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THE SAFETY IMPLICATIONS OF LITHIUM RECHARGEABLE BATTERIES ONBOARD UK CIVIL AIRCRAFT

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Executive Summary

This paper has been prepared by the Defence Evaluation Research Agency (DERA). It reports on the work carried out by DERA, in fulfilling a CAA contract, to investigate the potential hazards that could arise from the use of lithium rechargeable batteries in aircraft. Potential applications of lithium rechargeable batteries are to power aircraft equipment, such as electronics, to supply power as the aircraft main battery and for use in portable equipment brought on to an aircraft by passengers.

Widely used lithium rechargeable batteries, which may be brought on-board aircraft by passengers in portable electronic equipment, have already been subject to extensive safety testing to meet consumer safety standards. Potential safety hazards that could arise from the use of lithium batteries in aircraft equipment are discussed. Primary (non-rechargeable) and secondary (rechargeable) batteries are compared. Differences in hazard potential from different types of battery are considered.

Electronic controls are necessary in multi-cell battery packs of lithium rechargeable batteries. Their design and the safety implications of any failure of electronic controls are discussed.

Safety standards for lithium batteries have been reviewed to determine which are appropriate to rechargeable batteries in aircraft applications. Standards have been compared and manufacturers' claims concerning standards, to which their batteries adhere, are described. The only safety test which is specifically applicable to aircraft is the altitude / decompression test in BS 2G239 or EN4240. This is not included in consumer safety standards and it is recommended that this should be included in any approval requirement for secondary rechargeable batteries.

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1 INTRODUCTION

1.1 This report was written by the Defence Evaluation Research Agency (DERA) Haslar Electrochemical Power Sources Centre for the Civil Aviation Authority Safety Regulation Group, Gatwick Airport. The aim is to discuss safety implications of lithium rechargeable batteries being used on aircraft both as part of the aircraft equipment and in portable equipment carried on to the aircraft by passengers. In particular, potential hazards of lithium rechargeable batteries are compared with those of lithium primary (non-rechargeable) batteries which have been widely used for many years now. It is not intended to cover the safety of transporting lithium batteries as cargo since this has already been addressed. [1,2].

1.2 Many types of battery would have been brought on-board aircraft inside portable equipment since the early days of civil aviation. Airline instructions forbid the carriage by passengers of briefcases with alarms powered by lithium batteries or carriage of corrosives, such as acids, alkaline, or mercury, which can be contained in batteries. Large high-power lead-acid or nickel-cadmium batteries have long been used for engine starting and as an emergency electrical power source, being float-charged off the aircraft bus-bar or charged through a charger.

1.3 Lithium primary batteries started making their appearance in domestic products such as cameras around two decades ago. Considerable numbers of small button cells and possibly small metal-cased cylindrical R6 size cells have probably been brought on-board civil aircraft by passengers for several years. Lithium primary batteries have also been used for aircraft instruments and regulations exist which cover their use [3,4]. It is also possible that civil carriers may occasionally ship larger and higher-energy lithium primary batteries intended for military or industrial use. Lithium rechargeable batteries are now being brought on to aircraft inside portable consumer equipment, such as portable telephones, computers, stereos, camcorders, etc.

1.4 The scope of this work was to look into the safety implications of having lithium rechargeable batteries on-board UK civil aircraft in three main scenarios:

(a) small ones already brought on by passengers to their cabin seats or stowed in lockers. These batteries could also be charged by passengers at their seats using battery-charging sockets provided on some aircraft.

(b) small ones which may power instruments in the aircraft cockpit in the future.

(c) larger ones of capacity 10–50 Ah and voltages of 12–24V which might eventually be proposed to replace existing aircraft main power generation system batteries. However they are not expected to see service in this role for a few more years at least.

1.5 The purpose of the work is to inform the CAA Safety Regulation Group of the potential hazards, failure mechanisms, likelihood of failure, and consequences of failure of lithium rechargeable batteries in the above scenarios. Thus enabling them to consider if regulation is required to provide adequate safeguards to ensure that sufficient levels of safety are achieved on UK civil aircraft.

1.6 Section 2 of this report defines the types of lithium rechargeable battery, regarding both mechanical construction and electrochemistry, which have been considered. From a consideration of all these types, Section 3 then lists possible events that could occur with lithium rechargeable batteries on-board aircraft, which might lead to harm to either people or aircraft. Section 4 compares the various existing standards for lithium batteries, Section 5 discusses the effects of manufacturing or design defects, Section 6 covers battery packs, Section 7 accidental or deliberate misuse and Sections 8 and 9 comprise conclusions and recommendations.

2 TYPES OF LITHIUM RECHARGEABLE BATTERY

2.1 General

2.1.1 Lithium rechargeable batteries, as a class, may be considered as an extension of lithium primary (non-rechargeable) batteries, where the main impetus has been to provide much more economically advanced power sources through rechargeability. They then become much longer-lasting than conventional rechargeable lead-acid and nickel-cadmium batteries between recharging. In general though, lithium rechargeable batteries do not store as much energy (per unit size or weight) as lithium primary batteries, and this fact is worth noting concerning the potential for hazard.

2.1.2 Many types of lithium primary batteries have been developed, though not all are presently in use. There are many types of lithium rechargeable battery, which have been offered commercially, are presently in use, or could be in the future.

2.1.3 The main difference in status between lithium primary and lithium rechargeable batteries is one of maturity of the technology. Presently, it seems likely that both the types of physical design, and the number of different electrochemistries of lithium primary batteries has reduced to a short-list of those that are commercially available now or for the foreseeable future. The list of electrochemistries in use would be rather small in comparison to the list of couples which have been investigated in research and development, several of which did not reach the manufacturing stage. Some types, such as the lithium-copper oxide or lithium-copper oxyphosphate cells mentioned in British [5] and draft European Standards [6] are no longer made.

2.1.4 As lithium rechargeable battery technology is still immature, it will be difficult to predict exactly what types may be offered beyond the immediate future. Also, the electronic controls and chargers are similarly undergoing development and further miniaturisation, so may look rather different in future from what they do today.

2.1.5 We can however classify lithium rechargeable batteries according to cell electrochemistry, cell and battery design, and overall size, as described in the following sections.

2.2 Electrochemical types

2.2.1 Rechargeable batteries brought on to aircraft could have different anodes, electrolytes and cathodes, whereas their primary analogues vary only in their electrolytes and cathodes as the anode for a lithium primary battery is always lithium metal.

2.2.2 The two main anode types are lithium metal, as already found in lithium primary batteries, and lithium-carbon, as contained in the sub-class of lithium rechargeable battery usually known as 'lithium-ion.' Batteries with host materials other than carbon are also possible, but carbon is the most widely used material at present. Early lithium rechargeable batteries used lithium metal, but following the widely reported safety incident with a lithium/molybdenum disulphide battery [7] which caused the product to be withdrawn from the market, most manufacturers now offer lithium-ion cells instead. They are generally regarded as significantly safer, though one manufacturer still offers lithium metal rechargeable cells. However, a new electrolyte has been developed for lithium metal rechargeable batteries which is reported to improve their safety [8]. In rechargeable cells, unlike primary ones, when users recharge a battery, they are causing lithium metal to be plated on to lithium anodes or causing lithium ions to re-enter the carbon host (in lithium-ion cells). This would happen in lithium primary cells only if they were inadvertently charged and the normal anti-charging devices (such as diodes) failed. The drive in recent R&D away from lithium metal towards lithium-carbon has been due to a perceived reduction in the hazard associated with finely divided freshly plated lithium metal, as well as simply the desire for better performance by way of much longer cycle life. However, there have been suggestions that some lithium metal could form at the carbon interface even when charging lithium-carbon anode cells. Either way, the possibility of generating finely divided lithium metal or the presence of, possibly pyrophoric, lithium-carbon are two occurrences that would not normally be encountered in using lithium primary batteries, so their potential for hazard should be considered further. Hence the potential for hazard with lithium rechargeable batteries with lithium metal anodes, as compared with lithium primary, has increased due to the finely particulate and possibly pyrophoric nature of anodes of rechargeable cells, especially after many charge and discharge cycles.

2.2.3 Presently and at least in the near future, lithium rechargeable batteries are expected to have electrolytes composed of lithium salts in mixtures of organic polar solvents with or without organic polymers. Some of the materials used as liquids in lithium primary batteries, such as the corrosive, toxic and irritant sulphur dioxide, thionyl chloride, sulphuryl chloride, or chloroaluminates, are not expected to feature in lithium rechargeable batteries in the near future. However, lithium-ion sulphur dioxide batteries are under development by one manufacturer [9]. As a general type, lithium rechargeable battery electrolytes will thus be similar to those already seen in lithium-manganese dioxide primary batteries. However, whilst no radical changes are foreseen in the electrolyte salts, from those used in primary cells, the specific solvents have normally been selected on different technical criteria for rechargeable cells – that of stability to high charging potentials. Thus, new solvents like dialkyl carbonates will be present that have not been seen before, and again, others may result from further research, working their way into manufactured products in several years' time. These new solvents are not considered to pose any new direct hazard, above those already existing with primary batteries, since their volatilities, flash points, and chemical properties are not radically different from solvents used in primary cells. Overall then, there appear to be no new hazards with lithium rechargeable cell electrolytes in fresh cells, over those posed by lithium primary cell electrolytes. However, there is evidence that the prolonged electrical cycling of rechargeable cells may lead to a progressive, but slight, irreversible decomposition of the electrolyte solvent into other products. These may be solid, and eventually lead to cell performance failure due to a progressive internal resistance increase. Previous DERA cycling test results would be consistent with this failure mode for at least two types of metal-cased cylindrical cells examined. A particular sub-class of lithium rechargeable cell is the so-called 'lithium solid-state' cell or lithium 'polymer' cell. Chemically, most are expected to be no more than a slight derivative of the more conventional liquid-electrolyte cell. However, some use an organic polymer to immobilise the electrolyte so that it too may be laid down as a non-flowing film using coating techniques, rather than being injected into the cell as a liquid. Some designs will use true polymer electrolytes, without any immobilised electrolyte solvent. Most of these will still contain some flammable volatile solvent used as plasticiser and conductive medium, so claims that this type of cell presents a lesser flammability hazard should be treated with caution. It is probably true that the presence of the polymer will limit the rate of release of flammable vapour which can catch fire, as can the polymer itself.

2.2.4 Many cathodes have been investigated in research, but only a few – principally lithium cobalt oxide ($LiCoO_2$), lithium nickel oxide ($LiNiO_2$), and lithium manganese spinel oxide ($LiMn_2O_4$) – seem likely to feature in near-future batteries. Nickel and cobalt are somewhat toxic, more so than manganese, but are not as aggressive or incapacitating as the liquid cathodes, such as thionyl chloride or sulphuryl chloride used in some lithium primary cell cathodes. These solid materials are intrinsically safer than compressed liquefied gases, such as sulphur dioxide, used in some primary cells. Overall, the introduction of these new materials does not broaden the range of hazard from what has been seen in lithium primaries. Some, such as the manganese spiral, will be similar in behaviour to the manganese dioxide in primary Li-MnO_2 cells.

2.3 Cell design types

2.3.1 Single lithium rechargeable cells are appearing in shapes and with internal constructions similar to those of lithium primary cells. The most common type is the spiral wound cylindrical cell in the 18650 size (18 mm diameter, 65 mm high). This is not one of the IEC standard sizes, such as AA / R6 / 15505, used for existing rechargeable batteries, such as nickel-cadmium. The sizes for lithium rechargeable cells have probably been chosen to fit the equipment for which they were designed to power. However, it is an advantage to safety that the cells are not manufactured in the common IEC standard sizes. This prevents a lithium cell (of about 4 volts) being used where a nickel-cadmium one (of 1.2 volts) is needed. Generally, the internal construction of such cells is the same spiral-wound construction as used in high-power lithium-manganese dioxide primary cells. It is not known that any bobbin-design equivalents of lithium primary cells in lithium rechargeable technology currently exist. Cells are also manufactured in coin (button) cell format, but these are so small and contain so little active material that their potential for hazard is very small.

2.3.2 As time passes, there are expected to be cells manufactured in prismatic and thin flat envelope formats as well as cylindrical cells with metal cans. In the immediate future, the former are expected to be constructed mainly by an extension of the spiral-winding method, namely where the sheets of component are wound around two mandrels. This gives a "squashed" spiral with parallel sides but semicircular ends, which fits into an oblong case, and then packs more efficiently in multi-cell batteries. These might experience a possible enhanced hazard associated with the high curvature at the ends, especially effects due to lack of sufficient pressure keeping active materials adherent to the backing. This could also occur in packet designs where instead of winding round mandrels, the flat sheets of cell components are folded into multiple zigzags and where any tendency for active material to detach would be most extreme at the folds. Envelope designs are not a new feature in themselves, as primary lithium-manganese dioxide envelope cells are commercially available. Prototype envelope lithium rechargeable cells containing polymer electrolytes have been fabricated for some years now, but have not been commercially available until recently.

2.3.3 For solid electrode types, there could well be reduced damage in the event of an incident in rechargeable lithium, as opposed to primary lithium cells, since the rechargeable cells will generally store less electrical energy than primary cells. Hence there is less heat or propulsive energy produced in the event of a malfunction. Furthermore, the class of rechargeable lithium cells is not expected to include materials like thionyl chloride or sulphuryl chloride which necessitate very careful design of vents in order to ensure cell safety in adverse conditions. These cells have been the cause of a number of reported safety incidents [10]. Like lithium-manganese dioxide primary cells and unlike lithium-sulphur dioxide primary cells, the contents of rechargeable lithium cells are not pressurised under normal conditions. When accidentally heated, either externally or internally (for example due to a short-circuit) their behaviour should thus parallel lithium-manganese dioxide cells provided their designs have a comparable weak point such as a deliberate vent.

2.4 Multi-cell battery designs

2.4.1 Some safety features in designs of multi-cell lithium rechargeable batteries should be the same as those provided for lithium primary batteries, (e.g. incorporation of fuses or current-limiting devices, such as positive temperature coefficient resistors). Batteries may include complete discharge devices, i.e. resistors to discharge the battery completely at a safe rate and to hold the battery at zero voltage after discharge, to make it electrically safe for disposal. However, other safety devices normally included in batteries of primary cells, such as diodes, are not appropriate for rechargeable batteries as it must be possible to reverse the flow of current for recharging.

2.4.2 It is expected that all lithium rechargeable batteries, of all electrochemical types, which are assembled and supplied by reputable companies will have individual cell monitoring and control. Different schemes for cell monitoring and for battery control and charging are used by different manufacturers. The assessment of these must be done for individual batteries, as the hazard could be different for different batteries even if using the same number of the same type of cells. Cell monitoring will be done at least for every cell connected in series, but where cells are also connected in parallel, one monitor and control for the whole parallel string might be sufficient. As the intended functioning of these voltage controls will be to prevent any one cell ever straying outside of a cell voltage range recommended by the cell manufacturer at all stages in the life of the battery, the potential for hazard from multi-cell batteries in normal use should thereby have been minimised. In practice, it is important to control the voltages of individual cells in order to obtain the long cycle life of which the cells are capable. Overcharging cells could lead to electrolyte decomposition which would result in the cells drying out and developing a high resistance. If this resulted in gas production, this could cause a hazard. Over-discharging could cause the formation of chemical phases within the cathode, which would not recharge, damaging performance but probably not causing a hazard. Failure of voltage control resulting in a cell not being charged to a sufficiently high voltage would cause failure to achieve the possible capacity. Hence for performance purposes, careful control of voltages is essential for lithium rechargeable batteries and this will also ensure safety. Hence, it is important to assess the effectiveness of voltage control and to assess the likelihood of any protective devices failing and the consequences of such failure. Protective devices against overcharging of batteries are needed where the batteries can be connected to voltage sources greater than that for which they were designed

2.4.3 The potential hazard from a lithium rechargeable battery brought on-board an aircraft is obviously related to its size, since the amounts of energy-producing or flammable compounds it contains will increase approximately in proportion to overall size and weight. It is expected that the range of sizes in future will be from a single lithium rechargeable cell, (circa 3–4Wh), through to an aircraft main battery (circa 1kWh). However, the possibility cannot be excluded that larger batteries, such as those developed for electric vehicular traction, might in future be carried in civil cargo aircraft, possibly in a charged state. The amounts of active materials relate to the overall energy storage and hence indirectly to hazard potential, the current-delivering capability of the battery may be more directly related to potential hazards in many situations. This is a function of cell design rather than amount of material. This could directly affect safety factors such as the effect of any fragmentation of the battery and the severity of effects on people and equipment, just as much as the amount of stored energy. High-power spiral-wound consumer cells or high-performance multi-plate aircraft batteries of the future will thus need special consideration here. Lithium rechargeable batteries are intended as replacements for conventional rechargeable batteries like lead-acid and particularly nickel-cadmium. Both of these have high power capability, many types of lithium rechargeable battery can be expected to be designed for high power as well as high-energy storage. Conversely, some types of lithium primary battery are designed for high-energy storage but low power.

2.4.4 *Risk Analysis of Failure of Electronic Controls, and Consequences*

2.4.4.1 Introduction

In terms of their electrical operating requirements, rechargeable lithium batteries are generally not as robust as the other systems. For this reason, they often require to have an associated electronic management system. The interaction between the rechargeable lithium cells and the Electronic Management System (EMS), both under normal operating conditions and any potential hazards that may result from the breakdown of the EMS, is examined here. The aim is to:

Detail some of the variations and uses for lithium rechargeable batteries.

Explain the need for an Electronic Management System (EMS).

Describe the operation of some known systems in use and under development.

Examine the safety features of the EMS and the cells.

Examine ways in which the EMS might fail and hypothesise on the effects.

2.4.4.2 Scope

This study covers the three most widely used rechargeable lithium systems:

Rechargeable Lithium Ion (liquid electrolyte)

Solid Polymer (rechargeable lithium ion)

Rechargeable Lithium Metal.

The composition and characteristics of the three systems have already been covered. Manufacturers are constantly developing and refining their products. This study is therefore limited to stable designs that are readily available or by reference to manufacturers' data on established developments.

2.4.4.3 Rechargeable Lithium Cells

The functional requirements of the Electronic Management System, for each of the systems, are very similar. However, the exact electrical values and tolerances will depend on the chosen system and the cell manufacturer. In terms of the cell behaviour following a breakdown of the EMS, this is very different and will depend upon the chosen system.

2.4.4.4 Common Applications and Variations of Power Pack

Common applications for rechargeable lithium batteries are:

Portable computers, electronic note pads, mobile telephones, camcorders, data recorders, power tools, shavers.

Future applications are likely to include:

Leisure products, medical products.

The variations in power pack design often fall into the following categories:

1 Integrated. The cells and electronics form an integral part of the equipment and are not accessible to the average user.

2 Removable Pack. This often contains only the cells plus safety devices. In this case, the management systems for charge and discharge control are contained within the auxiliary equipment.

3 Retrofit. These are sometimes developed as replacements for existing nickel cadmium or metal hydride battery packs. In this case, the management systems for charge and discharge mimic the characteristics of the original battery packs that they replace.

4 Self contained. These power packs contain the cells and a complete management system for stand-alone operation.

5 Single cells. These are not generally available yet in standard IEC sizes. They contain safety devices and may include some degree of electronic management.

2.4.4.5 Need for an Electronic Management System (EMS)

Each of the rechargeable lithium systems requires some degree of electrical control. This is not only to ensure that the optimum capacity and cycle life are achieved, but also to prevent irreversible damage to individual cells should the operating limits be exceeded. This applies equally to single cell applications and multi-cell power packs. The following parameters must be controlled or at least monitored by the EMS:

Minimum Cell Voltage. (On Discharge).
Maximum Cell Voltage. (On Charge).
Maximum Cell Current. (Charge and Discharge).
Maximum Operational Temperature. (Charge and Discharge).

Other features of an EMS may include:

The use of 'sleep' or 'idle' modes to reduce internal current consumption.

Some form of cell balancing. (Multi-cell packs)
A 'gas gauge' or 'state of charge' monitor.
Communication with auxiliary equipment.
Regulated output voltage conversion.

In terms of complexity, EMS may range from microprocessor based systems, making use of increasingly available custom IC packages, to the use of discrete components and analogue ICs.

2.4.4.6 Cell Configuration

Rechargeable lithium cells are often connected in a series / parallel configuration to achieve the required output voltage and discharge capacity. An example of a pack consisting of 10 cells, five in series (5S) by two in parallel (2P) is given in Figure 1. Cells that have a close state of charge are normally coupled together during the manufacture of the pack. The pair can then be considered as a single cell by the EMS.

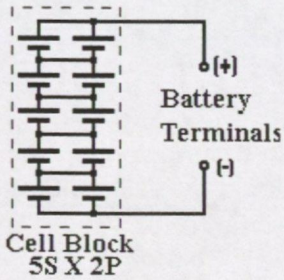

Figure 1: Cell block 5S X 2P

2.4.4.7 Principles of Electronic Management System Operation

On Discharge

The voltage of a rechargeable lithium cell is relative to its state of charge. There is considerable difference in the linearity and voltage limits depending on the system chosen, but the range (for a non-metal system) is between approximately 4.2 volts (fully charged) to 2.8 volts (discharged).

A typical example of a discharge control circuit is given in figure 2. During discharge the EMS has little to do other than to isolate the pack electrically (switch the field effect transistor into open circuit) if an excessive discharge load is presented, or an over temperature condition exists. The EMS continually monitors each cell and then isolates the pack when any cell reaches its minimum working voltage. The cut off voltage is normally set high to keep a reserve capacity in the cell until the pack is recharged.

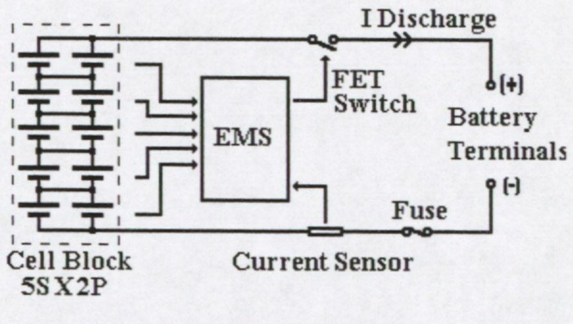

Figure 2: Typical Discharge Control Circuit

On Charge

During charge, the EMS must limit the current in the cells, usually to the 'C' rate (the charging rate at which the entire battery capacity is charged in 1 hour). Due to the necessity for power dissipating devices, this part is often external to the pack. The current limit is to protect the cells and to ensure that charge circuit is not overloaded. In a discharged state, the cells will often draw as much current as the charger circuit can supply.

As the voltage increases, the EMS must ensure that each cell voltage is maintained below the upper limit specified by the cell manufacturer (usually in the region of 4.2 volts). This can be achieved using a number of techniques from a direct control applied to each cell, to the reduction or termination of the charge current through the series string. Often the cells are required to be maintained at the upper voltage limit for a specified period, to ensure a full charge.

The optimum charge parameters are usually specified by the cell manufacturer.

When the pack uses a high number of series cells (often four cells or over) some form of cell balancing is desirable. Depending on the charge technique used, the pack performance may be limited by the performance of the weakest cell, which during cycling can perpetuate the problem. Some charge techniques combine charge and balancing as a feature of their design. A number of charge techniques are shown in Figures 3 to 6.

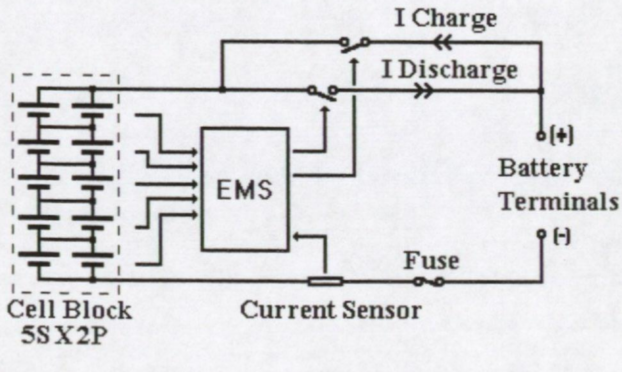

Figure 3: Cell Voltage Monitoring

During charge, the EMS monitors the voltage across each cell. When the voltage of any cell reaches the specified upper limit, the charge is terminated by switching the charge FET open circuit. This circuit does not incorporate any cell balancing, is unlikely to yield full capacity on discharge, and is considered the minimum control for a pack consisting of two or more series cells.

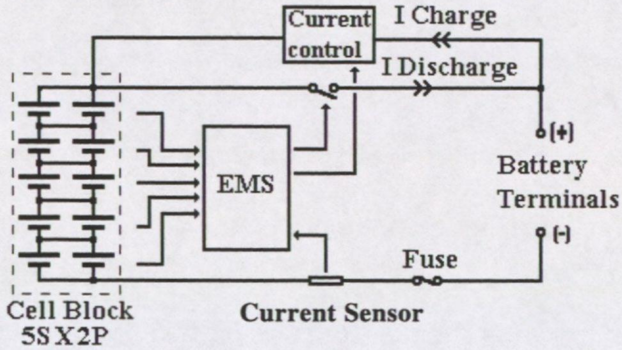

Figure 4: Cell Voltage Monitoring with Current Control

During charge, the EMS monitors the voltage across each cell. When the voltage of any cell reaches the specified upper limit, the charge current is reduced, thereby reducing the cell voltage. This technique will improve the discharge capacity over the previous example, but does not include cell balancing.

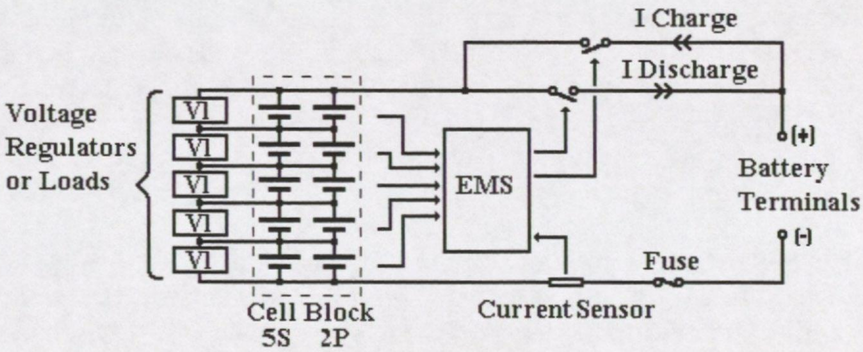

Figure 5: Cell Voltage Control

During charge, the EMS monitors the voltage across each cell. When the voltage of any cell reaches the specified upper limit, the voltage regulator or load resistor, applied across each cell, will divert charge current away from the cell. This has the effect of maintaining or reducing the cell voltage, and can hold the cell at the top of charge for longer periods. This technique will ensure a full charge for each cell and promotes cell balancing. Drawbacks of this system are that it reduces the overall charge efficiency and may generate heat in the voltage regulators or load resistors.

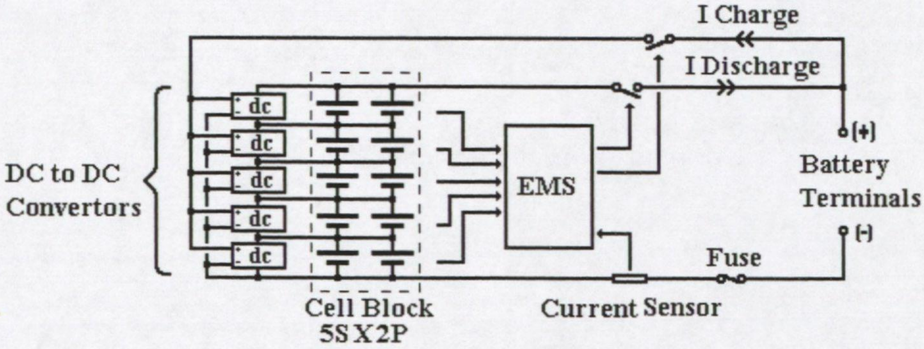

Figure 6: Isolated DC to DC Conversion

During charge, the EMS monitors the voltage across each cell, but only to determine when the charge is completed and as an additional safety feature. Each cell has a separate DC to DC converter that derives power from the battery terminals. Each converter contains its own current limit and voltage regulation circuitry, enabling each cell to be charged completely independently of the others. This technique will ensure a full charge for each cell and promotes cell balancing. It also enables the pack to be recharged as a self contained unit from a wide range of DC sources. The overall charge efficiency of the pack is determined by the design of the DC to DC converters. A drawback of this system is its complexity.

Output Voltage Conversion

The higher energy density of rechargeable lithium batteries is largely due to the increased output voltage of individual cells. An additional feature of these cells is the increased voltage differential between the fully charged state and the discharged state. These features sometimes present problems to the pack designer, as the target output voltage may result in an inefficient cell configuration, which can not maximise the full working voltage of the cells.

For this reason, some developments have taken place, using DC to DC converters to modify the output voltage. This efficiency of the conversion is often in the region of 85% to 90%. Figure 7 shows the layout of the discharge components for a typical system.

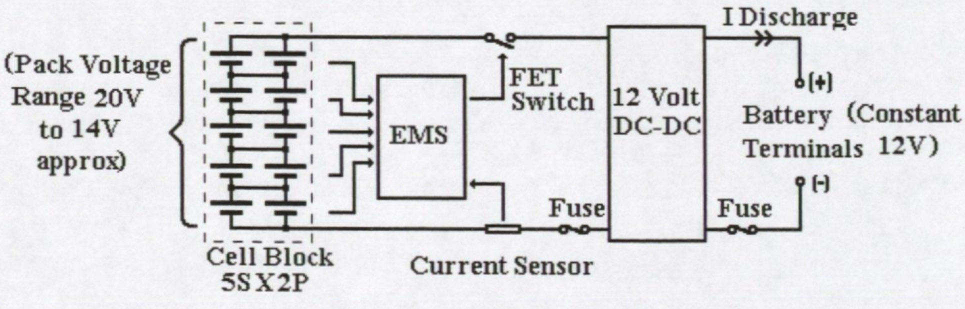

Figure 7: Output Voltage Conversion

2.4.4.8 Electronic Management System Protection Features

The EMS should be designed to protect against possible fault conditions. Depending on the nature of the fault, the EMS should either restore normal operation when the fault has been removed, or enter a shutdown state. When shutdown, the cell pack is isolated from the battery terminals. Fault conditions are discussed under the following headings.

Under-Voltage Cell(s)

On detection of a cell minimum voltage, the EMS should prevent further discharge by entering into the shutdown state. This will prevent over – discharge that could result in permanent cell damage. In the shutdown state, the internal battery drain can be reduced to a minimum. The shutdown state should be reversed following the application of a charger.

When charging the battery, it is recommended that a low charge rate is used while an under-voltage cell(s) condition exists.

Under-Voltage Battery

If the cell pack voltage is allowed to deplete over a period of time, eventually the EMS will cease to function. In this case, discharge through the battery terminals should remain inhibited. A path should remain for only a very low rate of charge to the cells and when the voltage has risen sufficiently, the EMS should recover to a fully functioning state.

Over-Voltage Cell(s)

Charging should not be possible when an over-voltage cell(s) condition exists, otherwise the cells may be destroyed. Discharge however, is permissible from this condition.

Out of Voltage Range Cell(s)

If any cell voltage is significantly out of its normal voltage range (possibly due to an open circuit or short circuit cell fault), further use of the pack should be prohibited and the EMS enter into the shutdown state.

Over-Voltage Charger

Where the charge control functions are shared between the battery and the charger, the EMS should protect against the use of an incorrect charger that exceeds the normal charge voltage.

Over-Current Sensing

If pre-set values of charge and discharge currents are exceeded, the EMS should isolate the current by entering into the shutdown state. The speed at which over-current is detected and isolated is critical to ensure that components are not damaged. Some microprocessor systems make use of analogue to digital converters (ADC) to monitor the current, but these systems tend to be slow. An analogue circuit is often required to isolate directly the current or send an interrupt signal to the microprocessor.

The over-current detection system sometimes requires a time delay to ensure that electrical noise does not cause unwanted shutdowns.

Over-Current in Discharge

In discharge, over-current may occur due to a faulty or incorrect load, or a short circuit. The over-current threshold should be set slightly higher than that expected during normal operation, but within the continuous rating recommended by the cell manufacturer. The continuous and switching ratings of the EMS components should also be taken into consideration.

The EMS should have the ability to restore the normal battery functions when the fault condition has been removed.

Over-Current in Charge

Where the charge control functions are shared between the battery and the charger, the EMS should protect against the use of an incorrect charger that exceeds the normal charge current. Where the charge control function is self-contained within the battery, over-current may be due to an internal battery fault. The EMS should isolate the charge if the limits of the battery are exceeded and restore the normal battery functions when the fault condition has been removed.

Charge Time-Out

Where the charge control function is self-contained within the battery, the charge sequence should be monitored by a watchdog timer. The EMS should isolate the charge if the battery fails to recharge within a certain time.

Temperature Monitoring

Operational limits often apply to the cells in charge and discharge modes. The EMS should prevent operation of the battery if these limits are exceeded.

The EMS should ensure that a reasonable amount of electrical abuse can be tolerated without damage to the battery pack. However the provision of fail safe devices must be made within the battery should the EMS fail. Such devices are discussed under the following headings.

Cell Protection Features

Individual cell protection features are discussed previously.

Series Fuse

An electrical fuse, located in series with the cell pack is essential. This device will isolate the pack in either charge or discharge if excessive current is drawn, regardless of whether the EMS is operational or not. A polyswitch or positive temperature coefficient device may be used.

Thermal Fuse

At least one thermal fuse should be located in proximity with the cell pack. Operation of the fuse should electrically isolate the pack from any external circuit including the EMS.

EMS Current Limit

The supply to the EMS should be fused or current limited should a fault occur in the EMS circuit.

2.4.4.9 EMS Design Considerations

Some of the design considerations for a pack are discussed below. References should be made to standards where applicable.

Fault Analysis: Failure of a key component such as power FET switch should not allow a direct access to the cell pack from the battery terminals. The FET should fail to open-circuit so that the battery cells would then be isolated from the battery terminals. The probability that such components would fail cannot be generalised, as it depends so much on the quality of the components used in particular devices.

Tolerances: Compatible with cell manufacturer's limits.

Reliability: MTBF to be sufficiently long that component failure is unlikely within normal cell life.

2.4.4.10 Suggested Test Headings

Proposed test headings for inclusion into a specification are listed below. National standards, specifications and test criteria exist to cover much of the detail.

Performance: *Verification of electrical performance within battery design limits.*

Mechanical: *Represent environment for transportation and use.*

Temperature: *Storage and operation at temperature extremes.*

Environmental: *Rapid decompression/temperature change.*

Electro Magnetic Compatibility, *Susceptibility and Radiated Emissions.*

Over-voltage/Over-current Charge supply: *Should present no hazards.*

Over-current Discharge/External Short circuit: *Should present no hazards.*

Simulated EMS Breakdown: *Should present no hazards when attempts are made to charge and discharge.*

Simulated cell O/C and S/C faults: *Should present no hazards when attempts are made to charge and discharge.*

2.4.4.11 In-service electronic management systems and battery chargers.

Passengers may take chargers on-board aircraft as well as batteries. As far as is known, all lithium rechargeable battery systems supplied to high-street domestic users come as a complete package consisting of the three basic elements: lithium rechargeable battery, dedicated battery charger and an electronic management system incorporated either inside the charger or the battery. Systems supplied in the UK and many other countries will normally be for fitting the mains plug directly into the usual 240 V 50 Hz supply, but American and some other nationals may have chargers designed for other mains voltages. It is reasonable to assume that all chargers supplied to domestic users, as dedicated lithium rechargeable battery chargers, will safely convert the domestic mains power characteristics to a suitable voltage and current level for the battery. Short of determined attempts to circumvent manufacturer's safety provisions, it is not foreseen that there is any significant hazard. However, when charging points become available on aircraft, consideration should be given to the characteristics of dedicated chargers, and the Portable Electronic Devices (PEDs) to ensure inappropriate power levels cannot be supplied.

An example of an in-use battery / EMS / charger system would be a laptop computer. This provides a complete battery / EMS / charger system with all connecting plugs / sockets and has a built-in state-of-charge monitor appearing on the laptop screen. From experience, the monitor suggests that the battery performance is gradually deteriorating due to a high impedance failure mode, which is benign.

3 POTENTIALLY HAZARDOUS EVENTS WITH LITHIUM RECHARGEABLE BATTERIES IN AIRCRAFT

3.1 Potential hazards

3.1.1 *Electrical hazards*

The hazards, which could arise in aircraft, are fire, explosion, and cell venting. It is expected that the batteries used will have a low overall voltage, so there will be no possibility of electrocution, even for high current batteries.

3.1.2 *Fire and explosion*

Lithium metal is readily combustible and reacts vigorously with water and most other fire extinguishing materials, such as carbon dioxide or halons. Most lithium rechargeable batteries are likely to be of the lithium-ion type, with no free lithium, as is found in lithium primary batteries. Electrolytes are organic solvents similar, though not identical, to those used in lithium-manganese dioxide primary batteries. Cathodes are solid materials, similar to the Li-MnO_2 batteries. Hence, the constituent materials are no more combustible than primary batteries. Lithium-ion batteries are less combustible due to the absence of lithium metal though lithium-carbon, found in charged cells, could still be pyrophoric. Hence, in the worst case, if a battery were to catch fire, the extent of any fire should be no worse than that for a similar-sized lithium primary cell. An explosion could occur only if an uncontrolled reaction occurred within a cell, e.g. due to a short-circuit heating the cell components. The absence of lithium metal (which melts at 180°C) should make lithium-ion cells safer to higher temperatures than lithium metal primary ones.

3.1.3 *Cell venting*

In the event of internal overpressurisation, a cell would vent, releasing its contents, provided that the cell was designed with a vent. This would be the case for cells apart from the very smallest ones, such as button / coin cells which do not contain sufficient reactive material to need one. The effect of venting cell contents, e.g. inflammable electrolytes should be assessed. Although, venting prevents explosions this is not innocuous, particularly for the liquid cathodes used in some primary cells (sulphur dioxide, thionyl chloride and sulphuryl chloride) as these are noxious materials. Venting of liquid cathodes would be hazardous to passengers, or to air crew, if a cell vented in the confined space of an aircraft, particularly in a cockpit. In this respect, rechargeable cells are safer than primary ones, as currently-available cells do not use liquid cathodes. However venting of flammable electrolyte solvents would pose a fire hazard, if it occurred where a source of ignition was present. Venting breaches the cell enclosure and could expose possibly pyrophoric lithium-carbon or lithium metal to air. This discussion considers the effects of fires or explosions but not their likelihood, which may be greater for lithium rechargeable cells, particularly for those containing metallic lithium.

3.2 Causes of Hazards

3.2.1 The most obvious seems to be inadequate sealing of the cell contents from the atmosphere. Inadequate sealing of cells will lead to a slow leakage of solvent vapour or liquid, but also possibly a slow progressive ingress of water vapour which will corrode anode material in both primary and rechargeable types alike. No additional hazard appears to arise because of the introduction of rechargeable types.

3.2.2 Inadequate limiting of short-circuit current in the cell design would be another potential hazard. However, it is considered that the most powerful domestic cells will be, in the near future, spiral-wound metal-cased cells which should be no more powerful than e.g. spiral-wound C and D – sized lithium manganese dioxide primary cells. This study thus compares the current-limiting measures provided by manufacturers of these, as compared with rechargeable types.

3.2.3 As for lithium primary batteries, the main manufacturing defect in cells might be accidental internal shorting. The effects of this will probably be similar to those of accidental abuse such as crush or spike penetration. The initial effect would be internal heat generation caused in all cases by a gross internal conductive dissipation pathway. Where the cell container remains sealed, the normally low internal pressure will increase and risk activating either a deliberate venting, if provided, or else venting through the weakest point. The amount of escape would depend on the severity of the short caused by the abuse. Where cells have been penetrated, the pressure will be relieved by the escape of warm electrolyte solvent vapours. This would normally be above their flash points, and hence ignitable, if at concentrations within the range of flammable concentrations in air. Either way, escape of cell components could occur. Where a gross gash has been made in the cell casing, escape of components other than liquids and warm vapours might occur, such as electrode pastes. As in similar events in other types of battery, like lithium primary, prolonged contact of electrolyte or electrode paste residues with the skin, though not likely to cause very serious harm or injury, is to be avoided. Where large amounts of lithium-carbon paste, at high local concentrations, are present, attempts to wash these residues off with small amounts of water could add a further risk of fire or explosion. However, the consequences are not foreseen to be more severe than those for lithium primary batteries. For small localised incidents in the aircraft the hazard may be ameliorated by brisk cabin ventilation, and washing contaminated skin and clothing with copious cold water.

3.2.4 Another possible hazard is overheating of a cell due to overheating of the equipment containing it. This would probably be a worse hazard for primary cells due to the presence of lithium metal in primary cells, whilst most rechargeable cells are of the lithium-ion type.

3.3 Actual hazards

3.3.1 Currently, the cumulative numbers of lithium rechargeable cells and batteries, produced world-wide, is very considerable (many tens of millions of cells) and is very likely to exceed the quantities of lithium non-rechargeable cells.

3.3.2 Since the lithium/molybdenum disulphide failure, there have been no widely reported hazardous failures (as opposed to performance failures) of lithium rechargeable batteries.

3.3.3 As with other battery types in service, it is difficult to obtain statistics on actual in-service failures due to their rarity.

3.4 Cell design features that limit hazards

These will include choice of materials, e.g. lithium-metal or lithium-ion, liquid or polymer electrolyte, standard or safety separator, more or less toxic cathode materials. Other design features pertinent to safety include cell construction, such as hermetic or crimped seals, types of vents, amount of head space to allow for electrolyte expansion, thickness of metal cans, thickness (and hence current-carrying capability) of electrode backing sheets. Apart from general construction, manufacturers often include specific design features to improve safety. Vents are included in all except coin (button) cells, which are too small to need them. Internal fuses may be used to prevent excessive currents being drawn and to ameliorate short circuit faults. Positive temperature coefficient devices (PTC) may be used to limit currents being drawn and to prevent excessive temperatures being produced inside cells. Safety headers may disconnect cells if excessive internal pressure is being produced.

3.5 Circuit design to limit hazards

Manufacturers often give instructions in their literature about elements, which should be included in any circuit connected to their lithium rechargeable batteries. These require for example positive temperature coefficient devices to limit the current if a cell overheats. In addition, the voltages applied to individual cells need to be controlled carefully (see section 2.4)

3.6 Battery design features limiting hazards

These have been discussed extensively in section 2.4 and include current, voltage and temperature control. Battery pack design must ensure that cell construction (e.g. packaging) does not block cell vents and that heat released from individual cells can be dissipated without causing battery pack overheating.

4 LITHIUM BATTERY STANDARDS

There are a number of standards that apply to lithium batteries [1,2,5,6,11-13]. These cover a number a different aspects, safety, performance, quality control and documentation but the tests in the standards are similar, though not identical, e.g. different standards will have temperature storage tests, but the actual temperatures used will differ from standard to standard. The British and draft European standards [5,6] are very similar, as the European standard was developed from the British one. The European standard will not be considered fully, as it is only at the draft stage, and could change when the final version is issued. Both these standards and the American RTCA standard [11] specifically apply to aircraft, though they refer only to primary batteries. The standard for Household and Commercial Batteries, UL 2054 [13], requires lithium batteries also to comply with the Lithium Battery Standard, UL 1642 [12], and so this is a more severe test. The standards available at the time of writing are compared in Table 1, which lists the tests and quotes the relevant section numbers in the standards. Standards also exist for the transport of lithium batteries as air cargo [1,2]. Although not directly relevant to the present study, the safety tests in these standards are similar.

4.1 Application of standards

British Standard BS 2G 239 [5] covers the requirements for primary lithium batteries for use in aircraft. This wording implies it does not specifically cover those brought on-board by passengers, nor batteries carried as cargo. The draft European Standard EN 4240 dated April 1997 [6] is very similar in its requirements to the British Standard, although more prescriptive in its conditions for some tests such as mould growth. The American document RTCA DO-227 dated 23 June 1995 [11] specifically covers only lithium non-rechargeable batteries. It is also generally similar in its safety test conditions to the British and draft European Standards. The Underwriters Laboratories standards [12,13] are general in their application and do not apply specifically to aircraft.

4.2 Regulatory requirements

Presently, CAA in their Airworthiness Notice No 12 Appendix 39 [3], require suppliers of lithium non-rechargeable batteries to demonstrate conformance to the safety requirements of BS 2G239 [5], as a means of ensuring safety of lithium primary batteries aboard UK civil aircraft. The American Technical Standing Order C142 [4] fulfils a similar function by referring applicants to the requirements of RTCA/DO-227 [11].

4.3 Comparison of standards

The existing CAA Airworthiness Notice refers to British Standard BS 2G239. The tests in this standard will be considered in relation to tests in other standards. Commercial lithium rechargeable batteries have undergone extensive safety tests but no batteries are known to have been tested to BS 2G239, probably because most batteries are made in Japan and BS 2G239 is a British standard. Furthermore, this standard applies specifically to aircraft, and the aircraft market for batteries is small in comparison with the consumer market for lithium rechargeable batteries which is currently taking tens of millions of cells per month. Most batteries have been tested to Underwriters Laboratories standards, as these are effectively accepted as the industry standard. The requirements of BS 2G239 will be considered in order and compared with other standards.

4.3.1 *Individual specification sheet*

BS 2G239 requires an individual specification sheet. Other standards (e.g. UL1642) do not specifically require this information to be tabulated. However, certain tests require parameters to be chosen by the manufacturer. Because of the different characteristics of batteries, in terms of chemistry and construction, it is not possible to test all batteries identically and appropriate parameters are needed.

4.3.2 *Identification and marking*

BS 2G239 requires the following marking:

(i) LITHIUM BATTERY (in capital letters)

(ii) Chemical system (in words or chemical symbols)

(iii) Manufacturer's name or identification

(iv) Manufacturer's type or part number

(v) Nominal battery voltage

(vi) CAUTION – NEVER CHARGE, SHORT CIRCUIT, PUNCTURE, DEFORM OR INCINERATE, REMOVE WHEN DISCHARGED (in capital letters). Note that the words 'NEVER CHARGE' are not applicable to rechargeable batteries and so this part of the standard cannot be applied to rechargeable batteries.

(vii) Positive terminal polarity.

The RTCA standard requires similar markings except that, in addition, the amount of lithium in the battery must be stated and the acceptance lot test number and date of manufacture must be included.

Other standards require markings, but the wording is different. For example UL1642 section 20.2 has:

> 'WARNING Risk of fire, explosion or burns. Do not recharge, disassemble, crush, heat above 212°F, or incinerate'.
>
> Note that 'Recharge' will apply only to primary batteries.

Section 20.3 has: user replaceable battery may be marked:

> 'CAUTION Risk of fire and burns. Do not recharge, disassemble, heat above 212°F or incinerate. Keep battery out of reach of children and in original package until ready to use. Dispose of used batteries promptly. Never put batteries in mouth. If swallowed, contact your physician or local poison control centre'.

Section 20.4 has:

for the end product with a user replaceable lithium battery

'Replace battery with (battery manufacturer's name or end product manufacturer's name, part number) only. Use of another battery may present a risk of fire or explosion. See owner's manual for instructions'.

Section 20.5 requires operating or maintenance instructions to include:

'CAUTION – The battery used in this device may present a risk of fire or chemical burn if mistreated. Do not recharge, disassemble, heat above 100°C (212°F) or incinerate. Replace battery only with (manufacturer's name or end product manufacturer's name and part number) only. Use of another battery may present a risk of fire or explosion'.

The following should be added:

'Dispose of used battery promptly. Keep away from children. Do not disassemble and do not dispose of in fire.'

UL2054 requires a word such as 'CAUTION', 'WARNING' or 'DANGER', a brief description of hazards and a list of actions to carry out to avoid possible hazards.

Although the standards are different, they have a similar philosophy.

4.3.3 *Design*

Section 6 of BS 2G239 covers general design, the battery case, venting, protective devices, electrical outputs, electrical terminals, attitude, fixing, environmental conditions and Declaration of Design and Performance (DDP). The discussion of general design (6.1) is brief and covers the aims, rather than means of achieving them. The RTCA document adopts a different philosophy and gives considerable background information on the chemistry of lithium batteries and details of design and construction. The Underwriters Laboratories' standards UL 1642 and 2054 briefly requires the construction to be sufficiently rigid to withstand handling.

Section 6.2 requires the battery case to be able to withstand environmental tests (acceleration, vibration, free fall, bump, rapid decompression, mould growth and fluid contamination). RTCA requires the battery 'packaging' to provide protection against the environment and also requires individual cells and safety devices (fuses, diodes etc.) not to be replaceable. UL 1642 requires the casing to resist abuses and to prevent access to lithium without using a hacksaw etc. UL 2054 is similar.

Section 6.3 requires cells to have vents and the battery case must be designed to cope with venting of any cell. RTCA (1.5.8) is equivalent.

Section 6.4 covers protective devices. These must form an integral part of the battery, they must not be susceptible to by-passing, must not be user-replaceable and must be rated so that reliable operation of the battery is not prevented. RTCA (1.5.7) covers this area. Where the possibility of external charging exists, this must be prevented by external diodes and fuses (BS 2G239, 6.4.3, UL 1642, 4.3) This applies only to primary batteries.

Section 6.5 requires batteries to have only single outputs wherever possible.

Section 6.6 requires output terminals to be mechanically polarised.

Section 6.7 requires batteries to operate in any attitude.

Section 6.8 requires batteries to be provided with suitable means of attachment.

Section 6.9 covers environmental conditions (temperature and altitude). The battery must be suitable for operation over the temperature range specified in the individual specification sheet. It must withstand storage over the temperature range –40 to +75°C. The battery must be suitable for operation over the altitude range –457 m to +16764 m. RTCA (2.1.8.1) also specifies altitude requirements.

Section 6.10 requires a Declaration of Design and Performance to be provided.

4.3.4 *Type approval*

Section 7 covers type approval, which depends on electrical, environmental storage and safety tests. Manufacturers must demonstrate to approving authorities that batteries meet requirements. In addition, appropriate quality assurance is needed. RTCA covers manufacturing standards in 1.4.1.3 and quality standards in 1.4.2.

4.3.5 *Electrical tests*

Section 8 covers electrical tests. Section 8.1 requires an insulation resistance of >10 Mohm. Section 8.2 requires the open circuit voltage to be recorded. Section 8.3 is the voltage delay test. Section 8.4 measures the duty discharge duration and section 8.5 the rated capacity.

4.3.6 *Environmental tests*

Section 9 covers environmental tests.

Section 9.1 covers acceleration tests, both normal and crash. RTCA includes a shock test (2.3.2). UL 1642 does not include an acceleration test but has an impact test (13).

Section 9.2 is the vibration test. RTCA (2.3.1), UL 1642 (15) and UL2054 (17) also have vibration tests.

Section 9.3 describes a free fall test, similar to the drop tests in UL 1642 (16) and UL 2054 (21).

Section 9.4 is a bump test, with similar purpose to the shock test in UL2054.

Section 9.5 describes the rapid decompression test. RTCA (2.3.5) also has a decompression test. These tests specifically relate to aircraft applications so there is no equivalent in the Underwriters Laboratories tests.

Section 9.6 covers mould growth and section 9.7 fluid contamination. Neither test has an equivalent in other standards apart from the related draft European standard (EN 4240).

4.3.7 *Storage tests*

Section 10 covers storage tests. The batteries are to be stored under temperate, desert (+20 to +50°C) and jungle (+20 to +35°C at 95% relative humidity) conditions. After storage the batteries should show no distortion or leakage. They are then to be subjected to the voltage delay test and the rated capacity test. The RTCA standard requires temperature cycling between –55 and +85°C, after which the batteries must not leak, vent, distort, catch fire, rupture or show significant changes in open circuit voltage. The UL 1642 standard requires batteries to be conditioned by oven exposure (+71°C for 90 days) and by temperature cycling (–54 to +71°C) and then for a range of safety and performance tests (short – circuit, heating, crush, impact, discharge, abnormal charging) to be carried out.

4.3.8 *Safety tests*

Section 11 covers safety tests.

Case containment (11.1) requires removal of all safety devices and then forcing the battery to vent e.g. by short-circuit or by forced discharge. The battery case must remain essentially intact with no fragmentation or break up. The RTCA standard has a venting test, somewhat similar (see 11.8 below). UL 2054 has a heating test in which the battery is heated to 150°C. The battery must not explode or catch fire.

The shock test (11.2) requires the batteries to survive shocks without any physical damage. The batteries must then conform to the rated capacity test. The RTCA shock test (2.3.2) requires monitoring of open circuit voltage on a fast recorder. Samples must not leak, vent, distort, catch fire, rupture, or show significant changes in open-circuit-voltage. UL 1642 does not include a shock test but has impact (13) and drop (16) tests. UL 2054 has a shock test (16). Samples must not explode or catch fire, nor should they vent or leak.

Section 11.3 covers temperature cycling. The battery must be cycled over a declared temperature range (depending on the battery) to establish the temperature range over which the battery can be cycled without significant leakage or physical degradation.

Section 11.4 is the forced discharge test. An external power supply of 28 volts is used. Batteries must not show physical distress or leakage. The RTCA test is similar. Batteries must not leak, vent, catch fire or rupture. UL 1642 also has a forced discharge test (17). UL 2054 forced discharge test (12) requires the battery not to explode or catch fire.

Section 11.5 is the over-discharge test. This requires discharge of batteries through resistors to ensure there is no physical distress or leakage of the battery.

Section 11.6 is the charging test. Batteries are charged from a 28 volt source with the current controlled to specific levels. Batteries must not show physical distress or leakage. The RTCA test is similar (2.4.1.5). Batteries must not leak, vent catch fire or rupture. UL 1642 requires batteries to be subjected to the abnormal charging test (18). The abnormal charging test in UL 2054 is similar (10). Batteries must not explode or catch fire.

Section 11.7 is the short-circuit test. Batteries must not leak, vent or explode. The RTCA test requires batteries not to leak, vent, catch fire or rupture. UL 1642 includes a short-circuit test (10). The UL 2054 short circuit test (9) specifies that the batteries must not explode or catch fire.

Section 11.8 is a high temperature test. In 11.8.1, batteries are heated to 70°C and must not leak, vent or explode. They are then heated to 160°C and must vent. This is similar to the RTCA venting test. The battery is forced to vent by heating and the battery is then examined to check that no fire or battery rupture has occurred. UL 1642 heating test involves heating the battery to 150°C. The UL 2054 test (24) is similar. The batteries must not explode or catch fire. The second high temperature test in BS 2G239 is a flame test. Cells should remain substantially intact. UL 1642 also includes a flame test. No flaming particles or projectiles should be produced nor should the battery explode. The UL 2054 test (22) is similar.

4.3.9 *Quality control*

Section 12 covers quality assurance and requires a quality plan to be produced, quality control to be carried out and records to be maintained. The RTCA standard also requires quality control (1.4.2).

4.4 **Summary of battery standards**

The foregoing description of lithium battery standards shows that there are several standards applicable to lithium batteries. Of these, only the British standard (BS 2G239), the draft European standard (EN 4240) and the American standard (RTCA) are specifically applicable to aircraft. These all apply to primary batteries only. The standards which apply to both primary and rechargeable batteries are the Underwriters Laboratories standards (UL 1642 and 2054). These are also the standards which are widely used in the battery industry. A comparison of these standards shows that they cover similar ground and so a battery which passes one standard would be likely to pass the others. However the aircraft battery standards are limited as they do not cover rechargeable batteries and even for primary batteries are much more limited than the Underwriters Laboratories standards in terms of initial battery conditioning. These latter standards provide comprehensive battery conditioning in terms of storage, partial discharge and, for rechargeable batteries, charge cycling. The aircraft battery standards provide more information on the design of batteries (particularly RTCA) and require more documentation, while the UL standards are more comprehensive in terms of tests. The presently published standards will not address the case of possible hazards from passengers plugging their lithium rechargeable battery chargers (where physically possible) into aircraft passenger cabin recharging points. The comments made in 2.4.4.11 should be considered in the drafting of any future aircraft standards applicable to lithium batteries.

5 CELL MANUFACTURING DEFECTS OR INADEQUATE CELL DESIGN

5.1 Lithium rechargeable cells will be offered for general sale by an increasing number of manufacturers world-wide. The vast majority of suppliers can reasonably be expected to design cells which, when properly made, have adequate safety features for their intended widespread domestic or commercial use. Since many will only be supplied in made-up battery packs with Electronic Management Systems, 'intended use' may well not include end-users removing or even handling individual cells. Indeed manufacturers will often supply only complete battery packs, including electronic controls, and will not sell individual cells, at least to the general public.

5.2 Manufacturers have funded their own programmes of hazard tests, particularly with the US Underwriters Laboratories and have freely published claims of adherence to these standards in their publicity sheets as a way of promoting the products' safety and customer acceptability.

5.3 Even though batteries on public sale will have passed extensive safety tests (such as UL 1642) and reputable manufacturers will adhere to comprehensive quality control procedures, there is always the possibility that the odd cell may be below standard and could pose a hazard.

5.4 The behaviour of a potential lithium rechargeable aircraft main battery would have to be considered not only in relation to existing lithium battery standards but also in relation to aircraft battery standards [14 – 17]. Large size lithium-ion batteries are being developed for electric vehicles and it is possible that electric vehicle battery modules would be suitable as aircraft main batteries.

6 DEFECTS IN, OR ABSENCE OF, CONTROLS IN BATTERY PACKS

6.1 Section 2.4 describes which controls are likely to be similar to those provided in multi-cell packs of lithium primary cells, and which should be focused on, as new in lithium rechargeable battery packs. A risk assessment is needed on the probability and consequences of failure of electronic controls (see 2.4). This should include possible heat build-up and thermal management issues as well as accidental subjection of cells to inappropriate voltages and currents.

6.2 The behaviour of the electronic control pack protecting the cells of a future aircraft main battery to long-term float charging from the aircraft bus-bar should also be studied.

7 EFFECTS OF ACCIDENTAL OR DELIBERATE ABUSE

7.1 The easiest batteries to abuse mechanically would be single cells in laminate foil envelopes. These could readily be accidentally pierced with pointed metal objects or even deliberately cut open with scissors. Fortunately, very large cells containing a lot of active material are not expected to be available for domestic users, but might eventually be packed into multi-cell batteries in strong plastic cases. These latter should resist penetration almost as much as metal-cased batteries. Rupture of single packet cells is not expected to have serious consequences due to the relatively high internal resistance and modest short-circuit current of these products as well as their small size. However, heat damage may occur together with minor injuries to occupants in close proximity.

7.2 The behaviour of metal-cased cylindrical cells when pierced is expected to be similar to that of equivalent lithium primary cells. As rechargeable ones will be mainly of the spiral-wound type, the nearest analogy would be the high-rate lithium-manganese dioxide cell. One of the main uncertainties with lithium rechargeable cells will be whether or not the effects of rupture would be any different for heavily-cycled cells than for fresh ones. It is only the latter that closely parallel primary lithium cells.

7.3 The possible harmful consequences of rupture include:

(a) toxication by solvent vapour

(b) the vapour catching fire

(c) physical injury caused by case fragmentation

(d) skin or facial injury caused by ejection of liquid or solid contents

All of these possible eventualities already exist with lithium primary cells, so it is a question of whether such an event is more likely with rechargeable cells. It is difficult to see any good reason to expect this for new cells, but could occur for heavily-cycled cells.

7.4 The consequences of accidentally rupturing lithium rechargeable aircraft batteries could be serious, and have no direct parallel in lithium primary battery usage. However, such batteries will nearly always be away from passengers and crew. The total amount of energy, the high power, and hence the potential for blast damage might well be severe. The consequences could however include complete loss of an emergency power source, or critical damage to nearby electrical or other essential equipment and the aircraft structure.

7.5 Exposure to heat or fire

7.5.1 In general, the High Temperature tests of BS 2G 239 (Sections 11.8.1 and 11.8.2) and other battery standards (as described in section 4) simulate many fire situations in the passenger cabin or cockpit, and possibly also the aircraft battery environment. The requirement of these tests is that the cells (if hermetically sealed) should vent, in order to avoid explosions, and that they should remain intact without ejection of solid components. For one type of lithium-ion cell [21], exposure to 75°C for 48 hours produced no leakage, explosion or abnormal weight loss. Overheating at 200°C caused venting and electrolyte release above 140°C but no flame or explosion below 200°C [21].

7.5.2 It is difficult to foresee lithium rechargeable cells in batteries reacting much differently from lithium manganese dioxide primary batteries in these tests, as both have flammable organic solvents in their electrolyte and similar materials for other components. It should be noted that lithium primary batteries can explode with considerable violence in a fire [18].

7.5.3 One major difference in consequences between primary and secondary lithium cells could be that, on heating, the lithium foil in lithium primary cells will melt at 180°C, thereby setting off very vigorous exothermic reactions with other cell materials and being a particular hazard in its own right if ejected from the cell. In contrast, the lithium-carbon compound, though highly reactive to water and air, does not have a particular trigger temperature, like a melting point, when events are expected to escalate. This might mean it is safer in the event of heat and fire than the metallic lithium anode.

7.6 Electrical abuse

7.6.1 This is another eventuality where lithium rechargeable batteries obviously differ from primary ones, viz., the former are intended to be charged many hundred times, so no anti-charging diodes would normally be fitted, as specified in BS 2G239 and other standards. However, unlike nickel-cadmium rechargeable cells and batteries, which may be recovered from virtually any charge state, the voltages of lithium rechargeable battery cells should not be allowed to stray outside recommended limits on either charge or discharge (see Section 2.4.2). Electrical abuse can occur through forced discharge (BS 2G239, Section 11.4), overdischarge (Section 11.5), overcharging (Section 11.6) or short-circuit (Section 11.7). These sections of BS 2G239 require cells to show no signs of physical distress or leakage after the test. Section 11.7 requires that the cells should not leak, vent or explode. Forced discharge of a lithium-ion cell showed no leakage, fire or explosion [21]. Repetitive overcharge and overdischarge by 150% caused no fire or explosion [21]. A short-circuit caused the cell to reach 120°C but no fire or explosion occurred [21].

7.6.2 There seems no reason why the behaviour of lithium rechargeable cells or batteries should be any different from primary ones in respect of the risk of cell polarity reversal in series strings, or when accidentally shorted. The special Electronic Management System should prevent reversal in the former case, and some form of current limiter, such as a polyswitch in the latter. The risk of malfunction of current-limiting devices should be the same for lithium secondary batteries as for lithium primary batteries, and lithium rechargeable cells and batteries should be designed to a similar standard to that of primary batteries.

7.7 Altitude effects

The rapid decompression test 9.5 of BS 2G239 and RTCA (2.3.4) examine altitude effects up to 55000 feet. BS 2G239 requires the external pressure to be reduced from 80.5 kPa to 4.5 kPa within 1 minute ± 20 seconds. A more recent requirement is to reduce the pressure within 15 seconds [20]. The test requires that the cells should show no signs of physical distress or leakage. As the sealing methods for lithium rechargeable batteries have exact parallels in lithium primary batteries, no significant differences are foreseen. As this test is not included in the widely used standard, UL 1642, it is not normally carried out on lithium rechargeable batteries. However, one report of exposure to 0.1 atmosphere, corresponding to 50 000 ft, for 8 hours found no leakage or explosion with cell voltages remaining stable [21].

7.8 Hazards of charging equipment

There are two important scenarios here which are obviously not of concern with lithium primary batteries. The first is the possibility of applying an incorrect voltage or current to the dedicated charger for a domestic lithium rechargeable battery, when a passenger plugs it into his seat-side socket. This eventuality should be considered along with the risk assessment on failure of electronic controls in the battery. The second is the possibility of a malfunction of the aircraft system applying an inappropriate voltage to the electronic management pack in a possible future lithium rechargeable main battery or those in aircraft equipment.

7.9 Safety effects of long-term charge / discharge cycling

This is obviously a situation which does not occur for primary batteries. Of all the potentially hazardous battery conditions, the effects of ageing are perhaps the least well predicted and documented. This will partly be because some available products have such a long cycle life (over 2000 deep-discharge cycles as individual cells) that it takes a long time to bring the condition of the cell to a point where it would be discarded on technical performance grounds. Previous tests indicate that lithium rechargeable cells are not prone to sudden internal temporary short-circuits, as nickel-cadmium cells can be under adverse conditions. Their very gradual capacity decline is consistent with drying out of the cells and an increase in internal resistance caused by solid product build-up. Tests on some lithium-ion cells from one manufacturer showed no hazardous events after cycling them for about 2400 deep-discharge cycles. However, this does not preclude the possibility that cells from other makers, which might use different chemicals or have slightly different internal cell constructions, could be less benign under prolonged cycling. Commercially available lithium-ion cells from well known manufacturers have passed all the safety tests in UL 1642 which require cells to have been conditioned by charge / discharge cycling at 25°C and 60°C for 100% depth of discharge for the cell's rated cycle life or for 90 days whichever is less. Experience has shown that commercial lithium-ion cells will cycle for over 2000 cycles with only slight performance degradation with no adverse safety effects. However these tests applied to only one type of cell from one manufacturer. Tests on some prototype polymer electrolyte cells showed no adverse effects on long term cycling though reducing the low voltage cut off caused a cell to fail prematurely. This shows the importance of adhering to the manufacturer's instructions to obtain the best performance. Cells should never be cycled outside their manufacturer's recommended voltage ranges. Indeed this will normally be prevented by electronic controls and so could occur only in the event of failure of the electronics. Cycling tests on a lithium-metal rechargeable cell showed that the cell cycled without any safety problems becoming apparent. However, more tests are needed to gain confidence in this conclusion (see Section 5.3).

Apart from any effects of long term cycling on individual cells, the effect of cycling on a complete battery needs to be considered. A test was carried out on cycling a battery pack without its electronic controls. The cells became out of balance and the capacity of the battery pack fell, indicating the importance of electronics to maintain full charge of all the cells to get the best performance from the battery pack. Within the limited testing carried out, no safety problems were encountered, though it could not be guaranteed that problems would never occur.

7.10 Battery response to safety tests

In their original announcement of the lithium-ion battery [21], a manufacturer reported detailed reaction of their cells to an extensive range of safety tests (Table 1 of [21]). These showed that their cells could withstand a short circuit with the cell temperature reaching 120°C without any fire or explosion. On a forced discharge of 300% at 1C and 3C currents, the cell reached 90°C without leakage, fire or explosion. On overcharge for 200% at 1C and 3C, the cell temperature reached 90°C at which point the protective current shut-off activated without any leakage, fire or explosion. On repetitive overcharge and forced discharge to 150%, the cell failed on first overdischarge but no fire or explosion occurred. On high temperature storage for 48 hrs at 75°C, there was no leakage, explosion or abnormal weight loss. On overheating to 200°C on a hot plate, venting and release of electrolyte and gas occurred above 140°C. There was no flame or explosion under 200°C. A high altitude simulation at 0.1 atm corresponding to 50000 feet for 8 hrs, produced no leakage or explosion and voltages remained stable. A vibration test of 0.06 inch amplitude with a sweep frequency 10 – 55 – 10 Hz with a sweep speed of 1 Hz/min for 90 min in 2 directions produced no leakage or explosion with the cell voltages remaining stable. A mechanical shock test with an average acceleration of 75 g with a peak acceleration of 125 – 175 g during 3 msec produced no leakage, explosion or damage in the cell. On a crush test of 10000 lbs using steel plates covered in plastic in a hydraulic press, the cell temperature increased to approximately 100°C. Leakage of electrolyte occurred without any fire. On a penetration test using a sharp metal spike of 4.0 mm diameter and 35 mm length, the cell temperature increased to 95°C. Leakage of electrolyte occurred but no fire.

A limited range of hazard tests on commercial lithium-ion cells conducted on behalf of DERA by a hazard test facility produced results broadly in agreement with these. Short circuit tests on 18650 cells (18 mm diameter x 65 mm high) at 20 and 70°C in accordance with BS 2G239 produced temperature increases of only 20 to 30°C without any physical damage to the cells. On a high temperature test at 70°C, nothing untoward was observed. On the second higher temperature test (to 160°C), the cells vented as required. Material leaked from the cell but did not ignite. In a flame test, the cells vented and material ignited but the cells did not explode and the venting was confined to the designated vent zone. Larger cells (26650 size, 26 mm diameter x 65 mm high) were similar though the temperature rise on short circuit was higher (45 to 55°C above ambient). During the high temperature (70°C) test, the weights of the cells remained unchanged and there were no signs of damage. At 160°C, the cells vented and the vapours from one cell ignited in the oven but the cells did not explode. In the flame test, the vapours ignited but the cells did not explode and venting was confined to the designated area.

Commercially-available cells from well-known manufacturers have already undergone extensive safety testing to meet the requirements of the battery standards discussed in section 4, above. However cells are not normally tested specifically for aircraft use, though a manufacturer did include an altitude test at 0.1 atm in their original report of their prototype cells. The only safety test in BS

2G239 which applies only to aircraft use is the altitude / decompression test so a range of cells were tested at DERA, Haslar, to see what effect reduced pressure had on cells. The cells included lithium-metal and lithium-carbon (lithium-ion) cells, cylindrical and prismatic format cells and a prototype polymer electrolyte envelope cell in plastic packaging. After conditioning with at least 50 charge / discharge cycles, the cells were put into a vacuum chamber and discharges were started. While the cells were discharging, the pressure was reduced to 45 mbar. The discharges continued normally while the chamber was under vacuum and when the pressure was returned to atmospheric. No venting or leakage of the cells occurred. The cells in cylindrical or prismatic containers showed no signs of deformation or indeed any effect from the reduction in pressure. The envelope cell in plastic packaging swelled as the pressure was reduced and remained in this state while the chamber was under vacuum. On raising the pressure back to atmospheric, this cell returned to normal shape. This was a prototype cell and is not necessarily representative of any cell now being manufactured but does suggest that cells in non-rigid packaging may be more vulnerable to pressure reduction than those in metal or rigid plastic containers.

8 CONCLUSIONS

The safety implications of the use of lithium rechargeable batteries on aircraft have been considered in respect of possible usage of these batteries:

(a) by passengers, to power portable equipment and also in battery charging at their seats

(b) in aircraft equipment

(c) as aircraft main batteries.

The potential hazards of primary and rechargeable batteries have been compared. Rechargeable batteries commercially available at present use solid cathodes (lithiated cobalt / manganese oxides) similar, but not identical, to those used in some primary lithium batteries (manganese dioxide). These systems are safer than liquid cathodes (sulphur dioxide, thionyl chloride) used in some primary batteries. Rechargeable batteries generally have less energy content for their size or weight than primary ones so the total energy available for release is less. However, additional energy imported into the cells from the on-board charger, could, if mismanaged, cause a hazard.

Early lithium rechargeable batteries used a lithium metal negative electrode. Cycling of lithium metal can cause fragmentation of the metal and cell short – circuiting by lithium dendrites penetrating the separator. This led to a safety incident, causing a product to be withdrawn. This causes greater hazards with lithium metal in rechargeable batteries than primary ones. However most manufacturers now use a lithium-ion (lithium-carbon) design, which avoids this problem, and such batteries are now in mass production.

Venting of lithium rechargeable cells inside batteries on-board aircraft poses a potential fire or toxic hazard especially near passengers, but not more than equivalent hazards from lithium non-rechargeable batteries that have long been taken on-board. Equally, lithium rechargeable batteries (like primary ones) could suffer one or more cells exploding inside the battery case in very unfavourable cabin circumstances such as a major fire. As with other batteries, this could be in quick succession as one-cell explosion triggers a neighbouring one by projectile impact or heat. This could cause battery case rupture, though often, fragmentation and projectile damage could be contained within the case. Of course, further physical protection of passengers would be afforded where the battery is inside their equipment, such as a laptop computer or mobile phone. However, cells are normally designed with vents and standard tests check the operation of the vents.

Lithium rechargeable batteries for consumer use from well-known manufacturers have passed the widely-used Underwriters Laboratory standards UL1642 or UL 2054. These specify a comprehensive range of safety tests to be applied to batteries which have been conditioned by a wide range of treatments including extensive cycling. These tests ensure a high standard of safety, though they are not specifically directed towards aircraft applications. In particular, they do not include the altitude/decompression test found in BS 2G239.

Lithium primary batteries for use in aircraft equipment already have to meet the standard BS 2G239. This specifies safety tests similar, but not identical, to UL 1642. BS 2G239 is not appropriate in its present form for rechargeable batteries as it specifically applies only to primary batteries. It could be developed relatively easily to include rechargeable batteries by including a requirement for rechargeable batteries to be tested, not only when new, but also after recharging, as in UL 1642. Some inappropriate existing clauses would need to be deleted.

Lithium rechargeable batteries which are available in the consumer market are normally packaged into battery packs, containing one or more cells. These packs contain electronic controls to ensure the safety and long cycle life of the batteries under normal usage and many types of minor abuse situations. The individual cells have normally already passed consumer safety standards, such as Underwriters Laboratories standards UL 1642 or 2054, so that, even in the event of a failure of electronic controls, a high standard of safety is assured. The electronic controls provide further protection. Adherence to these standards gives a good assurance that the total battery/charger system should be fundamentally safe on-board civil aircraft. However, attention needs to be given to the safety of the charging socket interface and the in-seat power supply, which are aircraft-specific features.

As with all equipment, random manufacturing defects could result in battery failure even though the battery type has been found to conform satisfactorily to the requisite safety standards. Resulting failures could present an on-board hazard. Furthermore, cells may vent in extreme circumstances (fire, very high temperatures) where often a hazard may already have arisen quite independently of the battery. The effects likely to arise in such rare events have also been predicted and mitigation measures described. They should be mainly of a toxic and inflammable vapour nature rather than fragmentation outside the battery case or within the equipment. Statistics on the probability of these hazardous events can be much better refined as consumer usage of this type of battery further increases in the home, in industry and in leisure activities.

9 RECOMMENDATIONS

The hazards presented by secondary lithium batteries in portable equipment carried on-board aircraft by passengers do not present a significantly greater hazard than that associated with primary lithium batteries.

However, on-board charging of secondary batteries, for example by the use of in-seat power supplies systems (IPSS) should be assessed to ensure that they do not compromise the inherent integrity of the batteries. This assessment should take into account the hazard affecting battery safety due to incompatibility between supply and device because, unlike primary cells, secondary cells are importing energy. Care therefore needs to be taken when the connection of Portable Electrical/Electronic Devices to the in-seat power supply, is being considered. Checks should be carried out to ensure compatibility and to ensure that the integrity of the Portable Device does not compromise the safety of the aircraft and its occupants. This will require consideration of new safety tests added to existing aircraft standards.

Lithium rechargeable batteries for use in aircraft equipment should be required to have passed the safety tests in recognised standards such as UL 1642 (with the addition of an altitude / decompression test), BS 2G239 (including tests on batteries which have been conditioned by charge / discharge cycling as in UL 1642).

Before lithium rechargeable batteries could be used for aircraft main batteries, they would need to demonstrate not only that they could pass the safety tests for lithium rechargeable batteries (above) but also the safety tests already applied to lead-acid or nickel-cadmium aircraft batteries.

REFERENCES

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19 IEC 61960, Secondary Lithium Cells and Batteries for Portable Application Part I: Secondary Lithium Cells.

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21 T Nagaura and K. Tozawa, Lithium Ion Rechargeable Battery, Progress in Batteries and Solar Cells, p 209, vol 9, 1990.

Table 1 Comparison of standards

TEST [reference]	BS 2G239 [5]	EN 4240 [6]	UL 1642 [12]	UL 2054 [13]	RTCA DO – 227 [11]	38.3 Lithium Batteries [2]
Primary / Secondary	Primary only	Primary only	Primary & Secondary	Secondary only	Primary only	Primary & Secondary
Case	6.2	6.2	4.1	4.1		
Vents	6.3	6.3			1.5.8	
Protective Devices	6.4	6.4	4.3	9.4 10.3 13.3	1.5.7	
Overload Protection	6.4.2	6.4.2	4.3	9.4 10.3 13.3		
Charge Protection	6.4.3	6.4.3	4.3		1.5.6	
Reverse Polarity	6.4.4	6.4.4	4.3			38.3.4.3.3.3
Temperature	6.9.1	6.9.1	7.1 7.2	25		
Altitude	6.9.2	6.9.2			2.3.4	38.3.4.1.3.1
Type Approval	7	7				
Acceleration / Shock	9.1 11.2	9.1 11.2		16	2.3.2	38.3.4.2.3.2 38.3.4.3.3.2 38.3.4.5.3.2
Vibration	9.2	9.2	15	17	2.3.1	38.3.4.2.3.1 38.3.4.3.3.1 38.3.4.5.3.1
Drop	9.3	9.3	16	21		
Bump	9.4	9.4				
Decompression	9.5	9.5			2.3.5	
Mould growth	9.6	9.6				
Fluid Contamination	9.7	9.7				
Storage temperature – temperate	10.1.1	10				
Desert	10.1.2 11.8.1	10	7.1			38.3.4.1.3.2
Jungle / Humidity	10.1.3	9.9 10	14.2			
Case Containment	11.1	11.1	4.1	4.1		
Temperature Cycling	11.3	11.3.1	7.2	25	2.3.3	

Forced Discharge	11.4	11.4	17	12	2.4.1.3	38.3.4.6
Overdischarge	11.5	11.5				
Charging	11.6	11.6	18	10 11	2.2.1.1 2.4.1.5	
Short circuit	11.1 11.7	11.7	10	9	2.4.1.4	38.3.4.1.3.3 38.3.4.2.3.3
High temperature / Heating (fire /flame)	11.8	11.8.1 11.8.2	11 19	22 23 24		
Quality Assurance	12	12			1.4.2	
Individual Specification Sheet	Annex A	5 Annex A				
Charge / discharge for secondary batteries			7.4			
Crush			12	19		
Impact			13	15		
Internal short circuit (rod compression)					2.4.2.1	38.3.4.4
Vent					2.4.2.2	

Notes:

1 Figures in table are numbers in standards for the corresponding tests. Note that the tests are not the same in the different standards (though BS 2G239 and EN 4240 are quite similar).

2 The standard EN4240 is a draft standard at present and may be subject to change in the final version.