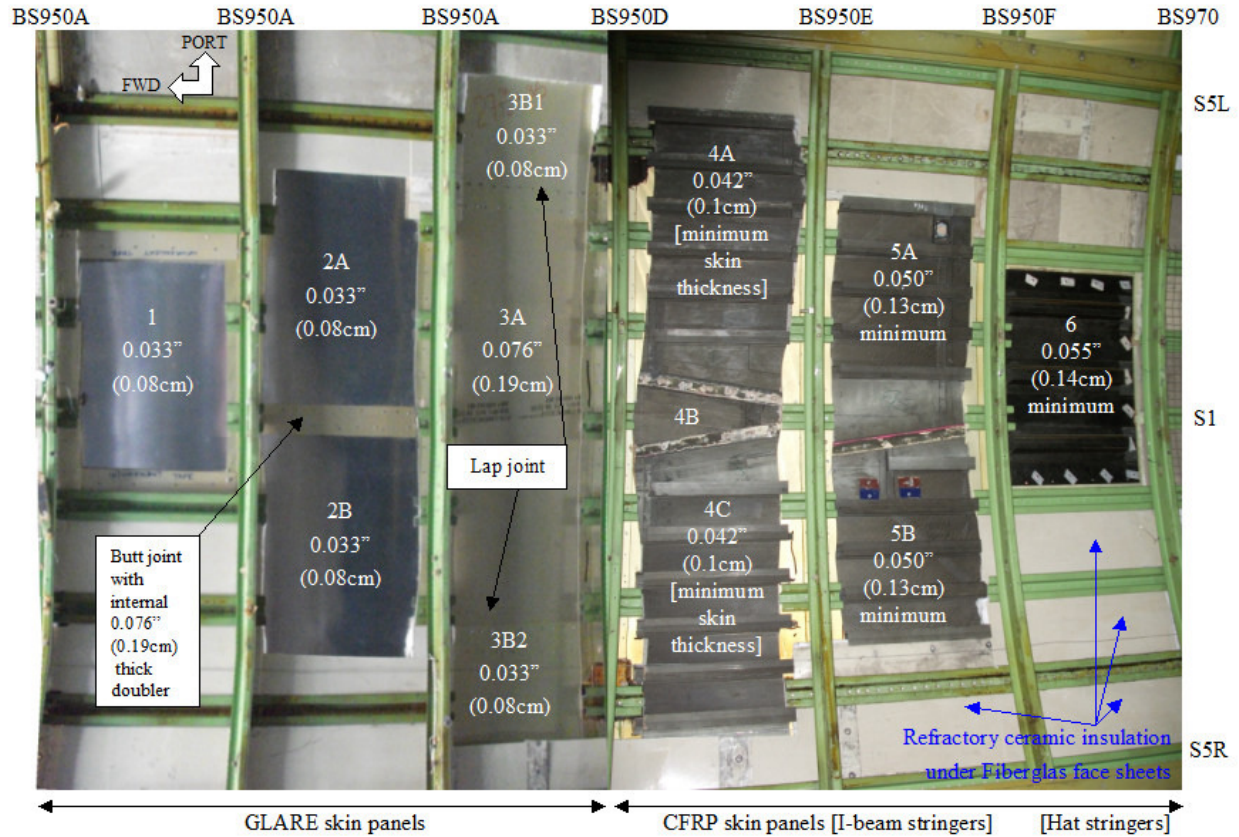
**Full-Scale Aircraft Fire Tests—A Comparison of Aluminium and Composite Burn-Through**

Figure 14: Interior view of Test 2 composite skin panels.

### **3.0 TEST 1 EXECUTION – ALUMINIUM BASELINE**

The baseline fire, Test 1, against the original aluminium structure, required flame penetration of the crown skin to demonstrate the impact of venting on smoke levels and temperatures within the fuselage. The baseline fire test fuselage penetration needed to be smaller than the re-skinned area of the composite fire test to ensure that Test 2 did not fail because of aluminium skin penetration outside of the re-skinned area. The test plan was to allow the baseline fire to burn until crown penetration occurred, measure the venting effect for a short period via the thermocouple data and qualitative smoke observations, and then immediately suppress and extinguish the fire.

#### **3.1 FIREFIGHTING TACTICS – TEST 1**

On August 22<sup>nd</sup> 2014, firefighting operations took place to control and extinguish the fire that was located in the forward cabin section of the Boeing 727. A safety briefing was conducted beforehand. The briefing included the following topics: command and control, role of safety officer, radio communications, vehicle positioning, tactics, escape routes, accountability, rehabilitation, scene dangers, no-go zones, medical provisions, rapid intervention team and provisions to respond to concomitant emergencies.

The location of the command post was at the nose of the aircraft due to wind conditions. The incident commander had access to video feeds from inside the airframe. The video screens were located 62.8 feet (20 meters) away from the command post. The City of Ottawa Fire Services graciously offered their assistance and provided a safety officer and a pumper with a crew of four firefighters. The safety officer was roaming the scene during the event.

Radio Communication channels were pre-assigned. Various agencies (Control Tower, Airport Media Officer, Security officers, etc.) were notified in advance.

The firefighting force included one chief officer, three captains, nine fire fighters and one safety officer.

A Rosenbauer Panther, call-sign “Red 10” and equipped with a 55 foot (17.5 meter) HRET and a water tank capacity of 3,000 US gallons (11,356 litres) was pre-positioned upwind on the starboard side of the B727-200, forward of the wing (Figure 15).



**Full-Scale Aircraft Fire Tests—A Comparison of Aluminium and Composite Burn-Through**

Figure 15. Initial firefighting was performed from the STBD side.

A walk-through inside the fuselage prior to the fire test was conducted to provide situational awareness to the firefighters. Fire crews were advised that no interior firefighting would take place. Firefighting activities began after fuselage crown burn-through was confirmed.

### 3.2 OVERHAUL

The HRET was pre-deployed in order to initiate a fuselage piercing. The HRET Stinger is equipped with a chisel-style tip with a flow capacity of 238 gpm at 196 psi (900 lpm at 13.5 bar). The Stinger pierced the fuselage through a cabin window and introduced roughly 210 US gallons (795 litres) of foam AFFF (Aqueous Film Forming Foam at 3%) in 53 seconds beginning 7 minutes after the start of the fire.

Both wings were laddered to allow airport & city of Ottawa firefighters (OFS) to gain access to the fire through the over-wing exits. Once the “one minute” HRET operation was completed, two airport firefighters were tasked to introduce a water stream via the right over-wing exit using a CAFS (Compressed Air Foam System) hose line for one minute. This hose line discharges 60 US gallons (227 litres) per minute and it was in operation for 32 seconds. The entire forward section of the cabin was blanketed by compressed air foam (AFFF – DC 3 – 3 %), Figure 21.

## Full-Scale Aircraft Fire Tests—A Comparison of Aluminium and Composite Burn-Through

The interior conditions were re-evaluated. No flames were visible but the level of heat & smoke remained elevated. A second application of the one inch CAFS line was ordered which lasted 1:08. The total CAFS application introduced approximately 101 US gallons (382 litres).

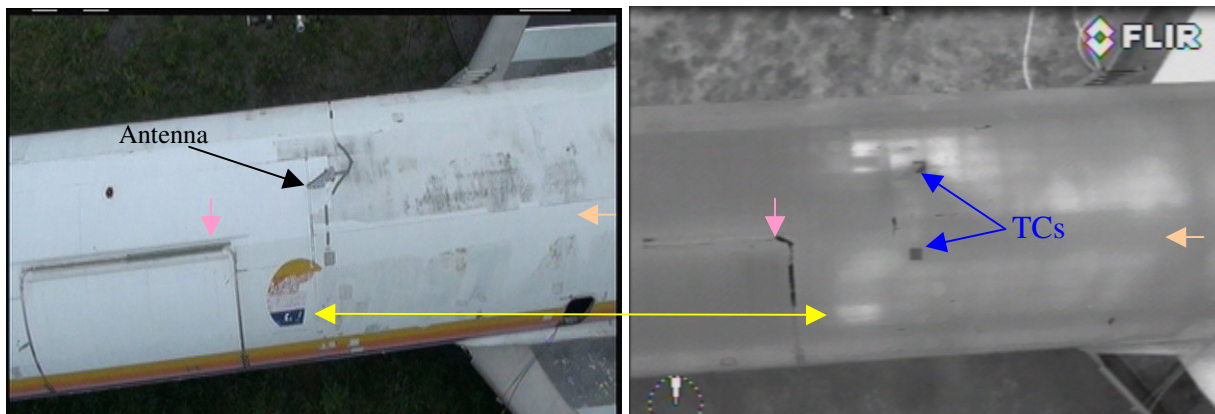
Two OFS firefighters deployed a line on the left wing. The line was a 1.5 inch (3.8cm) line with a TFT Flip Tip nozzle, which flowed at 150 gpm at 50 psi (568 lpm at 3.4 bar). That hose line was used to effect final extinguishment and cooling of the cabin environment and flowed in two actions for a total of 65 seconds.

A final pierce was completed by the HRET Stinger and a water flow was introduced for 57 seconds.

A total of approximately 700 US gallons (2,649 litres) of firefighting agent were used to control, extinguish and cool the cabin.

### 3.3 IMAGE AND TEMPERATURE DATA – TEST 1

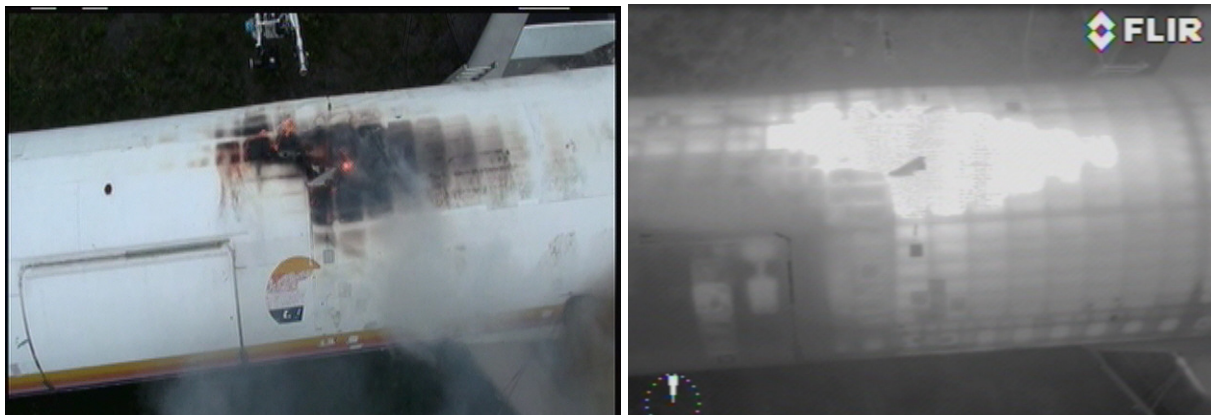
Figure 16 shows pairings of stills from the overhead video and TIC views starting before the fire until the crown has burned through.



a) Video and Thermal camera images of fuselage crown prior to test. Note solar heating and differences in paint and metal tape emissivity (arrows). TCs #11 & #12 were each covered by a ceramic insulation block held in place with duct tape which are more noticeable in the TIC view.

**Full-Scale Aircraft Fire Tests—A Comparison of Aluminium and Composite Burn-Through**

b) First exterior indication of fire (arrow) is in the region of solar heating.



c) First flames visible at beginning of fuselage crown burn-through.



d) Just prior to first extinguishment with Stinger. Area of crown with TC#11 attached has melted.

Figure 16. Overhead camera views of the progress of the fire.

The HRET fire truck TIC camera side-view is shown in Figure 17 before the fire. The Stinger hydraulic hoses and black-painted HRET water supply pipe appear white but they are not hot. The cause is the different in surface emissivity.



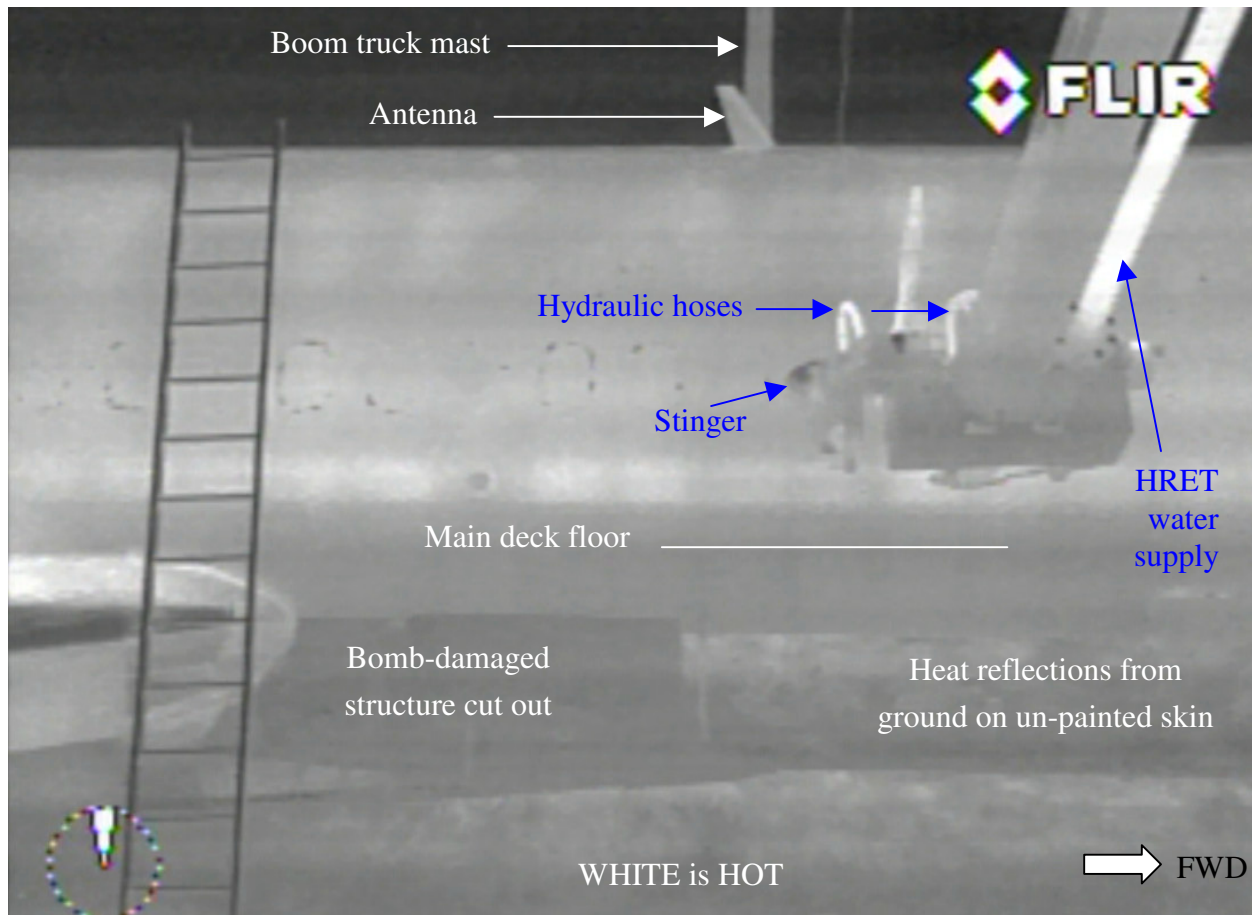
**Full-Scale Aircraft Fire Tests—A Comparison of Aluminium and Composite Burn-Through**

Figure 17. Red 10 TIC side-view of STBD side prior to Test 1.

The following stills, Figure 18, from the Red 10 TIC video are noisy with interference lines scrolling vertically that affect the still images making it difficult to discern the substructure. Live or when the video is re-played, this interference is less pronounced.

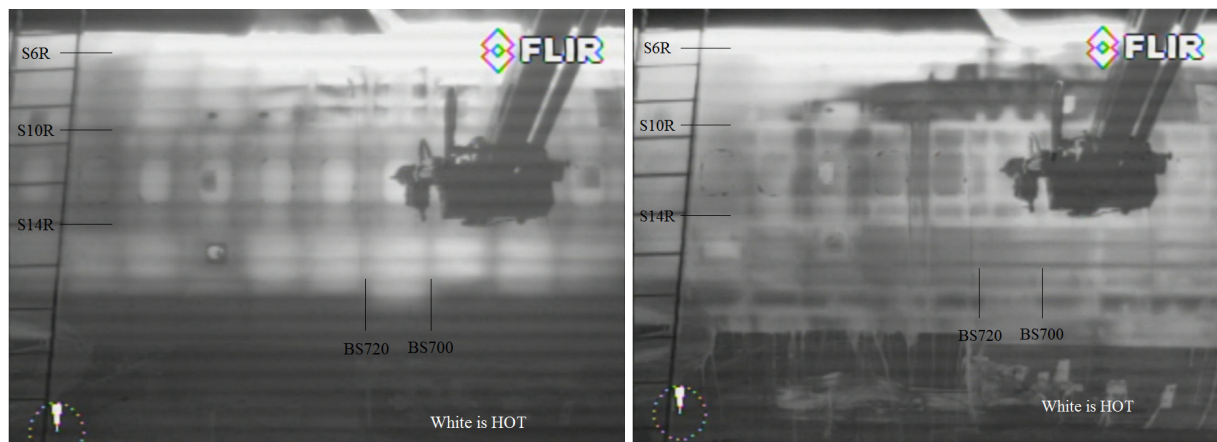


Figure 18. Red 10 TIC views at the beginning and end of the first Stinger extinguishment.

**Full-Scale Aircraft Fire Tests—A Comparison of Aluminium and Composite Burn-Through**

The first extinguishment with the HRET Stinger at 6:57 affected the outer skin of the aircraft as shown in the Red 10 TIC views, Figure 18. By the end of the extinguishment (7:55) water has cooled an area from just above S8R and down to the main deck floor. Heated water can be seen draining from the aircraft. The area cooled by the Stinger will be discussed further in Test 2.

The second HRET Stinger application at 16:27 was higher on the fuselage side and lasted for 57 seconds, Figure 19. A larger area was seen to be cooled but note that a hot spot remains.

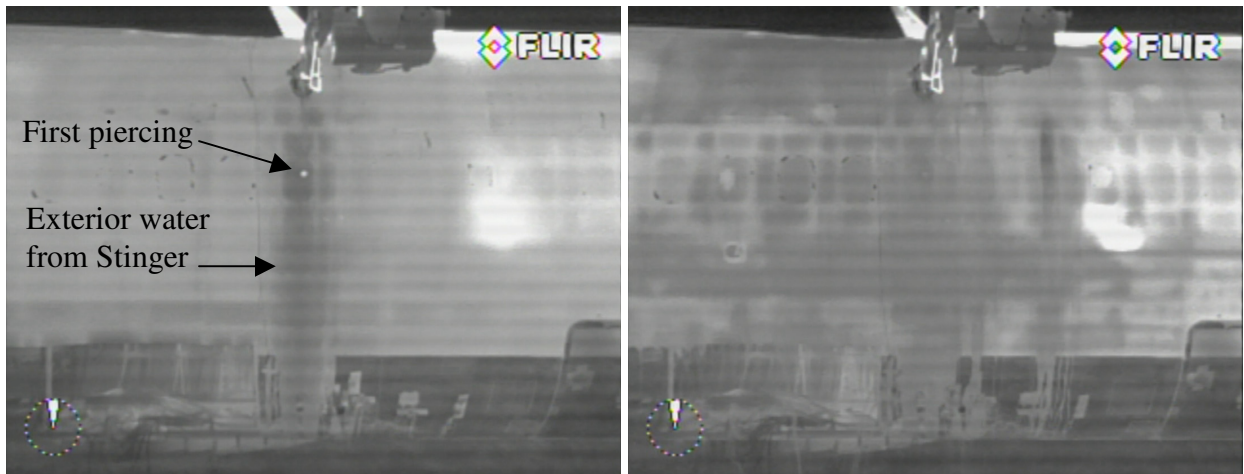


Figure 19. Red 10 TIC views just before and after second Stinger extinguishment.

Figure 20 shows the interior view of the lower STBD side post-test including, Stinger piercings and clearly shows the lack of heat/soot damage at the seat of the fire. There is little heat damage below S6 or sooting below S8 on either side. The figure partially illustrates the unburnt fuel (paper) remaining.

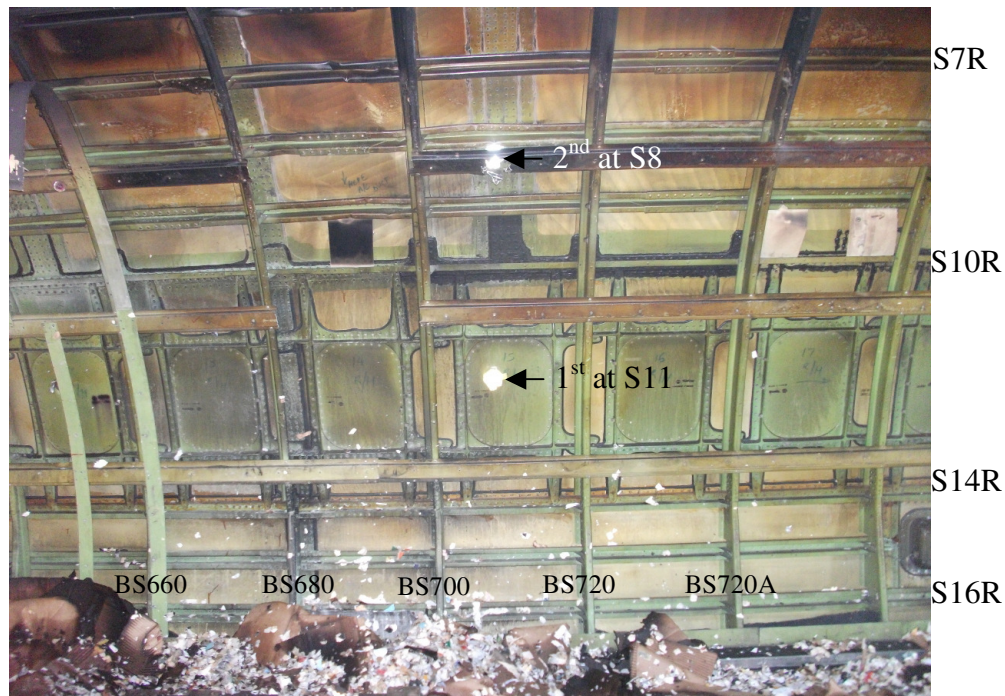
**Full-Scale Aircraft Fire Tests—A Comparison of Aluminium and Composite Burn-Through**

Figure 20. Interior view of lower STBD side.

Images of the main deck after the CAFS applications, second Stinger and hand-line work show a blanket of foam remaining and the un-burnt pile of boxes which was reported to be 18-inches deep (45.7 cm) when firefighters entered the zone, Figure 21.



a) Looking AFT

b) Looking FWD (Salvage tarp lowered)

Figure 21. Post-Test 1 overhaul. Foam and remains of fuel load.

The temperature data from the 12 TCs were collected at one second intervals. The data for Test 1 is presented graphically in Figure 22. Note that according to Matweb.com, the reported melting point of 2024 T3 aluminium ranges from 935-1180°F (502-638°C) and for 7075 T6 aluminium ranges from 890-1175°F (477-635°C).



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**Full-Scale Aircraft Fire Tests—A Comparison of Aluminium and Composite Burn-Through**

From analysis of the overhead video there is a 39 second period following the crown first being breached by fire before the first Stinger extinguishment starts. TC#11 fell into the top of the fuselage during those 39 seconds when the crown melted away. TC#1 and #2 at the top of thermocouple tree #1 read above 650°C (1200°F) a minute before TC#11 reached this temperature and this was after it had fallen into the fire when its readings drop dramatically and then recovered rapidly. Some of the TC#11 wire insulation was found to be burned off leaving the two wire conductors exposed. These wires may have come in contact during or after their fall into the fuselage affecting the data during this period.

Other than TC#1, all of the other upper level thermocouple readings declined between the start of the crown burn-through until the start of the first HRET Stinger extinguishment. TC#2 had the most rapid temperature decrease, dropping 570°F (300°C). TC#6, at the top of thermocouple tree #2 and 160 inches (4.6 m) away from the crown breach, dropped 188°F (87°C) in the same period. This is evidence of the heat released by vertical ventilation as a result of the crown burn-through. All of the temperature readings fall soon after the first Stinger extinguishment starts.

# Full-Scale Aircraft Fire Tests—A Comparison of Aluminium and Composite Burn-Through

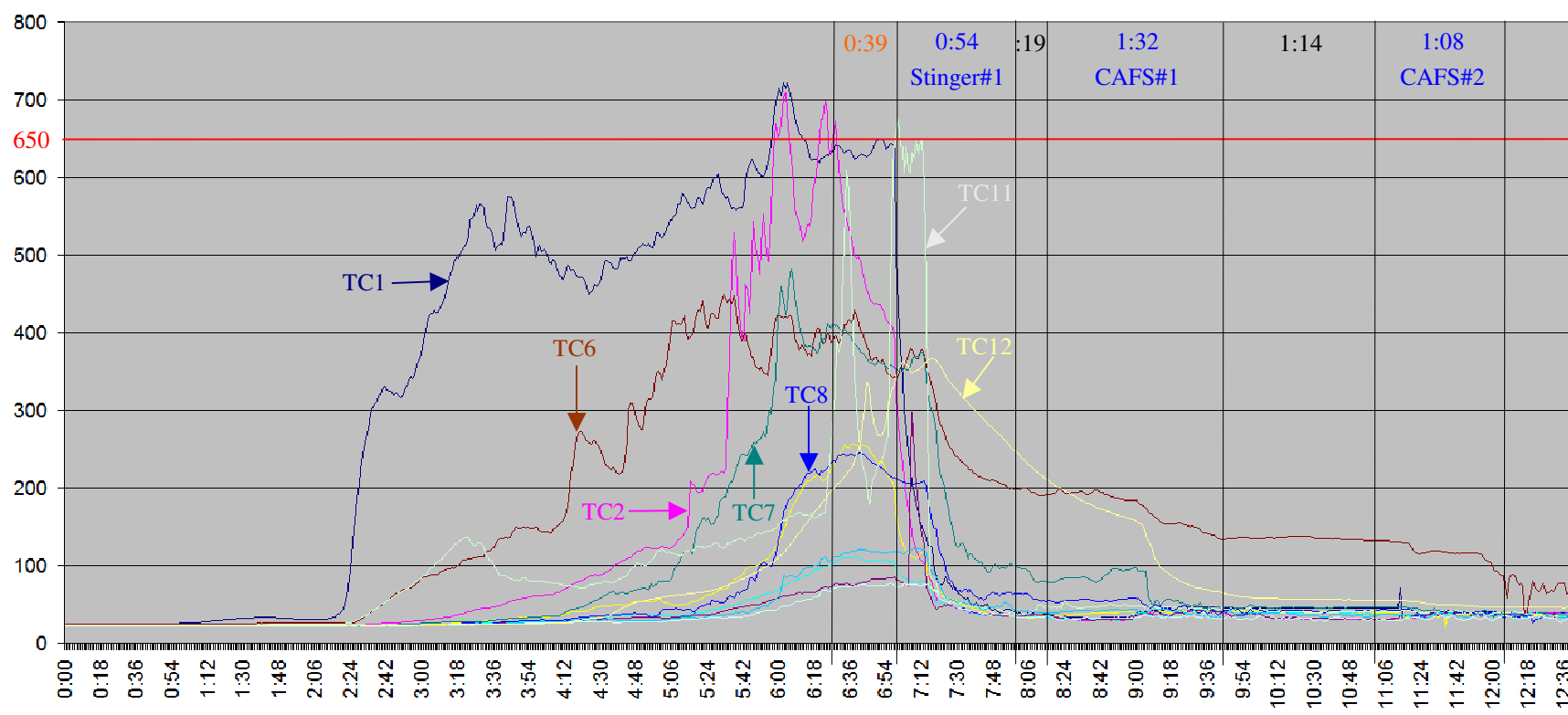


Figure 22. Thermocouple data (°C) for Test 1 with initial extinguishments annotated.

**Full-Scale Aircraft Fire Tests—A Comparison of Aluminium and Composite Burn-Through****3.4 OBSERVATIONS – TEST 1**

The time between fire start and first extinguishment was 6 minutes and 57 seconds. This established the target burn duration for the Test 2 fire as a minimum of seven minutes from first visible smoke.

Analysis of the audio and video from the baseline fire, Test 1, results in the following timeline of events.

00:00 Audible pop of Li battery fire-starter.	73 seconds between CAFS#1 and CAFS#2.
00:09 First smoke FWD side of fuel stack.	10:59 Start CAFS#2.
00:13 First smoke AFT side of fuel stack.	12:08.12 End CAFS#2 <b>Duration:</b> 1:08. 68 US Gal (257L)
02:11 First visible flames at top of stack by FWD camera.	97 seconds between CAFS#2 and OFS#1.
02:27 First audible skin buckle and exterior paint seen to blacken.	13:45 Start OFS#1 water application from PORT over-wing exit doorway.
06:21 Flames first seen through crown skin.	14:27 End OFS#1 water. <b>Duration:</b> 37 sec. 92.5 US Gal (350L)
06:53 Stinger pierce through cabin side-window.	34 seconds between OFS#1 and OFS#2.
06:57 Stinger - First flow of water (low pressure).	15:02 Start OFS#2 water.
07:00 Start Full pressure Stinger water flow.	15:29 End OFS#2 water. <b>Duration:</b> 27 sec. 67.5 US Gal (255L)
07:08 Last visible flames from overhead camera.	59 seconds between OFS#2 and Stinger#2.
07:54 End full pressure Stinger flow. <b>Duration:</b> 0:53. 210 US Gallons (795L)	16:21 Stinger 2 <sup>nd</sup> pierce through STR4R.
18.9 sec between Stinger end and hand-line CAFS #1 start.	16:27 Start Stinger#2 water flow.
08:13 Start CAFS#1 from STBD over-wing exit doorway.	17:24 End Stinger#2 water flow. <b>Duration:</b> 57 sec. 226 US Gal (855L)
09:45.26 End CAFS#1. <b>Duration:</b> 32 sec. 32 US Gal (121L)	Approximately 700 US Gal (2649L) of agent applied.

From the pop of the fire-starter to the end of the second Stinger application was 17 minutes 24 seconds.

Smoke was first seen only 9 seconds after the fire-starter popped.

The first firefighting attack was carried out 6 minutes and 57 seconds after the fire started.

The two separate Stinger applications totalled 111 seconds. The two sequential CAFS applications totalled 101 seconds with 73 seconds between them. The two sequential OFS hand-line water applications totalled 65 seconds with 34 seconds between applications.

The extent of the burn-through is illustrated in Figure 23 which is a collage of images. The crown breach extends as a narrow split for 58 inches (1.47m) from BS640 to 700 where it widens to a maximum of 22 inches (0.55m) between S2L and S3R and is 104 inches (2.64m) long overall. From this the composite re-skinned area for Test 2, at 120 inches long (3m), was deemed appropriate. The frames at BS680 through 720B have been burned away to a maximum of S5R and S4L. There are a

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**Full-Scale Aircraft Fire Tests—A Comparison of Aluminium and Composite Burn-Through**

number of splits in the skin outside the burn-through area (between BS700 and 720 on the PORT side) where flames had been observed from the outside. No evidence of molten aluminium was found on the main deck floor. A few examples of small stalactites of molten material were observed hanging at the end of burned frames, otherwise the missing structural material is assumed to have been vaporized. The largest skin buckles were between BS660 and 700 on the PORT side. Stringers S1 and S2L between BS700 and 720B were partially or completely burned away. Adjacent stringers were partially melted.

# Full-Scale Aircraft Fire Tests—A Comparison of Aluminium and Composite Burn-Through

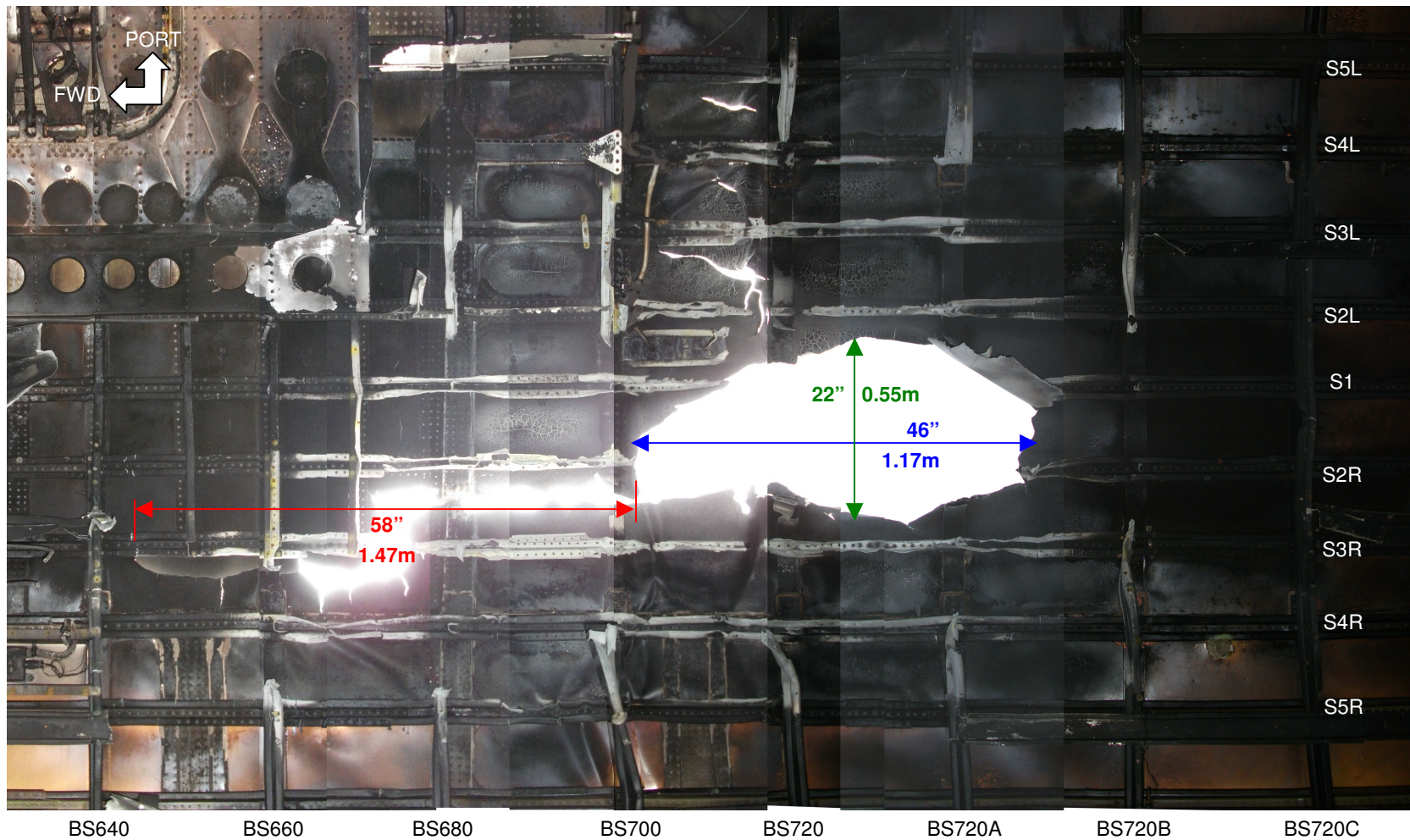
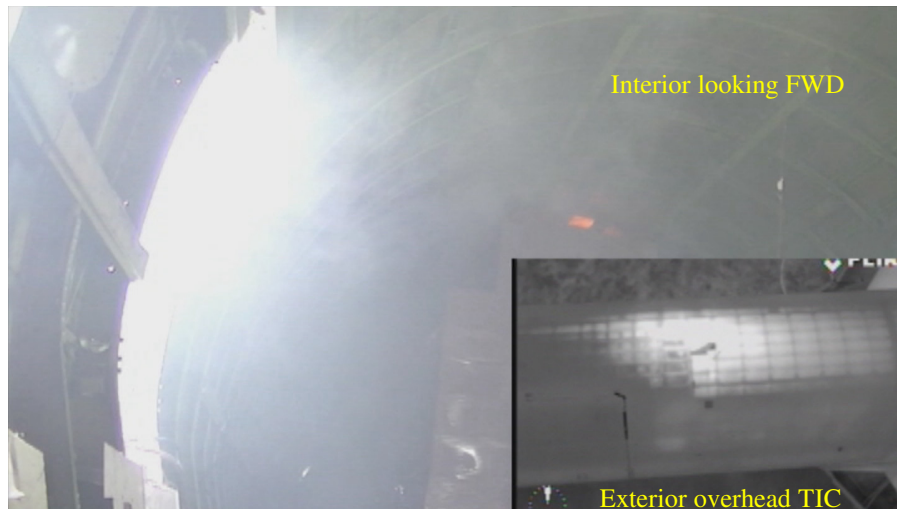


Figure 23: Test 1 fuselage crown, post-test damage.

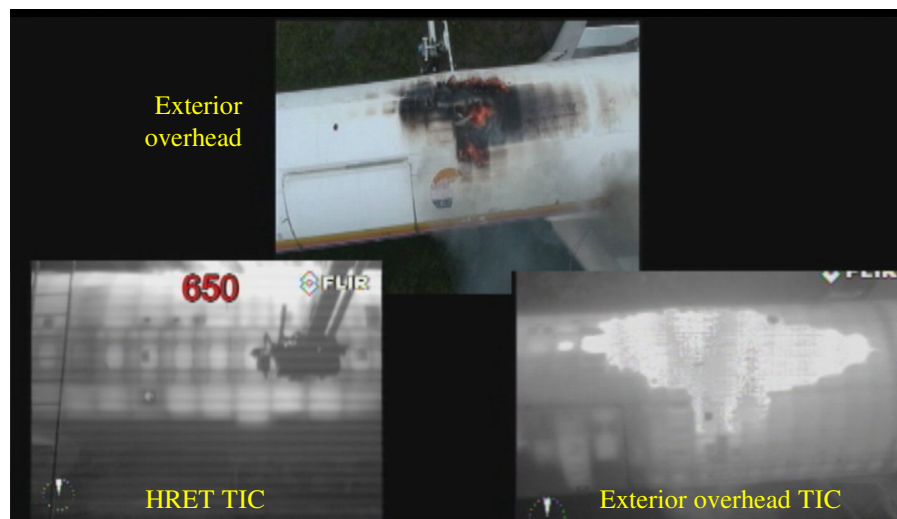


**Full-Scale Aircraft Fire Tests—A Comparison of Aluminium and Composite Burn-Through****3.5 TEST 1 COMPOSITE VIDEO**

The collected video and TIC views were edited into a composite of picture-in-picture views using Pinnacle Studio HD Version 15.0 software to create a summary of the progress of the fire and the extinguishments. Initially, the forward looking camera on the main deck provided an interior view of the start of the fire and movement of the smoke while the exterior overhead TIC view was inset in the bottom RH corner. At approximately 2:30 the interior view was completely obscured by smoke and so the overhead camera and Red 10 TIC views were substituted. Thermocouple readings for TC#1 (at the top of the tree #1 and closest to the crown on the interior) were displayed at 30 second intervals. The layout of the camera views are illustrated in screen shots taken from the composite video, Figure 24.



a) 90 seconds after fire start



b) 8 seconds before first extinguishment, 6:52 after fire start

Figure 24: Screen shots from Test 1 composite video.

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**Full-Scale Aircraft Fire Tests—A Comparison of Aluminium and Composite Burn-Through**

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## **4.0 TEST 2 EXECUTION – COMPOSITE**

The time to the burn-through of the crown in the Test 1 baseline fire, which was approximately 7 minutes from start to first extinguishment, provided guidance on a time limit for the Test 2 composite fire. The Test 2 plan was to allow the fire to burn for at least as long as the Test 1 fire and then decide when to put it out based on temperature observations or crown burn-through.

### **4.1 FIREFIGHTING TACTICS – TEST 2**

On September 9, 2014, firefighting operations took place to control and extinguish the fire that was located in the rear cabin section of the Boeing 727. As in Test 1 a safety briefing was conducted beforehand. The briefing was expanded and included the following topics: command and control, role of safety officer, radio communications, vehicle positioning, tactics, escape routes, accountability, rehabilitation, scene dangers, no-go zones, medical provisions, rapid intervention team and provisions to respond to concomitant emergencies and incorporated the lessons observed from the previous fire. Also, due to the presence of carbon fibres in the fuel load, air sampling, decontamination and containment procedures were presented.

The location of the command post was at the rear of the aircraft due to wind conditions and the incident commander had access to video feeds from above and inside the airframe.

A second OIAA ERS fire truck, Red 9, was positioned on the PORT side of the aircraft (out of view in Figure 25) to provide an overall side-view with its TIC.

The City of Ottawa Fire Services again offered their assistance and provided a safety officer, a pumper with a crew of four firefighters and a ladder truck. The safety officer was roaming the scene during the event.

Radio Communication channels were pre-assigned. As before, local agencies were notified in advance.

The firefighting force increased for Test 2 to included one chief officer, four captains, fourteen firefighters, one hazmat officer and one safety officer.

As in Test 1, Red 10 was pre-positioned upwind on the starboard side of the airframe to initiate a fuselage piercing. Red 9 was positioned to provide an overall view of the PORT side with its TIC.

**Full-Scale Aircraft Fire Tests—A Comparison of Aluminium and Composite Burn-Through**

Figure 25. Test 2 Command post, boom truck, Red 10 and PyroLance on STBD wing.

PyroLance® is a ultra-high pressure tool that cuts through walls, roofs, floors and other barriers to attack the hot gases and the fuel source of a fire and cool temperatures rapidly. The PyroLance hose reel length was 200 feet (63.7 meters). The PyroLance equipment trailer was staged behind Red 10 as shown in Figure 26.

Due to the presence of composite materials all equipment and firefighters were positioned upwind. Uncommitted resources and observers inside the security perimeter were staged 200 feet (61m) away from the fuselage. Onlookers outside the perimeter fence were directed to a location well away and upwind.

Firefighting activities began after 7:49 had elapsed from the start of the fire based on monitoring of the real time display of the thermocouple data.

**Full-Scale Aircraft Fire Tests—A Comparison of Aluminium and Composite Burn-Through**

Figure 26. Red 10 and PyroLance equipment trailer staged in preparation for Test 2.

## 4.2 OVERHAUL

The Sept 9th Composites fire timeline was derived from a review of the audio track of the camera mounted on the main deck floor at the PORT FWD over-wing exit.

The Stinger was applied for 1:06 [1 min 6 sec] and started 7:49 after smoke was first observed at the top of the stack.

The HRET Stinger pierced the fuselage through a cabin window blank at nominally S12R between BS680 and 700 and introduced 261 US gallons (988 l) of foam AFFF at 3% in 1:06.

The upwind STBD wing had been laddered to allow airport firefighters to gain access to the fire using the wing as an elevated platform. Two firefighters using the PyroLance tool pierced the fuselage and introduced class A foam at 1% induction rate with 10 gpm at 1500 psi (37.9 lpm at 103.4 bar) for 1:06. There were only 18 seconds between the end of the Stinger application and the beginning of PyroLance. The tool slipped and agent was introduced into the fuselage for only 41 seconds during this period. The difference between PyroLance beating on the skin and when water is flowing into the cabin can be discerned in the audio. After 5-6 seconds the PyroLance had pierced the skin. Water flows for 41 seconds before the operator slips and although the system is in operation for another 0:25 (total of 1:06) the effective firefighting is really confined to that first 41 seconds. Approximately 6.8 US gallons (25.7 l) of agent was dispensed.



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**Full-Scale Aircraft Fire Tests—A Comparison of Aluminium and Composite Burn-Through**

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Two airport firefighters were then tasked to introduce a water stream via the right over wing exit using a TFT Flip Tip 1.5 inch (3.8cm) nozzle. This hose line discharged at 150 gpm at 50 psi (568 lpm at 3.4 bar). The over-wing hand-line application started 1:45 after the end of PyroLance (or 4:15 after first firefighting with Stinger). The water flow was not continuous (4 sessions: the first being the longest at 1:09, the rest were just seconds each) and totalled 2:08 in the 3:41 duration of this operation delivering 320 US gallons (1211 litres).

Two firefighters gained entry into the cabin by using the rear air-stairs with a 1.75 inch (4.44cm) hose line equipped with the TFT Flip Tip. This line flowed 100 US gpm at 100 psi (378.5 lpm at 6.89 bar).

Upon entry, visibility was less than a foot (0.3m). The integrity of the floor was not compromised. Unburnt shredded paper and cardboard boxes were mixed with smouldering combustibles and had to be spread apart to effect complete extinguishment. Hydraulic ventilation was conducted to improve interior cabin visibility as well. The rear air-stair mounted attack was started 9:54 after firefighting started and 1:58 after the over-wing hand-line effort. Water was applied 9 times (the two longest were 0:45 and 0:38). Water was applied for a total of 2:57 in this 9:27 operation and totalled some 295 US gallons (1,117L).

A total of 27 minutes and 10 seconds elapsed from the start the fire to the end of the overhaul water applications. Water was applied (at various rates) for a total of 10:25. The entire overhaul involved approximately 884 US gallons (3,345 litres) of firefighting agent.

The city of Ottawa Fire Services provided a Carl Thibault Spartan Pumper equipped with a 575 US gallon (2,177 litre) water tank and 1,250 gpm (4731 lpm) pumping capacity. The backup line deployed was a 1.5 inch (3.81cm) line with a TFT Metro 1 nozzle, which flows at 200 US gpm at 75 psi (757 lpm at 5.17 bar). On the day of the test this line was used to decontaminate the firefighters that were exposed to the carbon fibres. Upon exiting, again via the rear air-stairs, both firefighters were decontaminated and their turn-out gear sent to a specialized cleaning facility.

The following day, the interior air quality of the cabin was evaluated. A four-gas detector was used and no abnormal readings for carbon monoxide or hydrogen sulphide were found and an explosive atmosphere was not present. The particulate concentration however was ranging from 0.002 mg/m<sup>3</sup> to 1.023 mg/m<sup>3</sup> depending on location in the fuselage as measured with the same DataRAM that had been mounted on the robot. Detailed discussion of particulate sampling is available in Appendix III.

A fixant, an acrylic-based floor sealer mixed with water, was applied with a hand-pumped sprayer to the inside cabin floors, ceiling and walls to immobilize the carbon fibres.

**Full-Scale Aircraft Fire Tests—A Comparison of Aluminium and Composite Burn-Through****4.3 IMAGE AND TEMPERATURE DATA – TEST 2**

The field of view of the two overhead cameras on the boom truck was checked prior to the start of the fire by raising the boom. The field of view was acceptable and both cameras operated properly. Unfortunately it was not discovered until after the test that the video camera had not been turned on before the boom was raised for the actual test. During the course of the test the overhead TIC camera (which does not have internal memory) was successfully relaying images of the fire as was observed on the laptop display at the command post. At the end of testing this laptop listed two very large data files (exceeding 2 Gigabytes each) but the software would not close the first file thus the first part of the overhead TIC video was lost. The video that was collected begins at 11:44 from the start of the fire which is after the Stinger and PyroLance extinguishments and just before the hand-line attack began.

The PyroLance piercing is shown in Figure 27 with a view after the fuselage has been pierced and while agent is being delivered inside the fuselage. The exterior and interior surfaces of the two-ply aluminium window blank are shown post-test. The upper and larger hole was the first piercing and agent flowed through this hole for 41 seconds. The exterior view also shows the track after the operator slipped and the operator triggered for abrasive media to try and pierce through again. The panel was pierced a second time at the very end of the action but no significant amount of agent was delivered through this hole.

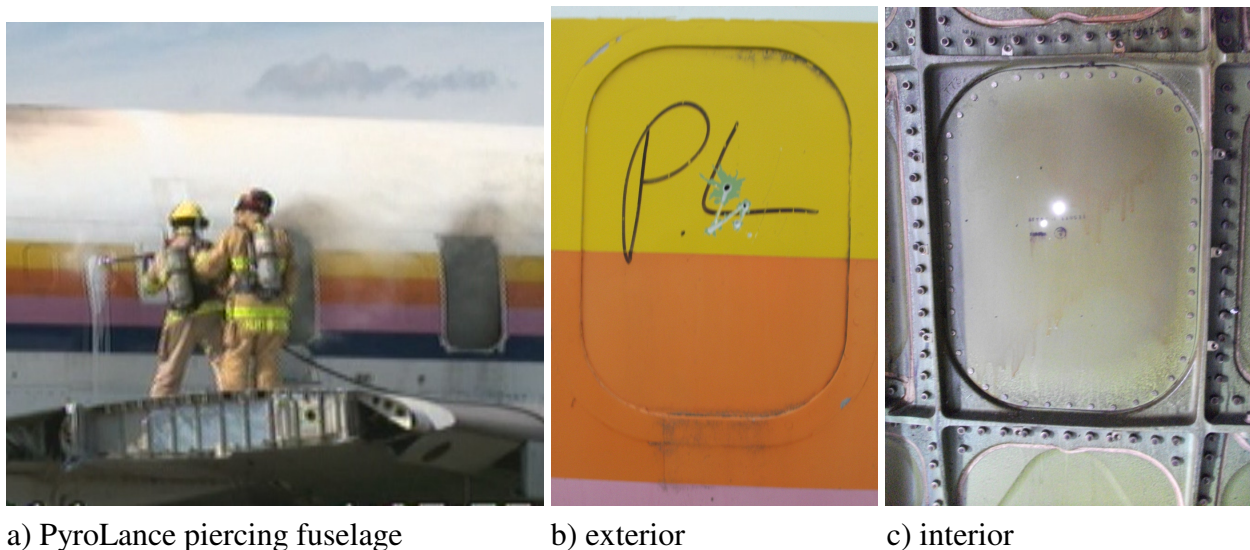


Figure 27. PyroLance piercing fuselage, Test 2.

The exterior condition of the entire composite area after the fire is shown in Figure 28. The GLARE panels are deformed and discoloured with most of the white paint burned off. The outer aluminium surfaces appear to remain largely intact. Most of the paint has burned off the CFRP panels which are



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**Full-Scale Aircraft Fire Tests—A Comparison of Aluminium and Composite Burn-Through**

also deformed and there are blisters where the glass transition temperature ( $T_g$ ) of the epoxy (approximately 200°C (392°F)) was far exceeded and flow occurred. The original aluminium skin beyond the areas protected by the interior insulation is heat damaged (paint blackened) whereas the paint on the skin in areas that were protected is not. The paint where the skin is connected to stringers has been affected by the internal heat. All of the composite panels remained attached to each other at the joints and to the perimeter aluminium structure. The panel buckling is partly accommodated by the fact that the internal frames were burned completely away.

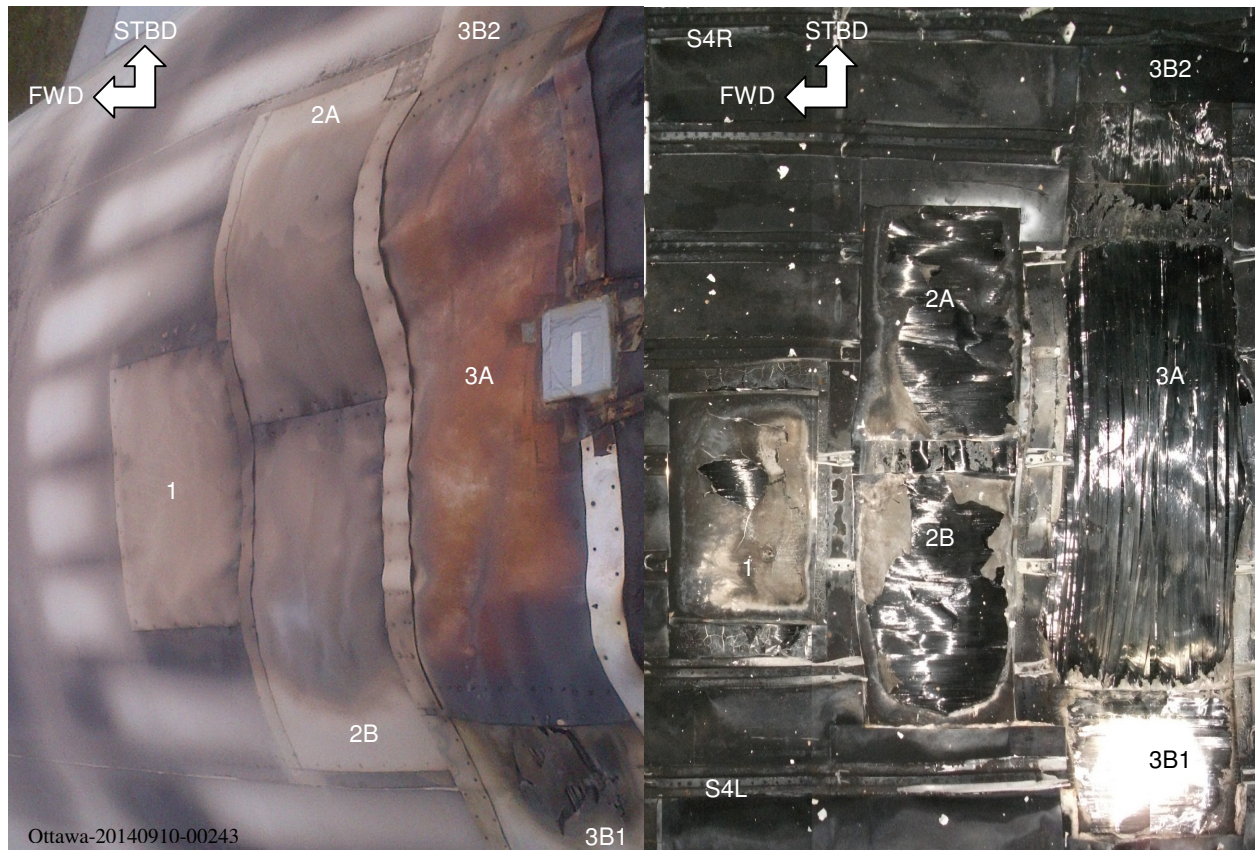
GLARE Panels 1, 2, 3B1 and 3B2 were of three-ply construction with the two face plies being of 0.013" (0.33mm) thick aluminium sheet with a single core ply of 0.008" (0.2mm) bi-axial glass fibres and epoxy adhesive. Panel 3A was a seven-ply laminate with four plies of aluminium sheet and three plies of bi-axial glass fibres of the same thickness as in the other panels.

Internal inspection of the GLARE panels, Figure 29, revealed that all of them had suffered disassociation (delamination) of the layers and loss of some or all of the inner aluminium sheets as well as the epoxy adhesive. In effect, only the outer aluminium sheets remained intact except for panels 3B1 and B2 which both suffered some degree of burn-through. The burn-through area (breach of the outer aluminium ply) was largest on Panel 3B1. Smoke was observed escaping the fuselage from these breaches.

**Full-Scale Aircraft Fire Tests—A Comparison of Aluminium and Composite Burn-Through**

Figure 28. Test 2. Overall exterior view of the fuselage crown, post-test.



**Full-Scale Aircraft Fire Tests—A Comparison of Aluminium and Composite Burn-Through**

a) exterior

b) interior. Image flipped to match view a)

Figure 29. GLARE panels 1 to 3.

The GLARE panels would have normally been attached to aluminium stringers. As seen in Test 1, the stringers would have burned away or been damaged. The fibres seen hanging loose, such as those of panel 3A in Figure 29b, would be the realistic result of fire damage for this type of construction. A closer view of the burn-through to panel 3B1 is shown in Figure 30. The inner sheet of aluminium has melted or burned away with material remaining only around the perimeter where it was attached to other structure. The outer aluminium sheet had just been breached by the end of the test and the fibres within can be seen in these areas. The glass fibres remain in place and act as a restriction to the escape of smoke and heat.

Figure 31 shows an overall view from the overhead TIC camera after burn-through as well as a close-up of the GLARE panels. The camera setting was “white is hot”. Panel 3B1 was not painted white and the emissivity of its outer surface caused this panel to show as black throughout the test. The heat escaping through the breach in panel 3B1 is being detected as hotter (white) as can be seen in the images.

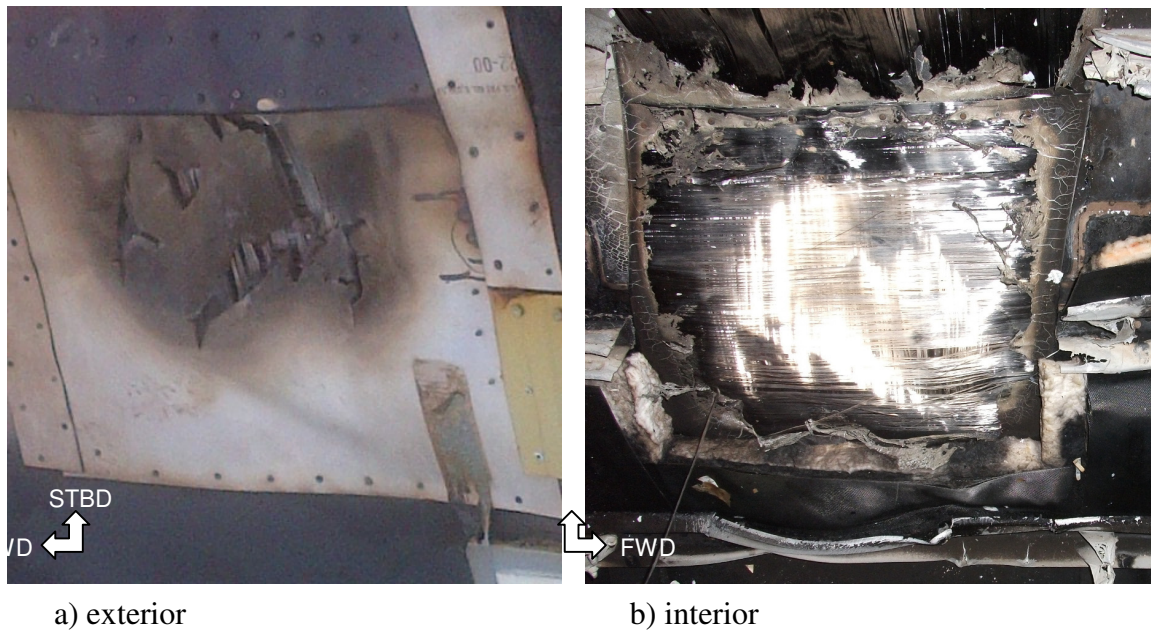
**Full-Scale Aircraft Fire Tests—A Comparison of Aluminium and Composite Burn-Through**

Figure 30. Burn through on panel 3B1.

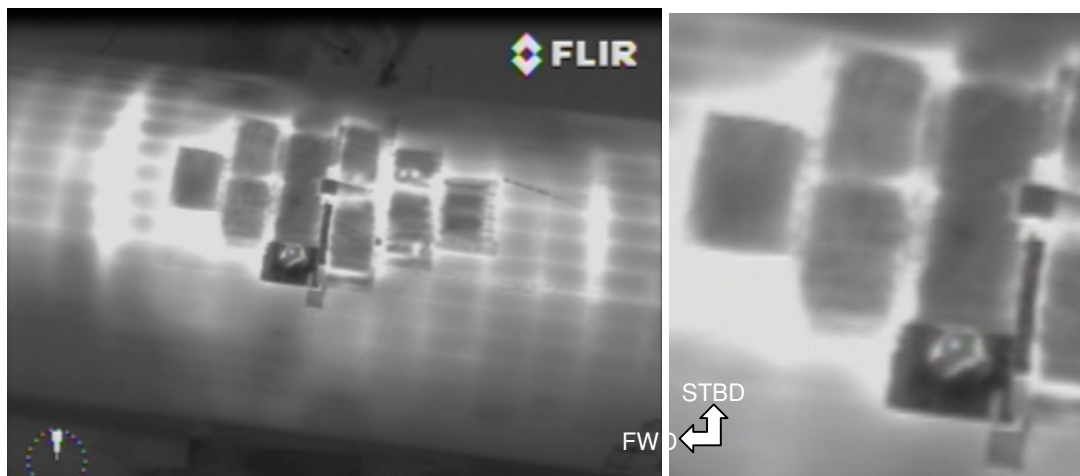


Figure 31. Overhead TIC image at 11:44 (after Stinger and PyroLance extinguishments).

The exterior and interior conditions of the CFRP panels, post-fire, are shown in Figure 32. None of the panels suffered burn-through. All of the co-cured stiffening stringers integral to panels 4 & 5 lost a sufficient volume of epoxy such that individual plies could separate and fall down and loose pieces were found in the debris or they remained hanging but could be pulled off easily. The three hat-shaped co-cured stringers on panel 6 had also lost some portion of their epoxy matrix. The middle stringer was pulled off with little effort (inset Figure 32). Most of the thickness of the CFRP panels was disassociated (delaminated) and a thin probe could be pushed almost completely through the thickness. Even if all the epoxy had burned off, the multi-axial fibre lay-up of these laminate panels would have been an effective barrier to smoke and heat venting out of the aircraft.



# Full-Scale Aircraft Fire Tests—A Comparison of Aluminium and Composite Burn-Through



Figure 32. CFRP panels 4, 5 & 6 (with close-ups).

An overall interior view of the post-fire condition of the composite panels is shown in Figure 33. The stringers adjacent to the burn-through at GLARE panel 3B1 have suffered significant heat damage yet the frames throughout have burned back farther than they did in Test 1. Not all of the damaged frames between BS950A and 950F can be seen in Figure 33 therefore the STBD and PORT sides are shown from S5 down to S8 in Figure 34.



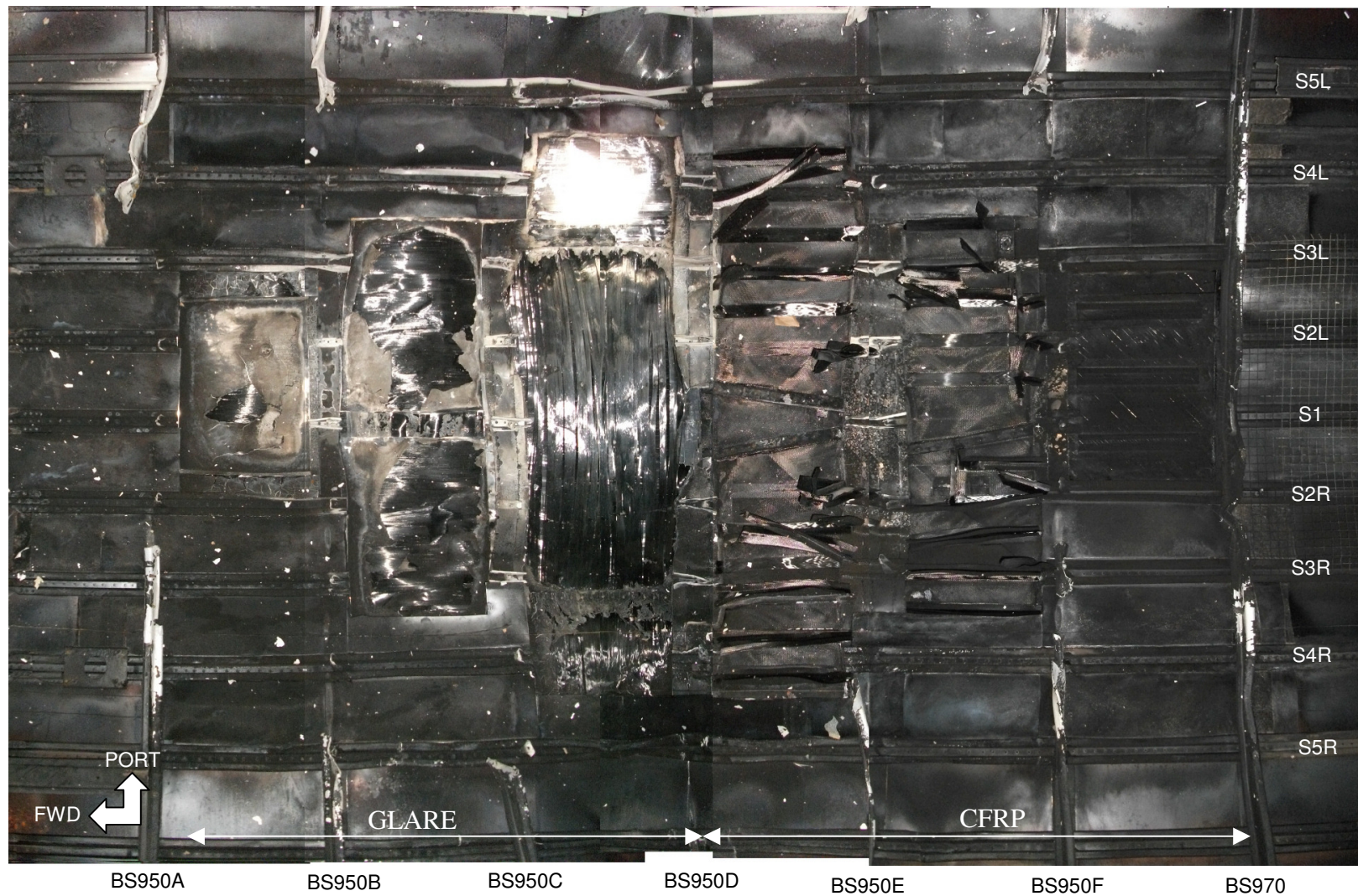
**Full-Scale Aircraft Fire Tests—A Comparison of Aluminium and Composite Burn-Through**

Figure 33. Test 2 fuselage crown, post-test damage.



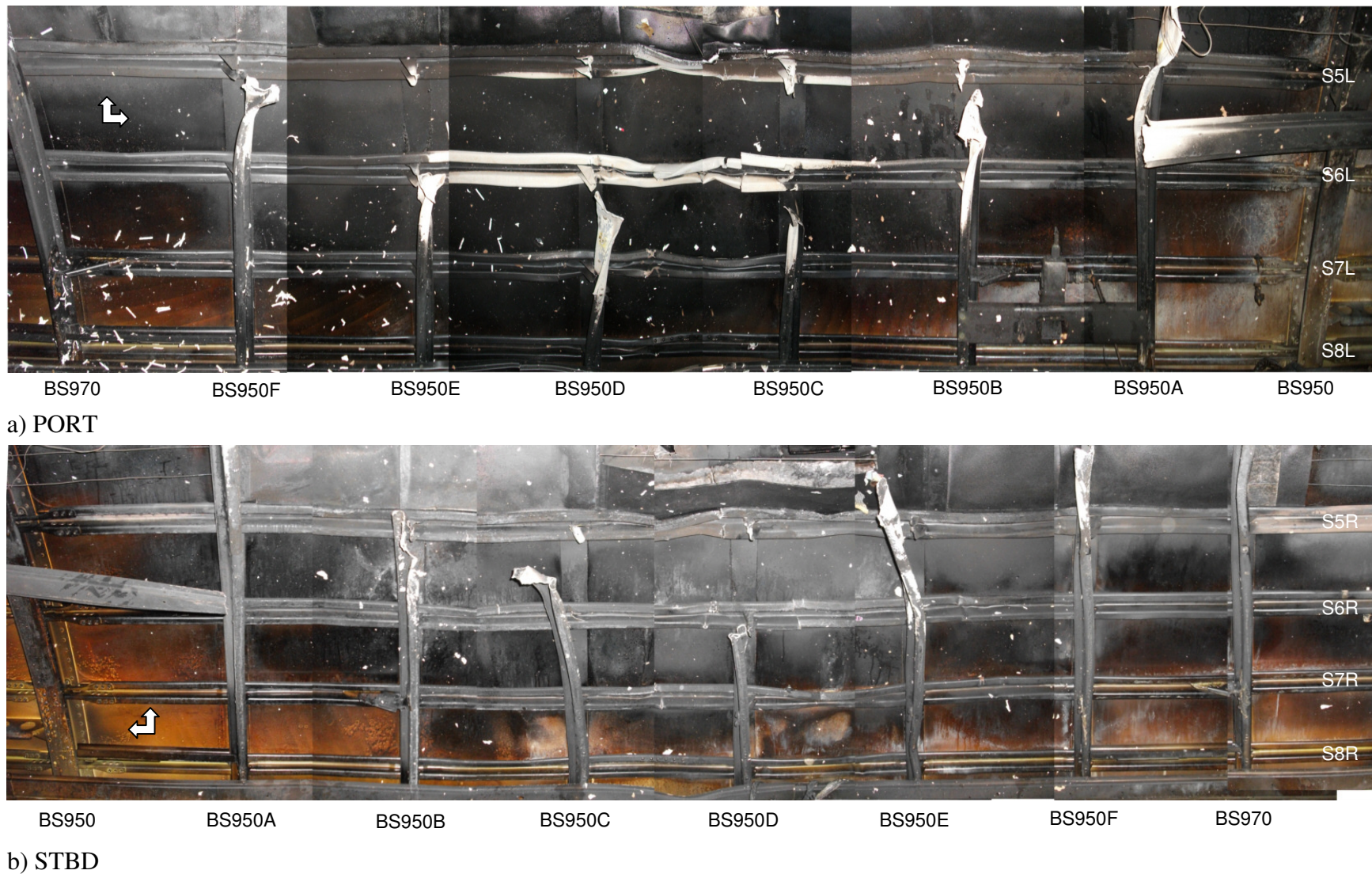
**Full-Scale Aircraft Fire Tests—A Comparison of Aluminium and Composite Burn-Through**

Figure 34. Test 2 fuselage sidewalls, post-test damage.

## Full-Scale Aircraft Fire Tests—A Comparison of Aluminium and Composite Burn-Through

With reference to the Red 9 TIC side-view in Figure 35: it can be assumed that solar heating has raised the temperature of the blackened skin around the Test 1 fire site. In both the overhead and side TIC camera views the exterior surface of GLARE panel 3B1 reports as black. Panels 3A and 3B1 were in the as-received condition with only a primer coating yet 3A did not report as black. All other GLARE panels were painted white. The source of the white (hotter) area just aft of 3B1 is unknown. It is interesting that the dark blue paint system on panels 4 and 5 and the unpainted black CFRP panel 6 are not being reported as hotter (by solar heating) than the surrounding aluminium although the Red 9 TIC side-view of these panels is minimal. The crown skin area forward of the V Stab and between S4L&R (circled in Figure 36 and shown in Figure 37) is painted black which may account for the reported heating or it may be an emissivity difference. The overhead TIC view did not include the area AFT of BS1010.

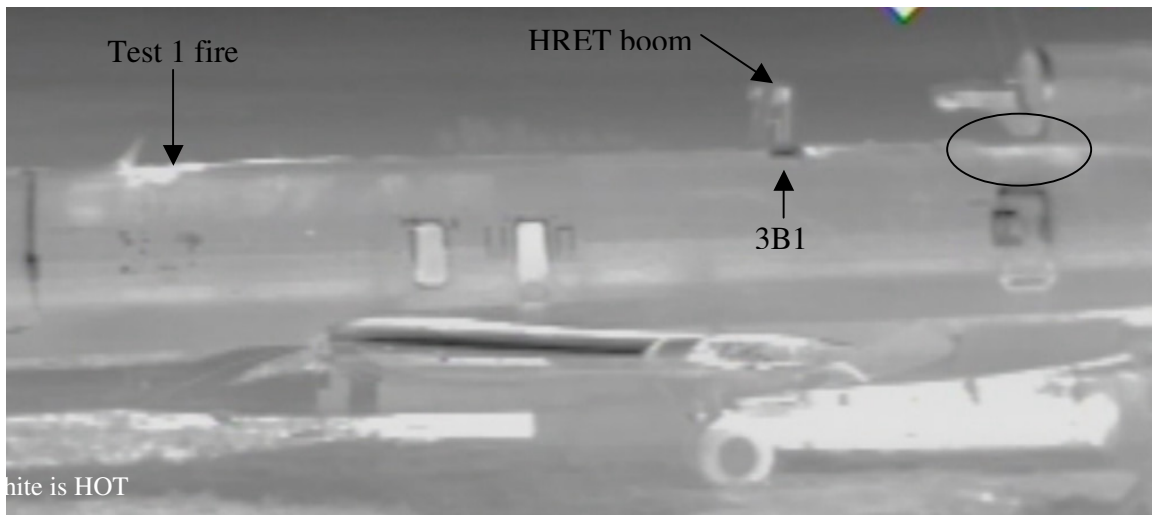


Figure 35. Prior to Test 2 fire start the Red 9 TIC side view shows panel 3B1 as 'black'.



Figure 36. View of AFT fuselage crown with black-painted crown area.



**Full-Scale Aircraft Fire Tests—A Comparison of Aluminium and Composite Burn-Through**

Figure 37. Red 9 TIC 1 minute after first heat detected on crown.

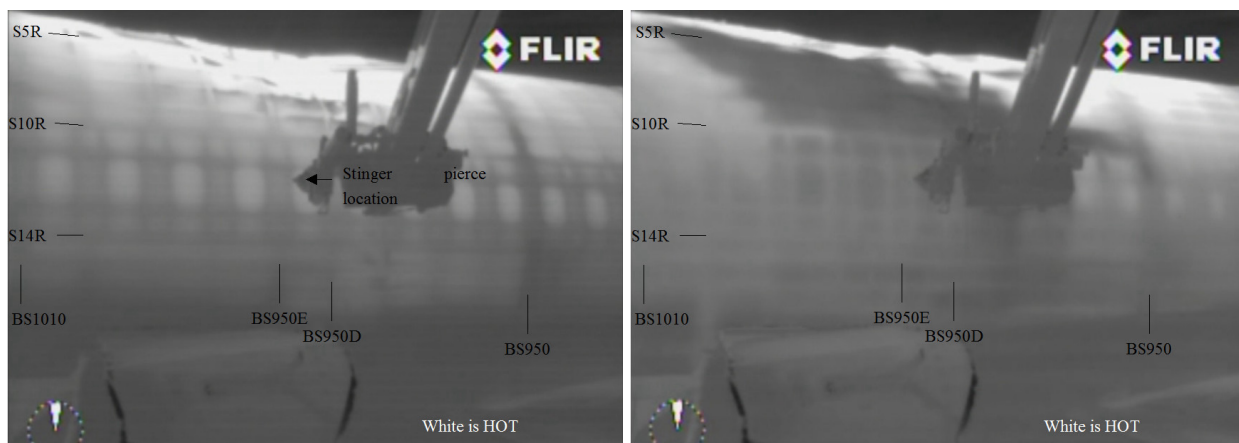


Figure 38. Extent of Stinger water spray cooling effect on STBD fuselage between 7:49 and 8:55.

The salvage tarp failed at 7:45. The Stinger pierced at 7:40 and water flowed from 7:49 to 8:55 (1:06 duration). Figure 41 shows that the water does not cross the fuselage and cool the opposite sidewall. This is because some portion of the fuel package may still be in-between and the flat-fan spray pattern of the chisel-style tip does not project very much water forward.

Figure 39, from LTR-SMPL-2012-0126, shows the water spray pattern of the chisel-type Stinger tip is a fan shape with little water projected forward.

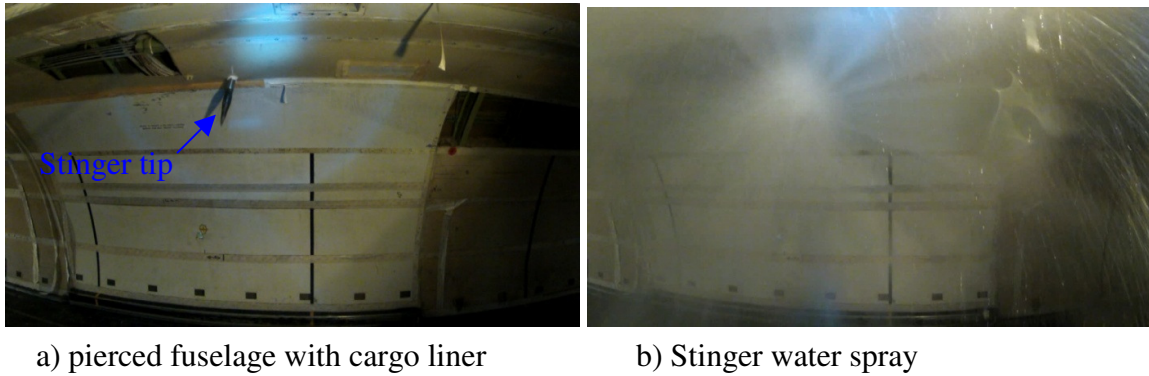
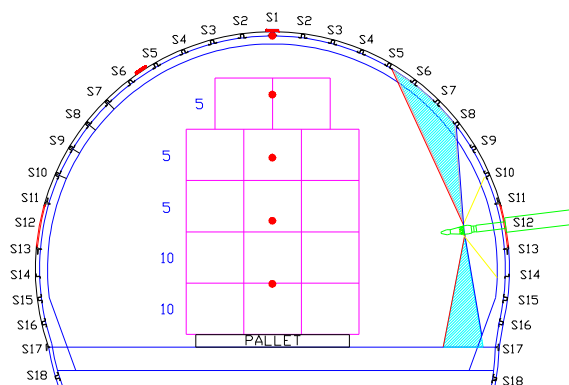
**Full-Scale Aircraft Fire Tests—A Comparison of Aluminium and Composite Burn-Through**

Figure 39. Example of unobstructed chisel-type Stinger tip water spray pattern.

The fibreglass cargo liner had been completely removed from the fuselage sidewall and as such there was no impediment to the water spray contacting the STBD fuselage skin and substructure. The piercing was carried out through the window blanking plate between BS950D and 950E. The maximum fuselage skin area cooled by the water spray is shown in Figure 38 and extends from BS950 to 1010 between S4 and S10R.

Based on the Red 10 TIC video stills in Figure 38 and the CAD sketch in Figure 40, the first water spray cooling is seen along S8R with a little impinging slightly above up to S5, (upper red and blue lines from Stinger in sketch). There isn't as definitive a cooling effect visible on the fuselage STBD side below the Stinger (reciprocal angle). By the end of the water spray event the cooling effect is seen to extend from S5R down to S10R. The cooling from S8R down to S10R is apparently not from direct spray but must be from gravity, otherwise water spray would also show from S14R down (Yellow lines in sketch) but it doesn't. No cooling was visible on the PORT side, Figure 41.



There are 32 orifices in the piercing tip arranged in four rings of 8 each. The rear two rows are large and project water radially. The front two rows are small orifices that are angled forward. The water spray from the small, forward-projecting orifices are not shown in the sketch.

Figure 40. Water spray from Stinger.

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Figure 41. Red 9 TIC at 8:00. No Stinger water spray cooling on PORT fuselage skin.



Figure 42. Red 9 TIC at 10:00. Evidence of PyroLance cooling PORT fuselage skin (circled).

As shown in Figure 42 and Figure 43, the water spray cooling effect of both the PyroLance and hand-line extinguishments could be witnessed by observing the Red 9 TIC side-view of the PORT side. The effect of water impinging on the PORT fuselage skin from the PyroLance being operated from the STBD side was observed to cool the PORT side, circled in Figure 42, starting at 9:27 and persisted throughout the 1:06 application. The cooled fuselage area caused by the initial hand-line water spray is circled in Figure 43.

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Figure 43. Red 9 TIC view at 13:24 showing effect of over-wing hand-line.

The temperature data collected during Test 2 are shown graphically in Figure 44 and Figure 45. The first shows the temperatures recorded from the beginning of the fire. The second shows the period with the initial extinguishments and intervals between annotated.

As evidenced by the TC#1 data the fire suffered two periods where the fire dampened. This is mirrored to a lesser extent in the TC#11 data. In both cases re-ignition could be seen as a flash through the smoke in the forward-looking interior camera views. TC#2 exceeded 650°C (1202°F) approximately 28 seconds before TC#1.



# Full-Scale Aircraft Fire Tests—A Comparison of Aluminium and Composite Burn-Through

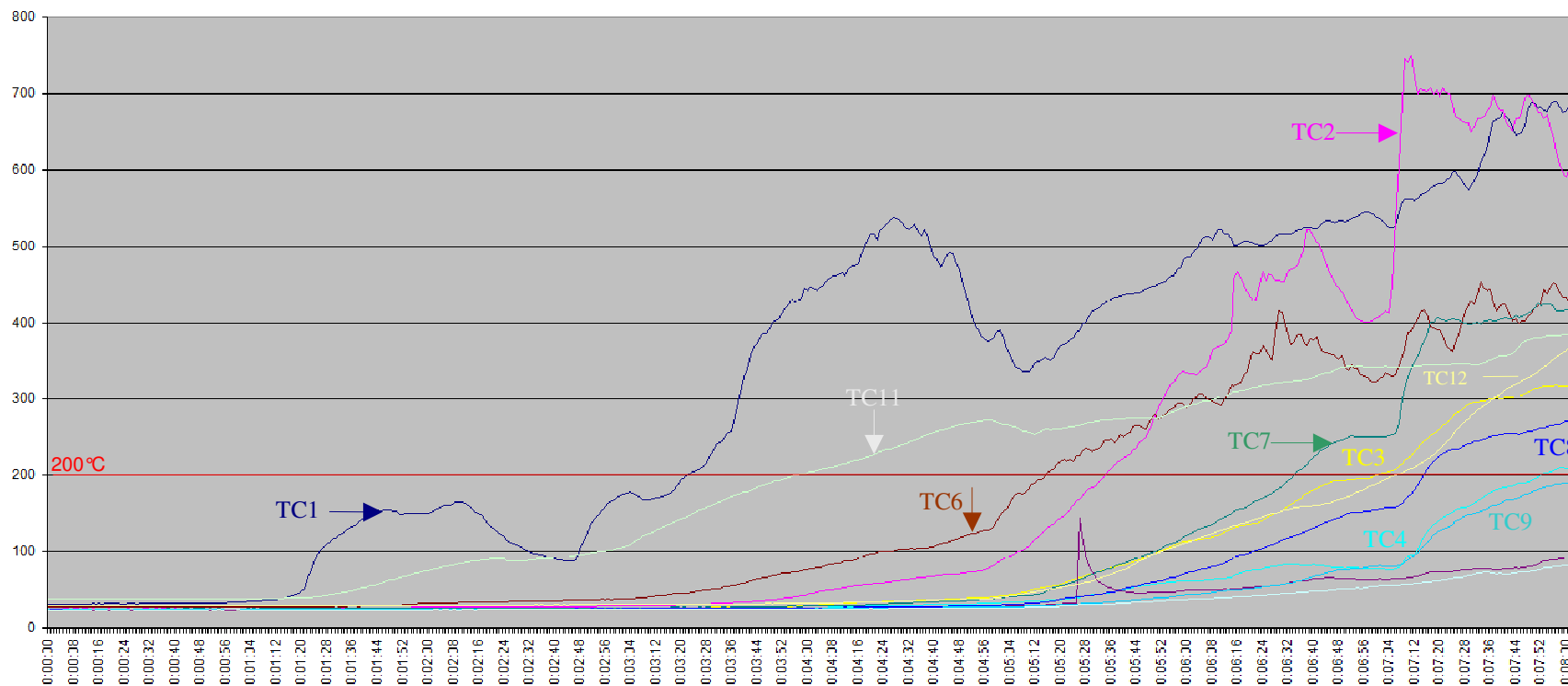


Figure 44. Test 2 fire temperatures (°C) prior to extinguishments.

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**Full-Scale Aircraft Fire Tests—A Comparison of Aluminium and Composite Burn-Through**

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In Figure 45 the period of the Stinger, PyroLance and over-wing hand-line extinguishments have been marked by vertical lines with the duration of the water sprays and intervals between marked. The Stinger spray was centred on the fuel stack and did not appear to cool above S8R. Its effect was initially between the STBD fuselage sidewall and the fire and had little immediate effect on the two thermocouple trees but it did eventually cause the thermocouple tree #1 temperatures to drop (TC#1 through #4). TC#6 was also affected but TCs 7 through 9 of thermocouple tree #2 continued to rise until the PyroLance was applied. The PyroLance spray likely passed between the two thermocouple trees based on the position and angle it was operated at and almost all TCs show a drop caused by this extinguishment. The two exterior thermocouples slow their rise during the Stinger event and begin to decline during the PyroLance extinguishment but this is likely a cumulative effect as all of the interior thermocouples registered rapid declines in temperature at about the same time.

There is a sharp fall in the TC tree 2 temperatures measured by TC#6, 7 and 8 (marked 'A'). During the hand-line water spray event TC#6, 7 and 8 all see a temperature rise but they then all drop off similarly (marked 'B'). The audio record from inside the aircraft along with the external and internal video, have been scrutinized to confirm that no water spray events caused the temperature drops at "A". This temperature drop may be the result of the collapse of the fuel stack and, for "B", its disruption or direct water contact with the TCs by the hand-line water spray.

# Full-Scale Aircraft Fire Tests—A Comparison of Aluminium and Composite Burn-Through

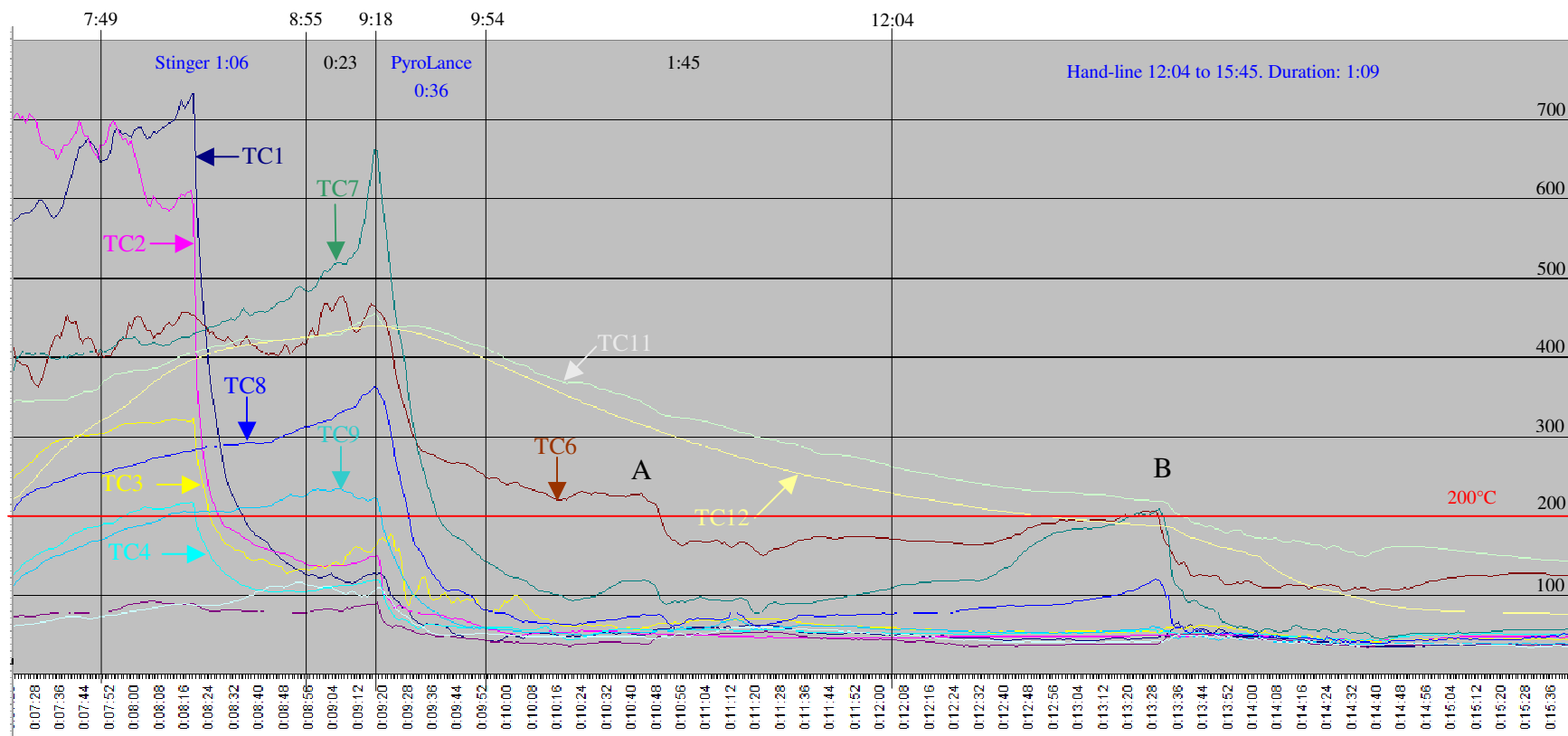


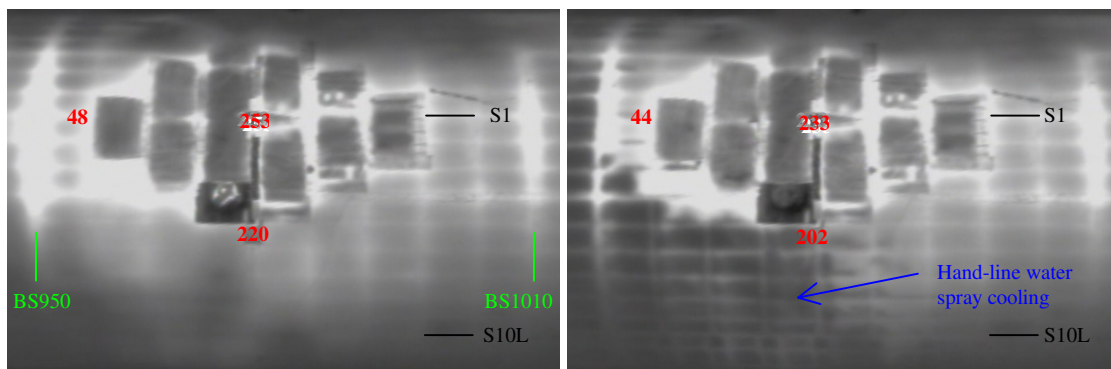
Figure 45. Test 2 temperature data during initial fire extinguishments.

## Full-Scale Aircraft Fire Tests—A Comparison of Aluminium and Composite Burn-Through

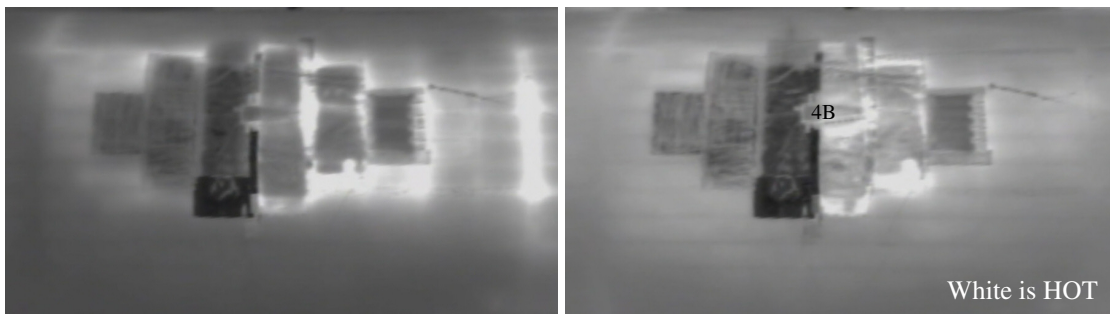
The overhead TIC video record of Test 2 started at 11:44 after the fire started. This is after the Stinger and PyroLance extinguishments and 20 seconds before the start of the STBD AFT over-wing hand-line attack (12:04) which lasted for 3:41 and ended at 15:45. Selected TIC video images are provided in Figure 46. Selected thermocouple data are provided in Table 2.

The thermocouple temperature recordings ended at 15:11, 34 seconds before the end of the hand-line attack. The firefighters were instructed not to apply water directly onto the composite panels in the crown. At 12:14 the effects of the initial water spray can be seen on the aluminium structure but this fades throughout the remaining attack indicating that water was being directed down onto the debris on the floor for the remainder of the extinguishment.

By 17:44 the heat has dissipated from the skin and the frame at BS950. Note that the frames at BS950 and 1010 are heavy forgings. Ten minutes later, at 27:44 the heat has almost completely dissipated at BS1010 yet the CFRP panels 4 & 5 remain hotter than their surroundings. It may be that where the CFRP panels are lapped over a second layer (CFRP or aluminium) they were protected from extinguishments and the decrease in cabin temperature and they continue to smoulder between the plies. This continued combustion of the adhesive is evidently heating the aluminium at the perimeter of the CFRP panels. Panel 4B is also hotter than its surroundings and this may also be evidence of heat from internal combustion emitting from the free edges of the panel.



11:44. Over-wing hand-line starts at 12:04. 12:14.



17:44. Start of rear air-stair overhaul 27:44. End of rear air-stair overhaul was at 27:10

Figure 46. Selected overhead TIC views of composite skin panels from 11:44 to 27:44.

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Table 2. Selected TC#1, 11 &amp; 12 readings at :30 and 1:00 min intervals.

Fire	TC1		TC11		TC12	
Clock	Deg C	Deg F	Deg C	Deg F	Deg C	Deg F
11:44:00	48	118	253	487	220	428
12:04:00	Start of over-wing hand-line					
12:14:00	44	111	233	451	202	396
12:44:00	46	115	224	435	191	376
13:14:00	57	135	186	367	166	331
13:44:00	44	111	168	334	116	241
14:44:00	37	99	152	306	78	172
15:11:00	37	99	142	288	76	169
15:45:00	End of over-wing hand-line					

Although the hand-line extinguishment starts at 12:04 the effect on the thermocouples is not seen to be an influence until 12:59 (Figure 47). TC#11 and #12 drop at the same rate initially but TC#11 levels off at around 300°F (150°C) while TC#12, on aluminium, decreases to level off just above 167°F (76°C). The persistent higher temperature recorded by TC#11 is most likely due to continued smouldering. TC#1 is hovering around 122°F (50°C) and then gets down to around 95°F (35°C). TC#6, far away at the top of thermocouple tree #2, sees a temperature rise during the extinguishment as heat is pushed away from the seat of the fire and up towards the crown.

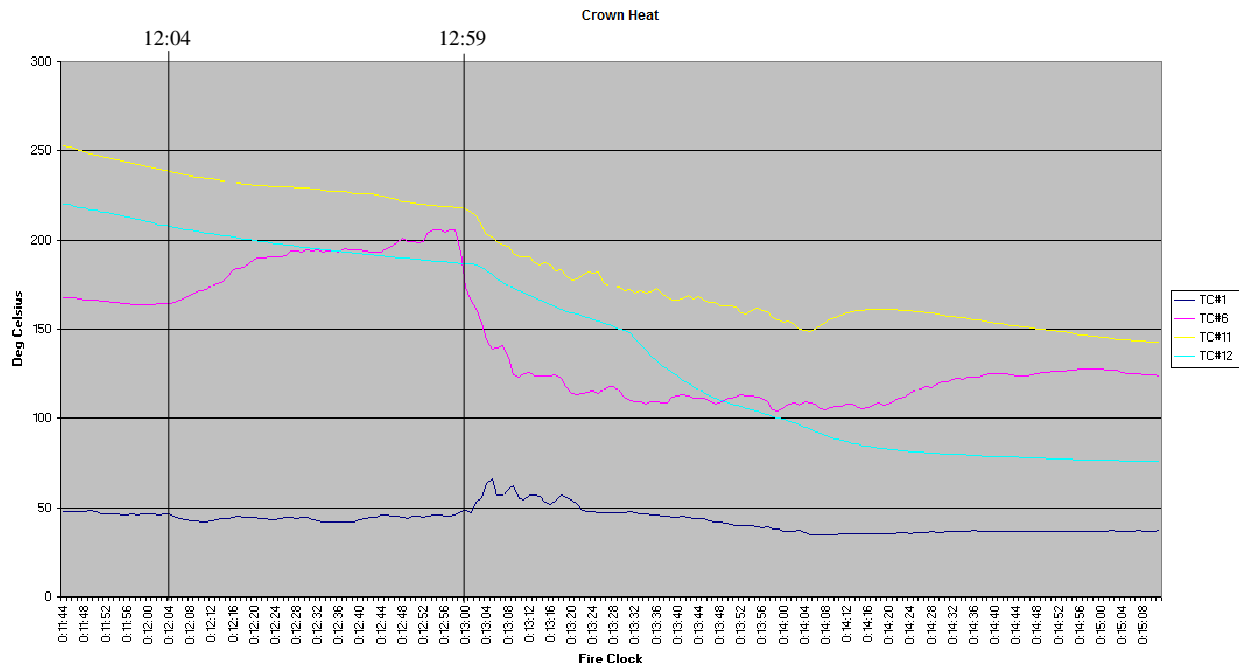


Figure 47. Crown (TC#1 &amp; 6) and exterior skin (TC#11 &amp; 12) temperatures.



## Full-Scale Aircraft Fire Tests—A Comparison of Aluminium and Composite Burn-Through

### 4.4 AIRBORNE PARTICULATES

The 38.8 ft<sup>2</sup> (3.6m<sup>2</sup>) of CFRP panels installed in the crown for Test 2 constituted the largest area of composite material burned at the OIAA ERS training area to date. This report will not attempt to draw conclusions on any health issues related to exposure to the products of combustion of CFRP yet it is understood that inhalation of fibre particulates is a concern. At the same time, the current safety measures (based on aluminium aircraft fires), specifically, exclusion zones for unprotected responders and the public, may have to be modified because of this concern. With this in mind, measurements of the particulate concentration in the down-wind airflow were taken well away from the seat of the fire. The current recommendations for exposure limits, set-up and measured results are detailed in Appendix III.

### 4.5 OBSERVATIONS – TEST 2

The interior and exterior records were analysed frame by frame to determine the timing of each event. This analysis results in the following timeline for the composites fire, Test 2.

00:00 First smoke FWD side of fuel stac.	10:19 End PyroLance. <b>Duration:</b> 0:41 over 1:06. 6.8 US Gal (25.7 L)
00:15 First visible flames at top of fuel stack by FWD camera.	1:45 between end of PyroLance and hand-line start.
07:40 Stinger pierce through cabin side-window.	12:04 Start hand-line from over-wing position.
07:45 Failure of Salvage Tarp.	15:45 End over-wing hand-line <b>Duration:</b> 2:08 in four applications over 3:41. 320 US Gal (1211 L)
07:49 Stinger - First flow of water (low pressure).	1:58 between end of hand-line and start of overhaul.
07:52 Start Full pressure Stinger water flow.	17:43 Overhaul from rear air-stair starts. 8 applications.
08:55 End full pressure Stinger flow. <b>Duration:</b> 1:06. 261 US Gallons (988 L)	27:00 End overhaul. <b>Duration:</b> Total of 2:57 over 9:27. 295 US Gal (1117 L)
18 seconds between Stinger end and PyroLance start.	Approximately 884 US Gallons (3345 L) of agent.
09:13 PyroLance start.	
09:18 PyroLance pierces skin and first flow of water.	
09:54 PyroLance slips and flow to interior ends.	

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**Full-Scale Aircraft Fire Tests—A Comparison of Aluminium and Composite Burn-Through**

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The pop of the fire-starter could not be discerned from the audio records. The time from first smoke detected at the top of the stack to the end of the rear air-stair overhaul was 27 minutes. Open flame was first seen at the top of the fuel stack 15 seconds after first smoke.

There were two flashovers that could be seen in the aft internal camera view as well as in the thermocouple temperature record.

The first firefighting attack was carried out 7 minutes and 49 seconds after the fire started. Only one Stinger application took place followed almost immediately by PyroLance with 18 seconds between them. These two applications were each restricted to nominally one minute. The over-wing hand-line water applications totalled 2:08 with the first being the longest at 1:09 while the following three were each less than 30 seconds. There were eight water applications during the overhaul mounted from the rear air-stairs and they varied in duration between six and 45 seconds. The overhaul water application totalled 2:57 over a period of 9:27.

None of the interior fibreglass sheet was structurally compromised in the fire and it succeeded in holding the insulation in place around the perimeter of the advanced composite panels.

All six aluminium frame members directly above the fuel package (BS950A to F) and supporting the advanced composite panels were melted/burned away between S4L and S4R.

The CFRP skinned area is nowhere near burnt through. The CFRP sheets softened such that they deformed as an intact unit to conform to the sagging and buckling of the surrounding aluminium structure. The co-cured stringers had lost most of their adhesive and so woven carbon fibre plies were freed from the structure and some fell into the fire. The hat-shaped stringers on panel 6 could be removed by hand as most of the adhesive had been burned off.

Contrary to standard practice, water was not applied to the interior or exterior of the CFRP panels. The perimeter of the CFRP panels was seen to remain hotter than their surroundings and this may illustrate that internal smouldering continued.

The 0.034" thick GLARE panels mounted between BS950C-D were most heavily degraded, between S2 and S4 (L and R) and where approaching "burn-through" in that only the outer aluminium ply remained, the inner ply having melted away leaving only the fibreglass inter-ply.

The 0.034" thick GLARE panels farther from the centreline (between BS950A-B and B-C) were not near "burn-through" in that their innermost aluminium skin was heat affected, disassociated from the fibreglass interlayer but remained in place.

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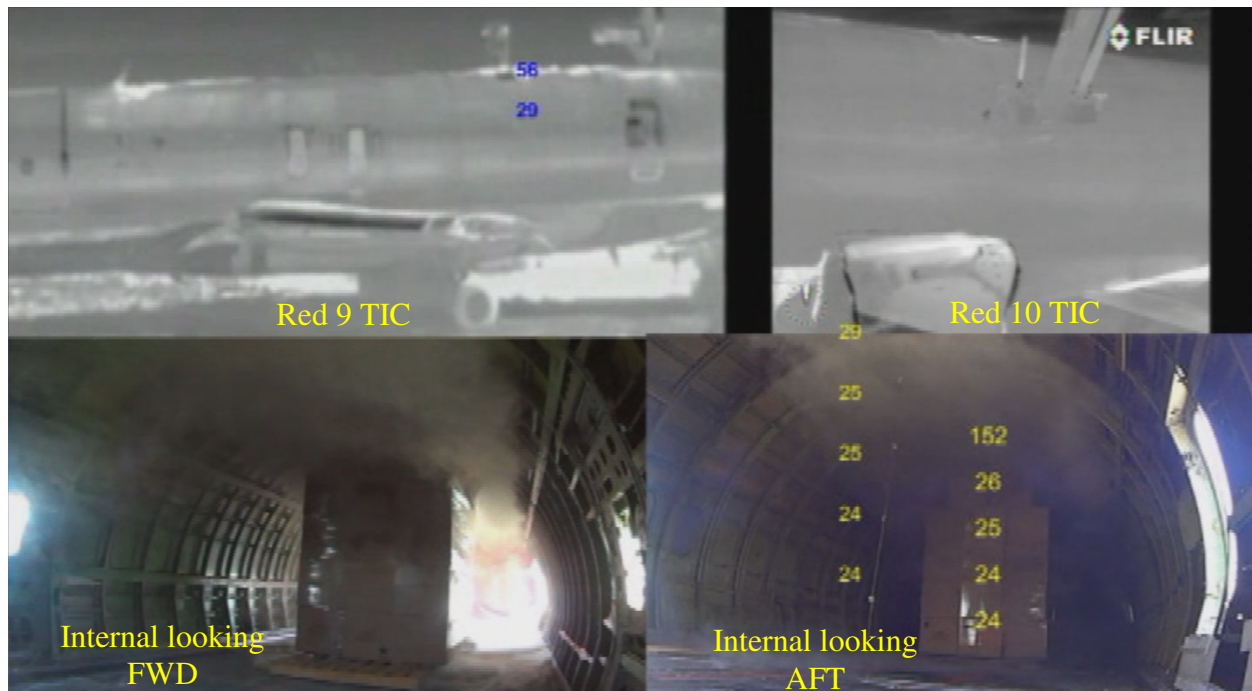
**Full-Scale Aircraft Fire Tests—A Comparison of Aluminium and Composite Burn-Through**

The next day the airborne particulate count remained high therefore the interior of the fuselage received an application of acrylic wax as a fixant. The gaseous contaminants were sampled and found to have decreased to permit safe entry.

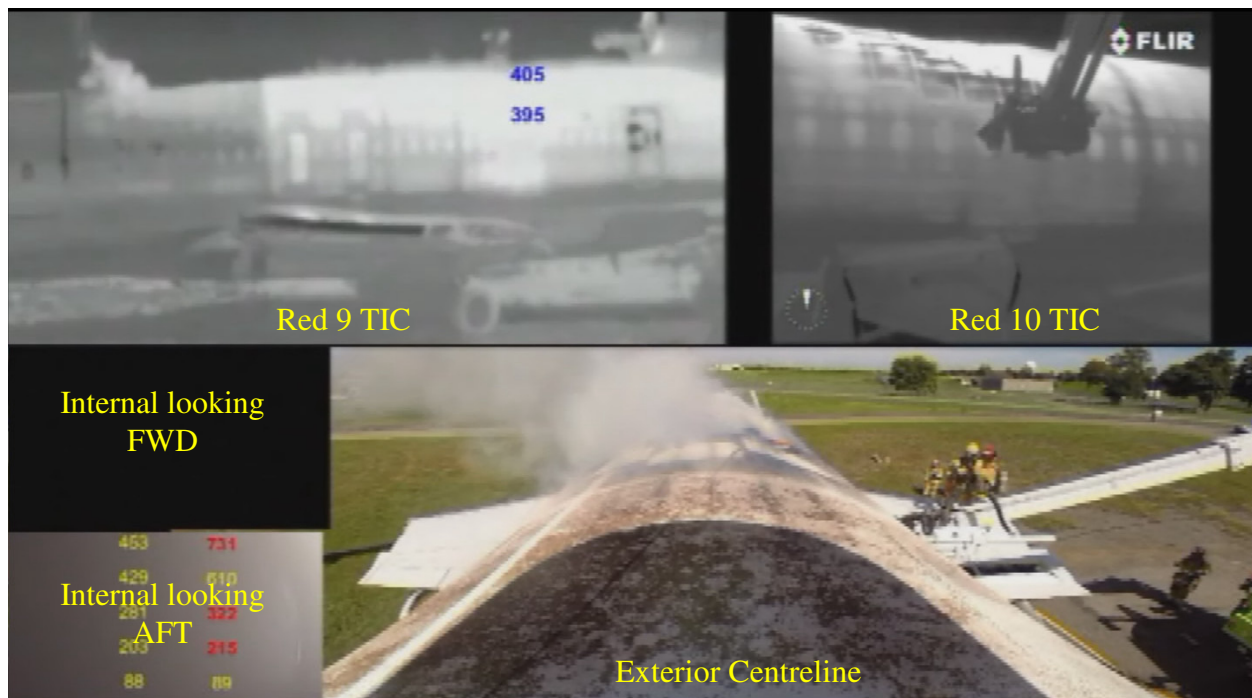
#### **4.6 TEST 2 COMPOSITE VIDEO**

The collected video and TIC views were edited into a composite of picture-in-picture views using Pinnacle Studio HD Version 15.0 software to create a summary of the progress of the fire and the extinguishments. The overall side-view from the TIC on Red 9 and the close-up TIC view from the HRET fire truck (Red 10) were shown at the top. Initially two interior camera views were shown at the bottom (one looking FWD and one AFT) as they documented the start of the fire and the accumulation and movement of the smoke. Once these interior views were obscured by smoke they were reduced in size to permit the addition of the exterior centreline camera view (mounted in the centre engine inlet duct). The thermocouple readings were presented at 30 second intervals in their relative positions on the internal (looking AFT) and the Red 9 TIC views. The temperatures, in degrees Celsius, for the internal thermocouples were displayed in yellow and then red when they peaked. The external thermocouples were shown in blue except when they peaked (red). Two screen shots from the compilation video for Test 2 are shown in Figure 48.

# Full-Scale Aircraft Fire Tests—A Comparison of Aluminium and Composite Burn-Through



a) 2 minutes after the start of the fire



b) at start of Stinger extinguishments, approximately 7 minutes after the start of the fire

Figure 48. Screen shots from Test 2 composite video.

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### 5.0 CONCLUSIONS

Final Test 1 versus Test 2 comparative data temperature data sets have been provided for thermocouple tree 1 (Figure 49), tree 2 (Figure 50), and the exterior fuselage thermocouples (Figure 51). Points of interest on each image where comparative conclusions can be drawn have been identified and numbered.

TC Tree 1 - Test 1 versus Test 2 temperature data conclusions, Figure 49:

Point 1: Test 1 and Test 2 were remarkably similar in their peak TC#1 temperatures of 1330°F and 1348°F respectively (721°C and 731°C). Also, both fires ran at temperatures over 750°F (400°C) in the upper half of the cabin for 4 minutes (Figure 49 and Figure 50). The composite fire (Test 2) was hotter for a longer period of time lower down in the cabin which may explain why a much larger area is heat damaged as evidenced by the blackened paint on the exterior.

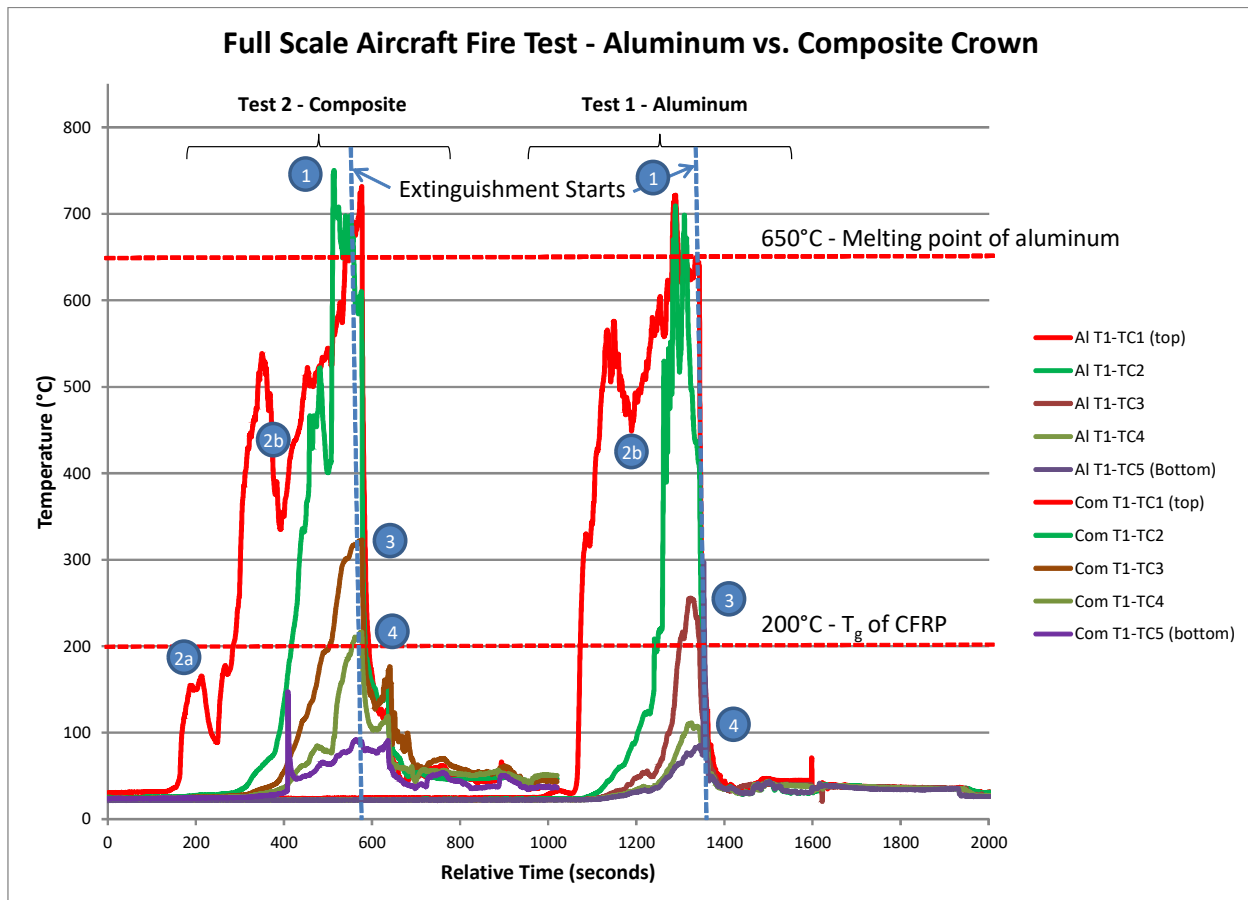


Figure 49. Test 1 versus Test 2 TC Tree 1 Temperatures.



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**Full-Scale Aircraft Fire Tests—A Comparison of Aluminium and Composite Burn-Through**

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Point 2 (a and b): The Test 2 fire appeared to starve for oxygen which may have been related to wind speed and direction as well as variation in general test configuration (despite best efforts to make the two fire tests as similar as possible). Two “flashover” events, where the fire appeared to be self-extinguishing and then reignites with a visible flash, are pointed out as 2a and 2b for Test 2. This compares to a single event (2b) in Test 1. Also note that the 2b event lasted for a longer period of time with a greater temperature drop for Test 2 compared to Test 1. Despite the fact that the Test 2 fire was choked relative to the Test 1 fire, it managed to reach slightly higher temperatures.

Points 3 and 4: TC#3 and TC#4 also measured higher temperatures for Test 2 compared to Test 1. For Test 2 TC#3 and TC#4 measured maximum temperatures of 608°F and 415°F (320°C and 213°C) respectively compared to 491°F and 232°F respectively (255°C and 111°C). Also note that after initial extinguishment the Test 2 fire contained the energy to reignite unlike that of Test 1, as indicated by the temperature spike underneath point 4 in Test 2.

TC Tree 2 - Test 1 versus Test 2 temperature data conclusions, Figure 50:

Point 5: Test 1 and Test 2 had remarkably similar TC#6 peak temperatures of 840°F and 900°F respectively (449°C and 482°C). The temperature difference of Test 1 and Test 2 TC#7 peak temperatures, 900°F and 1222°F respectively (482°C and 661°C) is one of the few major temperature disparities measured between the two tests. It is important to remember the fire temperature data includes only 12 finite points for comparison and that the maximum temperatures are almost certainly located outside of the measurement points i.e. inside and near the top of each fuel package. Also note that the salvage tarp was relatively undamaged after Test 1 and destroyed after Test 2 even though it was located at the same distance from the fuel package seat.

Point 6: The Composite fire Test 2 also shows evidence of being more starved for air than the Aluminium fire Test 1. The Test 2 was choked for a longer period of time which resulted in a more significant TC#6 drop as compared to Test 1.

Point 7: The Test 1 data demonstrates cooling after the peak temperatures were recorded and the aluminium crown melted, thereby venting the heat and smoke. The Test 2 data demonstrates no such temperature drop prior to the firefighting attack. Also note that firefighters reported lower levels of smoke i.e. better visibility in Test 1 as compared to Test 2 where the composite materials prevented venting of heat and smoke. The composite materials also promote a smokier fire as compared to aluminium.

Points 8 and 9: TC#8 and TC#9 also measured higher temperatures for Test 2 compared to Test 1. For Test 2 TC#8 and TC#9 measured maximum temperatures of 682°F and 450°F (361°C and 232°C) respectively compared to 471°F and 252°F respectively (244°C and 122°C). The TC#8 and

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TC#9 positions are further from the base of the fire and lower to the deck compared to the similar TC#3 and TC#4 comparison made previously. Again in Figure 50 the re-ignition of the Test 2 Composite fire is seen. No such secondary ignition is reported for the Test 1 Aluminium fire.

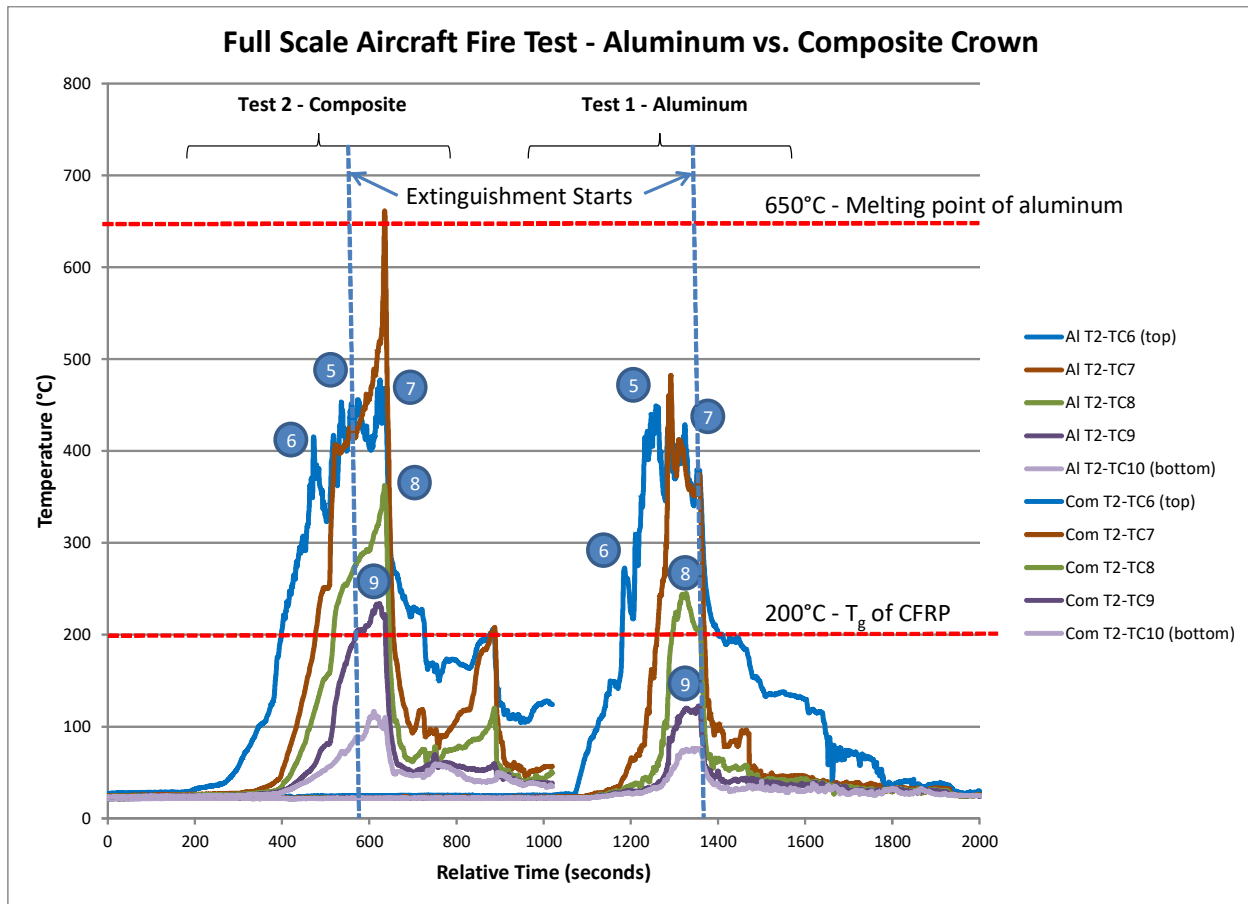


Figure 50. Test 1 versus Test 2 TC Tree 2 Temperatures.

The HRET Stinger was applied first in the firefighting attack against both fires but it was noted that in both cases the recorded cooling effect of the applied water was not immediate partly because of the spray pattern of the Stinger and also by the distance from the seat of the fire to the TC trees. The cooling effect on the temperatures measured at both trees was almost immediate during the PyroLance application because the water vapour was directed between the two TC trees.

Exterior TC's - Test 1 versus Test 2 temperature data conclusions, Figure 51:

Point 10: The peak temperature of Test 2, 849°F (454°C) compared to 1128°F (609°C) (first peak) of Test 1 is most likely due to the difference in the way the fire attacks the composite material versus the aluminium. The layers (plies) of the composite material closest to the fire delaminate and char which insulates the remaining material from the heat of the fire compared to the aluminium which simply vaporizes (which is also demonstrated in the Test 2 fire GLARE skin sections). Despite the

## Full-Scale Aircraft Fire Tests—A Comparison of Aluminium and Composite Burn-Through

aluminium sheets melting away from the GLARE panels, they remained largely intact with respect to not allowing the Test 2 fire smoke and heat to vent. The fact that the aluminium sheets within the GLARE melted also indicates that the fire temperature was above the melting temperature of aluminium, approximately 1202°F (650°C).

Point 11: The much smaller difference between TC#11 and TC#12 for Test 2 compared to Test 1, almost zero compared to 441°F (245°C), respectively can most likely be attributed to the lower thermal conductivity of CFRP (approximately 0.87 Btu/hr·ft·°F (1.5 W/m°C) versus 69.3 Btu/hr·ft·°F (120 W/m°C) for aluminium) or could have been a result of the insulating properties of the burning laminate construction where the inner plies separated, creating separate insulating char layers.

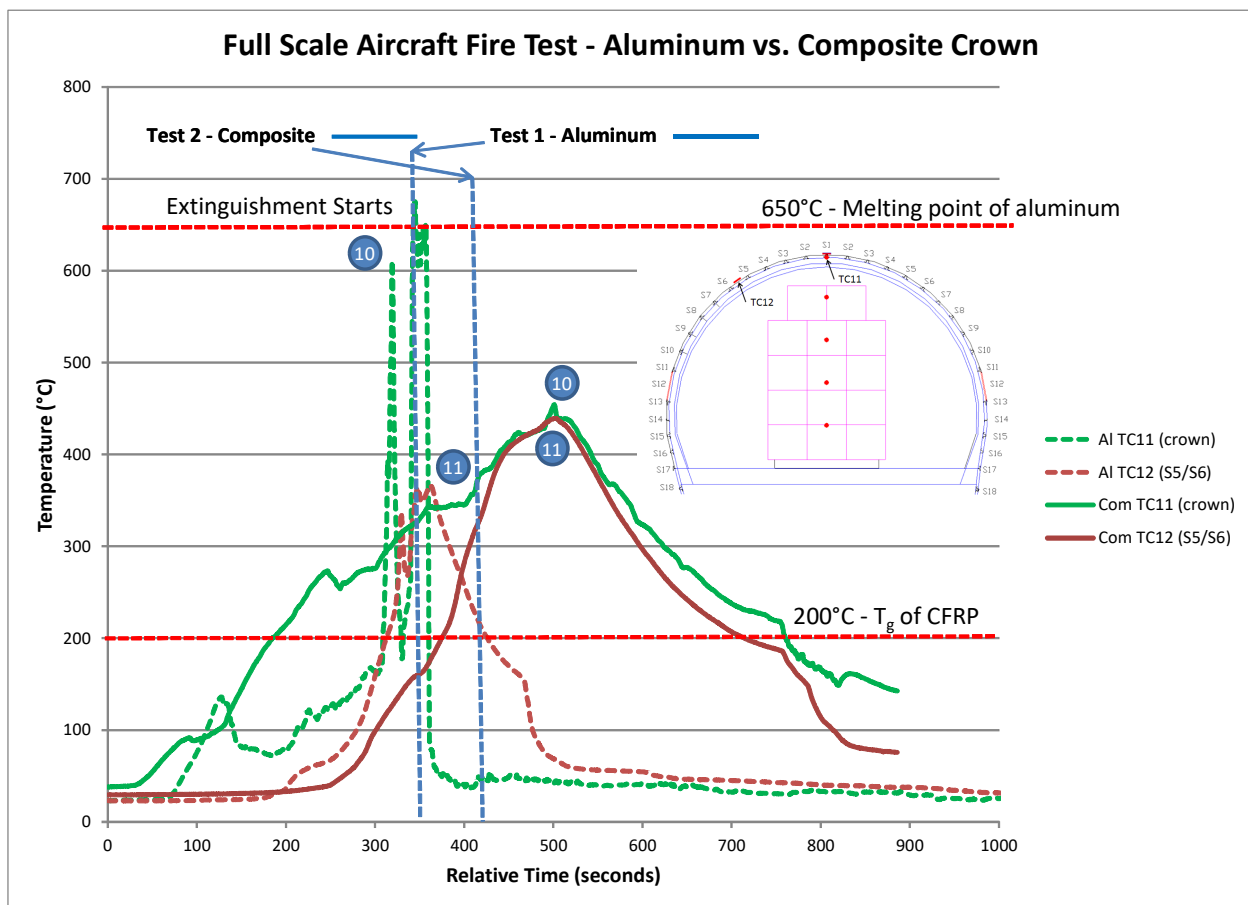


Figure 51. Test 1 versus Test 2 Exterior TC Measurements.

Lastly, although the maximum recorded temperatures for each test were remarkably similar, there was a much higher volume of unburnt fuel remaining in the Test 2 Composite fire as compared to the Test 1 Aluminium fire. Despite the general lack of recorded temperature evidence, it can be assumed that the Composite Test 2 fire reached higher temperatures than the Aluminium Test 1 fire, even with

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**Full-Scale Aircraft Fire Tests—A Comparison of Aluminium and Composite Burn-Through**

significantly less energy, as evidenced by the unburnt fuel. The higher temperatures for Test 2, reached under the assumption of lower energy levels, could be explained by the lack of venting in Test 2 as postulated prior to running the tests. The other major expectation proposed prior to testing i.e. persistent smoke levels in composite material fires, was also verified by firefighter observation.

Direct exposure to temperatures exceeding 1202°F (650°C) will result in the local loss of material in an aluminium fuselage whereas less than a third of that temperature (392°F or 200°C), the glass transition temperature ( $T_g$ ) for a CFRP fuselage cured at 350°F (177°C), the material's strength and stiffness will have been lost and the structure may collapse.

Appendix A-I is an excerpt from DOT/FAA/AR-00/28 which was used as the basis to size the fuel package.

Appendix A-II is a description of the Pyrolance component tests which were conducted outside of the scope of the two aircraft fire tests.

Appendix A-III is a description of the conduct of the airborne particulate measurement effort.

Appendix A-IV is a study of the electrical conductivity changes to the aluminium skins in the Test 1 and Test 2 locations and includes a thickness map of the fuselage skins in the two fire zones. Electrical conductivity data have been used in the past to demonstrate a change in aluminium temper which can be achieved with significantly lower temperature cycles than those generated by the fires in this project. Therefore the authors proposed using electrical conductivity data to map the fire effected zone for each test.

Some of the most important outputs from this work are the lessons learned from a firefighting perspective which are presented in the following Section 1.1. The OIAA ERS as well as OFS equipment was exercised and the Pyrolance was successfully demonstrated as an effective aircraft firefighting tool. Airport firefighters were provided with realistic aircraft firefighting training opportunities which demonstrated some of the critical differences between fighting fires on traditional aluminium versus composite material aircraft structures.

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**Full-Scale Aircraft Fire Tests—A Comparison of Aluminium and Composite Burn-Through**

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**5.1 LESSONS LEARNED – FIREFIGHTING TACTICS**

In Test 1, the fire attack was conducted from two fronts, upwind and downwind using the wings as an access platform. This placed two firefighters in the smoke plume. This was corrected for the Test 2 fire where all firefighters remained upwind.

For Test 1 the command post was remote from the viewing screens showing interior conditions. This forced the Incident Commander to move back and forth. This was corrected during Test 2 where all viewing screens were co-located with the command post.

The characteristics of both fires were known. The fuel load, location of the seat of the fire, cabin layout, and fire behaviour was known in advance. This places the incident commander and firefighters in an advantageous position which would not be the case during an actual fire event.

After both tests a substantial amount of heat was trapped in the remnants of the main pneumatic ventilation duct located in the attic. This could be observed with the outside thermal camera overlooking the fuselage crown. The duct space was inaccessible to water streams and that space could not be easily cooled down. Concealed spaces and voids such as cheeks and attics are areas where fire can spread undetected. Access to concealed spaces is problematic and presents a unique firefighting challenge.

In Test 1 the fire melted the aluminium fuselage skin at the crown level and allowed a rapid decrease of interior temperatures and the release of gases and smoke into the atmosphere. This in effect had a positive impact on extinguishment and smoke release.

The incident commander should continuously size up & monitor the fire situation. Factors such as smoke colour, condition and pressure should be observed and evaluated. Fire stream effects on the fire and heat should be evaluated. Fire streams discharged into void spaces will have little impact on heat and flames. If there are no rapid visible changes to the fire conditions within one or two minutes, fire streams should be relocated.

Both fire loads were identical. The presence of composite materials in the crown created a noticeable difference in the size of the burn-through area in Test 2 which was quite small and confined to the GLARE panels. Heat and gases did not escape as readily into the atmosphere as observed in Test 1.

The heat trapped inside the cabin melted the salvage tarp that was used to separate the cabin into two sections for the fires. The salvage tarp met the NFPA 701 Standard Methods of Fire Tests for Flame Propagation of Textiles and Films, 2010 Edition. In the first fire, the salvage tarp suffered discoloration and minor degradation due to heat damage but it was severely compromised in the



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**Full-Scale Aircraft Fire Tests—A Comparison of Aluminium and Composite Burn-Through**

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second fire which allowed smoke and heat to escape forward through the crown burn-through area from Test 1.

The overhead and HRET truck TIC cameras both provided a specific close-up view of a small section of the aircraft. For Test 2 a fire truck equipped with a TIC was positioned to one side of the fuselage to provide an overall thermal view. This provided an illustration of the movement of heat in the fuselage during the fire, effectiveness of water steam applications and areas of trapped residual heat that might require additional overhaul after the main fire was considered extinguished.

A composite fuselage adds two additional firefighting problems. The first one is the addition of toxic combustible material in the form of the matrix material holding the fibres (such as epoxy) which produces thick smoke that may contain loose/buoyant fibres and the second one is the lack of burn-through which holds heat and gases inside the cabin for a longer period of time.

The Pyrolance tool used during Test 2 demonstrated that it is well suited for extinguishing concealed fires. The tool is light and was easily deployed by a firefighter. It allowed the introduction of a water stream from the outside of the aircraft thus avoiding the need to make a forced entry. To maintain a water stream, the PyroLance must be held steady relative to the small hole in the skin. The three contact-point tip of the tool provides little support for off-axis contact and as a result the tool slipped on the wet surface thus reducing the amount of agent directed into the aircraft during the extinguishment period.

In the pre-fire equipment demonstration event, the PyroLance easily penetrated the laminated glass cockpit window and introduced foam onto the flight deck. This is not otherwise easily achieved with standard firefighting tools.

The introduction of large amounts of foam & water into an aircraft will create weight and balance problems. Four drain holes to evacuate firefighting water, approximately 8 square inches (51.6 cm<sup>2</sup>) in total area, were cut through the skin at the lowest point of the structure below the Test 2 site which is the forward end of the AFT cargo hold. Throughout the firefighting operations these four drain holes were continuously flowing. The skin in this area, between the two keel beams, is 0.144 inches (3.66mm) thick. Firefighters tried to use a Halligan tool and a fire axe to create a purchase point but had to resort to using a portable drill to create a large enough hole to insert the blade of a portable reciprocating saw to complete the cuts. Aircraft firefighters require an understanding of the variations in construction of the aircraft. The skin thickness and location rendered axes and piercing nozzles unsuitable for this task. These holes were affected prior to the test but the material thickness made the job difficult, time consuming and required non-traditional tools. Carrying out this task in proximity to a real fire would present multiple difficulties. The PyroLance tool might be employed

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**Full-Scale Aircraft Fire Tests—A Comparison of Aluminium and Composite Burn-Through**

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for this task but would require additional training to learn to create large diameter holes or intersecting linear cuts.

In both fires the damage was limited to the upper portion of the fuselage. The cabin floor maintained its integrity and did not sustain any fire damage. Due to its construction and design, a fire located beneath the cabin floor would likely compromise its integrity. This should be taken into consideration by an incident commander prior committing firefighters inside the cabin.

The smoke released during the Test 2 fire exited the aircraft through the over-wing exits. It then hugged the ground parallel to the fuselage on the PORT side. The unmanned robot, carrying a personal DataRAM, was tasked to operate in the smoke plume with the intent of collecting information on particulate size and concentration. The personal DataRAM screen was monitored by a camera mounted on the robot. Unfortunately the sunlight reflection onto the screen made interfered with the recording of the particulate content readings.

During Test 2, as soon as firefighting agents were applied to the cabin interior, smoke colour and behaviour changed. The smoke was no longer hugging the ground but lifted approximately 65 feet (20 meters) above ground and became lighter in colour.

The presence of carbon fibres complicates the task of the fire and rescue personnel working at the site. Turn-out gear and self-contained breathing apparatus offer an adequate level of protection. Other emergency responders, who may be present at the scene or contacted by the smoke plume, do not have this level of protection. More research is needed on particulate geographic distribution modelling at an aircraft crash site and its impact on first responders and the environment.

In both fires the equipment and personnel were pre-staged and ready to carry out the extinguishments. The daylight conditions were conducive to communication and co-ordination of activities.

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**Full-Scale Aircraft Fire Tests—A Comparison of Aluminium and Composite Burn-Through****5.2 POTENTIAL FUTURE WORK**

Samples of the GLARE and CFRP panels should be collected and the fire damage more closely examined. The CFRP panels should also be examined for matrix material (epoxy) loss through the thickness.

The subject aircraft is to be scrapped in 2015. Prior to this, a final larger fire is being planned. This fire may include an exterior fuel source in addition to the combustion of materials in the AFT cargo hold and on the AFT main-deck. The intention is to have sufficient fuel and fire duration to destabilize the structure such that the fuselage behind the main gear will collapse. This will present a more realistic crash scenario that will be further complicated by being conducted at night.

CFRP materials may be included in the fuel load on-board the aircraft so that additional particulate measurement data may be collected during the course of the fire and extinguishment.

Work is currently underway to add a thermal imaging video camera to the head of the HRET boom. This installation will have wireless video connections to both the HRET fire truck, Red 10, and the command truck Red 1. When the HRET is employed for firefighting the boom TIC will assist in water cannon deployment (over-the-top visualization for the operator) and piercing target selection. When not firefighting the boom can be extended towards its full height and the TIC utilized to provide an overhead view of the scene. If available at the time of the next fire test, this tool should be employed.

PyroLance will be invited to participate again, along with the OFS. Post-test, the OFS would be invited to practice cutting structure for emergency ingress with hand-held power tools.

## **6.0 ACKNOWLEDGEMENTS**

Mr. R. Elmer of Ottawa volunteered many hours of his time before and during the tests to provide both video equipment and related technical support. Except for the TIC units and GoPro camera belonging to the OIAA ERS, all of the video cameras were supplied with customized mounting fixtures and, where required, interconnect cables, wireless hub and lap top computers. A portable power supply and two TV monitors at the command post were also supplied and installed by Mr. Elmer. Post-production video download and conversion services were also supplied.

Ms. L. Preston, a summer student with the OIAA ERS, assisted in the installation of the cameras and acted as the roving videographer during the tests.

Mr. S. Muradori and Mr. M. Weinfurter from the NRC Construction Portfolio provided and installed the thermocouples and their associated DAQ system. Ms. C. Lam carried out a literature search for relevant guidance documents related to fuel package sizing and configuration.

Ottawa Fire Services provided personnel & equipment during both fires. We would like to thank District Chief Paul Fortin, Capt. Trevor Woodside, Lt. Guy Pollock, Safety Officer Peter Barton, Respiratory Protection Manager John McGrath as well as Acting District Chief Scott Grakist and Acting Capt. Nick Georgitsos.

The Canadian representative for PyroLance, Mr. M. Biernat along with Mr. C. Seyffert and D. Hutchinson from the US headquarters in Aurora, CO., USA carried out demonstrations of their equipment and answered questions from the attendees in the morning before Test 2. Mr. Hutchinson then assisted a fire fighter from the OIAA ERS in the PyroLance extinguishment during the Test 2 fire.

Mr. P. Rocco and B. Smith of Provectus Robotics Solutions Inc., Ottawa, volunteered to support airborne particulate monitoring during Test 2 with the use of an ODG Argo J5 wheeled robot complete with a remote control station.





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**APPENDIX A:****Appendix A.I DOT/FAA/AR-00/28**

Excerpt from Executive Summary:

“...This report documents the testing program that was commissioned by the International Halon Replacement Working Group (IHRWG) to develop the minimum performance standard for aircraft cargo compartment built-in fire suppression systems. The evaluation tests were conducted at the Federal Aviation Administration (FAA) William J. Hughes Technical Center in a modified DC-10 aircraft. The results from these tests, based on the Halon 1301 performance under well-defined cargo fire scenarios, were used to define the acceptance criteria that will be used to certify alternate gaseous extinguishing agents for aircraft cargo compartment fire protection.

Four different fire test scenarios were specified in the standard developed by the IHRWG; bulkload fire, containerized fire, flammable liquid fire (surface burning), and an aerosol can explosion. The deep-seated fire scenarios (bulk load and containerized load) used shredded paper loosely packed in cardboard boxes to simulate the combustible fire load. The difference between these two test scenarios was that in the containerized fire load the boxes were stacked inside a LD3 container, while in the bulk-load fire scenario the boxes were loaded directly into the cargo compartment...

**2.3.1 Bulk-Load Fire**

The fire load for this scenario was 178 single-wall corrugated cardboard boxes, with nominal dimensions of 18 x 18 x 18 inches (45.7 x 45.7 x 45.7 cm). A fire load of 30% of the cargo volume was selected by the IHRWG task group as the best compromise between a realistic loading percentage, ensuring enough combustible material for the spread of the fire, minimizing unnecessary set up and cleanup efforts, and preventing too high of an initial suppression agent concentration due to the air displaced by the fire load. The weight per unit area of each cardboard box was 0.11 lbs/ft<sup>2</sup> (0.54 kg/m<sup>2</sup>). These boxes were filled with 2.5 pounds (1.13 kg) of shredded office paper, loosely packed without compacting. The weight of each filled box was 4.5 ± 0.4 lbs. (2.05 kg ± 0.18 kg). The flaps of the boxes were tucked under each other with no staples or tape used. The boxes were stacked in two layers inside the cargo compartment without any significant air gaps between them. Ten 1-inch (2.5-cm) -diameter ventilation holes were placed in the side of the initially ignited box to ensure that the fire did not self-extinguish (Figures A-2 and A-3).”

# Full-Scale Aircraft Fire Tests—A Comparison of Aluminium and Composite Burn-Through

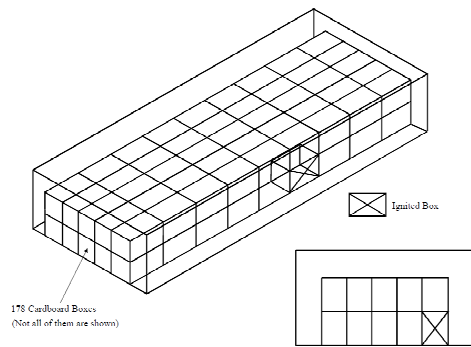


FIGURE A-2. BULK FIRE LOAD TEST SETUP

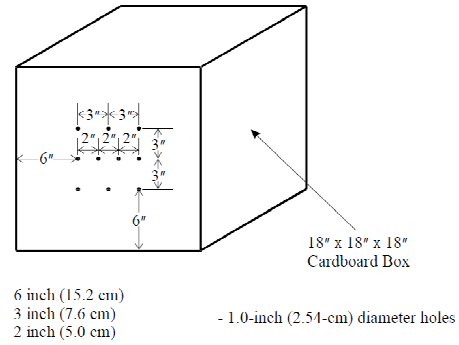


FIGURE A-3. IGNITER BOX

**Full-Scale Aircraft Fire Tests—A Comparison of Aluminium and Composite Burn-Through****Appendix A.II Pyrolance Component Tests**

As there were many structural firefighters in attendance the first Pyrolance demonstration was against a concrete block. The water pump was operated at 1500 psi and granite particles constituted the abrasive media. The abrasive media is metered and introduced from a reservoir at the pump and then delivered to the piercing lance. With 150 feet of hose on the reel it takes approximately 30 seconds for the abrasive media to reach the tool after the trigger on the lance is pulled. There may have been some residual granite media in the system but this first application might be considered as being accomplished with minimal media in the high-pressure water jet. The application cut through the first wall of the block in five seconds and completely through the opposite side in another 19 seconds for a total time of 24 seconds (Fig. A.II-1.).

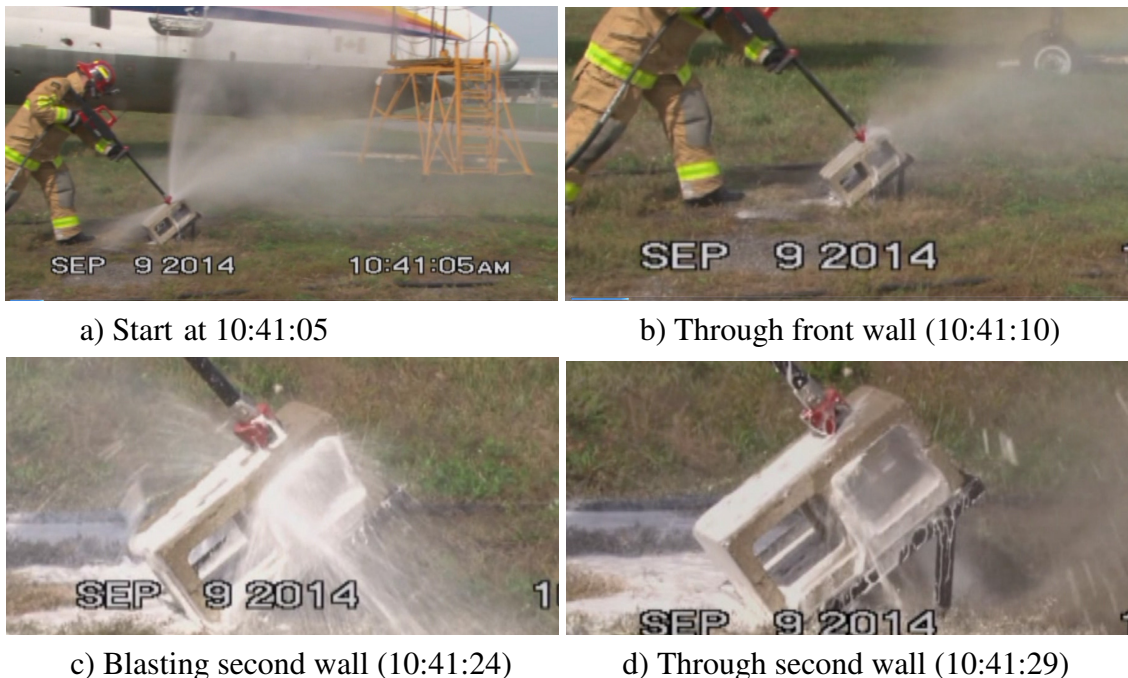


Fig. A.II-1. Concrete block. Water jet only. Duration:0:24.

With abrasive media in the water flow for the second demonstration on the concrete block the jet pierced the first wall in one second and went completely through the block in nine seconds (Fig. A.II-2.).

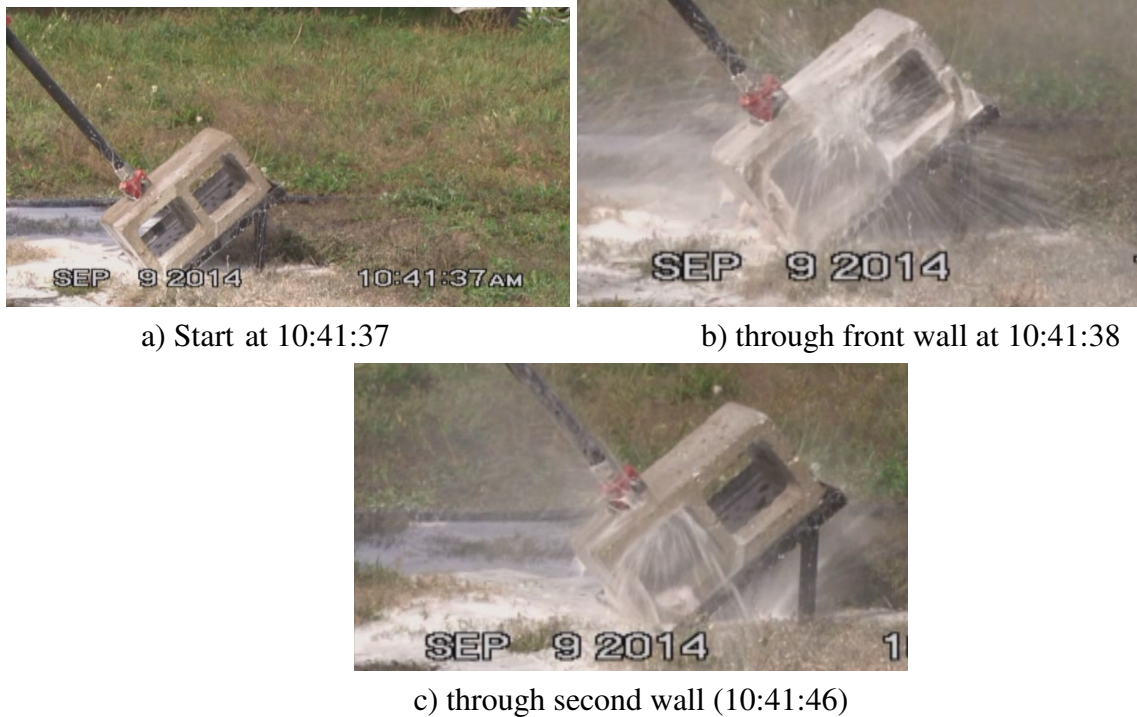
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Fig. A.II-2. Concrete block. Abrasive media & water jet. Duration: 0:09.

The next demonstration was on-aircraft against the cockpit windshields which are typically difficult to cut for emergency access to the cockpit. The Direct Vision (DV) side windows in this case are laminated stretched acrylic which is easy to cut with an abrasive disc or toothed circular saw blade. The PyroLance pierced through the outer layer but completely delaminated the plies such that water began to accumulate. This water layer absorbed the energy of the water jet abrasive media and delayed complete penetration. The trial was halted after 14 seconds (Fig. A.II-3.). The window might have been fully penetrated with a longer application as evidenced upon close examination from the inside (Fig. A.II-4). The water level was observed to be more than half the height of the window. The water was observed draining out during the second cockpit window trial.





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c) Quit without full penetration at 10:47:04. Plies were delaminated and water filled cavity.

Fig. A.II-3. STBD DV cockpit window (laminated stretched acrylic). Duration: 0:14.

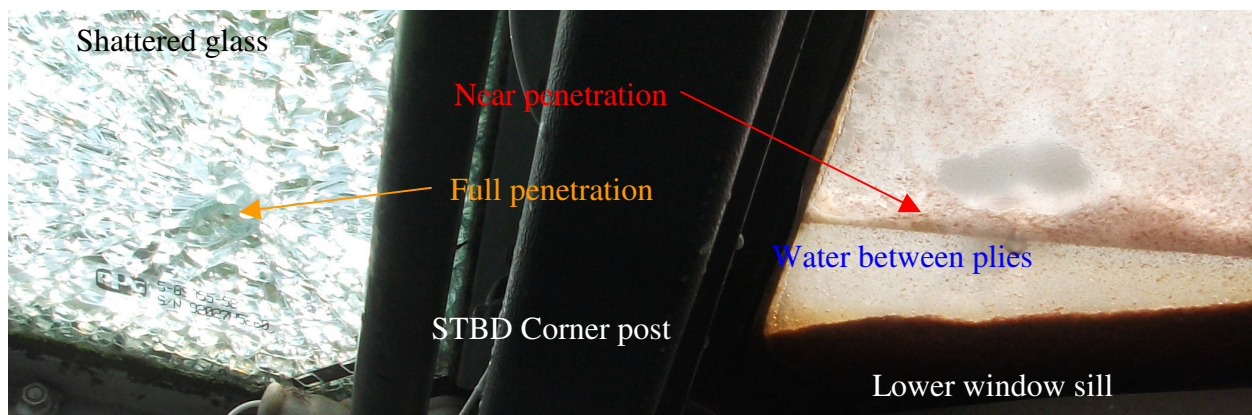


Fig. A.II-4. Interior view of STBD Cockpit windows.

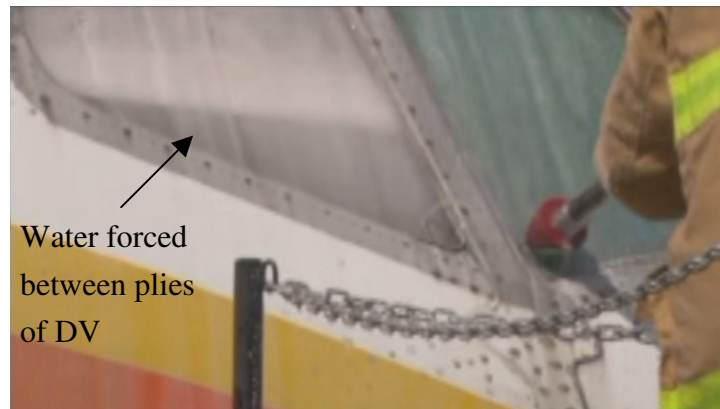
The front cockpit windshields are constructed as a glass panel laminate. These are very difficult to cut due to the multiple glass layers or punch through as they have a bird impact rating. The water jet abrasive media shattered the glass plies as expected (they are tempered) and pierced through the laminate thickness in 32 seconds (Fig. A.II-5.). Thus a rapid method of introducing firefighting agent into the cockpit was demonstrated.



a) Start at 10:47:11)

b) Media blasting (10:47:37)



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c) End at 10:47:43. Window was fully penetrated.

Fig. A.II-5. STBD cockpit window (laminated glass). Duration: 0:32.

A panel of CFRP had been attached to the fuselage of the aircraft for Pyrolance demonstration. The aluminium skin behind the panel had been removed. The composite panel was nominally 0.3 inches thick. It was pierced and the stream of firefighting agent was introduced into the main deck area of the forward fuselage within approximately 6 seconds. The result was a very clean hole and only the inner fibreglass (anti-corrosion) ply was delaminated (Fig. A.II-6).



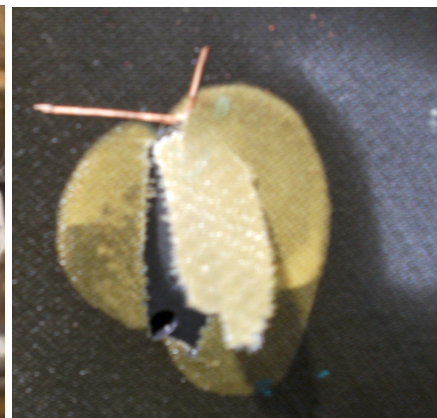
a) Start at 10:59:52



b) Media blasting (10:59:58)



c) End at 10:59:59 with full penetration



d) delamination of fibreglass ply

Fig. A.II-6. CFRP panel (0.030 inch thick). Duration: 0:06.

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The PORT side of the FWD fuselage has an extra 0.1 inch thick (2.54mm) skin installed that surrounds the main-deck cargo door. This external skin doubler was installed over the existing fuselage skins and so a combined thickness of 0.145 inch (3.68mm) had to be pierced to accomplish penetration into the cargo hold, just above the floor and below the sidewall cheek area. Between the outer skins and the hold there exists only a thin fibreglass liner. The PyroLance succeeded in piercing completely and introducing a stream of firefighting agent into and across the width of the hold in seven seconds (Fig. A.II-7). This location is too low on smaller aircraft to permit a HRET Stinger piercing and too high on larger aircraft for expeditious manual piercing.

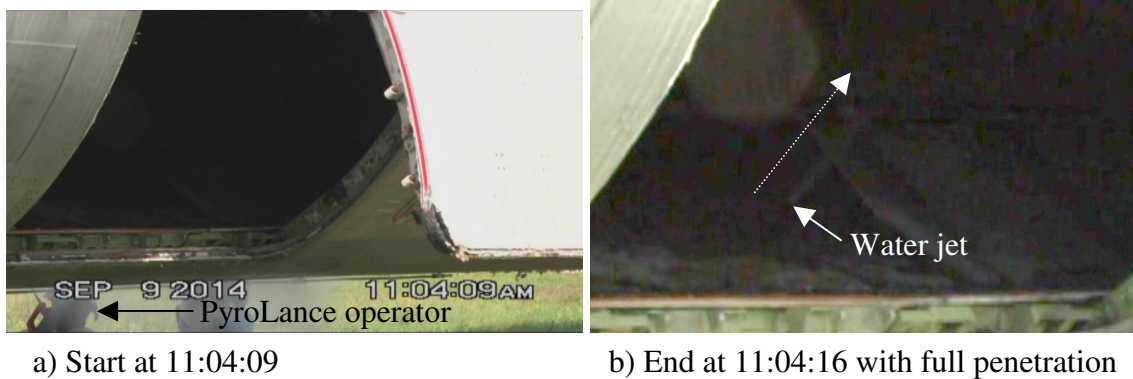
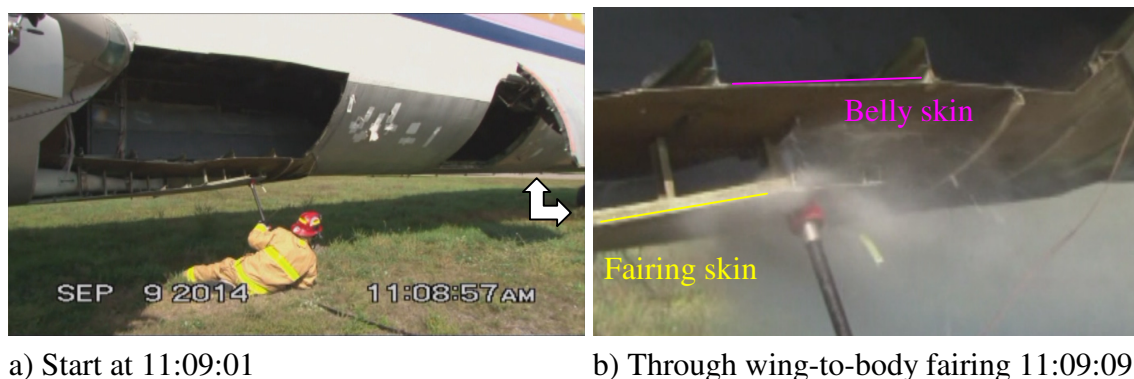


Fig. A.II-7. FWD Cargo hold. PORT side. Skins are 0.1" + 0.045" tk. Duration: 0:07.

External access to the aft end of the FWD cargo hold (or FWD end of the AFT cargo hold) is obstructed by the wing-to-body fairing. A portion of the fuselage sidewall and fairing had previously been removed giving access to view the action of the water jet stream through the structural elements. The Pyrolance succeeded in piercing both the fairing (8 seconds) and fuselage skin within 53 seconds but the stream then encountered the side of a longitudinal stringer whose shape appeared to redirect the water stream although some erosion was accomplished. Piercing multiple layers at a distance from each other may have diffused the water stream and degraded its effectiveness. The trial was halted after 1:36 without piercing the cargo bay floor, Fig. A.II-8.

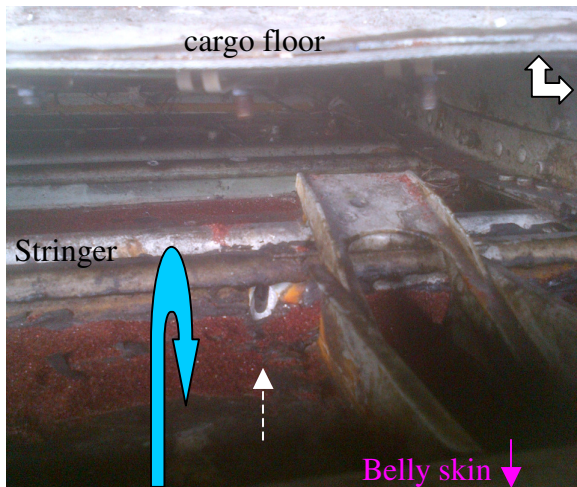


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c) Through cargo belly skin at 11:09:54.



d) End after no progress (11:10:37)



e) Water jet deflected by curvature of stringer flange. Did not penetrate flange or cargo floor.

Fig. A.II-8. Rear of FWD Cargo hold. STBD side. Floor skin not penetrated. Duration: 1:36.

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**Full-Scale Aircraft Fire Tests—A Comparison of Aluminium and Composite Burn-Through****Appendix A.III Particulate Measurement****BACKGROUND AND REGULATORY FRAMEWORK**

Particles in the atmosphere have various shapes & sizes and can be solid particles or liquid droplets. Particles are divided into two major groups. Their diameters range from 0.005 to 100µm. The size range of concern to human health and Indoor Air Quality (IAQ) is 0.1-10µm. Particulates within that range are breathable, unfiltered by the nose and not exhaled. These particulates reach the thoracic and lower regions of the respiratory tract and create health problems.

The U.S. Environmental Protection Agency ASHRAE Standard 62-1989 set an exposure level PM10 of 0.15 mg/m<sup>3</sup> for 24-hour exposure. The American Conference of Industrial Hygienists (ACGIH) sets threshold limit value (TLV) of 10 mg/m<sup>3</sup> for amorphous silica and other common non-hazardous dusts. The current exposure limit for Particulate Not Otherwise Specified (PNOS) in Ontario workplaces as per O. Reg. 833 is 3 mg/m<sup>3</sup>.

Provectus Robotics Solutions Inc. of Ottawa had supported previous NRC/OIAA ERS full-scale fire tests with antonymous robots employed to provide video coverage from within smoke plumes but the robots had not been instrumented to assess for environmental hazards. The wheeled robot provided for Test 2 was an ODG Argo J5 carrying a Thermo Scientific personal DataRAM™ pDR-1000AN Monitor and it ran a track just beyond the perimeter fence but within the down range smoke plume. The robot's onboard video camera was trained to view the display on the DataRAM unit. The sensor measures mass concentrations of dust, smoke, mists and fumes in real-time. Various readings were taken at distances from 0-197ft. (0-60m) from the airport fence which was 108ft. (33m) from the seat of the fire onboard the aircraft. The 32.8ft. (10m) intervals between sensing stations were marked by pylons set in the field (Stn 1 to Stn 6 with the fence being Stn 0). The robot was controlled remotely from a vehicle in the parking lot, Fig. A.III-3.

Sunlight and surface scratches on the sensor display bezel obscured the robot's onboard video camera view of the top line of the display for Concentration (CONC). The Time Weighted Average (TWA) readings on the bottom were observable as shown in Fig. A.III-1. The TWA values are an average of the CONC values over one minute.



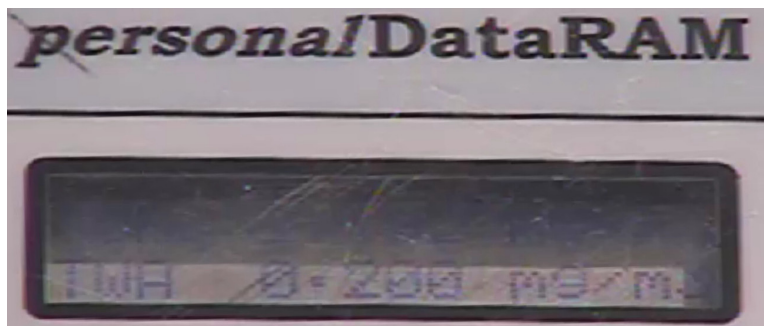
**Full-Scale Aircraft Fire Tests—A Comparison of Aluminium and Composite Burn-Through**

Fig. A.III-1. DataRAM pDR-1000AN Monitor display at 6:29.

The fire had started 5:43 before the first reading. The first extinguishment, using the Stinger, occurred between 7:49 and 8:55. The PyroLance was employed between 9:18 and 9:54. The hand-line extinguishment started at 12:04 and ended at 15:45. Table 3 shows the timings of the readings and the distance of the robot/sensor from the seat of the fire.

Table 3. Time, interval, distance and particulate concentration as a Time Weighted Average.

Fire Clock (min:sec)	Interval between readings	STN	Distance from fire*		TWA (mg/m <sup>3</sup> )
			(feet)	(meters)	
5:43		2	174	53	0.094
6:29	0:00	3	207	63	0.200
6:47	0:00	3	207	63	0.298
7:27	0:00	4	239	73	0.662
8:01	0:00	5	272	83	0.824
8:37	0:00	6	305	93	0.895
9:33	0:00	1	141	43	0.918
10:09	0:00	2	174	53	0.903
21:07	10:58	1	141	43	0.889
22:01	0:54	0	108	33	0.876

\* airport perimeter fence 108 ft (33 m) from the seat of the fire

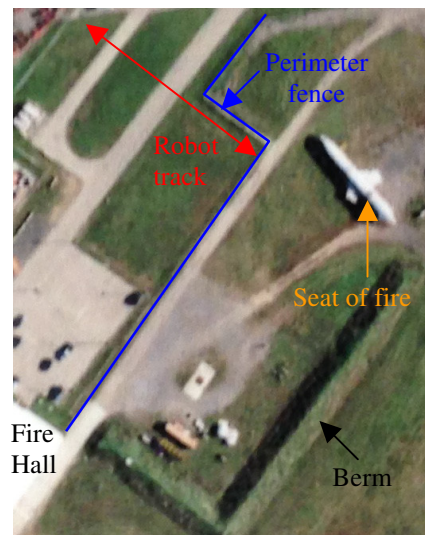


Fig. A.III-2 is a graphical representation of the data in Table 3. The latter two readings occur near the end of the overhaul actions on the main deck which started at 17:43 and ended at 25:12 and show that the airborne particulate readings remained elevated, at least as far away as the perimeter fence, after the open fire was suppressed.



# Full-Scale Aircraft Fire Tests—A Comparison of Aluminium and Composite Burn-Through

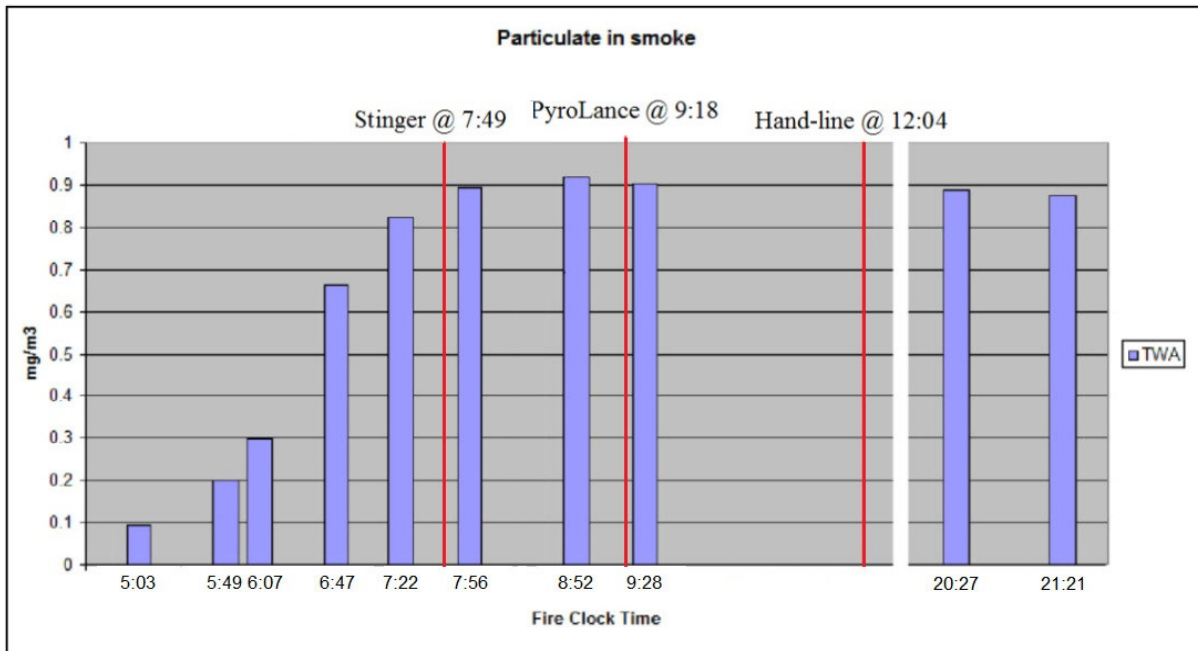


Fig. A.III-2. Plot of particulate TWA values with start of extinguishments annotated.

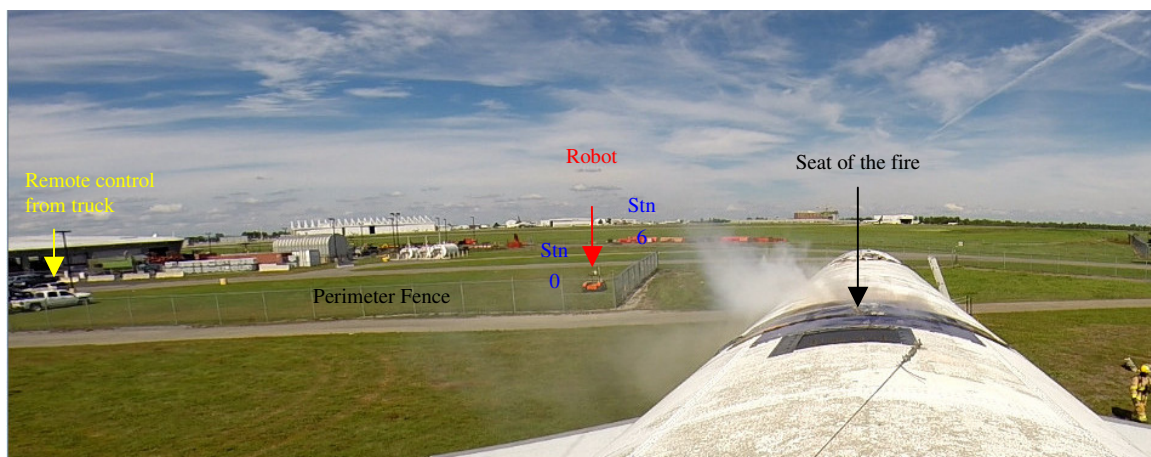


Fig. A.III-3. View of robot and command truck from GoPro camera position atop aircraft fuselage.

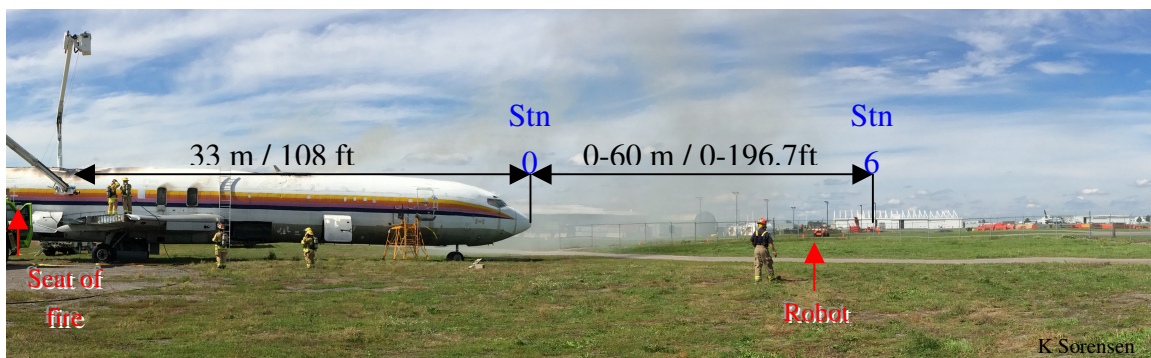


Fig. A.III-4. Side view showing seat of fire and robot sensing station track.

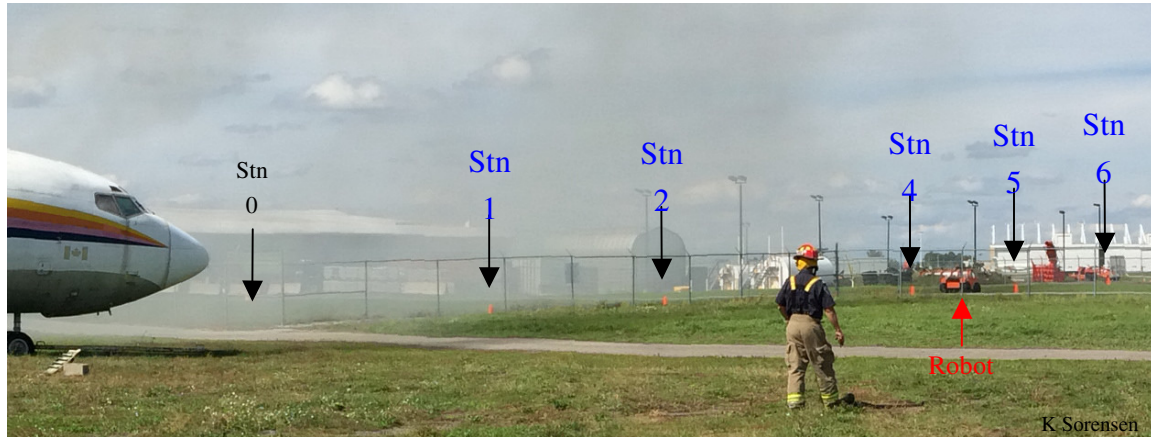
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Fig. A.III-5. Side view shows robot at Station 5 (50 m, 164 ft) and station cones 1 to 6 in field.

In the side views, Fig. A.III-4 and Fig. A.III-5 the smoke is moving from the fuselage into the area patrolled by the robot carrying the particulate sensor almost exactly parallel to the fence and patrol route of the robot. This is true even for the smoke exiting the STBD over-wing emergency exits as this smoke crossed over the crown and joined the smoke from the PORT door openings as shown in Fig. A.III-6. The robot is at Station 5 from 7:47 as shown in Fig. A.III-5 but exactly when it moves away to Station 6 is obscured by smoke. This view exemplifies the smoke density at Stn 5 when the reading was recorded at 8:01. The density of the smoke is much higher when observed at the source and from behind rather than perpendicular to the air flow. This is shown in Fig. A.III-7 as a series of frames from a camera that was mounted in the centre engine inlet duct.



Fig. A.III-6. STBD side smoke crossing over fuselage crown.



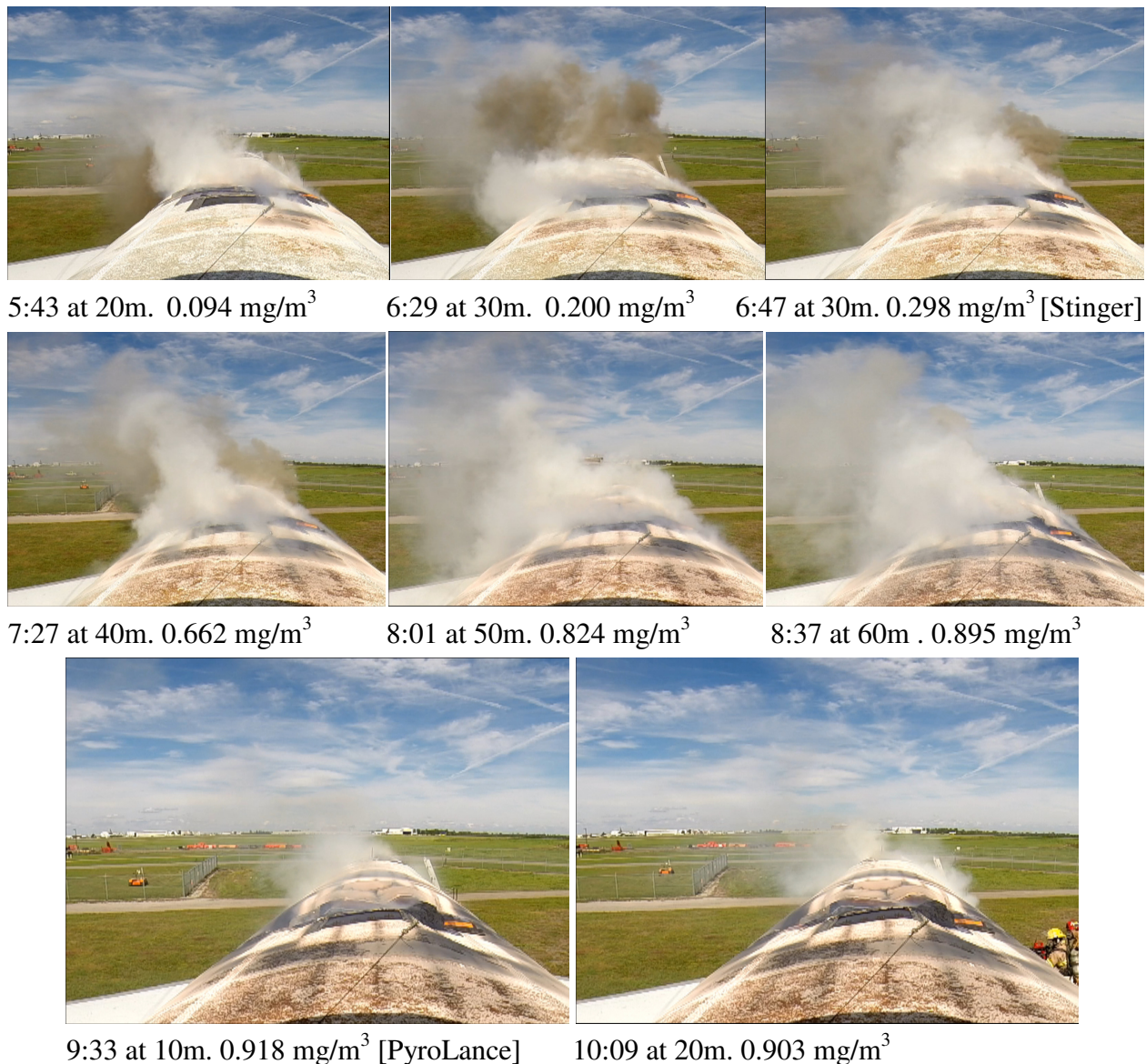
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Fig. A.III-7. Camera views of smoke conditions at the times of particulate sensor readings.

The centre-line engine inlet duct video was also analyzed to determine the path of the robot and timing between moves from station to station, Table 4. Still images of selected video frames taken at the same time as the sensor readings where the robot was visible (Fig. A.III-7) were imported into a CAD program where the front of the robot, fence elements and station cones were traced. These CAD sketches were superimposed to create the sketch shown in Fig. A.III-8. The numbers in the boxes illustrate the sequence of robot movement. It may be that the smoke forced the robot away from the direct line of the station cones as the operator needed to see the robot to manually execute the drives. The robot position was obscured by smoke in this camera view for two periods: 6:17 to 7:13 (0:56 duration) and again between 7:53 to 8:41 (0:48 duration).

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Table 4. Robot position and time at each station. Some robot movements obscured by smoke.

Position	Station	Fire Clock Time		Position	Station	Fire Clock Time	
		Reading @	Time at Station			Reading @	Time at Station
1	2	5:43	5:09 to 6:08	6	6	8:36	(obscured) to 8:58
2	3	6:29	6:14 to (obscured)	7	1	9:33	9:10 to 9:52
3	3	6:47		8	2	10:08	9:54 to 10:33
4	4	7:27	7:14 to 7:40	9	<1	21:07	(on the move)
5	5	8:02	7:47 to (obscured)	10	0	22:01	20:55 to end

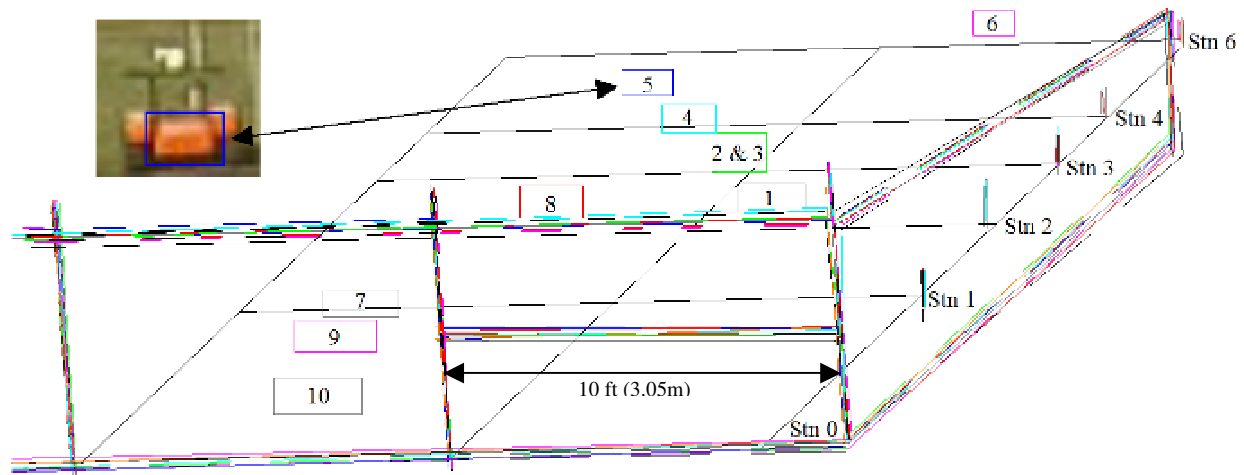


Fig. A.III-8. Path and position of robot (front of hull) during particulate sampling.

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## Appendix A.IV Electrical Conductivity and Fuselage Skin Thickness Measurements

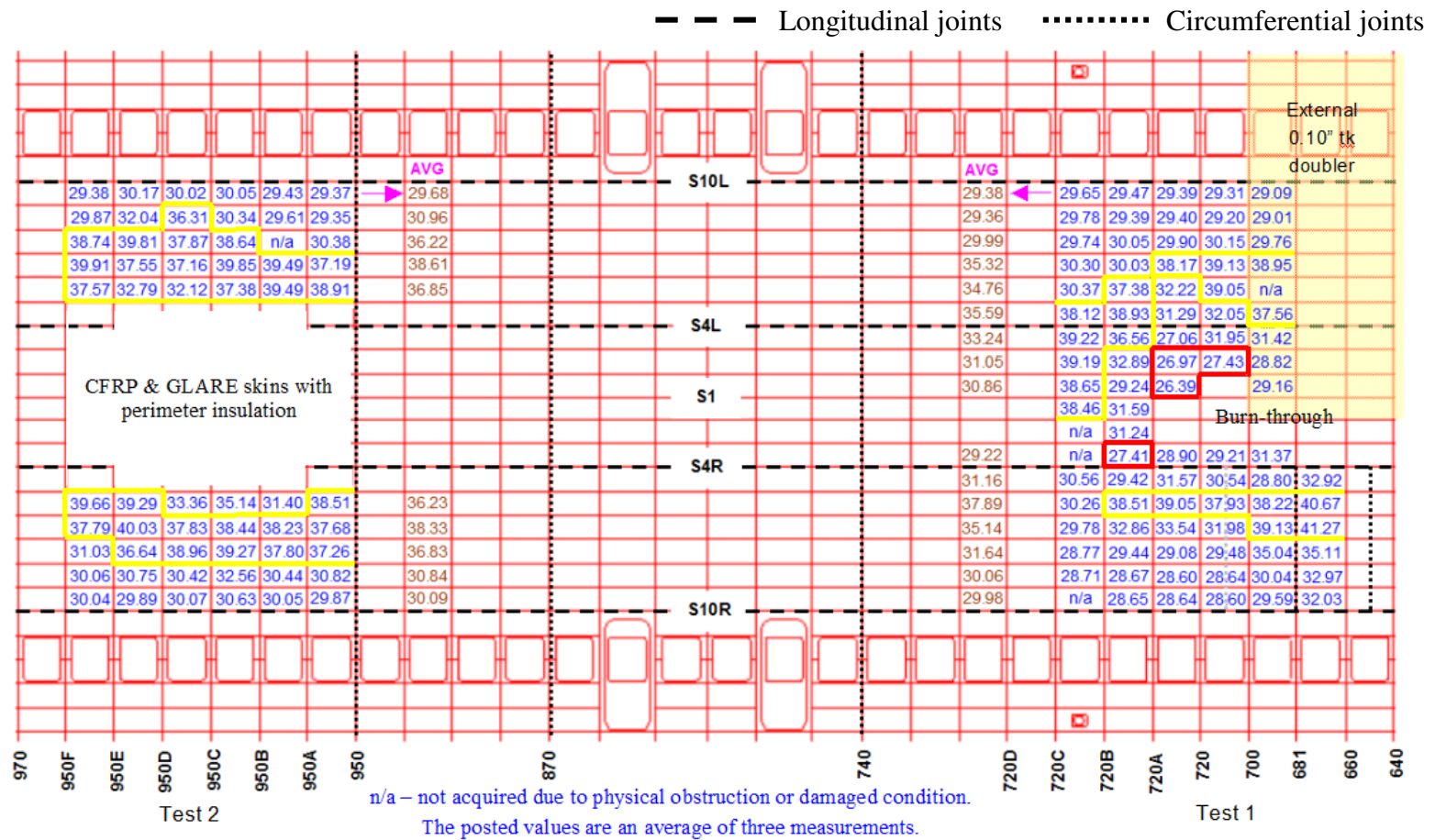


Fig. A.IV-1 Post-test 2024-T3 aluminium skin conductivity (% ICAS) measurements and average values (horizontally).



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The value for undamaged 2024-T3 aluminium sheet is given as ranging between 28.6 and 36.1 % ICAS. In Fig. A.IV-1 the areas with measured values exceeding the upper limit are bordered by yellow lines. Note that the majority of measurements taken on obviously heat damaged sheet adjacent to the burn-through area of Test 1 are not outside the range for the undamaged condition except in two areas (red border).

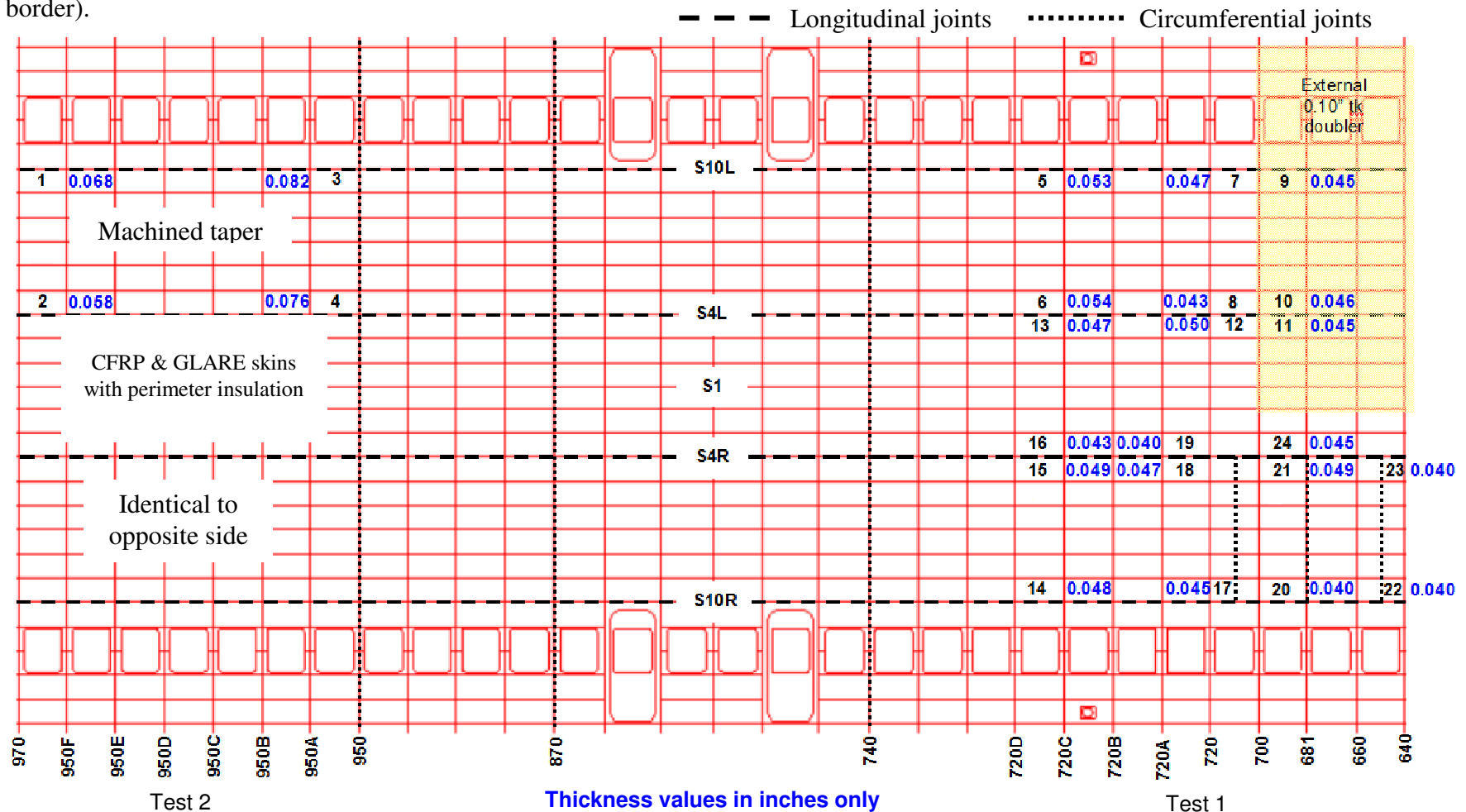


Fig. A.IV-2. Post-test aluminium skin sample locations (black) and skin thickness (blue).

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Fig. A.IV-2 shows the locations and thickness measurements recorded from fuselage skin samples removed after both tests were completed. The paint was stripped off prior to measurements being taken. In some cases a carbonized surface layer remained that could not be removed with chemical strippers. This residual surface contamination was not deemed to be significant to the overall thickness measurement. The posted values are an average of three measurements.