SABATAIR

Deliverable 4a:

Lithium ion cell exposure to an on-board external fire: Test Program

Task	**4**	Characterisation of on-board fire-protection facilities; assessment of their contribution to the effectiveness of the proposed packaging solutions

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[1] Dissemination level: **PU** = Public, **PP** = Restricted to other programme participants (including the JU), **RE** = Restricted to a group specified by the consortium (including the JU), **CO** = Confidential, only for members of the consortium (including the JU)

[2] Nature of the deliverable: **R** = Report, **P** = Prototype, **D** = Demonstrator, **O** = Other

[3] Creation, modification, final version for evaluation, revised version following evaluation, final

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Chapter I: Introduction

Several incidents with lithium battery fires have risen the question, if today's cargo compartment fire protection design is able to contain cargo fire with a significant quantity of lithium batteries involved [1]. The existing cargo compartment fire protection systems are certified considering the fires that are likely to occur in a cargo compartment. The demonstration of compliance with the applicable certification requirements does not does not consider the specific hazard posed by a fire event involving lithium batteries transported in the cargo compartment.

One of the objectives of the Sabatair project is to identify mitigating measures that could be put in place to ensure that the severity of lithium battery fire could be reduced to a level that could be within the capability of the aircraft's onboard fire suppression system. This involves the evaluation of the following battery fire scenarios:

- a thermal runaway initiated from inside this package (**internal** fire)
- a lithium battery fire which does not originate but eventually involves transported cells/batteries (**external** fire)

The tests described in this document study the **external** fire threat considering different level of protection for the packaging of lithium batteries at different state of change, taking also into account the expected typical performance of cargo compartment fire protection systems installed on large aeroplanes.

Chapter II: Aircraft Fire Protection: Detection and Suppression

Fire detection systems are designed to alert the flight crew in the cockpit within 1 minute after the start of a fire. Based on the information provided by the detection warnings, flight crew initiate the suppression of any fire by discharge of Halon gas into the affected cargo compartments.

Halon is a very effective suppression agent which operates by chemically reacting with the radicals generated by a fire, to inhibit the reaction. To achieve the extinguishing effect, sufficient Halon needs to be released to achieve a volumetric concentration of 5% in the compartment for a fire knock-down effect. Following this, a concentration of at least 3% must be maintained for the rest of flight. Maintaining the concentration of Halon is crucial to the effectiveness of the fire suppression system, and therefore it is essential that the cargo compartment is designed to be air-tight.

The phenomenon of thermal runaway of lithium batteries in an aircraft environment can be catastrophic [1]. In the case worst situation, thermal runaway in high density package of Lithium batteries can result - and has been implicated - in hull losses.

Tests conducted by the FAA Tech Center tests show that even a small number of cells involved in a thermal runaway event can emit gases that can cause explosions and fires that cannot be prevented or controlled by the aircraft fire suppression systems.

Chapter III: On-board external fire test setup

III.1 Test chamber

The test chamber shall be in dimensions (56.6 m^3) and in accordance with the Minimum Performance Standard for Aircraft Cargo Compartment Halon Replacement Fire Suppression Systems [2].

Figure 1 shows a picture of the mock-up in which the tests shall be performed with some more details about the dimensions.

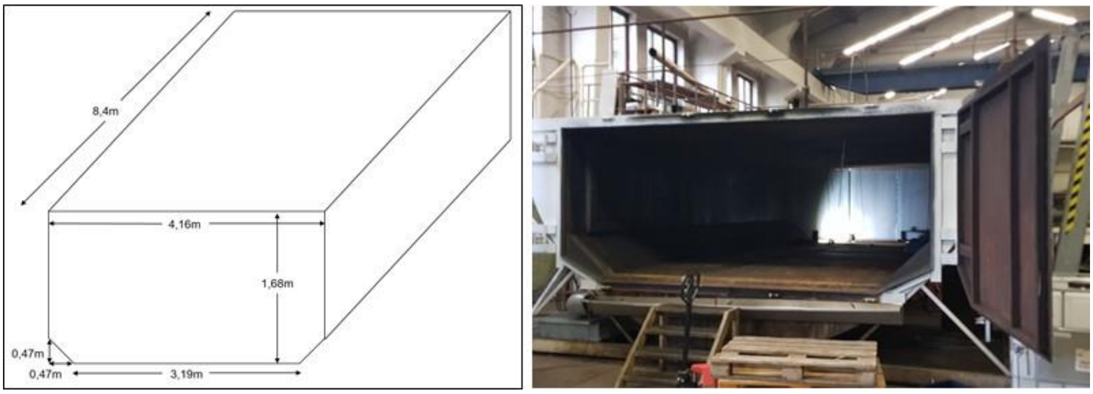


Figure 1: On the left a sketch of the fire test chamber and on the right a photograph of the fire test chamber

III.1.1 Leakage rate

It shall be possible to adjust the leakage rate in the test chamber to 6l/sec which is representative of modern aircraft manufactured in the European Union.

III.1.2 Air supply

It shall be possible to supply the test chamber with additional fresh air to supply oxygen for the burning process.

III.1.3 Fire suppression system

The test room shall be equipped with a Halon 1301 fire suppression system representative of the aircraft system architecture.

The fire suppression system shall comprise a high-rated discharge container and a flow-metered container.

The fire suppression system shall deliver a halon mass equally to a commercial aircraft of comparable cargo compartment volume.

The fire suppression system shall be able to be triggered manually.

The weight of Halon Bottle 1 and Halon Bottle 2 shall be continuously monitored during the tests (see description in Figure 2).

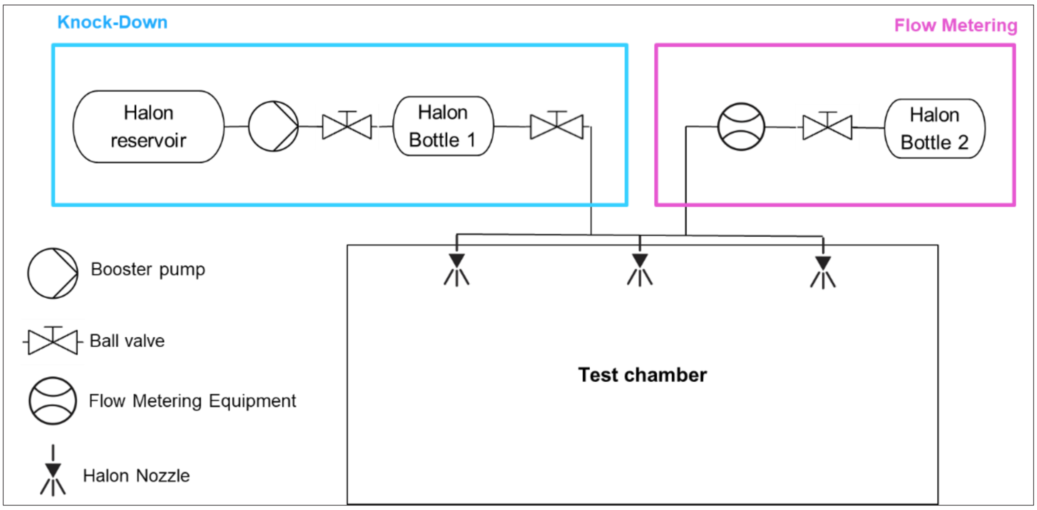


Figure 2: Schematic of the Halon Discharge system of the test chamber

III.2 Test specimen

III.2.1 Lithium ion cell selection

The cells to be tested are standard 18650 lithium ion rechargeable cells. More details related to the cell selection are available in the deliverable D2a.

Two different cell brands have been selected to represent a random mix. The cells underwent successfully the UN38.3 tests. The technical specification of the cells are as follows:

Brand	Manufacturer 1	Manufacturer 2
Nominal Capacity (based on manufacturer Datasheet)	3500mAh	3500mAh
Chemistry	$LiNiCoMnO_2$	$LiNiCoAlO_2$
Dimensions	18650	18650
SOC	50%	50%

III.2.2 Cell packaging

The battery packaging shall be representative for commercial shipment. The 2 cell manufacturers Manufacturer 1 and Manufacturer 2 use slightly different packaging philosophies.

III.2.2.1 Manufacturer 1 cells packaging

The Manufacturer 1 cells we received were packed in cardboard boxes of 100 cells each. In an arrangement of 10x10 (see Figure 3). In the picture some cells were missing because they were taken out for some voltage checks. Every cell is isolated The separators between the cells are made out of a thin cardboard paper. 2 of these boxes are stacked on top of each other in one outer box made of corrugated cardboard. This outer box contains the hazardous materials labeling. The two inner boxes didn't contain any label

Figure 3: Manufacturer 1 cells packaging (the missing cells were taken to do some voltage checks). On the right a close up picture showing the separation between the cells.

III.2.2.2 Manufacturer 2 cells packaging

Manufacturer 2 cells were packed in cardboard boxes of 100 cells each (see Figure 4). The cell rows are separated in one direction by a thick corrugated cardboard and in the perpendicular direction the cells are separated two by two by a thinner cardboard (see right hand picture in Figure 4).

2 of these boxes are stacked next to each other in one outer box made of corrugated cardboard. Only this outer box contains the hazardous materials labeling.

Figure 4: Manufacturer 2 cells packaging. On the right a close up picture showing the separation between the cells.

III.2.3 Fire load

The fire load for this scenario consists of single-wall corrugated cardboard boxes, with nominal dimensions of 45.7 by 45.7 by 45.7 cm (18 by 18 by 18 inches). The weight per unit area of the cardboard is 0.5417 kg/m^2 (0.11 lb/ft^2). The boxes are filled with 1.1 kg (2.5 pounds) of loosely packed standard weight office paper shredded into strips (not confetti), see. The final weight of the box and shredded paper is 2.0 ±0.2 kg (4.5 ±0.4 pounds). The boxes are conditioned to room standard conditions. The flaps of the boxes are tucked under each other without using staples or tape. The boxes are stacked in two layers in the cargo compartment in a quantity representing 30% of the cargo compartment empty volume. For a 56.6m^3 (2000-cubic-foot) compartment, this requires 178 boxes. The boxes touch each other to prevent any significant air gaps between boxes.

Figure 5: Cardboard Box filled with shredded paper

The ignition process shall be in accordance with [2]. An ignition box shall be prepared as shown in Figure 6.

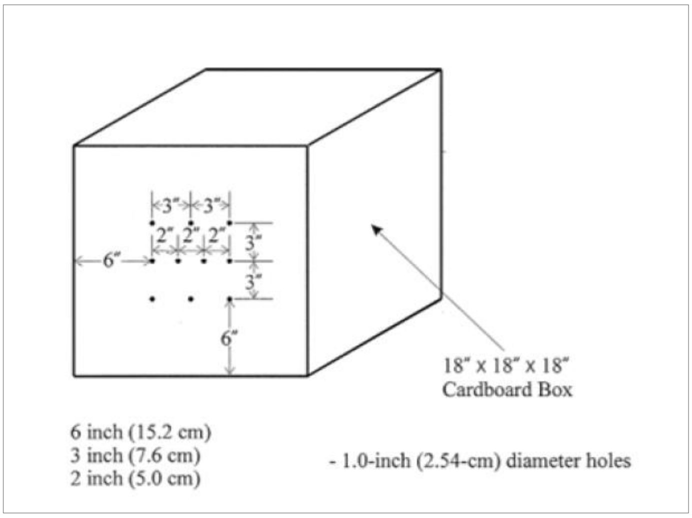


Figure 6: Ignition Box

The fire inside the ignition box is started by applying 115 volts alternating current (VAC) to a 2.1m (7 foot) length of nichrome wire. The wire is wrapped around four folded (in half) paper towels.

The resistance of the nichrome igniter coil is approximately 7 ohms. The igniter is placed into the center of a box on the bottom outside row of the stacked boxes. Several ventilation holes are placed in the side of the box to ensure that the fire does not self-extinguish.

The configuration of the cardboard boxes and the position of the ignition box shall be adopted to the needs of this test.

III.2.4 Pallets and Fire Containment Covers

A standard PMC pallet (dimensions: 96in/243.8cm – 125in/317.5cm) shall be used. The fire containment cover shall have a height of 162.56cm (64in). The fire containment cover (FCC) shall be fixed to the pallet during the test as shown in Figure 7. Refer to [3] for a technical data sheet of the FCC.

Figure 7: FCC mounted on PMC pallet

III.2.5 Thermal Insulation

As thermal insulation, Insulfrax LTX blankets shall be used. Refer to /4/ for a technical data sheet.

III.3 Measurement instrumentation

III.3.1 Compartment Temperature and oxygen measurement

III.3.1.1 Temperature sensors

As temperature sensors type K thermocouples (NiCr-Ni) shall be used and be evenly distributed within the test chamber.

III.3.1.2 Oxygen Sensors

Oxygen sensors shall be evenly distributed within the test chamber.

III.3.1.3 Temperature and oxygen Sensor location

The temperature and oxygen sensors shall be evenly distributed in the test chamber. As minimum temperature sensor configuration, the setup used for the MPS tests according to [2] shall be used (see Figure 8).

Figure 8: thermocouple and oxygen sensor location in the test

III.3.2 Battery Box Temperature measurement

III.3.2.1 Temperature Sensors

As the temperature inside the cells shipment boxes shall be monitored and some type K thermocouples shall be mounted on some cells.

III.3.2.2 Temperature Sensor location

2 temperature sensors shall be installed in the ignition cardboard box.

Temperature sensors shall be installed in the cardboard boxes adjacent to the cells box.

Temperature sensors shall be installed in the cells boxes under test in a way to be able to estimate the thermal propagation within one box and between different boxes.

One temperature sensor shall be installed directly on the cells package closest to the fire ignition source. This sensor shall deliver the temperature to be used as a trigger criterion for the Halon discharge.

III.3.3 Halon Measurement

III.3.3.1 Halon Sensors

12 Halon Sensors shall be evenly distributed within the test chamber. Halon measurement shall be based on Non-Dispersive Infra Red NDIR spectroscopy.

Functioning principle of NDIR spectroscopy: The main components of an NDIR sensor are an infrared (IR) source (lamp), a sample chamber or light tube, a light filter and an infrared detector. The IR light is directed through the sample chamber towards the detector. In parallel there is another chamber with an enclosed reference gas. The gas in the sample chamber causes absorption of specific wavelengths according to the Beer–Lambert law, and the attenuation of these wavelengths is measured by the detector to determine the gas concentration. The detector has an optical filter in front of it that eliminates all light except the wavelength that the selected gas molecules can absorb. This wavelength is optimized and calibrated by the sensor manufacturer to detect Halon 1301.

III.3.3.2 Halon Sensor location

The Halon sensors shall be located in a setup comparable to the sensor location typically used for aircraft flight testing (see Figure 9). 8 Sensors shall be located 20 cm below the ceiling in order to estimate the distribution on this level. Additionally, 20 cm distance from the sidewalls shall be kept.

4 Halon Sensors shall be located 20 cm above the floor.

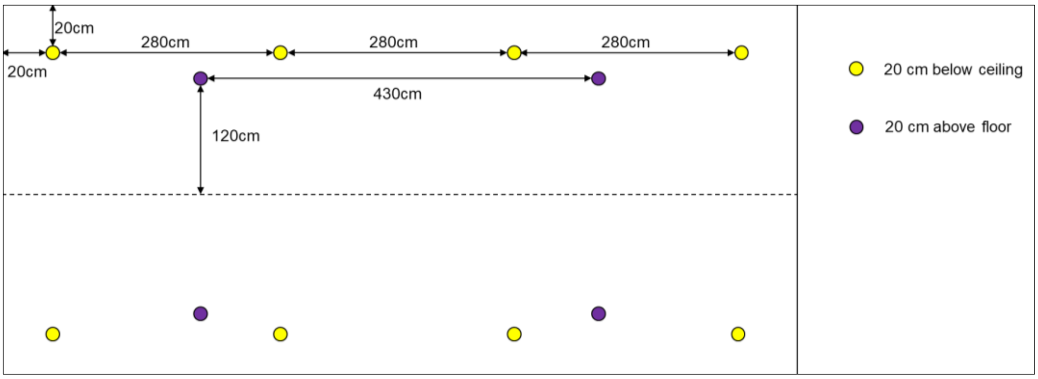


Figure 9: Halon Sensor location

III.3.3.3 Halon Sensor calibration

To achieve the maximum measurement accuracy of the NDIR Halon Senor, a regular check of the calibration values and eventually a re-calibration of the device is recommended. The Sensor is factory-calibrated to the span value (100% Halon) and the zero value. If during the check with the test gas, a difference in the span value is detected, a calibration of the zero value shall be performed. For further information refer to the data sheet of the NDIR Sensor (Infrarotmodul GS IRM 100 – Halon 1301, Manufacturer: GS Messtechnik, Ratingen, Germany).

III.3.4 Video capturing

Two video cameras shall be located in the compartment in such a manner that an optimum view to the ignition box and the cells boxes is provided.

Either the interior of the test chamber shall be illuminated or the video cameras shall be equipped with integrated illumination (*e.g.* infrared)

The video camera system shall be able to record the absolute time. The internal time of the video system shall be synchronized with the time stamp of the data acquisition system (Temperature, Halon concentration, oxygen concentration)

III.3.5 Pressure measurements

The pressure shall be measured inside the FCC (pressure difference between "under the FCC" and the test chamber).

The pressure shall be measured inside the compartment (pressure difference between the inside of the test chamber and the ambient surrounding).

Chapter IV: Test Program

IV.1 Cold Test

A cold test (without initiating fire) shall be performed to verify that the Halon concentration at every measurement point is above 3% after 360 min.

The amount of Halon to be discharged from the high rated system part shall be 25kg. This corresponds to a representative system installed on commercial aircraft of comparable compartment size to the measurement chamber. The amount of Halon to be used for the high rated system part has been calculated by the Airbus system design office.

The flow metering equipment with a pre-set flow rate of 6l/s shall be used to provide the flow-metered part.

Pass-fail criterion: The Halon concentration at every sampling point is equal or above 3%.

IV.2 Commissioning test

The objective of the test is to determine the minimum duration of the flame exposure to initiate some heat generation inside the box filled with cells.

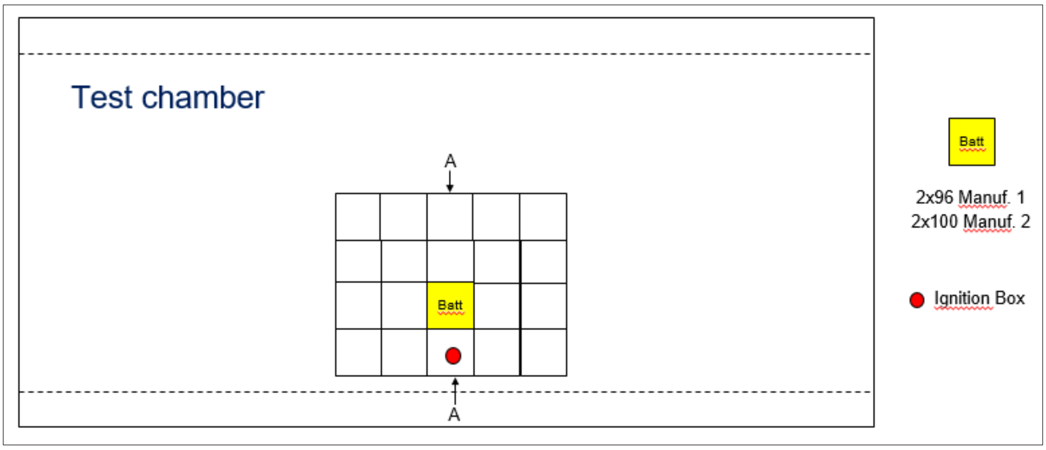
392 cells (200 Manufacturer 2 and 192 Manufacturer 1) are placed in proximity of the ignition box.

The cardboard boxes shall be arranged in 2 layers of 5x4 matrix. One line of cardboard boxes shall be placed in between the ignition box and the cell boxes (see Figure 10). The cell boxes shall be placed on top of a supportive structure to avoid that the cells falls on the ground in case the bottom box burns.

The ignition shall be started in accordance to [2].

The fire suppression system shall not be activated.

Pass-Fail criterion: At least one temperature reading inside a cell box shall exceed 80°C.



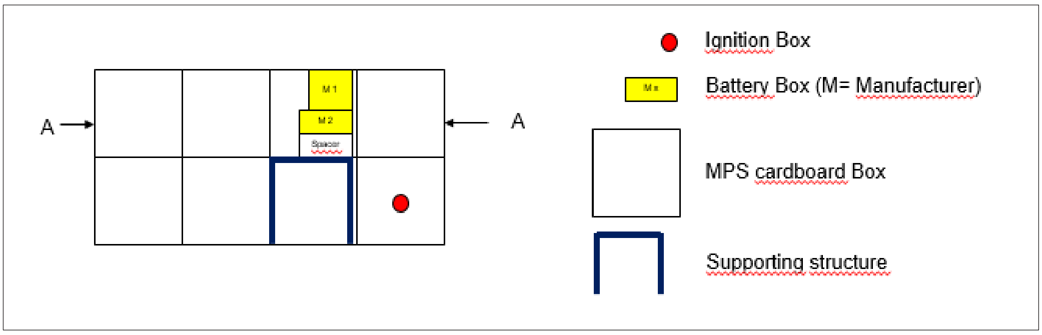


Figure 10: Test setup for the commissioning test top view and side view

IV.3 Halon Baseline Test

The ignition box and cell box positioning shall be similar to the cold test. However, the setup with the large pallet requires more cardboard boxes.

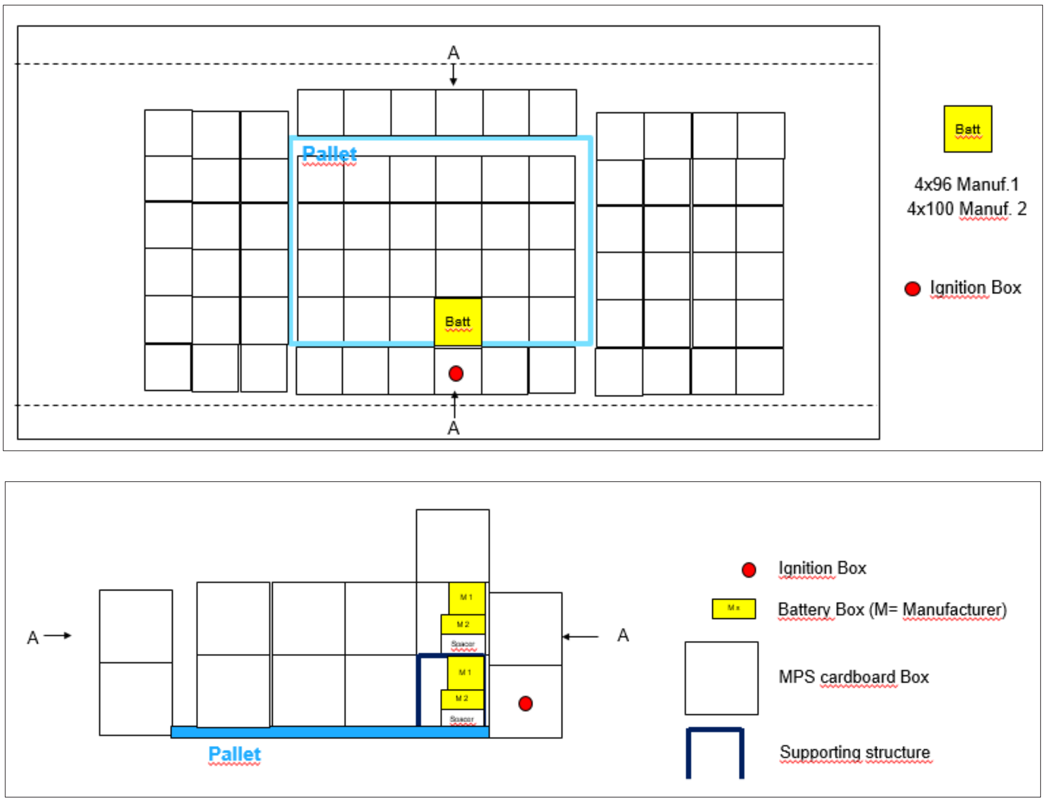


Figure 11. Test setup for the Halon test top view and side view

For the Halon test, 800 cylindrical cells (2 boxes of Manufacturer 1 batteries and 2 boxes of Manufacturer 2 batteries) shall be used.

In proximity to the fire source, 3 layers of cardboard boxes shall be applied in order to better accommodate the physical shape of the FCC in the consecutive tests.

Test sequence:

- Start the ventilation system
- Ignite the ignition box

- Record the time when the temperature readings inside 2 different battery boxes exceed 80°C
- Stop the ventilation system
- Wait for 60sec
- Start the Halon Fire Suppression System
- Continue the test and record the data for another 180 minutes

Pass-Fail criterion: No batteries in thermal runaway

IV.4 FCC/ Halon Test

The objective of this test is to assess the effectiveness of the Halon suppression system combined with a FCC to mitigate a battery fire.

The second objective is to investigate the thermal propagation through the cells inside a box and through adjacent cell boxes. So ideally the flame exposure should be long enough to heat up some cells inside the boxes.

For the FCC/Halon test, the test program used for the Halon test shall be applied.

Additionally, the pallet shall be fully covered with the FCC.

Pass-Fail criterion: No cells in thermal runaway

IV.5 FCC / Halon / Thermal insulation Test

The objective of this test is to assess the effectiveness of the Halon suppression system and the FCC complemented with the thermal isolation cover to suppress the cells fire, if any, and to stop the heat propagation inside the cells' boxes.

The FCC has the primary function to prevent direct impingement of the cells by the external fire but has limited thermal insulation capability. Therefore the objective of the test is to investigate if a thermal isolation cover is enough to stop the heat propagation to and between the cells' boxes.

For the FCC / Halon / Thermal insulation test, the test program used for the Halon test (para 5.3) shall be applied.

The test program used for the Halon test shall be applied.

Additionally, the pallet shall be covered with a FCC.

Pass-Fail criterion: No batteries in thermal runaway

IV.6 Test Documentation

To achieve an optimum recording describing the test output, every test run shall be at least documented as follows:

- Plots of the measurement data for Halon and oxygen concentration and readings of all temperature and pressure sensors as described in §III.3.1, §III.3.2, §III.3.3 and §III.3.5
- Video capturing over the entire test duration as described in §III.3.4. The location and field of view of the video cameras shall be documented in the test report

- Documentation by photographs of every test setup. Especially the pre- and post test conditions shall be captured
- Achievement of pass-fail criterion

Bibliography

[1] SAFO - Safety Alert for Operators 10017, U.S. Federal Aviation Administration, Flight Standards Service Washington, DC, October 2010

[2] Minimum Performance Standard for Aircraft Cargo Compartment Halon Replacement Fire Suppression Systems (2012 Update), U.S. Federal Aviation Administration, DOT/FAA/TC-TN12/11, May 2012

[3] AmSafe Bridport FCC Data Sheet_AC80-0319111

[4] Insulfrax LTX Product information sheet, Form U-216, Effective 1/18, © 2018 Unifrax I LLC