DEVELOPMENT OF A TESTING PROCEDURE TO EVALUATE THE PERFORMANCE OF AVIATION FIRE CONTAINMENT SOLUTIONS FOR LITHIUM-ION BATTERY FIRES

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Degree of Master of Engineering in Manufacturing Systems Engineering

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DECLARATION

I declare that this is my own work and this thesis does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or institute of higher learning and to the best of my knowledge and belief, it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

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Name of the supervisor: Dr. L. U. Subasinghe

Signature of the supervisor: Date: 05/12/2022

ABSTRACT

Fire containment is an important element within the air cargo industry when transporting lithium-ion batteries (LIBs). Existing fire suppression systems and fire detection methods used in aircraft are seen as incapable of preventing fires that are originating within the Unit Load Devices (ULD) especially fires originating inside ULD containers. Halon based fire extinguishing systems presently available in aircraft cargo compartments are not enough to put down lithium-ion battery fires. The development of Container Fire Containment Covers (CFCCs) is a latest innovation that has a large impact on the safety of both passenger and freighter aircraft. CFCCs which use a passive fire suppression system are becoming a global norm that can be used to protect each individual ULD container separately and prevent fire from spreading to the adjacent cargo loads. However, there is a lack of evidence on an experimental method to determine the capability of industrial fire containment solutions used in aircraft for containing LIB fires initiated inside ULD containers. Therefore, this study proposes an experimental test method to evaluate the fire containment performance of CFCCs under a LIB fire. The fire containment capability of CFCC designs developed for two different ULD container configurations (AKE and AMJ) are assessed using the developed test method with 2000 and 5000 18650-sized LIB cells respectively with each CFCC design validating the test method. The condition of the ULD containers is also assessed to guide container manufacturers on damages caused by a LIB fire. The results and observations of the fire tests show that ULD containers alone cannot withstand a LIB battery fire and the CFCCs are capable of containing a LIB battery fire for the tested magnitude. Based on the results CFCCs can be considered an acceptable solution to safely transport LIB shipments in commercial aircraft.

Keywords: Fire containment, Lithium-ion battery fire, fire tests, Fire containment cover

DEDICATION

I am dedicating this thesis to two beloved people who have meant and continue to mean so much to me. Although they are no longer of this world, their memories continue to regulate my life. First, to my maternal grandfather, Austin Dias whose love for me knew no bounds and, who taught me how to patiently achieve goals in life. And to Rev. Fr. Bonnie Fernandopulle who taught me the value of hard work and the need for a good education to live a good and happy life. May you both find peace and happiness in heaven.

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Secondly, the lecture panel at University of Moratuwa, who guided me throughout my MEng. All the lecturers who have supported me in their areas of expertise.

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Finally, I should remind the MEng batch 13 members who supported me to come to the end of the program.

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LIST OF ABBREVIATIONS

Abbreviation	Description
AS	Aerospace Standard
BOI	Board of Investments
CFCC	Container Fire Containment Cover
EASA	European Union Aviation Safety Agency
FAA	Federal Aviation Administration
FCB	Fire Containment Bag
FCC	Fire Containment Cover
FRC	Fire Resistant Container
HDPE	High-Density Polyethylene
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
PFA	Perfluoroalkoxy
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analysis
SAE	Society of Automotive Engineers
SOC	State of Charge
T&C	Touch and Close
ULD	Unit Load Device

CHAPTER 1 INTRODUCTION

This chapter describes the background on the use of LIBs and introduces the need for fire containment solutions to transport LIBs on-board aircraft. It also introduces the need for large full-scale burn testing of LIBs and relevant test procedures to evaluate the performances of fire containment solutions. Further, it consists of the aim and the objectives of the research. Finally, it describes the structure of the thesis.

1.1 Background

With the exponential increase of science and technology and industrialization, significant growth in the use of LIBs is seen since the 1990s [1]. These batteries have become the choice of energy storage for almost all portable electronic devices [1]. LIBs, as the main technology used in electronic devices (such as smartphones, cameras, tablets, and laptops), play an important role in the quality of life in modern society. In addition to this field of application, LIBs are the first choice in the field of emerging electric vehicles, but the usage of LIBs in the power generation sector is still questionable, especially in solar and wind power. As an integral part of this technology, LIBs have the potential for sustainable energy development and a significant reduction in carbon emissions in global scale [2]. With the current rate of expansion in the market, it is seen that the global LIB market to rise to $129.3 billion by 2027 with just $36.7 billion in 2019 [3]. Figure 1-1 illustrates the exponential increase in the revenues of the global lithium-based battery market which explains the increasing use of lithium-based batteries globally.

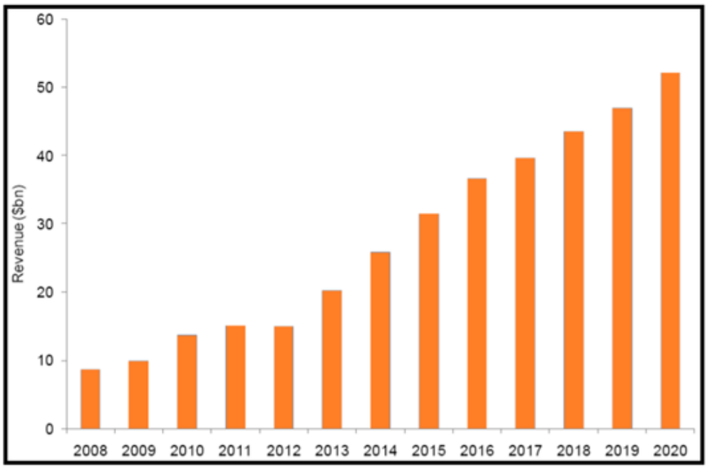


Figure 1-1: Revenues of the global lithium-based battery market [4]

With the rise of demand for various applications as mentioned above, volume of raw materials and parts that need to be manufactured will also rise exponentially. Therefore, with today's changing global market manufacturers all around the world are trying to transport more and more LIBs by air which is the fastest option. Some supply chain management experts state that it is a very smart business move to use air freight in the rapidly changing global market and also using a multimodal shipping provider brings many advantages to the process, especially along the lines of the mode-neutral relationship [5].

In the current market, Cathay Pacific, UPS, and Emirates are a few of the major airliners carrying dangerous goods, especially a significant number of LIBs. The increase and development in the E-commerce market have opened many opportunities but pose a threat as the amount of undeclared cargo which includes LIBs has increased to a very high amount. Although there are rules and regulations in place to declare dangerous goods, millions of small individual shipments are unable to be handled with the pace of the daily cargo movement.

There are a significant number of incidents involving LIB fires that have caught the attention and have been reported over the past decade. From previous surveys, it has been found that fires and explosions involving LIBs rarely occur, ranging from one part per million to one part per 10 million batteries [6]. However, these widespread incidents still raise concerns for customers and end-users, forcing them to recall millions of expensive batteries [6].

There have been significant aircraft accidents in the past ten years where lithium batteries have been involved [7]. These accidents have raised serious red flags about LIB transportation through air. Table 1-1 lists the three biggest accidents involving Lithium batteries within that period.

Table 1-1: Most significant aircraft accidents due to LIBs [7]

	Accident #1 B744 Jeju	Accident #2 B744 Dubai	Accident #3 DC-8 Philadelphia
Lithium batteries on board	Yes	Yes	Yes
Declared?	Yes	No	Yes
Hull loss	Yes	Yes	Yes
Fatalities (as a % of total crew)	2 (100%)	2 (100%)	0 (0%)
Phase of flight	Early cruise	Early cruise	Descent
Time into flight	50 min	22 min	2 h
Time to uncontained fire	17 min	23 min	27 min 45 s

The first accident was a result of a fire caused within the cargo compartments where the dangerous goods are stored including LIBs. In the second incident, it was concluded that the accident was caused due to a fire that propagated in a container that contained thousands of LIBs. The third incident occurred as a result of fire spreading over to the lithium batteries [7]. Apart from these major accidents, there are multiple fires reported inside the aircraft ranging from the cargo belly to the passenger cabin [8].

The aforementioned incidents show that there is a huge impact on the air freight industry from Lithium batteries which need to be given solutions, especially from a fire containment point of view to move forward with the growing economic markets. The unpredictable nature of LIBs raises the question about the safety of transporting batteries through airfreight especially on passenger aircraft with multiple hundreds of passengers on board. By analysing the fire hazard of the LIBs, the safety margin can be increased and it helps offer guidance to facilitate safe handling.

1.2 Motivation

A new design concept that was developed rooting to FCCs is the CFCC. Unlike the FCCs which are used to contain and isolate fires on individual palletized cargo loads [9], CFCCs are used to contain fires that occur within ULD containers and are specially designed with the hope of containing LIB fires preventing the fire from spreading to adjacent cargo loads. Even though authorities like the FAA have done large scale LIB testing to evaluate the impact of LIB fires [10], limited literature was found on testing conducted incorporating FCCs and CFCCs to evaluate their fire containment capability to contain LIB fires. This leaves a question on the extent to which the developed fire containment solutions can contain a LIB fire on-board an aircraft.

As per the available literature, there is also no proper test method defined to measure and evaluate the fire containment capability of CFCCs as per the aviation standards and regulations. Some of the reasons for the lack of literature in this area are because conducting these sorts of experiments requires a large amount of expenditure and there are many technical difficulties when conducting fire tests ranging from LIB fire ignition issues to battery sourcing and logistics. There are also special considerations when disposing of battery waste that have to be discussed with local environmental agencies. Therefore, conducting large scale LIB fire testing is mostly limited to governing bodies and very hard for an independent researcher to move forward with unless there is any source for funding.

With the availability of funding from a leading airline, the scope of this study is to develop and standardize a test method to evaluate the performance of CFCCs during a LIB fire. The scope further extends in performing full-scale LIB fire tests on two selected CFCC designs to validate the derived test method and to evaluate the fire containment capabilities of the two developed CFCC designs with the intention of bridging the aforementioned research gap.

1.3 Aim and objectives

1.3.1 Aim

To develop a test method to analyse the thermal performance of a CFCC in a LIB fire scenario within a ULD container.

1.3.2 Objectives

1. Ascertaining current knowledge and identifying key parameters such as ULD container dimensions, contours, and location within the aircraft, LIB fires, LIB battery quantities within shipments, existing fire containment solutions in aircraft,

and minimum performance standards required by fire containment solutions used in aircraft.

2. Developing a test method to evaluate the temperature inside and outside ULD containers, the ability to withstand a LIB fire for a required amount of time when CFCCs are used, and the potential damages that can be caused to ULD containers through the propagation of a LIB fire.

3. Performing full-scale fire tests with LIBs stored in ULD containers.

4. Analysing observations and results and, validating the testing procedure according to aviation standards.

1.4 Structure of the thesis

Chapter 1 describes the background on the use of LIBs and the need for fire containment solutions in the air cargo industry, the motivation for the study and the research aim and objectives that are to be achieved. Finally, it describes the overview of this thesis.

Chapter 2 presents the literature review. This section initially describes the basic characteristics of LIBs and their uses. Then it explains the thermal runaway characteristics and propagation using previous experimental studies. Then it explains the different effects at various State of Charge (SOC) as per various experiments conducted and the temperature ranges obtained at different fire tests. The next section describes aircraft regulations on transporting LIBs and the existing fire suppression systems used in the aircraft. Finally, it discusses large scale fire testing done with LIBs.

Chapter 3 describes the methodology of the research where the pathway to fulfilling the objectives is discussed. It then discusses the data collection methods and mapping them to the research objectives of this study. Finally, it discusses methodology and related findings that are to be used to fulfil the different objectives listed above.

Chapter 4 gives an overview of the CFCC explaining the product. Next, it describes the test equipment, test methodology, test setup, and the parameters on which full-scale testing is done during this research.

Chapter 5 consists of the results and discussion which includes the temperature readings, observations during the test, and the post-test observations on the CFCC and the container as well as the cargo load.

Chapter 6 consists of the conclusions of the research. The chapter describes the research summary followed by the contributions to knowledge and practice. Research limitations that were faced during the study are then pointed out and finally, further research directions are proposed.

CHAPTER 2 LITERATURE REVIEW

This chapter identifies and describes the literature from various publications relevant to this research to develop a test method to evaluate the performance of fire containment solutions in a LIB fire scenario. It reviews various factors from battery characteristics and existing fire containment solutions to aircraft regulations on carrying LIBs which are required to be considered when developing the test method.

2.1 Lithium-ion battery fires

The 18650-sized cylindrical LIB is 18 mm in diameter and 65.2 mm in height. It is considered a common standard as they are widely being used on many devices as most applications are designed to host 18650-sized LIBs. Similar to AA, AAA, C, and D alkaline primary batteries commonly used in flashlights, toys, and radios which are used only once, the 18650-sized LIBs can be found in majority of the rechargeable applications. These range from electric vehicles (one car will use thousands of 18650-sized batteries) to power tools, laptops, personal electronic devices, and medical equipment. For example, NASA has used 18650-sized cells in the design of the spacesuit [11].

Unlike alkaline primary batteries, LIBs are highly vulnerable to thermal abuse. Overheating, overcharging, short circuit, puncture, compression, or crashing are abnormal operations where the thermal runaway can occur and can propagate to the adjacent LIB modules and packs which can result in fire and explosions [12]. Thermal runaway in LIBs is caused by exothermic reactions that occur involving the electrolyte, anode, and cathode where the temperature and pressure keep increasing and at a certain point the battery will rupture [6].

A battery cell that has gone into thermal runaway reaches temperatures more than 600 ^{0}C [13]. This means that it will surpass the combustion temperatures of the surrounding materials which are used for packaging the batteries during transportation including paper and cardboard. LIBs going into thermal runaway are more dangerous and raises safety concerns even when they are stored in ULD containers because the melting point of aircraft aluminium is around 500 ^{0}C to 640 ^{0}C [13]. The larger quantities of

LIBs that will be transported in a single shipment have more than the capability of damaging the structure of the aircraft [13].

A study that had been conducted on 18650-sized LIBs with three different cell types having different chemistries shows that each of the battery types has its unique thermal runaway characteristics for different chemical compositions. The experiment was performed by deliberately sending the batteries to thermal runaway. A maximum surface temperature of 850 ^{0}C was observed during the experiment on battery cells consist of the cobalt-rich LCO/NMC cathode [14]. The temperature profile for each cell chemistry is illustrated in Figure 2-1.

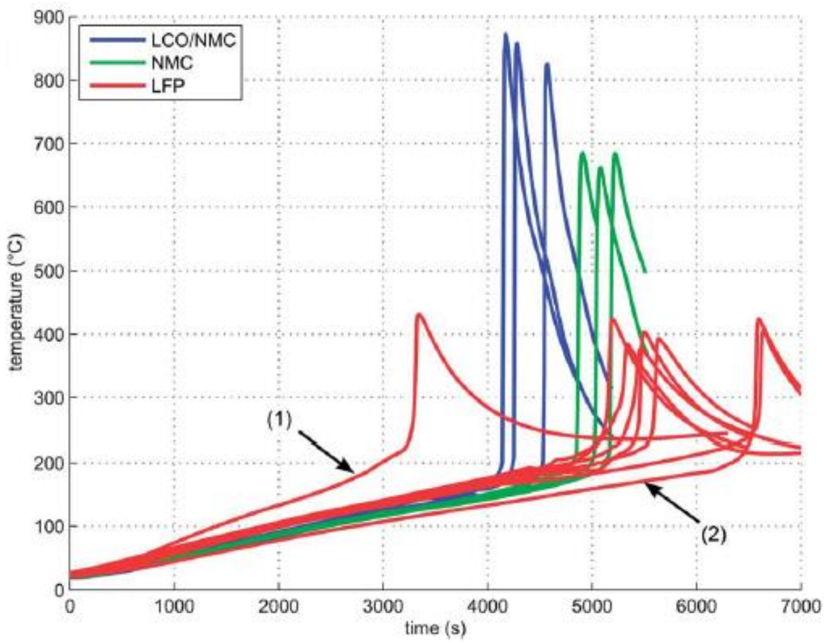


Figure 2-1: Surface temperature variation with cell type [14]

Here,

LCO - Lithium Cobalt Oxide ($LiCoO_2$)

NMC - Lithium Nickel Manganese Cobalt Oxide ($LiNi_xMn_yCo_zO_2$)

LFP - Lithium Iron Phosphate ($LiFePO_4$)

Note: x, y, and z in NMC represent different molar ratios

These experimental data are deemed valuable for studies focusing on developing fire containment solutions to substantiate the developments using full-scale burn tests.

Especially in justifying the type of cells that can give out the worst-case scenario and also have a basic idea of the surface temperature ranges during LIB thermal runaway.

LIB fire behaviour can be categorized into the following five different stages: White smoke releasing, ignition, combustible solids and liquid droplet ejection, stable combustion, and extinguishment [15]. The white smoke releasing stage is especially crucial when it comes to fire detection as it will help activate the smoke sensors within the cargo compartments. This characteristic can also be taken into consideration when designing fire containment solutions. There is a huge impact on the behaviour of lithium battery fires related to altitude [15]. Lithium batteries tested at lower altitudes have more energetic exothermic reactions of the electrodes with the electrolytes and thus more heat and gas will generate making the explosion much easier to occur [15]. The heat release rate, mass loss, combustion efficiency, combustion heat and heat flux is much higher at lower altitudes making lithium batteries more dangerous [15].

Another important factor affecting the thermal runaway of LIBs is the SOC. This is an important parameter to consider especially in the process of developing fire protection systems [15]. Table 2-1 illustrates the variation of time to ignition and the time to explosion with respect to varying SOC.

Table 2-1: 18650-sized LCO/graphite LIB ignition and explosion time for different SOC [16]

Incident heat flux (kWm^{-2})	SOC (%)	Time to ignition (s)	Time to explosion (s)
50	100	40	81
50	70	83	156
50	65	131	200
50	50	49	No explosion
50	0	72	No explosion
30	100	157	182
60	100	17	55

It is seen that the time to ignition is low at 50% SOC when compared to batteries at 65% and 0% SOC under the same incident heat flux. Another important characteristic is that batteries from 0% to 50% don't explode. This is very crucial to understand if any level of puncture resistance is required for the materials used for the fire containment solutions. However, there may be cases where violent explosions can occur where the cap assemblies of the LIBs are ejected with large amounts of gas released followed by the ignition of the disintegrated battery pieces [16].

Various LIB abuse tests have been conducted to study and improve the safety of LIB shipping methods [13]. The standard method used by battery manufacturers to transport batteries is in cardboard boxes containing 100 cells in each box [13]. A recent step taken to minimize thermal propagation between batteries is using interlocking cardboard separators between each cell as shown in Figure 2-2 [13].

Figure 2-2: Shipping box with interlocking cardboard separators [13]

From a previous full-scale burn test study that was conducted on a 50 Ah LFP/graphite battery module composed of five single 10 Ah cells, it was observed that the surface temperatures of the batteries reach approximately around 180 ^{0}C during thermal runaway and the maximum flame temperature reach to about 1500 ^{0}C [17]. The highest flame temperatures occurred within an area of 100 mm from the battery surface. The typical distance between batteries or battery modules is much smaller than 100 mm. Therefore, when a battery or battery module goes into thermal runaway, the potential for the adjacent batteries also to overheat and go into thermal runaway is very high [17]. By comparing this research with the study of using interlocking cardboard separators it can be seen that the cardboard separator mechanism is not much of use once batteries start going into thermal runaway. However, to make things worse it is seen that not all battery manufacturers use at least this sort of separation mechanism to reduce the potential of batteries going into thermal runaway.

2.2 Aircraft regulations on transporting LIBs

Two of the main transportation bodies which regulate dangerous goods transportation by air are the International Air Transport Association (IATA) and the Federal Aviation Administration (FAA). The regulatory bodies have implemented restrictions that are based on the existing solutions available when transporting LIBs and various safety measures and precautions are to be taken to ensure the safety of both the aircraft and the crew preventing any sort of fire hazard [18].

One of the most important areas within an aircraft is the cargo compartment. During flight, the cargo compartment is mostly inaccessible however there can be combustible materials that may or may not be categorized as dangerous goods inside passenger luggage. Even though the probability of fires that could happen in a flight is low, the consequences of even a small fire could be disastrous. FAA and other regulatory authorities representing all countries require mandatory fire detection and suppression systems equipped within the cargo compartments to immediately suppress and control the fire incidents and also to warn the crew about the situation [19].

Some of the mandatory requirements for fire suppression are as follows.

- Any fire that occurs within the cargo must be contained within the cargo
- The increase in temperature due to the fire should not affect the integrity of the aircraft structure
- The smoke generated through the fire cannot cause any hazard to the occupied areas [19]

Moreover, temperature constraining clauses such as “the temperature four (4) inches away from the cargo should not be more than 204 ^{0}C” are stated in the SAE AS6453 standard for fire containment covers [20].

With the technological advancements that are happening in the high energy density lithium battery industry and as a result of various fire and explosion incidents related to LIBs, the regulations that govern the transportation of LIBs keep changing dramatically. The International Civil Aviation Organization (ICAO) which is the United Nations agency that regulates the transportation of dangerous goods has put a ban on carrying standalone LIBs as cargo on passenger aircraft, implemented from April 2016 [21] as the risk was too high and ideal solutions were not in place. The SOC of a LIB should be 30% or less so that it can be transported by air, which is applicable to all cargo aircraft [21]. The value of 30% has been tested and approved as the peak heat released with this SOC is approximately equivalent to a battery cell with 0% SOC [22].

SAE AS6453 standard [20] specifies the testing methods and the minimum design and performance criteria of FCCs. According to it, the FCCs are required to contain a fire for 6 hours so that the aircraft can be landed safely in case of a fire emergency.

2.3 Fire suppression systems and methods used in aircraft

The existing fire detection and suppression systems are installed on the ceiling of the aircraft at specific locations. Although it is easy to check and maintain the fire detection and suppression system at fixed positions on a compartment-based system some disadvantages can be very costly. The undeclared goods containing LIBs that go in passenger luggage are placed within cargo containers are usually the origins of the fire. A fire can be initiated from a LIB going into thermal runaway inside passenger luggage and could eventually spread and ignite the surrounding combustible materials including fabrics, cardboard, and polymers. Only a very little smoke is leaked through the ULD containers even though there is a massive fire occurring inside it. Taking these types of issues into consideration, currently, a very sensitive smoke detection threshold has been set [19] which eventually causes the number of false alarms triggered by even small airborne particles to be very high. Since the cargo compartment is non-accessible raising false alarms will have severe consequences like flight diversion, emergency declaration and passenger evacuation, compartment inspection, passenger disappointment and most importantly no-confidence in the warning system. Research has been carried out to develop a container-based fire detection and suppression system with the aim of reducing false alarms by checking the feasibility of the application and suitability for various fire scenarios through qualitative analysis [19]. The relevant certification standards and specification is still in the development stage. Oxygen starvation inside the ULD container is another possibility to suppress a fire [19].

Most airlines at the moment are looking into transporting LIBs within the Class C (a cargo or baggage compartment that is not accessible to crewmembers) cargo compartments [13] restricting the batteries to only that particular area where the fire can be mitigated. However, by this way, the hazard is still not eliminated. The Halon 1301 fire suppression system which is available in the Class C cargo compartments has proven its capability and effectiveness with regard to fires involving LIBs with the burning electrolyte [13]. Halon 1301 (Bromotrifluoromethane) fire suppression system decreases the chances of ignition of adjacent cargo especially if they are flammable materials. However, this method is not effective to stop batteries that have gone into thermal runaway [13]. Because of this, the cells adjacent to the ignited battery will also go into thermal runaway and this will eventually propagate to the entire shipment. As discussed earlier previous studies have shown that LIBs going into thermal runaway can cause some cells to explode by also increasing the pressure within the cargo compartment. It is sufficient for the overpressure devices within the cargo compartment to get activated even if the pressure is increased by even 1 psi [13]. In this scenario, the Halon 1301 filled in the area will be lost making the cargo more vulnerable to any open fire [13].

Commercial air cargo is carried in the cargo holds of passenger and freighter aircraft located at both upper and lower decks [13]. Class E (a cargo compartment used only for the carriage of cargo on cargo aircraft) cargo compartments are located on the main deck and classified only for freighter aircraft which are used only for the transportation of cargo [23]. Similar to Class C cargo compartments located on the lower deck of the aircraft, the design principle is to suppress a fire and not extinguish it [23]. Various measures have been taken in terms of mitigating a potential fire that can cause by general commercial cargo. With the large volumes of cargo being transported, even the general cargo needs to be safe, and innovations are required to suppress and contain the fire to a single unit. An innovative solution that was developed over the years is the FCC which enables to isolate each palletized cargo load separately and prevents fire from spreading to the adjacent cargo loads.

Committing to the air cargo transport industry requirement with regard to transporting undeclared dangerous goods, companies such as “AmSafe Bridport” and “Newtex” have stepped up and developed FCC solutions that can especially isolate and suppress the fire through oxygen starvation without further spreading [9]. The FCCs are able to withstand temperatures up to 1500 ^{0}F (815 ^{0}C) [9]. There are developed solutions that can withstand heat and explosions that are caused by the thermal runaway of LIBs [9] on a smaller scale. FAA has independently tested the Fire Containment Bags (FCBs) of AmSafe Bridport and has proven that it can withstand a fire of 1000 LIBs [24]. The tests that were conducted by the FAA used 18650-sized LIB cells and had the SOC at 30%. AmSafe Bridport has also conducted fire testing with their TSO-C203 certified FCCs [25] with 1500 18650-sized LIBs [26] which has helped to push aviation safety boundaries. Further, it has been identified that this kind of fire containment solution has a minimal effect on the surrounded cargo loads [26].

The industry is also focusing on replacing the existing ULD aluminium containers with a Fire Resistant Container (FRC) which can withstand damages caused by LIB fires or fires created by dangerous goods as a whole [9].

2.4 Full-scale fire tests

LIBs are transported in bulk on top of pallets as cargo shipments. However, there are only very few literatures on full-scale burn tests that were done to evaluate the characteristics, impact and how severe and damaging the LIB battery fire can be in a bulk shipment. FAA has conducted full-scale burn testing to see the hazards involved in bulk shipments [10]. This study shows that LIB bulk shipments are very dangerous and pose a very serious threat to the safety of the aircraft when compared to the other common battery chemistries. Fires of this magnitude occurring within Class E compartments is more than capable to do significant damage to the aircraft structure and also the heat and pressure generated are enough to force the smoke to the flight deck. Class C compartments are equipped with Halon 1301 fire extinguisher systems which can help prevent smoke from forcing into the flight deck as it can suppress the open flames from a LIB fire [13]. However, the propagation of the thermal runaway cannot be stopped as discussed earlier in this chapter. The other crucial concern is that there is a risk of flash fire or explosion that might occur when the compartment is opened because there can be an unburnt hydrocarbon build-up formed from the released electrolyte within the compartment [10].

Figure 2-3 illustrates an experiment conducted by the FAA and it is apparent that not all the batteries have gone into thermal runaway and almost 50% of batteries are still intact. The worst-case scenario is when all 5000 LIBs used in this experiment go into thermal runaway. Based on these results and observations it can be stated that the actual potential damage that can be caused by 5000 LIBs going into thermal runaway is very high and much more severe when compared to this testing and measures need to be taken in order safely transport bulk LIB shipments by air.

Figure 2-3: FAA fire test burnt battery load [10]

2.5 Summary

Various research has been carried out on LIB fires to understand its behaviour and performance under different scenarios including altitude, SOC, number of batteries, type of batteries, and battery packaging. Most of the analysis and research has been done only with a limited number of batteries ranging from one battery to 16 batteries.

These studies are enough to understand the behavioural patterns and performance under various conditions. However, with the uncertain behavioural nature of the LIBs under extreme conditions, it is very difficult to predict the outcome of fire characteristics that will occur in a LIB bulk shipment. FAA has conducted full-scale testing of a battery shipment. However, only approximately about 50% of the 5000 LIBs have gone to thermal runaway leaving questions about the severity of the fire in case of all 5000 batteries go into thermal runaway. To contain and suppress a fire of this magnitude and to develop suitable fire containment solutions, it is crucial to explore and analyse the worst-case scenarios occurring when bulk LIBs catch fire.

LIB fires have the potential to damage ULD containers which carry all sorts of cargo including undeclared dangerous goods. The existing fire suppression systems that are installed within the cargo compartments like Halon 1301 are not enough to control and prevent LIBs from going into thermal runaway creating a possibility of the entire cargo load and the surroundings catching fire. Fire-resistant containers are being developed currently to replace the existing aluminium containers and also container-based fire detection and suppression systems are being developed in the hope of reducing false alarms that could be very costly. Until these solutions are put into play, there is an urgent requirement for an intermediate solution that can contain and withstand LIB shipments within containers.

Strict regulations have been imposed on the transportation of LIBs by air as a result of the aircraft accidents that occurred in the recent past due to LIB fires. Currently, there is a strict limitation where only 30% or less SOC batteries are allowed to be transported via air and no lithium-ion standalone battery shipments are allowed in passenger aircraft. FCCs are an innovative product that has been developed as a result of the imposed regulations which can help to contain and suppress fires within palletized cargo loads through oxygen starvation and prevent adjacent cargo loads from catching fire.

CHAPTER 3 RESEARCH METHODOLOGY

This chapter first describes the pathway to fulfilling the objectives of this research and then describes the approaches taken and relevant discussions to address each pathway using different data collection methods. Finally, it discusses the relevant methodology findings.

3.1 Pathways to fulfil objectives

- Pathway to fulfil objective 1:

1.1 Investigate different ULD container configurations and locations within the aircraft through websites and by consulting aeronautical professionals.

1.2 Study previous research to understand the ideal test conditions and understand previous tests conducted.

1.3 Discuss with aircraft carriers to understand quantities of LIB shipments within containers.

1.4 Investigate existing container fire containment solutions in the aviation industry.

1.5 Investigate the latest fire containment regulations as per aerospace standards to understand the minimum performance standard.

- Pathway to fulfil objective 2:

2.1 Define testing criteria as per industrial requirements like the LIB quantity, type of ULD container to be used for testing, and location of testing.

2.2 Identifying thermocouple positions and different types of thermocouples required for the test.

2.3 Defining LIB positions within the ULD container to analyse LIB fire behaviour at different locations.

2.4 Defining ignition sources required for testing.

2.5 Define the arrangement of Class A (ordinary solid combustibles such as paper, wood, cloth, and some plastics) cargo covering the remainder of the volume of the container.

- Pathway to fulfil objective 3:

3.1 Propose idea to leading airlines and obtain funding for testing.

3.2 Create a test plan.

3.3 Find a safe location and get approval from government authorities.

3.4 Source materials required for testing such as thermocouples, LIBs, heaters for ignition, Class A material, generators, and electrical components.

3.5 Calibrate thermocouples.

3.6 Use a data logging system to capture the thermocouple temperature readings.

3.7 Source ULD container variants for testing from aircraft carriers.

3.8 Coordinate a camera crew for covering the fire testing.

3.9 Arrange a logistics plan for all items related to the fire test.

3.10 Arrange a clean-up crew for disposal of residues of fire tests.

3.11 Take note of all movements and smoke emissions, battery pop sounds during tests, and other visible observations.

- Pathway to fulfil objective 4:

4.1 Collect all the observational results and recorded data throughout the tests.

4.2 Visually inspect the container and analyse the degree of damages and locations of damages.

4.3 Inspect the CFCC for damages.

4.4 Analyse the quantity of LIBs that have gone into thermal runaway.

4.5 Compare and analyse the results against the aviation regulations to validate the performance of the CFCCs and evaluate the fire containment capability.

3.2 Data collection methods

The research objectives are achieved through literature review, background study, consultation of industry professionals, research experiments, observation, inspection, and performance analysis. The research objectives and their specific data collection methods are summarized in Table 3-1.

Table 3-1: Mapping of objectives with data collection methods

Research objectives	Addressed through
1. Understanding key parameters such as ULD container dimensions, contours and location within the aircraft, LIB fires, LIB battery quantities within shipments, existing fire containment solutions in aircraft, and minimum performance standards required by fire containment solutions used in aircraft.	▪ Literature ▪ Background study ▪ Consultation
2. Developing a test method to evaluate the temperature inside and outside ULD containers, the ability to withstand a LIB fire for a required amount of time when CFCCs are used and, the potential damages that can be caused to ULD containers through the propagation of a LIB fire.	▪ Literature ▪ Consultation
3. Performing full-scale fire tests with LIBs stored in ULD containers.	▪ Research experiments ▪ Observation
4. Analysing observations and results and, validating the testing procedure according to aviation standards.	▪ Inspection ▪ Performance analysis

3.3 Review methodology

An approach that systematically discovers and analyses existing knowledge relevant to a particular field of study can be viewed as a literature review [27]. A good literature review will provide a good foundation for the research topic, provide guidance for a better research methodology approach, it will demonstrate the research findings and exhibit the novel aspects and research gaps for a researcher to carry out the relevant study [28].

The methodology used for the literature review was the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) method which is an evidence-based minimum set of items aimed at helping authors to report systematic reviews [29].

Initially, non-duplicate citations were subjected to a title/abstract screening and research publications were retrieved based on the inclusion/exclusion criteria. Subjecting the retrieved publications further to a full-text screen, final publications were selected to be used within this study. The research publications were screened and prioritised based on the following criteria.

- Keywords - Passive fire suppression, lithium-ion battery fire, thermal runaway, fire containment cover, fire behaviour, fire detection, full-scale burning, aircraft unit load devices and fire-resistant aircraft containers.
- Sources - Research studies that have been published in journals and also studies that have been presented at various international conferences related to LIBs and the air cargo industry on the subject were given priority while filtering out the screened studies. Databases used to search relevant studies are Science direct, Google Scholar, IEEE Xplore, Research gate, IOP science, Cambridge Core and also fire containment solution providers' websites and websites of aircraft regulatory bodies.
- Year of publishing - literature that was published after 2005 was subjected to the screening process and priority was given to the publications that were done recently where more than 70% of the literature that is referenced in this research is between 2014 and 2021.

3.4 Methodology findings

Both passenger and cargo aircraft are separated into two different decks. Namely, the main deck which is the upper half of the aircraft and the lower deck which is in the lower half. Cargo is carried in compartments on both decks in ULD containers. These containers allow a large quantity of cargo to be bundled into a single unit [30].

Many different ULD container contours are currently used in the industry and are designed especially considering the structural dimensions of aircraft to suit each aircraft model in such a way that the maximum amount of cargo can be carried out as every free space has value in an aircraft [31]. Multiple ULD container types are used within a single aircraft at different positions within the cargo belly to match the shape of the aircraft.

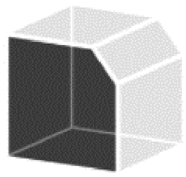
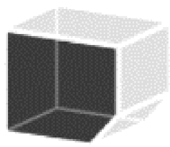
The aircraft is also segregated into different classes of cargo compartments depending on the accessibility of the crew members and also with regard to means of fire protection. The ULD containers will be positioned in their specific compartments within the aircraft [30].

Classes C and E cargo compartments are characterized as compartments that are inaccessible by the crew but have means of extinguishing or suppressing fire without a person required to enter the cargo compartment [30]. These cargo compartments have smoke detection systems signalling the crew of a potential fire [30]. Thus, fire containment solutions that enable smoke emission during a fire scenario while containing the fire can be of distinct advantage when comparing solutions to implement in cargo operations.

As per the industry professionals, LIBs can be transported on both the main deck and the lower deck of the aircraft. Therefore, two ULD container configurations (AKE and AMJ) used on the two different decks and fall into the compartment classes C and E will be discussed in this study.

Each ULD configuration is assigned a three-letter code to clearly distinguish between them in terms of the type, size, and shape of the ULD as illustrated in Table 3-2.

Table 3-2: ULD container specifications [32]

Configuration	Type of ULD	Base size of the ULD	Contour	Other Information
AMJ	Certified aircraft container	96” x 125”		Location – Main deck Width – 96” Height – 96”
AKE	Certified aircraft container	60.4” x 61.5”		Location – Lower deck Width – 79” Height – 64”

After discussing the requirement of ULD containers with a few airlines, a leading airline that is also currently a major partner in air freighting LIBs stepped forward and donated the two required ULD containers to be used for the fire tests.

To perform full-scale fire testing on ULD containers using LIBs as intended in this study, it is necessary to understand the size of LIB shipments to imitate and conduct a fire test close as possible to a real-life scenario. After consulting industry professionals from leading airlines who currently airfreight LIBs to understand the size of battery LIB shipments that are transported through each container type, shipments of about 5000 LIBs on AMJ container configuration and shipments of about 2000 LIBs on AKE container configurations were suggested to be suitable for a fire test evaluation as the battery shipment sizes cannot be operationally controlled and varies for each shipment.

During an IATA ULD Dangerous Goods board meeting with industry professionals and regulatory authorities like the FAA and EASA (European Union Aviation Safety Agency) about aircraft regulations and requirements in the air cargo industry, it had been discussed to define the LIB fire testing requirements based on an estimate of standard shipment sizes rather than a worst-case scenario with a much larger quantity of batteries filled inside the container as it is very unlikely to occur in a real-life air cargo operation. Based on this discussion it can be justified that the aforementioned battery quantities which were proposed by the sponsors are acceptable to be used to evaluate the fire containment performance of the CFCCs.

The test location was selected to be in the BOI export processing zone in Wathupitiwala, Sri Lanka. The location was selected mainly as it is located at a low altitude position which suits an aggressive test condition where batteries behave more aggressively as mentioned in previous studies [15]. This will enable to demonstrate and validate the product performance in harsh environmental conditions. A safe test environment was also a major concern when selecting a test location as ignition of a large quantity of LIBs simultaneously can pose a significant safety concern, especially with the explosive nature of the batteries. The location is to be a closed contour where there is no disturbance or any effect from winds or change in the surroundings.

As per the requirement defined in the SAE AS6453 standard [20], the temperature 4 inches away from the fire containment solution surface should not exceed 204 ^{0}C therefore the external thermocouples should be placed accordingly to measure the temperature at the given distance. This requirement is because the ULD containers are designed to be close as possible to the aircraft structure and there is a temperature limit that can be handled by the interior panels of the aircraft. Internal thermocouples can be used to measure the temperature inside the battery boxes inside the ULD container.

A data acquisition system with a higher number of channels was planned to be used to capture as many as possible variations in temperature obtained through connecting a higher number of thermocouples. It was decided to measure the temperature with intervals of 1 second at the start of the experiment as frequent observations can be seen and later with higher intervals as the fire test progresses and fewer observations are seen.

CHAPTER 4 TEST DETAILS AND PROCEDURES

The chapter first describes the items to be tested. Then it lists out the test equipment and the fire loads to be used for each test and their compositions. Then the full-scale LIB generic battery fire test procedure is discussed. Then the pass/fail criteria are pointed out and finally the pilot LIB fire test, AMJ fire test, and the AKE fire test details followed by the test setups are discussed.

4.1 Items under test

The CFCC is a passive safety device consisting of a fire retardant fabric cover to be used in conjunction with an aircraft ULD container. In-flight, the CFCC is intended to ensure that a container cargo fire is safely contained for a rated period, allowing sufficient time for the aircraft to be landed and evacuated if necessary. CFCCs can be customized to suit almost any ULD container configuration. CFCCs are designed in such a way that the cover is not airtight after being assembled into the container as it is important for the smoke detection systems that are currently installed within the cargo compartments. CFCCs does not rely on detection or suppression systems and do not require additional tooling or equipment to be operated. All of the textile parts that are incorporated into the design of the CFCC meet the requirements for flame penetration resistance and vertical flammability tests in accordance with SAE AS6453 [20].

Figure 4-1 and Figure 4-2 illustrate two different types of CFCC variants that are specifically designed to suit the AMJ and AKE ULD containers. These two CFCC variants are subjected to the fire tests in this study. ULD containers have ‘pull handles’ to support moving the containers inside the aircraft. CFCCs contain flaps (see Figure 4-3) to provide access to container pull handles after the CFCC is installed. Access to the inside of the container is allowed using a roll-up door mechanism (see Figure 4-1).

Figure 4-1: AMJ CFCC

Figure 4-2: AKE CFCC

4.1.1 CFCC components

The overall design features and the components of the two CFCC variants (AMJ and AKE) used in this study are the same as they were sourced from the same supplier. The main difference is the contour of the two ULD containers. Figure 4-3 illustrates the various components of a CFCC. The door panel and flaps are sealed to the CFCC using Touch and Close (T&C) fasteners when in use.

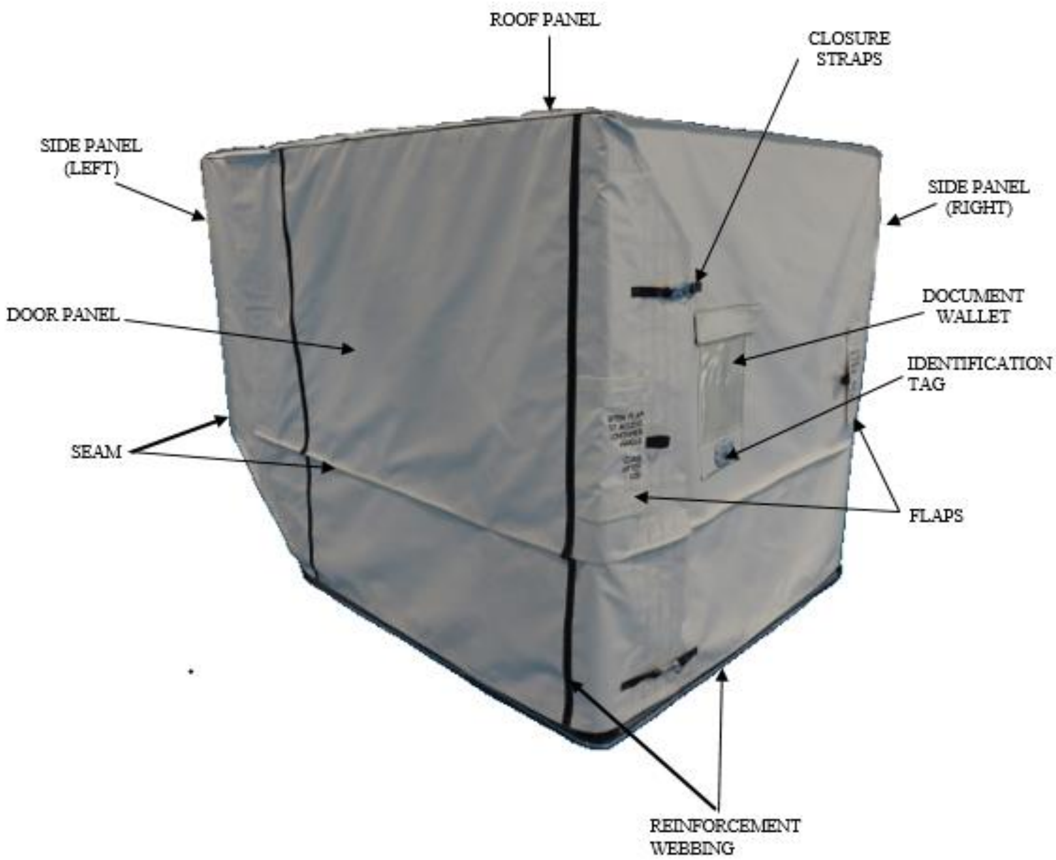


Figure 4-3: CFCC components

4.2 Test equipment

I. Cartridge heaters

The batteries are assembled around the cartridge heater as shown in Figure 4-4. The heater must have a temperature range of at least 485 ^{0}C to 660 ^{0}C to push LIBs into thermal runaway as the thermal runaway of batteries occurs in this temperature range [33]. 1000 W cylindrical cartridge heaters are used for the fire tests for this purpose. Each battery box is equipped with a cartridge heater setup so that all battery boxes can go into thermal runaway and the expected maximum output can be obtained from this study.

Figure 4-4: LIB bundle, worm-screw clamps and ignitor

II. Worm-screw clamps

The batteries are to be tightly bound together using a metallic worm-screw clamp or tape and twisted wire as shown in Figure 4-4. This binding should be strong enough to minimize the potential for battery cases to be ejected and/or the bundle to fall apart due to other reasons such as cargo load deformation during the test. Tightening the batteries together eases the heat flow to adjacent batteries which in turn helps to push all the batteries (or as many as possible) towards thermal runaway simulating the worst-case scenario.

III. Thermocouples

K-type thermocouples are used to measure both the internal and external temperatures. For internal measurements inside the battery boxes, thermocouples rated to 1000 ^{0}C tip temperature are used. The rating of the thermocouples was selected based on the previous research on LIB fires [14]. The spike in temperatures will help indicate batteries going into thermal runaway [14]. These thermocouples consist of a 3 mm x

300 mm long probe with 310 stainless steel sheath, a plain pot seal, and a 20 metres long glass fibre lead with stainless steel over braid and bare wire tails. For external measurements outside the container, thermocouples rated to 260 ^{0}C tip temperature are used. As per the pass/fail criteria the external temperature is expected to be less than 204 ^{0}C 4 inches away, therefore the external thermocouples used for this purpose were rated to 260 ^{0}C. These thermocouples consist of a 3 mm x 300 mm long probe with 316 stainless steel sheaths, a plain pot seal and 20 metres long 7/0.2mm PFA insulated flat pair cable with tails. The wire lengths of the thermocouples are defined in such a way that they can be connected to the data acquisition system which is placed a bit further at a safe distance from the location of the test article. The thermocouples need to be calibrated to obtain high quality and accurate temperature readings. The need for calibration arises as the thermocouple wires will lose their consistency over time because of the conditions they are exposed to, where the thermocouple circuit will generate a different voltage and impact the temperature reading. Therefore, all the thermocouples are calibrated to their respective tip temperatures before being used for the burn test. With the nature and the scale of testing, extra thermocouples are kept as backups in case of any failures during the test setup.

Firstly, a thermocouple is affixed to batteries in the first row around the heater in each box. Thermocouples measuring the temperature in the batteries are placed on opposite sides of the heater but not in contact with the heater. It is worth mentioning that wire lengths of the heater and thermocouple wiring should be adequate to route out from the top of the box and to accommodate remote control/monitoring from a safe distance outside the covered container.

IV. Data acquisition system

A 16-channel data measurement processor is configured and used for the fire tests to capture the readings obtained from the thermocouples (see Figure 4-5). Having a higher number of channels in the data measurement device enables to use a higher number of thermocouples in return capturing a higher number of temperature readings from various locations of the battery assembly. This type of measurement device was selected as it provides simple and cost-effective means of connecting to standard computers for real-time temperature monitoring and data acquisition [34].

Figure 4-5: Data measurement processor

V. Hygrometer

A hygrometer is used to measure the ambient temperature and relative humidity around the fire test setup as these two parameters directly affect the temperature readings of the thermocouples. When there is a change in environmental conditions, some external variables must be adjusted to maintain a constant test environment which in turn will lead to fewer errors in the experimental results. This will also help to define the LIB fire behaviour under the set environmental parameters.

VI. Irreversible temperature indicators

Irreversible temperature stickers can be used to measure the surface temperature of the CFCC. Stickers with 4 different temperature ranges are used in the experiments ranging from 70 ^{0}C to 260 ^{0}C as illustrated in Figure 4-6. These stickers are inexpensive and easy to use, and immediate responses can be obtained and the temperature readings are permanent which is useful as the temperature reading will be obtained only after the fire is extinguished. The maximum surface temperature that occurred during the period of the test can be identified by the last black event that is visible on the sticker.

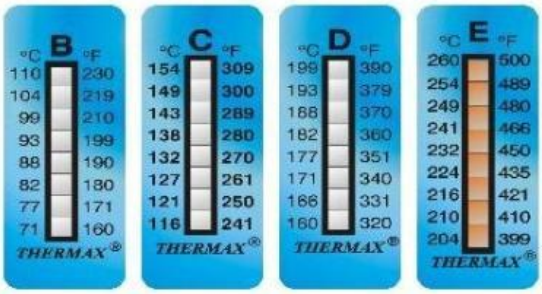


Figure 4-6: Irreversible temperature indicators [35]

VII. Video recorders

Video recorders are used to capture the observations during the fire tests. Five video recorders are used to record observations from all four sides and also from the top. Video recorders capture all the events during the fire at all positions in the entire setup so that the video footage can be replayed and see for any details that are missed during the live test.

4.3 Fire load compositions

I. Lithium-ion batteries

3.7 V 18650-sized LIB cells with an average capacity of 2200 mAh at 50-70% SOC are used for the fire tests. From previous studies [16] it has been proven that batteries with high SOC (similar to the ones that are used in this study) are more aggressive than the ones with lower SOC. Even though the maximum allowable SOC of standalone LIBs that could be transported by air is 30% [21], using a higher SOC can help to push the safety boundaries of transporting LIBs with the success of these types of fire tests proving the capabilities of the fire containment solutions available in the industry.

Six battery bundles are to be assembled for the AMJ test as per Figure 4-4. A total of 5000 LIBs are spread across the fire load with three 400 LIB bundles, one 600 LIB bundle, one 800 LIB bundle and one 2400 LIB bundle. The battery bundles are placed (except for the 2400 LIB bundle) in the centre of the Class A battery boxes in between the shredded papers. The bigger battery load (2400 LIB bundle) is placed directly on the bottom surface of the container at a specified location.

Five 400 LIB bundles are assembled similarly for the AKE test and all battery bundles are placed inside cardboard boxes at the specified location. A total of 2000 LIBs are used for the AKE fire test.

Batteries are arranged as per Figure 4-4 so that the battery rows are uniformly spaced around the heater. All batteries must be oriented with their vents facing upward direction.

II. Class A (general combustible materials)

Standard corrugated cardboard boxes measuring approximately 450 x 450 x 450 mm^3 (18” x 18” x 18”) with approximately 1.13 kg (2.5 lbs.) of shredded paper as per AS6453 [20] (see Figure 4-7) are used as Class A load. The quantity of the boxes depends on the contoured space taken up by the central battery load. Each box is filled at least 75% of its volume by shredded paper as per AS6453 [20].

Figure 4-7: Class A load - boxes and shredded paper

For the AMJ test, 144 boxes are used to fill up the AMJ container. Except for 9 boxes, each box is closed by interlocking the box flaps. No packing tape or staples are used. These 9 boxes are used to place the LIBs and the flammable fluid.

For the AKE test, 36 boxes are used. Except for 5 boxes, each box is closed by interlocking the box flaps and no packing tape or staples are used. Similar to the AMJ test, the five open boxes are used to place the LIBs and the flammable fluid.

III. Class B (flammable fluid – Ethanol)

The quantity of the flammable liquid if used for the experiment can be at the sole discretion of the researcher with the purpose of having a mixed class cargo load setup for the LIB fire tests to be close as possible to a real-life scenario. Considering the requirements of the sponsors for the experiment, two different amounts of ethanol are used for the two fire tests as described below.

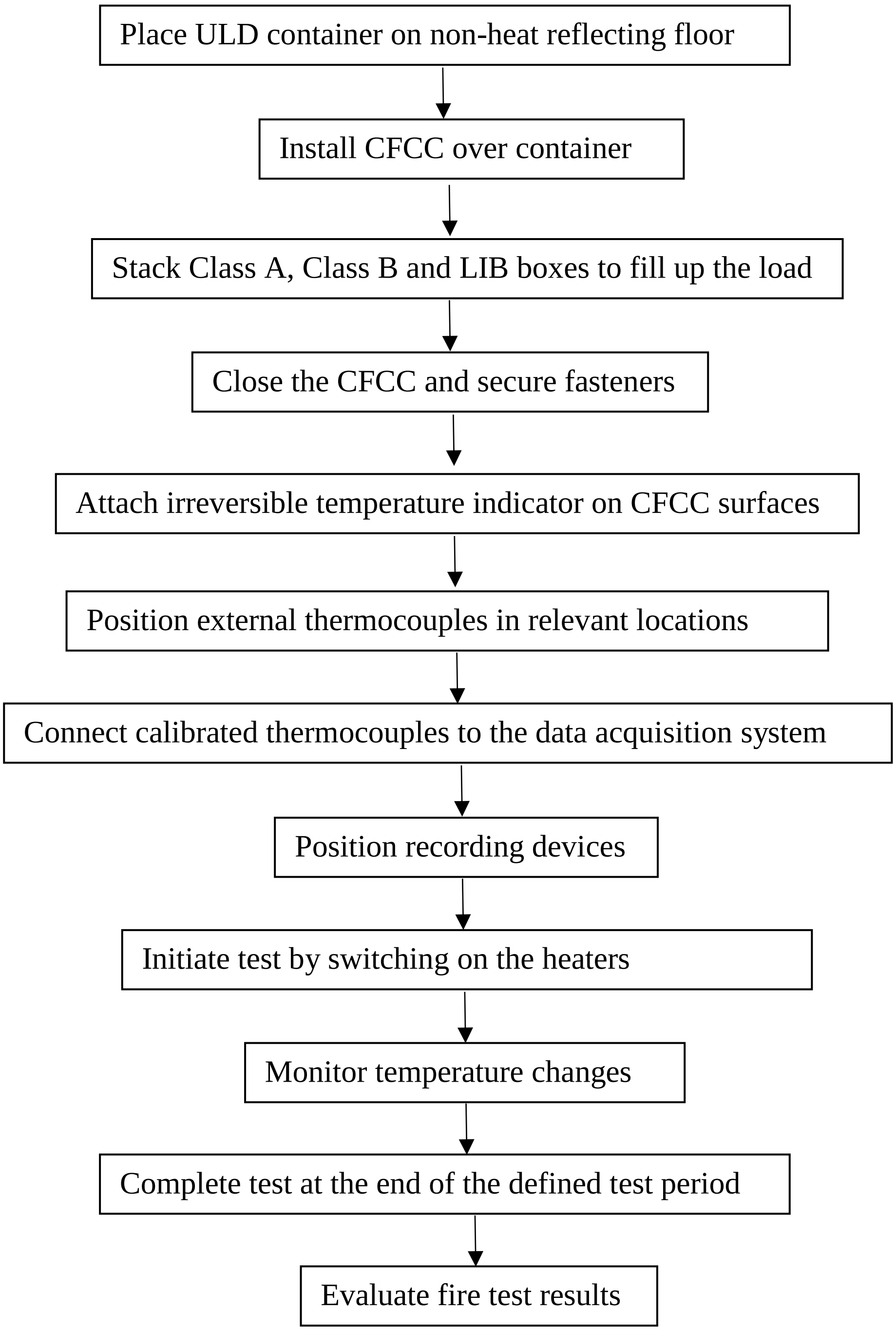
For the AMJ fire test, three two-litre flat-sided High-Density Polyethylene (HDPE) containers with two containers with one litre of flammable fluid and one container with two litres of flammable fluid are used.

For the AKE fire test, two two-litre flat-sided HDPE containers with one litre of flammable fluid in each container are used.

These containers are placed in the centre of Class A load boxes filled with shredded paper and denoted as "Class B boxes". A small opening is made on one of the flat surfaces of the containers as shown in Figure 4-8 to allow easy ignition of the flammable liquid within the cargo load therefore a worst-case scenario can be simulated. Ethanol with 95% purity is used as the flammable fluid in this experiment.

Figure 4-8: Ethanol filled HDPE bottle

4.4 LIB full scale test procedure flow chart



The detailed process of the LIB test procedure is discussed in Section 4.5.

4.5 LIB full-scale test detailed procedure

1. Level and provide support to the AMJ/AKE ULD container at the four corners with at least 8.0” over a non-heat reflecting floor (such as concrete). The 8.0” inch height requirement is based on the existing fire test standard for testing fire containment cover [20].
2. Install the CFCC over the container as intended in the product operation manual. A deployment kit or similar handling aid may be used to assist with the installation and may remain between the CFCC and the container for the duration of the test.
   A forklift may be used to place the main deck CFCCs similar to the AMJ CFCC on top of the container as it will be hard to lift and place the CFCC on top of the container with just bare hands. The lower deck CFCCs can be placed without the need for any supporting device as the top of the container can be reached.
3. Stack Class A, Class B, and LIB boxes inside the container as illustrated in the AMJ and AKE fire test setups in sections 4.8.2 and 4.9.2 respectively.
   The positioning of the LIBs within the container can be at the sole discretion of the researcher based on the testing requirements.
4. After the fire load is set up, close the CFCC door and secure all fasteners and locking mechanisms as required similar to how it will be transported within the aircraft.
5. Mark quadrants on the cover surface to identify each part of the CFCC and paste irreversible temperature indicators on each quadrant. This will ensure that we can record the maximum temperature readings in case any of the internal thermocouples gets damaged during the test. This step can be disregarded if measuring the surface temperature of the cover is deemed unnecessary and/or the risk of losing thermocouples and relevant data is acceptable.
6. Assemble framing to support recording thermocouples located 4.0” ± 0.5” away from the surface of the container and under the pallet at predefined fixed locations. This distance as mentioned in the SAE AS6453 [20] is to ensure that the adjacent systems in the aircraft and also the aircraft structure are not adversely damaged.
7. Connect all ignition devices and thermocouples to appropriate data acquisition instrumentation and calibrate as required. Calibration is required to ensure that results are accurate and precise.

8. Position video cameras so that all four sides and the top surface can be recorded for the total duration of the test. The video cameras are positioned at a safe distance from the setup to avoid any possible damage to the equipment during fire. The number of cameras is not a mandate, but the goal is to cover the entire test setup to gather as much video evidence as possible during the fire tests.
9. Start recording all the test parameters with the onset of battery heating or just before the onset of battery heating.
10. Initiation of the tests starts with simultaneously switching on the heaters placed in the battery boxes increasing the heater temperature. Monitor the temperature of the associated batteries in each LIB box. Thermal runaway in a battery bundle can be detected by a temperature spike in batteries relative to the temperature of the heater. The sudden increase in temperature depicts thermal runaway of the batteries [14]. When this occurs in any one of the battery boxes, start the test duration timer. (i.e. test time: T=0).
11. Continuous attention is paid to the behaviour of the CFCC and the container and any partial or complete melting, combustion, or drippings (if any), are recorded together with the relative location and duration of each event.
12. Thermocouple readings at locations above and around the CFCC and below the base are obtained throughout the duration of the test to measure the temperature at a rate of not less than one reading per thermocouple per 30 s. Thermocouple readings at locations above and around the CFCC where it has deformed, collapsed or shifted due to heat are not taken into account from the point in time where the 4” spacing is compromised [20].
13. Thermocouple time history data is used to determine the length of protection time afforded by the system.
14. Video recordings of all four sides are continued for the entire test period to capture all the events.
15. The test may be terminated after 6 h [20] or at a point where a failure criterion is fulfilled.
16. After completion of the test, examine each LIB bundle to determine if there are any batteries that did not experience thermal runaway. The validity of the test increases with the lesser batteries per battery bundle that haven’t experienced

thermal runaway as evidenced by the expulsion of the battery case or burning thereof.

17. Examine and record the CFCC and the container for damages and deformation that had occurred during the test.

Further to the aforementioned procedure, the following additional data is also recorded:

- Test performed by
- Test witnessed by
- Test date
- Temperature and humidity readings during testing
- Calibration data for test equipment
- Photographs of the test articles before and after the test
- Thermocouple readings / Data acquisition

Additionally, a transparent safety cover made of Perspex sheet is placed around the test setup to prevent any debris from shooting out and causing any potential injury to the personnel involved in the testing.

4.6 Pass/Fail criteria for LIB full-scale fire tests

- No flame penetration through the CFCC at any given time over the total duration of the test.
- Peak temperatures measured by the external thermocouples located 4” away from the surface of the CFCC shall not exceed 204 ^{0}C (400 ^{0}F).
- Duration of any flames external to the CFCC must be less than 15 s as specified in the AS6453 fire containment cover standard [20].

4.7 LIB thermal runaway pilot test

A pilot test is conducted to demonstrate that LIBs selected for use in the full-scale burn tests are of high quality and will display thermal runaway propagation when exposed to heat.

4.7.1 Test details

Table 4-1: LIB thermal runaway pilot test details

Quantity of batteries used	36
Thermocouples	TC-35, TC-36, TC-37, TC-38, TC-39, TC-40
Ambient temperature	28 °C / 82 °F
Relative humidity	82%

4.7.2 Test setup

36 LIBs are selected at random from the batteries sourced for the full-scale fire tests. Then the LIBs are assembled around a 1000 W cylindrical cartridge heater as shown in Figure 4-9 similar to how it was attached for the full-scale fire tests as explained in section 4.3 sub-section I with batteries uniformly spaced around the heater with the batteries oriented with their vents facing upwards. Figure 4-9 also illustrates how 6 thermocouples are assembled around the cylindrical heater using a wire clamp as mentioned earlier in section 4.2.

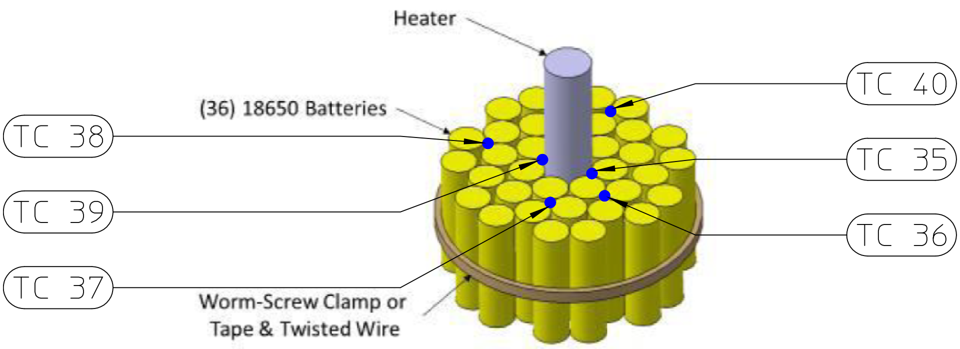


Figure 4-9: LIB thermal runaway pilot test setup & thermocouple position diagram

4.8 AMJ ULD container fire test

4.8.1 Test details

Table 4-2: AMJ fire test details

ULD details	Standard aluminium AMJ container with a fabric door. (Container damages repaired using FR tape patches)
Cargo Load	Class A – General combustibles: 144 cardboard boxes filled with 2.5 lbs. shredded paper Class B – Flammable liquid (Ethanol): 4 l

	Lithium-ion battery (18650-sized cells): 5,400
Thermocouples	Battery Box: TC-40, TC-41, TC-34, TC-44, TC-15, TC-36 External 4” away: TC-18, TC-12, TC-32, TC-20, TC-17, TC-42, TC-13
Ambient temperature	28 °C / 82 °F
Relative humidity	75.4%

4.8.2 Test setup

5 layers of Class A cardboard boxes are used to fill up the AMJ container as illustrated in Figure 4-10. Two LIB boxes are positioned on two opposite diagonal corners of the first layer. Another two battery boxes are positioned on the third layer one box close to the door side of the container and the second battery box close to the centre of the load. Position Another battery box is placed on the topmost layer towards the centre of the container. The battery positions can be at the sole discretion of the researcher to evaluate performance of the CFCC at the defined condition. It is not practical to test all scenarios as the batteries in real life shipments can be spread across to any position within the cargo load. The main battery load is positioned on the first layer towards the centre of the container. An FCB is placed additionally with 400 LIBs next to the main LIB load to observe the behaviour of the FCB in case of a fire on the outside. The three Class B boxes are placed randomly in such a way that it is spread across the volume of the container. The battery positions and the Class B box positions are illustrated in Figure 4-10**Error! Reference source not found.**. Internal thermocouples (inside the battery boxes) are fixed to the relevant locations as per Figure 4-10 and the external thermocouples are fixed as per Figure 4-11. The CFCC is divided into quadrants as marked in Figure 4-11 and the irreversible temperature indicators are attached to each of these quadrants.

The addition of the FCB can be omitted for future tests to evaluate the performances of the container or the CFCC. Class A boxes are stacked up in parallel in the rest of the locations to fill up the AMJ container profile while placing the battery boxes.

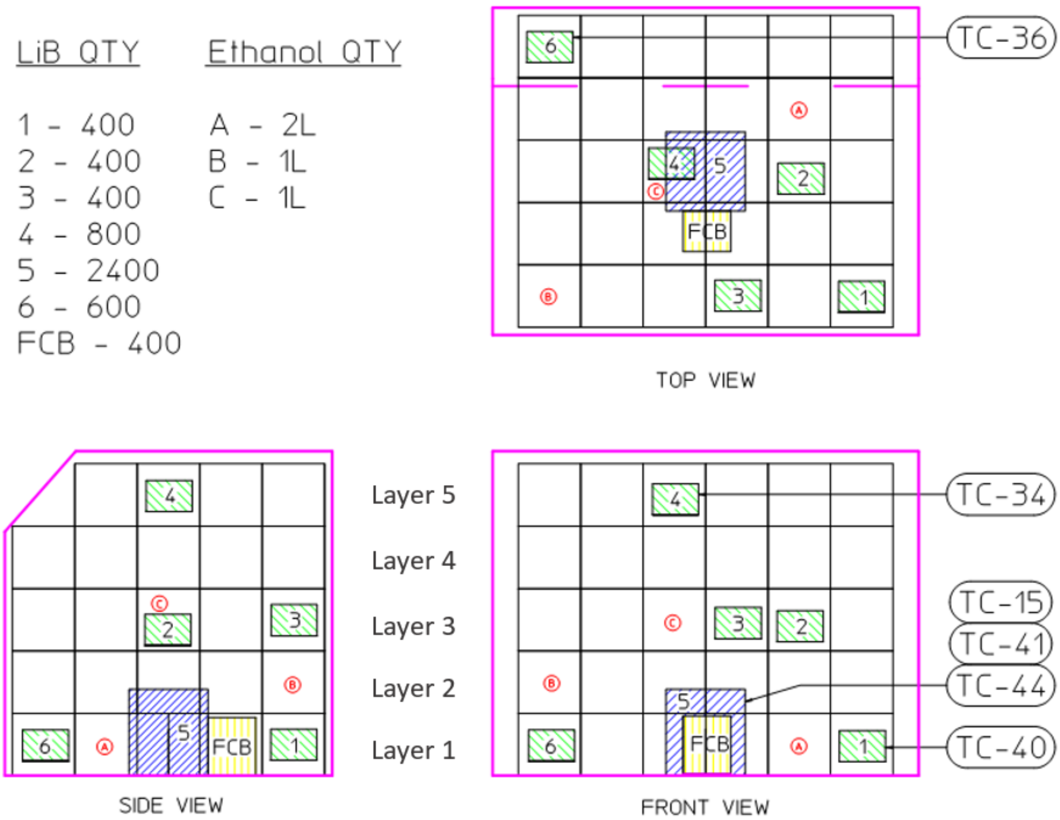


Figure 4-10: Interior thermocouple and battery box positions of AMJ fire test

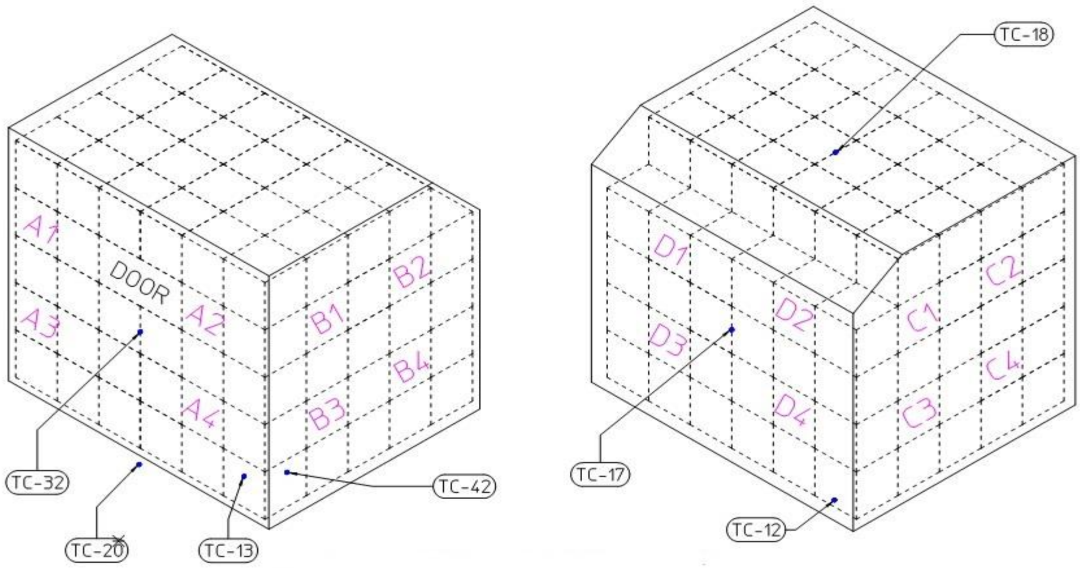


Figure 4-11: Exterior thermocouple positions and quadrant marking

4.9 AKE ULD container fire test

4.9.1 Test details

Table 4-3: AKE fire test details

ULD details	Standard aluminium AKE container with aluminium door in serviceable condition.
Cargo load	Class A – General combustibles: 36 cardboard boxes filled with 2.5 lbs. shredded paper Class B – Flammable liquid (Ethanol): 2 l Lithium-ion battery (18650-sized cells): 2,000
Thermocouples	Battery Box: TC-A, TC-B, TC-C, TC-D, TC-E External 4” away: TC-13, TC-15, TC-17, TC-18, TC-19, TC-32
Ambient temperature	27 °C / 81 °F
Relative humidity	78.2%

4.9.2 Test setup

The position of the LIB boxes is illustrated in Figure 4-12 through Balloon items A to E. The battery boxes are distributed through the volume of the container exposing to all the sides of the contour. Similar to the AMJ test, the battery positions can be at the sole discretion of the researcher to evaluate performance of the CFCC at the defined condition. It is not practical to test all scenarios as the batteries in real life shipments can be spread across to any position within the cargo load. The two Class B boxes are to be placed randomly in such a way that it is spread across the volume of the container.

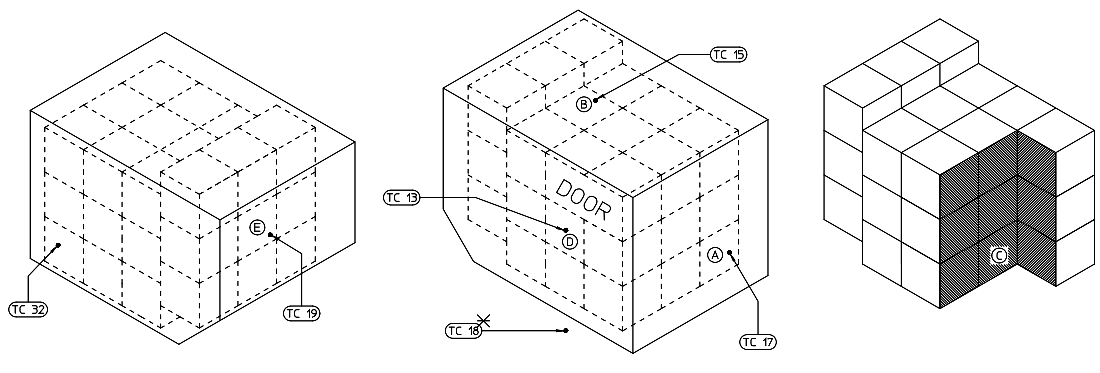


Figure 4-12: AKE fire test setup and thermocouple positions

4.10 Disposal of batteries and test articles

All materials including the LIBs used for the fire tests are disposed as industrial waste in a manner acceptable to good waste management practice and compliance with applicable local and national environmental protection regulations. The two CFCCs subjected to the fire tests are sent for disposal in a waste incineration plant or used as a constituent in producing cement as suggested by the CFCC manufacturer. The metal parts are separately sent for recycling.

CHAPTER 5 RESULTS AND DISCUSSION

This chapter discusses the results and observations of the three LIB fire tests conducted namely LIB thermal runaway pilot test, AKE test, and AMJ test. Observations during the test period are listed alongside the time of occurrence. The temperature readings obtained from the thermocouples are also reported. Finally, the conditions of the test articles and the ULD containers post-test are discussed and evaluated.

5.1 LIB thermal runaway pilot test

5.1.1 Thermocouple readings

Table 5-1: LIB thermal runaway pilot test thermocouple readings

Temperature (°C)	Thermocouple					
	TC-35	TC-36	TC-37	TC-38	TC-39	TC-40
Min	30.96	29.52	29.46	29.62	31.27	29.17
Max	787.26	556.09	626.31	373.86	760.20	544.31
Rise	756.29	526.57	596.85	344.24	728.92	515.14
Average rise	578 °C (1072 °F)					

5.1.2 Post-test observations

All batteries in the first two rows experienced thermal runaway as evidenced by burned internal contents or ejection of battery contents (see Figure 5-1). At least 15 batteries in the outer row of 18 batteries experienced thermal runaway. The average temperature rise recorded by the thermocouples was 578 ^{0}C (1072 ^{0}F).

Figure 5-1: Battery thermal runaway post-test

5.2 AMJ ULD container fire test

5.2.1 Observations during test

The fire test was divided into two different phases as it was deemed unnecessary to carry out the test for the entire period of 6 hours as the observations remained unchanged after a certain time as mentioned in in Table 5-2. Evaluation of the CFCC and the AMJ container under a normal fire scenario was tested in phase 1.

Having the option of continuing the fire test given that the condition of the CFCC is visibly acceptable, phase 2 of the fire test was used as an opportunity to evaluate the performance of the CFCC in a scenario where the CFCC cover is not installed properly. The observations of phase 2 of the test are listed in Table 5-3.

Table 5-2: AMJ fire test phase 1 observations

Phase 1	Burn test standard
Elapsed time following ignition (h:min:s)	Observation
-00:00:30	Video recording and Data logging commenced
Start (Phase 1) 00:00:00	Testing commenced with the ignition of all igniters/heaters in battery boxes.
00:01:20	First visible signs of smoke from beneath the bottom seam of the door on the front side and left Side
00:07:30	First audible sounds of battery explosion/venting
00:11:00	First visible signs of smoke from the bottom of side panel (right)
00:07:30 – 03:23:00	Continued smoke release, battery thermal runaway/venting with pop sounds but no notable external observations
03:23:00	CFCC door corner (left side) raised by 6 inches
03:24:00	Smoke release was observed from the door corner opening
03:30:00	All 4 CFCC handle flaps opened for a few seconds to further increase ventilation/oxygen flow
03:30:00 – 04:00:00	Increased smoke release but no notable external observations.
Finish – 04:00:00 (Phase 1)	Phase 1 of the test passed successfully (see Figure 5-2)

After 3 h and 23 min into the fire test, no notable external changes were observed. The CFCC door was slightly raised about 6” from the left bottom corner to increase ventilation and allow oxygen flow into internal fires. Later at the 3 h 30 min mark, the CFCC handle flaps were opened as well to increase ventilation and closed off after a few seconds. Once the ventilation was improved only an increase in the smoke released was observed.

Figure 5-2: AMJ CFCC at completion of phase 1

Although the test was originally planned for a duration of 6 h according to the test method, it was decided to evaluate the test at the end of 4 h as there were no further notable external observations. The smoke release was seen continuously throughout the test till the completion of 4 h.

Table 5-3: AMJ fire test phase 2 observations

Phase 2	Ventilation and oxygen flow into fire load is increased intentionally to represent the worst-case scenario of incorrectly installed CFCC or performance of non-fire resistance container (Standard aluminium container) in a similar fire situation. CFCC door corner (quadrant A3) was opened creating a gap of approximately 3’ (vertically) by 2’ (horizontally).
Elapsed time following ignition (h:min:s)	Observation
Start (Phase 2)	CFCC door corner (left side) was opened

04:12:00	
04:13:00	Increased smoke was observed coming out of the door opening and handle pocket openings
04:14:00	Internal flames were seen intensifying at the CFCC door bottom seam (section A4), close to the entry location of heater cables and thermocouple wires. Electrical sparks/fires were observed internally from the same location.
04:15:00	Blackening of the exterior surface of the cover's fabric at the door bottom seam (section A4)
04:18:00	Consumed shredded paper/debris fall through the gap created between seam and container
04:20:00	Further browning of fabric on the upper quadrant of CFCC door (section A2)
04:28:00	Flaming debris was observed at the door bottom seam and bulging out of CFCC door was observed due to internal load collapse
04:32:00	Expended battery ejection through the gap created between seam and container. External flaming was observed (less than 2 s).
04:33:00	Fabric was failed due to battery ejections/projectiles and internal load was collapsed straining the fabric at the bottom seam. External flames and burning load spillage through failure/hole were observed. (See Figure 5-3) Expended battery ejections through failure/hole were also visible.
Finish – 04:35:00	Test Terminated

Phase 2 of the fire test was conducted only with the purpose of understanding the behaviour of the CFCCs in an unconventional scenario. During phase 2 of the test, the door side was further opened as described in Table 5-3 allowing more ventilation and increasing the supply of oxygen. The four flap pockets that are part of the CFCC design which are used to access the strap handles of the container were also left open throughout the phase 2 test period. These straps are used to move and position the container as required within the aircraft and also during ground operations. Keeping the flaps open will simulate a situation where the cargo operators accidentally would not close the flaps as intended which can happen in a real-life scenario.

With increased ventilation more intensified flames could be seen from the inside of the container and the overall observations were much more severe as described in Table 5-3 than those observed during phase 1. Severe charring of the fabric was a key observation seen on the door side. The power cables of the heaters which were inserted under the bottom seam of the CFCC door on fire had damaged the CFCC fabric creating an opening at the bottom of the CFCC door allowing flaming debris to fall outside (see Figure 5-3). As the load collapsed further, bulging of the door was seen damaging the weakened fabric. Batteries started shooting out from the gap created at the door and also the burning load continued to pop out through the damaged areas therefore the test had to be terminated for safety reasons after approximately 35 min into phase 2 of the fire test.

Figure 5-3: Fabric failure in phase 2

5.2.2 Thermocouple readings

Table 5-4: AMJ fire test thermocouple readings

Thermocouple	Position	Temperature (°C)	Time at peak (h:min:s)	Meets peak temp requirement
TC-40	Box 1 (per Figure 4-11)	70.68	04:35:58	-
TC-34	Box 4 (per Figure 4-11)	649.15	04:16:13	-
TC-41	Box 5 (per Figure 4-11)	581.03	04:33:58	-
TC-44	Box 5 (per Figure 4-11)	685.23	04:17:13	-
TC-15	Box 5 (per Figure 4-11)	>1000	04:21:43	-
TC-36	Box 6 (per Figure 4-11)	50.29	04:35:43	-
TC-20	Bottom Centre – 4”	42.34	04:34:43	YES
TC-17	Rear Centre – 4”	31.86	00:25:26	YES
TC-42	Section B3 Bottom – 4”	33.49	03:28:43	YES
TC-18	Roof Centre – 4”	88.28	03:41:58	YES
TC-12	Section D4 Bottom – 4”	35.75	04:34:43	YES
TC-32	Door Centre – 4”	60.27	04:33:58	YES
TC-13	Section A4 Bottom – 4”	35.33	00:05:57	YES

Peak temperatures measured by the external thermocouples positioned 4” away from the cover must be below 204 ^{0}C (400 ^{0}F) as per the SAE AS6453 standard [20] for fire containment covers for the test to be considered a ‘PASS’. As per Table 5-4, all temperature readings from the external thermocouples are below 204 ^{0}C. The AMJ CFCC thus meets the temperature criteria required by the fire containment cover standard.

Thermocouple (TC-15) has a peak temperature reading exceeding the readable temperature range of 1000 ^{0}C (1832 ^{0}F). The thermocouple is considered malfunctioned following this peak.

The temperature variation profile of the AMJ CFCC fire test recorded by the thermocouples is illustrated in Figure 5-4.

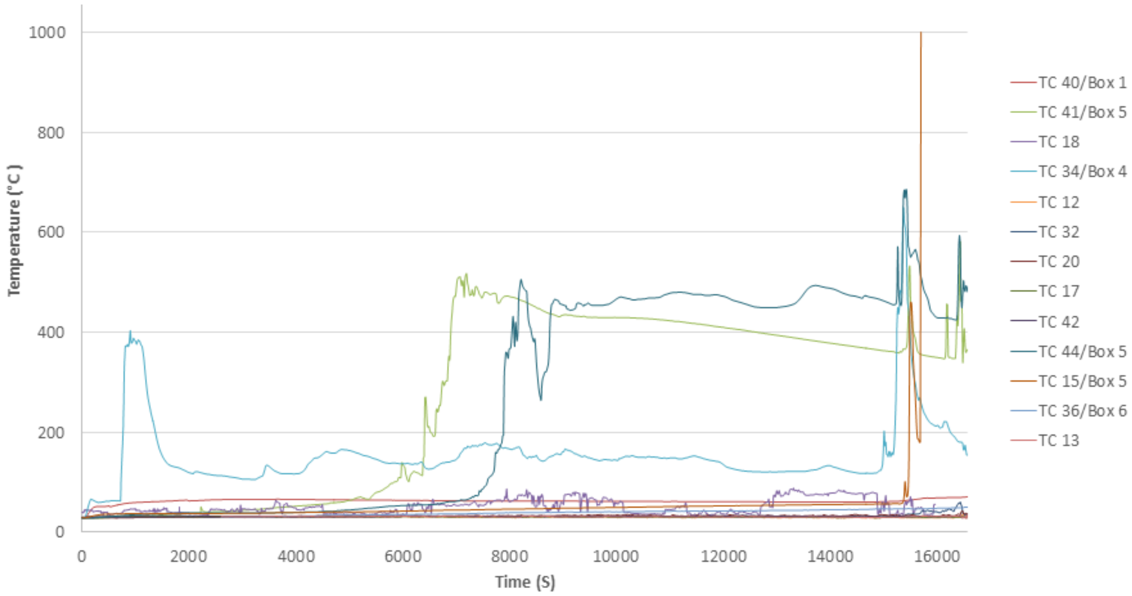


Figure 5-4: AMJ fire test temperature profile recorded by thermocouples

The temperature spike indicated by TC-34 at about 7 min 30 s indicates that the LIBs in battery box 4 have started going into thermal runaway. The temperature spikes seen from TC-41 and TC-44 indicate that the main LIB load has also gone into thermal runaway. The continuous pop sounds compared with the temperature spikes indicated that the LIBs in the main battery load continued to go into thermal runaway throughout the duration of the test. Further temperature spikes are seen at the 4 h mark from multiple thermocouples after partially opening the door as a result of increased ventilation and oxygen flowing into the container. The temperature profiles of the thermocouples placed 4” away from the CFCC surface indicate that the temperature has not passed the 204 ^{0}C (400 ^{0}F) temperature limit at any stage of the test.

Table 5-5: AMJ fire test peak temperature recorded by irreversible stickers

CFCC Quadrant	Peak Temp (°C)	Comment
A1	>260	Maximum possible reading
A2	>260	Maximum possible reading
A3	>260	Maximum possible reading
A4	>260	Maximum possible reading
B1	77	-
B2	<71	Not activated / Low temperature
B3	<71	Not activated / Low temperature
B4	<71	Not activated / Low temperature
C1	82	-
C2	154	-
C3	<71	Not activated / Low temperature
C4	<71	Not activated / Low temperature
D1	138	-
D2	99	-
D3	<71	Not activated / Low temperature
D4	<71	Not activated / Low temperature

As per Table 5-5, it is seen that the surface temperature on quadrants A1 to A4 which is the door side has exceeded the maximum possible reading on the temperature sticker. The reason for the door side to have a significantly higher surface temperature on the cover is that the door is made of fabric unlike the rest of the CFCC sides which are made of aluminium. AMJ containers are used on the upper deck of the aircraft and the door side in most of the containers has a fabric door.

Based on the physical observations, no flame penetration or burn through was seen from the AMJ CFCC during phase 1 of the test and also there were no external flames visible. Considering the peak temperatures 4” away from the surface of the CFCC, the phase 1 fire test can be considered as a ‘PASS’. This means that the AMJ CFCC design is capable of holding a LIB shipment of 5400 batteries.

5.2.3 Post-test observations

Following removal of the CFCC at the completion of the 4 h and 35 min test period, it was observed that all of the battery load boxes and all the combustible load boxes were consumed, penetrated, or damaged by fire. More than 75% of batteries had experienced thermal runaway, vented, or exploded. It was seen that the thermal runaway in battery boxes 1 and 6 had not completely propagated. This explains the reason to have a lower temperature reading from thermocouples TC-40 and TC-36 which were placed in battery box 1 and box 6 respectively. However, the cells in close proximity to the heater had gone into thermal runaway.

5.2.4 Post-test observations on the AMJ ULD container

AMJ container showed burn damages and discolouration on both the interior and exterior sides. The door side vertical edges circled in red in Figure 5-5 point out the identified exterior fire damages. Warped panels, gaps created at joints, and scorched panels were identified as means of failure and distortion of the container. Figure 5-6 illustrates fire damages that had occurred on the interior of the AMJ container.

Figure 5-5: AMJ container exterior fire damages

Figure 5-6: AMJ container interior fire damages

5.2.5 Post-test observations on the AMJ CFCC

The interior of the CFCC showed fabric discolouration and blackening on all panels. Figure 5-7 shows the post-test interior condition after the CFCC was pulled out of the container. No fabric failure was observed apart from the failure which was clearly visible on the CFCC door bottom during the test where the heater wires had caught fire. Blackening of the fabric was largely seen on the exterior side of the CFCC door panels as well. It is evident that the door side of the CFCC will be blackened more than the rest of the sides as there is no aluminium barrier between the fire load and the CFCC. The T&C fasteners which were used as a securing mechanism in this particular CFCC design (used for this fire test) were intact for the duration of the test which proved to be a successful method to secure the CFCC door properly as required without creating any openings for the flames to come out in a fire scenario.

Figure 5-7: Post-test interior condition of AMJ CFCC

5.3 AKE ULD container fire test

5.3.1 Observations during test

Table 5-6: AKE fire test observations

Elapsed time following ignition (h:min:s)	Observation
-00:00:30	Video recording and Data logging commenced
Start 00:00:00	Testing commenced with the ignition of all 5 igniters/heaters in battery boxes
00:04:30	First visible signs of smoke from beneath the bottom seam of the door on the front side in the left corner
00:06:00	First audible sounds of battery explosion/venting. Spikes in battery thermocouple readings (Battery Box D)
00:08:57	First visible smoke from the left side of the CFCC
00:10:15	First visible smoke from the right side of the CFCC
00:17:00	Increasing smoke from the front bottom
01:02:00	All 5 igniters/heaters are switched off
01:02:00 – 06:00:00	Continued smoke release and battery thermal runaway/venting but no significant external observations.
Finish – 06:00:00	Test completed
06:10:00	Fire extinguished completely

The exterior surface of the cover's fabric did not display any browning or discolouration. In fact, there were no significant external observations for the entire period of 6 h as intended. There were no external flames throughout the period of the test and also no flame penetration through the CFCC was observed.

5.3.2 Thermocouple readings

Table 5-7: AKE fire test thermocouple readings

Thermocouple	Position	Temperature (°C)	Time at peak (h:min:s)	Meets peak temp required
TC-A	Box A (per Figure 4-12)	199.93	00:08:22	-
TC-B	Box B (per Figure 4-12)	220.77	01:13:00	-
TC-C	Box C (per Figure 4-12)	486.59	00:46:52	-
TC-D	Box D (per Figure 4-12)	548.41	00:43:02	-
TC-E	Box E (per Figure 4-12)	526.49	00:31:29	-
TC-19	Side C Centre – 4"	32.97	00:25:38	YES
TC-32	Section D3 Bottom – 4"	52.84	00:30:28	YES
TC-17	Section B4 Bottom – 4"	45.24	00:30:28	YES
TC-13	Front Door Centre – 4"	33.49	02:52:00	YES
TC-15	Roof Centre – 4"	35.30	02:37:00	YES
TC-18	Bottom Centre – 4"	32.48	02:52:00	YES

As per Table 5-7, all temperature readings from the external thermocouples are below 204 ^{0}C. The AKE CFCC thus meets the temperature criteria required by the fire containment cover standard.

The temperature variation profile of the AKE CFCC fire test recorded by the thermocouples is illustrated in Figure 5-8.

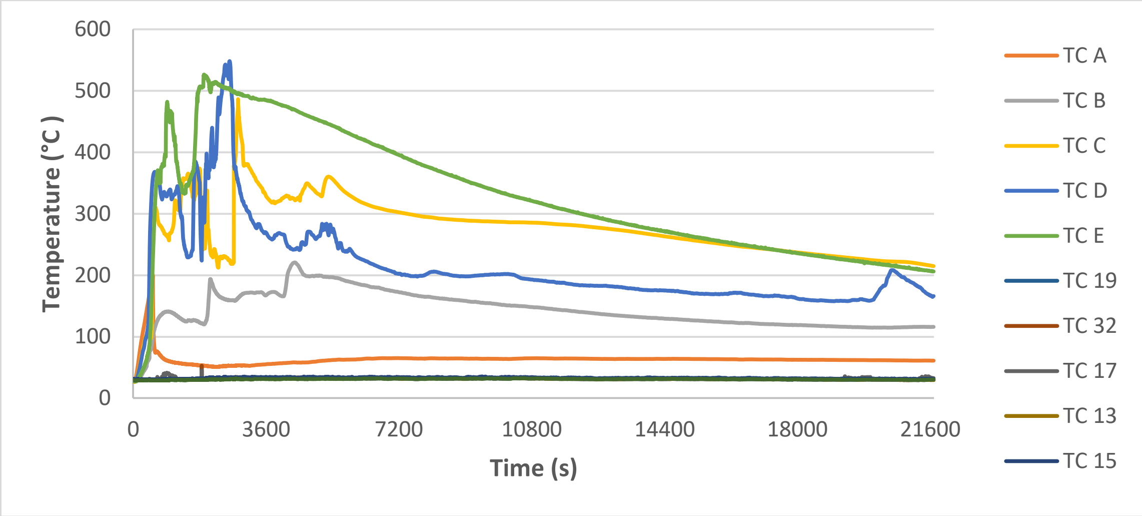


Figure 5-8: AKE fire test temperature profile recorded by thermocouples

Based on the temperature spikes shown in Figure 5-8, it is clear that almost all LIB boxes started experiencing thermal runaway within a few minutes from the start of the test. Comparing the observations of the test tabulated in Table 5-6 with the temperature profiles, it is evident that LIBs continued to go into thermal runaway throughout the test. It is apparent that the overall temperature inside the container is gradually reduced once the majority of the LIBs had gone into thermal runaway. The temperature profiles of the thermocouples placed 4" away from the CFCC surface indicate that the temperature has not passed the 204 ^{0}C (400 ^{0}F) temperature limit at any stage of the test.

5.3.3 Post-test observations

Following removal of the CFCC at the completion of the 6 h test period, it was observed that all of the battery load boxes and all the cardboard boxes were consumed, penetrated, damaged or blackened by fire (see Figure 5-9). More than 75% of the batteries had experienced thermal runaway, vented or exploded. Irreversible peak temperature indicators that were attached to the surface of the CFCC did not show any temperature rises above 70 °C (160 °F). Unlike the AMJ container with a fabric door, the AKE container is equipped with an aluminium door. This is one of the reasons for the peak surface temperature of the AKE CFCC is limited to the above given temperature.

Figure 5-9: Post-test observations of AKE container

5.3.4 Post-test observations on the AKE ULD container

AKE container showed burn damages and discolouration on both the interior and exterior sides. The exterior damages were on the outer surface of the roof, bottom corners, and bottom edge of the slanted side (see Figure 5-10**Error! Reference source not found.**, Figure 5-11**Error! Reference source not found.** and Figure 5-12**Error! Reference source not found.**). Similar to the AMJ container, damaged warped panels, gaps created at joints and scorched panels were identified as means of failure and distortion of the container. Figure 5-13**Error! Reference source not found.** illustrates the post-test scorched condition on the interior of the AKE container.

Figure 5-10: AKE container roof damages

Figure 5-11: AKE container side damages

Figure 5-12: AKE container slanted edge damages

Figure 5-13: Post-test interior condition of the AKE container

5.3.5 Post-test observations on the AKE CFCC

The CFCC did not show any discolouration on the outside (see Figure 5-14). CFCC's interior fabric surfaces were discoloured/blackened however no significant damages were observed (see Figure 5-15). The attachment fasteners in the design were still intact and proves to be a successful securing method similar to the AMJ CFCC.

Figure 5-14: AKE CFCC post-test

Figure 5-15: AKE CFCC fabric inner side discolouration

CHAPTER 6 CONCLUSION

This chapter initially presents the research summary. Then it describes the contributions to the research community based on the literature review, experimental set-up, full-scale fire tests and the results and observations. Thirdly, the research limitations are discussed and finally, further research directions on which the research can be further continued are suggested.

6.1 Research summary

This research was carried out with the aim of developing a test method to measure the capabilities and performance limitations of industrial fire containment solutions in a LIB fire scenario within the air cargo industry with the hope of improving the safety and reliability of safely transporting LIBs by air. To achieve this aim, four objectives were defined. The necessity of a test method was identified through a detailed literature review focusing on fire performance evaluation methods and techniques of existing fire containment solutions in aircraft.

The CFCCs which are one of the latest innovative fire containment solutions used in aircraft were subjected to the LIB fire tests. CFCCs are used in both the upper and lower decks of the aircraft. A test method was developed based on the requirements that were imposed by the relevant authorities like the EASA and the FAA which needed to be fulfilled by fire containment solutions while ensuring airworthiness for air cargo operations.

Based on the developed test method, an AKE and AMJ type ULD containers with a CFCC installed were subjected to fire tests with 2000 LIBs on the AKE and 5400 LIBs on the AMJ container. Observations during the test were noted down for evaluation. The CFCCs and the ULD containers were post-test reviewed for any damages and modes of failure. Both the AKE and AMJ CFCCs were considered as ‘PASSED’ as the CFCCs met all the requirements of SAE standards.

6.2 Contribution to knowledge and practice

The contributions from this study can be addressed according to the set of objectives. The first objective of ascertaining current knowledge and identifying key parameters related to transporting LIBs is achieved through a comprehensive literature review and discussions with industry professionals. A LIB fire is considered a special case where it cannot be classified into a single class of fire. The flammable liquid electrolyte in a LIB which is the first to ignite is classified as Class B fire. The outer cover of a LIB is made of plastic or polythene and ignition of these materials are classified under Class A fires. The casing of a LIB is made of a metal and metal fires are classified as Class D fires. Therefore, various classes of fire can be seen during a LIB fire. Furthermore, the oxygen required for ignition is produced within the LIB which are accumulated through the release of oxygen in the cathode material during thermal runaway [36]. The LIB self-ignites as a result of this hence it can be identified as an internal combustion process. Therefore, to tackle a LIB fire it is important to understand under which class of fire it will fall under and also the chemical composition of the LIB. Based on the LIB fire characteristics, it is hard to extinguish a LIB fire and the most suitable way is to contain the LIB fire without spreading it. From the literature, it was identified that both upper and lower deck ULD containers carry LIB shipments. The requirement of having a temperature less than 204 ^{0}C (400 ^{0}F) 4” away from the surface of the fire containment solution and the capability to contain a fire for a period of 6 h are two critical parameters identified through the literature review.

The second objective was achieved by developing a test method with scientific justifications for each step for LIB fire testing while measuring the temperature inside and outside of the ULD container during a LIB fire for the rated period of 6 h and to observe any potential damages that can be caused to the structure of the container through a LIB fire of this magnitude.

The third objective was achieved by conducting several fire tests with LIBs stored in ULD containers. A LIB thermal runaway pilot test with 36 LIBs and two full-scale fire tests with 2000 LIBs on an AKE container and 5400 LIBs on an AMJ container were conducted as part of the third objective. Brand new and unused CFCCs were installed onto the containers and were subjected to the fire tests. The AKE fire test was carried out for the entire 6 h. Since there were no further external observations, the AMJ fire test was completed after 4 h. The test was then continued after creating openings from the sides to measure the effects in a case where a CFCC was not installed properly. The test had to be terminated due to electrical wires catching fire and creating an opening on the CFCC.

The final objective of analysing the observations and results and validating the testing procedure was achieved through the post-fire test evaluations. Both CFCCs have successfully sustained the LIB fire with no external flame penetration and also no temperature readings exceeded the allowable limits. Both ULD containers had sustained burn damages showing that the ULD containers alone cannot withstand a LIB fire of a similar magnitude. The test method has successfully enabled the evaluation of the performance of the CFCCs according to the fire containment solution requirements and is designed in such a way that the test can be repeated easily, sand the results can be compared accordingly.

Finally, it can be concluded that the study has successfully achieved all the defined set of objectives and developed a systematic test method that has the potential to be used as a standard test procedure in the future by regulatory authorities like EASA and FAA when regulating LIB fire test procedures for the approval of fire containment solutions. Therefore, the aim of the research, to develop a test method to analyse the fire performance of CFCCs in a LIB fire scenario is successfully achieved.

6.3 Research limitations

The research was conducted under several limitations as described below.

- Due to the high cost per test, each test could only be conducted once. Therefore, the relevant temperature readings were only taken from a single experiment under the defined test specifications.
- Once the testing is started there is no turning back and potential malfunctions of devices are uncontrollable and cannot be fixed. A potential malfunctioning of the igniters in a couple of battery boxes may have hindered the propagation of thermal runaway to the batteries further away from the igniter cartridge which was seen during the AMJ fire test.

6.4 Further research directions

This research was conducted to develop a test method to evaluate and analyse the fire performance of existing air cargo fire containment solutions like the CFCCs.

- Further research can be done using the described test method to rate the CFCCs under different fire scenarios and test conditions. Further, there are many variants of ULD containers used in the air cargo industry. Testing can be carried out for the new CFCC designs which are developed for these ULD container variants.
- The allowable damage limitation is a crucial factor that should be considered during operations. Future research can be carried out on how the intensity of the battery fires affects the damages to the CFCC and to which extent the CFCC can be used safely in operations and define the maximum allowable damage limits for each CFCC design.

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