Safety Regulation Group

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Dealing With In-Flight Lithium Battery Fires In Portable Electronic Devices

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M J Lain, D A Teagle, J Cullen, V Dass

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Enquiries regarding the content of this publication should be addressed to:
Research Management Department, Safety Regulation Group, Civil Aviation Authority, Aviation House, Gatwick Airport South, West Sussex, RH6 0YR.

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Foreword

Based on the information, design knowledge and expertise provided by AEA plc, regarding the in-built safety devices used in lithium ion battery packs, together with past in-service experience, it is considered that the likelihood of an incident (i.e. smoke, fire or explosion) involving a Portable Electronic Device (PED) with a lithium ion battery pack is relatively low.

However, in the event of a fire involving a PED with a lithium ion battery pack, the fire extinguishers available to the flight and cabin crew have been shown by test to be effective in extinguishing the fire.

It is intended to provide UK operators with a summary of the recommendations from this report as guidance material to ensure that the flight and cabin crew training programs and operating procedures contain the most effective methods available when faced with a fire involving a PED.

The test results have verified the effectiveness of existing fire extinguishing agents in coping with a lithium ion battery fire. Therefore, no further recommendations are made regarding the use of any alternative fire-extinguishing agents.

Information from the report will be used to up-date, where necessary, existing guidance material concerning In-seat power and Portable Electronic Devices (UK - CAA and JAA Guidance material).

Operators will be advised regarding Mandatory Occurrence Reporting of PED incidents to ensure that specific information regarding the PED and its use at the time of the incident is recorded in the report.

Executive Summary

1 Portable electronic devices like laptop computers contain rechargeable batteries. Some airlines have now installed charging points in passenger seats, which allow devices to be used (and hence charged) in-flight. This has raised concerns about the possibility and consequences of an in-flight fire.

2 This project report describes experiments in which a battery fire was deliberately initiated, allowing the effectiveness of various fire extinguishers to be evaluated. The tests included battery packs of representative size and type, battery packs in portable devices, and portable devices with battery packs in carrying bags.

3 The portable devices and battery types used were as follows:

- laptop computer	- lithium ion prismatic cell pack
- laptop computer	- nickel – metal hydride cell pack
- video camera	- lithium ion cylindrical cell pack
- still camera	- lithium metal primary cell

Devices like mobile phones were considered to be smaller versions of laptop computers. They would not normally be used or charged in-flight.

4 Battery pack manufacturers recognise that cells can be hazardous under abuse conditions, and include various protective devices to avoid these conditions. The cells can contain thermal or pressure disconnects, and shutdown separators. The packs will contain overcharge and over-discharge protection circuits. The charger units will limit the maximum voltage and current. In combination, these features make the probability of a fire occurring extremely low.

5 In this project, it was necessary to cause battery fires. Therefore, all the pack and charger level protection systems were excluded. Fires could then be initiated by the following procedures:

- lithium ion prismatic cell	- overcharge at four times the manufacturer's recommended charging current.
- lithium ion cyclindrical cell	- overcharge at four times the manufacturer's recommended charging current, then heat.
- nickel – metal hydride cell	- overcharge at thirty times the manufacturer's recommended charging current (smoke not fire).
- lithium / MnO_2 primary cell	- heat with a naked flame.
- lithium / $SOCl_2$ primary cell	- heat with a naked flame.

6 The extinguishers used in the project were water, halon, FE-36 (halon replacement), ABC powder, BC powder, and fire blankets. All the fire extinguishers were tested on all five of the battery fires. In subsequent tests on packs with devices, the number of extinguisher types was reduced, but fire blankets were included.

7 The tests shows that battery fires can be initiated, if all three levels of protection fail at the same time.

8 The "explosive" effect as the battery case fails and the solvent vents is not judged to be of a size that would cause damage to the aircraft structure. However, there will be severe harm to any passengers in the immediate vicinity of the fire. There may also be other effects from smoke inhalation and panic.

9 In none of the tests was the fire aggravated by the use of any of the fire extinguishers.

10 For some of the fires, halon and FE-36 halon replacement were more effective than water in extinguishing flames.

11 Fire blankets were only effective if they completely enclosed the fire, which may not be practical in all circumstances.

12 With multi-cell lithium ion battery packs, the individual cell fires can be spread out over several seconds, for at least a minute into the fire. Such fires should be approached with this possibility in mind, and appropriate protective equipment should be worn.

1 Introduction

1.1 This report describes work undertaken on the Civil Aviation Authority contract No. 668 "Dealing With In-Flight Lithium Battery Fires In Portable Electronic Devices". Rechargeable battery technology has changed markedly in recent years, with batteries getting smaller, but energy densities increasing. Electronic devices like laptop computers, which are designed to use rechargeable cells, will have protection systems against over current, over voltage, and over temperature built into the charging system. However, there is a concern about the risk of fire from these devices, in the event that the protection systems failed while the battery was being charged in-flight. The most common battery types used in these devices are lithium ion and nickel metal hydride, both of which can be a potential hazard if overcharged. Although there are several levels of protection, there is a remote possibility that there will be a battery fire, as discussed in Appendix 1. Therefore, it is important to know which fire extinguisher would be most effective in fighting this specific type of fire. This is the overall aim of this project.

There are a range of different fire extinguishers available, for different applications, and a range of different battery types and sizes. The first phase of the work programme looks at the effectiveness of fire extinguishers on representative battery fires. Subsequent stages look at battery packs in representative devices, and devices stored in cloth bags, both of which could contribute to an initial battery fire.

1.2 Batteries and Portable Devices

The main portable electronic devices under consideration are laptop computers, mobile phones, video cameras and still cameras. These devices, and the batteries they would normally use, are shown in Table 1. Of these, laptop computers represent the biggest hazard, because they have the biggest battery, and they are the most common devices that would normally be charged in-flight. Apart from dangers during charging, the other failure mode that needs to be considered is the development of an internal short circuit. Again there are protective features built in to the battery, but short circuits can lead to fires in both primary and rechargeable batteries.

1.3 Fire Extinguishers

There are a number of standard fire extinguisher types, for different applications, as indicated in Table 2. Halon extinguishers are currently being replaced in most applications, because of their ozone depletion potential. The two substitutes are FM200 (FE-227), which is 1,1,1,2,3,3,3 heptafluoro propane, and FE-36 (HFC-236), which is 1,1,1,3,3,3 hexafluoro propane. For the same effect, the extinguishers are typically 60 % bulkier than halon, and the long term stability is not quite as good. The AFFF or aqueous film forming foam is mainly water, with various fluorocarbon and hydrocarbon surfactants to produce the foam. Of the dry powders, ABC is normally ammonium dihydrogen phosphate, and BC is normally sodium bicarbonate. Different types of D powder are recommended for different metal fires e.g. sodium chloride for lithium. The powders contain trace components to help them to flow, and sometimes moisture repellent additives as well.

Table 1 Batteries Used In Portable Electronic Devices

Battery Type	Laptop Computer	Mobile Phone	Video Camera	Still Camera
Lithium Ion - Cylindrical	Yes But Decreasing	-	Yes	Starting To Appear
Lithium Ion – Prismatic	Yes	Yes But Decreasing	Starting To Appear	Starting To Appear
Lithium Ion – Polymer	Yes And Increasing	Yes And Increasing	-	-
Nickel Metal Hydride	Yes	Yes (USA)	Yes	-
Lithium / Manganese Dioxide	-	-	-	Yes
Lithium / Sulphur Dioxide	-	-	-	-
Lithium / Carbon Fluoride	Memory back-up	-	-	-
Lithium / Thionyl Chloride	Memory back-up	-	-	-

Table 2 Fire Extinguishers In Common Operation

Extinguisher	Class	Comments
Water	A	Suitable for solid fires e.g. wood, paper, plastic. Explicitly NOT recommended for liquid fires.
Halon	AB	Suitable for solid and liquid fires. Being phased out because of ozone depletion concerns.
FM200	AB	A non-ozone depleting replacement for halon.
FE-36	AB	A non-ozone depleting replacement for halon.
AFFF Foam	AB	Suitable for solid and liquid fires.
Dry Powder	ABC	Suitable for solid, liquid and gaseous fires.
Dry Powder	BC	Suitable for liquid and gaseous fires.
Dry Powder	D	Specially designed for metal fires. Different types for different metals.
Carbon Dioxide	BCE	Good for electrical fires. Not ideal in an enclosed environments (asphixiant).
Wet Liquid	F	Newly introduced for “chip pan” fires.
Fire Blanket	F	Effective for localised fires.

Currently, water and halon extinguishers are normally fitted in the passenger compartments of aircraft. Airlines have a dispensation to continue using halon for the time being. In selecting extinguishers for the test programme, carbon dioxide was excluded, because of the risk of asphixiation in an enclosed space. ABC dry powder was included, even though it is considered to be a class IV poison. D dry powder was excluded, because different powders are used for different metals, and some conduct electricity and could cause further problems. The less optimum extinguishers (for aircraft) would only be considered if the optimum extinguishers were ineffective.

1.4 Project Objectives

The probability of an in-flight fire associated with the battery of a portable electronic device is considered to be remote. However, the possibility of a fire is still recognised, and therefore it is expedient to investigate the most effective fire fighting mechanism should such a fire occur. The main project objectives are thus:

- To identify the best fire extinguisher(s) for fires in lithium ion, nickel metal hydride and lithium / manganese dioxide battery packs.
- To determine whether the best extinguishers are still effective when the cells are in real devices and cloth carrying bags.

This will ultimately contribute to CAA recommendations and guidance to manufacturers and airlines. A secondary objective of the project is to produce video recordings of extinguishers operating on battery fires, potentially to assist in training of airline crews.

2 Experimental Method

2.1 Description of Cells and Battery Packs

It is unrealistic to test every cell or battery in every size and combination with every type of fire extinguisher. Various battery types and sizes were therefore selected as representative, as indicated in Table 3. To achieve sufficient capacity and the required operating voltage, battery packs often use a number of individual cells, connected in series and / or parallel. The actual cell sizes used to construct typical battery packs are shown in Table 4.

Table 3 Cells and Battery Packs Used In First Project Stage

I. D.	Chemistry	Shape	Cells In Pack	Representing
1.01	Lithium Ion	Prismatic	8	Laptop Computer
1.03	Lithium Ion	Cylindrical	2	Video Camera
1.05	Nickel Metal Hydride	Cylindrical	10	Laptop Computer
1.07	Li / MnO_2 Primary	Cylindrical	1	Still Camera
1.10	Li / $SOCl_2$ Primary	Cylindrical	1	Memory Back-up

Table 4 Cells Sizes Used In Constructing Battery Packs

I. D.	Type	Dimensions	Weight	Voltage / V		Capacity / A hr	
		/ mm	/ g	Cell	Pack	Cell	Pack
1.01	LP4	46 x 22 x 6.4	18.8	3.7	7.4	0.6	2.4
1.03	18650	65 x 18 ∅	42.7	3.7	7.4	2.0	2.0
1.05	4/3 A	67 x 17 ∅	54.2	1.2	12.0	3.7	3.7
1.07	DL123A	35 x 17 ∅	17.0	3.0	-	1.3	-
1.10	T04/8AA	25 x 15 ∅	9.7	3.6	-	1.0	-

In large scale manufacture of battery packs, plastic cases would be custom made to fit around the cells and their associated protection circuits, and in to the device. However, for this scale of testing, this is not appropriate. Therefore, standard cases of suitable size were used to prepare the battery packs. Figure 1 illustrates the pack arrangements used, at approximately half scale. The plastic in the cases was ABS (acrylonitrile – butadiene – styrene). The cells were connected in series and parallel to match the capabilities of the test equipment, rather than as they would be in a real device. For example, the eight prismatic cells were connected in parallel, whereas in a laptop computer battery a four parallel, two series arrangement would be used. This does not change the effect on the battery pack of the abuse test used to initiate a fire.

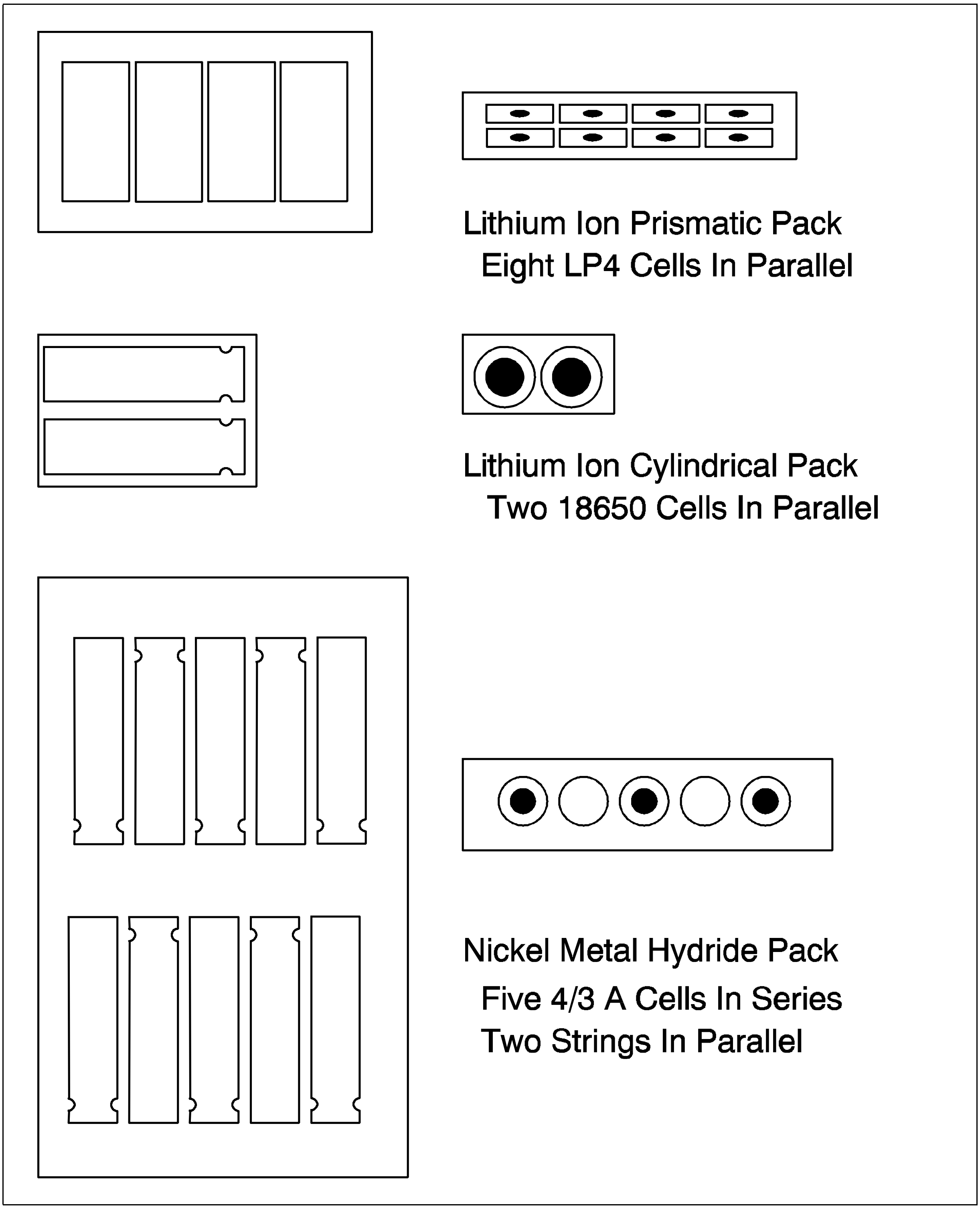


Figure 1 Pack Designs Used In Tests

All the cells under test had safety vents, which operate if the cell becomes pressurised. The lithium ion and lithium metal primary cells had shutdown separators, which stop current passing if they reach 120 – 130 ^{o}C. Some nickel – metal hydride cells also utilise a shutdown separator, but those under test in this project did not seem to shutdown up to 200 ^{o}C . The LP4 lithium ion prismatic cells had a pressure disconnect. This did not stop the cell catching fire during a fast overcharge test. The 18650 lithium ion cells contained a PTC (positive temperature coefficient) device, which stopped the current passing at around 60 ^{o}C. During some initial tests, the PTC was circumvented, as illustrated in Figure 2. A section of the positive terminal plate was carefully cut away, and the space between the top plate and the aluminium washer was then partially filled with conducting epoxy. After setting overnight, the epoxy provided a conduction path in parallel with the PTC, so that current could be passed after the PTC had switched to high resistance. However, the cells still did not catch fire during overcharge tests. Therefore, unmodified 18650 cells were used in the battery pack tests. Further details about these cell level protection devices are given in Appendix 1.

To summarise, all the cells used in the battery pack tests were as supplied, with no modifications. The difference from normal portable devices was the complete absence of protection circuits in the battery packs, and the disregard of the charging voltage / current limits incorporated into the battery chargers.

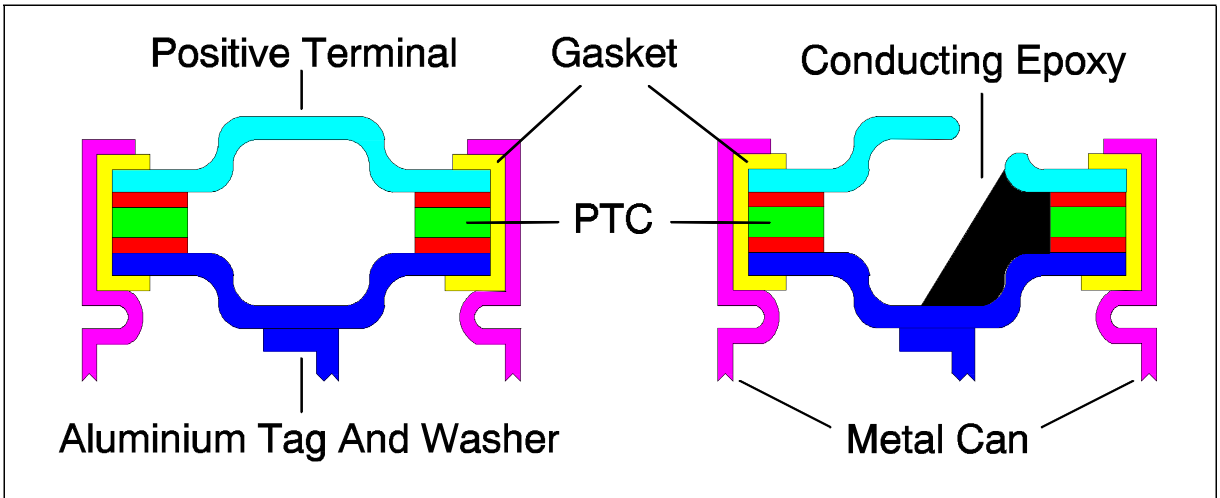


Figure 2 Modification to 18650 Top Cap to Disable PTC Device

In the second stage of the project, the same battery fires were induced, but this time with the battery pack inside a device. The test identifications and devices used are listed in Table 5. The devices were obtained from dealers who recondition and sell second-hand items; those supplied were not economic to repair. In the third stage of the project, the fires occur with the battery pack in a device, and the device wrapped in material typically used to carry the device. The identification codes for these tests are also given in Table 5.

Table 5 Batteries and Devices Used In Second and Third Project Stages

I. D.	Description Of Test Arrangement
2.01	As 1.01, but installed in a lap top computer
2.03	As 1.03, but installed in a video camera
2.05	As 1.05, but installed in a lap top computer
2.07	As 1.07, but installed in a still camera
3.01	As 2.01, but wrapped in flammable bag material
3.03	As 2.03, but wrapped in flammable bag material
3.05	As 2.05, but wrapped in flammable bag material

2.2 Description of Fire Extinguishers

The fire extinguishers and materials used in the project are listed in Table 6. The extinguishers were adapted so that they could be used remotely, but not modified in any other way. The water extinguisher was connected to its spray nozzle through a solenoid valve, using 10 mm pipe and fittings. An initial attempt to operate an ABC powder extinguisher through the solenoid failed. Therefore, the gas and powder extinguishers were manually operated from the control area. Around 5 m of pressure hose was used to connect them to a spray nozzle taken from an ABC powder extinguisher. The BC powder extinguisher was supplied with a 10 mm x 6 mm rectangular nozzle. The whole top cap assembly was removed, and replaced by a 6.35 mm stainless steel pipe, with a lab jack to supply the pressure when required.

Table 6 Fire Extinguishers and Materials Used In The Project

Type	Supplier	Size
Water	Lichfield Fire And Safety Equipment	9.0 litres
Halon	Chubb Fire Security Ltd. (via UKAEA)	1.5 kg
ABC Powder	Lichfield Fire And Safety Equipment	2.0 kg
BC Powder	Firemaster (via RS Components Ltd.)	1.0 kg
FE-36	Lichfield Fire And Safety Equipment	2.0 kg
Fire Blanket	Kidde Safety Europe Ltd. – BS EN 1869 : 1997	-
Fire Blanket	E.I. Company Ltd. – BS EN 1869 : 1997	-

2.3 Description and Operation of Test Rig

All the tests were performed in a safety test area, with continually running extract. There were two walls and two locked doors between this area and the operators in the control and observation area. The area had previously been used for standard safety and abuse tests on lithium ion batteries e.g. overcharge, short circuit, crush, and thermal exposure. A special rig was built to perform the specific tests for this project, as illustrated in Figure 3.

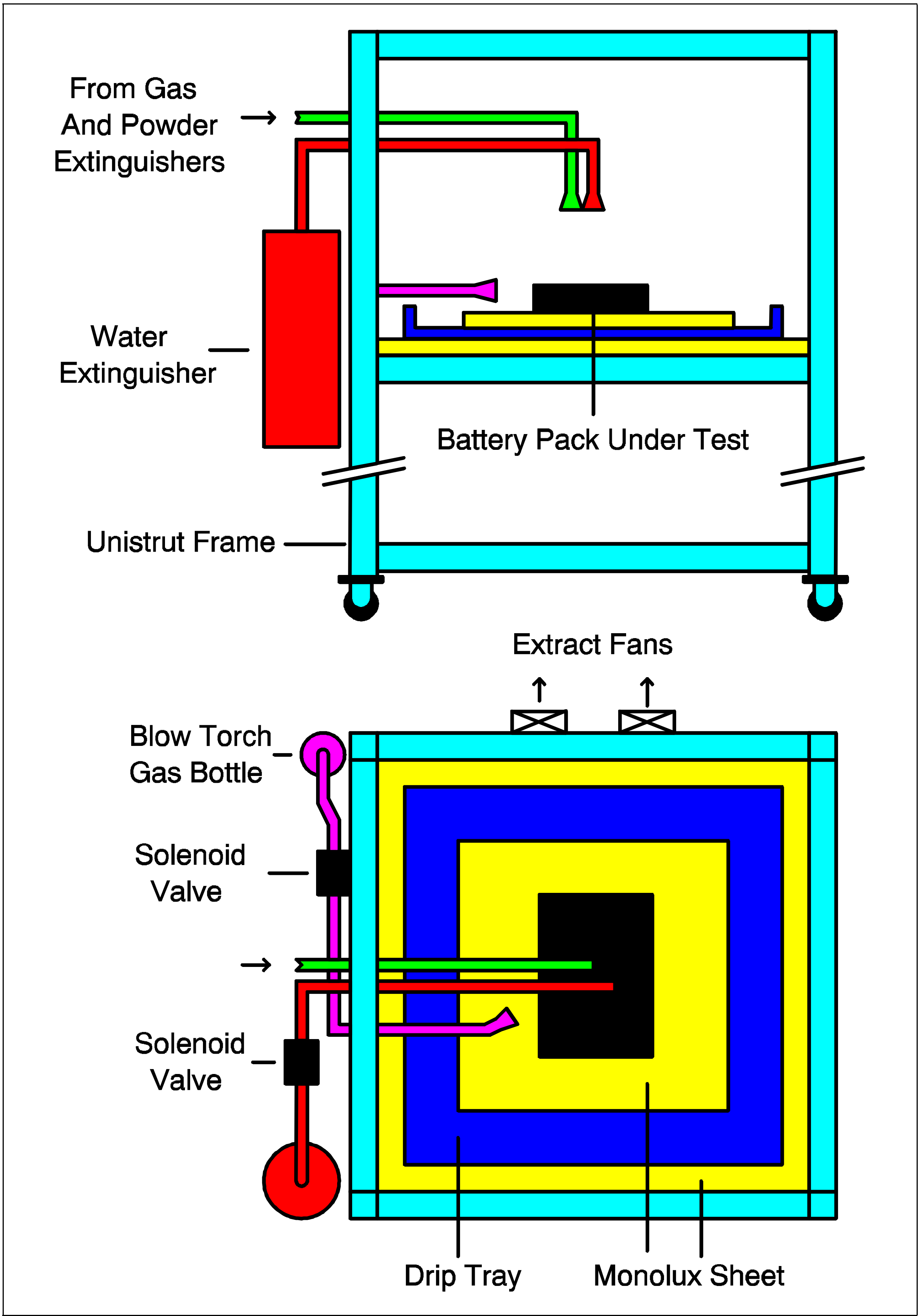


Figure 3 Test Rig Used to Perform Experiments

The test chamber had a solid metal plate on one side, metal mesh on two sides, and removable plastic mesh on the front face. The roof was also metal mesh, and the floor was Monolux, a fire-proof material used as a replacement for asbestos. Two small instrument fans were fitted to the back of the test chamber, to simulate the air flow in an aircraft cabin. Two video cameras were used to monitor the experiment, one in close up on the battery pack, and the other covering the whole test chamber. They were connected to TV / video recorders, to allow the results to be watched repeatedly.

Battery fires were achieved either electrically (through overcharging), or thermally, using a naked flame or heat gun. Charging was performed using a Maccor 2200 battery cycling unit, which produced up to 10 A and up to 12.3 V per channel. Higher currents were obtained by using two channels at the same time. The cycling unit recorded current, voltage, and temperature, using a thermocouple attached to the battery pack. The naked flame was produced by a small blow torch, modified so that the propane / butane tank was outside the test chamber, and connected to the burner head through a solenoid valve. As the torch was not self-igniting, a small candle was used as a pilot light. This allowed the operator to light the candle and leave the test area, before lighting the torch.

The fire blanket was the most difficult extinguisher method to operate remotely. A simple frame was constructed with four vertical tubes, and a square of metal. A 50 x 50 cm piece of fire blanket was taped to the metal square. When the release mechanism was activated, the fire blanket dropped over the device. The weights on the metal square ensured that the gap between the fire blanket and the insulating base plate was as small as possible. The design is illustrated in Figure 4. This approach worked well for battery fires which were triggered electrically. However, in the first test with the blow torch, one side of the metal square had to be removed, and that side of the fire blanket rested on the gas pipe rather than the base plate. Subsequently, the gas pipe entry point was re-positioned so that all four edges of the fire blanket rested on the base plate.

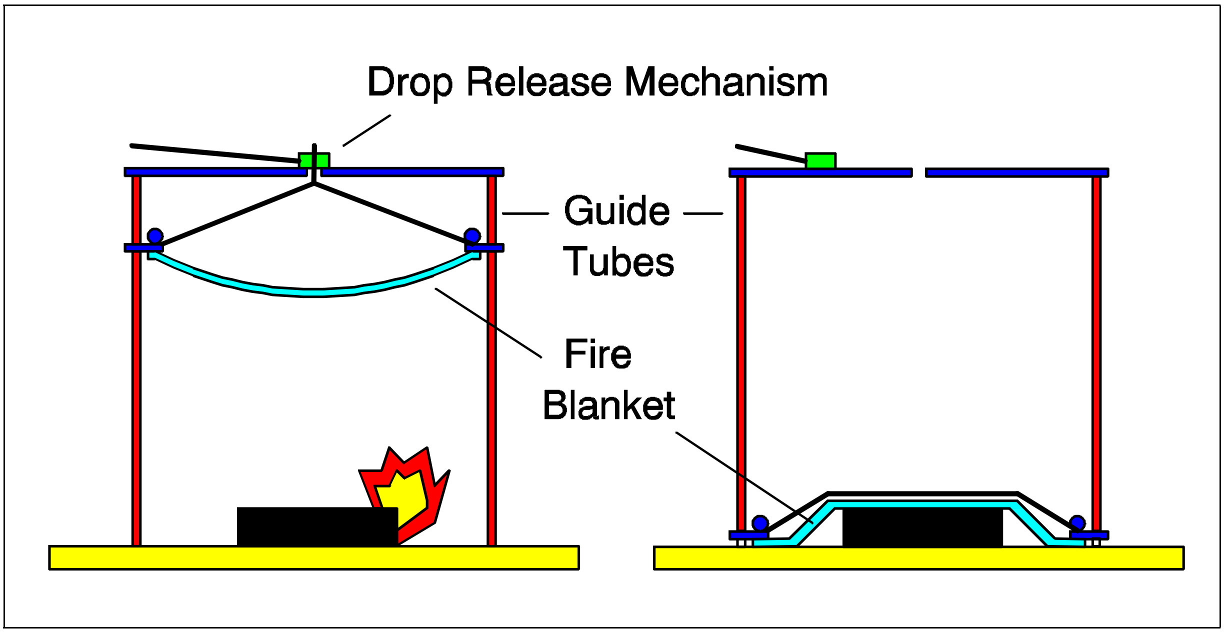


Figure 4 Modification to Test Rig for Experiments Involving a Fire Blanket

The devices were also used with a minimum of modification. The laptop computers were IBM Thinkpads, model 380Z. The side slots were large enough to contain the lithium ion prismatic and nickel – metal hydride cylindrical packs. They were therefore used as supplied, with two metal straps to hold them in position. The video cameras were Canon E60, E110, E200 or E230 models. The battery compartment had to be widened by around 2 mm, to allow the lithium ion cylindrical cell pack to be inserted. A single metal strap was used to hold the battery pack in place. The still cameras were Practica model SK320, purchased new rather than used. The battery compartment is designed for two AA alkaline cells. This compartment was cut open, and a single lithium / manganese dioxide cell was attached. This allowed the flame from the blow torch to be directed at the cell, while minimising contact between the flame and the camera body. The threaded tripod mounting point was used to hold both the video and still cameras in position.

3 Results

3.1 Scoping Trials On Single Cells

Prior to using the battery packs, single cells were tested, to determine the optimum procedure to produce a cell fire. In this context, optimum means reproducible, quick, and representative of a real / worst case fire. Graphs of cell voltage and temperature during the tests are given in Appendix 2. For rechargeable cells, overcharge is usually considered the most dangerous scenario. Overcharging increases the energy in the cell (and hence in any subsequent fire), while the short circuit test removes energy from the cell. For lithium metal primary cells, over-discharging and charging are considered to be hazardous. However, heating the cell with a flame is the most reliable method of producing a fire.

A single LP4 lithium ion prismatic cell was discharged to 2.5 V, and then charged at 1.2 A. This cell had a rated capacity of around 0.6 A hr, and a recommended charging current of around 0.3 A. After about 50 minutes on charge, the cell started to heat up. At 55 minutes, the cell caught fire. This test regime was therefore applied to the battery pack containing eight LP4 cells.

Single 18650 lithium ion cells were discharged to 2.5 V, and then charged at currents of 3 A, 4 A or 5 A. This cell had a rated capacity of around 2.0 A hr, and a recommended charging current of around 1 A. At 3 A and 4 A, the cell voltage increased suddenly after around 2.9 A hr, with the cell temperature at about 60 ^{o}C. At 5 A, the sudden voltage increase came much earlier. This suggested the operation of a PTC device, which prevented any further current being passed. To circumvent the PTC, conducting epoxy was introduced into the top cap of the cell, as described in Section 2.1. The overcharge test was repeated at currents of 4 A or 6 A. The cell voltages increased suddenly after around 3.1 A hr, with the cell temperature at around 100 ^{o}C. This suggested the operation of a shutdown separator, which is impossible to circumvent. The recommended test regime for the battery pack test was therefore to charge until the PTC operates, and then heat the cell pair, either with a heat gun or in a naked flame. This simulates the thermal runaway that can occur with a less sophisticated 18650 cell.

Single 4/3 A nickel – metal hydride cells were charged at currents of 3.6 A, 7.4 A or 10 A. This cell had a rated capacity of 3.7 A hr, and a recommended charging current of around 0.4 A. Even at 10 A, the cells did not catch fire. However, the cell temperature exceeded 200 ^{o}C, which damaged the plastic sleeve around the cell. It is also likely to damage the plastic case in the battery pack. Therefore, the recommended test regime for the battery pack was to charge at 10 A per cell.

A single DL123A lithium / manganese dioxide primary cell was heated with a heat gun. The cell vented at 141 ^{o}C, but did not catch fire. This confirmed that to cause a cell fire requires either a heat gun / ignition source combination, or a naked flame. In consequence, it was not necessary to perform any scoping trials on the lithium / thionyl chloride primary cell

3.2 Tests On Battery Packs

The test matrix for the first stage of the project is shown in Table 7. A battery fire was initiated for the five different battery pack types, and one of the five fire extinguishers was deployed, two minutes after the fire was first detected. The effectiveness of the extinguishers are summarised in Table 8. Further graphs of cell voltage and temperature during the tests are given in Appendix 3. Photos, including before and after shots, are presented in Appendix 4. In battery testing, the rated capacity of the cell is frequently abbreviated to C. Thus a C rate discharge will fully discharge the cell in one hour, whereas a 2 C discharge will discharge the cell in thirty minutes.

Table 7 Test Matrix For First Stage Of Project

I. D.	Water	Halon	FE-36	Dry Powder	
				ABC	BC
1.01	✓	✓	✓	✓	✓
1.03	✓	✓	✓	✓	✓
1.05	✓	✓	✓	✓	✓
1.07	✓	✓	✓	✓	✓
1.10	✓	✓	✓	✓	✓

Table 8 Test Results For First Stage Of Project

I. D.	Water	Halon	FE-36	Dry Powder	
				ABC	BC
1.01	Extinguished	Extinguished	Extinguished	Extinguished	Extinguished
1.03	Extinguished	Extinguished	Extinguished	Extinguished	Extinguished
1.05	Continued	Continued	Continued	Continued	Continued
1.07	Extinguished[1]	Extinguished[1]	Self Extinguished		
1.10	Extinguished[1]	Extinguished[1]	Self Extinguished		

1. Minimum practical delay, rather than standard two minute delay

The eight LP4 lithium ion prismatic cell pack (1.01) was overcharged at 9.6 A, corresponding to a 2 C overcharge for each cell (about four times the manufacturers recommended charging current). After around 50 minutes, there was a series of explosions, as the cells vented in flames. The plastic case then continued to burn, until extinguished by all five extinguishers. In one test, where the extinguisher failed to operate properly, the plastic fire continued to burn for 18 minutes. Either way, the cells and case were left as charred residue.

The twin 18650 cylindrical lithium ion cell pack (1.03) was overcharged at 8.0 A, corresponding to a 2 C overcharge for each cell. After about 40 minutes, the PTC operated, and no further current could be passed. The pack was then heated, with either a blow torch or heat gun, until the cells caught fire. The heat gun was preferred, because it allowed greater control and did not set fire to the plastic case. However, the blow torch was used for the test with the water extinguisher. The cell fires were violent, and usually separated by a few seconds. Unless the pack was well strapped down, it could be blown apart, and the separate pieces would then burn out in less than two minutes. If the pack remained intact, then the fire continued for two minutes, at which point it was extinguished by all five extinguishers.

The ten 4/3 A nickel - metal hydride cell pack (1.05) was overcharged at 20 A, corresponding to a 3 C overcharge for each cell (approaching thirty times the manufacturer's recommended charging current). Puffs of smoke began to appear at around 14 minutes, with continuous smoke from around 15 minutes. The extinguishers were operated two minutes after the start of continuous smoke. They cooled the battery pack, but did not stop the smoke. The charging current continued to pass, until manually stopped five minutes after the start of continuous smoke. The smoke then continued for at least another minute, before dying away. After the test, the packs were disassembled and examined. The source of the smoke appeared to be the plastic wrappers around the individual cells, rather than the cell contents or the plastic case. The extinguishers were unable to penetrate the case, or remove the heat source (the current).

A single DL123A lithium / manganese dioxide cell (1.07) was heated in the naked flame of a blow torch. After a few seconds, the cell appeared to vent, and a "solvent" type flame appeared. About ten seconds after this, a more spectacular "lithium metal" fire occurred. The fire quickly self-extinguished, and the red glow disappeared within a minute of the fire starting. The blow torch was switched off as soon as the initial cell fire occurred. In the initial test, the fire extinguisher was not used, because the cell fire self-extinguished before the standard two minute delay. In subsequent tests with water and halon extinguishers, the delay was reduced to the minimum possible (3 – 5 seconds). In both cases, the extinguisher put out the "solvent" fire, before it progressed to a "lithium metal" fire.

A single T04/8AA lithium / thionyl chloride cell (1.10) was heated in the naked flame of a blow torch. After a few seconds, there was a brief fire involving the plastic wrapper and the lithium metal in the cell. Thionyl chloride itself is not flammable. The blow torch was switched off as soon as the initial cell fire occurred. In the initial test, the fire extinguisher was not used, because the cell fire self-extinguished before the standard two minute delay. A water extinguisher was then used on the cell residue. There was no obvious reaction between the water and any residual thionyl chloride, suggesting that all the later had evaporated during the fire. In further tests with water and halon extinguishers, the delay was reduced to the minimum possible (3 – 5 seconds). In both cases, the fire was quickly put out, and the extinguishers certainly did not aggravate the situation. However, it is difficult to say that the fire was shorter with the extinguishers than without.

3.3 **Tests On Packs and Devices**

Following the tests on representative battery packs described in the previous section, the same packs were fitted to laptop computers, video cameras, or still cameras. Table 9 shows the tests which were performed, and Table 10 summarises the results.

Table 9 Test Matrix for Second Stage of Project

I. D.	Water	Halon	FE-36	Dry Powder	Fire Blanket
				BC	Blanket
2.01	✓	✓	✓	✓	✓
2.03	✓	✓	✓	-	✓
2.05	✓	✓	✓	-	✓
2.07	✓	✓	✓	-	✓

Table 10 Test Results for Second Stage of Project

I. D.	Water	Halon	FE-36	BC Powder	Fire Blanket
2.01	Flame Extinguished. Some Residual Smoke				
2.03	Flame Extinguished			-	Flame Extinguished
2.05	Smoke Continued			-	Smoke Probably Continued
2.07	Flame Extinguished			-	Fire Continued

Packs of eight lithium ion prismatic cells were placed in a laptop computer (2.01), and overcharged at the 2 C rate. This lead to a fire in the battery, which spread to the plastic case at the side and back of the computer. Installation of the packs in a laptop did little to dampen or reduce the explosive energy of the battery fire. The fire extinguishers and fire blanket were deployed two minutes after the start of the battery fire. All four extinguishers were effective, as was the fire blanket. The extinguishers were directed at the top of the computer, rather than into the battery compartment at the side. (In many laptop computer designs, the battery compartment is not directly accessible). The battery pack continued to smoke for some time after the extinguisher was fired, particularly with the water extinguisher. The halon, FE-36, and BC powder extinguishers were all rated as equally effective.

Packs of two cylindrical lithium ion cells were placed in a video camera (2.03), and overcharged at the 2 C rate. After around 30 minutes, the PTC safety devices within the cells operated, stopping any further current. The partially overcharged cells were then heated until they caught fire. For the tests involving the halon and FE-36 extinguishers, the cell pack was heated with a heat gun. For the tests involving the water extinguisher and the fire blanket, the cell pack was heated with a blow torch. (The pack lid was not fitted for these two tests). The cell fire spread to the surrounding plastic in the video camera. In some cases, the venting and subsequent fire of the second cell was sufficiently violent to rotate the video camera about its mounting point. The extinguishers or fire blanket were deployed two minutes after the start of the cell fire. All three extinguishers stopped the flame, though some smoke persisted from the plastic. All three were rated as equally effective. Following problems with the still camera / fire blanket combination (see below), the gas pipe was re-routed so that it did not obstruct the fire blanket (see also Section 2.3). Although the seal around the fire blanket was not perfect, the fire seemed to be extinguished quite effectively.

Packs of ten nickel – metal hydride cells were also placed in a laptop computer (2.05), and overcharged at the 3 C rate. This lead to smoke from the battery pack, and heat damage to the surrounding plastic computer case. The fire extinguishers and fire blanket were deployed two minutes after continuous smoke was observed. After a brief pause, the smoke continued, and indeed increased. The charging current was stopped five minutes after the start of continuous smoke. The smoke continued for several minutes, but gradually abated. With the fire blanket, puffs of smoke occasionally emerged from folds and gaps, until some time after the current was switched off.

Single DL123A lithium / manganese dioxide primary cells were mounted in still cameras (2.07), and heated with a naked flame. After a few seconds, the cells vented and the solvent caught fire. The blow torch was extinguished at this point. The solvent fire spread to the adjacent camera, and lead eventually to a lithium metal fire. The delay between solvent and lithium metal fires was typically ninety seconds, much longer than in the test of the cell on its own (1.07). The fire extinguishers and fire blanket were deployed two minutes after the start of the solvent fire. All three extinguishers were effective, though the camera body continued to smoke for a while afterwards. For the water extinguisher, the lithium metal fire started just as the extinguisher was fired. There was some reaction between the water and lithium metal, with bright flashes and small exlosions. Ironically, the FE-36 extinguisher did not extinguish the candle used as a pilot light. (The candle was away from the extinguisher application area, and close to the cell, which was still glowing white hot). The fire blanket was not effective in extinguishing the fire, and smoke and flame continued for around forty minutes. The gas pipe to the blow torch kept one side of the fire blanket off the base plate. In this arrangement, the blanket helped to keep heat in, while still allowing air access to the fire.

3.4 Tests On Packs and Devices and Bags

Following the tests on battery packs in portable devices described in the previous section, some of the tests were repeated with the devices inside typical carrying bags. Table 11 shows the tests which were performed, and Table 12 summarises the results. The bags were supplied by The Incentive Group, and were made of 100 % nylon.

Table 11 Test Matrix For Third Stage Of Project

I. D.	Water	Halon	FE-36	Fire Blanket
3.01	✓	✓	✓	✓
3.03	✓	✓	✓	✓
3.05	✓	✓	✓	✓

Table 12 Test Results for Third Stage of Project

I. D.	Water	Halon	FE-36	Fire Blanket
3.01	Flame partially extinguished	Flame extinguished. Smoke continues for some time		Smoke continues for some time
3.03	Flame extinguished. Smoke slow to clear			Flame continued. Smoke slow to clear
3.05	Smoke continued			

Packs of eight prismatic lithium ion cells were placed in a laptop computer, which was then placed in a carrying bag (3.01). The cells were overcharged at the 2 C rate, which caused a cell fire. This spread to the laptop computer and carrying bag, in the area around the battery pack. The extinguishers or fire blanket were deployed two minutes after the start of the fire. With halon and FE-36, the flames were extinguished, but smoke continued for several minutes afterwards. With water, the flame was reduced, but it took three applications of ten seconds each to stop the flame completely. Again smoke continued for several further minutes. With the fire blanket, it was impossible to say if the flame was extinguished. However, smoke appeared under the blanket for a similar length of time to the other extinguishers.

Packs of two cylindrical lithium ion cells were placed in a video camera, which was then placed in a carrying bag (3.03). A hole was cut in the side of the bag, to allow the battery pack to be heated. The cells were overcharged at the 2 C rate until the PTC operated, and they were then heated until the cells caught fire. For the tests involving the halon and FE-36 extinguishers, the cell pack was heated with a heat gun. For the tests involving the water extinguisher and the fire blanket, the cell pack was heated with a blow torch. (The pack lid was not fitted for these two tests). The cell fire spread to the surrounding plastic in the video camera, and rapidly across the whole carrying bag. The extinguishers or fire blanket were deployed two minutes after the start of the cell fire. There was a significant quantity of smoke produced during this period. For the halon extinguisher, there was so much smoke that the room darkened during the two minutes.

All three extinguishers stopped the flame, though the smoke persisted for several minutes. All three were rated as equally effective. For the FE-36 extinguisher, one of the cells was propelled to the mesh at the side of the enclosure, and the centrally aimed extinguishant was unable to stop the fire in this location. Although the seal between the fire blanket and the base of the apparatus seemed reasonable, the fire blanket did not extinguish the fire. A small region of flame could be seen for at least twenty minutes after the blanket was deployed.

Packs of ten nickel – metal hydride cells were placed in a laptop computer, which was then placed in a carrying bag (3.05). The cells were overcharged at the 3 C rate, causing smoke to emerge from the battery pack. The three extinguishers and fire blanket were deployed two minutes after continuous smoke was observed. In all four cases, the smoke continued, and the charging current was therefore stopped after a further three minutes. There was much less observable smoke than in the tests on the battery pack (1.05), and the pack in a laptop computer (2.05). Presumably, the carrying bag trapped much of the smoke, with some escaping through gaps and folds. Under these circumstances, it is likely that a “smell of burning” would have been detected before the smoke.

4 Conclusions and Recommendations

4.1 General Conclusions

The following conclusions can be drawn from the tests described in this report:

a) Fires can occur in the battery packs of portable electronic devices, though the probability of such a fire in-flight is considered to be extremely low, because of the built in safety devices.

b) For a lithium ion battery fire to occur in a portable electronic device, there needs to be a failure of the built in protection devices; most PEDs have three levels of protection. Multiple failures in the protection system are unlikely, but not completely unknown during ground based operation. They must therefore be considered as a potential risk, and treated as a hazard to an aircraft during the ground or flight phases of operation.

c) If a battery fire does occur, it will almost certainly cause severe harm to any passengers in the immediate vicinity. There is also a risk that the fire will spread to adjacent flammable material e.g. clothing, newspapers, rugs, carpet.

d) If a battery fire does occur, then there is a risk of harm from smoke inhalation to passengers and crew members, particularly if the electronic device is inside a carrying bag. Additionally, panic can be expected amongst the passengers who see the fire, or subsequently smell burning plastic.

e) It is beyond the scope of this project to assess how quickly the smoke would be cleared by the cabin air conditioning system, or how passengers would behave in such a situation. However, these are issues that the CAA may want to consider.

f) If a battery fire does occur, the explosive effect is not judged to be of a size that would cause damage to the aircraft structure. For example, the energy was not sufficient to shake a video camera positioned within two metres of the battery fire. However, individual cells may be propelled out from the battery pack.

g) The use of fire extinguishers did not aggravate the situation in any of the tests performed during the project.

h) With some fires, halon and the halon replacement FE-36 were more effective than water in extinguishing the flame. This was particularly true when the water could not be aimed directly at the fire. (There is no guarantee that the fire will be pointing towards the person operating the fire extinguisher).

i) The halon and FE-36 halon replacement extinguishers were rated as equally effective. Standard tests on more quantifiable fires can almost certainly be used as indication of their relative effectiveness.

j) Fire blankets were effective in extinguishing the fire, provided they completely enclosed the item on fire. In this context, they may be more appropriate for wrapping a still smoking item, after the initial flames have been knocked down by a water, halon, or halon replacement extinguisher.

4.1.1 Conclusions Relating to Batteries not Installed in a Device

a) The following procedures can be used to intiate battery fires in single cells:

- lithium ion prismatic cell - overcharge at four times the manufacturer's recommended charging current.
- lithium ion cyclindrical cell - overcharge at four times the manufacturer's recommended charging current, then heat.

- nickel – metal hydride cell	- overcharge at thirty times the manufacturer's recommended charging current (smoke not fire).
- lithium / MnO_2 primary cell	- heat with a naked flame.
- lithium / $SOCl_2$ primary cell	- heat with a naked flame.

b) A shutdown separator on its own is not necessarily sufficient to prevent a lithium ion cell from catching fire, particularly with a higher than recommended charging current. The main protection comes from the voltage and current protection circuits incorporated in battery packs, and deliberately excluded in these tests.

c) With a pack of lithium ion prismatic or cylindrical cells, the battery fire started as a series of explosions. There was no visual indication that this was about to occur, though the pack would have felt hot to the touch. All the extinguishers were effective in dealing with the fire. No extinguisher aggravated the situation, or reacted in an adverse way with the battery materials.

d) There may be an instinctive reaction against using water on a "lithium" fire, but it is actually the resultant plastic fire that needs to be extinguished.

e) With a pack of nickel – metal hydride cells, there was no fire or explosion, just copious smoke. None of the extinguishers stopped the smoke, but they did not make the situation worse. The smoke was stopped by switching off the charging current.

f) The fires with lithium / MnO_2 and lithium / $SOCl_2$ primary cells self extinguished within two minutes. With the former, immediate application of a fire extinguisher prevented the fire from progressing from a "solvent" to a "lithium metal" fire. With the latter, it was difficult to say that the extinguisher actually shortened the fire.

4.1.2 Conclusions Relating to Batteries Installed in a Device

a) The fires with the lithium ion prismatic cell pack in a laptop computer, and with the lithium ion cylindrical cell pack in a video camera, were the same as the fires without the devices. All the extinguishers, and the fire blanket, were effective in putting out the fire, though smoke from the plastic continued after the flame was extinguished.

b) The smoke from the nickel – metal hydride cell pack in a laptop computer was also the same as the fire without the device. None of the extinguishers, or the fire blanket, were effective in stopping the smoke, but switching off the charging current was effective.

c) The fire with the lithium / MnO_2 primary cell in a still camera was different from the cell fire with no device. The progression from "solvent" to "lithium metal" fire took around ninety seconds rather than around ten seconds, probably because the cell was vertical rather than horizontal. All the extinguishers were effective in putting out the fire, though the water reacted with the lithium metal fire, which started just as the extinguisher was operated. The fire blanket was not effective, because it did not enclose the burning camera completely.

4.1.3 Conclusions Relating to Batteries Installed in a Device in a Bag

a) The fires with the lithium ion prismatic cell pack in the laptop computer, inside a plastic carrying case, were similar to the fires without the case. The plastic case burned in the area around the battery fire. The halon and FE-36 extinguishers were more effective than water in knocking down the flames. Smoke from the plastic continued for some time after the flame was extinguished, as it did with the fire blanket.

b) The fires with the lithium ion cylindrical cell pack in the video camera, inside a carrying case, were much worse than fires without the case. All of the case was consumed in flames, and fire spread to parts of the video camera which did not burn with no case present. All the extinguishers, and the fire blanket, were effective in stopping the flame. However, a large quantity of smoke was produced, which took a considerable time to clear.

c) The quantity of smoke from the nickel – metal hydride cell pack in the laptop computer, inside a carrying case, was less than in the absence of the case. None of the extinguishers, nor the fire blanket, were effective in stopping the smoke, but switching off the current was effective.

4.2 Recommendations

In the light of the above conclusions, the following recommendations are made:

4.2.1 If a battery fire is suspected, the power to ALL recharge points should be turned off as quickly as possible (arguably before deploying any fire extinguishers).

4.2.2 For battery fires involving packs with more than one lithium ion cell, the individual cell fires occur over a period of several seconds rather than simultaneously. There is thus a possibility of further cell explosions (similar to a firework) for at least a minute into the fire, which represents a danger to those in close proximity to the fire. Such fires should be approached with this possibility in mind, and appropriate protective equipment should be worn. Multiple cell packs are used in lap top computers and video cameras, but not normally in mobile phones.

4.2.3 Halon and FE-36 halon replacement extinguishers were more effective than water for some of the fires, and should be used first, if a choice is available.

4.2.4 Fire blankets can be effective in dealing with fires in portable devices. However, it is essential that the blanket completely encloses the device, preventing further contact with air. This was not always successfully achieved in the laboratory tests, and may be impractical in a real situation. Additionally, the person deploying the blanket will need to wear a smoke hood or similar device to prevent smoke inhalation.

4.2.5 In general, the deliberate charging of portable electronic devices from aircraft supplies should be avoided. Unfortunately, when devices like laptop computers are plugged into an electrical supply, battery charging normally occurs automatically. Passengers should be discouraged from plugging in devices solely for the purpose of charging, to minimise the risk from a battery or charger fault. Passengers should be discouraged from charging video cameras on board aircraft.

4.2.6 In the unlikely event of a fire, a thorough investigation should take place to determine the cause. The following questions should be answered wherever possible:

- what was the manufacturer and model number of the device?
- was the battery pack supplied by the device manufacturer or a third party?
- was the battery being charged when the fire started?
- was the charging cable supplied by the airline or the passenger?

Appendix 1 Safety of Lithium Ion Batteries

The safety of lithium ion batteries during transport is an important issue, as reflected in the stricter UN Transport test regulations produced recently [1]. In the airline industry, the two main concerns are the bulk transport of manufactured cells, and the safety of battery packs belonging to individual customers. Under normal operating conditions, lithium ion batteries are safe, but there is a risk of fire under certain abuse conditions, particularly overcharge. The reasons for this are explained below.

The safety of lithium ion cells and battery packs is generally ensured through a combination of protective features:

- the inherent safety of the cell, through thermal and pressure disconnects and shutdown separators.
- protective electronics built into battery packs, to prevent overcharge, over-discharge, and external short circuit.
- regulation of the external charging device, to limit voltage and current.

The cells would normally be subjected to a series of safety and abuse tests, like those published by the IEC [2] or Underwriters Laboratory [3]. Cells are not sold directly to the public, but only to reputable pack assemblers. In theory, an abuse condition like overcharge could only arise through a failure of all three levels of protection at the same time. However:

- heat transfer out from the cell is reduced when the cell is enclosed within a battery pack, which can increase the risk of thermal runaway.
- some manufacturers are simplifying the protection circuits in battery packs for devices like mobile phones, to reduce costs.
- some airlines have installed power supplies for recharging batteries in the seats of passenger aircraft, with power outputs of up to 100 W. The detailed design and specification of these power supplies is beyond the scope of this report.
- some passengers may use auxillary battery packs during long flights, including generic packs supplied by third parties, and packs which they have not used previously.
- some passengers may customise the leads used to connect devices to the charging points in airline seats.

In consequence, there is a remote possibility that there will be fires associated with the battery packs of laptop computers, video cameras, or other portable devices on aircraft.

Lithium ion batteries use two insertion electrodes, a transition metal oxide cathode ($Li_{1-y}MO_2$) and a graphite anode (Li_xC_6). During charging, lithium is extracted from the cathode and inserted into the anode. During discharge, the reverse reactions occur. There is no lithium metal, which makes the battery safer, and gives an operating life of several hundred cycles.

At present, most commercial lithium ion cells use cobalt as the transition metal in the cathode. To achieve the required cycle life, this can only be used over the range $0 < y < 0.5$. In practice, this is achieved by limiting the charging voltage to 4.2 V. If this voltage is exceeded ($y > 0.5$), then there are irreversible phase transitions, and eventually decomposition. This final stage can be represented as:

$$2\ Li_{0.1}CoO_2 \rightarrow Li_{0.2}CoO_2 + CoO_2$$

$$3\ CoO_2 \rightarrow Co_3O_4 + O_2\ (g) + \text{Heat}$$

During charging, it is possible to plate out lithium metal, rather than insert lithium into the carbon anode. To avoid this, the charging current is limited, and the cell is designed with an excess of anode capacity. However, during overcharge the anode will eventually fill up, and lithium metal will deposit. The ultimate consequence of overcharge is finely divided lithium metal, oxygen, and a flammable organic solvent, all being heated inside a pressurised metal can. Above about 80 ^{O}C, there are a number of exothermic chemical reactions, which contribute to the problem.

The fate of the cell will depend on the relative rates of heat generation within the cell and heat removal from it. If the rate of heat generation is less than the rate of heat removal, then the cell will reach a peak temperature and then cool. However, if the rate of heat generation is greater than the rate of heat removal, the cell will continue heating, and eventually catch fire.

To prevent this happening, there are safety devices included at the individual cell, the battery pack, and the system level. The most basic safety feature in cells is a pressure vent. This is designed to operate at 10 – 20 bar in response to an increase in internal pressure. It prevents the more variable and violent explosion which would otherwise occur if the pressure continued to increase. Pressure disconnects are also activated by increasing cell pressure, and stop any further current from flowing. Pressure disconnects are designed to operate at a lower pressure than cell vents. They generally work by mechanical deformation of a thin strip of metal, which is carrying current through the cell. Some manufacturers include a gassing agent in their cell, which generates gas (and hence internal pressure) if the cell is overcharged.

Shutdown separators are activated by temperature. The two electrodes in a cell are kept apart by a porous, insulating sheet. When this material is heated above its plastic transition temperature, it starts to deform. When it operates properly, the pores get blocked, and the cell resistance increases to stop current flowing. However, the separator can also shrink, allowing the two electrodes to make contact as an internal short circuit. PTC or positive temperature coefficient devices are also temperature activated. They are best considered as partially resetable fuses. As the temperature increases, the resistance of the PTC suddenly increases by several orders of magnitude. The trigger temperature also depends on the current; a lower temperature is required at higher currents

The standard reactions in a nickel – metal hydride cell are:

$$Ni(OH)_2 + OH^- \leftrightarrow NiOOH\quad H2O\quad e^-$$

$$M + H_2O + \leftrightarrow MH_{ads} + OH^-$$

In the event of overcharge, the following reactions occur:

$$4\ OH^- \rightarrow 2\ H_2O + O_2\ (g) + 4\ e^-$$

$$4\ H_2O + 4\ e^- \rightarrow 4\ OH^- + 2\ H_2\ (g)$$

$$2\ H_2\ (g) + O_2\ (g) \rightarrow 2\ H_2O + \text{Heat}$$

In some cell designs, a recombination catalyst e.g. platinum is included, to facilitate the reaction between hydrogen and oxygen. However, there is some build up of pressure within the cell, and the cell temperature increases. If the cell vents, then there is a possibility of an explosive reaction between the hydrogen and oxygen. Unlike lithium ion cells, though, the electrolyte is not volatile or flammable.

References

1 UNST/SG/AC.10/27/Add.2 from ST/SG/AC.10/11/Rev.3
"Amendments to the third revised edition of the recommendations on the transport of dangerous goods, manual of test and criteria"

2 IEC 61960-1"Secondary lithium cells and batteries for portable applications. Part I: Secondary lithium cells."

3 UL1642 "Standard for lithium batteries."

Appendix 2 Scoping Tests

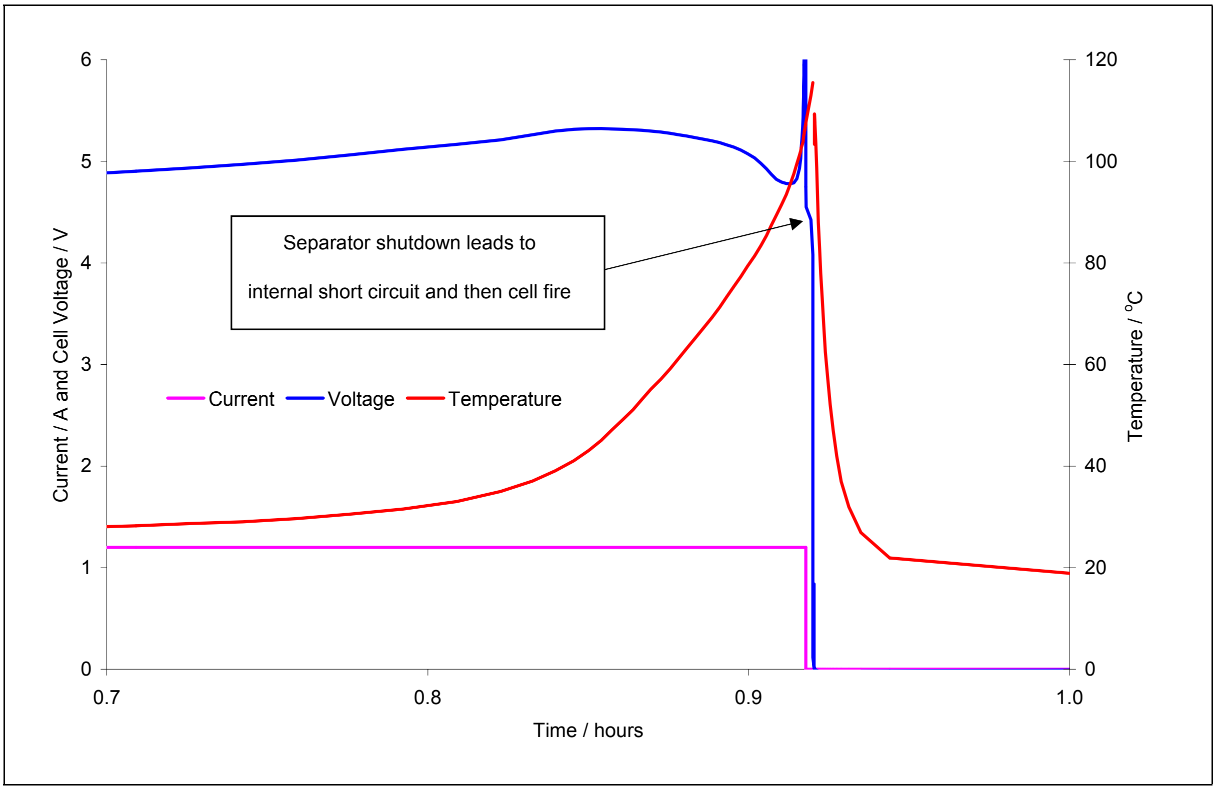


Figure 5 Overcharge of Single LP4 Lithium Ion Prismatic Cell

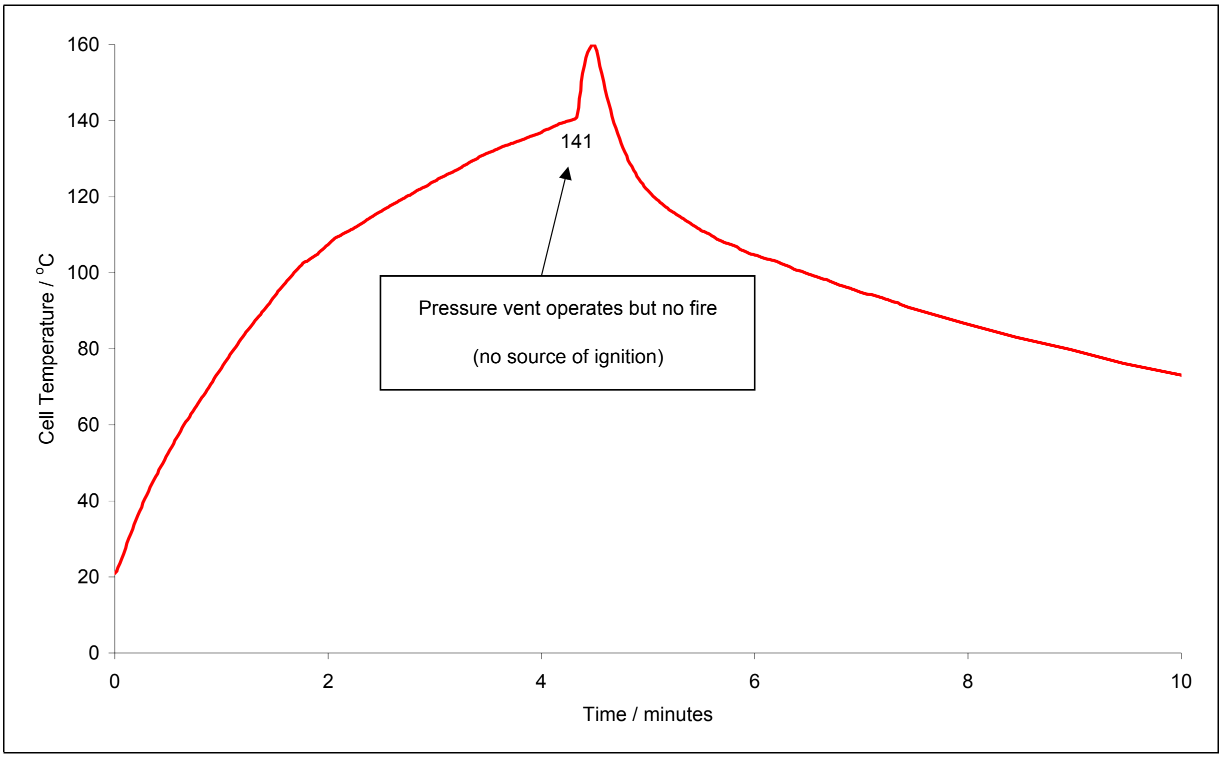


Figure 6 Heating of Single DL123A Lithium / Manganese Dioxide Cell

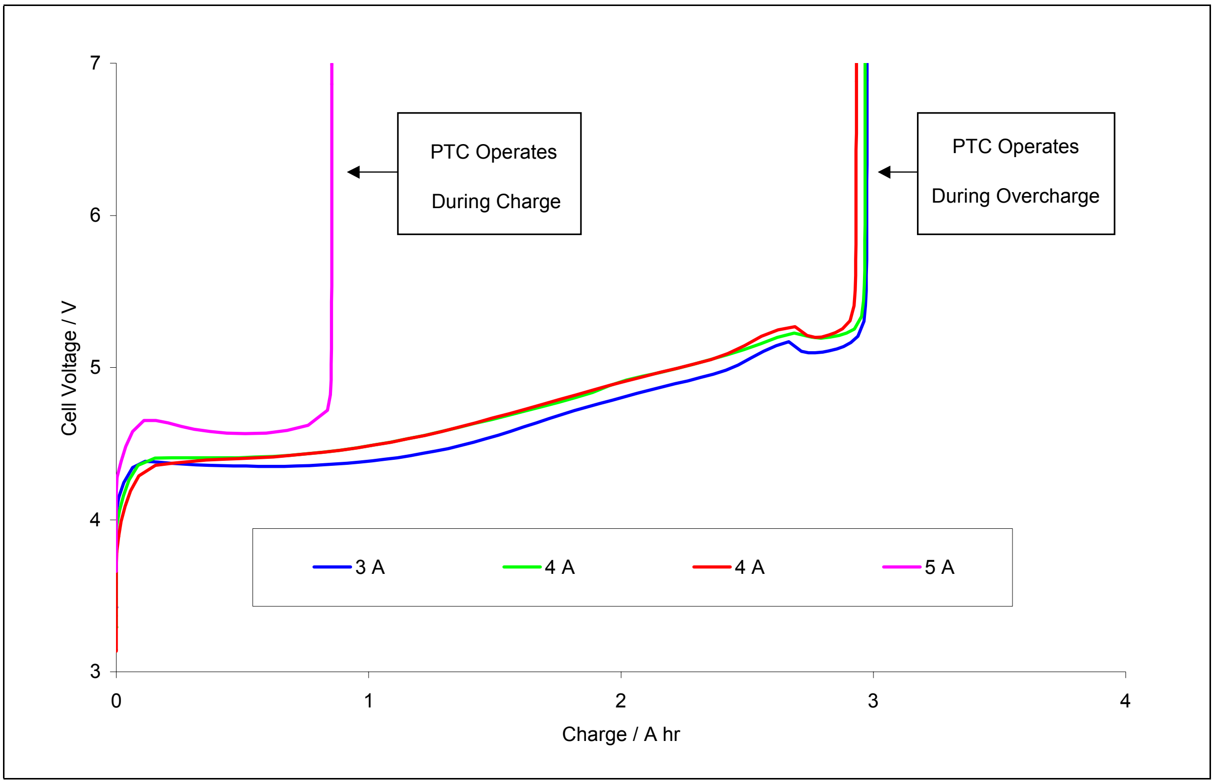


Figure 7 Cell Voltage During Overcharge of Single 18650 Lithium Ion Cell

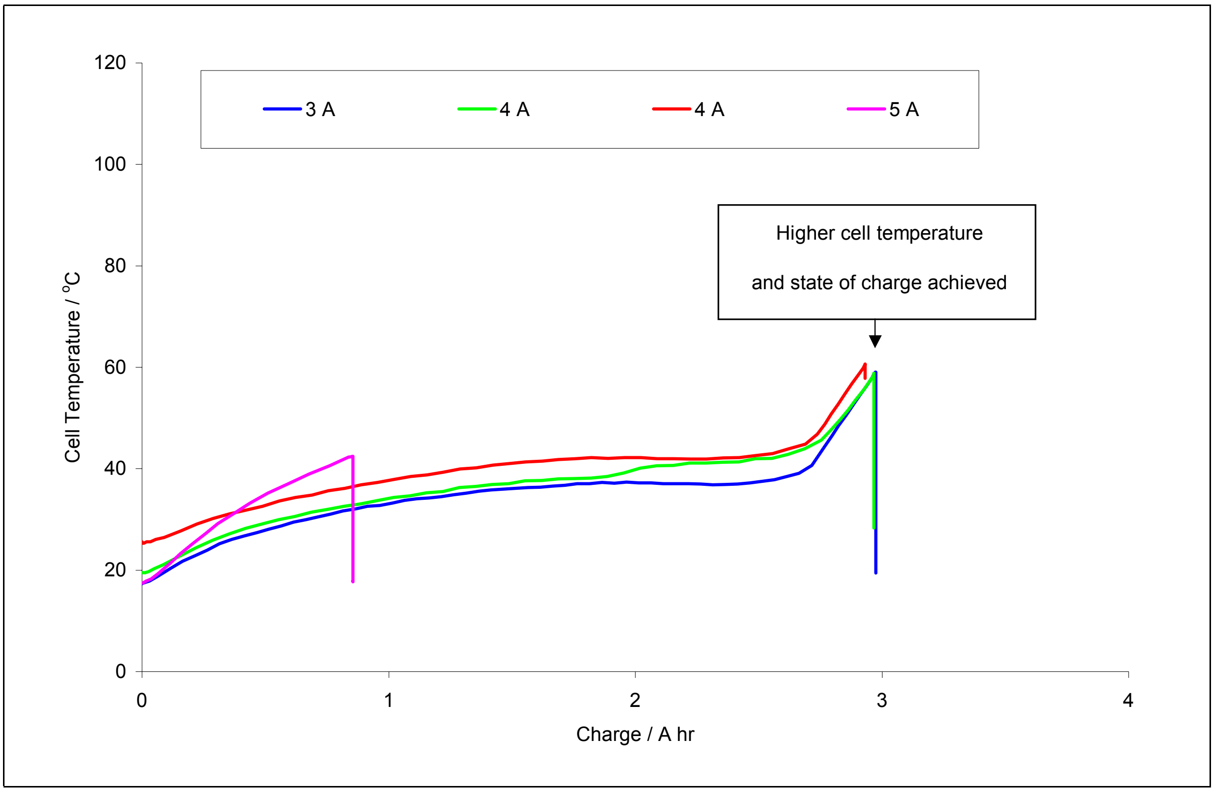


Figure 8 Cell Temperature During Overcharge of Single 18650 Lithium Ion Cell

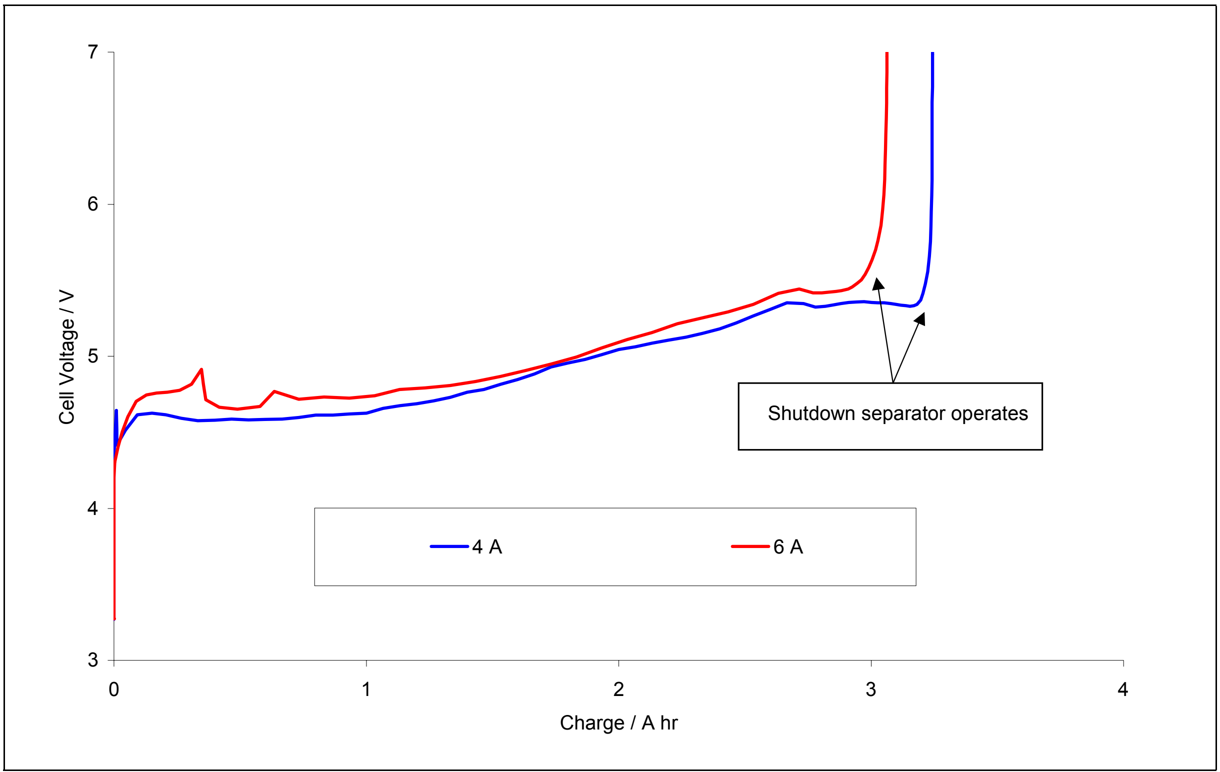


Figure 9 Cell Voltage During Overcharge of Modified 18650 Lithium Ion Cell

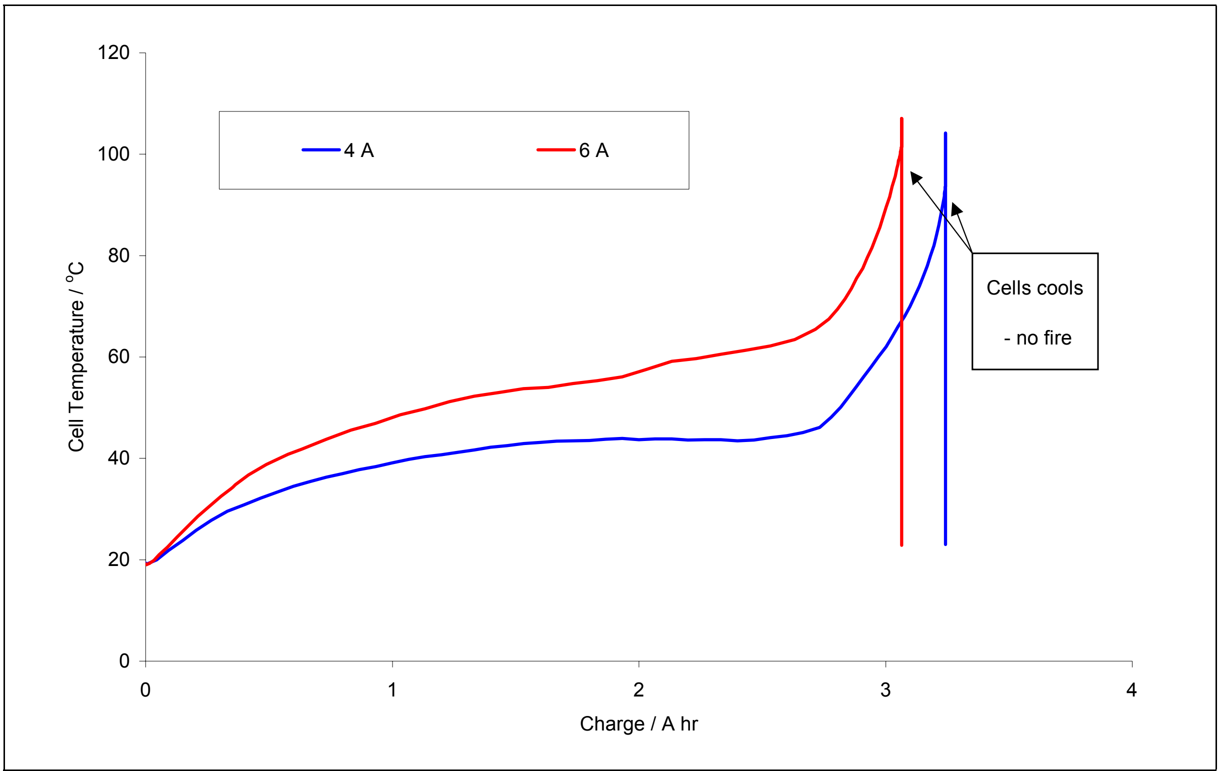


Figure 10 Cell Temperature During Overcharge of Modified 18650 Lithium Ion Cell

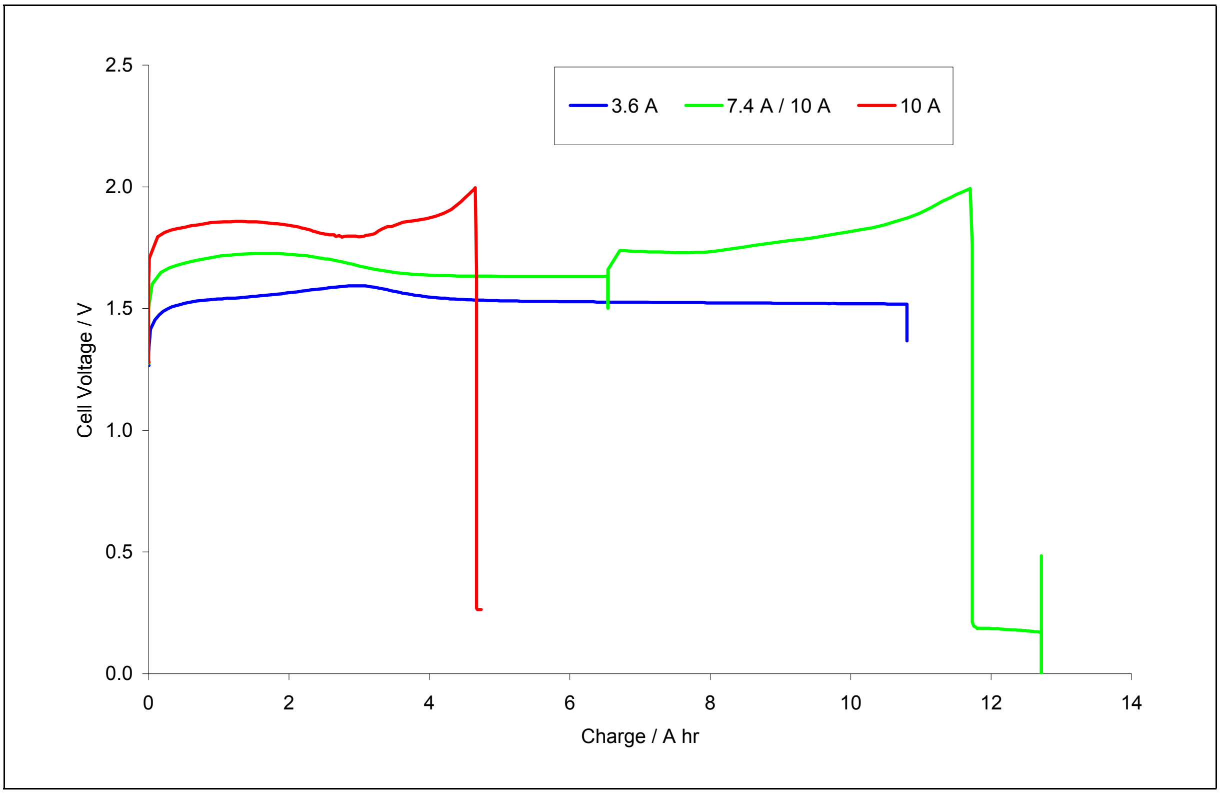


Figure 11 Cell Voltage During Overcharge of Single NiMH Cell

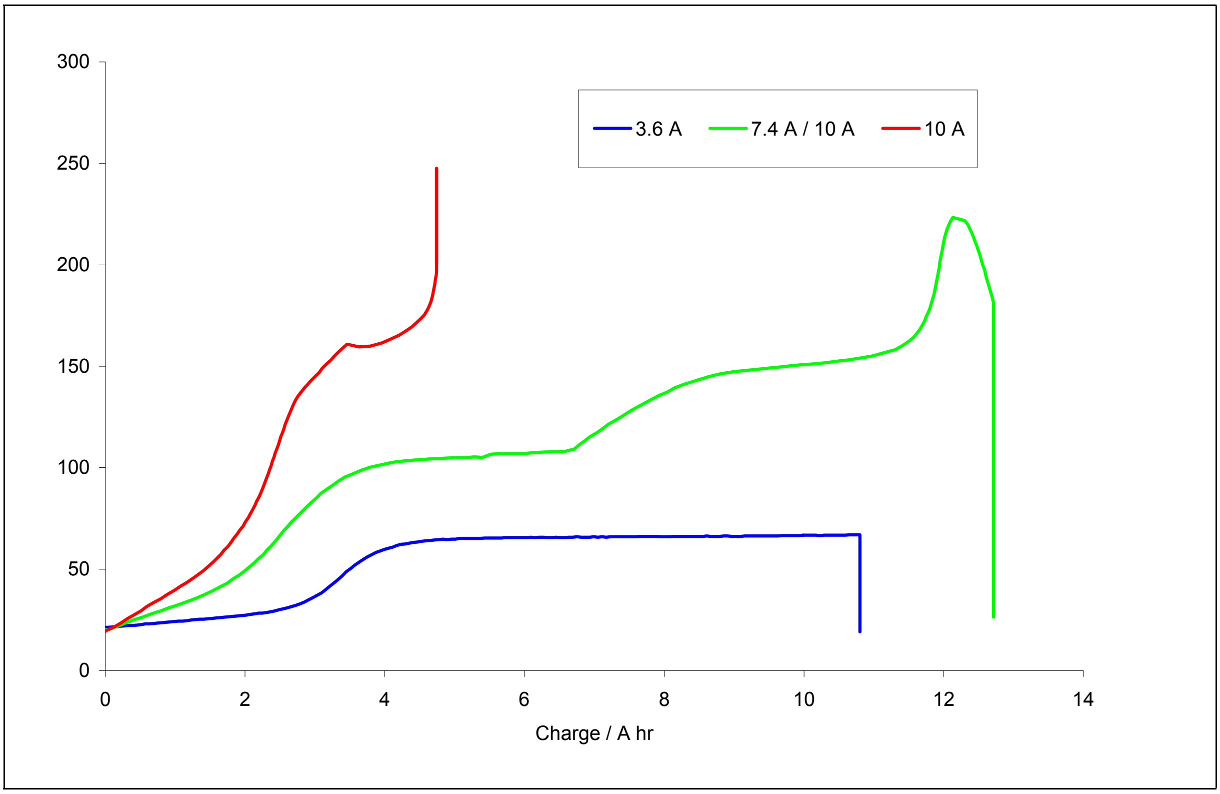


Figure 12 Cell Temperature During Overcharge of Single NiMH Cell

Appendix 3 Battery Pack Tests

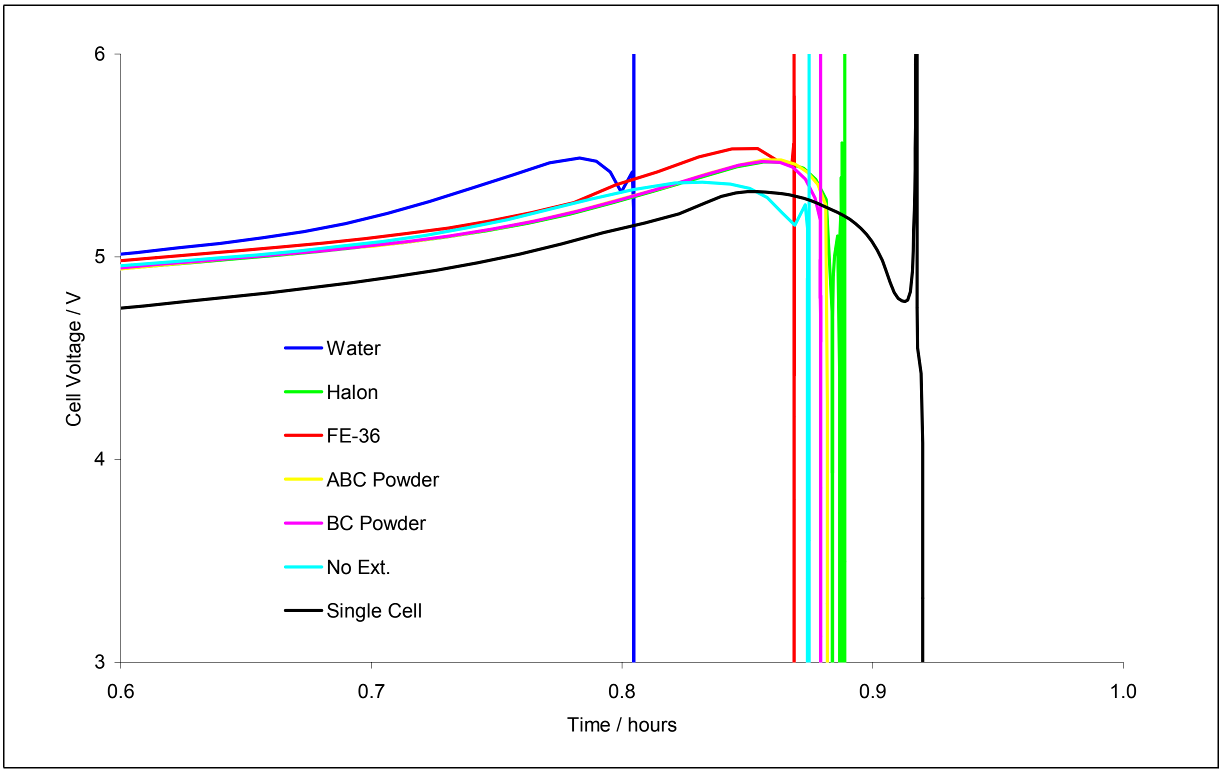


Figure 13 Pack Voltage of Eight LP4 Lithium Ion Prismatic Cell Pack

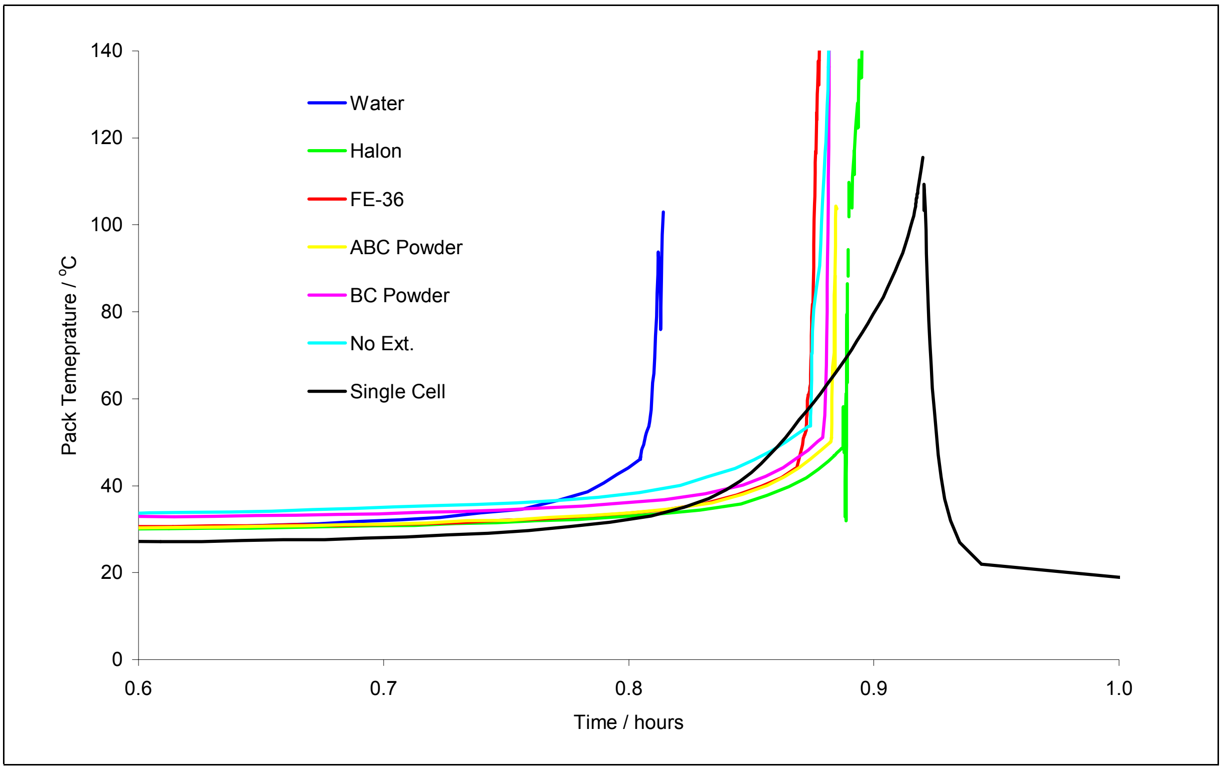


Figure 14 Pack Temperature of Eight LP4 Lithium Ion Prismatic Cell Pack

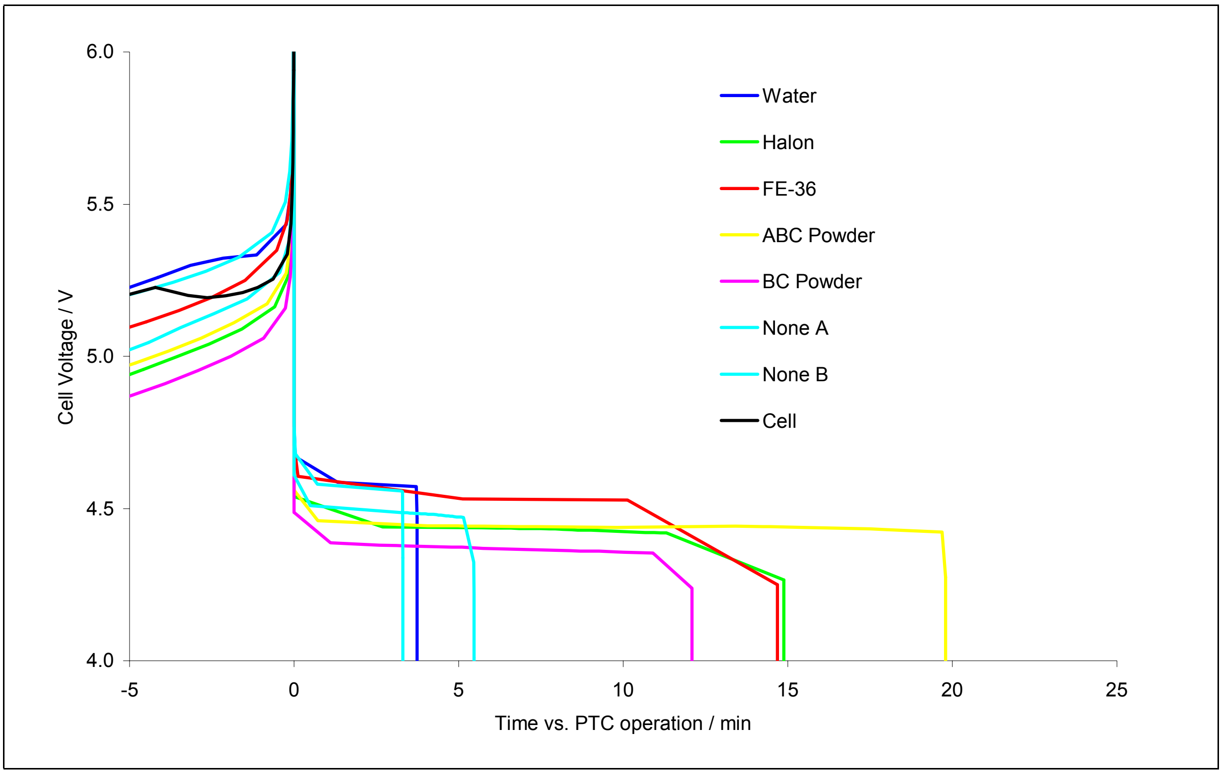


Figure 15 Pack Voltage of Twin 18650 Lithium Ion Cell Pack

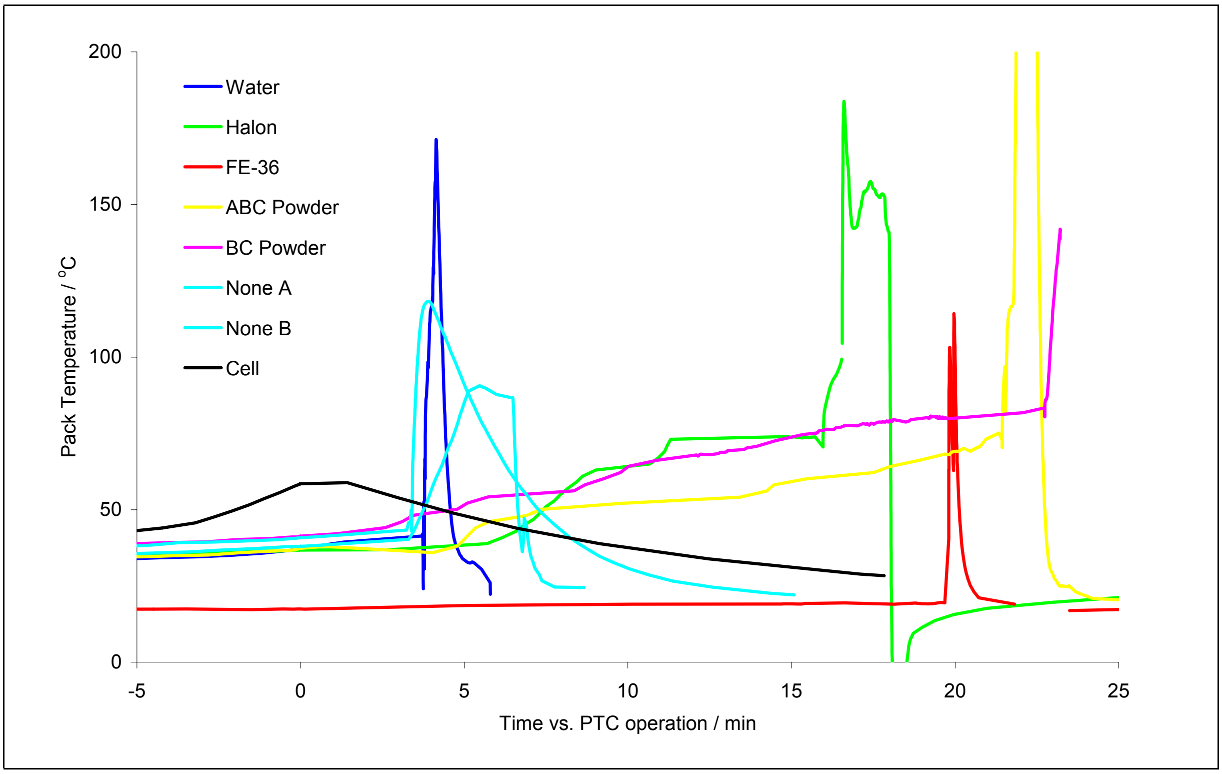


Figure 16 Pack Temperature of Twin 18650 Lithium Ion Cell Pack

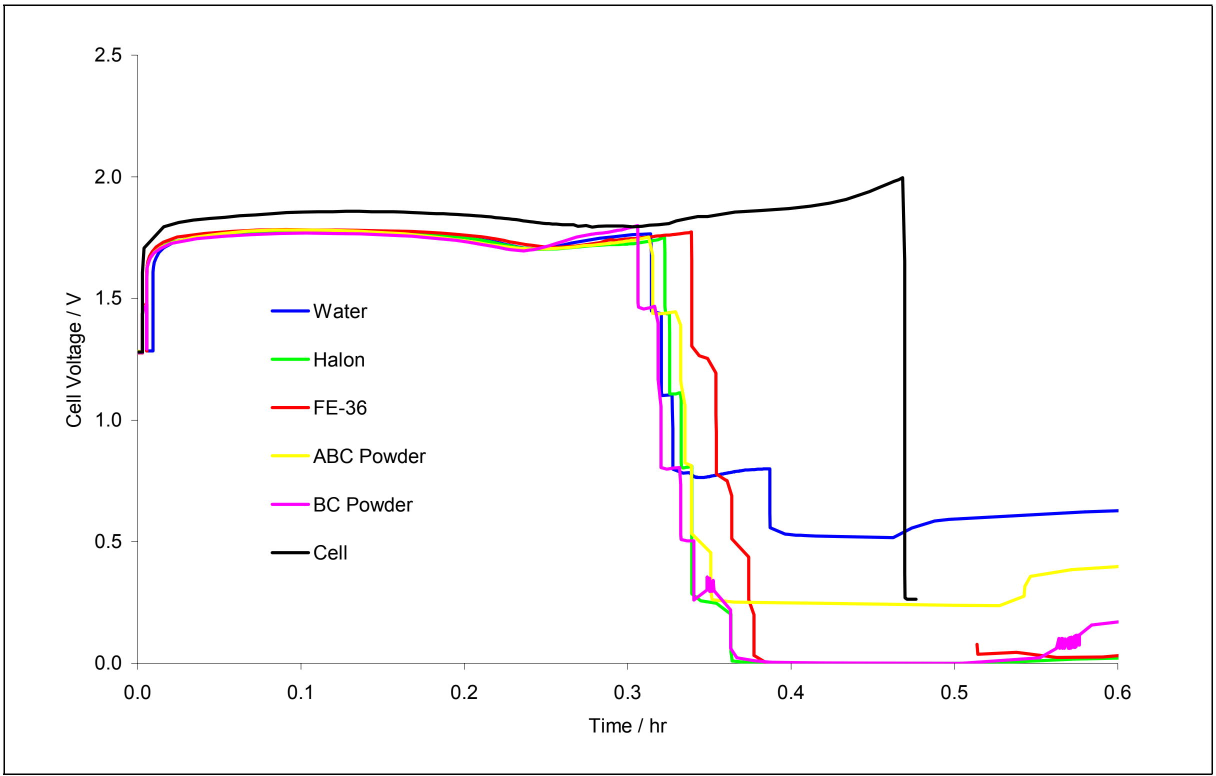


Figure 17 Average Cell Voltage of Ten Nickel – Metal Hydride Cell Pack

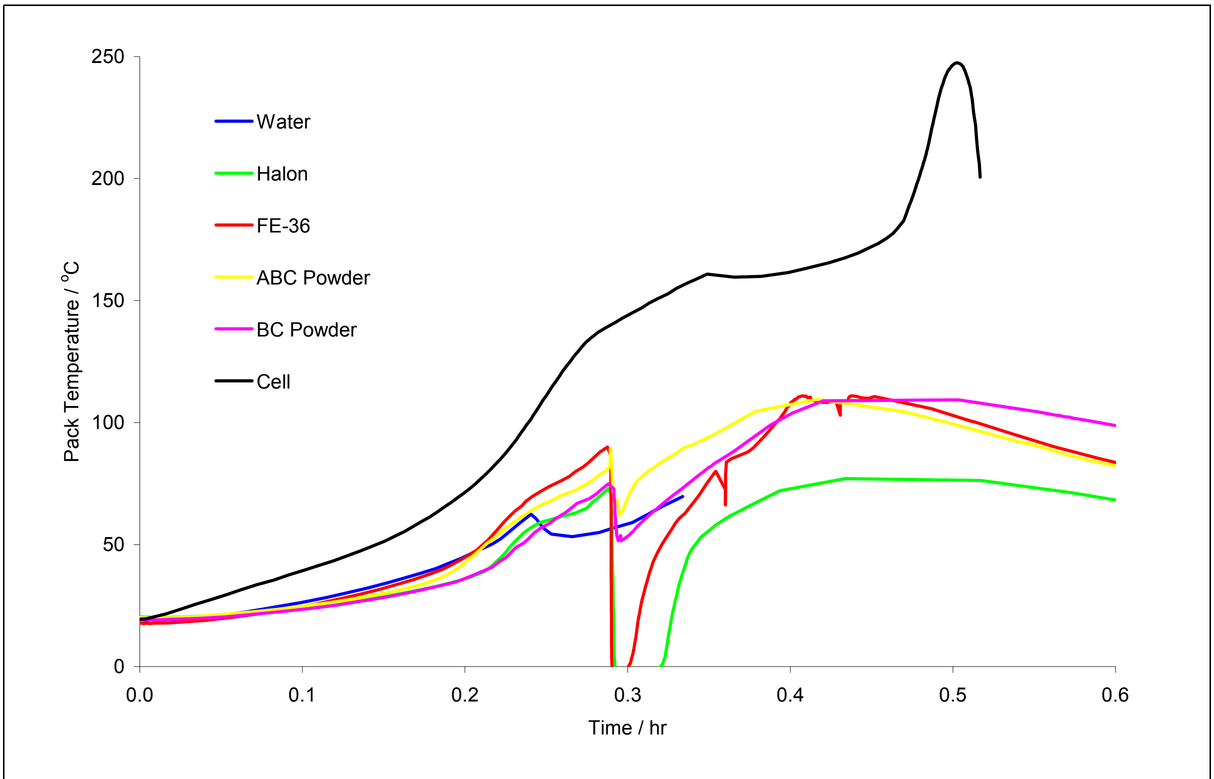
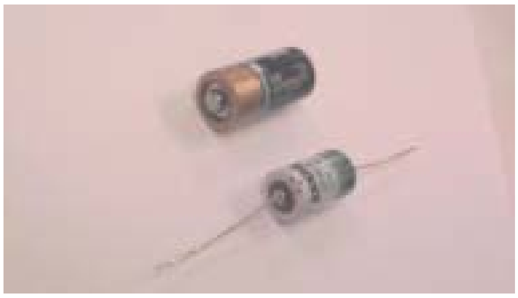


Figure 18 Pack Temperature of Ten Nickel – Metal Hydride Cell Pack

Appendix 4 Cell Pictures

Rechargeable Cells



Lithium Metal Primary Cells

Eight LP4 Cell Pack (Before)

Eight LP4 Cell Pack (After)

Twin 18650 Cell Pack (Before)

Twin 18650 Cell Pack (After)

Ten NiMH Cell Pack (Before)

Ten NiMH Cell Pack (After)

Lithium / Manganese Dioxide Cell

Lithium / Thionyl Chloride Cell

Blow Torch Lit

Blow Torch Lit

"Solvent" Fire

Cell Fire

"Lithium Metal" Fire (Wide Angle)

Cell Fire (Wide Angle)