Quality Assurance Requirements for a Large $Li/SOCl_2$ Battery for Spacecraft Applications

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A large lithium thionyl chloride ($Li/SOCl_2$) spacecraft battery is currently being fabricated. When flown, this battery will consist of as many as 1080 "F"-size cells with an ultimate capacity of more than 2000 A-h. This work presents the acceptance and qualification test flows used for evaluating and screening the cells that compose the modules and battery assemblies. We also present data and analyses on the acceptance and qualification testing of the $Li/SOCl_2$ cells. On the average, these F cells have a mean capacity of 18 A-h; select lots meet our goal of having less than a 5% coefficient of variation for the cell capacity.

Nomenclature

CV = coefficient of variation
LDL = lower decision limit
UDL = upper decision limit
$\bar{x}$ = average or mean
σ = standard deviation
$\sigma/\bar{x}$ = coefficient of variation

Introduction

A CURRENT spacecraft program at the Johns Hopkins University Applied Physics Laboratory requires a battery with a total capacity of 2000 A-h at a nominal 30 V at 21°C and a total weight of less than 500 lb. Such a battery has been designed and consists of 1080 F-sized lithium thionyl chloride ($Li/SOCl_2$) cells. The F-sized cells were the largest cells available commercially that were qualified for some other miltary program, did not require an intensive design effort, and had an acceptable delivery schedule. These cells are packaged into modules of 72 F cells; the modules will be mounted on the outside of the spacecraft as shown in Fig. 1. Each of the modules is further submodularized into a triangular box of nine cells, see Fig. 2. The submodules, shown in the electrical schematic of Fig. 3, are wired in series with redundant blocking diodes, a thermostat, three thermal fuses, and an electrical fuse. The motivation for this electrical and packaging design was caused by safety factors, which were discussed previously in another publication.[1,2]

Quality Assurance Considerations

A prior safety fault-tree analysis[1,2] showed that manufacturing defects such as internal mechanical shorts between anode and cathode, low cell capacities due to improper fill or failure of hermeticity, and current leakage due to lithium diffusion through the ceramic insulator can lead to a decrease in the reliability of the battery and an increase in risk with respect to safety. It was therefore decided that a rigorous quality assurance procedure must be implemented with the cell manufacturer, with proper controls for acceptance and qualification of cell lots. We incorporated the quality assurance documents from NASA[3,4] and the U.S. Army[5] and Navy[6] and negotiated with the cell vendor to arrive at specific quality assurance procedures for the procurement of the battery; flowcharts of the battery quality assurance procedures are shown in Figs. 4–6. Although these quality assurance procedures are tailored to this program and this vendor, The Johns Hopkins University Applied Physics Laboratory will be procuring lithium battery systems with similar specifications in the future.

Of particular concern to us is the uniformity of the cell capacity within each string or submodule because of the possibility of cell reversal during the later stages of battery discharge. The relevant parameter to measure the uniformity of cell capacity is the standard deviation of the cell capacity or the coefficient of variation, which is the ratio of the standard deviation to the mean for a set of randomly selected samples. The usual coefficient of variation on commercially available Li cells is 0.10 or 10%. From the previous fault-tree study,[1,2] a decrease of the coefficient of variation from 10 to 5% would translate to a decrease by a factor of 10^4 in the probability of having a cell that is 25% low in capacity assuming a normal distribution. The lower probability is directly connected to increased battery safety. Thus, we desire to maximize the uniformity of the 1080 cells used in the battery by working with the vendor to institute a strict regimen of material control; we wanted each of the active materials used to come from the same lot and each cell to be weighed, filled, and checked for uniformity, see Fig. 5. Each of the factors affecting capacity, such as lithium anode weights, carbon cathode weights, electrolyte fill, and cell dimensions, must be controlled to less than 2% in order to achieve cell capacity uniformity (i.e., minimal coefficient of variation) of around 5%. This reasoning was based

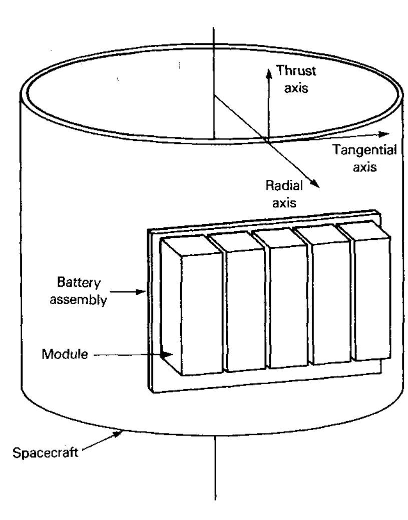

Fig. 1 Module orientation relative to spacecraft axis.

Presented as Paper 87-9062 at the 22nd Intersociety Energy Conversion Engineering Conference, Philadelphia, PA, Aug. 10–14, 1987, received Aug. 3, 1987; revision received Dec. 3, 1987.

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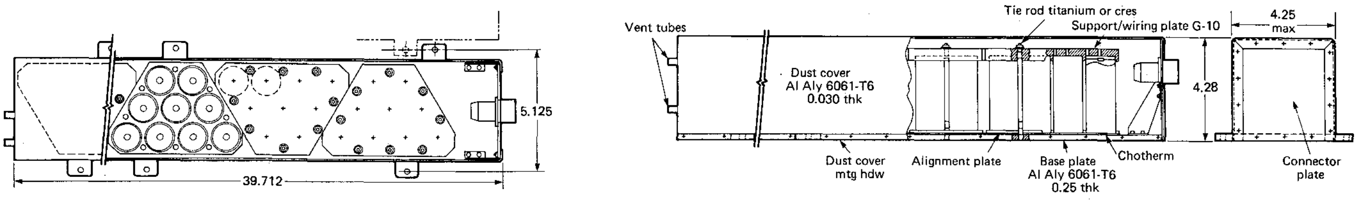


Top view **Side view**

Fig. 2 Module and submodule configuration.

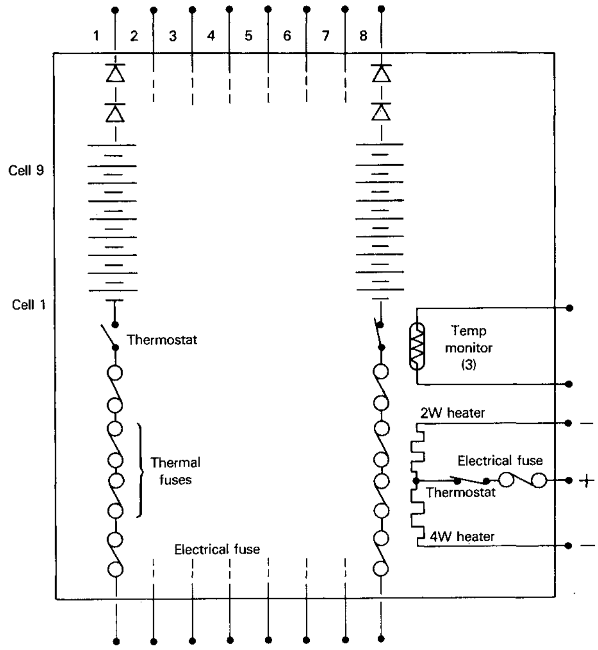


Fig. 3 Module circuit configuration.

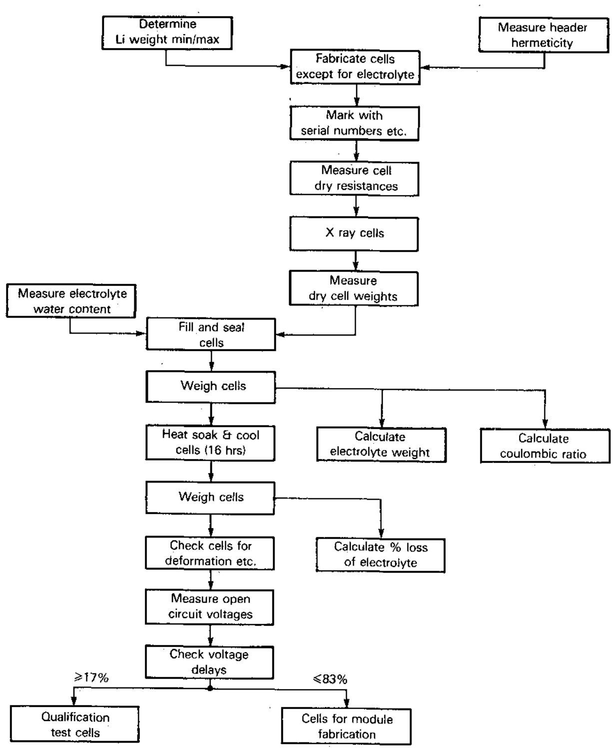


Fig. 5 Cell acceptance test flowchart.

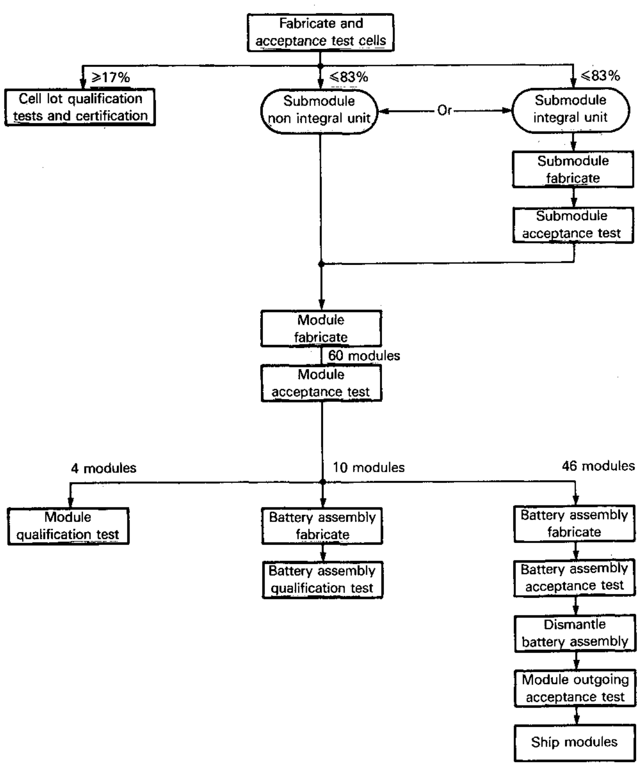


Fig. 4 Battery test flowchart.

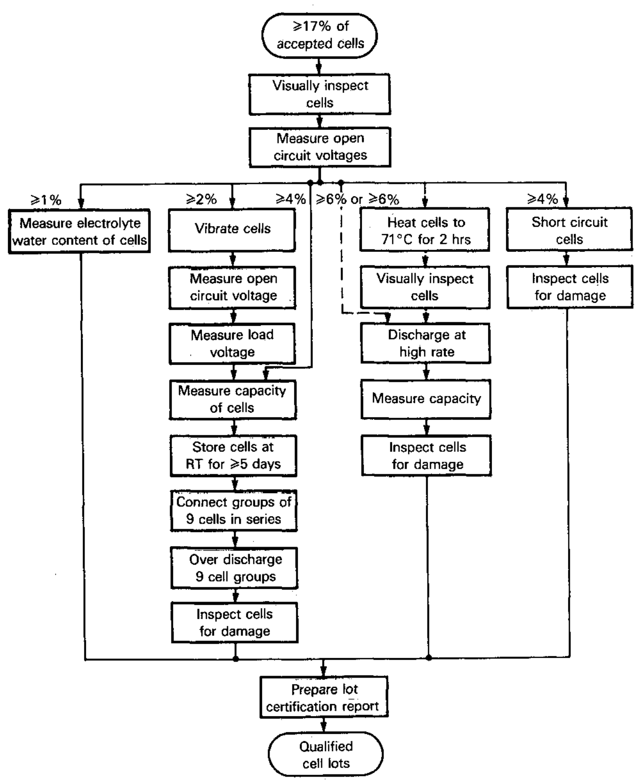


Fig. 6 Cell lot qualification test and certification flowchart.

Table 1 Li/SOCl₂ cell data

Lot no.	Sample no.	X-ray rejects	VUL rejects	High-fill rejects	Low-fill rejects	$\bar{x},\sigma$ A-h 2-A Capacity	4-A Capacity	Postvibration 2-A Capacity
70471	0001–0317	13	1	1	2	17.373, 1.237 $n = 14$	18.647, 0.543 $n = 17$	18.497, 0.542 $n = 8$
70481	0318–0817	42	1	1	4	18.426, 0.961 $n = 20$	18.539, 0.468 $n = 28$	18.523, 0.938 $n = 6$
70491	0818–1312	45	1	0	1	18.228, 1.174 $n = 19$	18.375, 0.717 $n = 30$	18.870, 0.498 $n = 9$
70501	1313–1910	24	3	0	0	17.925, 0.973 $n = 24$	18.231, 0.516 $n = 34$	19.236, 0.419 $n = 13$
70511	1911–2436	22	2	6	0	19.074, 0.372 $n = 24$	18.198, 0.737 $n = 34$	19.138, 0.570 $n = 11$
70541	2437–3023	20	10	2	0	19,070, 0.485 $n = 19$	17.555, 0.716 $n = 27$	19.126, 0.531 $n = 12$
70551	3024–3620	19	4	7	0	19.000, 0.518 $n = 24$	17.442, 0.733 $n = 19$	19.436, 0.326 $n = 9$
70681	3621–4256	17	31	0	0	17.384, 1.284 $n = 25$	18.299, 0.547 $n = 36$	18.996, 0.850 $n = 12$
70691	4257–5015	24	155	0	0	18.267, 0.742 $n = 23$	18.271, 0.758 $n = 32$	19.220, 0.338 $n = 13$
70701	5016–5586	50	90	0	7	18.417, 0.491 $n = 16$	18.343, 0.553 $n = 26$	19.578, 0.394 $n = 12$
70711	5587–6214	35	52	0	21	19.152, 0.567 $n = 15$	18.285, 0.807 $n = 22$	19.738, 0.372 $n = 11$
	All	311	350	17	35	18.391, 1.042 $n = 223$	18.210, 0.716 $n = 305$	19.171, 0.617 $n = 116$

n = number of sample cells.

on the rms theory of propagation of errors in which at least six factors with individual error contributions of 2% would generate a resultant error of 5% in the cell capacity.

Figures 4–6 show the battery fabrication process flow, including the acceptance and qualification tests on cells. Figure 4 is a broad overview of the battery manufacture from cell fabrication to module shipment.

Figure 5 is a cell acceptance test flowchart in which emphasis has been placed on lithium anode weights, cell weights, electrolyte water content, and fabrication of balanced cells.

Figure 6 indicates that 17% of the cell population was selected as a sample to undergo water content, vibration, overdischarge, high-rate discharge, and short-circuit qualification tests. The results of these cell acceptance and qualification tests make up most of the remainder of this paper.

Subsequent to cell acceptance and qualification, the battery was fabricated in modular units. First, nine F cells were fabricated into submodules. Then, eight submodules were assembled into a battery module. Finally, five accepted modules were mounted on a honeycomb test panel in the same configuration that they will be mounted on the spacecraft and submitted to both thermal vacuum and vibration testing. Three of these honeycomb panels, each mounted with five modules and symmetrically placed around the spacecraft, will power the mission.

Analysis of Results on Cell Acceptance and Qualification Testing

We report here on the data taken during the cell acceptance and qualification test flows (Figs. 5 and 6). Table 1 summarizes the number of cells rejected for reasons of high or low electrolyte fill (fill and seal cells, Fig. 5), voltage under load (check voltage delays, Fig. 5), and x-ray examination (x-ray cells, Fig. 5). Most x-ray rejects were caused by the telescoping of electrodes with a much smaller number because of incorrect anode tab placement.

The cell capacity data summarized in Table 1 by mean and standard deviation in ampere-hours, as well as the number of samples tested, are a result of the test in Fig. 6. The data on the 2-A rate capacity and the postvibration capacity (also at 2-A) come from the second vertical path from the left of Fig. 6. The data on 4-A rate capacity come from the third vertical path from the left (high-rate discharge). The short-circuit testing has also been completed (fourth vertical path from the left of Fig. 6).

Nondestructive Inspections

Table 1 summarizes the number of each lot, the number of cells in each (6214 were produced in all), and the cells rejected for each lot for the reasons indicated as well as the capacity data. We see that 311 of the 6214 F cells (5%) failed the x-ray screen. Greater numbers of voltage under load and low electrolyte fill rejects occurred in the last 2 or 3 of the 11 lots produced. In the case of the voltage under load, the number of rejects became so high that we recommended that the manufacturer re-examine his strip chart data and look for possible test anomalies. However, no test anomalies were found. The voltage under load was recorded during the voltage delay test of Fig. 5 in which each cell is discharged at a constant current of 2 A for 15 s. Within this period, the cell voltage must increase to 2.9 V or greater. Further investigation showed that this voltage under load requirement could be reduced to 2.5 V without incurring a loss in cell capacity. By retesting and rescreening the data, 334 of the 350 cells originally rejected were found to be acceptable. Similarly, cells originally rejected due to electrolyte weight loss or missing data were rebaked (93% were then acceptable), and cells originally failing the tab-pull test were reterminated (97% were then acceptable). Cells rejected in the x-ray and electrolyte fill weight screens were not accepted under any conditions.

Short-Circuit Test

Four percent of each lot of cells, as shown in Fig. 6, is submitted to a short-circuit test; that is, each cell is discharged through a resistive load of not more than 50 mΩ. Cell voltages, currents, and temperatures are recorded until the currents and voltages fall to zero. None of the 183 cells discharged in this manner vented or leaked during this test—the pass/fail criterion.

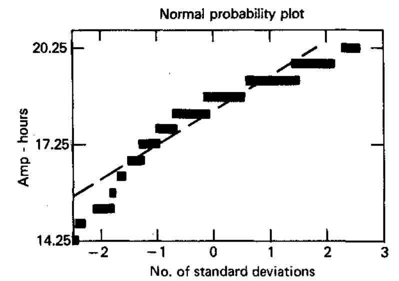


Fig. 7 Normal probability plot of 2-A F-cell capacity.

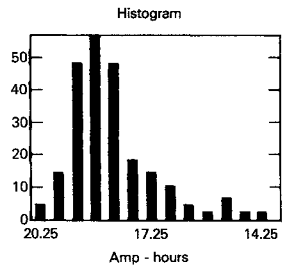


Fig. 8 Histogram of 2-A F-cell capacity.

Cell Capacities

Table 1 summarizes the means, standard deviations, and sample sizes for the cell capacities of each of the 11 production lots. At the bottom of the table, the row labeled "All" gives the grand mean, grand standard deviation, and total sample size for the three conditions: 1) 2-A discharge, 2) 4-A high-rate discharge, and 3) postvibration 2-A discharge. We note that all three grand mean values exceed 18 A-h. (This covers the 2-A and 4-A discharges of 644 cells!) Thus, we can state with high confidence that this $Li/SOCl_2$ F cell is an 18-A-h cell. Furthermore, the coefficients of variation for the three conditions are the following:

1) 2-A discharge:

$$\sigma/\bar{x} = 1.042/18.391 = 0.057$$

2) 4-A discharge:

$$\sigma/\bar{x} = 0.716/18.210 = 0.039$$

3) 2-A postvibration discharge:

$$\sigma/\bar{x} = 0.617/19.171 = 0.032$$

These values are near or below our target value of 5%, which was determined in the previous fault-tree analysis.[1,2]

Figures 7 and 8 show a normal probability plot and a histogram, respectively, of the 2-A capacity data (condition 1). Although there is some skew toward low-capacity values in the distribution and some departure from a straight line on the probability plot (the straight line is determined by using the mean and standard deviation of the data), the hypothesis that the 2-A capacity data are normally distributed cannot be rejected at a 95% confidence level.

Figures 9 and 10 show a normal probability plot and a histogram, respectively, of the 4-A capacity data (condition 2). Here, the fit to a normal distribution is even better; again, the hypothesis that the 4-A capacity data are normally distributed cannot be rejected at a 95% confidence level.

Having proved that the cell capacity data are normally distributed in a rigorous statistical manner, we can use other statistical methods that rely on normality to compare the individual lots and the test conditions and to make inferences about the population from which these samples are drawn.

Figures 11a and 11b are control charts comparing the mean values and standard deviations of the 2-A cell capacities of each lot with the grand mean and grand standard deviation following the methods developed by Ott[7] and Schilling.[8] The upper (UDL) and lower (LDL) decision limits represent 95% confidence. Figure 11a shows that lots 5, 6, 7, and 11 have mean capacities significantly greater than the grand mean, whereas lots 1 and 8 (produced on startup days) have mean capacities significantly lower than the grand mean. Figure 11b shows no significant differences among the standard deviations of the cell capacities for the 11 lots when compared with the grand standard deviation. However, when the largest of the 11 variances (lots 1 and 8) are compared with the smallest (lot 5), there is a significant difference at a 95% confidence level. Thus, although each standard deviation is not different from the grand standard deviation, the largest ones of the set are greater than the smallest.

Figures 12a and 12b are control charts comparing the mean values and standard deviations of the 4-A cell capacities of each lot with the grand mean and grand standard deviation.

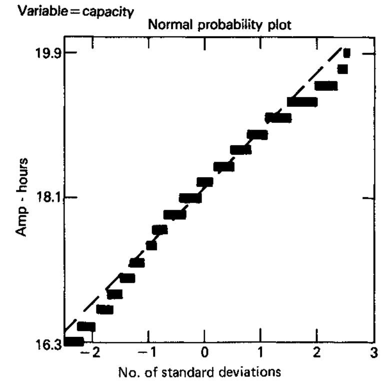


Fig. 9 Normal probability plot of 4-A F-cell capacity.

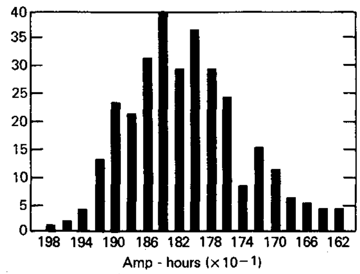
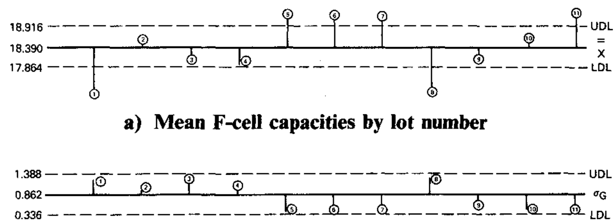


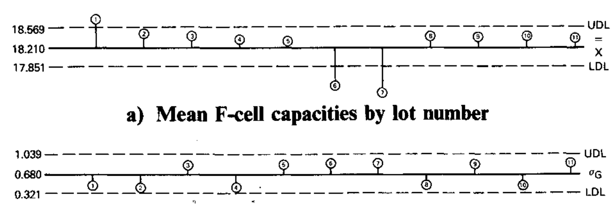
Fig. 10 Histogram of 4-A F-cell capacity.



a) Mean F-cell capacities by lot number

b) Standard deviation of F-cell capacities by lot number

Fig. 11 Control charts—2-A capacity (in ampere-hours).



a) Mean F-cell capacities by lot number

b) Standard deviation of F-cell capacities by lot number

Fig. 12 Control charts—4-A capacity (in ampere-hours).

Figure 12a shows that lot 1 has a mean cell capacity significantly greater than the grand mean, whereas lots 6 and 7 have mean capacities that are significantly lower at a 95% confidence level. Figure 12b shows no significant differences among the standard deviations of the cell capacities for the 11 lots when compared with the grand standard deviation. In this case, when the largest of the 11 variances (lot 11) is compared with the smallest (lot 2), there is no significant difference at a 95% confidence level; this means that the standard deviations or variances of the 4-A cell capacities form a homogeneous group.

The two sets of comparisons point out some inconsistencies in the capacity data. Although lots 6 and 7 have significantly higher mean capacities when tested at the 2-A rate, they have significantly lower mean capacities at the 4-A rate. Conversely, although lot 1 has a significantly lower mean capacity at the 2-A rate, it has a significantly higher capacity at the 4-A rate. Thus, the data are confounded; we believe that this outcome may be an artifact of the test procedure.

To reach a rational conclusion from the statistical analysis, we will consider two more factors: 1) the grand mean capacities of the three conditions (shown in the "All" row of Table 1) and 2) the coefficients of variation of the individual lots. Because of the large sample sizes involved, a student's "t" test readily shows that, at a 95% confidence level, the mean capacity at 2 A after vibration (19.171 A-h) is significantly greater than the mean capacity at 2 A without vibration (18.391 A-h), which, in turn, is significantly greater than the mean capacity at 4 A without vibration (18.210 A-h). The vibration exposure is a random vibration for 3 min along both the radial and longitudinal axes. Overall, the 2-A rate mean capacities are higher than the 4-A capacities, and vibration seems to be beneficial possibly because of the removal of insulating films.

From Table 1, we can compute the coefficients of variation for each of the three capacity test conditions for each of the 11 lots. When these values are compared, we see that each of lots 5–7 and 9–11 has three coefficients of variation less than 0.05 or 5%, our target value. Thus, the flight battery and its spare will be built from these lots.

Conclusions

We conclude that we currently have lithium thionyl chloride F cells that have a mean capacity of 18 A-h and a ratio of the standard deviation of the capacity to the mean capacity of less than 0.05 in certain select lots. From these lots, we can draw a sufficient number of cells of adequate capacity and uniformity to meet the requirements of a flight and a spare battery. Future work will concentrate on the correlation of certain design information with capacity data and the performance and safety testing of battery modules and assemblies.

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