Impact of Lithium Battery Vent Gas Ignition on Cargo Compartment Fire Protection

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16. Abstract

One of the dangers of shipping lithium batteries in an aircraft is the risk of thermal runaway propagation, which can cause an uncontrollable fire in the cargo compartment. During thermal runaway, a significant quantity of hydrogen and hydrocarbons may accumulate and ignite in the shipping boxes and the free space within the cargo compartment. This can cause a pressure pulse sufficient to compromise the safety of the aircraft. With the pressure relief panels removed or the liner compromised, the compartment would no longer be able to fully contain the Halon 1301 fire extinguishing agent.

A series of tests were conducted to determine the minimum quantity of 18650-sized battery cells required to produce a flammable gas mixture that, if ignited, would be capable of producing a pressure rise that would open pressure relief panels and possibly dislodge cargo liners. A mixture of bottled battery vent gas and air was metered into a balloon at a concentration that was previously shown to maximize the pressure rise of combustion. A spark igniter located within the balloon ignited the mixture. Validation tests were conducted to determine if the pressure rise from the combustion of the bottled battery gas mixture replicated the pressure rise of the actual vented battery gases. The results showed an identical pressure rise. Depending on the state of charge, the ignition of the vent gases from a relatively small number of lithium batteries in thermal runaway created a pressure pulse that dislodged the pressure relief panels in an aircraft cargo compartment.

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SOC	State of charge

EXECUTIVE SUMMARY

One of the dangers of shipping lithium batteries in an aircraft is the risk of thermal runaway propagation, which can cause an uncontrollable fire in the cargo compartment. During thermal runaway, a significant quantity of hydrogen and hydrocarbons may accumulate and ignite in the shipping boxes and the free space within the cargo compartment. This can cause a pressure pulse sufficient to compromise the safety of the aircraft. With the panels removed or the liner dislodged, the compartment would no longer be able to sustain the Halon 1301 fire extinguishing agent required to suppress and control a fire for the duration of the flight.

A series of tests were conducted to determine the minimum quantity of 18650-sized battery cells required to produce a flammable gas mixture that, if ignited, would be capable of producing a pressure rise that would open pressure relief panels and possibly dislodge cargo liners. A mixture of bottled battery vent gas and air was metered into a balloon at a concentration that has been previously shown to maximize the pressure rise of combustion. A spark igniter located within the balloon ignited the mixture. Validation tests were conducted to determine if the pressure rise from the combustion of the bottled battery gas mixture replicated the pressure rise of the actual vented battery gases. The results showed an identical pressure rise.

The tests were conducted in two test articles. Initially, tests were carried out in a 10.8 m^3 pressure chamber to determine the relationship between the volume of lithium battery vent gases and the pressure rise in the chamber when the gases were ignited. The chamber was filled with boxes to represent a cargo compartment that was 70% loaded with cargo. Later, tests were performed in a 737 forward cargo compartment, also with 70% loading, to determine the pressure rise from the ignition of vented gases, and the impact on the cargo compartment pressure relief panels and the cargo liner. During these tests, a bottled gas mixture of battery gases was used to carefully control the experiments and vary the quantity of the gas mixture.

The pressure chamber tests showed that a pressure rise of 1 psi, which would open pressure relief panels, was achieved with a gas mixture corresponding to one cell at 100% state of charge (SOC) or 3 cells at 50% SOC, at a reduced pressure approximately equivalent to the cabin pressure at cruise altitude. Tests in the 737 forward cargo compartment at sea level showed that the equivalent of eight cells at 50% SOC or 2.6 cells at 100% SOC were sufficient to cause a 0.59 psi pressure rise in the compartment, which marginally opened the pressure relief panels. With a greater volume of the gas mixture, corresponding to 6.4 cells at 100% SOC or 20 cells at 50% SOC, the pressure rise was 1.2 psi, which completely opened the pressure relief panels in the forward and aft walls. A third pressure relief panel located above the main door was also dislodged, and the cargo liner was damaged at one location.

Overall, if ignited, a relatively small quantity of vented lithium-ion battery cells was capable of opening pressure relief panels in an aircraft cargo compartment. The opening would allow for extinguishing agent leakage from the cargo compartment, reducing the duration of protection produced by the onboard fire suppression system.

INTRODUCTION

BACKGROUND AND MOTIVATION

One of the dangers of shipping lithium batteries in an aircraft is the risk of thermal runaway propagation, which can cause an uncontrollable fire in the cargo compartment. During thermal runaway, a significant quantity of hydrogen and hydrocarbons [1] may accumulate and ignite in the shipping boxes and the free space within the cargo compartment. This can cause a pressure pulse sufficient to compromise the safety of the aircraft.

The below-floor cargo compartments on passenger aircraft are required to have both fire detection and fire suppression systems. The suppression agent currently used is Halon 1301, a gaseous total flood agent. The fire suppression system is designed to produce an initial extinguishing concentration of 5% in the empty volume of the cargo compartment and to maintain a concentration of at least 3% for the duration of flight.

Cargo liners are installed in aircraft cargo compartments as both a fire resistant barrier and to contain smoke and fire suppression agent. Certification flight tests are conducted to demonstrate that the Halon concentration exceeds the minimum requirement for the required length of time. If the leakage from the compartment exceeds the leakage that was present during the certification testing, the fire suppression protection time will be less than designed. Another safety feature designed into below floor, Class C cargo compartments is the ability to equalize a pressure differential that could occur between the inside of the cargo compartment and the surrounding space inside the fuselage. This feature is needed in the event of a rapid inflight decompression and is achieved with pressure relief panels/liners that are designed to break free from the structure they are attached to when a differential pressure exceeds approximately 0.5 to 1.0 lb/square inch (psi).

Flight safety may be compromised if a small quantity of lithium batteries undergo thermal runaway and the released gases ignite to cause a pressure rise sufficient to release the depressurization pressure relief panels or dislodge the cargo liner.

Previous studies have shown that a large quantity of lithium batteries in thermal runaway could vent gases that ignite and cause an explosion in a cargo container or cargo compartment [2, 3]. However, the minimum quantity of cells capable of creating pressures that would compromise the effectiveness of the Halon system had not been determined.

OBJECTIVE

Determine the minimum quantity of battery cells required to produce a flammable gas mixture that, when ignited, is capable of displacing cargo liners or dislodging depressurization pressure relief panels.

SETUP

Tests were conducted in two test articles. First, tests were carried out in a 10.8 m^3 pressure chamber to determine the relationship between the volume of lithium battery vent gases and the pressure rise in the chamber. Next, tests were performed in a 737 forward cargo compartment with a volume of approximately 10.48 m^3 to determine the pressure rise and corresponding number of lithium-ion batteries required to dislodge the compartment pressure relief panels or damage the cargo liner. In each of the tests, pressure rise was measured with a 0–30 psia Honeywell pressure transducer and recorded with a data collection system at approximately 50 Hz.

In each of the two test articles, cardboard boxes were used to attain the desired free space typical of a loaded cargo compartment. The free space volume in the pressure chamber corresponded to a 70% loading in the aft cargo compartment of a 737 (see figure 1). The aft cargo compartment has a total volume of 14.3 m^3, so the pressure chamber was loaded to have 4.29 m^3 of free space. The tests in the 737 were conducted in the forward compartment with 70% loading so that the free air volume was 3.14 m^3 (see figure 2) The boxes were filled with packing peanuts, which are typically found in air shipments, and sealed with tape.

Figure 1. Pressure chamber loaded to 70% with cargo

Figure 2. The 737 forward cargo compartment

A balloon/spark igniter was used in the tests to create a controlled volume and concentration of flammable vent gases. Figures 3 and 4 show that the rig was configured to allow the battery gas composition to pass upwards through the center of a tube. The metal tube was one leg of the circuit and a wire that passed through the center of the tube was the second. The balloon covered the tube and was filled with a specific volume of battery vent gas and air. The two legs of the igniter circuit allowed a spark to be generated within the filled balloon to ignite the mixture.

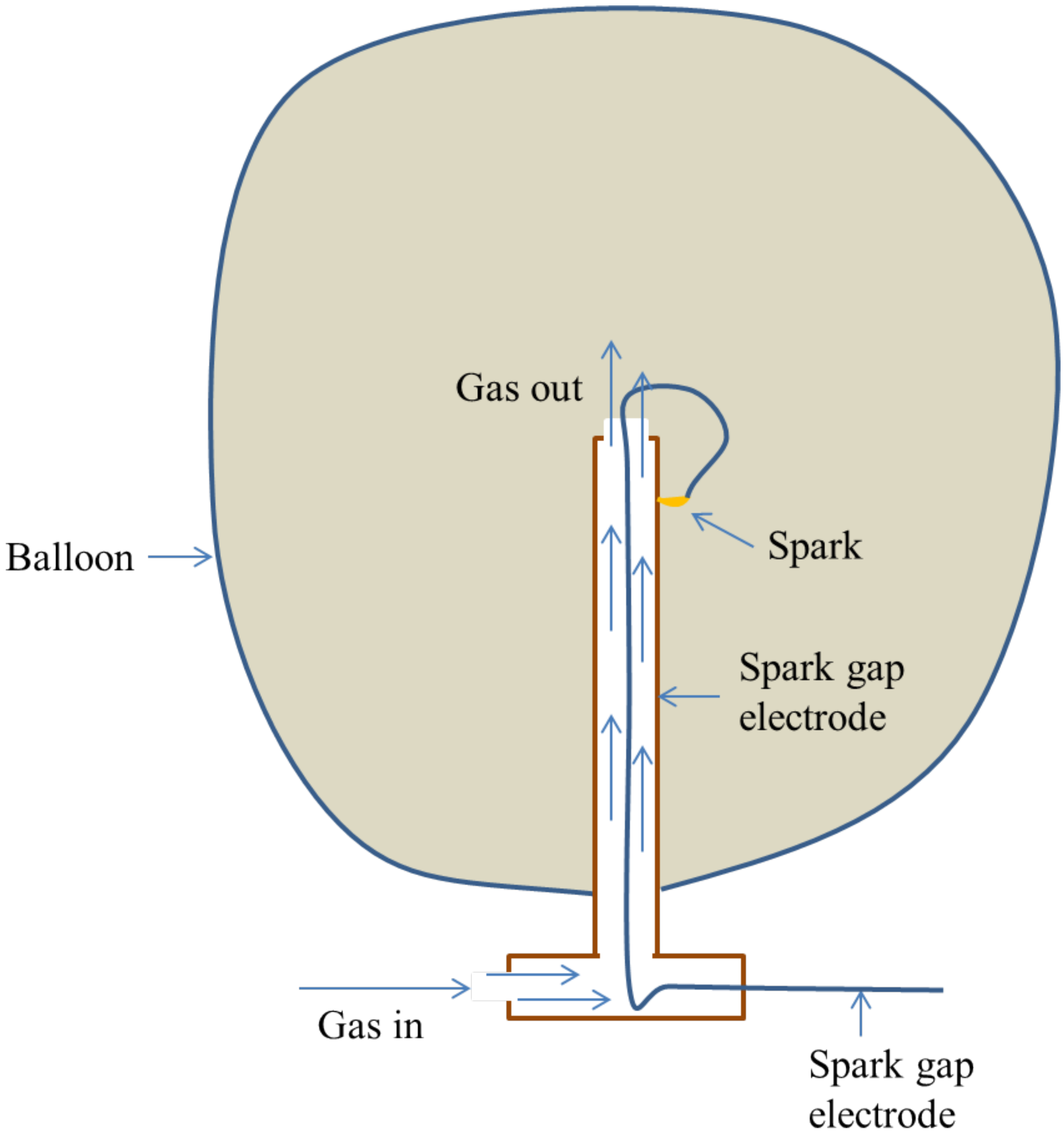

Figure 3. Balloon test rig diagram

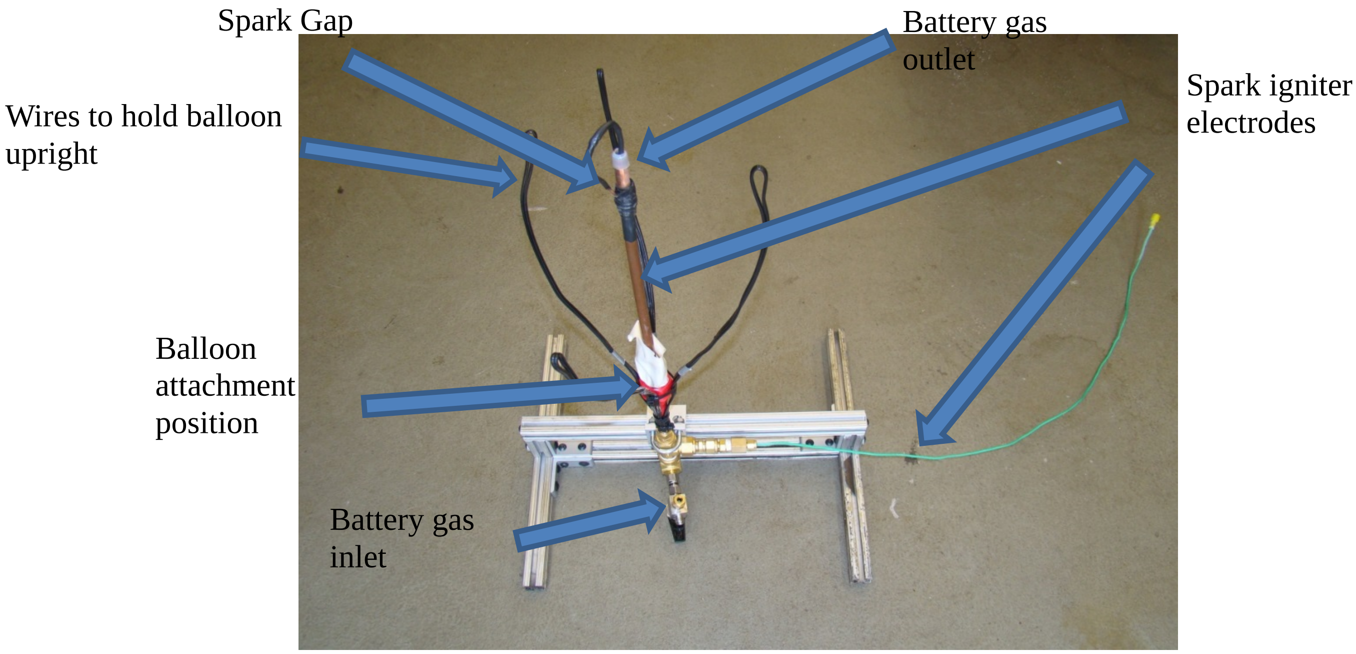

Figure 4. Balloon filling and ignition test rig

The flammable gas used for the tests was metered by an Environics gas divider that was connected to a gas cylinder containing a flammable gas mixture similar to what was measured from battery cells (see table 1) [1]. The concentration of the gas mixture added to the balloon was 21.7% battery gas and 78.3% air, shown previously to be the concentration near the peak pressure rise [1]. Gas was added to the balloon at one liter per minute until the desired volume was attained. To verify that the pressure rise from the bottled gas was similar to the pressure rise from the vented battery gas, a comparison was made in a 21.7 liter combustion sphere. The battery gas was obtained by inducing thermal runaway in $LiCoO_2$ cells and using partial pressures to achieve a 21.7% concentration in the combustion sphere [1]. On ignition, the pressure rise profiles from the actual battery gas and the bottled gas mixture were nearly equal (see figure 5). Therefore, the bottled gas was used in subsequent tests to represent the flammable gas mixture vented by $LiCoO_2$ cells in thermal runaway. To prevent stratification of gases within the balloon, a fan was directed toward the balloon to shake it and mix the gases. Figure 6 shows the balloon setup immediately prior to ignition.

Table 1. Bottled gas used to fill balloons

CO_2	30.10%
H_2	27.60%
CO	22.90%
CH_4	6.37%
C_3H_6	4.48%
C_2H_4	2.21%
C_4H_{10}	1.57%
C_2H_6	1.17%
C_4H_8	0.56%
C_3H_8	0.27%

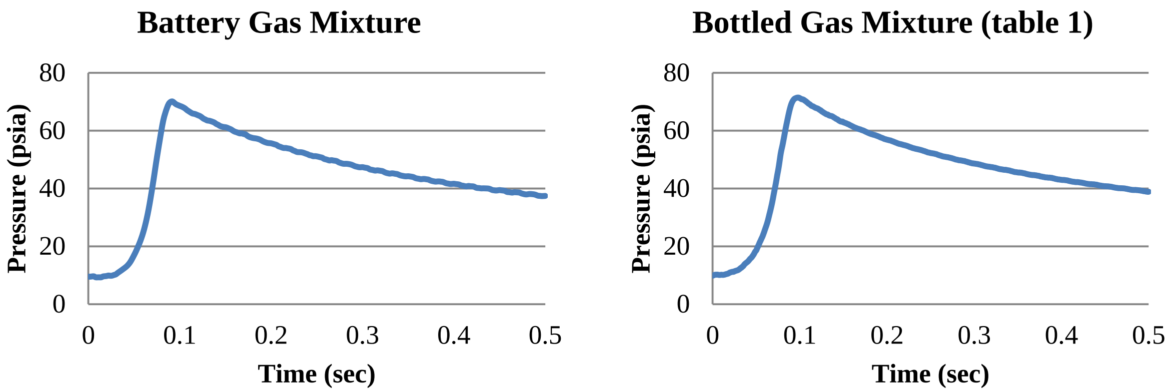

Figure 5. Comparison of pressure rise between actual gas and bottled gas

Figure 6. Balloon rig in pressure chamber immediately prior to ignition

The tests in the pressure chamber were performed at reduced pressure to simulate altitude conditions (10 psia) and at sea level pressure. Table 2 shows the pressure chamber tests that were performed.

Table 2. Tests performed in pressure chamber

Ambient Pressure	Combined Air and Battery Gas Volume (Liters)	Equivalent Number of Battery Cells 100% SOC	Equivalent Number of Battery Cells 50% SOC
Sea Level	48.6	2.2	6.8
Sea Level	35.6	1.6	5
Sea Level	78.4	3.5	11
Sea Level	35.6	1.6	5
Sea Level	48.6	2.2	6.8
Altitude	52.4	1.6	5
Altitude	31.4	1	3
Altitude	10.5	0.3	1
Sea Level (in aircraft)	35.6	1.6	5
Sea Level (in aircraft)	141.2	6.4	20
Sea Level (in aircraft)	57	2.6	8

SOC = state of charge

The forward cargo compartment in the 737 is equipped with three pressure relief panels: one mounted on the forward wall, one mounted on the aft wall of the compartment, and one located above the main entry door (see figure 7). The forward and aft pressure relief panels were seated in place within a rubber channel that would flex to allow the panel to dislodge in an overpressure event (see figure 8). The pressure relief panel above the door was clamped in place with a metal flange and screws through the cargo liner. Prior to testing, the pressure relief panels were expected to activate between 0.5 and 1.0 psi.

(a) (b) (c)

Figure 7. The 737 forward cargo compartment (a) forward panel, (b) aft panel, and (c) panel behind door

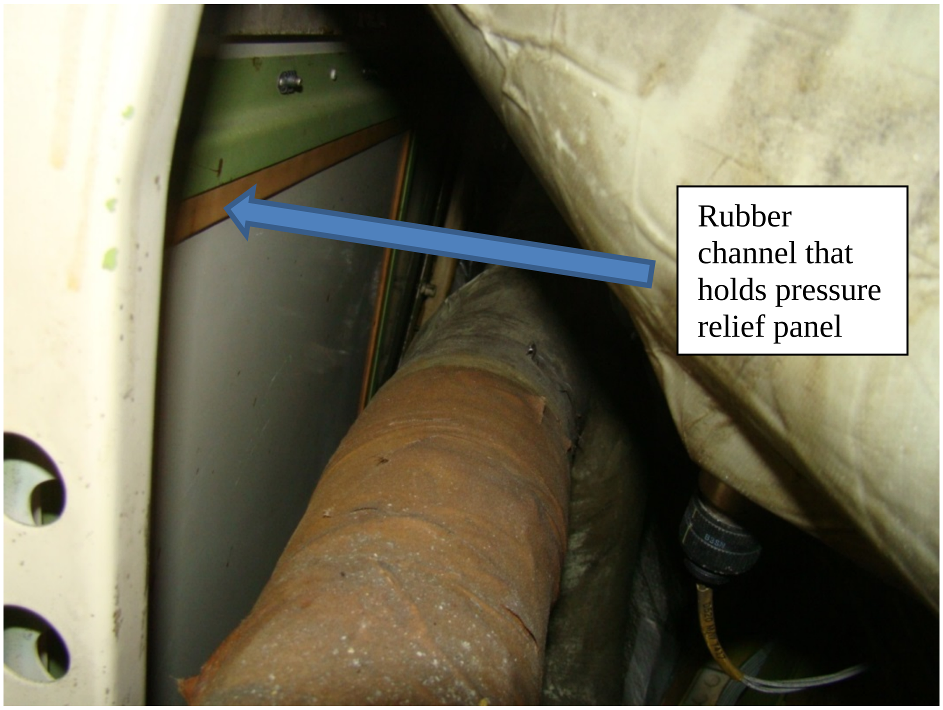

Figure 8. Aft side of aft pressure relief panel (behind the bulkhead)

The gas volumes used for the three tests in the 737 are shown in table 3.

Table 3. Battery gas volumes for 737 tests

	Gas Volume (Including Air)	Equivalent Number of Battery Cells 100% SOC	Equivalent Number of Battery Cells 50% SOC
Test 1	35.6 L	1.6	5
Test 2	141.2 L	6.4	20
Test 3	57 L	2.6	8

SOC = state of charge

DISCUSSION OF RESULTS

PRESSURE CHAMBER TESTS

Tests were conducted in the 10.8 m^3 pressure chamber at sea level pressure and at a pressure of 10 psia, which roughly corresponded to cabin pressure at altitude. The results showed a nearly linear increase in pressure rise with the equivalent number of batteries corresponding to the gas mixture volume (see figures 9 and 10). The slope of the line is greater at 100% state of charge (SOC), which reflects the increase in gas volume with SOC [1]. Moreover, the number of cells required to achieve a given pressure rise decreases with altitude. Table 4 shows that the pressure rise was reasonably repeatable. Tables 4 and 5 show the results in tabular form including the measured peak pressure rise. Table 6 shows the calculated number of cells that resulted in a pressure rise of approximately 1 psi, which would be sufficient to completely dislodge the pressure relief panels.

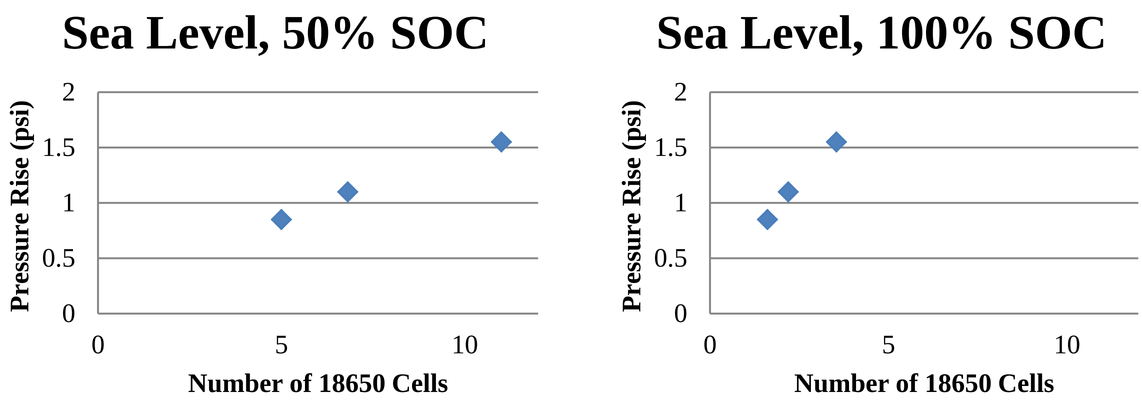

Figure 9. Pressure rise in chamber at sea level

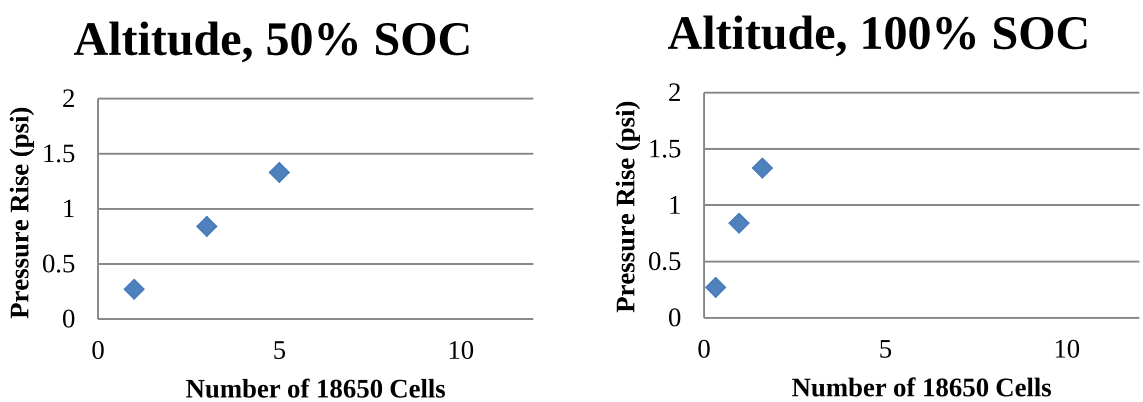

Figure 10. Pressure rise in chamber at altitude

Table 4. Results of sea level pressure tests

Gas Volume (Including Air)	Number of Cells (100%)	Number of Cells (50%)	Pressure Rise (psi)
48.6 L	2.2	6.8	0.93
35.6 L	1.6	5	0.85
78.4 L	3.5	11	1.55
35.6 L	1.6	5	0.96
48.6 L	2.2	6.8	1.1

Table 5. Results of altitude tests

Gas Volume (Including Air)	Number of Cells (100%)	Number of Cells (50%)	Pressure Rise (psi)
52.39 L	1.6	5	1.33
31.4 L	1	3	0.84
10.5 L	0.3	1	0.27

Table 6. Number of 18650 cells required to produce 1 psi in pressure chamber

	Approximate Number of Cells Required to Create 1 psi
50% SOC, Sea Level	6
100% SOC, Sea Level	2
50% SOC, Altitude	4
100% SOC Altitude	1.3

737 TESTS

Three tests were carried out in the 737 forward cargo compartment at varying bottled mixture gas volumes (see table 3). Results showed that a pressure rise as low as 0.6 psi was sufficient to dislodge the pressure relief panels, corresponding to 8 cells at 50% SOC and 2.6 cells at 100% SOC (see figure 11). This condition caused both panels to open. The aft panel (shown in figure 11) opened on the bottom with a 3-inch gap, and the forward panel was fully removed.

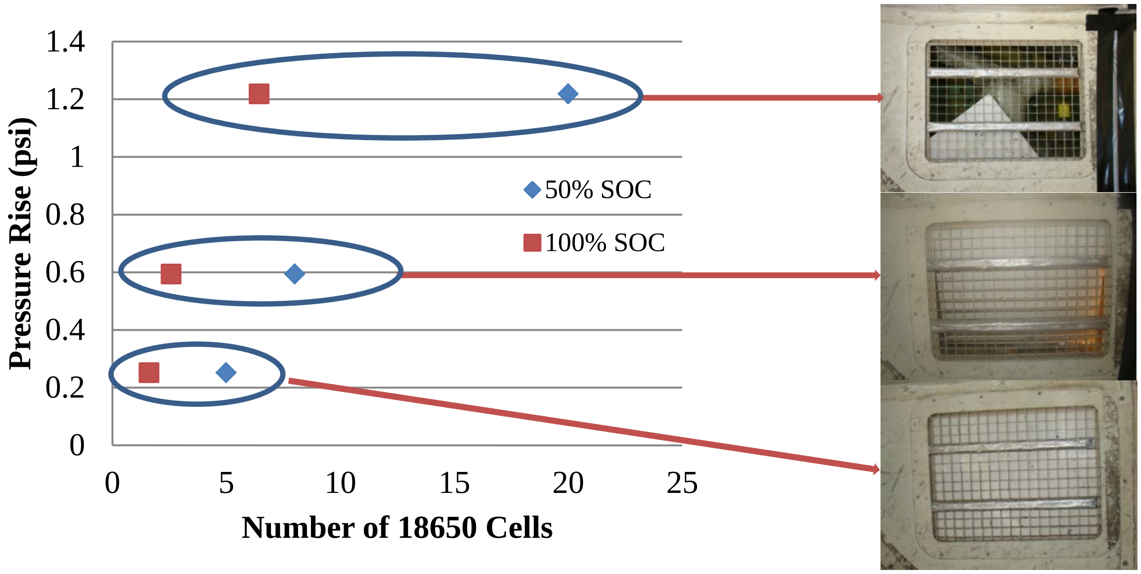

Figure 11. The 737 test results

The test with the greatest bottled mixture gas volume, corresponding to 6.4 cells at 100% SOC or 20 cells at 50% SOC, produced a pressure rise of 1.2 psi that completely dislodged the forward and aft panels and also dislodged the third panel above the door (see figure 12). In addition, a section of cargo liner was damaged as a result of the test.

Figure 12. Pressure relief panel above the door after a 6.4 cell at 100% and a 20 cell at 50%

The test with the lowest bottled mixture gas volume, corresponding to 1.6 cells at 100% or 5 cells at 50% SOC, caused the pressure relief panels to momentarily bulge outward while remaining in place. The pressure rise was 0.25 psi, below the documented threshold required to open the panels.

SUMMARY

Tests in the 737 cargo compartment showed that a relatively small volume of ignited battery gases, equivalent to 2.6 cells at 100% SOC or 8 cells at 50% SOC, was capable of creating a pressure rise that would open pressure relief panels. This would compromise the effectiveness of the aircraft Halon system by allowing the agent to leak out.

Tests in the pressure chamber at sea level showed that the ignited gas mixture corresponding to 2.2 cells at 100% SOC or 6.8 cells at 50% SOC was capable of producing a 1-psi pressure rise in a simulated cargo compartment, which would dislodge pressure relief panels. However, at altitude, approximately 1/3 fewer cells would be required to produce a 1-psi pressure rise.

The test results in the 737 cargo compartment and pressure vessel were fairly consistent in terms of the measured pressure rise corresponding to the ignited gas mixture volume. Dislodging of pressure relief panels in the 737 cargo compartment also occurred with measured pressure rises consistent with the relief panel design range values.

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