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Reliability of lithium batteries in search and rescue beacons

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Abstract

Search and rescue beacons, such as ELTs, EPIRBs and PLBs, use a variety of lithium batteries. Similar electrical demand on the battery and the requirement for low temperature performance in particular are common amongst all SAR beacon batteries. They must remain inactive for many years then operate the beacon in a life or death situation — this is the essence of the reliability issue. How is reliability to be assessed? The condition of lithium batteries retrieved after five years of field use in EPIRBs was ascertained. Cell failures, inadequate battery designs, poor assembly techniques and quality control lapses were all in evidence. Studies of cells commonly used in beacons have called into question their ability to power the beacons for typical service lifetimes. Deterioration in the performance of some of the lithium products contradicted the oft-quoted '10-year shelf-life' for lithium batteries.

This paper will discuss:
(a) the feasibility of a test to predict performance of beacon batteries;
(b) preliminary results from experiments with a predictive test conducted on Li/SO_2, $Li/SOCl_2$, Li/MnO_2 and $Li/(CF)_n$ cells;
(c) factors identified with the degradation of reliability in SAR beacon batteries;
(d) some simple and inexpensive methods that beacon battery assemblers, cell manufacturers and others can adopt to improve the overall reliability and quality of their lithium batteries.

Keywords: Lithium primary batteries; Applications/rescue equipment; Reliability

1. Introduction and background [1]

1.1. EPIRB battery study

The Canadian Department of Fisheries and Oceans supplied a number of used EPIRB battery packs for a research study at Farrington, Lockwood Company Limited. The objectives of the project were to assess the status of the batteries and to develop methods and practices to improve performance and reliability. Whilst the current EPIRB battery study is the main focus of this paper, its application is broader, encompassing many different SAR beacons as noted in the Abstract. It is also the culmination of several years' R&D in lithium batteries for airborne SAR beacons for military and aerospace organizations.

1.2. Some issues related to reliability

SAR beacons are required to perform critical tasks in emergencies, regardless of the long-term effects of the environment to which they may be exposed. Usually these tasks are during life-threatening situations and therefore the utmost in performance and reliability should be expected. A common thread in all SAR beacon applications is the requirement for the battery to withstand several years of storage, then operate on demand. SAR beacons are installed in boats, ships, spacecraft and aircraft where the environmental conditions can be extreme: temperature, humidity, ambient pressure, mechanical and thermal shock, mechanical vibration, etc. These will all have some impact on battery reliability, especially in the long term.

When installed in an SAR beacon the battery may be tested periodically or infrequently to see if it works. At the other extreme, some batteries may never be examined in any way. It is usually taken for granted that the lithium battery manufacturers' claims of up to 10-years shelf-life guarantee a long storage life. However, many users downgrade the cell manufacturers' longevity claim. They assign a lesser and some-

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[1] Abbreviations: ELT, emergency locator transmitter; EPIRB, emergency position indicating radio beacon; PLB, personal locator beacon; SAR, search and rescue.

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what arbitrary storage time equal to 5 years; the so-called battery expiry date. This is arbitrary insofar as there is a paucity of substantial data to support the fixing of a 5 year battery replacement requirement, or for that matter, the 10-year shelf-life claims. Discarding a perfectly good (and expensive) battery only because it is time-expired, then replacing it with a newer one that may in fact be inferior, is a frustration to the user community, but it happens far too often [1].

In summary, it is long-term storage, coupled with a variable and often severe environment, that characterize the SAR beacon battery requirement. Reliability means that when called upon in a life or death situation the battery must operate. One of the objectives of the EPIRB battery study was to investigate a way to assure the owner that his battery will perform to his expectations, but without having to discharge it to destruction, or to cause it to fail prematurely through the use of inappropriate and unproven testing.

1.3. Other lithium battery technology issues

The reasons for using lithium batteries in SAR beacons are obvious: long shelf-life, high specific energy (i.e. lightweight) and good low temperature performance. But they are relatively expensive. It should be understood that lithium batteries are still an evolving technology. In comparison with consumer type batteries (e.g. alkaline cells and watch batteries) which are mass produced in the billions, lithium battery production is several orders of magnitude lower. Additionally, the details of cell design are much more likely to vary with time. Ongoing changes in the manufacturing processes and procedures are the rule rather than the exception. This is not widely appreciated as a fact of the market place, and leads many to assume that all lithium batteries are interchangeable. Many years of experience have brought home this lesson; careful investigation needs to be done when seeking a replacement for a product which may no longer be available. In most cases there is really no large data base on a fixed design of lithium battery, so expectations for good reliability may not be very well founded.

The age of a cell is a very important issue. Despite their superior shelf-life, they are electrochemical species, which by their very nature will begin to deteriorate as soon as they are made. Since reliability is so critical in SAR beacon batteries it is essential that both the age of the cells and the date of manufacture (DOM) of the battery be as close as possible. For lithium batteries it is reasonable to expect that the cells be no older than 6 months when they are built into a battery. Such has long been the requirement of military organizations for Li/SO_2 batteries [2]. Another factor having a direct effect on age is the handling and storage of cells and batteries. In beacon applications there is often little choice about where the battery will be located in the ship, aircraft, etc. Often ELTs are mounted inside dark colored aircraft panels where heat exposure is extreme, sometimes as high as 100°C [3]. EPIRBs may be installed onboard vessels in places where the temperature may reach 50°C [1,4]. Both of these deployments cause accelerated aging in chemical systems and therefore can have a significant impact on shelf-life. Excessive heating could also lead to safety problems if battery design were inadequate.

Another issue is the influence of intermittent discharging such as might be done during the manufacturing process and for performance checks of the installed battery. Very little relevant data have been reported in this respect, so it is often taken for granted that performance would be unaffected. This may be due to widely held misconceptions about the protective film which forms on the lithium when a cell is filled with electrolyte. The film is often touted as being the all important factor that gives lithium batteries their long shelf-life. What is not so clear, however, is how the properties of the film vary with the electrolyte, nor how susceptible these films are to disruption caused by (intermittent) discharging, or the presence of electrolyte-borne impurities and other factors such as heat and aging.

These concerns are being addressed in the EPIRB battery study. Battery users are always wanting assurance that their battery will work when they need it and would like a test to prove it. However, it would be futile to use a test that had not been carefully studied and proven effective beforehand and thereby perhaps ruin a perfectly good, expensive battery.

In the recent EPIRB battery project and some other recent studies it became apparent that a wide variation in cell performance was occurring in the Li/MnO_2 battery system. In 1995–96 these changes were quite significant and were probably due to a number of manufacturing processes which were undergoing adjustment. The data presented here must therefore must be understood to represent a snapshot of the developing technology rather than an accurate description of the system as it may eventually evolve. In order that the reader not mistakenly identify the various products, the names of the cell manufacturers have been disclosed. This paper does not endorse one product over another and reiterates the conclusion that the Li/MnO_2 cell type is obviously still in a state of development.

Most SAR beacons find use in large organizations such as the military and fleets of fishing, transport ships and airlines. However some are sold to the public at large to provide assistance in the event of safety incidents in boating, hiking, skiing, mountain climbing, etc. Hence the user community is varied and in some cases not responsive to regulatory pressures. It is curious that the United Nations' International Maritime Organisation controls the transportation of lithium batteries because some of their components are hazardous materials, yet there is no technical standard to approve their safe use in marine applications. In aviation, controls have been in place since 1979. This gives concern for safety, especially since some SAR beacons are used by the public at large.

It is our conviction that safe and reliable lithium batteries will be achieved, assuming those involved in their manufacture, handling and use take reasonable precautions to maintain a good level of technical expertise, or failing that, ensure its availability.

Finally, this paper will recommend some practices that have been found effective in screening lithium cells for use in making SAR beacon batteries with high reliability. A number of suggestions are offered to improve reliability above that currently available for lithium batteries in some SAR beacons.

2. Experimental

Lithium batteries that were retrieved from EPIRBs after use in Canadian ships were produced by two different manufacturers. While these batteries were in service they were tested indirectly using the EPIRB self-test procedure, but comprehensive servicing records were not available. The self-test consists of up to 15 min of beacon operation in order to verify function. This is a beacon transmission test — not a battery test. It was of concern in the current study that, even though the beacon did transmit, the battery may have supplied inadequate or poor quality power, hence causing an encoding error in the radiated beacon signal. Elsewhere, laboratory testing has shown this fault to occur for many time-expired EPIRB batteries [1]. No accurate information was available concerning battery testing that may have been done after the batteries had been taken from the beacons and warehoused prior to shipping to Farrington, Lockwood Co. Ltd.

There is a variety of EPIRBs in current use which employ different lithium batteries and cell types.

The most common are the solid cathode types: Li/MnO_2 and $Li/(CF)_n$ and the liquid cathode types: Li/SO_2 and $Li/SOCl_2$.

The batteries in the present study consisted of three to five, series-connected, R20/D-size cells, except for the $Li/(CF)_n$ batteries, which had two parallel strings, each having five R14/C-size cells in series. The $Li/(CF)_n$ cells were produced by Panasonic; the Li/SO_2 cells by two sources: SAFT America and Ballard Battery Systems (now BlueStar Battery Systems). The Li/MnO_2 cells came from three sources: Hoppecke, Ultralife (UK) (formerly Dowty) and BlueStar Battery Systems. SAFT, France was the source of the R20/D-size $Li/SOCl_2$ cells. In the EPIRB battery study new batteries were purchased for comparison of their performance with the used batteries. Likewise, small quantities of new lithium cells were procured from cell manufacturers for performance comparison and for carrying out other experimental work. Suppliers were requested to provide the date of manufacture (DOM) for cells and batteries.

In cell experiments the end of discharge was taken as 1.4 V for the Panasonic $Li/(CF)_n$ R14-size cells and 2.0 V for all the R20-size cells. Discharging of all R20-size cells was performed in accordance with the average transmitter power requirements of EPIRBs that was determined from a survey of several instrument suppliers. Discharging was performed with a periodic load: a 1.3 A, 440 ms pulse, followed by a background of 130 mA for 50 s. For the R14-size Panasonic cells the currents were 650 and 65 mA, respectively, to comply with a unique battery design which used a parallel cell arrangement (see above). All voltage and temperature data were recorded using custom-built PC-based data acquisition equipment. Open-circuit voltages (OCV) for cells and batteries were recorded with a precision equal to 1 mV or better.

3. Discussion of results

3.1. *Shelf-life studies*

The bar graph in Fig. 1 summarizes the data which were averaged for triplicate cell experiments. The manufacturer, cell type and DOM are indicated at the left margin. Discharging was done in Spring 1996 in the beacon pulse load profile, at −20°C for cells that had been stored at 55°C for 1, 6 and 17 weeks. When cells had been stored only at room temperature (18–25°C) the legend states 0 weeks. The capacity results in Fig. 1 are expressed as the time (in hours) for the cell voltage to reach the end of life limit, which invariably occurred during the pulse portion of the periodic discharging profile. Fig. 1 includes the initial capacity data for comparison (i.e. 0 weeks storage).

Storage at elevated temperatures has often been used to accelerate the aging processes within electrochemical cells, because the capacity loss with temperature often follows an Arrhenius type behavior [7]. In the current work this assumption was necessary, because of time constraints and because 55°C was also the specified upper temperature requirement for EPIRB operation. If the data followed the Arrhenius rule, then these results indicated that a significant annual capacity loss should be expected from several cell types. Such degra-

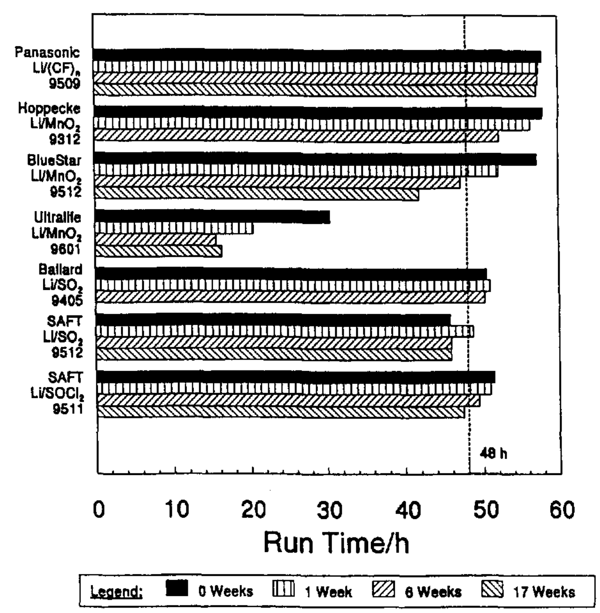

Fig. 1. Average performance for lithium cells after storage at 55°C. Legend indicates storage time in weeks. Performance expressed as duration to end-of-discharge voltage (see text).

dation of performance was most prevalent in the various Li/MnO_2 type cells. The Hoppecke Li/MnO_2 cell was the best performer, however that product is no longer being manufactured. Such variations in Li/MnO_2 cell data have recurred in much of our research over the years. The current results merely support the contention that all manufacturers do not produce same-size-same-type cells with identical performance. The results in Fig. 1 clearly depicted little capacity loss for the $Li/(CF)_n$ and the two liquid cathode systems. Whilst losses for the liquid cathode systems were relatively minor, their new cell performance capabilities only marginally met the beacon requirement. The best thermal stability and shelf-life according to these results was the $Li/(CF)_n$ cell.

3.2. Study of used EPIRB batteries

EPIRB batteries that were retrieved from the Canadian Department of Fisheries and Oceans' ships, were inspected to reveal a number of examples of poor workmanship and quality control lapses in the battery assembly process.

Soldering had been used to connect tabs to cells as well as for inter-cell connections. Overall quality of the work was poor. Soldering the inter-cell connectors in a lithium battery pack is not a recommended technique, since heat from the soldering iron can crack the cell's terminal insulator seal or melt the lithium electrode and produce a safety hazard during assembly. Inter-cell connectors were soldered too close to cells in one product. In some instances the connector was soldered on the side of the cell case. Such practices are likely to have a chronic, detrimental thermal effect on the cell chemistry. The spot welding of inter-cell connecting tabs is always preferred for lithium battery assembly. The cell placement scheme varied from one pack to another within a single product.

Electrical configurations deviated from the schematic diagrams provided by the manufacturer of another battery. In one particular battery, two out of the three shunt diodes across the cells were missing. Expiry dates marked on the battery packs of one manufacturer varied from 4.7 to 7.5 years from the DOM of the battery, whereas they should have been uniformly 5 years. A number of batteries with low OCV were found, suggesting defective or used cells within the pack.

In addition, corrosion and cell leakage were observed in seven of the forty-one batteries that were inspected. Some of this might have been caused by moisture ingress in marine service, as frequent buoy failures of this type have been reported [1,4]. Cell leakage has also been observed in the laboratory for another group of Hoppecke Li/MnO_2 R20-size cells which were stored for approximately 6 years at room temperature. Hypothetically, if say 30% of lithium cells from a batch begin to leak before 10 years, and on average the batteries were constructed from four cells — then at best reliability is poor, while at worst, some batteries would constitute a safety hazard.

The lack of quality of the EPIRB batteries was surprising, especially given the small numbers that were inspected. By comparison, much higher standards are seen in beacon batteries that are used in aerospace applications. Cell defects and deficiencies and lax workmanship will all have a degrading effect on beacon battery reliability. Correction of the corrosion and cell leakage faults and better workmanship would definitely enhance reliability of the EPIRB battery and therefore the beacon.

3.3. Acceptance testing for improved battery reliability

An improvement in battery reliability can be achieved by the use of certain simple and inexpensive cell acceptance testing. A group of sixty-five Li/SO_2 cells was procured from SAFT America as part of the EPIRB battery study. The test data demonstrated that the group consisted of cells of distinctly different ages. Initially, this was not apparent, because the date code was underneath the wrapper. How this disparity was detected is discussed below.

In acceptance testing, it is recommended to measure the OCV, the a.c. impedance (1 kHz) and the mass of all cells. Cells must be visually inspected for workmanship, corrosion and leakage, especially at welds, pressure relief vents and the fill tube. It is also important to verify the DOM, which should be visible and indelibly printed on the cell wrapper or on the can. It has been found in many other studies of lithium cells, during more than 15 years of research, that a graph of the a.c. impedance (R) versus OCV is very useful for detecting outriders. Such cells often turn out to exhibit performance deficiencies or other anomalies in later testing. Shown in Fig. 2 is just such an example, which was for the group of sixty-five SAFT Li/SO_2 cells mentioned above. In this plot three groupings of the R versus OCV data can be seen. Examination of the date codes on the cells revealed that they were from two different dates of manufacture: Aug. 1992 and Dec. 1995, making one set 40 months older than the other. As expected, the older cells had the higher OCV and R. The age of a cell

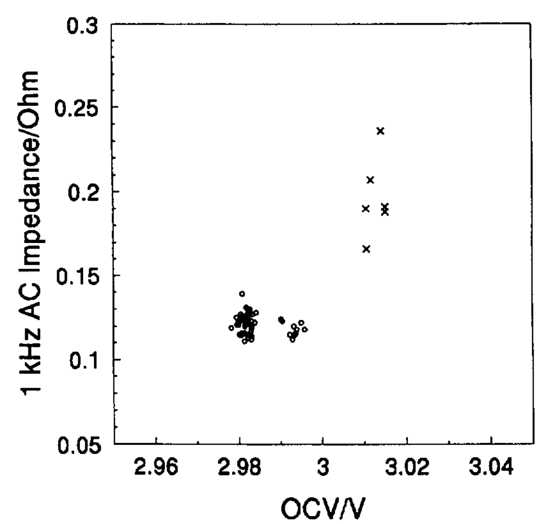

Fig. 2. Plot of a.c. impedance R (measured at 1 kHz) vs. cell OCV for a group of Li/SO_2 R20/D-size cells, as received from the manufacturer. Dates of manufacture: x, Aug. 1992; o, Dec. 1995.

has a definite effect on performance and reliability as already discussed. Without the practice of measuring *R*–OCV data the different cell ages would probably have gone unnoticed and the performance differences might have remained a mystery and been ascribed to a poor quality of product.

The measurement of a.c. impedance is also very useful in battery assembly as it can detect poor connections and faulty components. We have also used it extensively to examine batteries and cells for defects caused by environmental testing, such as in the airworthiness approval process [5].

Again by example, in a group of sixty-five SAFT, Li/$SOCl_2$ cells, weighing revealed that the mass of one cell was very low, at 77.3 g. The average cell mass for the group (including the outrider) was 96.4 g with a standard deviation of 2.3 g. Further inspection verified that this cell was not leaking. The deficiency in mass was probable due to a manufacturing problem in electrolyte filling. If this cell had been built into a multicell battery, this defect would certainly have resulted in a loss in performance, or perhaps a safety incident due to unbalanced cell capacities. That such an obviously poor cell went undetected by the manufacturer gives some concern for the prospects for good lithium battery reliability. It indicates that circumspection is warranted. Additionally, one of the sixty-five SAFT Li/SO_2 cells (in the group discussed above) was approximately 5% lighter in mass than the average; once again, a deviation not usually associated with good cell manufacturing practice. Clearly those wishing to have assurance of good lithium battery reliability must be vigilant.

3.4. Development of a test for predicting battery reliability

Using the EPIRB self-test does not reveal much about the battery's future performance, i.e. reliability. This procedure allows for up to 15 min of testing before the inspector may declare a failed beacon. Therefore batteries, especially older ones whose performance may have diminished slightly (but could still be fully adequate), may get tested for up to the 15 min limit on several occasions. The main concern is that such testing could result in a degradation of performance by damaging the integrity of the protective lithium electrode film, or by some other mechanism. Repeated or prolonged use of the EPIRB self-test could in fact ruin otherwise good batteries.

This is one reason behind the non-destructive cell testing that is currently being researched. Its objective is to develop a simple, predictive, technique for improved assurance of battery reliability without compromizing performance. One testing protocol which is under study consists of analyzing the electrical response before, during and after a cell has been subjected to a single 60 s high-rate pulse discharge. (It is estimated that one pulse should have very little harmful effect, in contrast to the 15 or more pulses that constitute the EPIRB self-test procedure.)

Preliminary results for the four lithium cell types have indicated that only for the Li/$(CF)_n$ cells did the results correlate with the capacity remaining in cells of different ages

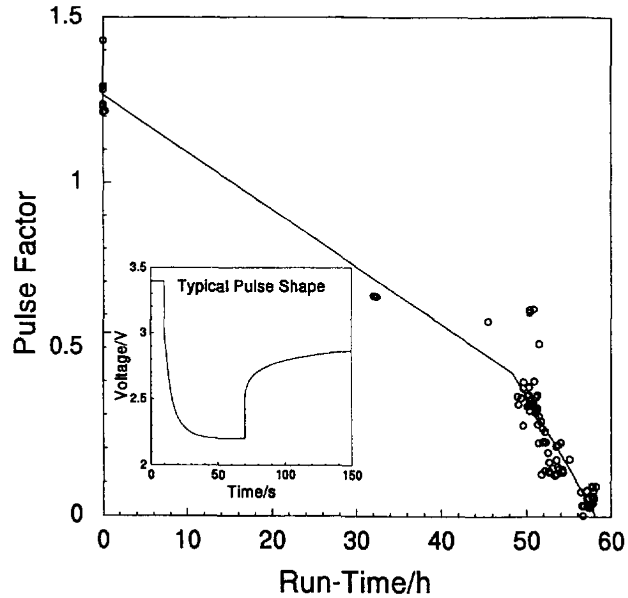

Fig. 3. Non-destructive pulse testing of R14/C-size Li/$(CF)_n$ cells. Pulse (shape) factor is plotted against run time (discharge duration) to 1.4 V. Inset: example of pulse shape.

(see Fig. 3). Analysis of the data made use of the fact that the shape of the voltage pulse changed, depending on the amount of total capacity a cell delivered when subsequently discharged. If selected points in the pulse were plotted against the measured capacity, then a trend was found such as is depicted by Fig. 3. Each point in the graph represented a unique cell whose capacity was measured some time after the non-destructive pulse test. The pulse factor parameter plotted in Fig. 3 was a measure of the change in slope of the pulse at selected points. This factor appeared to be independent of the discharge history of the Li/$(CF)_n$ cell, or the time spent at open-circuit before or after the pulse. Measurement of the pulse factor parameter is easily done and is predictive of the run time at the prescribed discharge rate.

Such was not the case for the other lithium systems in which the pulse shape and recovery to open-circuit showed the influence of open-circuit rest intervals. Results are incomplete at this stage of the research, but the use of this test showed promise, at least for the Li/$(CF)_n$ system. If this test, or another simple technique, can be further refined and be proven valid for a class of batteries, it would find wide application as an easy and inexpensive predictive tool to substantiate reliability.

4. Recommendations for enhanced lithium battery reliability and safety

4.1. Lithium battery research

It is important that the best lithium battery technology finds its way into SAR equipment. It is equally important that it be highly reliable as well as operate safely. The use of lithium batteries is most desirable as it extends the operating time, drastically reduces the maintenance intervals and broadens greatly the operating temperature range which is commonly from −40 to 55°C.

Continuing research into lithium battery technology has resulted in the accumulation of a wealth of technical background and experience. Lessons learned in one sector of lithium battery applications can benefit another. One of these lessons has been to recognize the importance of designing the lithium battery specifically to meet the operating as well as non-operating requirements of the application [8]. Another is that no matter what the application, experienced and knowledgeable users find it essential to constantly monitor lithium cell production. The quality and performance characteristics of lithium cells can vary from lot to lot and from manufacturer to manufacturer. This is due in part to the low volume of production compared to consumer batteries. It is also affected by the fact that lithium battery technology is still evolving. Continuing product development is the rule rather than the exception. The study of EPIRB batteries and earlier SAR beacon battery projects confirm this opinion.

4.2. Other recommendations

Based on more than 15 years of such experience, it is recommended that 100% of cells that are intended for assembly into SAR beacon batteries be inspected. Cells must be visually checked for workmanship, corrosion and leakage, especially at welds, pressure relief vents and the fill tube. The DOM must be visible and indelibly printed on the plastic jacket or on the metal case if cells are not clad. All cells should have their their OCV, mass and R (a.c. impedance, taken at 1 kHz) measured.

An abnormal OCV is cause to reject a cell, but a normal value does not guarantee reliable performance [6]. Mass data will help to screen out those leaking or incompletely filled cells that have normal OCVs. The a.c. impedance measurement is a most useful complement to OCV data. This simple measurement will help to cull those cells which may have a number of subtle and sometimes potentially hazardous faults, including damaged electrodes, partially broken, cracked or otherwise damaged internal connections and other anomalies that are not detectable by other methods.

These measurements (i.e. OCV, R) should also be taken again, both during and after the assembly of battery packs. Their use will add assurance that handling, accidental abuse, environmental testing etc. have not caused damage and that connections and other components are in a good state. These screening practices were established in conjunction with SAR beacon battery development and evaluations for airworthiness [5,9]. During the course of these and similar projects several batteries had serious, potentially hazardous, flaws as a result of shock or vibration testing. These problems might not have been discovered by applying the procedures set out in technical standards for aircraft batteries such as, TSO C-97 and the British Standard BS 2 G 239, because they do not specify the measuring of the a.c. impedance.

4.2.1. General guidelines for cell choice/selection

(a) All cells intended for battery assembly should be subjected to an incoming inspection and established acceptance tests to confirm that they meet the requirements of the technical specification.

(b) Do not use lithium cells in which the lithium is cold-welded directly to the can.

(c) Do not use lithium cells unless their design includes a pressure relief vent (except for extremely low rate applications).

(d) Ensure that potting compounds, glue or other packaging materials do not obstruct the pressure relief vent in the cell.

(e) Never use a cell for battery assembly that shows signs of leakage, heat scorching, corrosion, mechanical deformation or other unusual appearance.

(f) Never use a cell for battery assembly if it has been dropped, accidentally shorted, partially discharged, or subjected to any unusual or harmful handling or abusive usage.

(g) It is preferable in beacon batteries, where long life is a prime concern, that cells are able to safely withstand forced overdischarge, rather than to rely on shunt diodes which may develop electrical leakage.

4.2.2. General guidelines for battery assembly

(a) Confirm that cells were produced within 6 months from date of intended manufacture of the battery.

(b) Verify that the OCV and a.c. impedance of the cells to be used in a battery are within an acceptable tolerance as defined by testing (i.e. do not use outriders).

(c) Make sure all batteries comply with engineering design drawings and all components are located properly.

(d) Cell connections should be made by spot welding metal strip/inter-cell tabs.

(e) Do not solder wires and other components directly to the cell case.

(f) Solder may be used to connect to other components, however use heat sinks to protect cells from heat conduction when welding or soldering.

(g) The use of dissimilar metals is to be avoided whenever possible to prevent the onset of corrosion.

(h) Minimize the length of non-insulated conductors.

(i) Conductors should be secured to avoid short-circuits in the event of an insulation failure, also to prevent their movement when in high shock and vibration environments.

(j) Avoid sharp edges that could pierce insulation or other soft materials.

(k) Glues, resins or other substances should be selected to ensure proper bonding, electrical insulation, resistance to shock and vibration, temperature extremes and to deter corrosion.

(l) When applying resins, potting compounds, etc., special care must be exercised to ensure that the proper functioning of the pressure relief vents is not compromised.

(m) Do not use excess of glues, resins or other materials (do neat work).

(n) Use extreme care when heating shrink-wrap, using potting compounds, etc. so as not to expose the battery to excessive heating.

(o) The battery pack should be sealed against the ingress of moisture, water and salt water.

(p) Batteries should be labeled with the correct assembly date, not the shipping date (also, see cell DOM, above)

(q) Battery replacement date must be correctly noted on the battery label, preferably in a tamper-proof fashion.

In the absence of a reliable, non-destructive and predictive measurement for installed battery reliability, a good practice is to retain a stock of cells and batteries from the lot that was put into service. These can be drawn upon from time to time to measure their actual performance capability as a function of time. To minimize costs, most of such testing can be done on the cell basis, assuming of course that sufficient performance data were developed beforehand. In this way, not only will the user be able to predict the useful shelf-life of the in-service batteries, but will be able to detect any unusual changes in performance should they develop over time. He will then be able to take steps to preclude problems from occurring unexpectedly in the field.

5. Conclusions

Studies to date have raised many issues regarding the design, workmanship, quality control and regulation of SAR beacon batteries. Recommendations which are offered have been made based on our findings and experience with lithium batteries acquired over more than 15 years. The reliability and safety of lithium batteries can be enhanced by the application of guidelines and practices which are recommended for lithium cells and batteries.

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