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Aircraft Skin-Penetrating Nozzle Testing of a Freighter Aircraft Cargo Liner

December 2012

Final Report

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16. Abstract

Following the in-flight cargo fire accident involving United Parcel Service (UPS) flight 1307 at the Philadelphia International Airport on February 7, 2006, the National Transportation Safety Board determined that the Aircraft Rescue and Firefighting personnel did not have adequate training in fighting freighter aircraft fires. A post-incident, on-aircraft analysis by UPS personnel suggested the cargo liner interfered with the aircraft skin-penetrating nozzle's (ASPN) ability to discharge firefighting agent on the fire. The UPS analysis suggested that the firefighting agent became trapped between the cargo liner and the fuselage, implying that the liner separated from the fuselage and acted as a shield, which prohibited the firefighting agent from controlling the cargo fire. The research described in this report evaluates the role of cargo liner in penetration of an aircraft with an ASPN.

Small-scale scoping tests identified the penetration behavior of heated cargo liner within an area of approximately 480 square inches. The cargo liner was mounted in a frame and penetrated with an ASPN that was fitted to a hydraulic ram. Initial penetration tests were conducted with cargo liner intact. Heated tests involved penetration while the material was directly exposed to a kerosene burner flame. Full-scale tests examined the role of cargo liner mounting hardware in ASPN penetration. The full-scale test article was composed of a mockup section of the freighter aircraft. This was created by mounting the cargo liner in a section of a modified C-133 aircraft. A cargo liner mounting frame was duplicated from an example freighter aircraft. The frame used normal aircraft construction techniques and materials. Electric radiant heaters and liquid fuel pool fires served as heat sources. An ASPN mounted on a high-reach extendable turret (HRET) was used to penetrate the aircraft.

Penetration results were evaluated based on the number of unblocked ASPN holes on the interior side of the cargo liner. Under ambient conditions, the cargo liner did not significantly stretch or otherwise impede penetration. The heated cargo liner exhibited limited stretching or sagging, but not enough to obstruct the ASPN. Only 1 of the 45 full-scale heated tests demonstrated significant nozzle obstruction. Small-scale heated tests indicated that incomplete penetration or reduced penetration depth could lead to obstruction of 33% to 77% of the nozzle. Overall, tests indicated that cargo liner material does not normally hinder the use of an ASPN for application of firefighting agent. Given sufficient penetration length, it was observed that the ASPN is capable of penetrating through the cargo liner into the interior of the aircraft.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

AFFF	Aqueous film forming foam
ARFF	Aircraft Rescue and Firefighting
ASPN	Aircraft Skin-Penetrating Nozzle
CFR	Code of Federal Regulations
FAA	Federal Aviation Administration
FedEx	Federal Express Corporation
GPH	Gallons per hour
GPM	Gallons per minute
HRET	High-reach extendable turret
MD	McDonnell Douglas
NTSB	National Transportation Safety Board
PHL	Philadelphia International Airport
SPAAT	Skin penetrator agent application tool
TC	Thermocouple
UPS	United Parcel Service, Inc.

EXECUTIVE SUMMARY

Following investigation of the in-flight fire accident involving United Parcel Service (UPS) flight 1307 at the Philadelphia International Airport on February 7, 2006, the National Transportation Safety Board determined that the Aircraft Rescue and Firefighting personnel did not have adequate training in fighting freighter aircraft fires. A post-incident, on-aircraft analysis by UPS personnel suggested the cargo liner interfered with the aircraft skin-penetrating nozzle's (ASPN) ability to discharge firefighting agent on the fire. An ASPN is a nozzle designed to pierce an aircraft fuselage to apply firefighting agent without the need for firefighters to make entry into the fuselage. Cargo liner is a thin, fiberglass composite installed in cargo compartments as a fire barrier. It also serves to reduce damage to aircraft systems from loose cargo.

UPS personnel suggested that the firefighting agent was trapped between the cargo liner and the fuselage, implying that the liner separated from the fuselage and acted as a shield that prevented the firefighting agent from controlling the cargo fire. In response, members of the Federal Aviation Administration (FAA) Airport Technology Research and Development Branch initiated research to evaluate aspects of ASPN penetration of cargo liner material. The research described in this report evaluates the role of cargo liner in penetration of an aircraft with an ASPN.

Small-scale tests were initially conducted to identify and scope the behavior of heated cargo liner while being penetrated with an ASPN. These tests included penetration under both unheated (ambient) and heated conditions. An ASPN mounted on a hydraulic ram was forced through the cargo liner. The heated tests used the FAA's 2-gallon-per-hour, oil-fired burner to apply flame directly to the cargo liner. Small-scale heated tests showed that incomplete penetration could lead to obstruction of 33% to 77% of the nozzle holes. Full-scale tests were conducted to examine the role of mounting hardware in the effectiveness of ASPN penetration. A mockup section of freighter aircraft was created in part of a C-133 fuselage at the FAA William J. Hughes Technical Center in Atlantic City International Airport, New Jersey. A cargo liner framework was built with normal aircraft materials and construction techniques. The frame was installed in the test fuselage, and penetration tests were performed with an ASPN mounted on a high-reach extendable turret. Similar to the small-scale tests, penetrations were performed under both heated and unheated conditions. Electric radiant heaters and liquid fuel pool fires served as heat sources during the full-scale tests. This isolated the effects of fire and flame-heated behavior versus the purely radiant-heated behavior of the cargo liner.

The test results were evaluated based on the number of nozzle holes that were blocked by the cargo liner. Under ambient conditions, the cargo liner did not impede penetration at all. When heated, the cargo liner exhibited limited stretching, but did not obstruct the ASPN. The flame-heated tests showed that, in most cases, resin loss allowed the ASPN to pass through the cargo liner easily. Only 1 of the 45 full-scale, in situ, heated tests demonstrated significant nozzle obstruction. This one exceptional test demonstrated the effect of hardware failure. In this

instance, hardware failure caused the cargo liner to hang loosely from the fuselage. Because the cargo liner material was not held tightly, the ASPN could not effectively penetrate it. Overall, the results indicated that cargo liner material does not normally block the ASPN. Conditions that would cause the cargo liner to hang loosely are likely to cause unmitigated damage to the aircraft and contents.

1. INTRODUCTION.

In the 2009 Advisory Circular 150/5210-17B, the Federal Aviation Administration (FAA) added freighter aircraft familiarization as a requirement for Aircraft Rescue and Firefighting (ARFF) training [1]. To help the ARFF community find the best methods for fighting cargo fires on freighter aircraft, the FAA tasked members of the Airport Technology Research and Development Branch's (ANG-E261) ARFF program to research freighter aircraft firefighting.

One event that influenced the inclusion of freighter aircraft familiarization in ARFF training was a fire incident involving United Parcel Service (UPS) Flight 1307 at the Philadelphia International Airport (PHL) on February 17, 2006. The National Transportation Safety Board (NTSB) Accident Report, NTSB/AAR-07/07 [2], states that the first officer of Flight 1307 reported an odor that smelled like burning wood approximately 25 minutes prior to landing. After trying to identify the cause of the odor for approximately 20 minutes, the flight crew confirmed the presence of smoke in the cargo area. The captain declared the flight an emergency to air traffic control and requested that emergency personnel meet the aircraft upon landing. The aircraft landed safely, and ARFF operations began. After approximately 4 hours, PHL ARFF personnel declared the fire under control. The NTSB determined that PHL ARFF personnel did not have adequate training in fighting freighter aircraft fires [2].

A post-incident, on-aircraft analysis by UPS personnel suggested the cargo liner interfered with the aircraft skin-penetrating nozzle's (ASPN) ability to discharge firefighting agent on the fire. UPS personnel noted the floors of the main cargo deck were "fairly pristine," and the back of the cargo liner was very clean. The interior temperatures, however, would have been high enough to melt or burn the plastic in the cargo liner. Since it did not, UPS personnel suggested that instead of getting to the fire, the discharged agent remained trapped between the cargo liner and the fuselage. They theorized that the aircraft cargo liner became pliable, separated from the fuselage, and therefore acted as a curtain or a shield to block the flow of extinguishing agent from effectively reaching and controlling the cargo fire. This unofficial finding warranted testing and investigation into the interaction between cargo liner and the ASPN.

1.1 PURPOSE.

The purpose of this research was to understand the interaction between unheated and heated cargo liner during penetration by an ARFF vehicle ASPN. Initial small-scale scoping and characterization tests preceded full-scale tests with cargo liner material attached to an airframe to represent the main cargo deck of a freighter aircraft. An ASPN was used to penetrate cargo liner during exposure to various heat and fire threats.

1.2 OBJECTIVES.

The objectives of the small-scale tests were to:

- Determine the effect of penetration on constrained cargo liner at ambient temperatures.
- Determine if heating the constrained cargo liner would cause stretching upon penetration.

The objectives of the full-scale tests were to:

- Establish the characteristics of penetrating the cargo liner as mounted in an aircraft under ambient conditions.
- Determine if a radiant-heated cargo liner presents conditions that could prevent interior application of firefighting agent.
- Determine effects of various fire exposure durations on the material, such as softening that allows sagging, combustion, and complete material failure or melt.
- Evaluate the possibility of cargo liner mounting system failure during penetration attempts at ambient conditions or after fire exposure.
- Determine if the presence of flame and evolution of surface material into intumescent char have any additional effect on the mechanical properties of cargo liner at elevated temperatures, thus determining any differences an open fire has on the installed cargo liner and mounting system as compared to purely radiant heat.
- Review results from the small-scale tests with the full-scale tests to see if both tests provide comparable results.

1.3 BACKGROUND.

On June 4, 1996, the FAA published "Airport Rescue and Firefighting Mission Response Study" in the Federal Register [3]. It states:

> "The civil airport fire service requirement, pursuant to 14 CFR Part 139, is to provide an escape path from a burning airplane.
> …
> Civil airport fire service requires sufficient water mixed with firefighting agent (in terms of quantity and delivery rate) to control or suppress any fire in an area of sufficient size to permit the occupants of the aircraft to escape."

In pursuit of these objectives, training and apparatus provided to ARFF personnel focused on providing effective lifesaving measures when responding to aircraft incidents. However, the increase in the frequency of freighter aircraft flights and the intent of improving ARFF response to interior freighter fire incidents together have caused a concern to better understand the events that occur during freighter aircraft fires. This effort is not only to help save the lives onboard freighter aircraft but also to help mitigate the loss of property up to and including the aircraft itself.

1.3.1 Cargo Compartment Fire Resistance.

Aircraft regulations ensure that the cargo compartment provides a smoke and fire block in the event of a cargo fire. This is accomplished through lining the compartment with fire resistant material that was tested according to Title 14 Code of Federal Regulations (CFR) Part 25,

Appendix F [4], such that it complies with the current regulations in 14 CFR 25.855. This requires that the material does not burn through (allow a visible breach, opening, etc., through which a flame may penetrate) for 5 minutes and that the temperature cannot reach 400°F 4 inches above the material when subjected to the 2-gallon-per-hour (GPH), oil-fired burner [4]. This means that cargo compartments must be constructed with materials that act as a fire block. The majority of these materials are fiberglass-bearing composites.

1.3.1.1 Cargo Compartment Liners and Panels.

Cargo compartment liners are one of two types of composite laminate panels. The first type of laminate is a thick composite sandwich that typically combines fiberglass or polymer fabric outer laminate layers over a core panel made from an aluminum honeycomb, a resin-coated polymer fabric honeycomb, or a plastic foam. Figure 1 illustrates the construction of a honeycomb panel. The core provides the rigidity necessary for decompression compensation. The second type of cargo liner lacks the stiff core, making it thinner, lighter, and more flexible. It has the appearance of a thin, flexible, plastic-covered fiberglass sheet versus a stiffened panel. It is common to use modified polyester resin to construct cargo liner. Phenolic resin is also available, though its relatively higher cost reduces its demand.

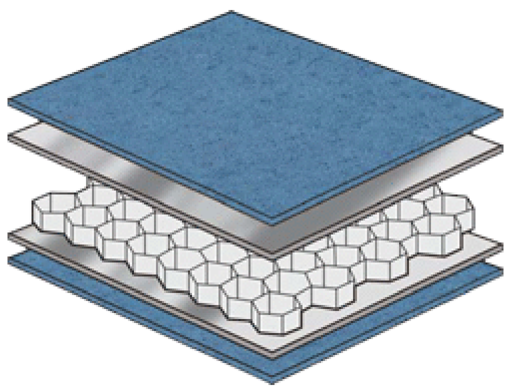

Figure 1. Honeycomb Panel Structure [5]

Decompression compensation comes from a mechanism that allows the panel to pop free from its mounting in the event of aircraft decompression. This prevents a pressure differential between the main deck and the lower cargo compartments that could result in the buckling of the aircraft structure. This buckling would cause the operating controls to work improperly, which is what occurred on American Airlines Flight 96 [6] and Turkish Airlines Flight 981 [7]. These panels are present in the walls of the lower cargo compartments, accompanied by main deck vents (dado panels) that serve a similar function.

Cargo liner also serves a secondary function of protecting aircraft insulation, and electrical, mechanical, and hydraulic systems from impact and abrasion damage that can occur from contact with bulk cargo or cargo containers. Adhesive patches temporarily repair the regular wear-and-tear damage to the cargo liner. These patches ensure compartment fire resistance, and remain in place until the damaged cargo liner is replaced. In an effort to save weight, reduce fuel consumption, and increase aircraft payload, freighter aircraft sometimes use multiple thicknesses of cargo liner to provide the appropriate amount of protection where needed.

The cargo liner used in these tests is the same model cargo liner used on UPS Flight 1307. It was comprised of two layers of 16-oz. and one layer of 9-oz. e-glass fiberglass cloth with a chlorinated polyester resin modified with antimony trioxide as a fire retardant [8]. The antimony trioxide is a common fire retardant and acts to assist the halogens present in the resin to capture free radicals from flame propagation reactions. At temperatures over 600°F, the chlorine in the resin forms hydrochloric acid. This combines with the antimony trioxide to form antimony trichloride or antimony oxychloride. These then act to further take up free radicals from the combustion-propagation reactions and help stop the fire by halting the chain reaction. The antimony oxides also promote char formation, reducing both the propagation of combustible material from the bulk of the resin and providing insulating protection of the resin from the flame [9].

1.3.1.2 Cargo Liner Mounting Hardware.

The cargo liner in freighter aircraft mounts to a lightweight frame [10] that holds the cargo liner in place while adding minimum weight to the aircraft. This nonstructural frame attaches to the aircraft frame through various brackets and fasteners. Some are solid brackets held in place with rivets, and others fasten to vibration isolation nuts held in rubber mounts riveted to the frame. Other fasteners, such as Hi-Lok® fasteners or Cherrymax® blind rivets, are sometimes used, but these are mainly for repairs and locations where it would be difficult to use solid rivets. The cargo liner framework is not a main, load-bearing, stressed structure, so the lightest weight hardware that can handle normal wear and tear is usually used. The full-scale tests described in this report used standard, aircraft supply, aluminum, solid-flush rivets, as well as steel nutclips, screws, and fender washers. This test did not include vibration-isolation hardware, which is discussed briefly in section 4.2 and shown in figure 2.

Figure 2. Rubber Vibration-Isolation Hardware

1.3.1.4 Aircraft Insulation.

Aircraft insulation protects the interior from the noise of wind and engines and provides thermal insulation from the cold of altitude and the heat of an external fire. The insulation used in this test was 3/8-inch- thick, 1.2 pounds per cubic foot Johns Manville Microlite® AA FG Insulation Premium NR Water Repellant fiberglass insulation covered in Orcon Corporation's Orcofilm®

AN-4C polymer moisture barrier forms an insulation blanket assembly. Plastic pins attached to the stringers or frame, shown in figure 3, hold the insulation blanket in place in production aircraft. These protrude through the insulation blanket, then metal or plastic clips slide over the pins to keep the insulation blanket in place. The test used plastic zip ties to hold the insulation blankets instead of plastic pins because of ease of installation and similar plastic material properties used for the clips and zip ties.

Figure 3. Plastic Insulation Retention Pin and Clip

1.3.2 The ARFF Tools.

ARFF personnel provide rapid response to aircraft accidents to preserve the life of passengers and flight crews. Due to the severity of postcrash fires, this response is primarily a firefighting and fire prevention effort, but it also includes passenger extraction if necessary. ARFF has a secondary goal of preventing destruction of property, but only after clearing the aircraft of people.

Appropriately equipped, ARFF personnel have a variety of firefighting agent and agent-delivery options to combat aircraft fires. In addition to water, they can also apply dry chemical agents, "clean" agents (nonresidue gaseous halocarbon agents), and mixtures with foaming agents, such as aqueous film forming foam (AFFF). Foaming agents allow water to "wet" or stick to surfaces better than water alone. This means that the water and agent will reach and stick to the surface rather than running off the surface. Foaming agents also provide a barrier blanket between the flame and pooling fuel that prevents fuel vaporization and combustion. Hand lines, vehicle-mounted turrets mounted on the roof, bumper, or high-reach extendable turret (HRET), or hand-held and HRET-penetrating nozzles are all used to apply these agents.

1.3.2.1 Skin Penetrators.

Skin-penetrating tools allow firefighters to apply agent to a fire on the opposite side of a barrier, such as a fuselage wall. These tools allow fire fighters to fight the fire from an area of relative safety. Agent flows through the nozzles directly through the fuselage, reducing the number of openings that would feed oxygen to the fire, and allowing agent to cover areas where access is otherwise physically blocked.

Penetration tools come in various forms, each requiring its own operating procedure. Some are human-powered and require ramming and hammering to penetrate the fuselage. Others are powered tools that use a rotary motion to drill into the fuselage. Another type gets the required thrust via apparatus boom extension or hydraulic penetration. Most ASPNs feature a hardened-steel tip and are essentially hollow tubes with holes that act as nozzles for flowing agent to a fire.

1.3.2.1.1 Unpowered Penetrating Nozzles.

Unpowered penetrating nozzles are impact driven and are available in battering ram, spike, and hammer styles, as shown in figure 4. Battering ram style penetrators have large, looped handles and hammer hit plates. The simple spike penetrating nozzles do not have the looped handles; they hammer inward. Both the battering ram and simple spike styles have hose connections at an angle to the main body of the nozzle and can flow about 125-300 gallons per minute (GPM), depending on size and model. Some can be fitted with extension tubes to give further reach inside the aircraft. Hammer-style penetrating nozzles, marketed primarily for structural firefighting, can have some limited use in fighting aircraft fires. Hammer-style penetrating nozzles can flow at about 80-100 GPM.

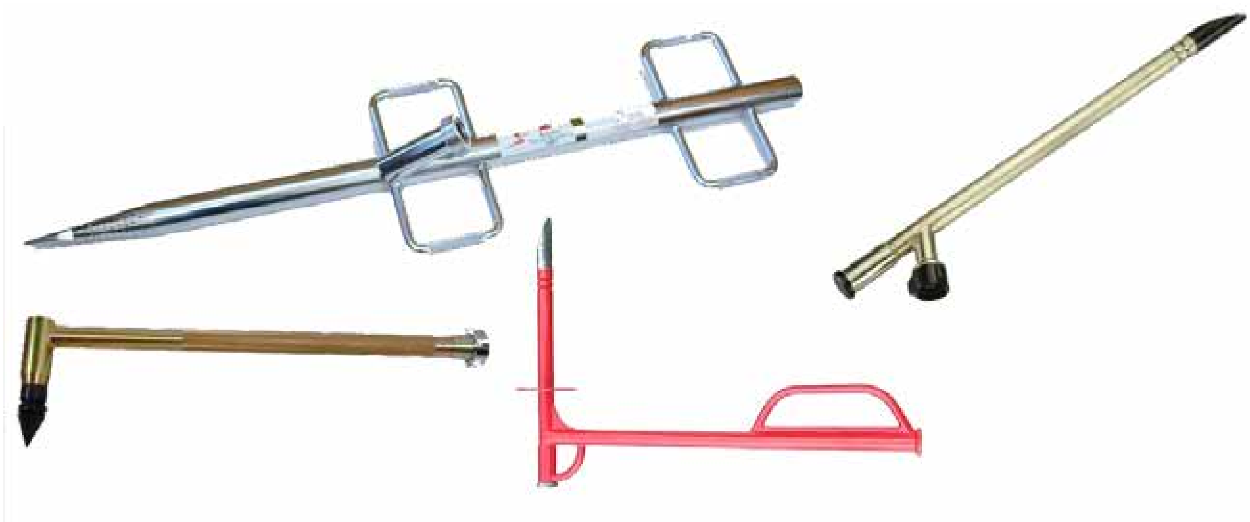

Figure 4. Examples of Unpowered Penetrating Nozzles

1.3.2.1.2 Powered Penetrating Nozzles.

Powered penetrating nozzles include handheld pneumatic impact tools, rotary tools, such as the skin penetrator agent applicator tool (SPAAT) (known as a fire drill), as well as equipment-mounted and fully plumbed penetrating nozzles.

Hand-held pneumatic impact tools, as shown in figure 5, combine a jackhammer or air hammer with a penetrating tool. They are mostly available in 0.5-inch and 1-inch pipe/nozzle sizes. This gives a greater restriction and reduced flow compared to dedicated ASPN nozzles with larger bore sizes. The impact tool itself can also be equipped with chisel-type cutting tools.

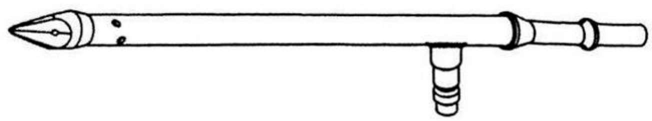

Figure 5. Hand-Held Pneumatic Impact Tool

The SPAAT pneumatic rotary tool, shown in figure 6, can flow about 100 to 150 GPM of firefighting agent. A hollow-bit pneumatic drill dispenses firefighting agent through the body of the drill. Pneumatic power is provided either by an on-site air compressor or by a portable compressed gas bottle. Bits are changeable to provide a different pattern of holes for use with each type of agent.

Figure 6. Firefighter Training Using a SPAAT [11]

The ASPN is a firefighting nozzle mounted on the HRET of a fire apparatus. The HRET allows the fire apparatus operator to extend nozzles, cameras, and other equipment out to and above different parts of the aircraft. The ASPN penetrates the aircraft skin to deliver firefighting agent to the aircraft interior. It consists of a conical nozzle attached to the HRET and is equipped with a solid-steel, sharpened ASPN tip. Figure 7 shows two basic ASPN models: the Stinger® (left) and Snozzle® (right). Both models are capable of flowing 250 GPM of water or foam agent through the piercing nozzle. The main difference between the two models is the method of aircraft penetration. The Stinger® hydraulically thrusts the ASPN in quick succession through the aircraft skin, and the Snozzle® uses the force provided from the boom to penetrate the skin of the aircraft slowly.

Figure 7. The ASPN System Models: Stinger® (left) and Snozzle® (right)

<u>1.3.3 Case Studies</u>.

The following case studies provide evidence that supports the necessity of this research effort.

<u>1.3.3.1 Case Study 1</u>.

In September 1996, a Federal Express Corporation (FedEx) McDonnell Douglas (MD) DC-10-CF performed an emergency landing due to a "cargo cabin smoke" indication. The cargo net and containers not involved in the fire obstructed attempts to fight the fire through the L1 door with hand lines. Firefighters then opened the cargo door to provide better access to the cargo deck. About 5 minutes after opening the cargo door, the fire breached or burned through the fuselage. The incident commander then withdrew firefighters from the interior and began using truck-mounted turrets aimed at the breached section of the fuselage. ARFF personnel extinguished the fire and began cleanup operations about 2.5 hours after the breach. The $95 million aircraft was lost, with an additional insurance loss estimated cost of about $300 million from the cargo. The ARFF apparatus did not have a HRET, but on-site ARFF personnel had access to a hand-held SPAAT. The incident commander tried to consult with MD to determine if there were (nondamaging) alternate routes of entry. In that time, the fuselage began to burn through, so firefighters did not use the SPAAT. [12]

The fire chief testified that, based on lessons learned from this accident, if a similar situation were to arise again they would immediately employ a penetrator tools with a firefighting agent. [12]

1.3.3.2 Case Study 2.

In December 2003, a FedEx MD-10-10F suffered a main landing gear collapse after experiencing excessive touchdown forces. Contact with the ground and a fuel tank rupture caused an external fuel-fed fire that eventually caused partial burn through of the fuselage. The “main body of fire” was under control by ARFF personnel within 10 to 15 minutes of arrival. ASPN use was concurrent with other exterior firefighting operations. Damage to cargo was minimal, but was mainly due to ARFF operations including fuselage penetration, agent application, and removal of the jammed forward cargo door. [13]

1.3.3.3 Case Study 3.

In February 2006, a UPS DC-8-71F landed at the destination airport after cargo smoke indicators activated. ARFF personnel arrived on the scene at 2359 hours and initiated extinguishment operations. ARFF personnel reported smoke exiting through the open L1 door and outflow vent in the tail, and entered the flight deck through the L1 door. They pulled back the smoke curtain and observed smoke but no fire in the main cargo compartment. There was no observation of smoke or fire in the lower cargo compartments. ARFF personnel also opened the L4 and R4 doors, unloaded some cargo, and began water extinguishment operations. The incident commander attempted to use a thermal imaging camera to locate high-temperature spots, but did not observe any at the time. Attempts to open the main cargo door resulted in breaking the door mechanism and unsuccessful entry. Fire fighters gained limited access through the right and left over-wing hatches, and then handline extinguishment operations started. The incident commander located high temperatures on the starboard side crown of the aircraft, forward of the wing; ARFF attempted ASPN piercing operations on the starboard side of the aircraft. After several unsuccessful attempts, ASPN operations moved to the port side, began aft of the left over-wing exit, and continued aft just above window level. AFFF was applied through the R4 door by another piece of fire apparatus. About the time that burnthrough occurred, ARFF units began applying AFFF using an ASPN through the pierced locations and through the areas where burnthrough occurred. Firefighters fully extinguished the fire after 4 hours and 8 minutes, but the aircraft and most of the cargo was lost. During post-incident interviews, ARFF personnel reported difficulty with use of the ASPN and had to reposition the tip of the nozzle a few times to achieve penetration. [2]

1.3.3.4 Case Study 4.

In June 2008, a ground fire in the supernumerary compartment of a Boeing 767-200 occurred due to a flaw in the supplemental oxygen system. ARFF personnel quickly located the fire, but could not open the L1 and R1 doors due to the fire melting the operating mechanism and door tracks for both doors. After a failed attempt to penetrate the cockpit window, the ASPN applied agent through the burnthrough areas above the supernumerary compartment. The fire was contained within 25 minutes and extinguished in about 43 minutes. The hull was lost, but most of the cargo was undamaged. The NTSB concluded that the ASPN was an effective tool for extinguishing the fire, especially since fire damage prevented access through the doors. [14]

2. EXPERIMENTAL SETUP.

In both small- and full-scale tests, an array of K-type thermocouples provided temperature data to a computer-based data acquisition system. The collection rate for thermocouple data was 1 Hz for the small-scale test and 2 Hz for full-scale test. The difference between the two was due to differences in data acquisition (DAQ) performance. The DAQ used in the full-scale test was calibrated, and the readout was adjusted to within 1°F or less of calibrator output. Calibration was verified between rounds of full-scale tests, and little to no drift was observed in the system. The DAQ was powered up 1 hour prior to testing to allow the system to warm up and establish a steady reference temperature.

2.1 SMALL-SCALE SETUP.

Performance of initial small-scale scoping tests helped to observe the behavior of heated cargo liner material when penetrated. These test results determined important test parameters for the full-scale testing. The small-scale tests were conducted at the FAA's Materials Fire Test Laboratory. The test apparatus used was the FAA's 2-gallon-per-hour, oil-fired burner and the frame that holds the test felt used to compare burner performance, as shown in figure 8. The cargo liner was attached to the inner frame with hardware of similar gauge to that used in the full-scale tests. A square tubular steel frame held the hydraulic ram that forced the penetrating nozzle through the cargo liner.

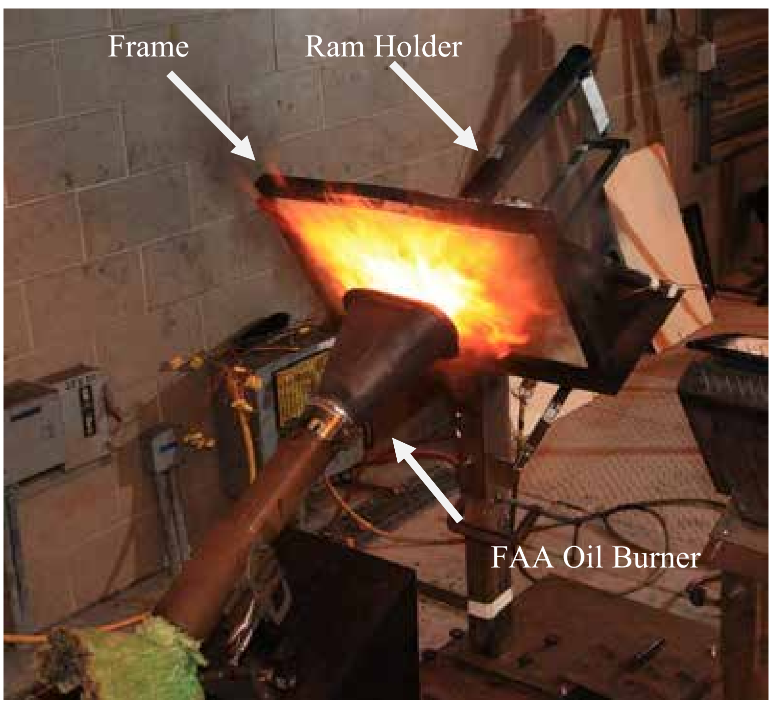

Figure 8. Small-Scale Test Setup

The burner was set to the same flame specifications used to test the burnthrough resistance of cargo liner, but used at an angle of 30° from vertical. Changing the location of the test frame relative to the burner placed the ASPN in different heat-affected zones. A hydraulic ram then forced an actual ASPN nozzle and tip through the cargo liner material. The thermocouples shown in figure 9 monitored temperatures. Thermocouple (TC) #3 was located near the point where the ASPN tip penetrated the material. Providing slack in the thermocouple leads and taping down the thermocouple ends with fiberglass tape reduced the occurrence of thermocouples detaching from the samples during the test.

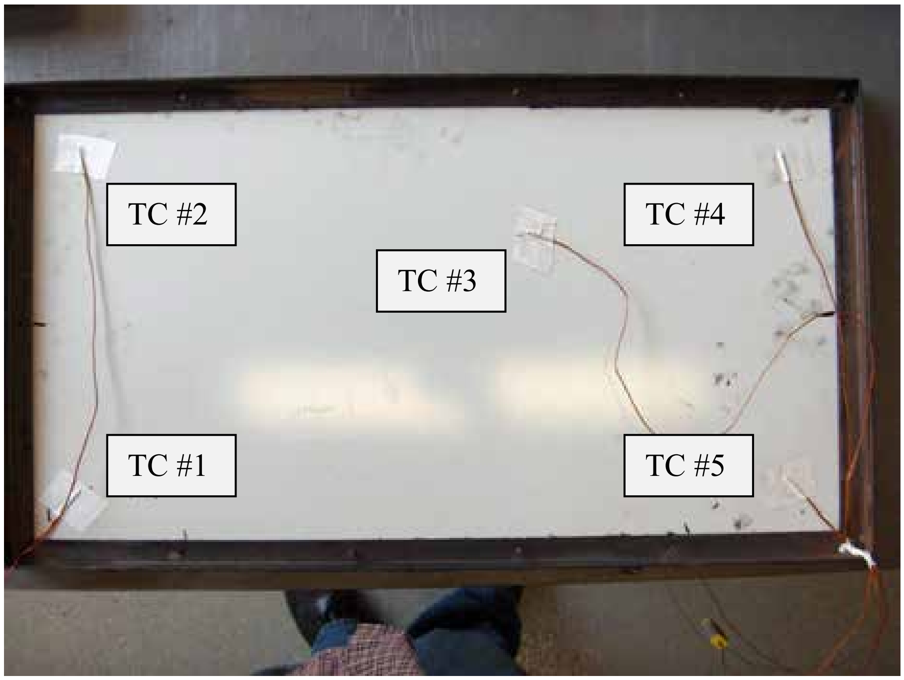

Figure 9. Small-Scale Thermocouple Placement

Preliminary tests verified the hydraulic ram setup (figure 8) would allow the ram to penetrate through the plane of the cargo liner as mounted in the frame. The ASPN passed far enough through the cargo liner sample to reach the full diameter of the ASPN. Penetration past this point would cause the ASPN to interfere with or impact and damage the burner in some test configurations. The penetration rate differed from an actual HRET/ASPN application, but this was determined to be acceptable due to variation from individual aspects of each situation, i.e. from variation in apparatus, penetration angle, how the operator performs the penetration, ASPN type (Snozzle versus Stinger), hand versus powered penetration, etc. Both blunt and sharp tips were tested to determine whether ASPN tip wear would affect penetration.

Heat in the penetration area was varied by changing the burner exposure time, burner position, and, for some tests, by enclosing the back of the test panel with fiberglass insulation and an aluminum panel to mimic the insulating effects of an aircraft fuselage. To keep the cargo liner closer to a real fire environment, the burner was left running throughout the duration of the test. Penetration occurred at the proper exposure time, and once the hydraulic ram had cycled to full extension, fuel to the burner was stopped. Still photographs were taken as the test progressed. As the sample was inspected, these photographs were used to document the distance between the sample and the hydraulic ram holder as well as the visible effects of penetration and heat exposure.

An initial exposure of 10 minutes was used because it was considered long enough to determine both when the material would reach steady state conditions under flame exposure (if burnthrough occurred) and how quickly initial changes happened. Subsequent tests had exposures varying from 15 seconds to 1 minute. Backside temperature data was compared to that taken during the FAA cargo liner certification test to verify agreement between the conditions of two tests, i.e., that each test exposed the cargo liner to similar conditions.

After observing these tests, exposures for subsequent tests were determined. Observations of the cargo liner delamination and discoloration locations relative to the burner centerline led to offset burner testing. This located the ASPN in the center of the heat-affected zone, as shown in figure 10. This zone marks the transition between unchanged cargo liner and the area of full delamination and complete resin loss. The gas pressure from resin decomposition products that is trapped between the fiberglass layers causes partial delamination. This pressure pries apart the layers in the cargo liner. Bare fiberglass cloth remains in areas where the resin completely burns away and can still function as a fire barrier.

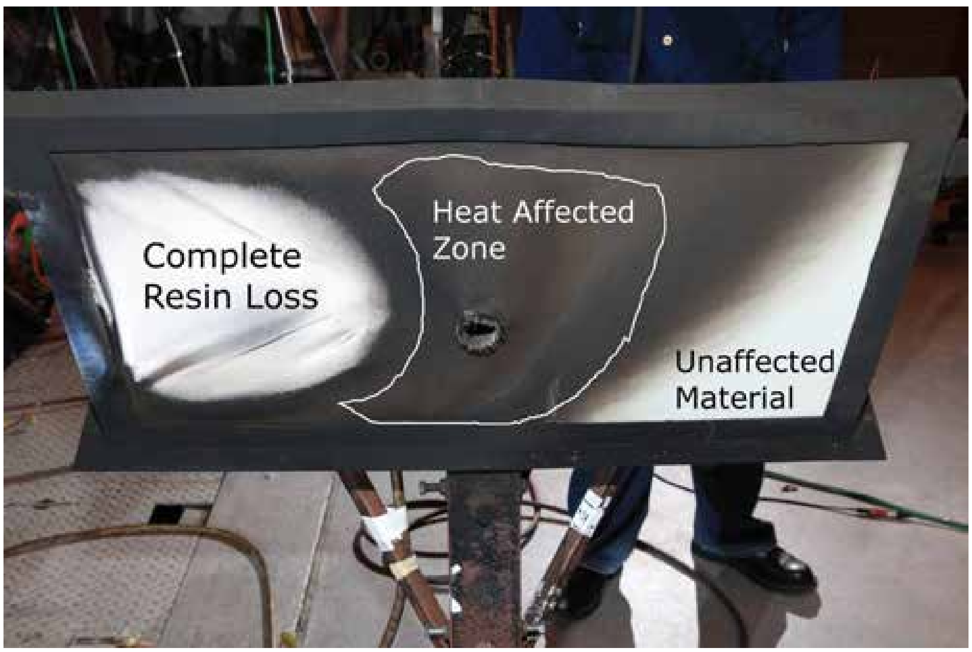

Figure 10. Offset Burner Heat-Affected Zones

Three test runs of each of the following small-scale test exposures were performed:

- Ambient penetration
- 10-minute burn (no penetration)
- 15-second penetration
- 1-minute penetration
- 15-second blunted penetration
- 1-minute assembly penetration
- 1-minute offset penetration

2.2 FULL-SCALE SETUP.

The following categories were tested for severity of obstruction of penetration in the full-scale penetration tests:

- Unheated—Penetration of a structurally intact cargo liner at normal temperatures.
- Radiant heated—Cargo liner is partially compromised by radiant heaters. This mimics areas close but adjacent to the fire where penetration and agent application might be performed to prevent spreading the fire.
- Flame heated—Penetration of cargo liner exposed to fire. The cargo liner surface is allowed to char and burn. Delamination, resin softening and loss, and other weakening can occur.

The full-scale test article was located in the aft section of a Douglas C-133 fuselage. Thermocouples collected data from two frame sections—one in the penetrated section and one in the adjacent section. The thermocouples were screwed to the interior surface of the aircraft's skin, placed on the interior face of the insulation blanket, and taped onto the backside of the cargo liner, as shown in figure 11.

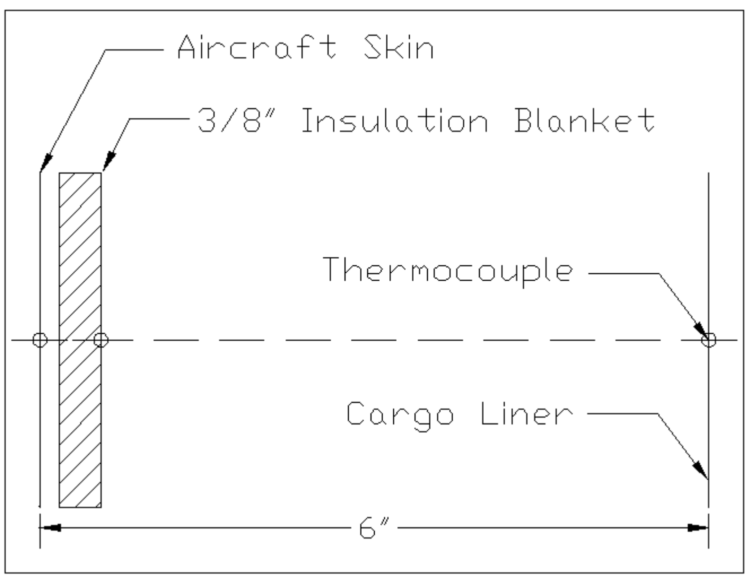

Figure 11. Thermocouple Placement Diagram

The thermocouple locations are numbered from bottom to top: TC 1-8 on the fuselage, TC 9-16 on the insulation, and TC 17-24 on the cargo liner. Thermocouples also were placed on the interior surface of the cargo liner in tests 8-13, and data was collected with additional equipment. Interior temperatures were monitored but not recorded in previous tests by on-site personnel. Interior thermocouple positions are shown in figure 12.

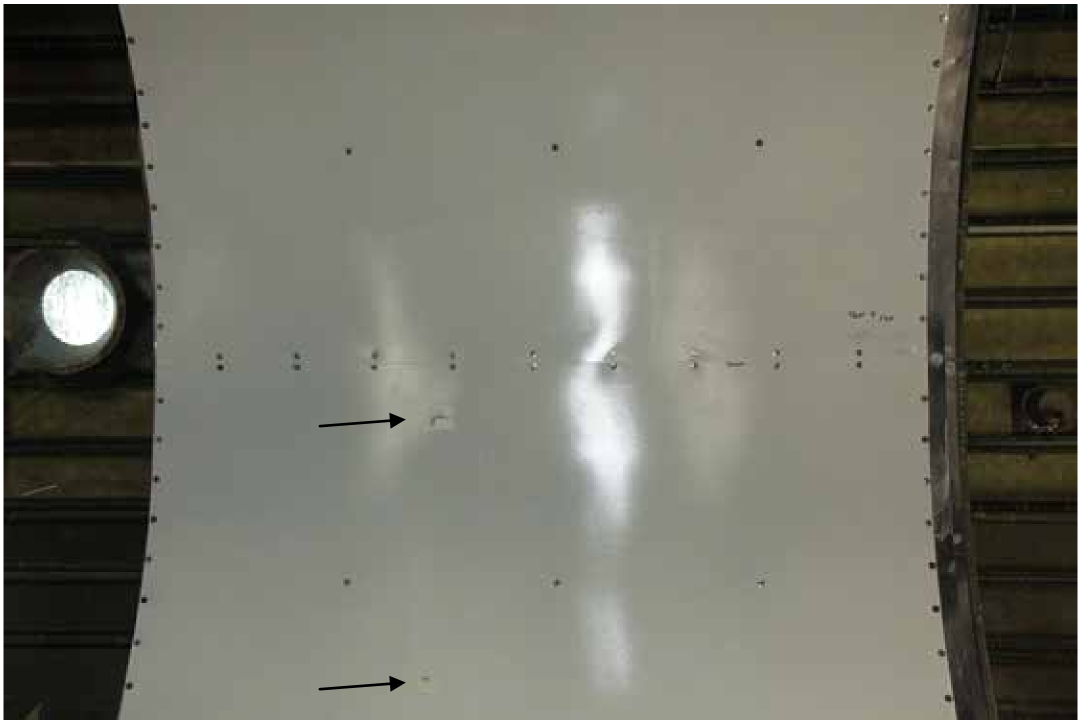

Figure 12. Location of Interior Thermocouples

The test section was four frames wide to reduce edge effects that could occur from the discontinuous nature of only partially lining the test fuselage, rather than fully lining the fuselage as is done with normal aircraft. The installed assembly was complete including thermal insulation, cargo liner, and hardware in accordance to current aircraft, as shown in figure 13.

Figure 13. Test Section With Insulation Blankets and Framing Installed

Figure 14 shows the exterior view of the test section. Color-coded fluorescent commercial construction marking paint was used to note the locations of the thermocouples and mounting hardware to the ASPN operator. Holes made at the penetration points were reused during each test to minimize variation from test to test. When wind and weather conditions dictated, gray cloth tape sealed the holes in the skin.

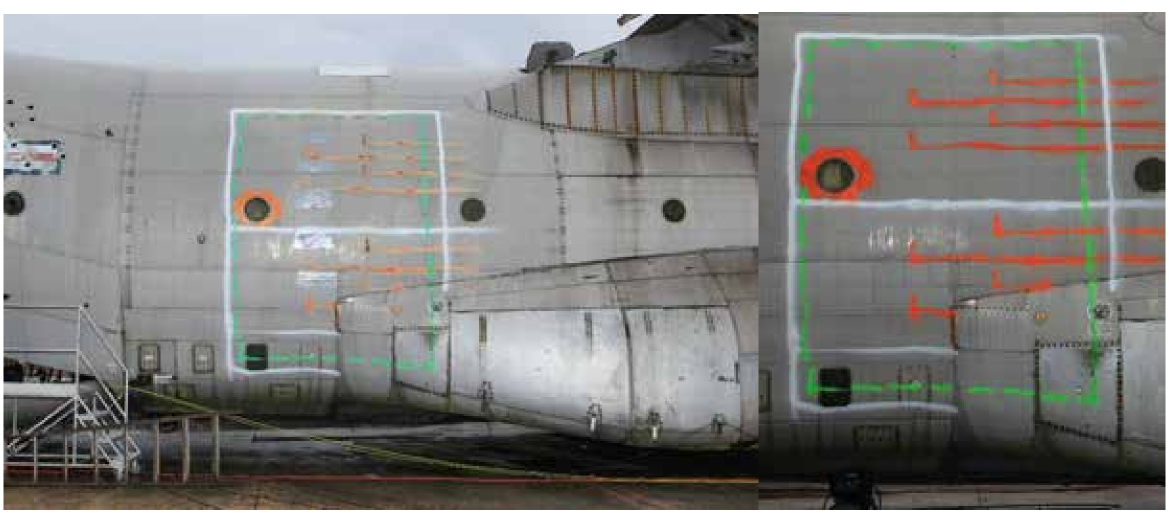

Figure 14. Test Section Exterior With Marking Detail

Three runs of each test occurred in the sequence of unheated, radiantly heated, and two fire heated scenarios. The radiant tests used an array of three 7.2kW electric heaters, as shown in figure 15. The heaters were approximately 18 inches from the cargo liner surface. This located them close enough to heat the cargo liner but kept them out of reach of the ASPN.

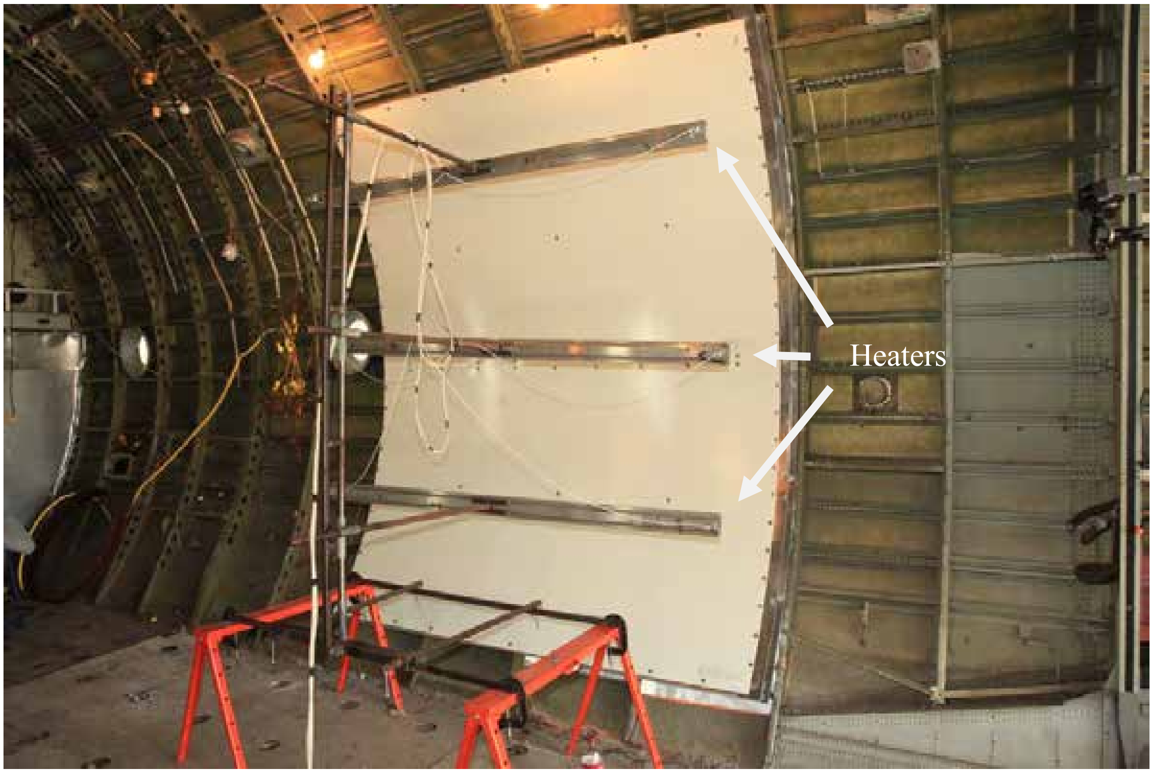

Figure 15. Electric Heaters in Place in Front of Test Section

Tests consisted of penetrations in the third (from left to right, as viewed from the interior) bay or frame section in the test area. Five penetrations were performed, starting near the top of the section and proceeding down the fuselage. Three penetrations were in the top panel, and two were in the bottom panel. This arrangement stemmed from consideration of the number of penetrations, fire apparatus positioning, location of test section within the aircraft, and ASPN skip. Improper penetration angle can cause the ASPN to skip off the fuselage. Freighter aircraft typically have a main cargo deck that elevates the position where penetration would occur, making penetration skip less likely. The test aircraft height prevented the lower parts of the test area to be used for penetration.

The fire tests used a pan fire within a 3-foot ring located 32 inches away from the cargo liner, with Exxon Mobile Corporation's Tekflame® used as the test fuel. This setup is shown in figure 16. Figure 17 shows the warm-up portion of the test. Penetration started once the cargo liner's backside reached the same temperatures of the small-scale tests.

Figure 16. Full-Scale Test Section Ready for Fire Heating

Figure 17. Fire Test

Mounting hardware failure near the end of the initial round of fire testing instigated a second round of fire tests to be run to determine if the hardware failure was a result of repeated penetration or normal behavior. During this series, any damaged hardware or fasteners were replaced after each test.

3. RESULTS.

3.1 SMALL-SCALE RESULTS.

The tabulated results for the small-scale tests are listed in table 1. Ambient tests showed that unheated cargo liner provided little stretch or deflection, and once the cargo liner was initially penetrated, 67% of the nozzle holes were unobstructed by the cargo liner. Heated tests showed that, in some instances, the added softening and deflection caused enough flex in the cargo liner to obstruct between 56%-78% of the nozzle holes and have them remain on the backside of the cargo liner. This is evident in the small amount of penetration that occurred in the offset test shown in figure 18. The dashed arrow in figure 18 indicates the approximate end of the ASPN. The solid arrows indicate the nozzle holes that protrude through the cargo liner.

Table 1. Small-Scale Results

	Number of Exposed Nozzle Rows					
Exposure	Ambient	15 sec	1 min	Blunted 15 sec	Assembly 1 min	Offset 1 min
Test 1	6	2	3	3	4	3
Test 2	6	4	3	3	4	1
Test 3	6	4	3	3	2	2

Figure 18. Incomplete Penetration During Heated Test

The test series in which the ASPN was equipped with a blunted tip showed no significant difference in penetration. There was a slight delay in penetration with a blunted tip, then the tip passed through with a popping sound and a sudden release of stress as the ASPN tore the material. Penetration then continued normally. Once the cargo liner was penetrated, the behavior was similar to penetration with a sharp tip.

Penetration through fiberglass aircraft insulation, insulation moisture barrier, and an aluminum sheet on the backside of the sample-holding frame was attempted to mimic the structure of the aircraft. This attempt did not adequately reproduce effects observed in full-scale tests. The assembly lacked the frame space that creates an air gap between the cargo liner and the insulation. This caused heat concentration on the backside of the liner that was not observed elsewhere during the test. This temperature difference is shown in figures 19 and 20. Furthermore, the concentrated heat in the burner exposure area and the subsequent cooling caused the outer layer of fiberglass cloth to become brittle. This caused the cargo liner to lose significant integrity in the center of the burner exposure area. Because the heat was concentrated in the center of the burner area, the remaining cargo liner exhibited less integrity loss, which provided a condition in which penetration was unhindered. Posttest examination showed the outer layer of fiberglass was brittle enough to fall apart under minimal disturbance.

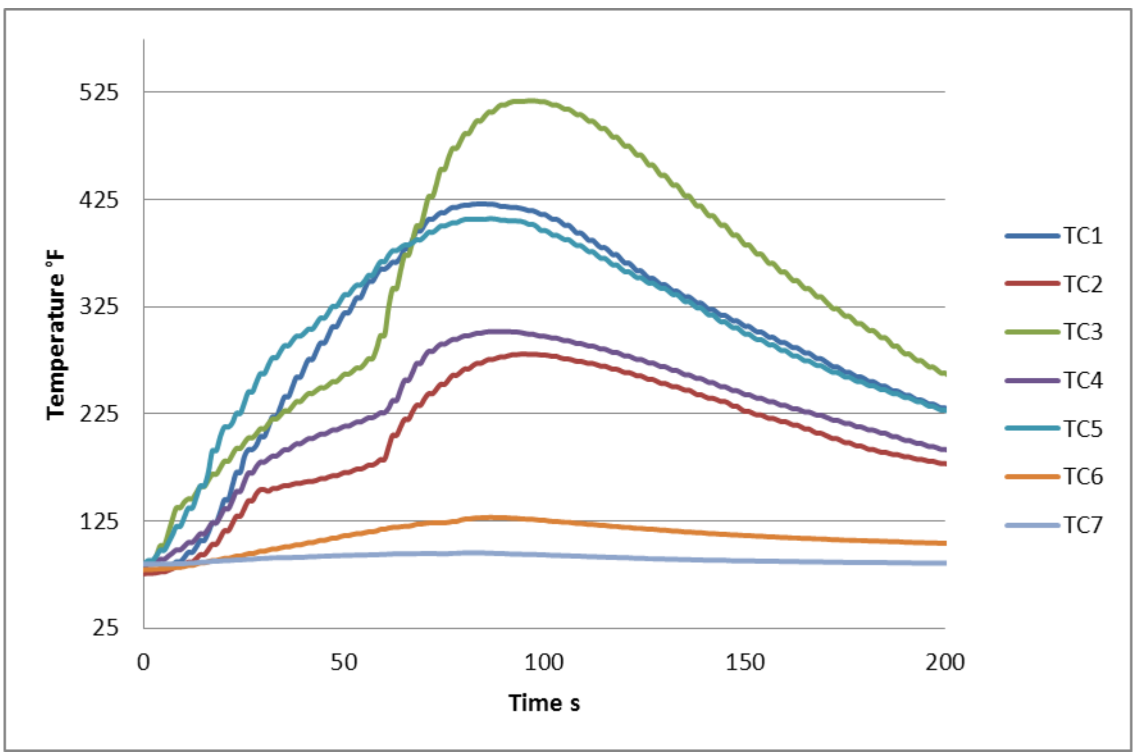

Figure 19. Small-Scale Cargo Liner Test 10 Backside Temperatures

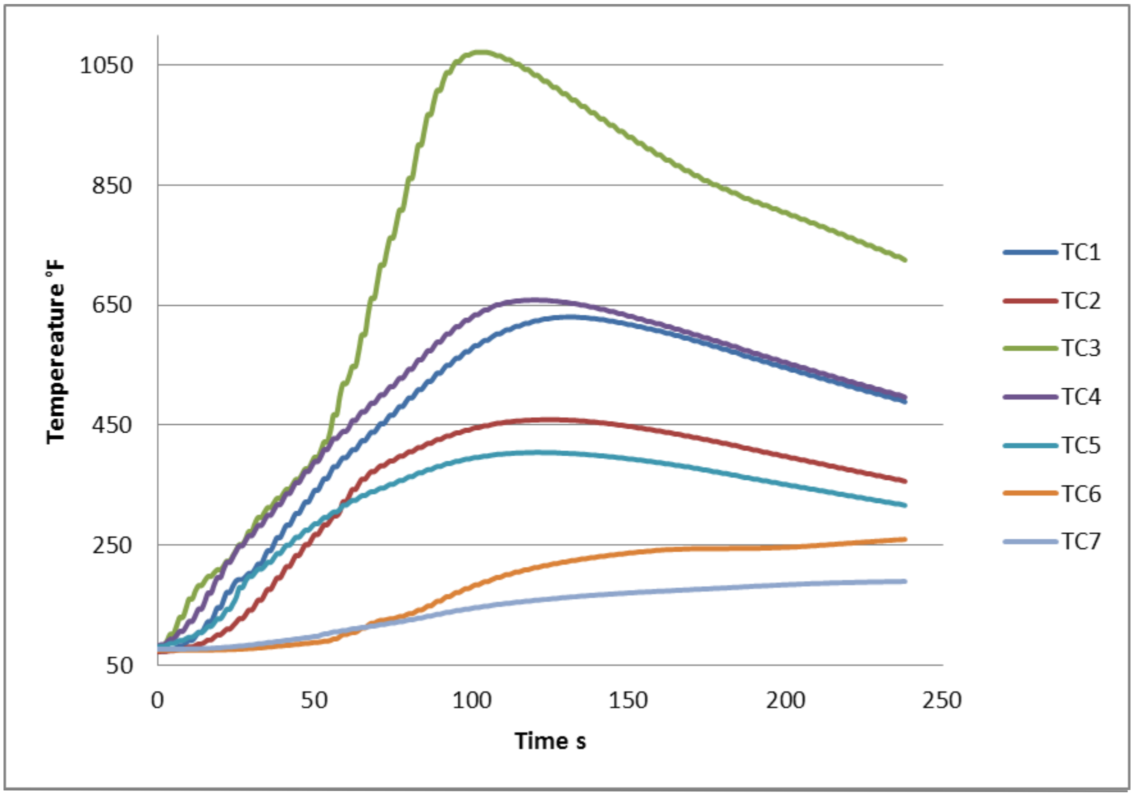

Figure 20. Small-Scale Cargo Liner Test 17 Backside Temperatures

3.2 FULL-SCALE RESULTS.

The ambient tests showed that intact and unheated cargo liner provided little resistance to penetration. The cargo liner did not bow or stretch significantly. The mounting hardware remained intact and kept the cargo liner close to the hull even after repeated penetrations. Figure 21 shows that the nozzle fully penetrated into the interior of the fuselage without any problem.

Figure 21. Complete Penetration During Ambient Test

During radiant-heated tests, the cargo liner softened and slightly relaxed, even before penetration. A strong odor of fiberglass resin vapor was present once the cargo liner started to heat. The mounting hardware generally remained intact and attached to the aircraft frame, but penetration sometimes bent the washers that attached the cargo liner to the mid-field support brackets. The brackets themselves were slightly bent, but remained attached to the aircraft. There was no significant damage where the cargo liner attached to the horizontal and vertical strips of the mounting frame. There was also no significant damage in the cargo liner, the washers, or the mounting frame. The cargo liner stretched slightly, but not enough to prevent penetration, as shown in figure 22.

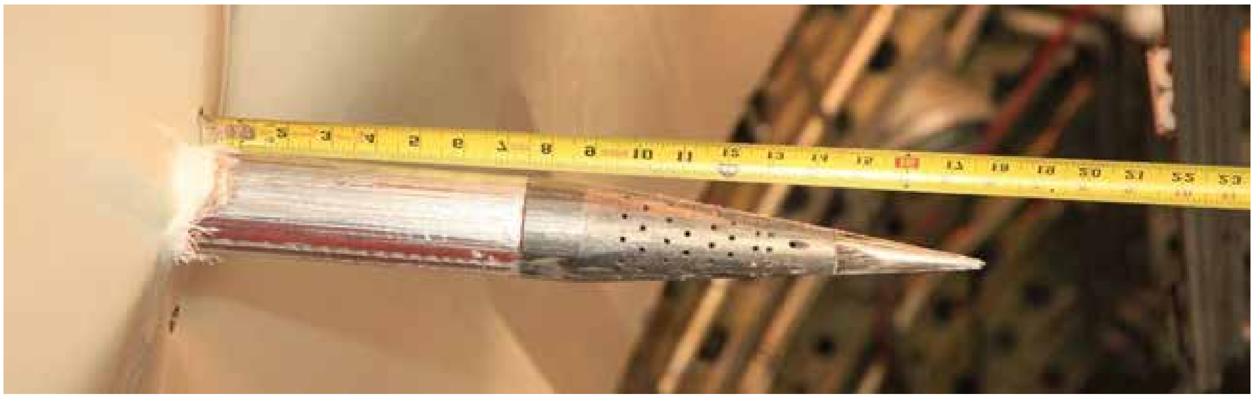

Figure 22. Complete Penetration During Radiant-Heated Test

The increased damage in the flame-heated tests did not interfere with penetration, as shown in figure 23. The increased heat resulted in delamination of the cargo liner, visible in the bubbled appearance of the backside in figure 24. It also came in the form of the obvious lamina separation reaching to the edge of the cargo liner as in figure 25.

Figure 23. Complete Penetration During Full-Scale Test

Figure 24. Posttest Backside Delamination Damage

Figure 25. Cargo Liner Delamination

Figures 26 and 27 show the temperature data from full-scale tests. Figure 26 data are from thermocouples in the center and upper parts of the lower cargo liner panel. The main mode of heat transfer in the full-scale tests was radiant heating. However, when the resin reached the right conditions, it would catch fire, and the surface flame would blend with the pan flame. The surface charred, but often the char would burn away from further exposure to heat. This left spots of bare fiberglass, which presented as brittle or flexible, depending on the amount of localized heat.

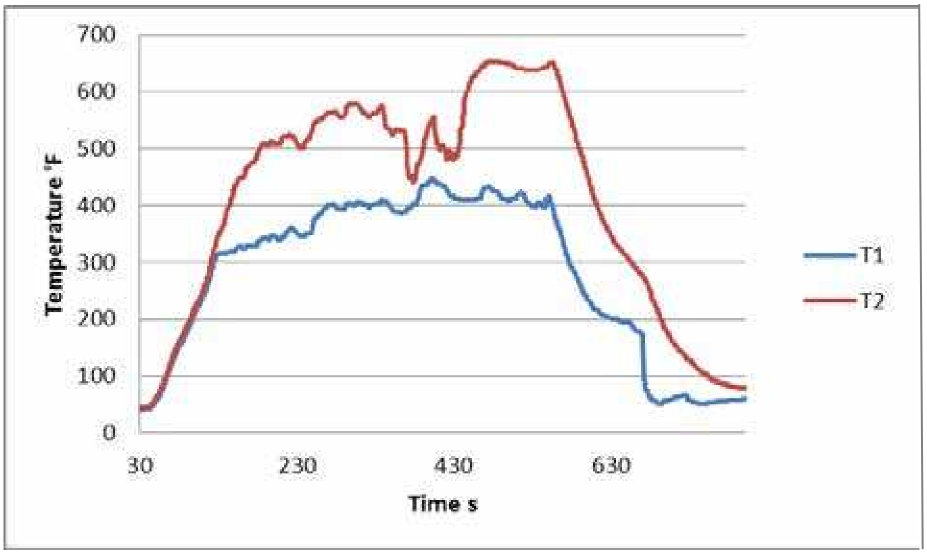

Figure 26. Inside Surface Temperature of Lower Cargo Liner Panel

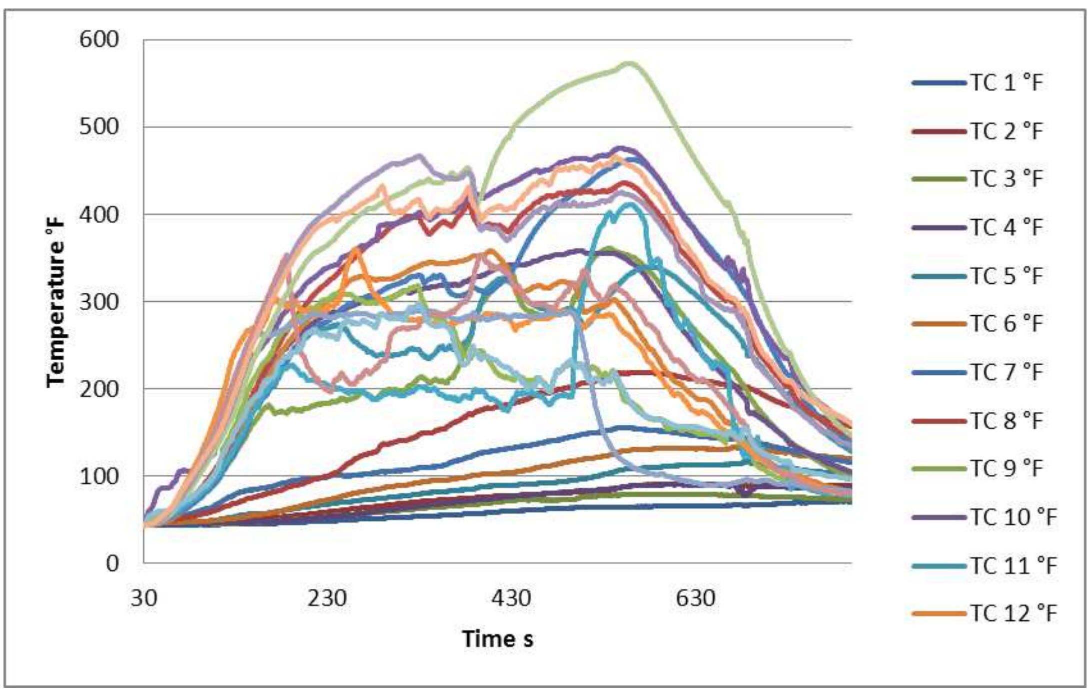

Figure 27. Test 21 Temperature Data

4. DISCUSSION.

4.1 MATERIAL BEHAVIOR.

The small-scale tests showed that the cargo liner could stretch, although stretching was minimal when close to room temperature and much greater under heat. Figure 28 shows the offset present in the small-scale tests, and figures 29 and 30 show the amount of stretch or deflection during respective heated and unheated penetration.

Figure 28. Deflection Offset

Figure 29. Heated Deflection

Figure 30. Unheated Deflection

Bluntness of the ASPN tip did not significantly affect penetration. A blunted ASPN tip slightly delayed penetration, but had no other discernable effect. There was discussion that a blunted tip could catch and hold a small mass of insulation, effectively making the ASPN tip push on rather than push through the cargo liner. Tests indicated that this concern was unwarranted.

The majority of the observed cargo liner behavior resulted because cargo liner itself was a composite of fiberglass cloth and resin. The bulk of the strength and the cargo liner's ability to contain flame come from the fiberglass cloth. The resin serves to protect the cloth from abrasion and maintains shape and strength by keeping the fibers in the proper orientation. At elevated temperatures, the normally rigid resin begins to soften and allows the glass cloth to deform when pushed on by the ASPN. At high-enough temperatures, the cargo liner acts like separate layers of fiberglass cloth and is easily penetrated by the ASPN.

The drawn fibers used in glass cloth are normally quite strong, yet still flexible. The type of glass fibers usually used for cargo liner typically loses its strength and softens at temperatures above 1200°-1500°F [15]. Thus, cargo liner maintains its structural integrity at typical Class A fire temperatures of 800°-1000°F. Exceptionally hotter fires can breach through the glass cloth, but are not typical in interior aircraft-related fires. Aircraft fuel fires can reach 700°-1200°F [16], and are well within the temperature range accepted by cargo liner. Fibers that are heated but cooler than their softening point maintain most of their unheated strength. However, rapid cooling of these fibers from contact with cool air or water makes them brittle. This was observed during one small-scale test in which penetration was performed when the burner inadvertently turned off early.

4.2 MOUNTING HARDWARE BEHAVIOR.

During full-scale tests under unheated conditions, the mounting hardware held up to penetration forces. The cargo liner was kept taut and close to the aircraft hull. Even after repeated penetration, the mounting hardware retained its shape. In the radiant-heated scenario, the cargo liner was able to maintain most of its strength and rigidity at the fasteners and therefore remained attached to the aircraft. In some tests, the washers attached to the mid-field fasteners bent from the cargo liner pulling the hardware toward the interior of the aircraft. This did not interfere with keeping the cargo liner attached to the mounting hardware.

In the flame-heated scenario, if the cargo liner completely lost the resin surrounding the hardware fasteners or became hot enough to become completely pliable, the cargo liner stretched around and popped off the fender washers and screws that held it in place. In testing, this happened with the mid-field fasteners attached to single brackets, as shown in figure 31. However, when the cargo liner popped free from the mid-field mounting hardware, the ASPN was able to penetrate the cargo liner in most tests. In only 1 of the 45 fire-heated penetration tests, the ASPN was obstructed enough to possibly prevent firefighting agent from being applied. Given sufficient length, the ASPN is capable of penetrating into the interior of freighter aircraft without problem.

Figure 31. Screw and Washer Still Attached to Bracket

In some instances, the cargo liner pulled on the mounting hardware hard enough to bend and partially fold the fender washers surrounding the screws, as in figure 32, allowing the cargo liner to pop free from the bracket. At that point, the only hardware holding the cargo liner panels in place were the edge fasteners attached to the cargo liner frame. These fasteners typically remained secure due to their closer spacing and stress sharing between fasteners.

Figure 32. Washer Bent From Penetration Force

The flame-heated tests showed that once the cargo liner loses its resin, it becomes more susceptible to certain kinds of damage. This is evident by the screws and washers pulling through the fiberglass and remaining attached to the mounting brackets during penetration. The flame-heated tests also showed that there are instances where the mounting hardware can provide protection to the resin, thus allowing the stress applied to the cargo liner to transfer to the cargo liner frame instead of tearing the cargo liner. This protection is evident in figure 33.

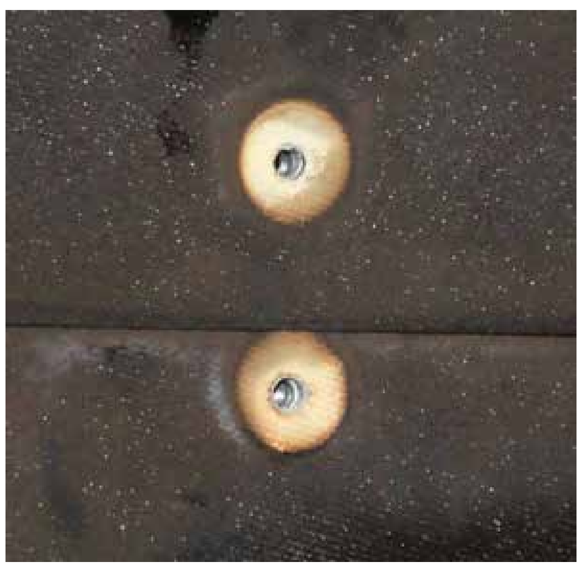

Figure 33. Cargo Liner Protected by Washers

The cargo liner also exhibited signs that under certain conditions, the mounting hardware could locally protect the cargo liner from heat-related degradation. At points where the cargo liner was mated flush with a surface (as it was with the mounting frame or sometimes even with a bracket), the cargo liner typically exhibited reduced charring and resin loss. This also gave better fastener grip on the glass fibers and helped spread the stress applied to the cargo liner.

In general, the amount and type of stress anticipated drives the specification of aircraft hardware. Normal solid aluminum rivets are designed to hold against shear (pulling across) stresses rather than normal (pulling out/apart) stresses. Unheated cargo liner is sufficiently rigid to act as a taut membrane that transfers force to the hardware as shear stresses rather than normal tensile stresses. When the ASPN impinged on the heated and softened cargo liner, the cargo liner slackened enough to pull on the hardware differently than when rigid. It pulled at an angle that combined shear and normal stresses in such a direction as to warrant pulling out the rivets. It is then congruent that the mounting hardware would fail in this situation. In this case, the normally beveled head of the rivet folded and pulled through the fastener hole, as shown in figure 34. The addition of heat to the rivets further exacerbates the problem by softening the rivet, further reducing the strength of an otherwise already relatively low resistance to the types of forces encountered. Most aluminum alloys have typical melting points between 900°-1200°F [1], and this is within the range of aircraft fuel fires.

Figure 34. Rivet With Bracket Pulled off Beveled End

Although not used in this test, note that the cargo liner is sometimes fastened to the airframe with rubber anti-vibration or anti-noise mounts, as shown in figure 2. However, the stress resistance of an elastomer mount (figure 2) would be equal to or less than that of aluminum fasteners, and the heat resistance could be considerably less. The failure of mounting hardware observed under the stronger conditions of all-aluminum construction would happen faster with elastomer mounts. Furthermore, elastomer hardware attaches to the airframe with aluminum fasteners, which become the point of failure even if the rubber does not deteriorate from heat or if the hardware was designed to maintain integrity with rubber failure.

4.3 DOMINANCE OF MOUNTING HARDWARE VS CARGO LINER BEHAVIOR.

The cargo liner stretched in both the small- and full-scale tests. In the small-scale tests, the stretching was somewhat restricted by the smaller sample area used. The full-scale tests showed that a larger panel showed more stretching, but only a limited amount. In most tests, the stretch of the cargo liner did not significantly prevent penetration. As long as the ASPN reached far enough into the aircraft, it could get past the cargo liner. This was evident in the completed penetration during full-scale tests and incomplete penetration during small-scale tests.

In the event of catastrophic mounting hardware failure, a detached cargo liner would not have sufficient restraint to be fully penetrated. The presence and location of the mounting hardware limits panel movement, so a loose or detached cargo liner could prevent agent application. However, in this event, the fire damage would most likely be severe enough to have already caused significant damage to the structure, i.e., the fire would have already caused the structure enough damage to declare a total loss of the aircraft.

5. CONCLUSIONS.

The following was determined from the small-scale tests:

- Under ambient conditions, the ASPN had little trouble penetrating the cargo liner. Two-thirds of the nozzle holes protruded through the liner. Test constraints prevented complete penetration of the liner.
- The heated cargo liner stretched when penetrated. The amount of stretch under test conditions was enough to block from three to seven of the nine holes on the nozzle, thus blocking 33%-77% of the nozzle.

The following was determined from the full-scale cargo liner tests:

- Under ambient conditions, cargo liner does not hinder penetration by an ASPN. The ASPN easily passes through the cargo liner and does not have issues with nozzle clearance.
- Radiant heat allows the cargo liner to soften but does not prevent ASPN penetration.
- The majority of penetrations occurred without significantly obstructing the ASPN nozzle. Furthermore, if the ASPN reached sufficient distance from the skin of the aircraft, then the penetration was likely to be successful even in the event of cargo liner detachment.
- It is not likely that the cargo liner mounting system will fail at ambient conditions. It may fail after fire exposure. Mounting hardware around the periphery of the cargo liner panels tend to remain intact, while central ones may fail.
- The cargo liner did not form significant char, intumescent or otherwise. Some charred resin burned away. There was little difference between fire and pure radiant of cargo liner under test conditions.
- The results of the small-scale tests appeared to be congruent with that of the large-scale tests.

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