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

An Evaluation of Fire Containment Products for Inflight Fires Resulting from Portable Electronic Devices (PEDs)

December 2024

Report

U.S. Department of Transportation
Federal Aviation Administration

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16. Abstract

The number of thermal runaway incidents from portable electronic devices (PEDs) in the aircraft cabin is growing at a notable rate. Recent data indicates that lithium battery incidents occur on average more than once per week on passenger aircraft. In response to this problem, many airlines have adopted the use of fire containment products as a means to mitigate the spread of fire and toxic fumes. An evaluation was conducted by the FAA to assess the effectiveness of commercially available fire containment products and assess their capability to mitigate the release of smoke, flames and shrapnel produced from a PED fire.

Fire containment products were procured from five different manufacturers and tested with three different fire loads, a tablet containing a 30 Watt-hour (Wh) battery, a 96 Wh power bank and a 154 Wh video camera battery. Products were only evaluated according to the maximum capacity that the product was advertised to withstand.

Key findings from this study include:

- The performance of fire containment products varied amongst the different products. Multiple products struggled to contain the hazards of PED fires near the maximum allowable energy limits permitted on aircraft (100 Wh and 160 Wh).
- Product performance varied based on the PEDs interior cell configuration and the rate at which cells experienced thermal runaway. Short periods between thermal runaway events can produce significant gas buildup, which some products are unable to vent quickly enough. This can create pressure spikes and mechanical failures (rips/tears) in the product.
- The suppression equipment included with some of the containment products was found capable of knocking down flames but unable to prevent heat propagation to adjacent cells.

Testing suggests that some containment products cannot currently meet the airlines' present expectations for product performance. Further testing on the use of fire containment products may be needed to ensure the safety of aircraft occupants.

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Acronyms

Acronym	Definition
DOT	Department of Transportation
EFB	Electronic flight bag
FAA	Federal Aviation Administration
NTSB	National Transportation Safety Board
PED	Portable electronic device
PID	Proportional Integral Derivative
PPE	Personal Protective Equipment
SCBA	Self-Contained Breathing Apparatus
SoC	State of Charge
UL	Underwriters Laboratories
Wh	Watt-hour

Executive summary

The number of thermal runaway incidents from portable electronic devices (PEDs) in the aircraft cabin is growing at a notable rate. Recent data indicates that lithium battery incidents occur on average more than once per week on passenger aircraft. In response to this problem, many airlines have adopted the use of fire containment products as a means to mitigate the spread of fire and toxic fumes. An evaluation was conducted by the FAA to assess the effectiveness of commercially available fire containment products and assess their capability to mitigate the release of smoke, flames and shrapnel produced from a PED fire.

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- The suppression equipment included with some of the containment product products was found capable of knocking down flames, but unable to prevent heat propagation to adjacent cells.

Testing suggests that some containment products cannot currently meet the airlines' present expectations for product performance. Further testing on the use of fire containment products may be needed to ensure the safety of aircraft occupants.

1 Introduction

Lithium batteries are used as power sources in many different types of portable electronic devices (PEDs) such as phones, tablets, e-cigarettes, power banks and laptops. The benefits of lithium battery technology include a high energy density, longevity and inexpensive cost compared to other battery chemistries. However, lithium batteries are classified by the Department of Transportation (DOT) as a Class 9 (Miscellaneous) Dangerous Good due to their associated hazards (Code of Federal Regulations Parts 171-180, 2023). Lithium batteries are known to undergo a process known as thermal runaway, an uncontrollable and self-sustaining process in which a sudden increase in temperature occurs, often expelling toxic gases and flame to the surrounding area. A thermal runaway event may occur when cells are overheated, overcharged, mishandled, or have a manufacturing defect leading to an internal short circuit.

Thermal runaway is a particularly prominent problem in air transportation, both as cargo and carry-on luggage. Three catastrophic in-flight aircraft accidents involving either loss of aircraft or life occurred between 2006 and 2011. Post-crash investigations suspected that bulk shipment of lithium batteries contributed to either the fire ignition or propagation (National Transportation Safety Board, 2007; South Korea Aircraft and Railway Accident Investigation Board, 2007; General Civil Aviation Authority of the United Arab Emirates, 2010). In addition to these major accidents, hundreds of small-scale thermal incidents have occurred within the cabin of aircraft involving PEDs carried on by passengers. Figure 1 displays the number of FAA recorded thermal incidents that occurred on passenger aircraft between 2006 and January 12th, 2024.

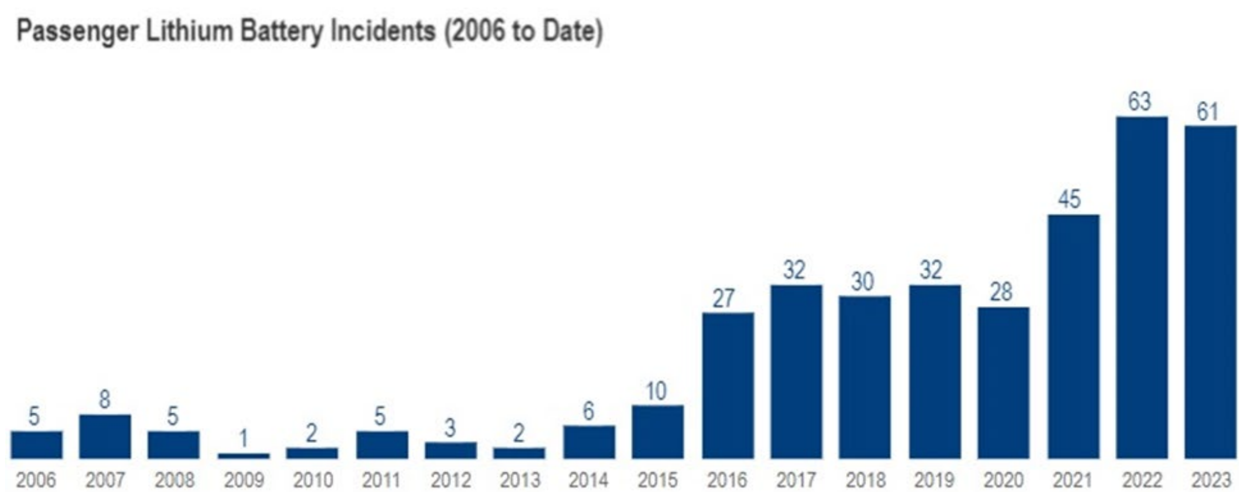

Figure 1. Lithium battery incidents involving smoke, fire, or heat on passenger aircraft

In total, 365 incidents have been recorded within this time frame, with a significant growth in occurrences within recent years (Federal Aviation Administration, 2023). As of 2022, lithium battery fires have been occurring on average more than once per week within passenger aircraft.

In response to this threat, airlines have explored the use of fire containment products as a means to diminish the effects of an overheating PED experiencing a thermal runaway event. These products are designed to fully encapsulate a PED fire, thereby mitigating hazards such as smoke and flame. Many fire containment products include personal protective equipment (PPE) such as fire-resistant gloves, tongs, pry bars, and face protectors/shields, which operators are encouraged to use.

In the event of a lithium battery PED fire, current FAA guidance recommends utilizing a Halon, Halon replacement, or water extinguisher to extinguish the fire and prevent its spread to nearby flammable materials. Once the flame is extinguished, the PED should be doused with water to cool the device and prevent additional cells from reaching thermal runaway (Federal Aviation Administration, 2009). Furthermore, the FAA recommends that crewmembers refrain from moving a burning, smoking or overheating device until that device has been thoroughly cooled (Federal Aviation Administration, 2017). Once the device has been sufficiently cooled for at least fifteen minutes after a fire has been extinguished or smoke has dissipated, the PED may be submerged into a water-filled container using protective equipment.

Presently, the FAA does not object to the use of fire containment products provided procedures outlined in the referenced Safety Alert for Operators (SAFOs) and Advisory Circulars (ACs) are followed. Although fire containment products are allowable, currently, there are no FAA test standards for these products, nor is there a mechanism in place for the approval of these products despite claims by some manufacturers that their product is “FAA certified” or “meets FAA standards” (Federal Aviation Administration, 2017).

Although no FAA standard for these products exist, Underwriters Laboratories (UL) produced a technical standard for battery fire containment products denoted as “ANSI/CAN/UL 5800”. UL developed the standard with input from airlines, containment product manufacturers, and regulatory representatives.

2 Objective

The objective of this study was to further explore the hazards associated with PED fires and to evaluate mitigation techniques and equipment used by some airlines. An analysis was conducted on various fire containment products to determine the effectiveness of these devices and assess their capability to mitigate the release of smoke, flames and shrapnel produced from a PED fire. The purpose of this study was not to compare products, but rather to determine if additional guidance is needed by the FAA to reduce the potential consequences of PED thermal runaway events within the aircraft cabin.

3 Test setup

3.1 Evaluated portable electronic devices

Federal regulations allow passengers to carry-on devices containing lithium ion batteries up to 100 Watt-hours (Wh). However, with airline approval, passengers may be permitted to carry-on two additional large lithium ion batteries not exceeding 160 Wh (49 CFR 175.10(a)(18)(ii), 2023). In keeping with regulations, many fire containment products are designed to withstand a lithium battery fire up to 100 or 160 Wh, respectively.

Fire containment products within this study were subjected to three different fuel loads; a mid-sized (9.8 by 6.8 by 0.2-inch) tablet, a large (7.0 by 3.2 by 0.9-inch) power bank and a large (5.9 by 3.7 by 2.2-inch) video camera battery. All PEDs were charged to 100% state of charge (SoC) in order to replicate a worst-case scenario for the device.

The tablet contained a 30 Wh battery comprised of two 15 Wh pouch cells. The tablet was selected to replicate a mid-sized thermal runaway scenario that may occur in both passenger and crewmember PEDs. Tablets are commonly carried on by passengers and pilots utilize tablets within the aircraft flight deck as an electronic flight bag (EFB) to aid in performing flight management tasks. Ignition of the battery gases released from the tablet proved to be inconsistent throughout testing. As a result of this problem and the high associated cost, the use of tablets decreased as testing progressed.

The power bank and video camera battery were selected to represent PEDs near the limit without airline approval (100 Wh) and with airline approval (160 Wh), respectively. The power bank contained eight electrically connected $LiNiMnCoO_2$ 18650 cells, composing a 96 Wh battery. The video camera battery was comprised of sixteen electrically connected $LiNiCoAlO_2$ 18650 cells, comprising a 154 Wh battery.

Products were only evaluated according to the maximum advertised capacity that the product could withstand. For example, a product which advertised the capability to withstand up to a 100 Wh PED fire was not tested with the 154 Wh video camera battery.

3.2 Test method

During setup, evaluated PEDs were opened and 1 by 3-inch self-adhesive polyimide film heaters with a power density of 10 W/in^2 were attached to the outermost cell within the device. The initiating cell was heated at a rate of 10°C/min (18°F/min) until thermal runaway was achieved, and then the heater was turned off. The heating rate was controlled by a proportional integral derivative controller (PID) controller.

Preliminary testing indicated that only one heater produced inconsistent heating rates for the tablet tests, so additional heaters were added to achieve the desired heating rate. Exposed junction Type K thermocouples were placed within the PEDs to monitor temperature and control the heating rate. PEDs were then resealed using adhesives and wiring. The internal setup of the tablet, power bank and video camera battery is shown below in Figure 2 and Figure 3.

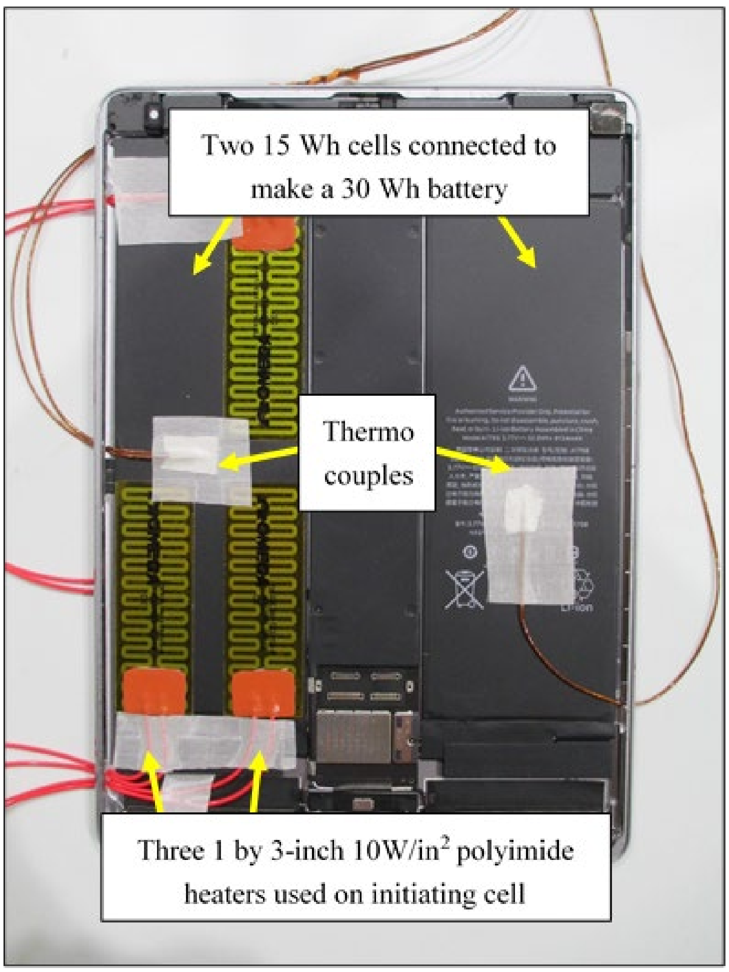

Figure 2. Interior 30 Wh tablet setup

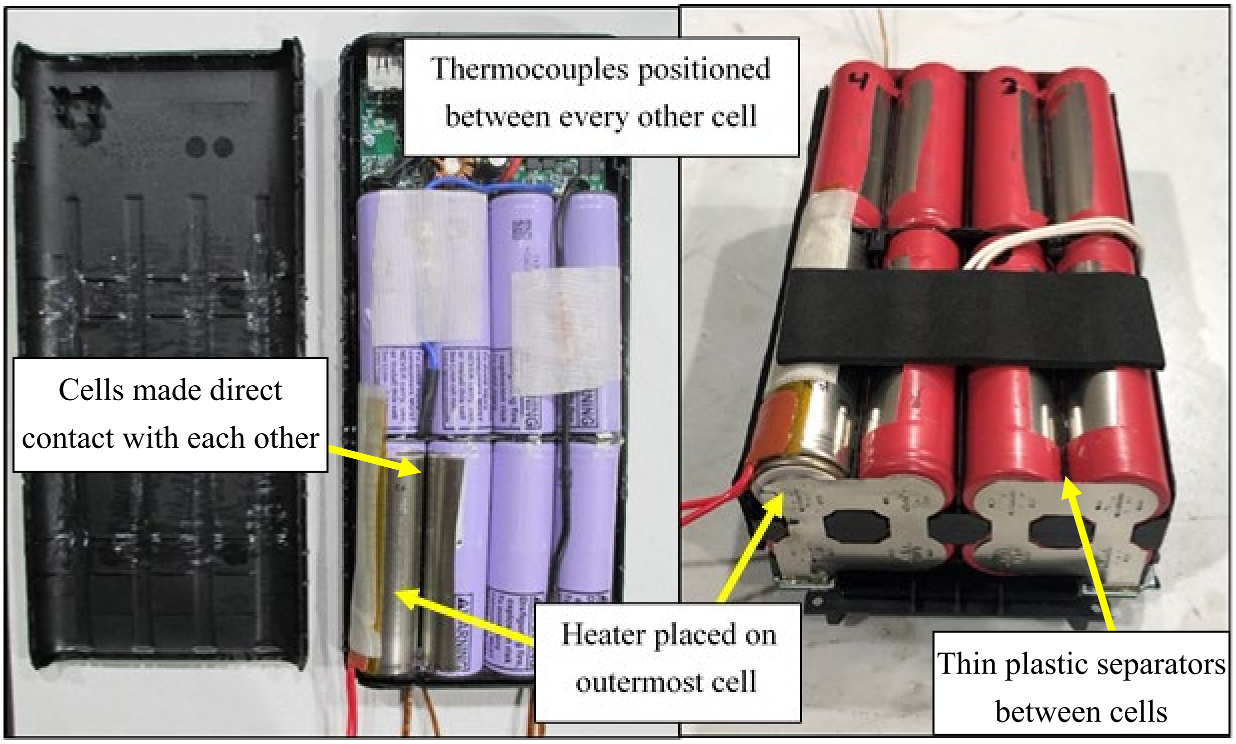

Figure 3. Interior of 96 Wh power bank (left) and 154 Wh battery (right) setup

Additional thermocouples were attached to the outside of fire containment products to collect exterior surface area temperatures. When possible, interior bag pressure data was also recorded using a pressure transducer accurate within 0.08% of its full-scale range (0 to 150 psia).

4 Fire containment bag testing

Fire containment products from five manufacturers were procured and tested at the FAA William J. Hughes Technical Center. These products were relabeled and denoted as “Manufacturer A - E” to protect company proprietary information. All evaluated products with the exception of Manufacturer D were single use only and were not reused after each test. Although fire containment bag manufacturers share a common goal of mitigating thermal runaway hazards, manufacturers utilize different approaches to accomplish this. In order to produce a test that is representative of a realistic thermal runaway incident, test procedures were tailored to incorporate manufacturer instructions and designs.

4.1 Manufacturer A

Manufacturer A developed two types of containment bags advertised to contain up to 100 Wh PED fires. One version was designed for the cabin and the other for the flight deck. The cabin variant (outer dimensions of 22 by 17 by 5-inches) was larger than the flight deck version (outer dimensions of 10 by 14 by 5-inches). Both versions included fire protection gloves, a fire blanket and two PED pads. The cabin version also included goggles and a mask. Furthermore, both versions also had a vent and a combination filter cartridge which could be attached, as a means for smoke to escape. Upon direct contact with heat, the PED pads were designed to release a non-crystalline granulate extinguishing agent produced from recycled glass. Figure 4 and Figure 5 show both bag versions and the included equipment, respectively.

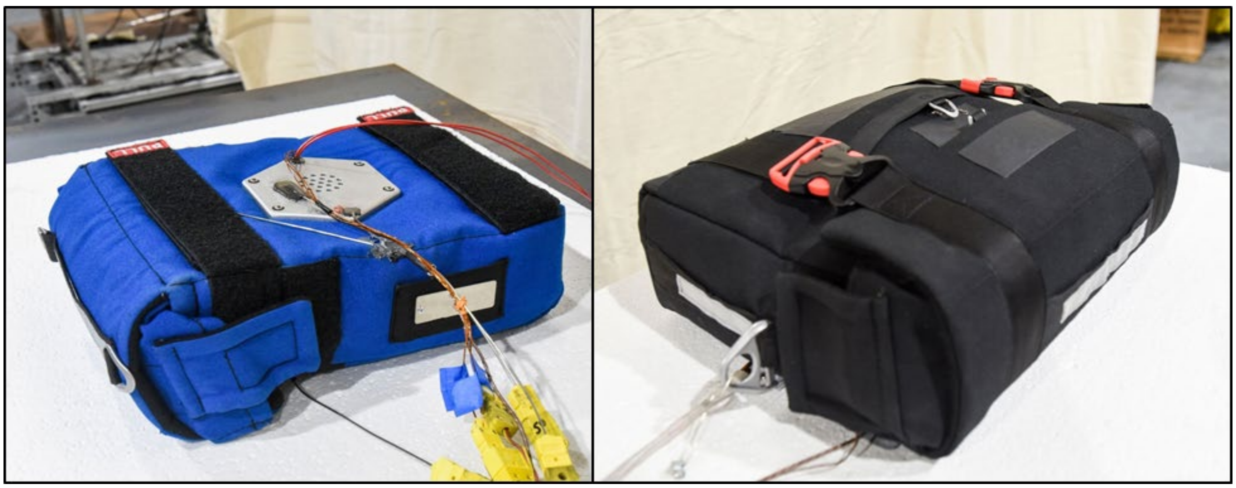

Figure 4. Flight deck (left) and cabin (right) versions

Figure 5. PPE (left), fire suppression pad (middle), and folded up fire blanket (right)

Manufacturer A provided two different sets of instructions, depending on the device's condition. In the event of an overheating device, the manufacturer recommends bundling the PED into the fire blanket and transferring it directly into the bag.

If a device is on fire, the manufacturer directs the user to equip PPE and utilize the blanket as a barrier to help shield the firefighter upon approach. Subsequently, a PED-pad and the fire blanket are to be applied over the device until it is fully extinguished. Once this is achieved, the firefighter could utilize the fire blanket to transfer the device into the bag.

Eight total tests were conducted with this product: four with each bag version. Four tests were conducted according to the manufacturer's instructions for each scenario, based on if the PED was overheating or already on fire (Figure 6). Since this product was marketed to contain PED fires up to 100 Wh, only the 30 Wh tablets and 96 Wh power banks were utilized.

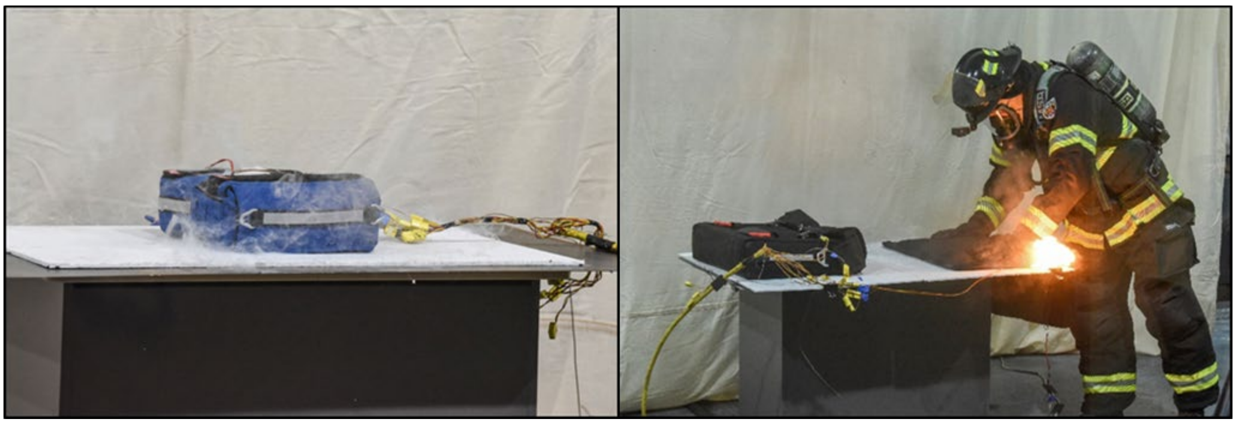

Figure 6. Two test scenarios – PED overheating (left) and PED already on fire (right)

4.1.1 Manufacturer A—Portable electronic device overheating tests

For the test scenarios in which the PED was overheating, devices were left inside the container and heated until thermal runaway was achieved. Testing yielded mixed results. Throughout all trials, no visible flames or shrapnel were observed to have escaped the product when tested with either PED. However, a considerable amount of smoke was released from the bag.

The effectiveness of the vent and filter proved to be inconsistent. The vent was observed to be more effective when the filter was oriented "face up" rather than "face down". Even despite this, smoke would often escape through other areas of the bag.

The cabin version was more effective in mitigating hazards compared to the smaller flight deck version. In one test with the flight deck bag, thermal runaway of the power bank generated enough pressure that it caused the bag to tear, releasing a substantial amount of smoke in the surrounding area, as seen in Figure 7.

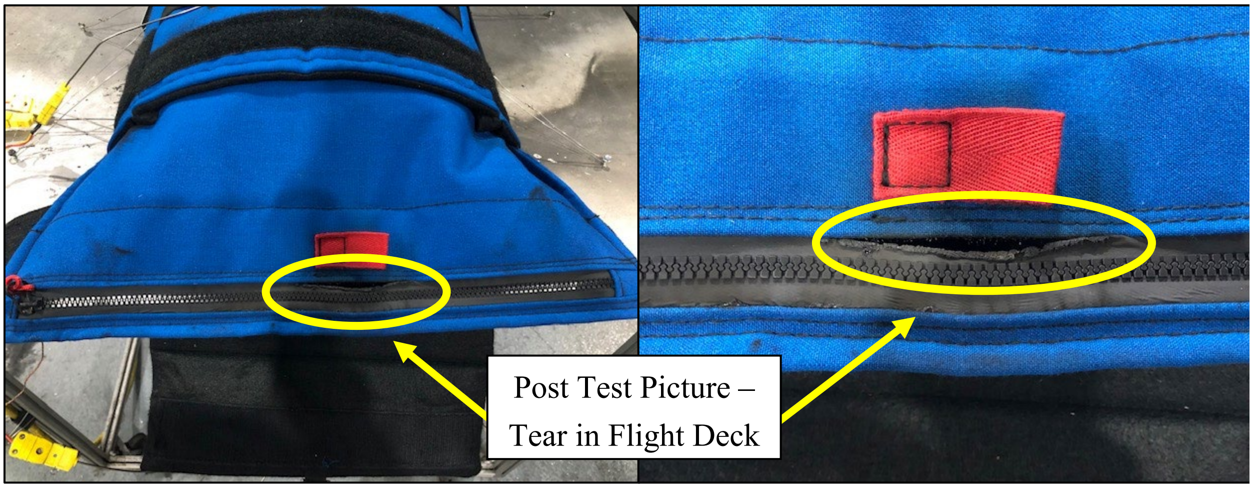

Figure 7. Tear produced in the flight deck bag after testing with the 96 Wh power bank

Despite this tear, no flames or shrapnel were observed to have escaped or penetrated the bag. This suggests that the two PED pads stored within the fire containment bag proved to be effective in knocking down flames.

Table 1 displays the maximum temperature collected throughout all four tests below.

Table 1. Max Data Values – All Tests – Manufacturer A

Max Data Values		
	°F	**°C**
Interior Temp	1729	943
Top Exterior Temp	191	88
Bottom Exterior Temp	134	57
	PSI (Absolute)	**kPa (Absolute)**
Pressure	---	---

Note: Pressure data was not collected in tests with Manufacturer A.

4.1.2 Manufacturer A—Portable electronic device already on fire tests

Additional testing was conducted to replicate the manufacturer's instructions for a scenario in which a PED was currently on fire. The evaluated PEDs were placed on a table two feet away from the fire containment bag and tied down with a thin metal wire strip to prevent movement during thermal runaway. A firefighter equipped with a self-contained breathing apparatus (SCBA) and full turnout gear was stationed near the table and attempted to transfer the PED into the bag. After achieving thermal runaway, a PED pad was placed over the device and then a fire blanket was subsequently draped over both as specified in manufacturer instructions.

Testing conducted with the tablets produced significantly less hazards compared to the power banks. A significant amount of gas was released during thermal runaway of the tablets, but no visible flame or shrapnel was observed. The firefighter was able to transfer the device into the containment bag with relative ease.

Much more severe hazards were observed in tests with the power bank (Figure 8). Upon thermal runaway, a significant amount of burning fragments was ejected more than ten feet from the device.

As the reaction subsided, the PED pad and fire blanket were placed over the device. These safety measures proved to be effective in one of the two performed tests. However, in the second trial, an additional thermal runaway event occurred after the PED pad was placed on the device but prior to application of the fire blanket.

Figure 8. Manufacturer A – power bank catches fire outside of bag

Heavy flames were released within the immediate area, and it is highly probable that an aircraft crewmember could potentially be severely burned if this were to occur during an actual thermal event.

4.2 Manufacturer B

Three fire containment bags obtained from Manufacturer B were evaluated; two capable of containing a PED fire up to 100 Wh and another up to 160 Wh. Fire protection gloves were also packaged with this product. The product was composed of an inner bag, designed to stop flames and shrapnel, and an outer bag designed to contain smoke. Figure 9 displays an image of the 100 Wh bag and the fire protection gloves.

Figure 9. 100 Wh fire containment bag (left) and fire protection gloves (right)

Manufacturer B did not provide any instructions or recommendations to move a flaming device, so testing was only conducted with the PED contained within the bag throughout entirety of testing.

4.2.1 Manufacturer B—Portable electronic device overheating tests

The fire containment bags produced by Manufacturer B proved to be effective in mitigating the hazards produced from PED thermal runaway events. 96 Wh power banks were utilized in testing with the 100 Wh bags and the 154 Wh battery was used with the 160 Wh bag. The bags are shown in Figure 10.

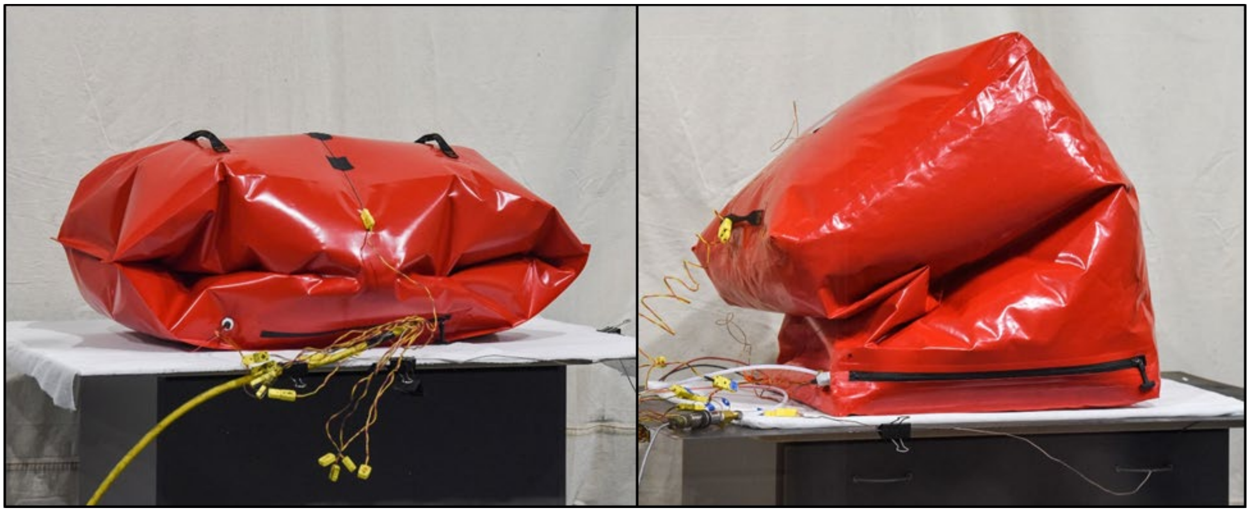

Figure 10. Manufacturer B – peak reactions of 100 Wh (left) and 160 Wh (right) bags when undergoing testing with the power bank and video camera battery, respectively

Throughout all three tests, no visible smoke, flames or shrapnel was observed to have escaped either bag version. Temperatures within the bag's interior were noted to reach over 2400 °F (1315 °C), but maximum temperatures on the exterior of the bag were noted to climax at approximately 220 °F (104 °C). Readings collected by a pressure transducer equipped within the outer bag measured no significant pressure increase.

Table 2 displays the maximum temperature and pressure values collected throughout all three tests below.

Table 2. Max Data Values – All Tests – Manufacturer B

Max Data Values		
	°F	**°C**
Interior Temp	2487	1364
Top Exterior Temp	206	97
Bottom Exterior Temp	220	104
	PSI (Absolute)	**kPa (Absolute)**
Pressure	14.8	102

4.3 Manufacturer C

Manufacturer C retailed a bundle of products including a fire containment bag, heat resistant gloves and a re-sealable storage container. The interior of the fire containment bag was composed of insulated material, advertising the capability to withstand temperatures up to 2000 °F (1093 °C). Once the PED is placed within the bag, product instructions direct the handler to fold a heat shield flap over the device, to provide extra protection. The bag is then sealed using multiple hook and loop strips positioned throughout the product. A picture of the bag's exterior is shown in Figure 11. The product interior and the heat shield flap folded over the device is shown below in Figure 12.

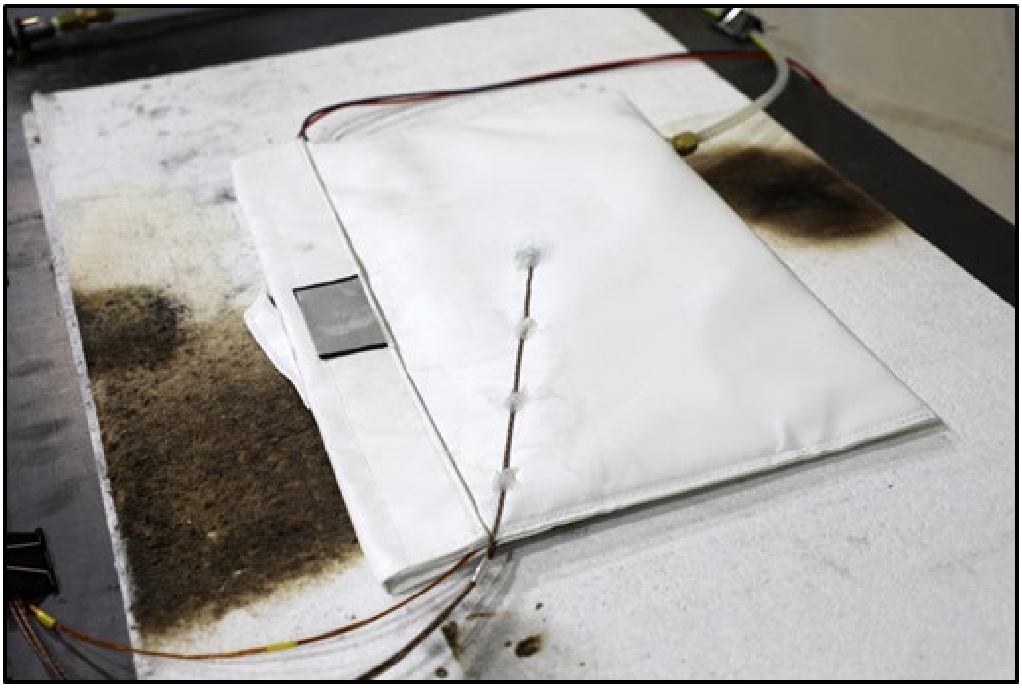

Figure 11. Exterior of the bag produced by Manufacturer C

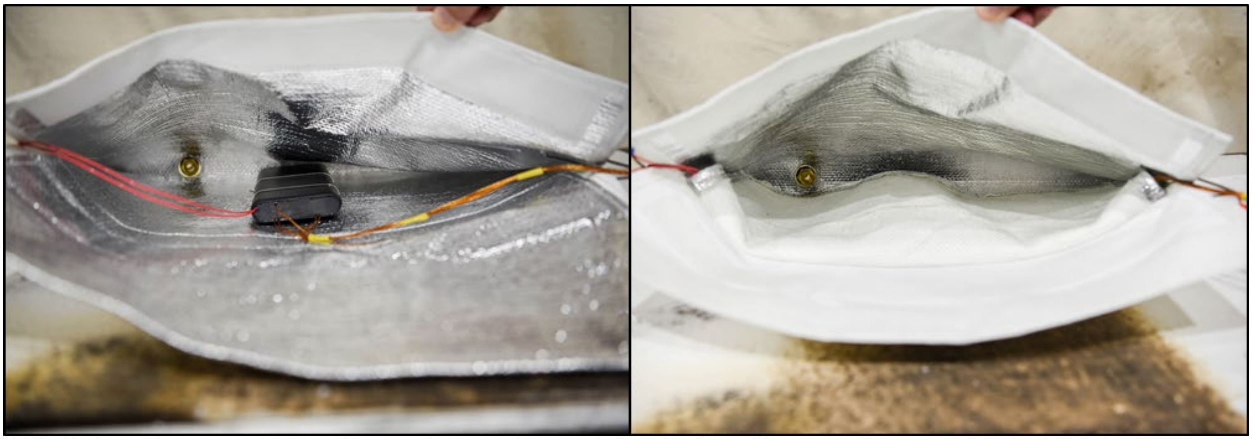

Figure 12. Interior of the bag (left) and the inner heat shield flap folded over the PED (right)

This manufacturer stated that this product was designed to store overheating devices that had not yet shown signs of smoke or fire. It is intended to contain heat, shrapnel and reduce the likelihood of proximity fires. However, this fire containment bag was not designed to contain the release of smoke. The manufacturer stated that this product is intended to work in conjunction with current FAA firefighting guidance and should not be used as a substitute. Therefore, no recommendations for moving a flaming device were suggested.

4.3.1 Manufacturer C—Portable electronic device overheating tests

One test was first conducted with the tablet. A small volume of smoke was released from the bag, but no visible flame or shrapnel. Only one of two cells within the tablet experienced thermal runaway, as not enough heat propagated to the second cell.

Testing with Manufacturer C's product proved to be ineffective when evaluated with the 96 Wh power bank. During thermal runaway, the large volume of generated smoke and ensuing pressure increase caused the hook and loop strips to become unattached, allowing a large quantity of smoke to escape. The released smoke would sporadically ignite from test to test, producing a burst of flames that could reach several feet out. Measured temperatures on the exterior of the bag were observed to exceed 800°F (426°C) when this occurred. Pressure increases up to 14.9 psia were observed within the interior of the bag. Peak reactions of the bag when tested with the power bank is shown in Figure 13.

Figure 13. Manufacturer C – power bank in bag - peak reaction

Table 3 shows the maximum temperature and pressure measurements recorded throughout all test trials.

Table 3. Max Data Values – All Tests – Manufacturer C

Max Data Values		
	°F	**°C**
Interior Temp	2454	1346
Top Exterior Temp	352	178
Bottom Exterior Temp	817	436
	PSI (Absolute)	**kPa (Absolute)**
Pressure	14.9	103

4.4 Manufacturer D

Manufacturer D developed a fire containment product that resembled an aluminum case type system. The external dimensions of this case measures 23 by 15.3 by 9.7-inches and has an internal volume of 2,584 in^3. It was stated by the vendor that this case would contain large battery fires, having the potential to contain two 160 Wh PEDs. PPE shipped with this product included heat resistant gloves, tongs and eye protection. Moreover, a granulate dry extinguishing agent made from recycled glass was also included. This manufacturer stated that the extinguishing agent could be poured directly onto the PED or preemptively stored within a sealed cardboard bag and placed over the device, releasing the agent when heated. A picture of the exterior of the product and the interior with the applied extinguishing agent is shown below in Figure 14.

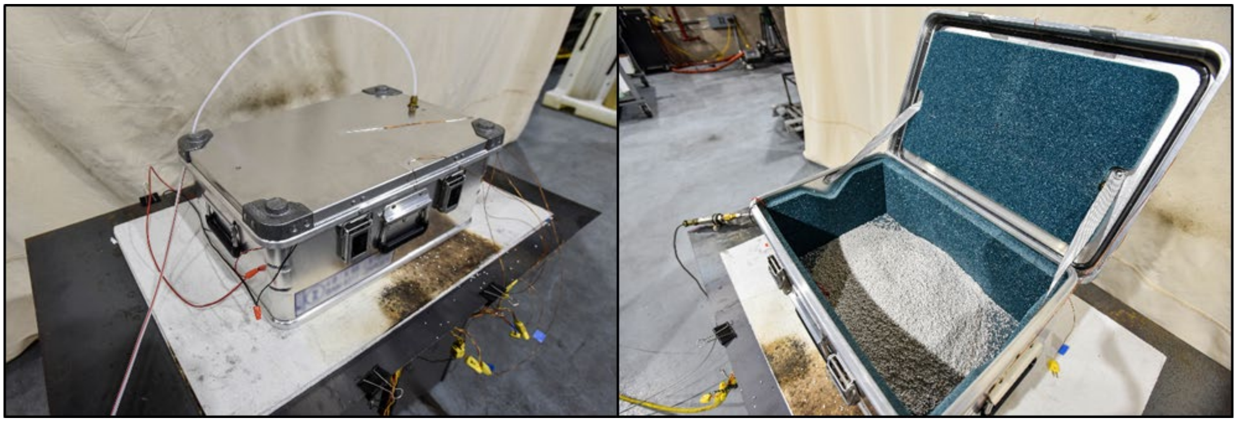

Figure 14. Case exterior and interior with 3 lbs. of suppressing agent poured on PED

4.4.1 Manufacturer D—Portable electronic device overheating tests

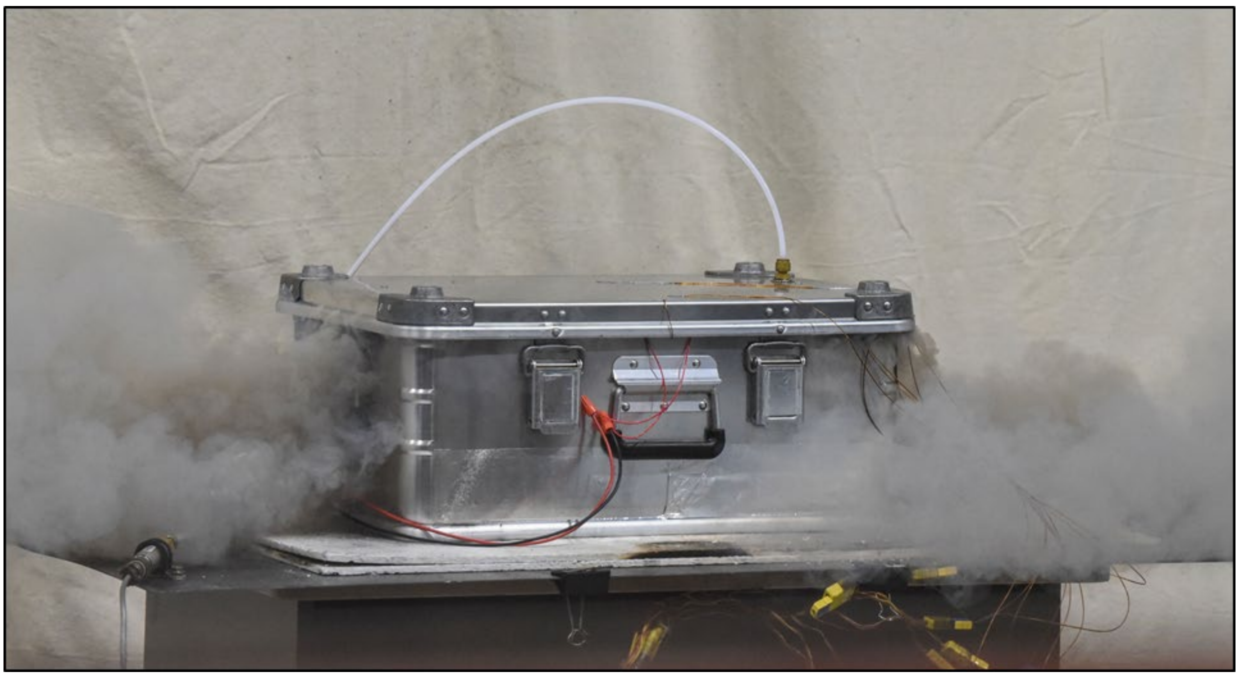

Figure 15. Manufacturer D – power bank in container – peak reaction

Four tests with Manufacturer D's product were performed: one with a tablet, two with a power bank and another with two 154 Wh video camera batteries. Two tests were performed with the power bank to see if the way the extinguishing agent was stored (poured directly on PED or stored on top of PED in cardboard bag) produced a difference in results. Figure 15 displays the peak reaction of the container in testing with the 96 Wh power bank.

In all four tests, smoke was released from the case, but no shrapnel or flame escaped. The case was designed to release smoke so interior pressure wouldn't build up. The volume of released smoke was correlated with the size of the PED. Tests with the tablet produced only a minor amount of smoke, whereas the power banks and video camera battery produced a significant amount. With the tests using two 154 Wh batteries, a large haze of smoke formed approximately six feet above the floor and did not dissipate until the test cell's exhaust fan was turned on. Figure 16 shows the haze of smoke produced during testing with two 154 Wh batteries in the case.

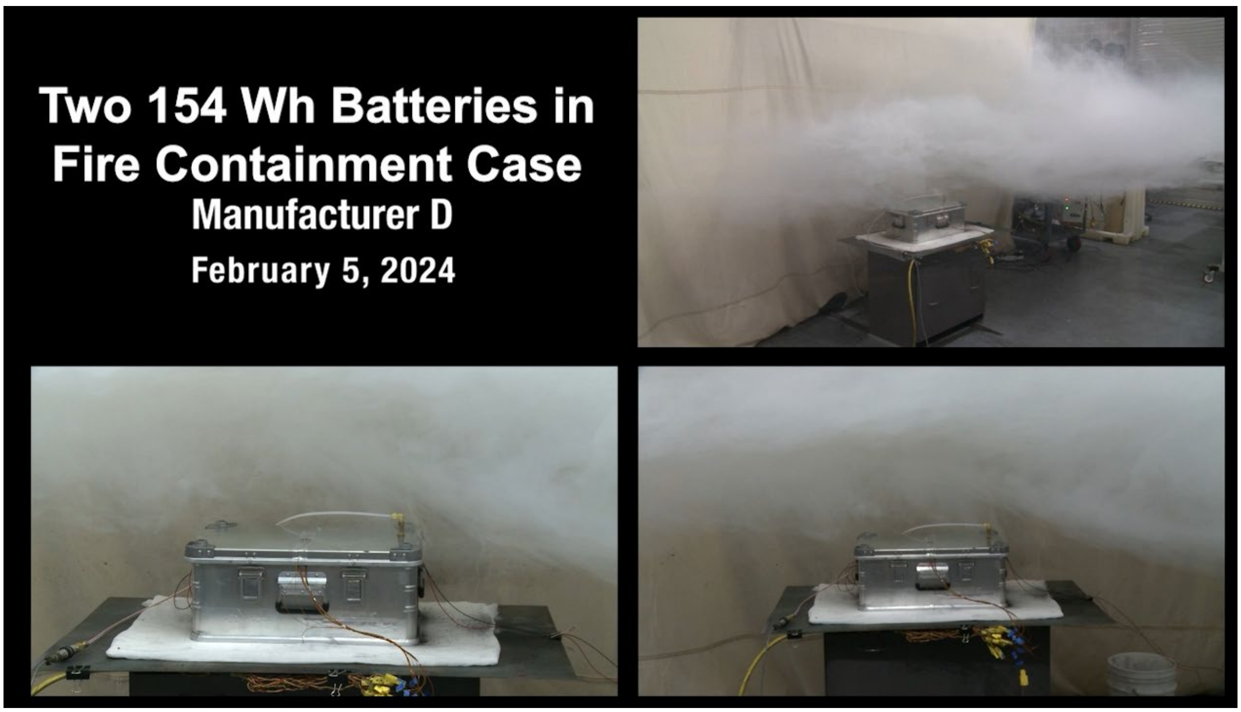

Figure 16. Smoke haze created during test with two 154 Wh batteries in product

The method used to store the extinguishing agent within the case, provided no distinguishable differences in volume of smoke released. However, higher temperatures were observed when the cardboard bag was used rather than the extinguishing agent being poured directly on the PED. When the extinguishing was agent was stored in the cardboard bag, temperatures on the bottom exterior of the product were noted to reach close to 400 °F (204 °C). This value nearly doubled the max recorded temperature of 206 °F (97 °F) which was observed when the agent was poured directly on top of the device.

Table 4 shows the maximum temperature and pressure measurements recorded throughout all four tests.

Table 4. Max Data Values – All Tests – Manufacturer D

Max Data Values		
	°F	**°C**
Interior Temp	2470	1354
Top Exterior Temp	267	131
Bottom Exterior Temp	396	202
	PSI (Absolute)	**kPa (Absolute)**
Pressure	15.6	108

4.5 Manufacturer E

Three bags from Manufacturer E were procured: two bags (14 by 14 by 2-inch outer dimensions) and an additional larger version (20 by 20 by 2.5-inch outer dimensions). The manufacturer advertised the capability of containing PED fires up to 100 Wh using the 14-inch bags and 160 Wh fires for the 20-inch version. Each bag was equipped with two smoke vents and numerous suppression bladders within, which release an extinguishing agent upon direct contact with heat. Bags were sealed with a zipper, hook and loop, and two metal lock snaps. The 20-inch bag was a part of a kit, which included equipment such as heat resistant gloves, goggles, a grabber tool (for devices stuck in difficult to reach places) and a suppression pad. A picture of the 100 Wh bag is shown below in Figure 17.

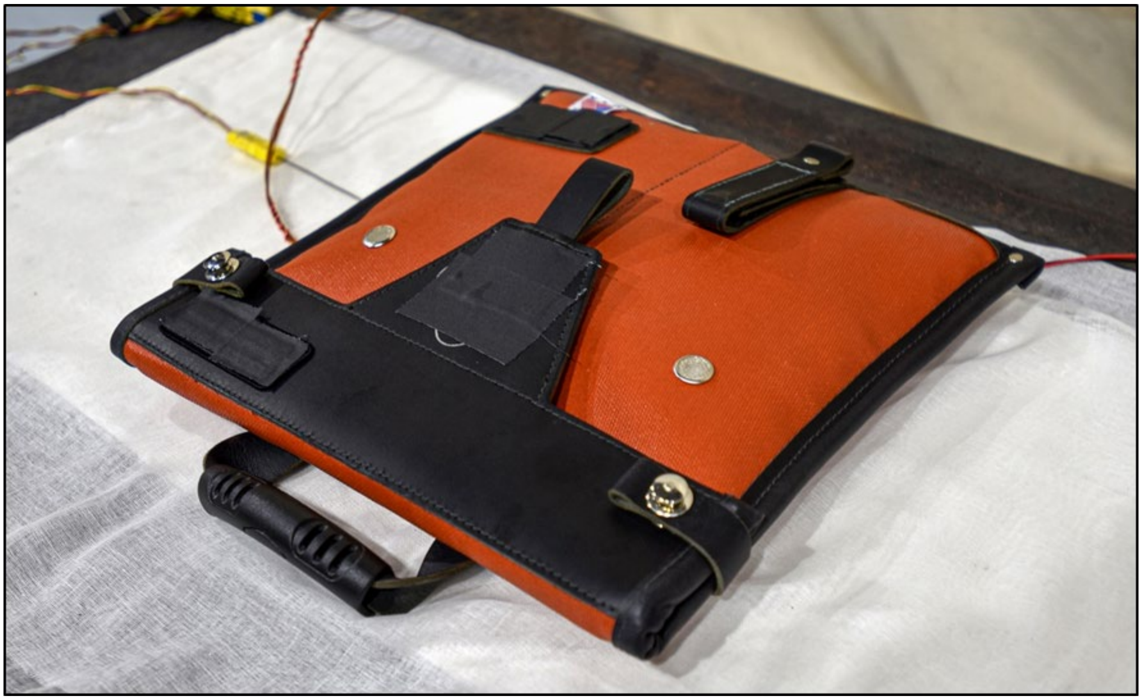

Figure 17. Manufacturer E 100 Wh bag

Manufacturer E also provided different instructions contingent on the device's condition. If an aircraft crewmember notices early signs of thermal runaway (high operating temperature or burning smell), the manufacturer specifies that proactive measures can be taken to transfer the device into the fire containment bag utilizing PPE. If the PED is in an unstable condition (actively smoking or burning) the user is directed not to move the device until it is thoroughly cooled. The manufacturer recommends using the suppression pad to cool the device and states that additional handheld extinguishers or non-alcoholic fluid **may** be utilized. A picture of the suppression pad is shown below in Figure 18.

Figure 18. Manufacturer E suppression pad

4.5.1 Manufacturer E—Portable electronic device overheating tests

Evaluations were conducted on all three bags. The 160 Wh bag proved to be effective in containing the 154 Wh battery. No visible flames or shrapnel were able to escape from the product and only a minor amount of smoke was released throughout the entirety of the test.

Both of the 100 Wh bags failed to contain hazards produced from the 96 Wh power bank. In both instances, pressure buildup caused the zipper to tear and a substantial amount of smoke to escape into the test chamber. Maximum pressure readings within the bag were noted to reach 16.9 psia. A picture of the peak reaction in the 160 Wh bag and the tear in the 100 Wh bag is shown below in Figure 19.

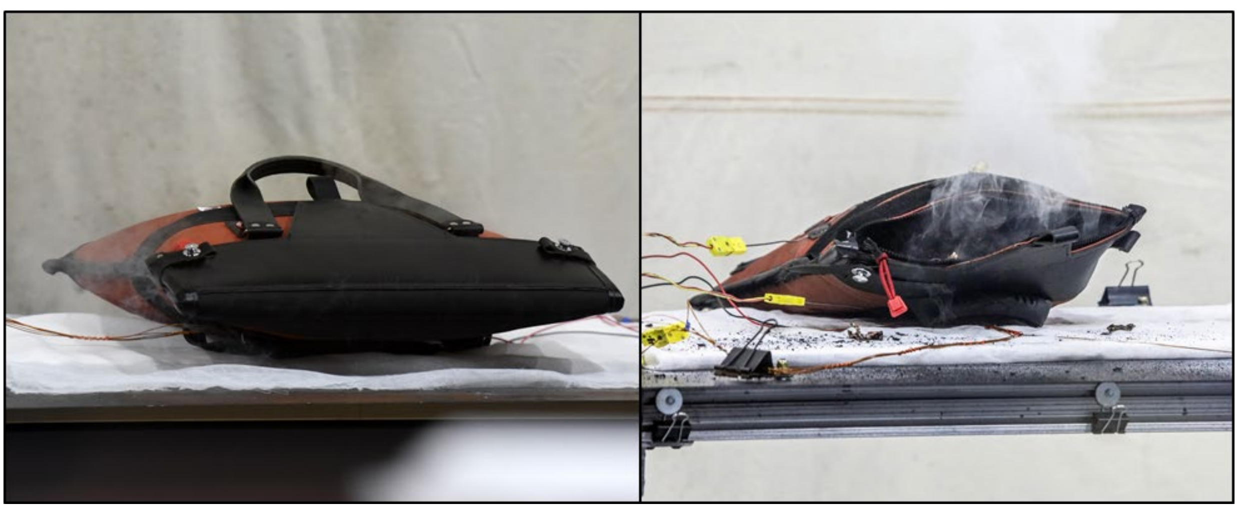
Figure 19. 160 Wh bag (left) with minimal smoke and the tear in the 100 Wh bag (right)

During the second test, a sizable explosion occurred approximately two minutes after the bag had been torn open. Bag fragments and debris were propelled several feet away from the test stand. This may have been a result of the accumulation of ignitable and explosive gases such as hydrogen near the top of the bag. Figure 20 displays a picture of the explosive event below.

Figure 20. Explosive event occurring after 100 Wh bag tore

Table 5 displays the maximum temperature and pressure values collected throughout all three tests below.

Table 5. Max Data Values – All Tests – Manufacturer E

Max Data Values		
	°F	**°C**
Interior Temp	2464	1351
Top Exterior Temp	177	81
Bottom Exterior Temp	169	76
	PSI (Absolute)	**kPa (Absolute)**
Pressure	16.9	117

4.5.2 Manufacturer E—Portable electronic device already on fire tests

Testing was conducted using the suppression pad without any additional extinguishers. The suppression pad was applied to the top of the power bank after the initiating cell underwent thermal runaway. When applied, flames were quickly knocked down. In the following minutes, however, adjacent cells continued to undergo thermal runaway and released flames were observed to extend several feet from the side of the pad. An image of this is shown below in Figure 21. This indicates that while the suppression pad did an adequate job in knocking down existing flames, it did not prevent the propagation of heat to adjacent cells.

One possible explanation for why the pad was unable to effectively stop heat propagation may have been due to the power banks orientation. Cells within the power bank were oriented horizontally and flames burned through the plastic casing on the side rather than the top. It may have been difficult for the released extinguishing agent to seep into the device from above as some plastic on the top was somewhat still intact.

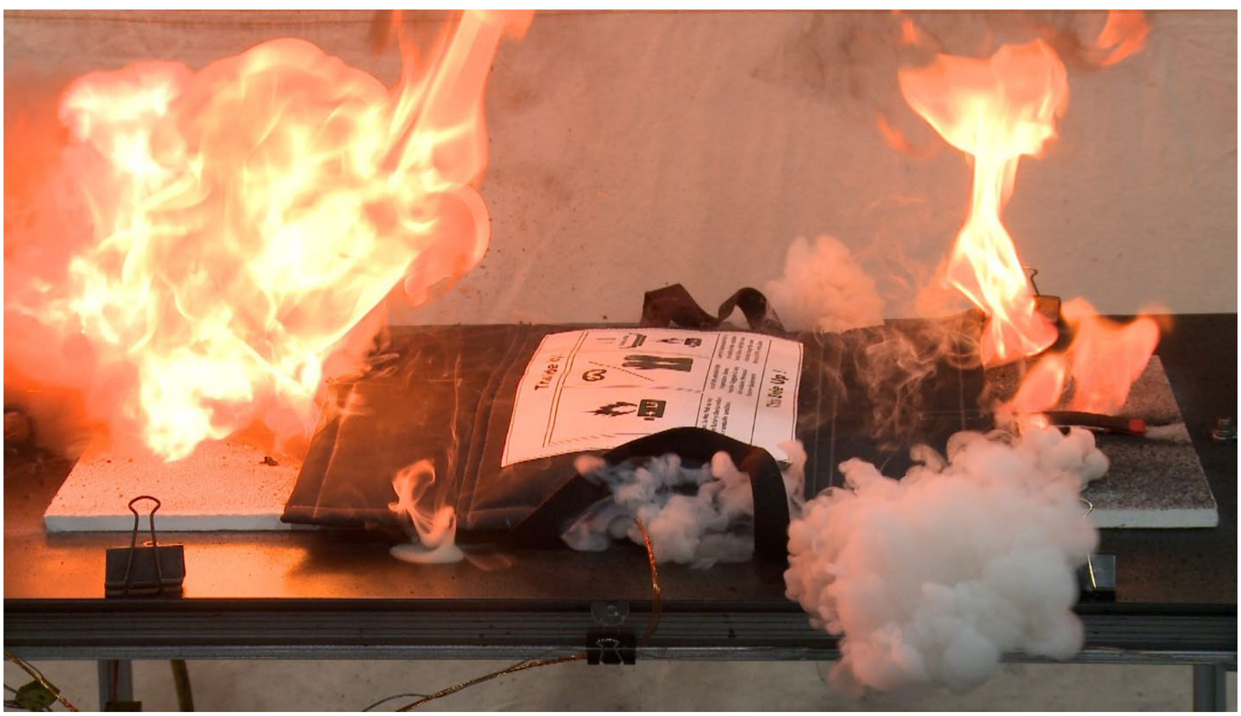

Figure 21. Flames escaping underneath suppression pad a few minutes after being applied

5 Analysis

The use of fire containment products is a significant challenge, as manufacturers must develop a product that can mitigate the hazards of high energy PED fires. Results from this study indicate that the effectiveness of commercially available fire containment products vary significantly. Some products proved to be effective in mitigating PED fires, demonstrating the capability to contain PED fires up to 100 Wh or 160 Wh respectively. Conversely, other evaluated products struggled to contain the hazards of lithium battery fires, especially when tested with PEDs near the allowable capacity limit (100 Wh) without airline approval.

Containment product performance was noted to vary greatly based on the type of PED tested and the orientation of the lithium ion cells within. In tests with Manufacturer E, the 160 Wh bag was able to effectively mitigate a fire produced from a larger device (154 Wh), as compared to the 100 Wh bag which was unable to contain the hazards of a 96 Wh power bank. The 160 Wh bag was larger than the 100 Wh bag, but the overall design remained similar. Cells within the power bank made direct contact with adjacent cells, whereas cells within the camera battery had thin plastic separators between them which increased time between thermal runaway events (shown in Figure 3). This factor greatly affected results, as short intervals between thermal runaway events led to large amounts of smoke generation within a short time period. Many bags were unable to vent out generated smoke quickly enough, producing interior pressure spikes and thus mechanical failures such as tears and rips. Throughout the course of this study, products that failed did so often due to excessive pressure rather than flame penetration.

Additionally, testing within this study further underscores the FAA's position against moving unstable devices. Although overheating is a clear prognostication of a thermal runaway event, the release of flame and smoke can occur suddenly and erratically. An aircraft staff member handling an unstable PED could be severely harmed if thermal runaway were to occur at an inopportune time. Burning fragments were noted to have been ejected more than ten feet away from the device's location. Figure 22 shows an example of the distance that the burning particles ejected from a power bank were able to reach in an open area.

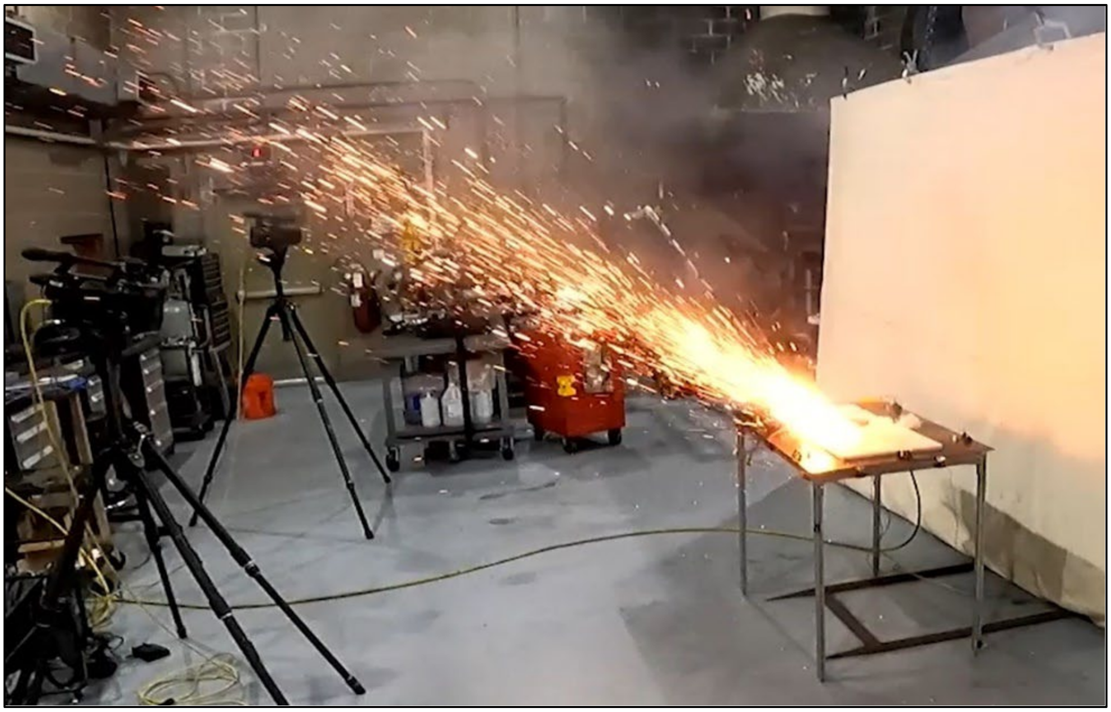

Figure 22. GoPro footage of the burning particles ejected from a power bank

A key component of PED firefighting is using swift action to knock down flames and cool the device to prevent propagation to nearby cells. The additional suppression equipment provided by evaluated manufacturers was capable of knocking down flames, but did not prevent the propagation of heat. Thermal runaway in other cells within the PED continued to occur after suppression items were applied and flames were still released into the surrounding area.

The results produced from this series of tests indicate that fire containment products should not be used as a substitute for firefighting procedures. Rather, the best use case for these products may be as a preventative measure, for example, storing a device that is starting to become warm to the touch, but not yet exhibiting characteristics of thermal runaway. These products may also find use as stowage containers for devices that have been sufficiently extinguished and cooled for 10 to 15 minutes after the occurrence of a thermal runaway event.

6 Conclusions

To summarize, the following key findings can be concluded from this study:

- The performance of fire containment products varied amongst the different products. Multiple products struggled to contain the hazards of PED fires near the maximum allowable energy limits permitted on aircraft (100 Wh and 160 Wh).

- Product performance varied based on the PEDs interior cell configuration and the rate at which cells experienced thermal runaway. Short periods between thermal runaway events can produce significant gas buildup, which products are unable to vent quickly enough. This can create pressure spikes and mechanical failures (rips/tears) to the product.
- The suppression equipment included with some of the containment products was found capable of knocking down flames, but unable to prevent heat propagation to adjacent cells.

Testing suggests that some containment products cannot currently meet the airlines' present expectations for product performance. Further research on the use of fire containment products may be needed to ensure the safety of aircraft occupants.

Specifically, future research in the following areas should be considered:

- Additional testing on large format cells within containment products. A single large format cell may release energy at a higher rate compared to its energy equivalent of smaller electrically connected cylindrical or pouch cells.
- A human factors study on the use of fire containment products and included PPE within confined areas. Products must be easy to operate, intuitive to use, and should not delay response time.
- Further testing to determine how the orientation of PEDs with respect to critical features (seams, vents) within the containment product affect performance.

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