Fire Behavior of E-Tablets Stored in Aircraft Galley Carts

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FIRE BEHAVIOR OF E-TABLETS STORED IN AIRCRAFT GALLEY CARTS

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16. Abstract

The use of electronic-tablets (e-tablets) as replacements for conventional in-flight entertainment systems has gained popularity among airlines globally. Innovative methods of storing and charging e-tablets in galley carts have been suggested or are already in service with some airlines.

The danger of thermal runaway in the lithium-ion-pouch batteries that are used in these e-tablets is well known, but the potential fire hazard resulting from e-tablets being stored and charged in galley carts or a similar enclosure has not been established. To examine this potential fire hazard, the Civil Aviation Authority of Singapore and the Federal Aviation Administration conducted a series of tests to investigate the behavior of e-tablet fires.

Tests were conducted within a galley cart and thermal runaway of the e-tablet lithium-ion-pouch battery was initiated by either a heat plate or an external alcohol fire. The arrangement of e-tablets inside the galley cart followed the typical methods of storage proposed by airlines and design organizations. The objectives of the tests were to determine a suitable storage configuration for the e-tablets, which would prevent the propagation of thermal runaway, and to determine the effect that thermal runaway would have on a typical galley cart.

Ten tests were conducted. The results of these tests showed the potential fire hazards associated with bulk storage of e-tablets in a galley cart or similar enclosure. Additional work is recommended to determine the desirable features of galley carts to contain a lithium battery fire and prevent the danger associated with fire, smoke intensity, and explosion.

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LIST OF ABBREVIATIONS AND ACRONYMS

CFR	Code of Federal Regulations
E-tablet	Electronic tablet
EMC	Electromagnetic compatibility
EMI	Electromagnetic interference
FAA	Federal Aviation Administration
IFE	In-flight entertainment
TSO	Technical Standard Order

EXECUTIVE SUMMARY

The usage of electronic tablets (e-tablets) as a replacement for the conventional in-flight entertainment system has increased in popularity among airlines globally. Innovative methods of storing e-tablets in galley carts have been suggested or are already in service with some airlines.

The electromagnetic interference/compatibility behavior that e-tablets may have on the avionics system has been well studied and documented. However, the potential fire hazard caused by lithium batteries in e-tablets stored in galley carts has not been determined.

A series of tests was carried out by the Civil Aviation Authority of Singapore and the Federal Aviation Administration to investigate the behavior of e-tablet fires. Tests were conducted within a galley cart and thermal runaway of the e-tablet lithium-ion-pouch battery was initiated by either a heat plate or an external alcohol fire. The arrangement of e-tablets inside the galley cart followed the typical methods of storage proposed by airlines and design organizations. The objectives of the tests were to determine:

1. The required e-tablet storage configuration to prevent thermal-runaway propagation from a single lithium battery in an e-tablet to adjacent e-tablets.

2. The ability of the galley cart to contain a lithium-ion battery fire and to prevent fire and smoke from spreading outside the galley cart.

Ten tests were conducted. The conclusions associated with these tests were as follows:

1. The risk of lithium battery thermal-runaway propagation was small when the e-tablets were arranged in a vertical orientation with sufficient spacing between them (1″ was sufficient in this study).

2. Thermal runaway may cause the accumulation of flammable gases in the galley cart and the risk of an explosion. The force of an explosion can force open a latched galley cart door.

3. The fire or explosion created within the galley cart has the potential to ignite adjacent aircraft cabin materials.

4. The heavy accumulation of smoke in the cabin may interfere with firefighting efforts and can be hazardous to airplane occupants.

The results of these tests showed the potential fire hazards associated with bulk storage of e-tablets in a galley cart. Additional work is recommended to determine the desirable features of galley carts to contain a lithium battery fire and to prevent the danger associated with fire, smoke intensity, and explosion.

INTRODUCTION

BACKGROUND

As electronic devices are increasingly miniaturized, commercial air operators are introducing portable electronic tablets (e-tablets) as a form of in-flight entertainment (IFE). E-tablet IFE has the benefit of weight savings and lower cost compared to the use of conventional IFE systems. In addition, passengers may prefer to use e-tablet devices to which they have become accustomed. However, lithium-ion-pouch batteries within the e-tablets can unexpectedly experience a thermal runaway—a rapid and uncontrolled rise in temperature—that may result in a fire and other hazards.

The certification issues related to the usage of e-tablets on board aircraft can be classified into two categories:

1. A possible electromagnetic interference (EMI) or electromagnetic compatibility (EMC) resulting from operating the e-tablets.

2. A fire safety concern in the cabin when storing multiple e-tablets because a majority of the e-tablets are powered by lithium-ion-pouch batteries.[1]

EMI/EMC testing procedures related to the usage of electronic equipment onboard aircraft are well established and there are numerous international standards, such as the Radio Technical Committee for Aeronautics DO-233 "Portable Electronic Devices Carried on Board Aircraft," which provide guidance to operators on how to demonstrate that the usage of e-tablets will not interfere with the aircraft systems.

The fire safety concern focuses on the fire containment capability of the containers that store the e-tablets as well as cabin crew firefighting issues. Whereas firefighting skills are already a part of the cabin crew training, the containers that are used in aircraft today are not tested to contain the fire hazards generated from e-tablets powered by lithium batteries.

This study assesses the fire hazards for various storage configurations of e-tablets in galley carts.

POSSIBLE STORAGE LOCATIONS IN CABIN COMPARTMENT

The possible storage locations for e-tablets in the aircraft cabin interior were assessed and galley carts were identified as the most ideal location. Technical Standard Order (TSO) C-175 describes the minimum performance standard for carts [1]. Recommendations or changes could be implemented as an amendment to the existing TSO. Additionally, the choice of a galley cart narrows the dimensions to only two standard sizes: full size, approximately 302 mm (w) by 1030 mm (h) by 813 mm (d), and half size approximately 302 mm (w) by 1030 mm (h) by 407 mm (d).

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[1] Lithium-ion-pouch batteries are flammable because of the flammable liquid hydrocarbon electrolyte present in the battery.

CERTIFICATION REQUIREMENTS FOR CARTS

The main certification requirements for carts are static load test, fire properties test, and fire containment test. Depending on the application, specified tests are required to be performed on the galley carts. Table 1 shows the test requirements for different applications.

Table 1. Galley cart certification test requirement vs. application

Type of Application	Static test	Fire properties Test	Fire containment Test
Sales cart (used for storage of in-flight purchase merchandise)	✓	✓	-
Meal cart (used for storage of food and food trays for in-flight meals)	✓	✓	✓
Waste cart (used for storage of waste material)	✓	✓	✓

The static load test requires the galley cart to be able to contain the contents and withstand the loads under Title 14 Code of Federal Regulations (CFR) Part 25.561 [3] (or equivalent) emergency landing requirements. The fire properties test requires the materials used in the construction of the cart to meet the flammability requirements of 14 CFR 25.853 (or equivalent) interior compartments.

A fire containment test is used to demonstrate that the galley cart is in compliance with 14 CFR 25.855 (or equivalent) for cargo and baggage compartments. This test requires the cart to be able to contain fire generated from common waste, such as napkins, plastic utensils, and trays. The fire containment test states that a fire should not be observed from the outside of the cart. Additionally, the internal compartment of the cart needs to be inspected to ensure that it did not sustain substantial damage. Guidance on the requirements of fire containment is stated in reference 2. The fire containment test may need to be expanded to include the storage of e-tablets because the fire generated from thermal runaway of a lithium-ion-pouch battery is more severe than a fire from common waste.

OBJECTIVE

The objective of this study was to determine whether propagation of thermal runaway would occur in the given galley cart configurations (tests 1 through 8) and to determine the possibility and severity of fire and smoke escaping the cart (tests 9 and 10).

EXPERIMENTAL SETUP

A typical full-size galley cart was used for the test (shown in figure 1). The cart was a movable enclosure on wheels used to store food and service trays. The cart's body had an overall size of 305 mm (w), 851 mm (d), and 1016 mm (h).

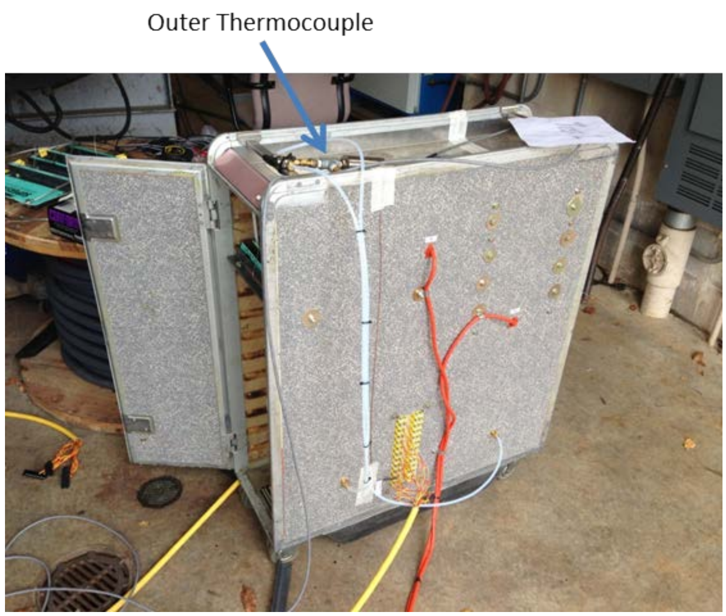


Figure 1. Galley cart used for the tests

The top panel was an aluminum sheet and the side panels were made from two bonded laminates with a foam sheet sandwiched in between. The base (bottom) panel was an aluminum plate and had a wheel brake system that locked all cart wheels. An interchangeable unvented door assembly was hinged on each end panel. For the purpose of this test, a metal sheet was installed in the mid-section of the cart to divide the full-size cart into two compartments and replicate two half-size galley carts. The metal sheet was sealed in position to fully isolate each side. According to the TSO C-175 requirement, with the doors properly closed, a fire within the cart should be contained with minimum smoke emission.

Three types of e-tablets manufactured by two different vendors were used. Table 2 shows the dimensions, battery characteristics, and outer materials of the e-tablets. The major differences between the three types of e-tablets (in regard to the tests) were the battery capacity and the outer material on the opposite side of the touch screen.

The e-tablets were turned off unless otherwise specified and all e-tablets were charged to 100% state-of-charge. The batteries in e-tablet type-1 and e-tablet type-2 had three cells. The battery in e-tablet type-3 had two cells.

There were two e-tablet orientations in these tests. The first orientation was with the e-tablets positioned vertically in a test rig with a 1″ separation. The test rig was lined with 1/8″ thick insulation sheets to minimize heat loss. The second orientation was with the e-tablets stacked horizontally without any separation.

Table 2. E-tablet description

E-Tablet	Dimensions	Battery Type	Battery Capacity	Outer Material Opposite of Touch Screen
Type 1	9.5″ x 7.31″	Lithium-ion-pouch	3.7V, 43 Watt-hour, 11560mAh	Aluminum
Type 2	9.5″ x 7.31″	Lithium-ion-pouch	3.8V, 25 Watt-hour, 6500mAh	Aluminum
Type 3	10.31″ x 7.08″	Lithium-ion-pouch	3.7V, 25.9 Watt-hour, 7000mAh	Plastic

Thermal runaway of the batteries was initiated by either a 200-Watt heat plate, which would reach a temperature of about 350°C, or an alcohol pan fire.

Type-K thermocouples measured the surface temperature of each e-tablet and the ambient temperature within the galley cart. An additional type-K thermocouple was placed on the outside of the cart, as shown in figure 1.

Ten tests were conducted with varying configurations, as shown in table 3.

Table 3. Test configurations

Test No.	E-Tablet Type	Remarks	Heat Source
1	1	Separated with 1″ distance and placed vertically.	Heat plate
2	1	Separated with 1″ distance and placed vertically.	Alcohol fluid
3	3	Separated with 1″ distance and placed vertically.	Heat plate
4	2	Separated with 1″ distance and placed vertically.	Heat plate
5	1	Separated with 1″ distance and placed vertically.	Alcohol fluid
6	1	E-tablets stacked horizontally with no separation.	Heat plate
7	3	E-tablets stacked horizontally with no separation.	Heat plate
8	1	E-tablets stacked horizontally with no separation.	Alcohol fluid
9	3	E-tablets stacked horizontally with no separation in ventilated aircraft cabin.	Heat plate
10	1	E-tablets stacked horizontally with no separation in ventilated aircraft cabin.	Heat plate

Additional details of each test setup are described below:

TEST 1 SETUP

Three e-tablets were held vertically with a 1-inch gap between each of them on an aluminum test rig, as shown in figure 2. Six thermocouples were used to measure the surface temperatures of the e-tablets and one was used to measure ambient temperature within the cart. A heat plate was installed on the innermost e-tablet.

Figure 2. Test rig with 1-inch spacing

TEST 2 SETUP

Three e-tablets were held vertically with a 1-inch gap between each of them on an aluminum test rig (shown in figure 3). Six thermocouples were used to measure the surface temperatures of the e-tablets and one was used to measure the ambient temperature within the cart. Two small circular metal trays containing 50 ml of flammable alcohol were placed adjacent to the innermost e-tablet.

Figure 3. Loading of the test rig into the cart

TEST 3 SETUP

Three e-tablets were held vertically with a 1-inch gap between each of them on an aluminum test rig (shown in figure 4). Six thermocouples were used to measure the surface temperatures of the e-tablet and one was used to measure the ambient temperature within the cart. A heat plate was installed on the innermost e-tablet.

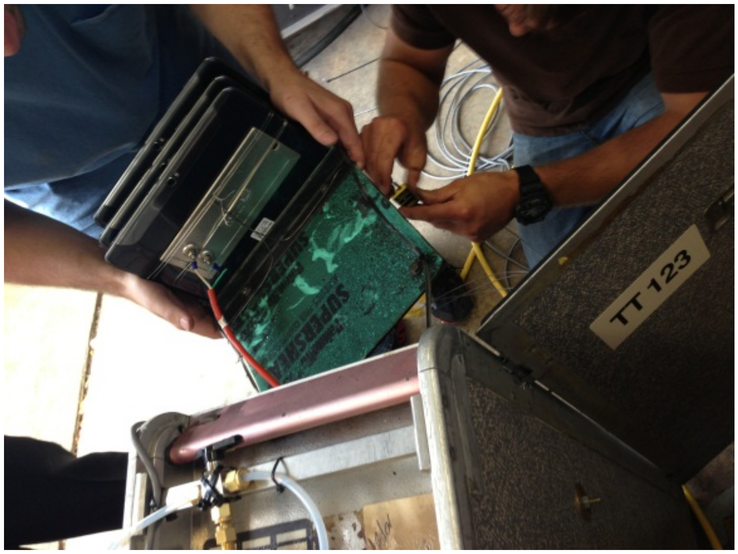


Figure 4. Loading of the test jig into the cart

<u>TEST 4 SETUP</u>

Three e-tablets were switched on and held vertically with a 1-inch gap between each of them on an aluminum jig (shown in figure 5). Six thermocouples were used to measure the surface temperatures of the e-tablets and one was used to measure the ambient temperature within the cart. A heat plate was installed on the innermost e-tablet.

Figure 5. Insertion of the test rig into the cart

<u>TEST 5 SETUP</u>

Three e-tablets were held vertically with a 1-inch gap between each of them on an aluminum test rig. Six thermocouples were used to measure the surface temperatures of the e-tablets and one was used to measure the ambient temperature within the cart. A rectangular metal tray containing 100 ml of flammable alcohol was placed near the innermost e-tablet, as shown in figure 6.

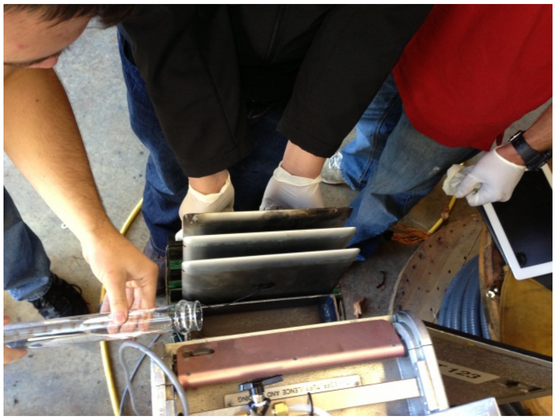


Figure 6. Alcohol poured into the tray

<u>TEST 6 SETUP</u>

Five e-tablets were stacked horizontally and bound together to simulate the smallest possible separation distance of e-tablets within the cart. The heat plate was placed between the second and third e-tablets from the bottom (shown in figures 7 and 8). Five thermocouples were used to measure the surface temperatures of the e-tablets and one was used to measure the ambient temperature within the cart. The thermocouples were positioned on the outside edge of the e-tablets to prevent any separation distance between them.

Figure 7. Test setup without spacing

Figure 8. E-tablets immediately prior to the test start

TEST 7 SETUP

Five e-tablets were stacked horizontally and bound together to simulate the smallest possible separation distance of e-tablets within the cart. The heat plate was placed between the second and third e-tablets from the bottom (shown in figures 9 and 10). Five thermocouples were used to measure the surface temperatures of the e-tablets and one was used to measure the ambient temperature within the cart. The thermocouples were positioned on the outside edge of the e-tablets to prevent any separation distance between the e-tablets.

Figure 9. Test setup without spacing

Figure 10. E-tablets immediately prior to the test start

<u>TEST 8 SETUP</u>

Three e-tablets were stacked horizontally and bound together to simulate the smallest possible separation distance of e-tablets within the cart. A circular metal container with 100 ml of alcohol was placed directly underneath the e-tablets to simulate fire inside the cart (shown in figure 11). Four thermocouples were used to measure the surface temperatures of the e-tablets and one was used to measure the ambient temperature within the cart.

Figure 11. Test 8 setup

TEST 9 SETUP

Five e-tablets were stacked horizontally and bound together to simulate the smallest possible separation distance of e-tablets within the cart. A heat plate was sandwiched between the second and third e-tablet from the bottom. Five thermocouples were used to measure the surface temperatures of the e-tablets and one was used to measure the ambient temperature within the cart. The entire assembly, containing the e-tablets, the heat plate, and the thermocouples, was placed on an aluminum sheet and inserted into the cart. An igniter was placed at the bottom of the cart to simulate sparking from the e-tablets during thermal runaway and was only activated if the flammable gases did not self-ignite during the test.

The cart was positioned at the front galley of a Boeing 737-200. Cabin ventilation air was supplied from an external ground cart. This was also the position where airflow was the weakest and had the potential to create the greatest accumulation of smoke within the cabin. Figure 12 shows the setup for test 9. All doors, including the cockpit door, were closed during the test. Two firefighters with protective breathing equipment were stationed inside the cabin to activate the heat plate and the igniter and to prevent damage to the aircraft.

Figure 12. Test 9 setup

TEST 10 SETUP

Five e-tablets were stacked horizontally and bound together to simulate the smallest possible separation distance of e-tablets within the cart. A heat plate was sandwiched between the second and third e-tablet from the bottom. Five thermocouples were used to measure the surface temperatures of the e-tablets and one was used to measure the ambient temperature within the cart. The entire assembly, containing the e-tablets, the heat plate, and the thermocouples, was placed on an aluminum sheet within the cart. The thermocouples were positioned on the outside edge of the e-tablets to prevent any separation distance between them. Figures 13 and 14 show the setup for test 10. An igniter was placed at the bottom of the cart to simulate sparking from the e-tablet during thermal runaway and was activated only if the flammable gases did not self-ignite during the test.

The cart was positioned in the front galley of a Boeing 737-200. Cabin ventilation air was supplied from an external ground cart. This was also the position where airflow was the weakest and had the potential to create the greatest accumulation of smoke within the cabin. All doors, including the cockpit door, were closed during the test. Two firefighters with protective breathing equipment were stationed inside the cabin to activate the heat plate and the igniter and to prevent damage to the aircraft.

Figure 13. Test 10 setup

Figure 14. Test 10 setup

EXPERIMENTAL PROCEDURE

The experimental procedures for the tests with the heat plate and alcohol fire ignition sources differed slightly and are described below.

HEAT PLATE

1. The e-tablets were placed inside the cart.
2. The cart door was closed and latched.
3. The heat plate was switched on.
4. When the first thermal runaway occurred, the heat plate was switched off.
5. In tests 9 and 10 the spark igniter was activated intermittently after the thermal runaway occurrences if the gasses did not self-ignite.
6. Visual observations and temperature measurements were taken during the test.

ALCOHOL FIRE

1. The e-tablets were placed inside the cart.
2. The alcohol fire was initiated.
3. The cart door was closed and latched (unless otherwise noted).
4. Visual observations and temperature measurements were taken during the test

TEST RESULTS

Thermal runaway always occurred in the e-tablet adjacent to the heat source, with the exception of test 2. The e-tablets in tests 1, 3, and 4 all had different battery capacities and showed a correlation of an increased temperature with increased e-tablet battery capacity (shown in figure 15).

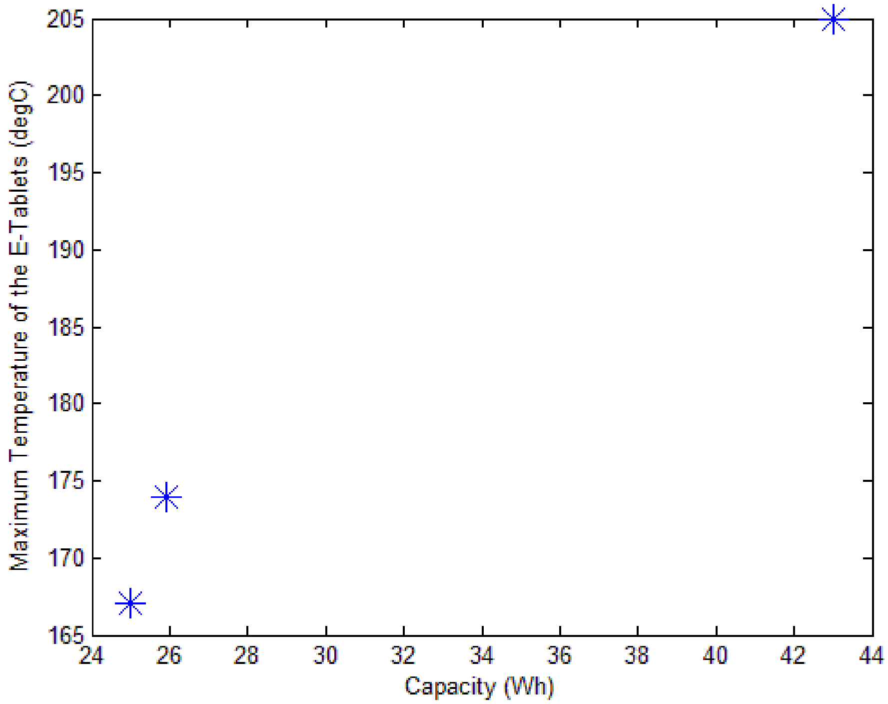


Figure 15. E-tablet temperature vs. capacity

In each e-tablet that had undergone thermal runaway throughout all ten tests, swelling of the cells was observed which caused the e-tablet to expand to approximately twice its usual thickness. In each of those instances, the LCD display panel was wrinkled and the glass that protected it was partially separated. The plastic was also melted in the e-tablets that had an outer plastic construction. In tests where fire was also present, the tablets were damaged in the same locations but the front screen was more disfigured.

In each e-tablet that did not undergo thermal runaway but had a nearby tablet which did undergo thermal runaway, soot deposited on the outside and char marks were sometimes evident. On occasion, the cells in those e-tablets would swell slightly and cause a slight bulge to the e-tablet.

Individual results and observations for each test are given below.

<u>TEST 1</u>

Thermal runaway occurred in the e-tablet adjacent to the heat plate after 14 minutes (shown in figure 16). External smoke was present but no fire was observed from the exterior of the cart. Figure 17 shows the temperature results for test 1.

After the test, the innermost e-tablet was found to be badly burned. The adjacent e-tablets were slightly sooted, and discolored on the exterior, but were otherwise functioning when they were activated (shown in figure 18). The heat released by the innermost e-tablet did not propagate to the batteries in the adjacent e-tablets to initiate further thermal runaways.

Figure 16. Thermal runaway event within the cart

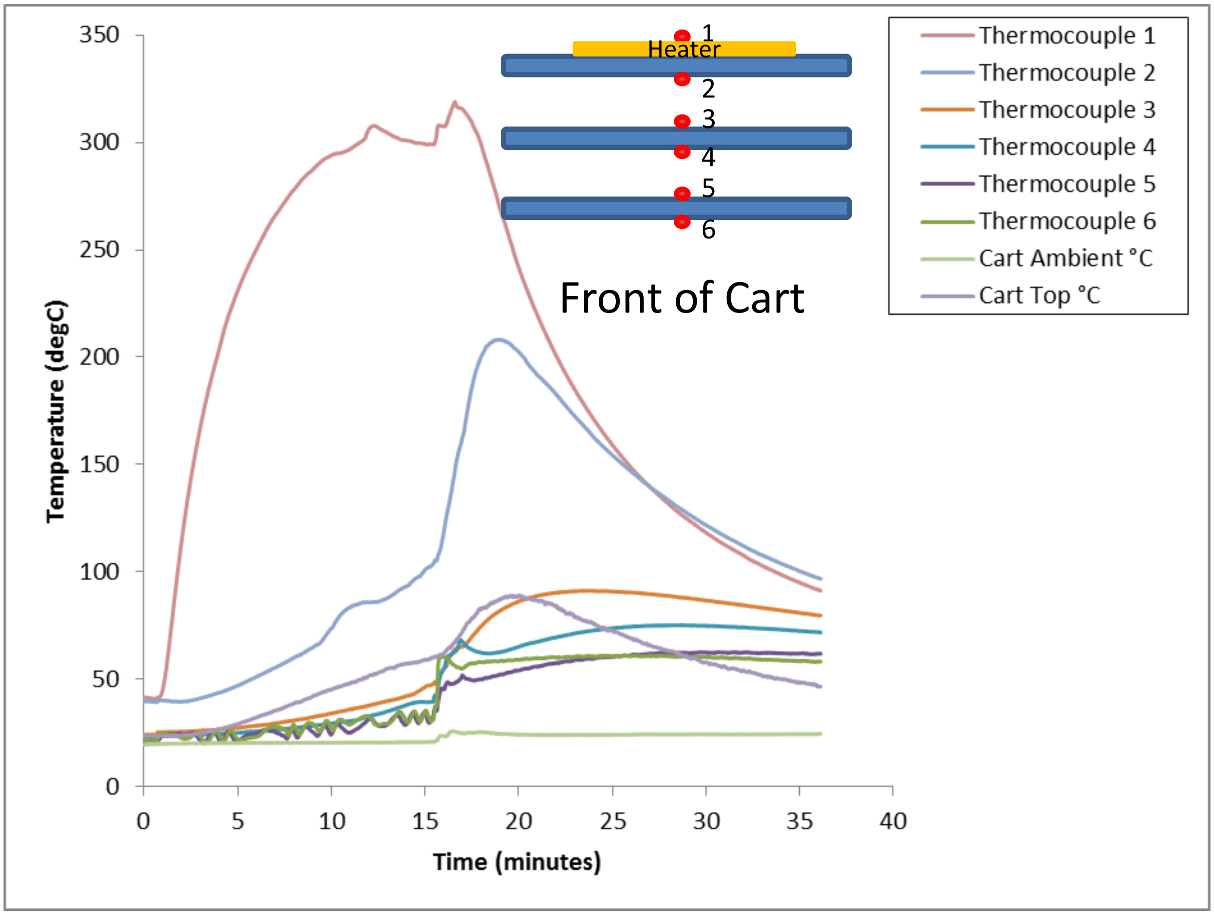


Figure 17. Test 1 temperatures

Figure 18. Removal of the e-tablets from the cart

<u>TEST 2</u>

No smoke or fire was observed on the outside of the cart. Thermal runaway was not observed. The test was stopped after the alcohol fire self-extinguished due to oxygen starvation. The test objective of inducing one battery into thermal runaway with the alcohol fire was not met so the test scenario was repeated in test 5. Figure 19 shows the temperature results for test 2.

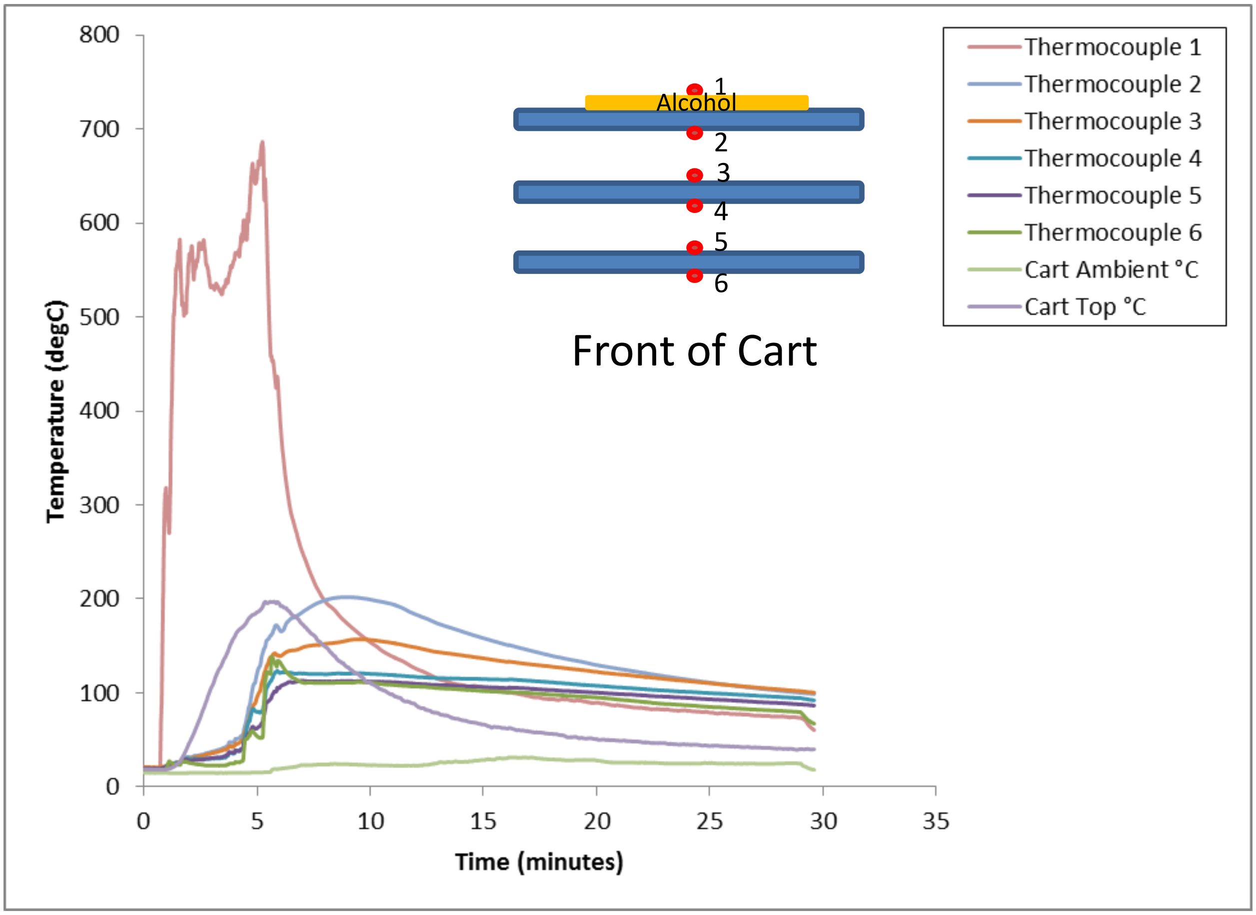


Figure 19. Test 2 temperatures

<u>TEST 3</u>

Thermal runaway occurred in the battery in the e-tablet adjacent to the heat plate after 10 minutes (shown in figure 20). External smoke was present but no fire was observed from the exterior of the cart. Figure 21 shows the temperature results for test 3.

After the test, the innermost e-tablet was found to be badly burned and the surface in contact with the heat plate was melted (shown in figure 22). The adjacent e-tablets were slightly sooted, and discolored on the exterior, but were otherwise functioning when they were activated. The heat released by the innermost e-tablet did not propagate to the batteries in the adjacent e-tablets to initiate further thermal runaways.

Figure 20. Thermal runaway event within the cart

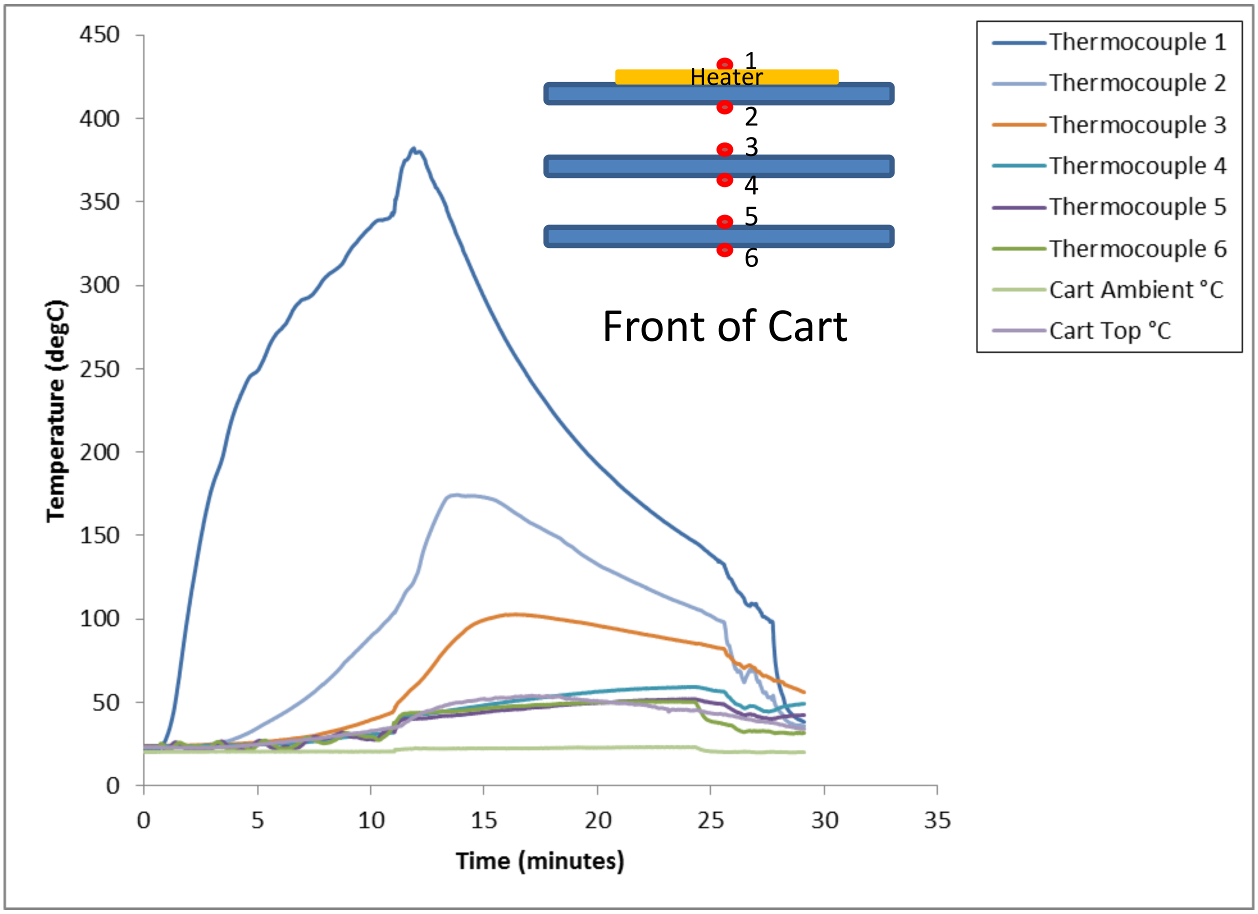


Figure 21. Test 3 temperatures

Figure 22. Removal of the e-tablets from the cart

<u>TEST 4</u>

Thermal runaway occurred in the e-tablet adjacent to the heat plate and smoke was observed after 24 minutes (shown in figure 23). A second thermal runaway from the same e-tablet occurred from a remaining cell within its battery and additional smoke was observed after 25 minutes. No fire was observed from the exterior of the cart. Figure 24 shows the temperature results for test 4.

After the test, the innermost e-tablet was found to be badly burned. The adjacent e-tablets were sooted, charred and discolored on the exterior. The middle e-tablet failed to power up, however, the outermost e-tablet was functional when the power button was activated (shown in figure 25). The heat released by the innermost e-tablet did not propagate to the batteries in adjacent e-tablets to initiate further thermal runaways. It took a longer time for the type 2 e-tablet to initiate a thermal runaway than it did for the type 1 e-tablet in test 1. This may have resulted because of the variation in pressure with which the heater made contact to the e-tablet or because of the variation in battery capacity and e-tablet geometry. Thermal runaway did not appear to be affected by the on/off state of the e-tablet.

Figure 23. Thermal runaway event within the cart

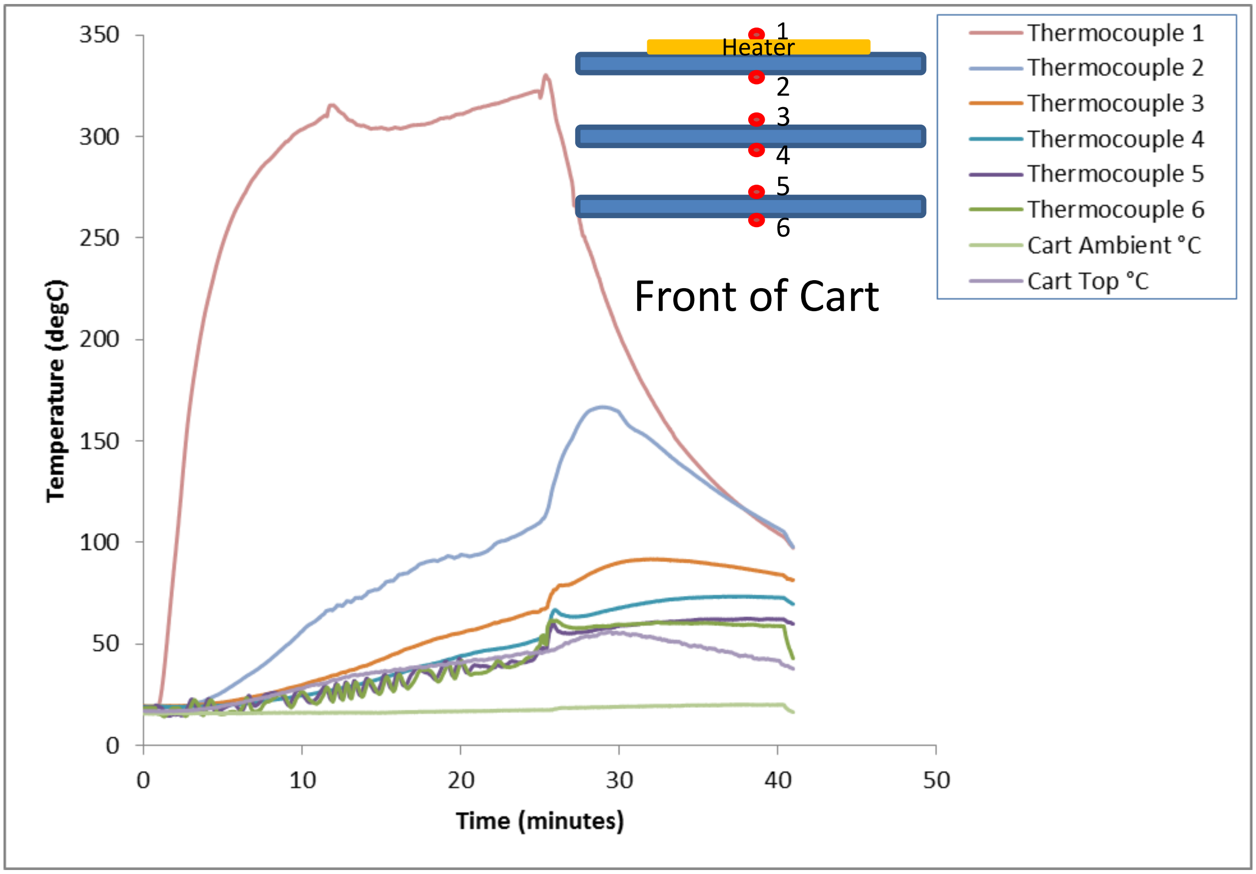


Figure 24. Test 4 temperatures

Figure 25. Post-test image of e-tablets

TEST 5

Test 5 followed the procedures for the alcohol fire tests except the cart door remained open until thermal runaway initiated. This was done to prevent oxygen starvation before runaway had a chance to occur. During the test, the alcohol fire was eventually extinguished due to oxygen starvation after thermal runaway had occurred and the door was shut. This was indicated by a decrease in temperature once the door was closed and unburnt alcohol which remained in the tray at the end of the test. Even though the alcohol fire was extinguished, the test was considered a success because the alcohol fire successfully initiated thermal runaway.

Smoke was observed at 5 minutes and again at 5.5 minutes. These events indicated an initial thermal runaway. A stronger intensity of smoke was observed at 5.75 minutes which indicated a second thermal runaway in one of the remaining cells in the same e-tablet. No fire was observed outside the cart during the test. Figure 26 shows the temperature results for test 5.

After the test, the remains were examined. The innermost e-tablet was charred and melted due to thermal runaway (shown in figure 27). The middle e-tablet was burned, but thermal runaway of the battery did not occur. The outermost e-tablet was undamaged and still functional. It took a shorter time to initiate a thermal runaway with the alcohol fire than it did with the heat plate in previous tests.

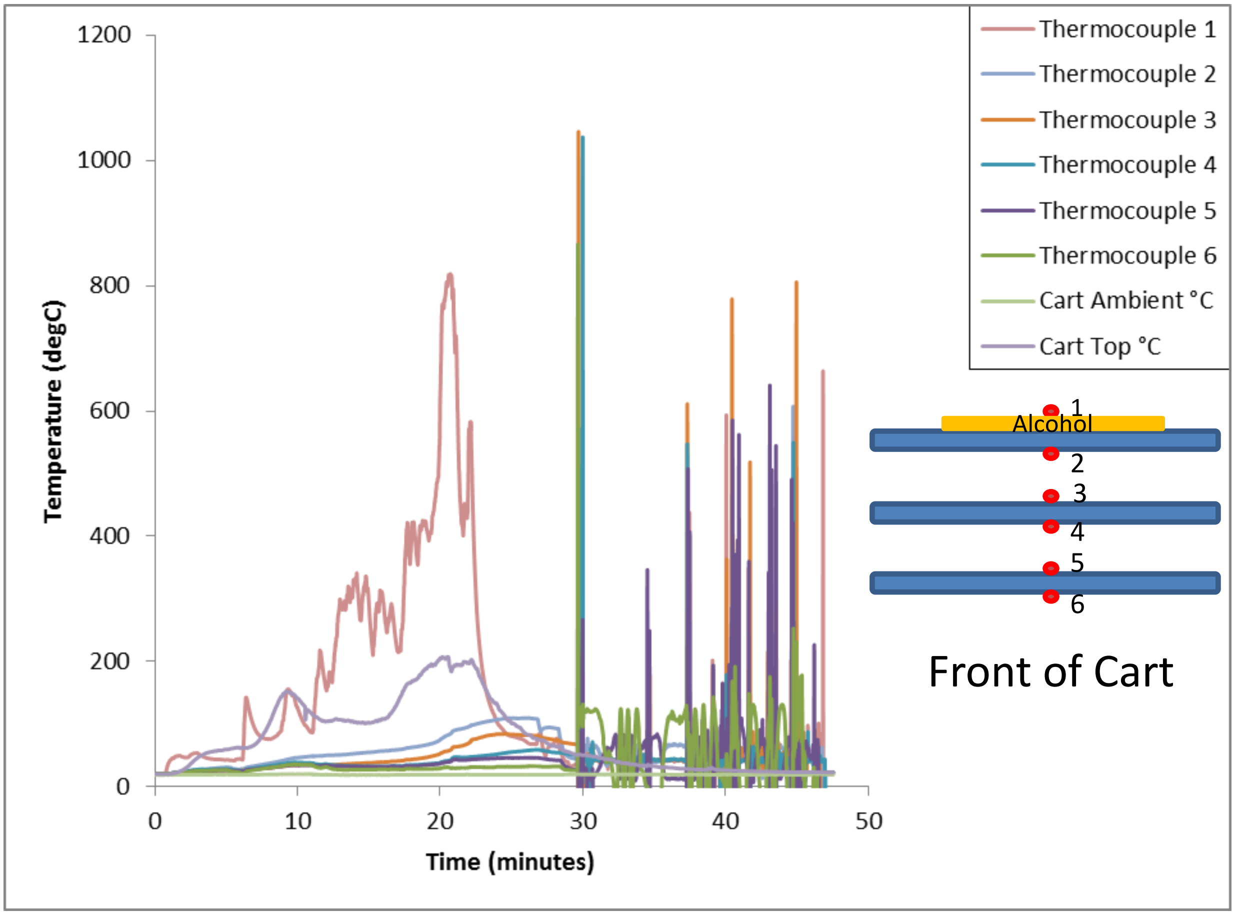


Figure 26. Test 5 temperatures

Figure 27. Removal of e-tablets from cart

<u>TEST 6</u>

Thermal runaway occurred in the e-tablet adjacent to the heat plate after 22 minutes (shown in figure 28). A second thermal runaway event occurred after 23.5 minutes. External smoke was present but no fire was observed from the exterior of the cart. Figure 29 shows the temperature results for test 6.

After the test, the third e-tablet from the bottom of the stack was found to be badly damaged. The adjacent e-tablets were slightly damaged on the exterior. The top and the bottom e-tablets powered up when the switch was activated. Further disassembly of the second, third, and fourth e-tablets revealed that thermal runaway occurred only on the third e-tablet (shown in figures 30 and 31).

Figure 28. Thermal runaway event

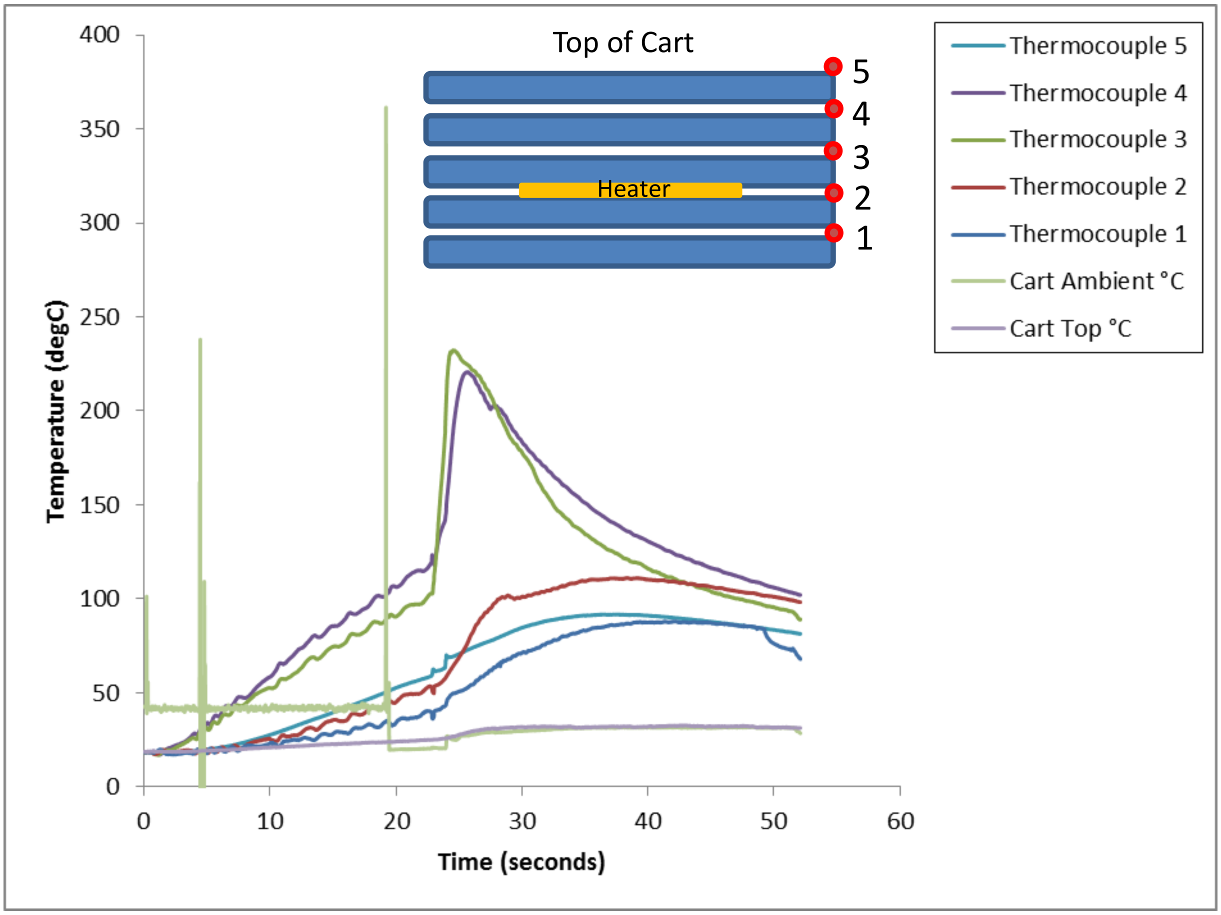


Figure 29. Test 6 temperatures

Figure 30. Disassembly of damaged e-tablets

Figure 31. Third e-tablet from the bottom

<u>TEST 7</u>

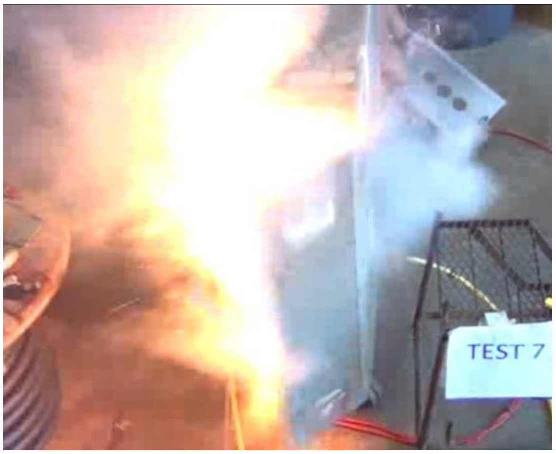
During the test, thermal runaway occurred and smoke was observed after 15 minutes. An explosion occurred 5 seconds later and forced the cart door open. The third e-tablet from the bottom of the stack had ignited and caused combustion of the surrounding flammable gasses. The door remained open and the fire self-extinguished at 18 minutes (shown in figure 32). Figure 33 shows the temperature results for test 7.

After the test, the following observations were made:

- The third e-tablet from the bottom of the stack was badly damaged. The adjacent e-tablets were slightly damaged on the exterior. The top and the bottom e-tablet powered up when the switch was activated. Further disassembly of the second, third, and fourth e-tablets revealed that thermal runaway occurred only on the third e-tablet (figure 34).

- The cart door remained attached to the cart at its hinges, as shown in figure 35. The door and the latch locks remained functional after the test. There was no indication of detachment of parts from the cart after the explosion.

(a)



(b)

(c)

Figure 32. Galley cart (a) immediately prior to explosion, (b) during explosion, (c) immediately after explosion

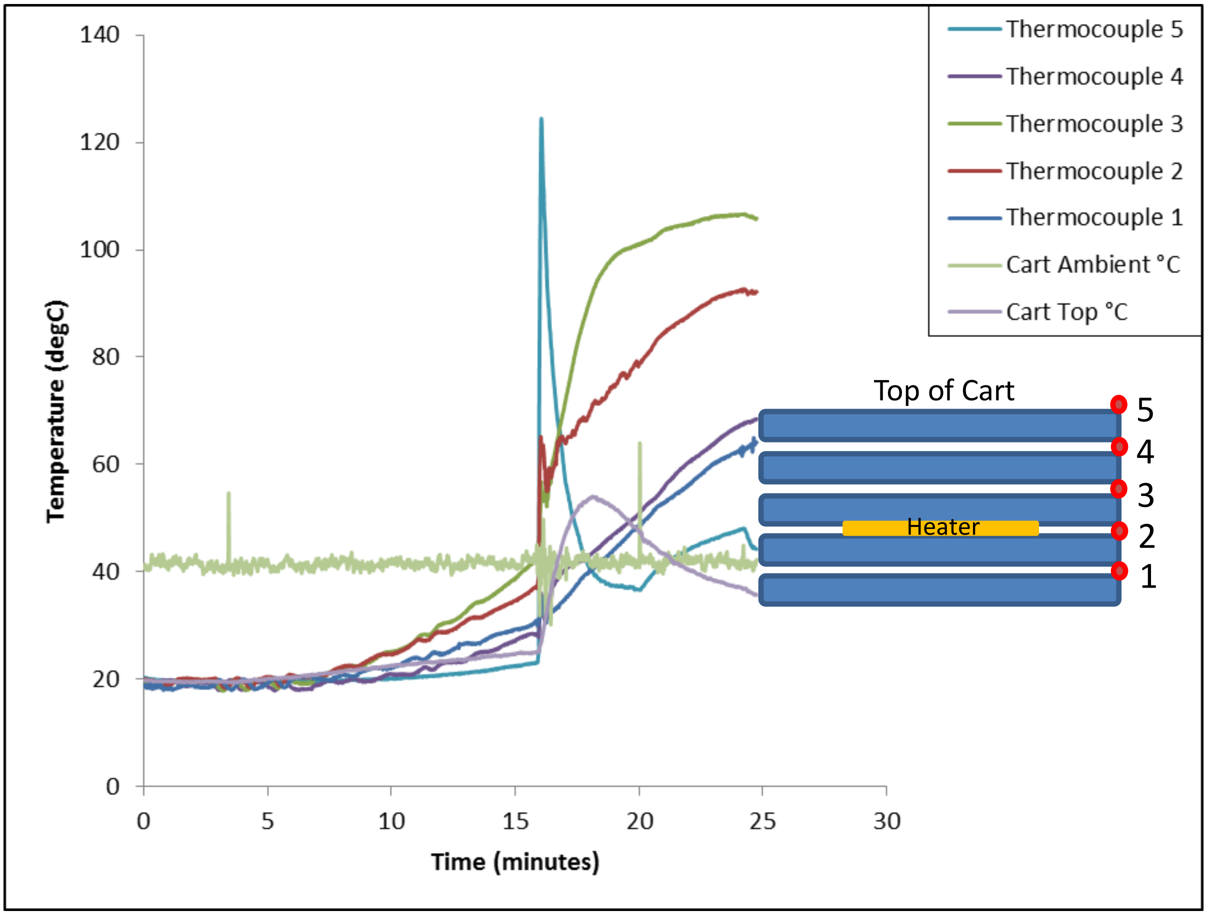


Figure 33. Test 7 temperatures

Figure 34. Post-test image of e-tablets

Figure 35. Soot marks from the fire

<u>TEST 8</u>

The cart door remained open to prevent oxygen starvation until the first thermal runaway event occurred and smoke and external fire was observed after 18.5 minutes (shown in figure 36). After 18.75 minutes smoke was again observed during a second thermal runaway event. No fire was observed at the exterior of the cart (shown in figure 37). Finally, after 19 minutes, smoke was again emitted as a third thermal runaway event occurred. Once again, fire was not observed at the exterior of the cart (shown in figure 38). Figure 39 shows the temperature results for test 8.

After the test, the bottom e-tablet of the stack was found to be badly damaged. The adjacent e-tablets were slightly charred and sooted on the exterior (shown in figure 40). Thermal runaway occurred only in the bottom e-tablet.

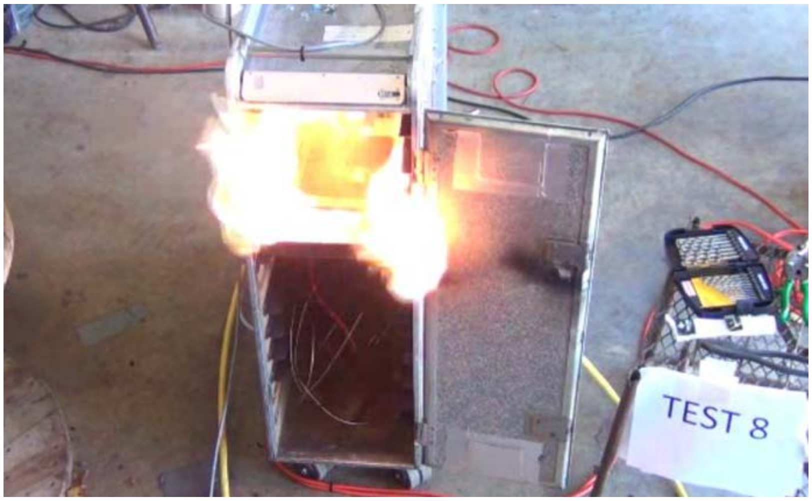


Figure 36. Test 8 thermal runaway event 1

Figure 37. Test 8 thermal runaway event 2

Figure 38. Test 8 thermal runaway event 3

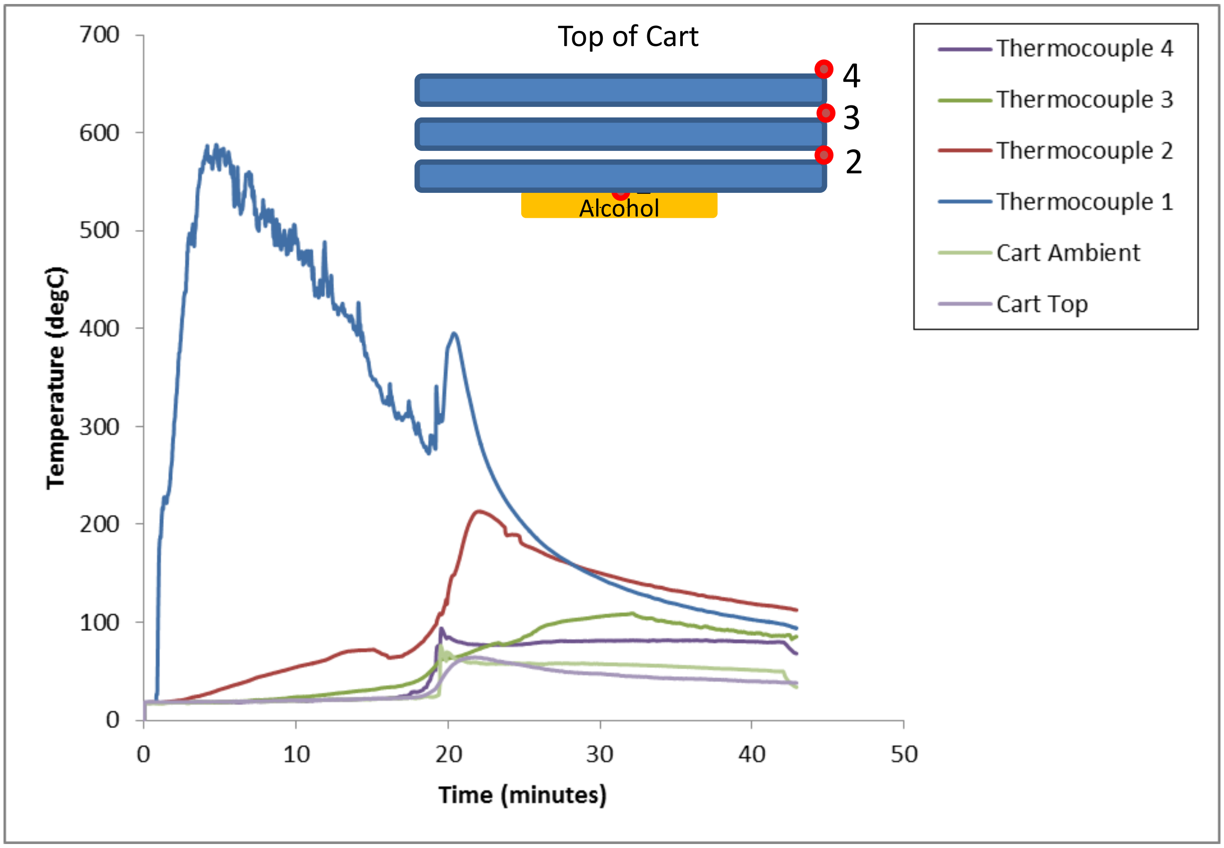


Figure 39. Test 8 temperatures

Figure 40. Post-test images of the e-tablets

TEST 9

During the test, thermal runaway occurred and smoke was observed after 31 minutes (shown in figure 41). An explosion occurred at 31 minutes and 20 seconds, as shown in figure 42, and the cart door was forced open as had occurred in test 7. The heat plate was then switched off and a short time later at 33 minutes the galley smoke alarm activated. The igniter was then switched on intermittently, which ignited the remaining flammable gases. Fire was later observed on the exterior of the cart at 34 minutes as it escaped from within the cart (shown in figure 43).

The test continued with the cart door slightly ajar, but not latched. Smoke was emitted continuously and filled up the cabin. The test ended at 41 minutes when the fire self-extinguished. Figure 44 shows the temperature results for test 9.

After the test, the second, third, and fourth e-tablets were found to be badly damaged (shown in figure 45). Thermal runaway occurred in the third e-tablet and did not propagate to the remaining e-tablets. The bottom e-tablet powered up when the switch was activated (shown in figure 46).

Figure 41. Thermal runaway event

Figure 42. Explosion

Figure 43. External fire

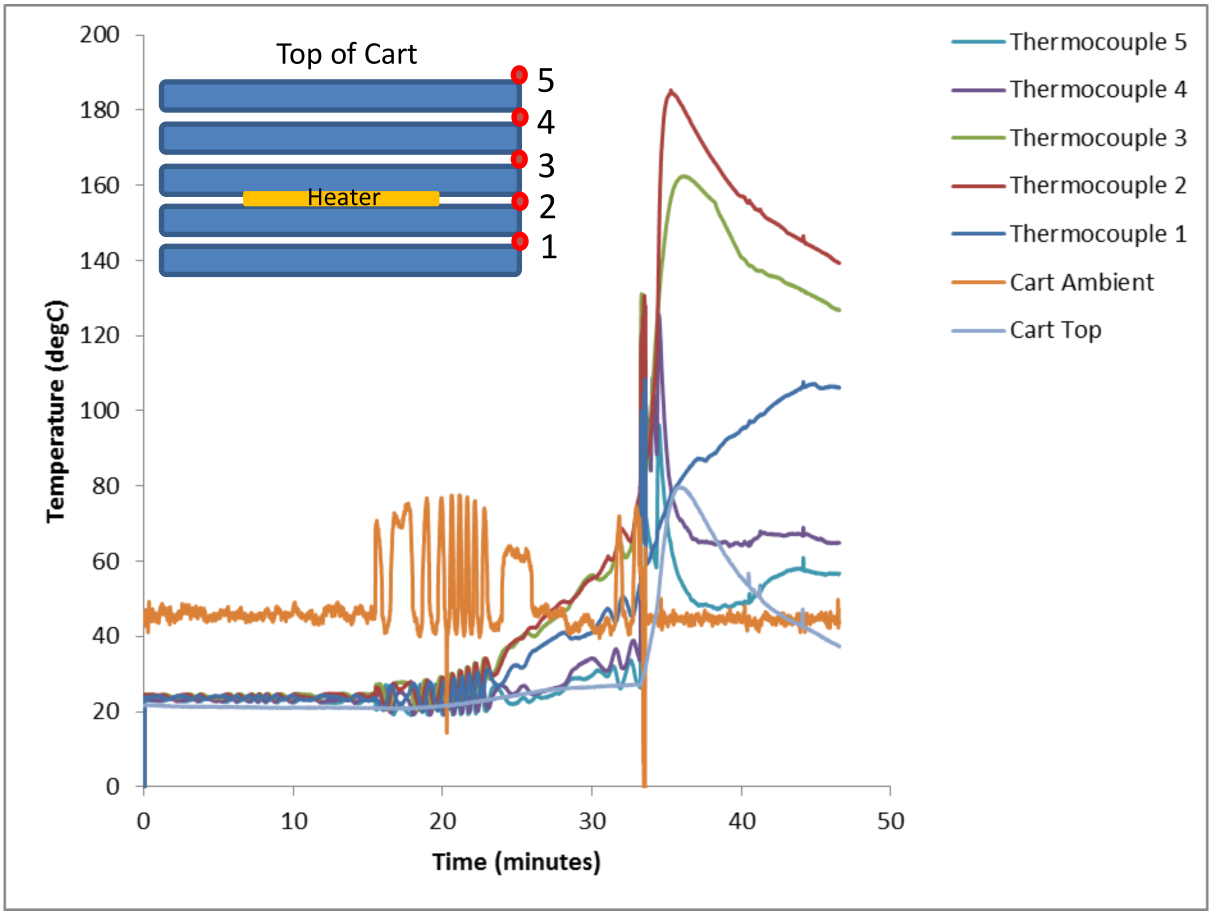


Figure 44. Test 9 temperatures

Figure 45. Post-test image of e-tablets

Figure 46. Functional e-tablet

<u>TEST 10</u>

During the test, the first thermal runaway occurred and smoke was observed after 44 minutes (shown in figure 47). Seven seconds later, the second thermal runaway event occurred and additional smoke was observed (shown in figure 48). Two seconds after the second thermal runaway event a third thermal runaway event occurred and additional smoke was again observed (shown in figure 49).

The igniter was switched on and the first ignition event occurred at 44.5 minutes. The cart door remained closed and latched (shown in figure 50). The galley smoke detector alarmed at 45 minutes. Steady flames and smoke were emitted from 44.5 minutes to 53 minutes (shown in figure 51). The igniter was then switched on for the second time at 53 minutes. An explosion occurred and the cart door was forced open (shown in figure 52). The test ended at 54 minutes when the fire was extinguished by the firefighters. The aircraft cabin was filled with dense smoke (shown in figure 53). Figure 54 shows the temperature results for test 10.

After the test, all e-tablets were found to be badly burned (shown in figure 55) and examination showed that thermal runaway initiated on the third e-tablet and propagated to additional e-tablets.

Tests 9 and 10 demonstrated the fire and smoke hazard posed in an operating aircraft environment and the potential of an explosion caused by the accumulation of flammable gases from the thermal runaway events. Flames were observed at the exterior of the galley cart and the heat from the reactions caused sequential thermal runaway of the lithium batteries in the remaining unburnt e-tablets. The burning e-tablets could expose aircraft occupants to hazardous combustion products and would require protective breathing equipment to effectively fight the fire.

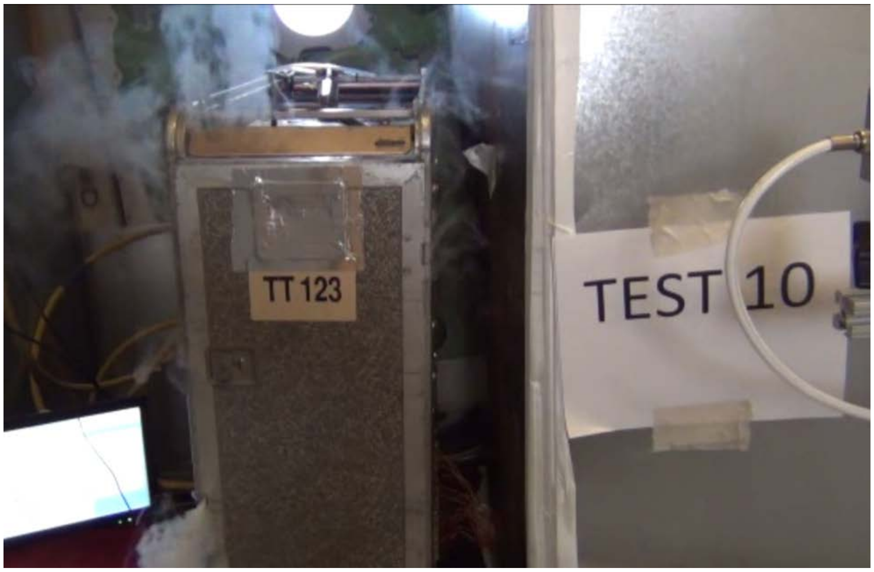


Figure 47. Test 10 thermal runaway event 1

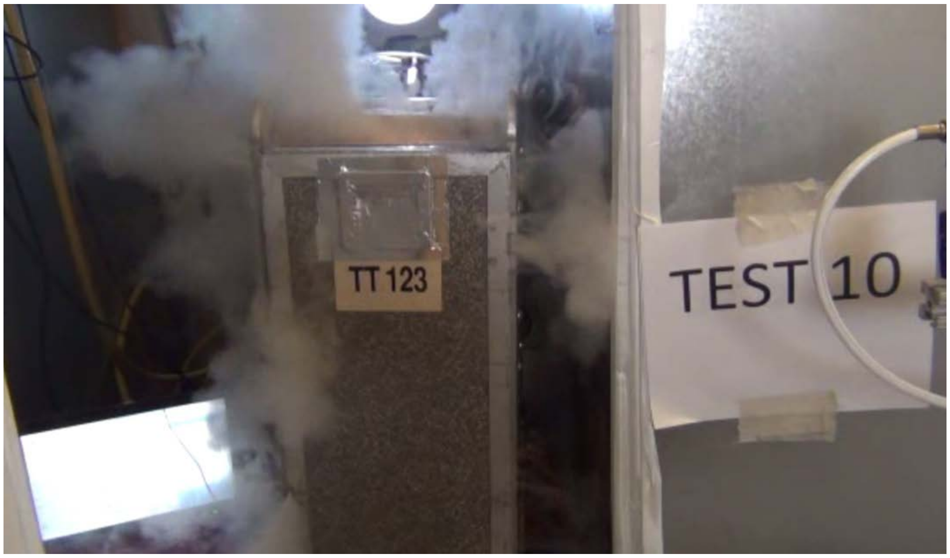


Figure 48. Test 10 thermal runaway event 2

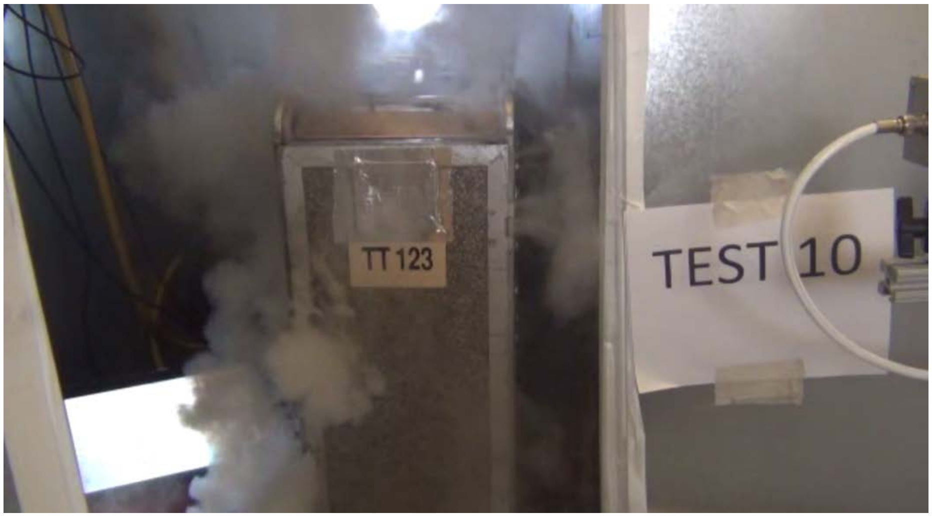


Figure 49. Test 10 thermal runaway event 3

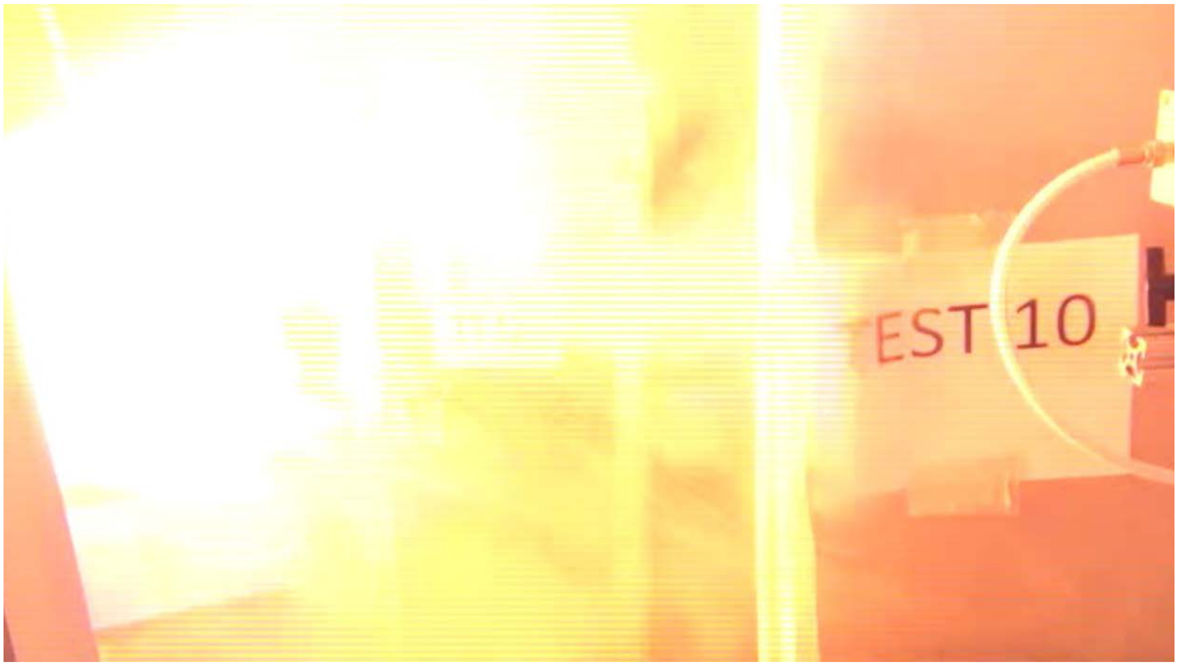


Figure 50. Test 10 explosion 1

Figure 51. Test 10 external flames

Figure 52. Test 10 explosion 2

Figure 53. Test 10 smoke generation

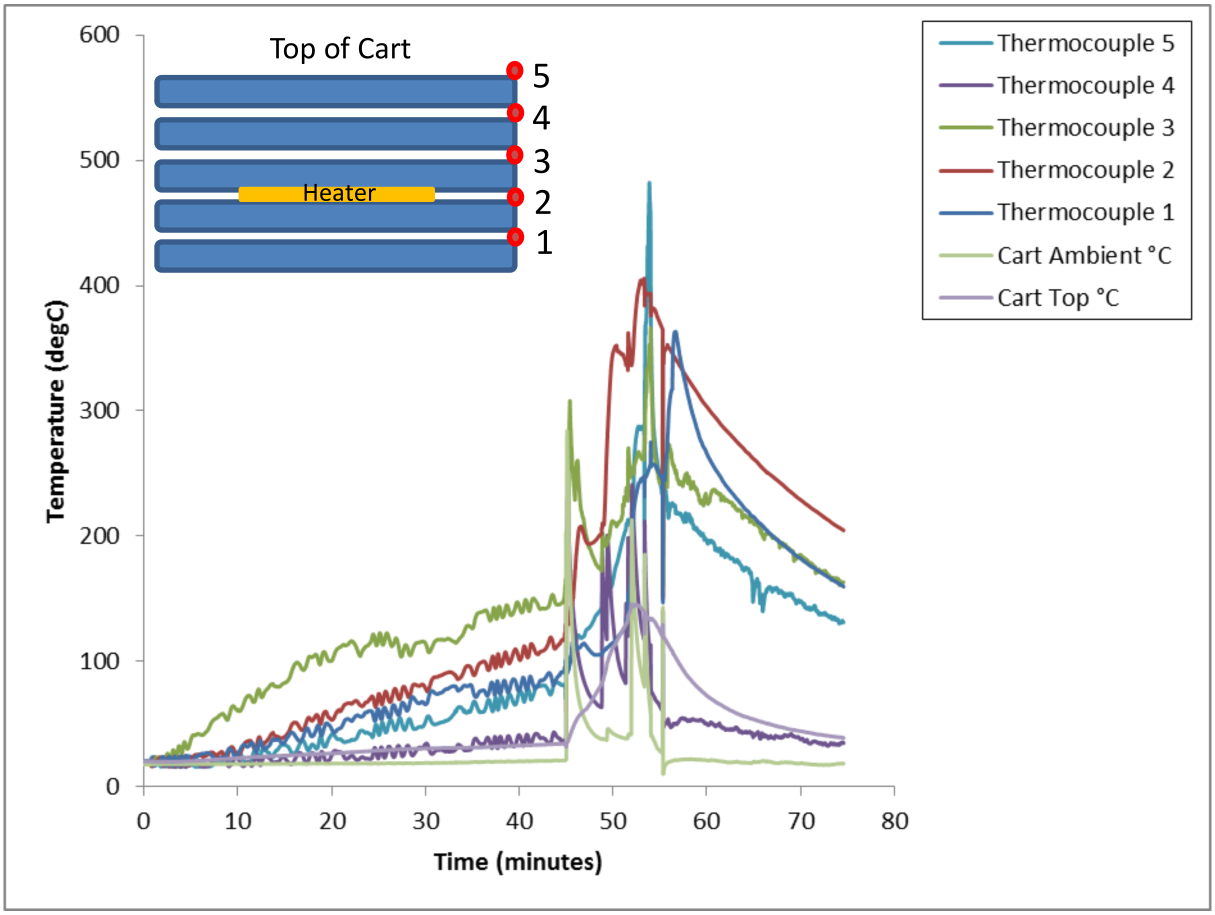


Figure 54. Test 10 temperatures

Figure 55. Test 10 post-test image of e-tablets

CONCLUSIONS

A summary of the findings from this study are listed as follows:

1) Bulk storage of e-tablets arranged in a vertical orientation in a galley cart with at least a 1-inch air gap separation did not cause propagation of thermal runaway to adjacent e-tablets (tests 1 through 5). This arrangement was acceptable only if the effects of an explosion were mitigated by the design of the cart.

2) Bulk storage of e-tablets in a horizontal-stacked orientation without separation demonstrated the potential for propagation of thermal runaway to the lithium batteries in adjacent e-tablets, as shown in test 10.

3) Thermal runaway of the lithium batteries caused the accumulation of flammable gases in the galley cart and the risk of an explosion. The explosions forced open the galley cart door, allowing greater fire and smoke hazards to escape into the cabin.

4) A significant amount of smoke was generated by the burning e-tablets. This could expose airplane occupants to hazardous combustion products and would require protective breathing equipment to effectively fight the fire. These conditions could also interfere with an emergency evacuation.

5) Temperatures on the outside surface of the cart and within the cart may cause burns to people and interfere with firefighting efforts.

6) In general, the tests showed that a galley cart might not be able to contain the fire caused by lithium-battery thermal runaway in an e-tablet. The flames will likely escape from the door gaps as they did in tests 7, 9, and 10, which would not be compliant with the TSO-C175 requirement for all fire to be contained inside the galley cart.

Further assessment is needed to compare the current fire-containment requirements in TSO C-175 for galley carts with the fires generated from these tests. Galley carts may also need to be designed with venting provision to prevent explosions and contain the fire within the cart.

The batteries in e-tablets continue to evolve and future e-tablets may have different fire risks when multiple units are stored in a confined space.

REFERENCES

1. Technical Standard Order (TSO) C-175, "Galley Carts, Containers and Associated Components."

2. AC 25-17A, "Transport Airplane Cabin Interiors Crashworthiness Handbook."

3. Office of the Federal Register National Archives and Records Administration, Code of Federal Regulations, 14 CFR 25.561, *Emergency Landing Conditions*, January 2002.