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50 to 100 Ah lithium-ion cells for aircraft and spacecraft applications

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Abstract

Battery weight is a continuing concern for the designers of power systems for aircraft and spacecraft. An obvious approach to lighter weight energy storage for these applications is to scale-up the lithium-ion battery technology presently being introduced into consumer portable electronics to meet the needs of larger power systems operating in severe environments. BlueStar is presently pursuing the development of 50 to 100 Ah cells for this application with funding from the US Air Force and Canada's Department of National Defence. Several 20 Ah cells have been built and preliminary testing is underway. The structure of the programme, test results with small cells and the design of the 20 Ah cell are described herein.

Keywords: Lithium-ion secondary batteries; Applications/space; Applications/aircraft

1. Introduction

The growing concern with managing the costs of military and commercial aircraft and spacecraft has placed an increasing emphasis upon developing more weight-efficient vehicle designs. The power sub-system, particularly the energy storage component of that sub-system, is an area in which significant weight reductions could be achieved if existing commercial lithium-ion battery technology could be extended to meet the requirements of the aerospace application. Trivially stated, this involves the scale-up of existing 1–5 Ah cells to the 20–100 Ah range. Recognizing that reconciling the thermal, mechanical and electrical requirements of a 100 Ah cell with existing small cell technology is decidedly non-trivial, the USAF and Canada's Department of National Defence (DND) have jointly funded (by means of the provisions of the Defence Development Sharing Agreement) BlueStar Advanced Technology Corporation (BATC) to develop 20–100 Ah lithium-ion cells specifically for aircraft/spacecraft applications.

The technical objectives of the project have been formulated at the cell, as opposed to battery, level and are shown in Table 1. This table requires two comments. The first is that two levels of technical objectives have been identified. One set of objectives, designated as targets, are rather conservative and should be achievable with existing cell chemistries. The second set, designated goals, are more ambitious and will require some improvements over the existing state-of-the-art components and cell designs. The second comment is that the conditions under which each of the cell characteristics is to be determined have been tightly specified in order to limit to some extent the battery developer's natural inclination toward prevarication. It should also be noted that the requirements have been formulated to satisfy the extremes of both aircraft and spacecraft needs and this one-size-fits-all approach gives rise to cycle life and specific energy requirements suitable for spacecraft and temperature requirements which more befit the needs of aircraft.

Table 1
Programme targets (expected) and goals (desired)

Cell characteristic	Target	Goal
Specific energy (Wh kg^{-1}) (Cycle 10, 25°C, to 3.0 V, $C/2$)	135	150
Energy density (Wh dm^{-3}) (conditions as above)	325	360
Cycle life, 100% D.O.D. (25°C, to 3.0 V, $C/2$, 75% initial capacity)	500	1000
Cycle life, 60% D.O.D. (conditions as above)	2000	5000
Capacity @ −20°C, % initial capacity (bare cell, Cycle 10, to 3.0 V, $C/2$)	50	75
Capacity @ −40°C, % initial capacity (conditions as above)		50

2. Programme structure

The programme is structured around two key milestones, namely the delivery of 20 Ah cells in Mar. 1997 and the

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delivery of 50 Ah cells in Mar. 1998, and this structure is based on the assumption that cell chemistry and cell engineering are largely independent of one another. This assumption permits the parallel development of cell components (and processes) and cell designs resulting in a development pathway in which improved components may be introduced into existing cell designs as these improvements become available. By including a specific task focussed upon cell and cell component fabrication techniques, the programme structure also takes into account the fact that cell performance is inextricably linked to the processes by which the components, particularly the positive and negative electrodes, are prepared.

Prior to Oct. 1996, the work focussed on mastering electrode preparation techniques and the evaluation of several candidate positive and negative electrode materials with the objective of selecting a cell chemistry for the first generation of 20 Ah cells. Welded C-size cells were chosen as the test vehicle for these evaluations. Coke and graphite samples were evaluated from several commercial sources and based on cell capacity and cycle life performance, Lonza/Timus SFG15 graphite was selected as the negative electrode material for the first generation of cells. The selection of the material for the positive electrode was more complex as it involved both a choice of chemistry ($LiCoO_2$ versus $LiNiO_2$ versus $LiMn_2O_4$) as well as source. Although $LiMn_2O_4$ is of particular interest for commercial applications, due to cost and environmental advantages, it was rejected, at least for the first generation of cells, because it exhibits a specific energy decidedly inferior to the other candidate materials. For aerospace applications specific energy must be considered along with cycle life as the key performance drivers. The choice between $LiNiO_2$ and $LiCoO_2$ was more difficult and was ultimately based on a tradeoff analysis in which several equivalent C-size cells of both chemistries were prepared and evaluated under a variety of conditions. Based on this evaluation, $LiCoO_2$ was selected as it exhibited, at least at BATC, less capacity fade with cycling than did $LiNiO_2$ resulting in a higher lifetime average specific energy.

The remainder of the programme consists of seven principal technical tasks as may be seen in Fig. 1. Three of these, Tasks 1, 2 and 4, are technology tasks related to cell components, processes and designs, two are cell development and fabrication tasks (Tasks 3 and 5), and two are test and evaluation tasks (Tasks 6 and 7).

Task 1 is focussed on pursuing the next generation of cell chemistries and at this time is continuing to explore potential improvements in $LiMn_2O_4$ positive electrode materials as well as continuing to search for improved carbons for negative electrodes. The so-called hard carbons prepared by the pyrolysis of various organic feedstocks are presently the subject of this activity. The efforts of Task 2 are directed toward improving process technology from the standpoint of both performance and material throughput. More readily assembled cell designs are also being explored as part of the effort.

The inclusion of Task 4 recognizes the rapidly evolving nature of this technology and is more specifically directed toward identifying new or improved components which will lead to enhanced performance, particularly at higher rates and lower temperatures.

Tasks 3 and 5 are cell development tasks which culminate in the delivery to the USAF of 20 and 50 Ah cells, respectively.

The two test and evaluation tasks have very different structures and objectives. Task 7 is devoted to the on-going testing and evaluation of the safety of all cells tested as part of the programme while Task 6 is specifically focussed on cell electrical and mechanical performance as determined by a series of test regimes closely modeled after the qualification tests of spacecraft flight cells.

Programme accomplishments to date include the development of processing techniques for positive and negative electrode materials, the identification of the chemistry to be used in the first generation of large cells, the initiation of cycle life testing of this chemistry in small cells, the verification of prismatic cell design features and construction techniques, and the development, fabrication and testing of 20 Ah prismatic cells. The accomplishments are described in the following sections.

3. Electrode processing

Initially, electrodes at BATC were processed by manual techniques which in the case of positive electrodes consisted of a manual doctor-blading approach and in the case of negative electrodes it involved the application by spraying with compressed air. Following coating, these electrodes were compacted by multiple passes through a manually operated jeweller's roller press. Electrodes produced by this methodology were adequate for the initial efforts but suffered from a lack of uniformity and were frustratingly time-consuming to produce. More recently BATC has begun to produce these electrode materials using a commercial bench scale coater (model HS-250) manufactured by the Thank Corporation. Post-coating compaction is accomplished with a motor driven desktop press roller also produced by Thank Corporation. The coating equipment is sized for a maximum foil width of 200 mm and a maximum speed of 1 m min^{-1}. The maximum speed of the press roller is 5 m min^{-1} and the maximum pressure is 1 tonne cm^{-2}.

Initial results obtained with this equipment indicate a significant improvement in electrode uniformity as well as a demonstrated capability of producing hundreds of Ah of electrode material during a single shift. The level of uniformity achieved has been quantified both in terms of thickness and loading and these results are shown in Tables 2 and 3. The improvement in electrode uniformity also results in a 5–10% increase in cell capacity when compared to cells produced with manually coated electrodes. At the time of this writing, cycle life evaluation of small cells assembled with electrodes

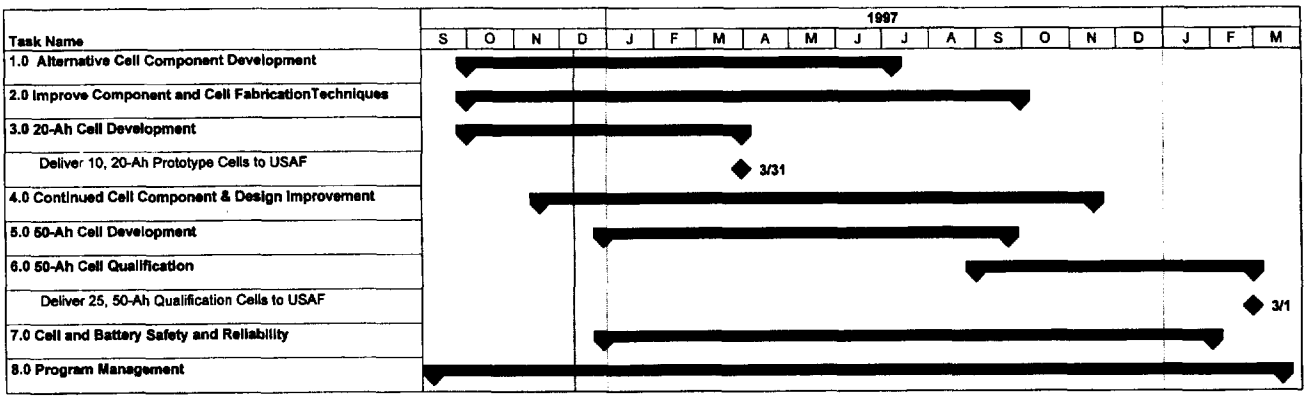

Fig. 1. Schedule of principal tasks and milestones.

Table 2
Uniformity of coating thickness (mm) for positive electrode material coated on 0.025 mm Al foil and measured 30 mm from each edge at 80 mm intervals

Single side		Double side	
Right	Left	Right	Left
0.17	0.17	0.31	0.31
0.18	0.17	0.30	0.30
0.17	0.16	0.30	0.29
0.16	0.16	0.30	0.30
0.17	0.17	0.31	0.29
0.16	0.16	0.29	0.29
0.16	0.16	0.30	0.29
0.17	0.16	0.30	0.29
0.16	0.16	0.30	0.29
0.16	0.16	0.30	0.29
0.17	0.17	0.30	0.29

Table 3
Uniformity of coater loading as determined by weight (g) of 200 mm×40 mm samples taken from 1000 mm×120 mm positive electrode segment

Position		
Right	Center	Left
4.25	4.33	4.22
4.16	4.33	4.12
4.08	4.25	4.20
3.95	4.19	4.14
4.10	4.30	4.18
$\mu\pm\sigma$	$\mu\pm\sigma$	$\mu\pm\sigma$
4.11 ± 0.15	4.28 ± 0.09	4.17 ± 0.05

prepared by these techniques has been initiated but insufficient data have been collected to permit meaningful comment.

4. Testing of small cells

As noted above, welded C-size cells were adopted as the standard test vehicle for component evaluation and this approach proved to be sufficiently useful that it was decided to continue to build cells of this type in order to accumulate cycle-life data on various cell components. The advantage of

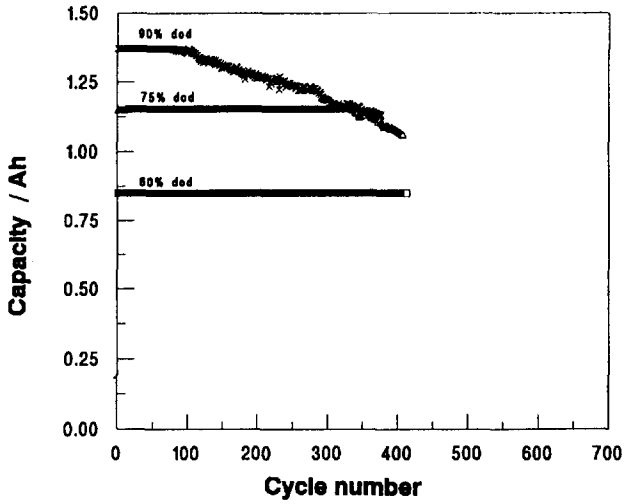

Fig. 2. Capacity vs. cycle number for Generation 1 status cells, discharged at $C/2$ and charged at $C/5$.

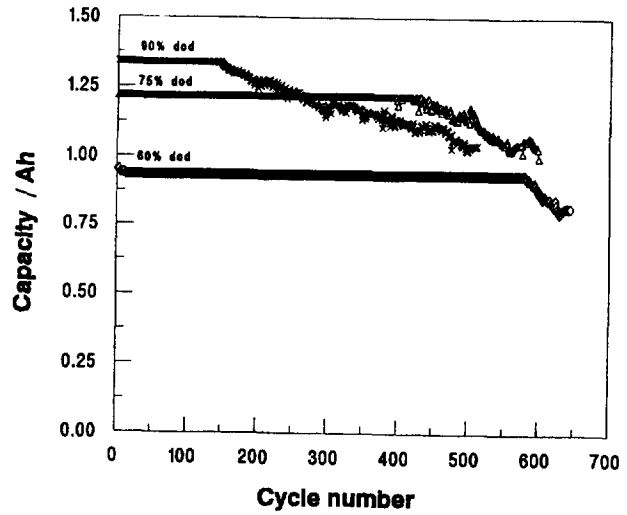

Fig. 3. Capacity vs. cycle number for Generation 1 status cells, discharged at $C/2$ and charged at $C/2$.

using smaller cells to establish a data base is largely economical in that smaller quantities of cell components are required and the more abundant, less expensive, low current test positions may be used for these tests. By using smaller cells it is also possible to include more cells in a given test matrix thereby enhancing the statistical credibility of the results. For purposes of discussion, sets of these cells produced at various times during the course of the programme have been designated 'status cells' as they are believed to be representative of the technology at a given point.

The first set of these cells (Generation 1 status cells) were produced using electrodes produced by manual techniques. The positive electrode active material was Honjo $LiCoO_2$ and the negative electrode was produced with Lonza/Timus SFG graphite. Thirty cells were assembled and subjected to formation which was followed by five cycles at the $C/5$ rate between 4.1 and 3.0 V and then five additional cycles at $C/10$ between these same voltage limits. Following these conditioning cycles each cell was discharged at the $C/5$ rate in order to determine a reference capacity. The Generation 1 status cells were divided into six groups of five cells each. Three groups (90%, 75%, 60% D.O.D.) were cycled at a $C/5$ charge rate and a $C/2$ discharge rate and three groups (90%, 75%, 60% D.O.D.) were cycled symmetrically at the $C/2$ rate. The results thus far for these tests are summarized in Figs. 2 and 3 in which each set of points represents the average capacity for the group of five cells.

At this time, these cells have completed over 400 cycles and the only obvious conclusion is that capacity decline is occurring at too high a rate, based on both industry experience and the cycle-life objectives of the programme. The source of this problem is undoubtedly related to electrode processing

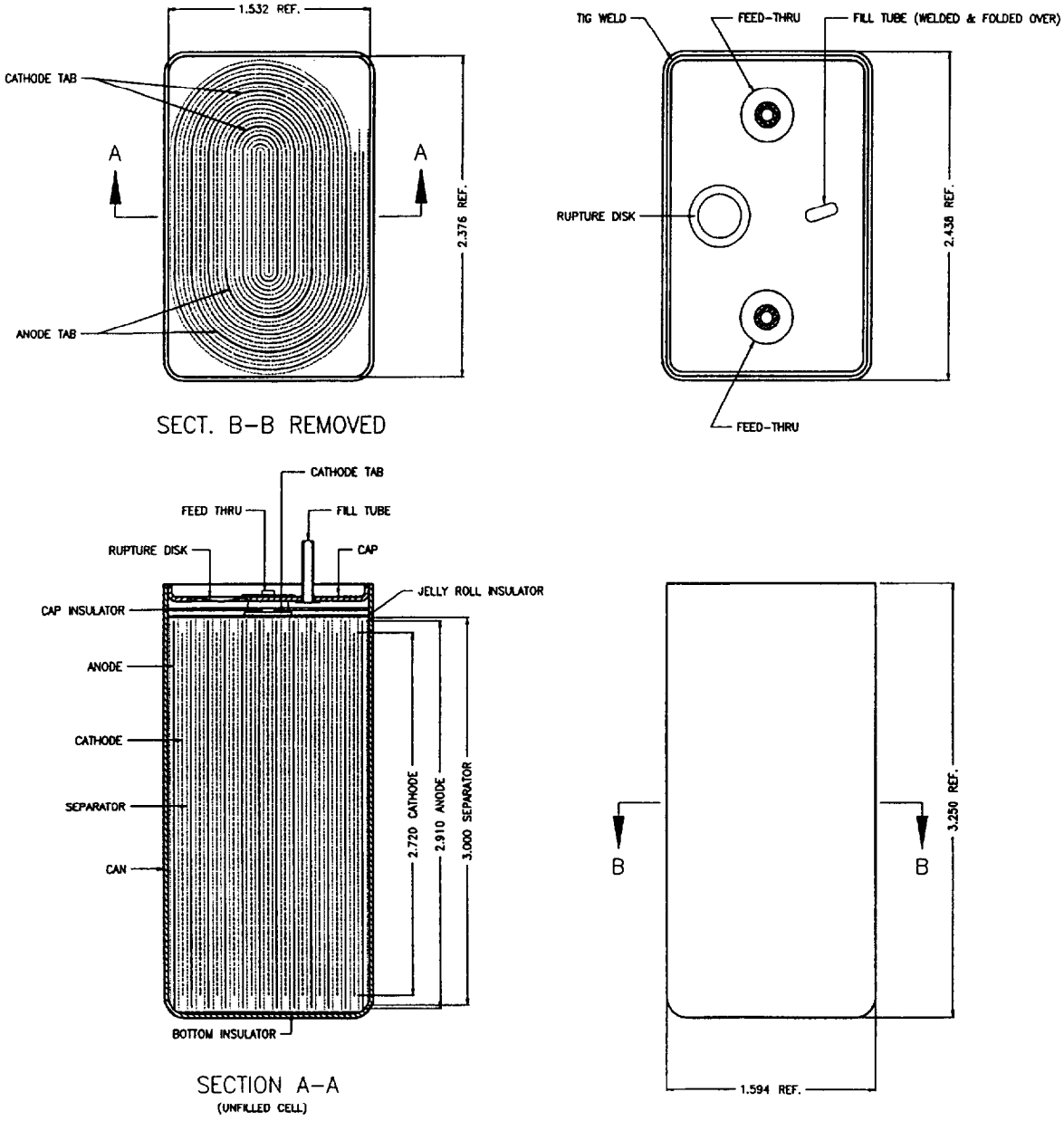

Fig. 4. Engineering drawing of a 10 Ah welded, prismatic, cell.

and is probably due to the de-lamination of the negative electrode material from the copper foil substrate. This hypothesis is presently being tested by cycling cells with individual electrodes being monitored against a reference electrode. These tests are progressing in demountable cells with Li reference electrodes and in welded cells which have been fitted with two feedthroughs in order to permit the use of the stainless steel cell case as a reference electrode. With respect to these data it is also worth noting that the higher charge rate is not detrimental to cell performance.

5. Large cells

As of this writing, work with larger cells is only just underway, a few 10 Ah welded prismatic cells having been constructed and placed on test. The designs are complete and hardware procured for the 20 Ah prismatic and cylindrical cells. Preliminary work with large cells included the fabrication and testing of several 5–20 Ah demountable cells which were built in order to evaluate various electrode configurations. Based on the results of these tests it was decided that the first generation of larger prismatic cells would be assembled using active elements wound in a pseudo-elliptical configuration. This choice was based on the ease of manufacturing offered by this approach and a geometric analysis which indicated that packing efficiencies in the range 90–95% of the prismatic limit could be achieved by this means.

The first welded prismatic cells were constructed with hardware which was available in-house and which had been originally procured for lithium/sulfur dioxide cells. Consequently, these cells are comparatively quite heavy due to the wall thickness required for prismatic lithium/sulfur dioxide cells. An engineering drawing of this cell is shown in Fig. 4 and the initial cycling data for the first of these cells are shown in Fig. 5. This chemistry of this cell was identical to that of the Generation 1 status cells and both positive and negative electrodes were produced with the commercial coating equipment.

Due to the paucity of data thus far accumulated, little can be said about the performance of this cell other than the electrode utilization is as expected and the capacity fade rate is roughly equivalent to that observed for the Generation 1 status cells. As noted above, the improvement of cycle-life

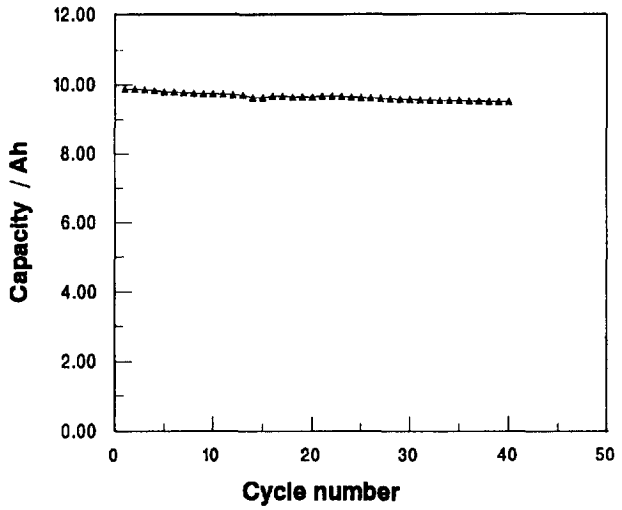

Fig. 5. Initial cycling data for the first 10 Ah welded, prismatic, cell charged and discharged to 100% D.O.D.

behavior has been designated a programme priority and is actively being pursued. It should also be noted that the geometry of this cell, because it was built with hand-me-down hardware, is sub-optimal, resulting in a calculated packing efficiency of only about 80%.

Designs have been completed and hardware procured for 20 Ah cells, both prismatic and cylindrical, and the assembly and testing of these cells began early in 1997. The dimensions of the rectangular cell are roughly 127 mm × 25 mm × 105 mm and the projected specific energy and energy density are 110 Wh kg^{-1} and 260 Wh dm^{-3}, respectively. The projected packaging efficiency is 90–95%. For the cylindrical cell, the dimensions are 89 mm diameter × 64 mm long and the projected specific energy and energy density are, respectively, 115 Wh kg^{-1} and 249 Wh dm^{-3}.

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