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Development of Prototype Nozzles for Freighter Aircraft Fire Applications

April 2013

DOT/FAA/TC-TN13/11

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16. Abstract

Advisory Circular 150/5210-17B, “Program for Training of Aircraft Rescue and Firefighting Personnel,” added freighter aircraft familiarization as a requirement for Aircraft Rescue and Firefighting (ARFF) training. To develop the tactics and strategies for this training, the Federal Aviation Administration (FAA) requested research in freighter aircraft firefighting. Part of this research entailed developing tactics for extinguishing freighter aircraft fires with an aircraft skin-penetrating nozzle (ASPN). Early in the research effort, it was determined that the current nozzle designs were not adequate to fight cargo fires on freighter aircraft, and a new nozzle design would have to be developed.

Four prototype ASPNs were designed and fabricated specifically to fight cargo fires on freighter aircraft indirectly. Various tests were performed on all four prototype ASPNs to measure flow rates, spray patterns, and extinguishment effectiveness. Flow and pressure readings were taken from each prototype ASPN to confirm that they met industry standards. All prototype ASPNs met industry standards when using the FAA Oshkosh Striker® ARFF research vehicle. Prototype Nozzle 3 exhibited the highest flow rate of all prototype ASPNs, while Prototype Nozzle 4 displayed the highest pressure readings. Photo documentation was taken of the spray pattern for each prototype ASPN to analyze the different spray trajectories each nozzle produced. These trajectories would show where water would go during a container fire. Prototype Nozzles 2 and 3 exhibited similar spray patterns consisting of a wide umbrella spray and a forward-projecting straight stream. Prototype Nozzle 4’s spray pattern consisted of three different range hollow spray cones. Container fire tests inside an aircraft section were conducted to determine the effectiveness of each nozzle. Visual inspection and thermocouple readings were used to determine the effectiveness. Although all prototype ASPNs were able to extinguish a portion of the fire, Prototype Nozzle 3 provided the best design based on these criteria and practicality of nozzle design. Prototype Nozzle 3 was selected to be used for full-scale cargo fires to validate the earlier testing.

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LIST OF ACRONYMS

AAY	Base dimension and shape of the ULD container used in testing
ARFF	Aircraft Rescue and Firefighting
ASPN	Aircraft skin-penetrating nozzle
FAA	Federal Aviation Administration
GPM	Gallons per minute
HRET	High-reach extendible turret
HPRV	High-performance research vehicle
NFPA	National Fire Protection Association
NTSB	National Transportation Safety Board
psi	Pounds per square inch
ULD	Unit load device

EXECUTIVE SUMMARY

In the 2009 Federal Aviation Administration (FAA) Advisory Circular 150/5210-17B, "Program for Training of Aircraft Rescue and Firefighting Personnel," the FAA added freighter aircraft familiarization as a requirement for Aircraft Rescue and Firefighting (ARFF) training. Because of this, the FAA requested research in freighter aircraft firefighting to the ARFF research section of the Airport Technology Research and Development team. Part of this research entailed developing tactics for extinguishing freighter fires with an aircraft skin-penetrating nozzle (ASPN). Early in the research effort, it was determined that the current nozzle designs were not adequate to attack cargo fires on freighter aircraft when presented with an indirect attack situation, and that a new nozzle design would need to be developed. Firefighting agents sprayed from these ASPNs tended to wrap around the cargo container and did not attack the seat of the fire.

Four prototype ASPNs were designed and fabricated at the FAA William J. Hughes Technical Center to specifically fight cargo fires on freighter aircraft. Various tests were performed on all prototype ASPNs to measure flow rates, spray patterns, and extinguishing effectiveness. Flow and pressure readings were measured from each prototype ASPN using the FAA Oshkosh Striker® to confirm if they met industry standards. The flow rate readings confirmed that all prototype ASPNs met industry standards. Prototype Nozzle 3 exhibited the highest flow rate, while Prototype Nozzle 4 displayed the highest pressure readings. Photographs were taken of each prototype ASPN spray pattern to analyze the different spray patterns each nozzle produced. Prototype Nozzle 1 produced a wide umbrella spray and four small forward streams. Prototype Nozzles 2 and 3 produced similar spray patterns consisting of a wide umbrella spray and a thick forward straight stream. Prototype Nozzle 4's spray pattern consisted of three different range hollow spray cones. Container fire tests were conducted inside an aircraft section to determine the extinguishment effectiveness of each nozzle. The FAA's high-performance research vehicle (HPRV) was used as the test vehicle since the Oshkosh Striker® was committed to another research effort. The effectiveness was analyzed through visual inspection and thermocouple readings. The prototype ASPNs extinguished the following mean percentage of their fires: Prototype Nozzle 1—87%, Prototype Nozzle 2—92%, Prototype Nozzle 3—90%, and Prototype Nozzle 4—88%. Although all prototype ASPNs were able to extinguish a portion of the fire, Prototype Nozzle 3 provided the best design based on these criteria and practicality of nozzle design.

INTRODUCTION

BACKGROUND.

In the 2009 Federal Aviation Administration (FAA) Advisory Circular (AC) 150/5210-17B, "Program for Training of Aircraft Rescue and Firefighting Personnel," the FAA added freighter aircraft familiarization as a requirement for Aircraft Rescue and Fire Fighting (ARFF) training [1]. An event that influenced the change in this AC was the incident involving United Parcel Service (UPS) Flight 1307. On February 17, 2006, this aircraft made an emergency landing at the Philadelphia International Airport due to the possibility of an onboard fire. The National Transportation Safety Board's (NTSB) Accident Report (NTSB/AAR-07/07) [2] states that the first officer of Flight 1307 smelled an odor that he compared to wood burning 25 minutes before landing. After 20 minutes, cargo smoke was confirmed inside the aircraft. Once the aircraft landed, it took approximately 4 hours to declare the fire under control. The NTSB found that the ARFF personnel who responded to this incident were not adequately trained with regard to freighter aircraft [2].

In an effort to aid the ARFF community on the subject of freighter aircraft fires, the FAA requested further research into freighter aircraft firefighting. The ARFF research team at the FAA Airport Technology Research and Development Branch at the FAA William J. Hughes Technical Center near Atlantic City, New Jersey was tasked with this research effort. Part of this research entailed investigating various tactics used to extinguish fires inside the unit load device (ULD) containers that are currently used in freighter aircraft. These extinguishing tactics involved using an aircraft skin-penetrating nozzle (ASPN) for container penetration as well as for indirect extinguishment attacks when cargo containers were out of reach. When it came to the indirect extinguishing attacks the current ASPN design and its effectiveness in extinguishing fires from a distance proved ineffective. Preliminary tests performed by the ARFF research team showed the current nozzle designs did not effectively extinguish container fires using an indirect attack 12 inches away from the container. A photograph of one of the preliminary tests is shown in figure 1. A standard ASPN from a Snozzle® high-reach extendable turret (HRET) was used to extinguish a container fire from a distance of 12 inches. During this test, fire extinguishment was not started until there was a significant breach of one container wall. It was observed that the water spray from this nozzle encapsulated the container but never adequately reached the fire seat inside the container. Since there was a breach in the container, the fire continued to grow, and the discharge had no effect in reducing the fire's growth. The water spray wrapped around the container, but no signs of fire extinguishment were present. Because of these results, it was concluded that there was a need for new ASPNs designed specifically to fight freighter aircraft fires. This study looked at the effectiveness of four prototype ASPNs that were fabricated with this design criteria in mind.

Figure 1. Indirect Extinguishing Attacks on ULD Container

OBJECTIVE.

The primary objective of this study was to develop an ASPN that would be more effective than the current technology for fighting freighter aircraft fires. To accomplish this objective, the following tasks had to be performed:

- Design and fabricate ASPN prototypes for use in extinguishing freighter ULD container fires.
- Characterize flow patterns, pressure, and discharge rate for each ASPN prototype.
- Determine the effectiveness of each ASPN prototype used in container fire test protocol.

EXPERIMENTAL SETUP AND TEST PROCEDURES

EXTINGUISHMENT DEVICE.

In the ARFF community, HRETs have revolutionized the way that aircraft fires are fought. An HRET is a master stream device (turret) accompanied with an ASPN mounted on an extendable boom [3]. The HRET allows ARFF personnel to position the turret at previously inaccessible locations and increase accuracy when discharging agent. Compared to a basic roof-mounted turret, the HRET is proven to be more effective in extinguishing a fire [3]. Additionally, the ASPN attached to the HRET allows ARFF personnel to penetrate the aircraft's fuselage and discharge agent inside the aircraft without having to enter it. This is particularly advantageous when dealing with cargo fires inside freighter aircraft because of the inaccessibility to the cargo compartment. HRETs purchased with Airport Improvement Program funds are required to have an ASPN installed on them. For this study, during the fire-testing phase, the FAA's high-performance research vehicle (HPRV) was used as the main apparatus to extinguish the fire. The

HPRV carries 750 gallons of water and 120 gallons of aqueous film forming foam (AFFF) agent. The HPRV has a 50-ft model 501 Snozzle® HRET system installed. The HRET can deliver 250 gallons per minute (GPM) through the penetrating nozzle. For spray pattern and flow rate tests, the FAA used its other research vehicle, an Oshkosh Striker® 6x6 with a 65-ft model 652 Snozzle® HRET system installed.

PROTOTYPE ASPN.

Four different prototype ASPNs were developed and tested for this study. Each ASPN is unique in its design and flow pattern. Prototype Nozzle 1, as shown in figure 2(a), was designed to have a similar hole pattern to the standard Snozzle® ASPN. However, Prototype Nozzle 1 contains four holes in the piercing tip to create a more forward-projecting discharge stream. Additionally, the last two rows of holes of the nozzle were closed off.

Prototype Nozzle 2, as shown in figure 2(b), was designed to include a center discharge with a flow similar to that found on a straight-stream, hand-line nozzle. To achieve this flow, Prototype Nozzle 2 was designed to have a removable piercing tip that separates from the nozzle after penetration is complete and agent discharge begins. The nozzle assembly consists of two pieces, the nozzle body and the piercing tip. The nozzle body has eight evenly spaced holes in a circular pattern at the end and a chamber for inserting the tip. In the middle of this chamber is an additional discharge hole. When the agent reaches the nozzle, the pressure at these holes forces the tip to separate from the nozzle body. After the tip is removed from the nozzle, these nine holes provide a concentrated straight stream, while the other holes in the nozzle provide a wide-angle, dispersed spray pattern around the container.

Prototype Nozzle 3, as shown in figure 2(c), was designed to provide a straight-stream pattern similar to Prototype Nozzle 2 but without the removable tip. In this design, the nozzle body has three rows of holes to provide the wide-angle spray pattern. The penetrating tip has six holes that aim forward to provide the more concentrated, forward-projecting straight stream.

Prototype Nozzle 4, as shown in figure 2(d), had a similar design to Prototype Nozzle 3 with three rows of holes in the body and six holes in the tip; however, the piercing tip was modified with a chamfer. This chamfer was designed to deflect some of the forward discharge into a midrange discharge. This provided the nozzle with three different simultaneous spray patterns instead of only two. One pattern provided a wide-angle spray, the second pattern provided a mid-angle spray, and the third pattern provided a forward straight-stream pattern.

The nozzle dimensions, number of holes, and the hole diameters for all ASPNs are listed in table 1. All the hole diameters in Prototype Nozzle 1 were 7/64 inch. Prototype Nozzle 2's hole diameters were 1/8 inch and 3/32 inch. The 1/8-inch holes were located in the flat top of the nozzle body, and three rows of 3/32-inch holes were around the sides of the nozzle body. Prototype Nozzle 3 contained 5/32-inch holes in the nozzle tip and a combination of 1/8-inch and 5/32-inch holes that wrapped around the nozzle body. Most of the holes in Prototype Nozzle 4 had a 1/8-inch diameter; the exception to this is the holes around the chamfer, which have a 5/32-inch diameter.

Figure 2. The Four Prototype ASPNs: (a) Prototype Nozzle 1, (b) Prototype Nozzle 2, (c) Prototype Nozzle 3, and (d) Prototype Nozzle 4

Table 1. Prototype ASPN Dimensions and Hole Characteristics

ASPN	Length (in.)	Number of Holes	Hole Sizes (in.)
Prototype Nozzle 1	10 1/4	70	7/64
Prototype Nozzle 2	8 1/4	56	1/8, 3/32
Prototype Nozzle 3	7 1/4	42	1/8, 5/32
Prototype Nozzle 4	7 7/8	48	1/8, 5/32

FLOW MECHANICS AND PATTERN SHAPE.

Different nozzle sizes, shapes, and hole patterns can greatly influence the flow mechanics of an ASPN. One of the most important characteristics of a nozzle is flow rate. National Fire Protection Association (NFPA) Standard 414 [4] requires that piercing nozzles must have a flow rate of at least of 250 GPM. A Task Force Tips® Sho-Flow® flow meter was used to obtain both discharge pressure and flow rate readings from each Prototype ASPN. These readings determined if the ASPNs met the NFPA 414 standard. Another important characteristic of an ASPN is the flow pattern created by the nozzle itself. This is important since it shows where the extinguishing agent actually is discharged. To visualize the different flow patterns produced by the four prototype nozzles, the research team used the upper cargo bay of a freighter modified Airbus A310 (donated by FedEx). The advantage of using this aircraft for testing was that the spray pattern was not affected by any environmental conditions, such as wind. The spray pattern was however affected by the interior curvature of the aircraft fuselage. Utilizing the aircraft for these tests also provided a more realistic observation of how the curvature of the fuselage, as well at the internal components such as air ducts, can affect each prototype nozzle spray-pattern design.

Figure 3. Task Force Tips® Sho-Flow® Flow Meter

THE ULD FIRE TESTS.

The ULD fire tests took place at the FAA William J. Hughes Technical Center, near Atlantic City, New Jersey. ULDs are found in two forms, pallets or cargo containers that vary in size and shape. The International Air Transport Association (IATA) designates three-letter codes to identify airports all over the world, and similarly identifies ULDs. The IATA ULD code is used worldwide to identify a specific size and shape ULD. The first letter describes the ULD category, the second letter describes the device's base dimension, and the third letter describes the ULD contour or shape. An AYY-type ULD container was used as the test container for all tests. For an AAY, the first A means certified aircraft container, the second A means base dimension of 88 inches by 125 inches, and Y describes its curved contour and forklift capability. The ULD that was used had its canvas door and ceiling skin removed to simulate a ULD that had been breached by the fire. The ULD's condition was selected to best represent the expected conditions when a direct penetration into the ULD is not possible and an indirect fire attack must be used. The lower-section Lexan® walls of the ULD were replaced with .025, 2024-T3 aluminum panels to allow for more fire resistance and continued use on subsequent tests. The ULD was positioned inside a cross-section of a DC-10 fuselage, shown in figure 4, to simulate a container inside a freighter aircraft.

Figure 4. Thermocouple/Sash Chain Setup Around ULD

The fire load was the standard Class A fire load established by the FAA Cabin Fire Safety Group for cargo fire testing [5]. The fire load consisted of cardboard boxes that were 18 inches long by 18 inches wide by 18 inches high. The boxes were filled with 2.5 pounds of shredded paper for a total weight of approximately 4.5 pounds per box. Since the test ULD container already had breached walls, the fire load was half (35 boxes) of what is commonly used in ULD fire tests.

The ignition source used in these tests consisted of a 7-foot-long nichrome wire wrapped around four sheets of folded paper towels. Nichrome is a nonmagnetic alloy of nickel and chromium

usually used as a resistance wire. Nichrome is used in the explosives and fireworks industry as a device that uses an externally applied electric current to ignite a combustible compound.

The ignition source was placed inside one of the boxes that contained shredded paper. This box was known as the ignition box. Ventilation holes were cut into one side of the ignition box to promote fire growth and prevent self-extinguishment from oxygen deprivation. An insulated wire was led out of the box, and connected the Nichrome wire to a 115 V AC source. When the electrical current was applied, the electrical resistance in the wire caused it to heat and ignite the paper towels.

Thirty-six thermocouples were used to collect temperature data from different parts of the container for one test for each nozzle. Metal sash chains were placed around the test container to hang thermocouples at various positions, as shown in figure 4. The thermocouples used were 24-gauge K-type thermocouples with fiberglass insulation. The thermocouples were installed to either just make contact with the container wall or hang in the air above. Due to the small space between the back of the container and the aircraft wall, chains were not able to be hung. Instead, a thermocouple tree with metal-sheathed thermocouple probes was placed at the back of the container with the probes touching the back wall. A map of the thermocouple locations is provided in appendix A. The data collected was interpolated into graphs of planes at various locations of the container. These planes help show both the growth of the ULD fire and the extinguishment effectiveness of each prototype nozzle. Figure A-2 shows the planes that were analyzed during these tests.

During each test, the fire was allowed to develop until approximately 75% of the fire load was involved. This was confirmed visually, and once this condition was reached, fire extinguishment was initiated. The extinguishing agent used for all the test runs was water, since it is the most commonly used agent for Class A materials. For each test, the water was applied for one minute. At the end of the agent application, the container was visually assessed for remaining flames or smoldering material. This observation was used to evaluate the effectiveness of each prototype nozzle.

RESULTS

FLOW AND PRESSURE MEASUREMENTS.

All prototype ASPN flow rates and pressure readings were recorded using the Sho-Flow® flow meter, and the results are shown in table 2. Readings from a standard Snozzle® nozzle were also collected and was used as a baseline for the prototype ASPN. To collect flow readings from stable flow, each reading was taken after water was allowed to flow for 30 seconds. For these tests, flow rates were measured using the Oshkosh Striker®. As shown in table 2, the prototype ASPNs meet NFPA 414 flow requirements. The Snozzle® ASPN and Prototype Nozzle 3 showed highest flow readings, and Prototype Nozzle 4 showed the lowest flow rates. During the container fire tests, the Oshkosh Striker was committed to another research effort in California. For this reason, the HPRV was used as the fire apparatus for those tests. Since the same nozzles were used for the flow rates and the container fire tests, one can assume that the nozzles would give the same results regardless of the ARFF apparatus used. A correlation between the number of holes in a nozzle and flow rate could not be determined since the two prototype nozzles with

highest flow rates either had the lowest number of holes or highest number of holes. A correlation between nozzle length and flow rate does not seem to exist either.

Table 2. Flow and Pressure Measurements of Nozzles Using Oshkosh Striker®

ASPN	Flow Rate (GPM)	Pressure (psi)
Snozzle®	345	105
Prototype Nozzle 1	280	170
Prototype Nozzle 2	265	175
Prototype Nozzle 3	310	140
Prototype Nozzle 4	250	185

FLOW PATTERNS.

A compilation of flow pattern images from each prototype nozzle is shown in figure 5. Prototype Nozzle 1 (figure 5(a)) exhibited a wide umbrella pattern that would in theory surround the container, while the four streams created a small umbrella pattern that would in theory enter the container and extinguish the fire. Prototype Nozzle 2 (figure 5(b)) exhibited a similar wide umbrella pattern to that of Prototype Nozzle 1, but it had a more forward trajectory. Also, it had one large, forward, straight stream that was created by the nine nozzle holes. Prototype Nozzle 3 (figure 5(c)) exhibited an umbrella-like pattern similar to Prototype Nozzle 1, while producing a straight stream similar to Prototype Nozzle 2. Prototype Nozzle 4 (figure 5(d)) had a wide umbrella pattern like the other prototype nozzles with a straight stream like Prototype Nozzles 2 and 3. This nozzle also created a midrange umbrella that would cover the interior container walls.

Figure 5. Flow Patterns for (a) Prototype Nozzle 1, (b) Prototype Nozzle 2, (c) Prototype Nozzle 3, and (d) Prototype Nozzle 4

EXTINGUISHMENT EFFECTIVENESS.

The process for each test consisted of the ignition of paper, development of the fire, as shown in figure 6(a), and extinguishment of the fire. The effectiveness of each nozzle was visually assessed at the conclusion of each fire, as shown in figure 6(b). A total of 12 fire tests were conducted using the prototype nozzles. Table 3 gives an overview of the time the fire burned, application times of the extinguishing agent, and the effectiveness of the nozzles. The total test times varied since the time to begin agent application and extinguishment were based on fire growth and the percentage of boxes consumed. The weather conditions at the outdoor test facility during test times were a major variable. These conditions affected the rate in which the fire grew to the desired intensity prior to extinguishment. The shortest test ran for 5 minutes and 36 seconds (Prototype Nozzle 2, Test 2.1), and the longest test ran for 7 minutes 54 seconds (Prototype Nozzle 3, Test 3.1).

Figure 6. Fire Developing Inside the Container (a) and the Container After Extinguishment (b)

Table 3. Summary of ULD Tests

ASPN	Test Number	Test Time	Extinguishment Time	Extinguishment Effectiveness
Prototype Nozzle 1	1.1	5 min 55 sec	1 min	85%
Prototype Nozzle 1	1.2	6 min 30 sec	1 min	85%
Prototype Nozzle 1	1.3	7 min 9 sec	1 min	90%
Prototype Nozzle 2	2.1	5 min 36 sec	1 min	90%
Prototype Nozzle 2	2.2	6 min 27 sec	1 min	95%
Prototype Nozzle 2	2.3	5 min 57 sec	1 min	90%
Prototype Nozzle 3	3.1	7 min 54 sec	1 min	90%
Prototype Nozzle 3	3.2	5 min 48 sec	1 min	90%
Prototype Nozzle 3	3.3	7 min 24 sec	1 min	90%
Prototype Nozzle 4	4.1	6 min 52 sec	1 min	85%
Prototype Nozzle 4	4.2	7 min 40 sec	1 min	90%
Prototype Nozzle 4	4.3	7 min 2 sec	1 min	90%

After three tests, Prototype Nozzle 1 produced an average fire extinguishment effectiveness of 86.67%. This nozzle extinguished a majority of the fire; however, there was always a small fire remaining near the left wall of the container. Figure 7 shows the temperature conditions collected from thermocouple data during one of the tests for Prototype Nozzle 1. Just prior to agent application, the fire was located in the back right of the container and had a top ceiling temperature of 697°F. The back and front walls of the container had top temperatures in the range of 316° to 338°F. After extinguishment, the highest temperatures registered by the thermocouple in this run were in the high 90s°F.

Prototype Nozzle 2 achieved an average fire extinguishment effectiveness of 91.67%. After each agent application, most of the fire was completely extinguished except for small fires located at both sidewalls of the container. Although these fires were small, they produced a significant amount of smoke. The recovery of the removable tip from the fire debris proved to be an issue with using this nozzle. Figure 8 represents one of the fire tests that were being conducted using Prototype Nozzle 2. Before extinguishment began, the fire was located toward the center back of the container. The highest ceiling temperature that was recorded by the thermocouples was 502°F. The front of the container registered temperatures in the range of 270° to 340°F. The back of the container had a top temperature of 486°F. The sidewalls exhibited temperatures that ranged from 80° to 255°F. Once two minutes had passed after extinguishment was over, the highest temperature recorded from the container was 145°F. This high temperature came from the remaining fires that were close to the container walls.

After evaluating Prototype Nozzle 3's tests, it was found that this nozzle had 90% fire extinguishment application efficiency. After each extinguishment, small fires remained in the front part of the sidewalls. Data collected from one of the test fires are shown in figure 9. The ceiling thermocouple recorded that the fire inside the container had a maximum temperature of 743°F. The front of the container had temperatures that ranged from 90° to the mid-360°F. The back of the container had a high temperature of 386° F. The sidewalls had temperatures that

ranged from the 83° to 272°F. From the thermocouple data, it was determined that the fire was located in the center of the container. Two minutes after extinguishment, the highest temperature that was recorded was 135°F.

After three fire tests, Prototype Nozzle 4 had an extinguishment effectiveness of 88.33%. After each extinguishment attempt was completed, only a small fire remained on the left side of the container. Figure 10 shows the results from one of the fire tests that used this nozzle. In this test, the fire was concentrated in the back right section of the container. The top ceiling temperature before extinguishment was 570°F. The back wall of the container had a top temperature of 571°F. The front of the container had a top temperature of 310°F. The sidewall of the container had temperatures that ranged from 90° to 220°F. After extinguishment, the container had temperatures no higher than 130°F, and that was located in the left wall of the container where a small fire remained.

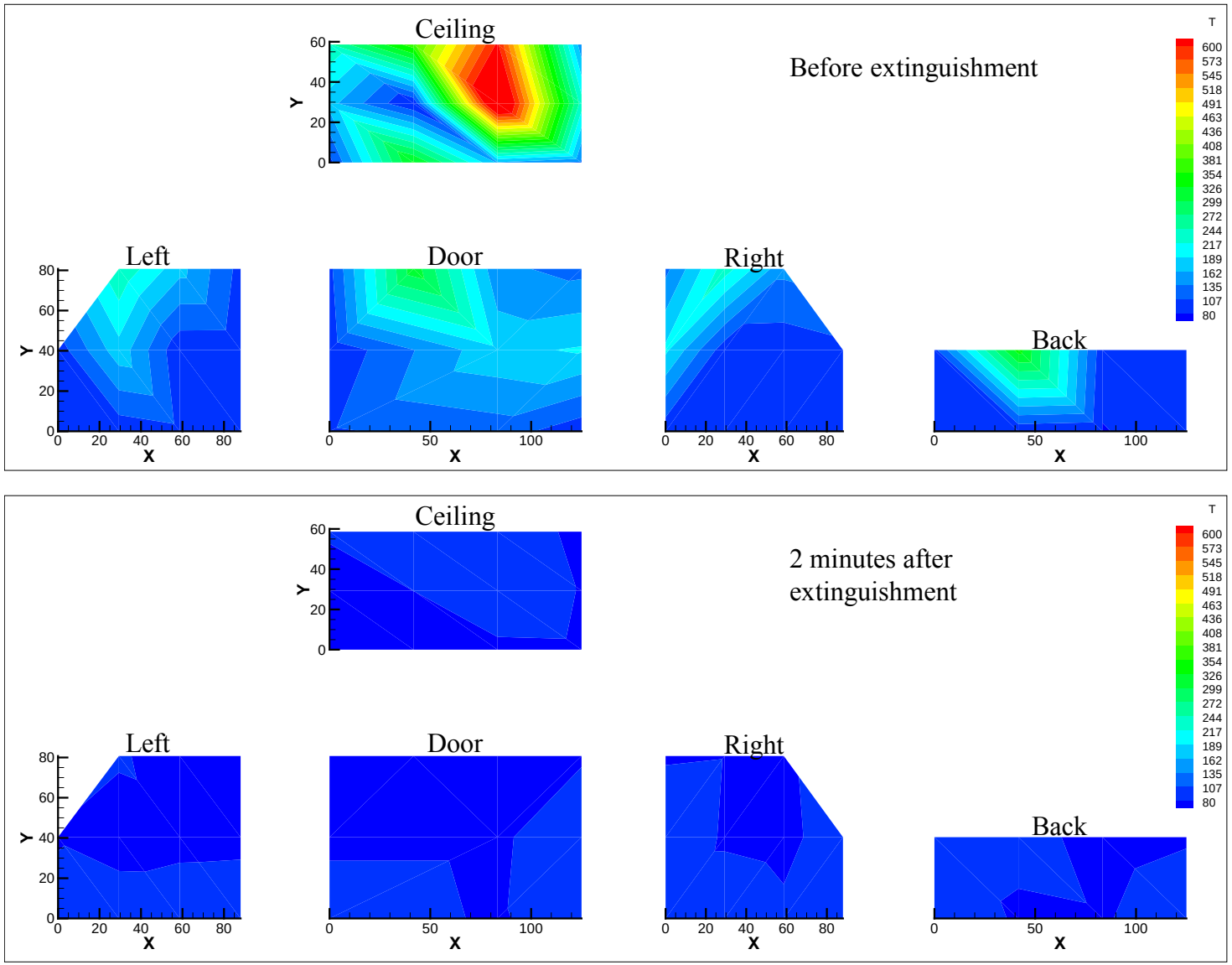

Figure 7. Prototype Nozzle 1 ULD Fire Test Results

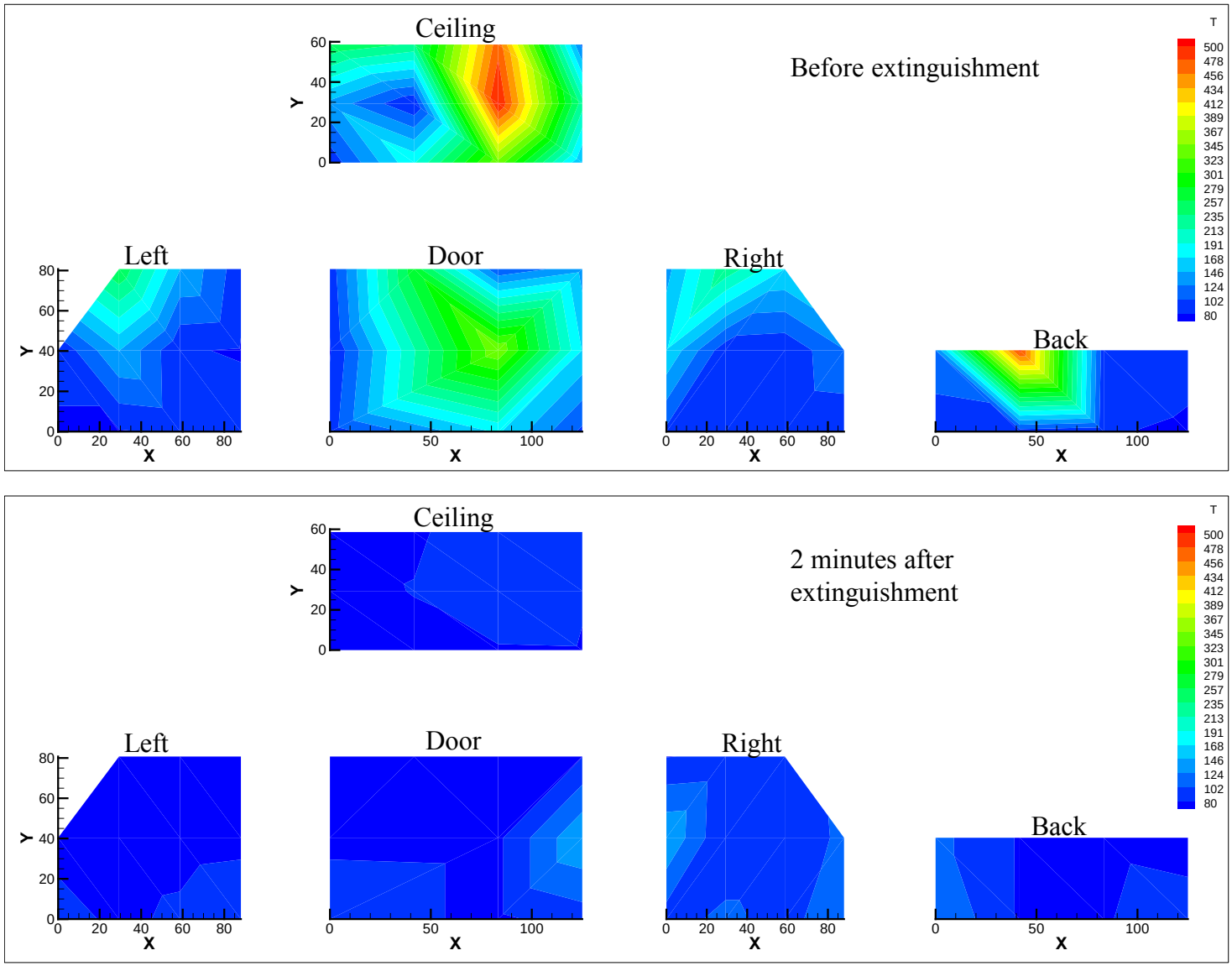

Figure 8. Prototype Nozzle 2 ULD Fire Test Results

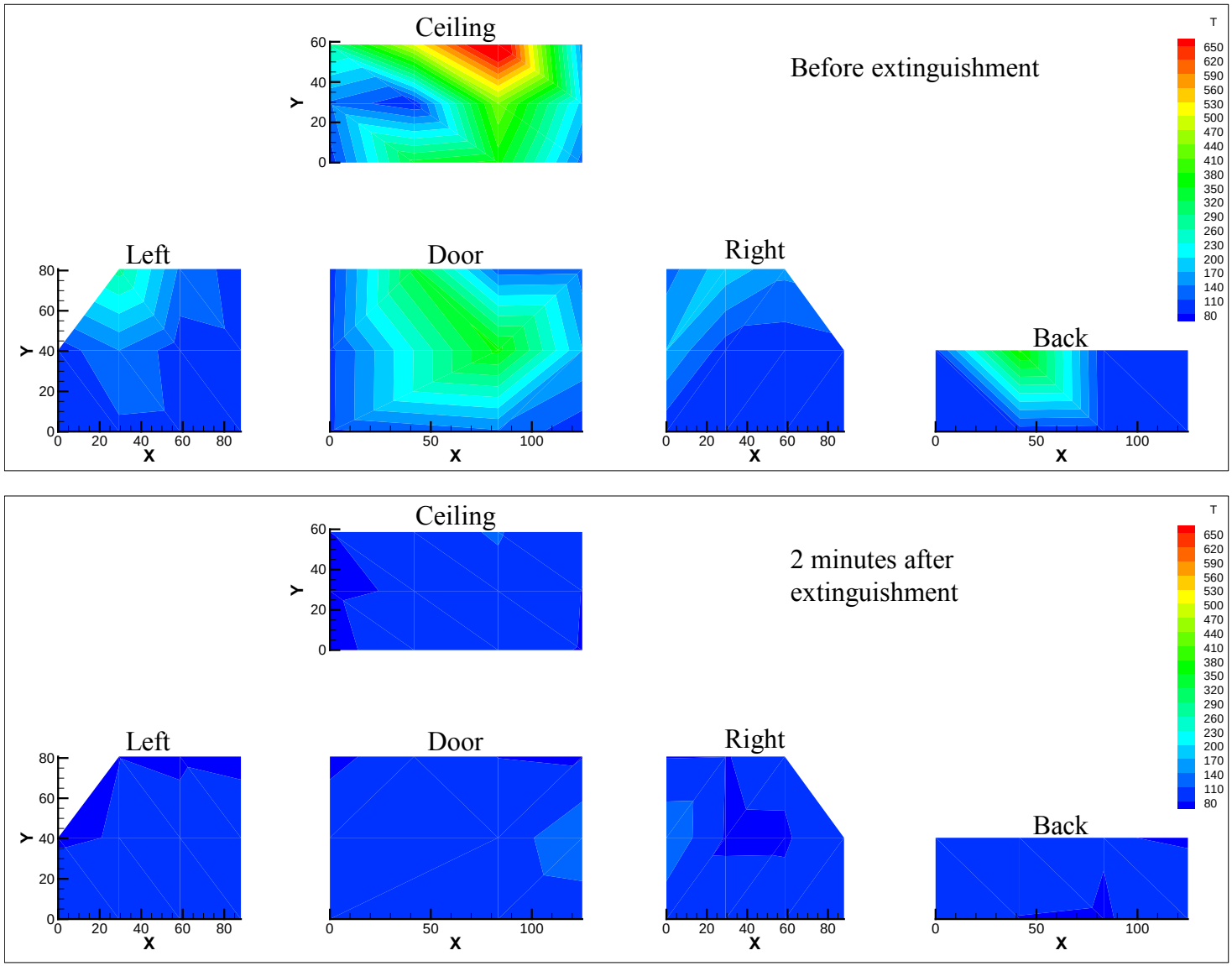

Figure 9. Prototype Nozzle 3 ULD Fire Test Results

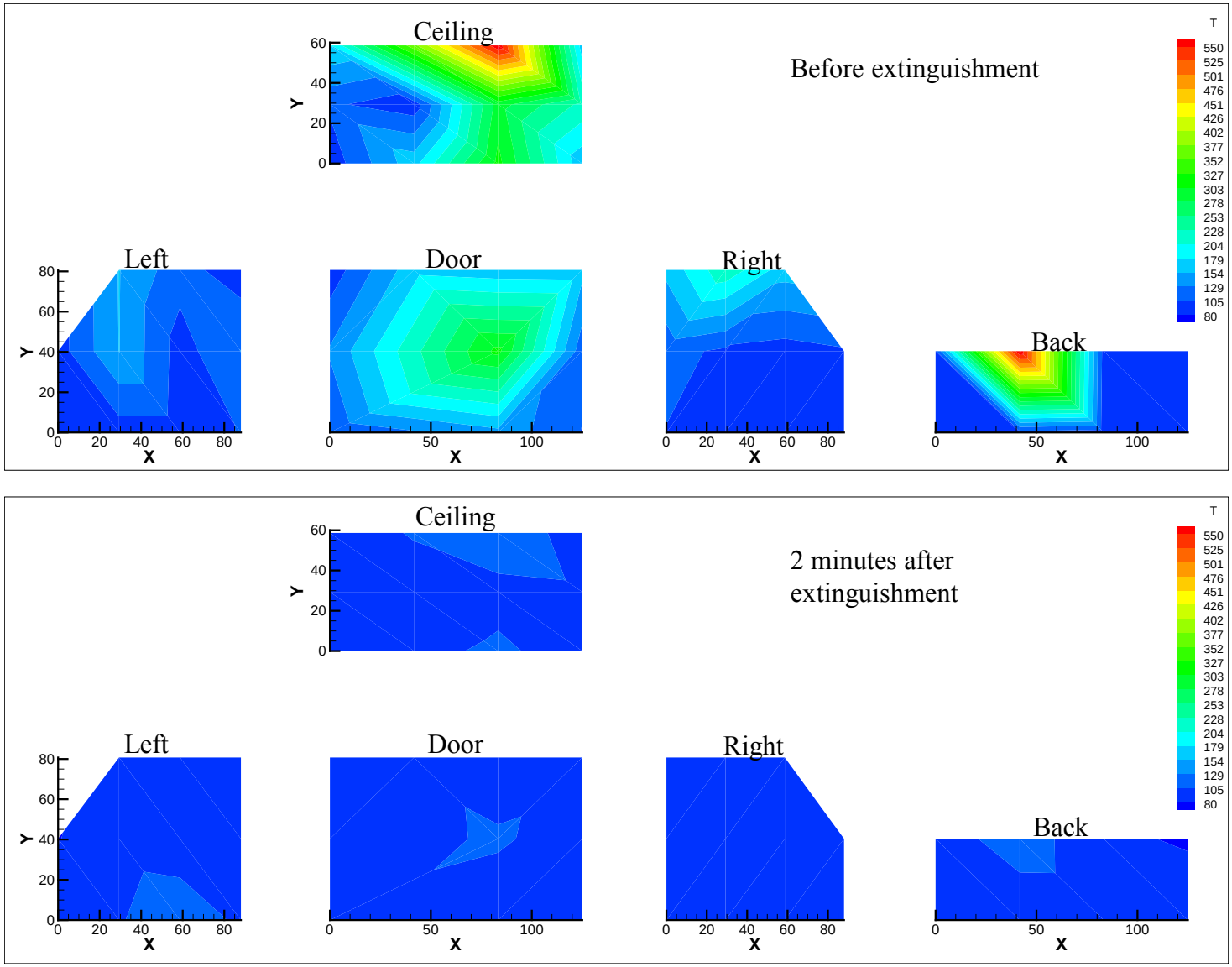

Figure 10. Prototype Nozzle 4 ULD Fire Test Results

CONCLUSIONS

Four prototype nozzles were designed and fabricated with the intent of extinguishing fires inside aircraft cargo containers, especially when the aircraft skin-penetrating nozzle (ASPN) cannot reach the inside of the container and an indirect fire attack must be used. The nozzle designs varied from adding a few holes to a current ASPN design to completely redesigning the hole patterns and adding different features to the tip. This ASPN study entailed different criteria that included flow rate measurements, flow pattern imaging, and testing the actual extinguishment effectiveness through live fire tests.

From the flow measurements, Prototype Nozzle 3 had the highest flow rate with 230 gallons per minute (GPM), and Prototype Nozzle 4 had the lowest flow rate with 180 GPM. However, Prototype Nozzle 4 had the highest pressure with 95 pounds per square inch (psi), and Prototype Nozzle 3 had the lowest pressure with 65 psi. This showed the flow rate and pressures of ASPNs are proportional. It was inconclusive whether the number of holes or the nozzle length had an effect on flow rate. Further research is needed to provide a conclusion for the difference in these design aspects. Information from the flow pattern study showed, Prototype Nozzles 2 and 3 had very similar flow patterns, which had a wide umbrella spray pattern and a forward-projecting straight stream. Prototype Nozzle 4 had three different streams: a wide-umbrella spray, a mid-angle spray, and a forward-projecting straight stream.

A series of test fires were conducted to find the extinguishing effectiveness of each nozzle. Overall, Prototype Nozzle 2 had the best extinguishment efficiency, and Prototype Nozzle 3 was the second best. One major negative aspect of Prototype Nozzle 2 was the need to recover the removable piercing tip. This would be impractical during real-life aircraft firefighting events because if fire fighters pierce the aircraft skin and then needed to relocate to a different penetration point, the tip would have to be replaced to make the next penetration. It is feasible that this may have to happen multiple times. This time-consuming operation would increase the chances of the fire spreading and potentially causing loss of cargo and aircraft. Overall, Prototype Nozzle 3 was determined to be the best design for use on freighter aircraft.

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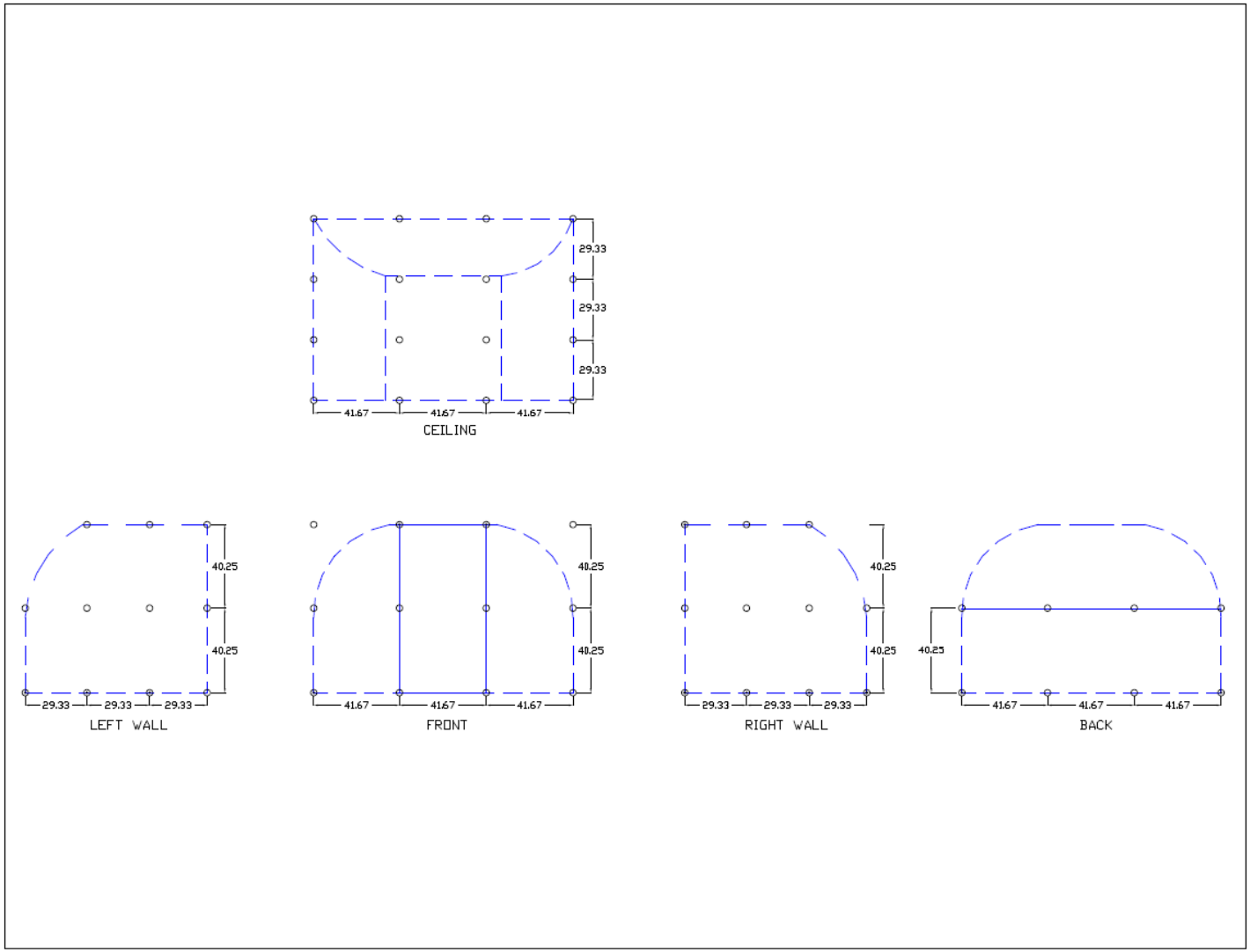

Figure A-1. Thermocouple Locations on AAY Unit Load Device

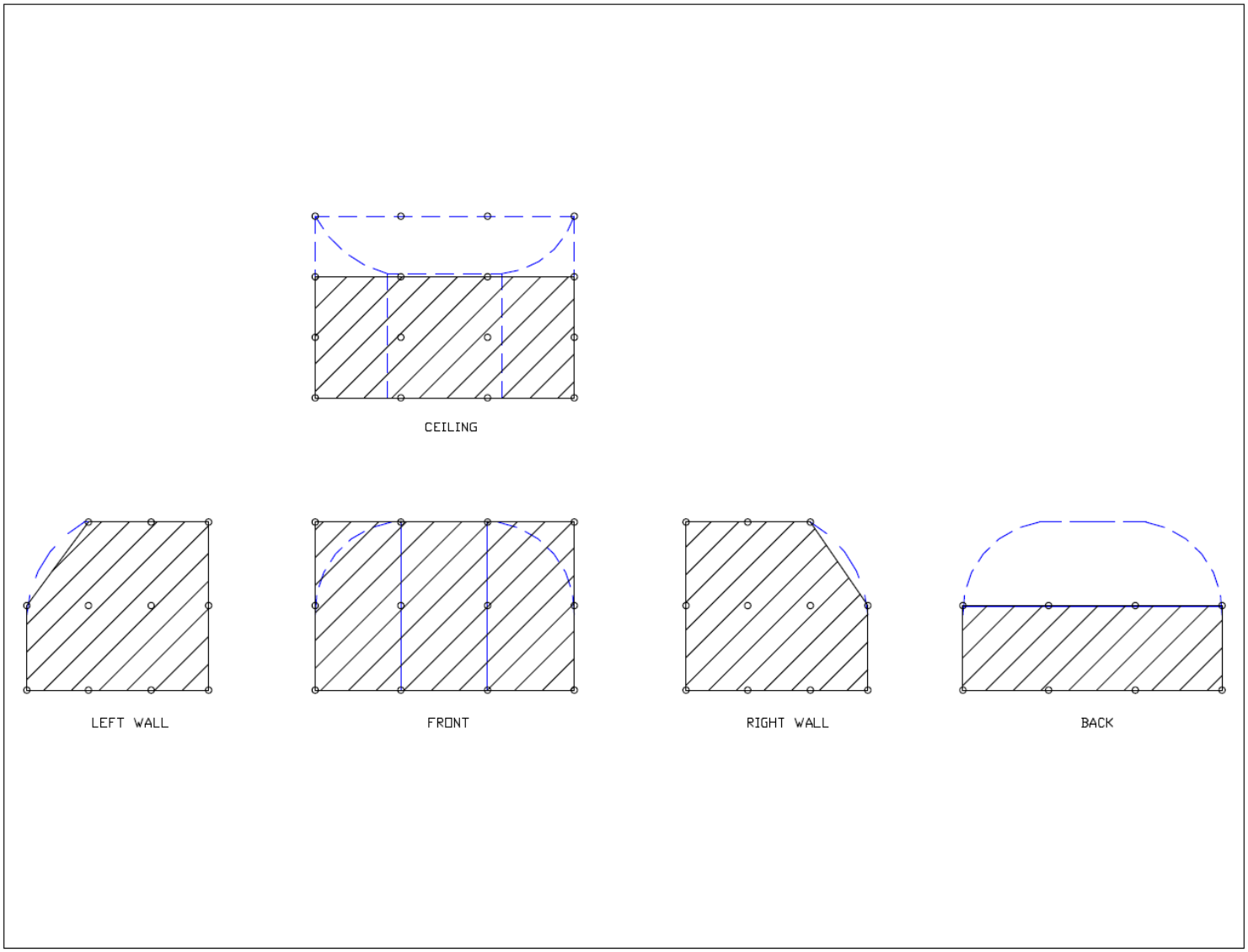

Figure A-2. Temperature Contour Plane Locations