

## GALILEO LITHIUM/SO<sub>2</sub>

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I would like to present today the general requirements of the Galileo lithium SO<sub>2</sub> battery, the current status on that program, as well as some general comments relative to the experiences we have already gone through in the development of that battery.

I will start, first of all, with the discussion of a general review of the specification requirements for this device.

(Figure 2-13)

First of all, it is a modular concept. The full battery is three modules. Our responsibility is for developing a single module which, in the system, three modules will be hooked in parallel and the diode isolation of those modules is included in the systems design.

The electrical characteristics required are 7.2-ampere hour minimum capacity at a minimal voltage of 28.05 volts. That is being accomplished with 13 high-rate D cells.

Capacity from module to module must be within 5 percent of each other in lot acceptance testing. Voltage delay requirements are required less than 100 microseconds voltage delay to 28.05 minimum voltage. Single point failure requirements required that bypass diodes, shunt diodes be placed on each cell in the series connected string.

The batteries also required to have a pyrotechnic tap in the 14- to 24-volt range, which runs up at about 7 amperes for 30 milliseconds. The actual discharge rate or discharge profile for the battery runs anywhere from a cruise timer load of 0.5 milliamperes on the module for 150 days up to 3.27 amperes at the end of discharge life, or at the end of the mission. And there are a number of steps between there as additional testing equipment comes on line.

The storage requirement is 5.4 years, basically under a controlled environment of 0°C. There is some 40°C requirement during some uncontrollable chipping times or while it is on the launch pad. But something over 4 years of that time is spent at 0°C.

Specification also requires that during that time there is 2.5 percent per year maximum, 2.5 percent per year capacity loss.

Reliability predictions required are 0.99 probability of completing the mission. The mission is defined right now at 6.65 ampere-hours. So, the total mission is under the minimum ampere-hour capacity requirements.

(Figure 2-14)

The basic configuration of the module is a rigid vented case that has to support its environment, mechanical environment in a beam type of mounting configuration. I have got a drawing a little later showing the general configuration of the module, and you can see what I am talking about there.

Maximum weight is 2.5 kilograms. Environments that it must survive are both sine and random vibration. Deceleration is at 410 gs for 30 seconds. There is a 150-g lateral shock load and a 30-grms random vibration requirement that the module must survive. It also must survive a low-rpm spin around the center of gravity of the probe. It must withstand radiation exposure, cobalt 60 up to 200 kilorads, and a pressure on entry into the Jupiter environment. Qualification is 16 bars, and acceptance is 13 bars.

(Figure 2-15)

Basic cell configuration used is a high-rate D cell jelly-roll configuration active, hermetically sealed. The header is laser welded into the case. Case and header materials are 304 stainless steel. The glass-to-metal seal uses a tandem feed through. The cell is lithium limited, that is a little bit of a misnomer. It is designed as a coulometrically balanced cell. So the stoichiometry of the thing is balanced between the SO<sub>2</sub> and the electrolyte with excess collector capacity from a dump-site point of view.

The cells do have safety vents in them, and have a relatively high surface area, active surface area.

(Figure 2-16)

Thirteen of these are mounted in a package that is approximately 13-1/4 inches long, and flange mounting occurs at the brackets on both ends. The brackets are attached to an arm which is supported off pivot point so that the entire device is suspended by those brackets and must withstand all the environments in all three directions.

The cells are stacked, as you can see, 13 of them. All the diodes and thermistors – there are two monitoring thermistors in there – are mounted on a flexible printed circuitboard that is manufactured to NASA's specification.

The shunt diodes are procured to a Marshall Space Flight Center specification for very, very low reverse current drain rates, because they have to stay on there 5 years. And we certainly cannot lose too much capacity from them.

The case is aluminum. It is of single-unit construction and is machined from a single block of aluminum. Connectors are in both ends. One is an instrument connector; the other is the power connector.

The battery in its current configuration does not have a fuse built into the battery. For shipping and general handling purposes, a special cap has been designed to be left with the battery

and mounted to the battery on one of the connectors. That does fuse the output leads or the power leads on the battery.

In its actual mounting location in the probe, it would not be fused. The primary considerations in that design choice right now is with respect to reliability. However, that is being reconsidered currently. We may, in fact, put a fuse in the actual unit.

(Figure 2-17)

To date, the electrical performance that we have demonstrated utilizing five cells stacked, series connected stacks. The mission has a rather sophisticated temperature profile also.

During the cruise portion of the mission, the minimum temperature is  $-5^{\circ}\text{C}$ . The five-cell stacks delivered 7.26 ampere-hours at the minimum temperature profile, or to the minimum temperature profile, which actually on entry drops down to  $-14^{\circ}\text{C}$  and then comes back up.

At a nominal or average temperature profile for the mission, the cell stacks delivered 7.73 ampere-hours, and at the maximum temperature the cell stacks delivered 7.79 ampere-hours.

The cells basically are not thermally insulated from the environment, and the thermal analysis of this module configuration says that the battery and the cells will track very closely the external environment that the probe is seeing. So, these tests were conducted without a great deal of thermal insulation around them, which generally adds to their overall capacity.

*Minimum Pyropulse Voltages.* – At the end of mission, which is an additional 7-ampere 30-millisecond pulse on the battery, would leave you with battery voltages as shown, 33, 32, and 31 volts, based on the different mission temperature profiles.

*Voltage Delay.* – Voltage delay requirements are 100 microseconds. Generally, there were problems in meeting that. There were systems design changes to include or add a preconditioning load before entry, and before the entry load profile begins to take place to clean the cell up.

The results of that testing indicated that a 1-ampere load for about 5 seconds would clean that, any passivation that was on the cells, up, and eliminate any problems with meeting that voltage delay requirement.

(Figure 2-18)

*Storage.* – There has been a little bit of accelerated storage test work done relative to the hermetic seals. However, 450 cells are going under  $0^{\circ}\text{C}$  storage environment, which is a real-time storage environment. Because of a stretchout of the program by about 2 years, we will have about 4 to 4-1/2 years of real-time data on this cell hardware.

The cells are evaluating the effects of the bypass diodes on storage as well as effects of orientation or the zero-g in the environment, so there are about three different configurations that are going into that test. The cells are being completed this month and will go on storage this month.

The other thing relative to storage, a protective cap has been designed for the glass-to-metal seal. There was at accelerated temperature, some corrosion of the glass-to-metal seal, or the glass in the glass-to-metal seal witnessed, and the protective cap is included on the hardware to basically take away the effects of orientation, which appear to be the primary difference in any corrosion rates that we have seen. In high-temperature inverted storage cell test, it has done an effective job. The cap has done an effective job in correcting it.

*Reliability.* – We did make a preliminary prediction of 0.99 probability of completing the mission, or the 6.65 ampere-hours. Basically, the way we accomplished that was with the excess capacity in the fact that a single cell could be lost at the 6.65 ampere-hour point, and the module would still be above the minimum voltage requirements in the program.

(Figure 2-19)

The first module is completed. It was completed this month. The actual weight of the unit was 2.2 kilograms. And we are in the process of completing five additional modules that will be subjected to the mechanical environments required.

Cells from phase 1 of the program have passed random and sinusoidal vibration and deceleration, both as individual tests and as sequential tests. And non-Galileo cell hardware of a similar construction has passed the radiation requirements.

Now I would like to make a few comments based on the experiences that we have run into so far in the development of this battery.

(Figure 2-20)

We believe from a safety point of view that the battery designs should be vented to design – and the original Galileo program did spec a sealed module to withstand the venting of individual cells. That was eventually changed, and the present module configuration is vented. We believe from a safety point of view that is necessary.

Isolate diodes should be used if parallel configurations are required. I think that is pretty standard at this point in time. That is part of the system as far as the way our program is put together.

The batteries should be fused. Cell designs, we believe, should be lithium limited, or at least coulometrically balanced in lithium and sulfur dioxide ratios.

We believe the people who will be eventually handling and operating these cells do need clear training and understanding of what they have in their hands. The battery module or concept should be incorporated in high-energy requirements. And by that I mean we do not believe that batteries should be built containing excessive amounts of cell hardware, large cell quantities in a single battery configuration. They should be split up into smaller, more handleable packaging-type configurations.

(Figure 2-21)

And lastly, from a reliability point of view, we feel that there is possibly some additional work that can be done in optimizing the voltage and capacity requirements to ensure that you can withstand a single cell failing within a battery, still meeting the minimum voltage requirements.

If you specify and order a four-cell battery, it is going to be very, very difficult to make 0.99 reliability predictions based on the analysis we have run so far. Single point failure can be eliminated, and it is almost a must in the high-reliability configuration.

The impact of that, of course, or the question that comes from that is relative to the losses in storage that might be incurred with the bypass diodes, which are currently undergoing tests to determine – by the way, those leakage currents for those specific diodes are in the nanoampere range.

*Performance.* – Cell manufacturing tolerances must be tightly controlled. We found some of the standard raw materials coming for our cell hardware are not adequate to meet the kind of tolerances that we are looking at for some of these applications.

Battery conditioning should be considered if there is a severe voltage delay requirement in the microsecond range. We do have long-term storage.

And again, if a long-term storage requirement is involved, control in temperature environment is very, very important in guaranteeing that you meet your storage requirements.

## DISCUSSION

MAHY: You never did tell us what the end use discharge current was.

BLAGDON: Actual load profile ranges from 0.5 milliampere on a module for 150 days on the front end, and winds up with full instrumentation on it about 3.27 amperes. End of life occurs under 3.27-ampere load.

MAHY: There is continuous use in a way over the whole 5.4 years?

BLAGDON: No. Basically, it is turned on 150 days prior to entry. During the other 4 years, it is under storage, or just inactive.

TATARIA: You said your cells are hermetically sealed. How are you taking hermetic sealing, the outside leak rate or the helium leak rate?

BLAGDON: We use the helium leak rate and a very high sampling plan on a hardware that we are currently building, the cell hardware that we are currently building to ensure that we have that. We also do 100 percent sort of all the glass-to-metal seals.

TATARIA: You did the helium leak rate?

BLAGDON: On the finished cell? No, our normal procedures require a 48-hour heat soak and then visual examination.

We are looking at some other alternatives to determine if there is any additional weight loss at that time. Currently it is a heat soak, visual and weight measurements on the cells after they are manufactured.

TATARIA: Thank you.

WATSON: Would you care to comment on the cause of the glass seal corrosion that you discussed, and how your protective cap prevents that from occurring?

BLAGDON: Basically, I don't know whether the actual causes of the glass seal corrosion are specifically known and understood today. The protective cap simply uses an O-ring pressure-type seal on the inside to not allow the electrolyte in full contact, in the inverted position, and in full contact with the cells.

It is not a second hermetic seal. It is not intended to be. The purpose is simply to take away the effects of orientation in turning the cell upside down and to reduce the amount of ionic activity that can be taking place there at that surface.

And it is accelerated, or high-temperature inverted storage tests of that cap indicate that it is doing a very nice job. It does not stop all corrosion, by the way, at the high temperature, but it is doing a very nice job.

SEITZ: I believe it was mentioned this morning that an alternate system is being considered for Galileo. Is that true?

BLAGDON: I don't think so. I don't recall that being mentioned. I guess you would have to talk to Hughes if you want to find out about that. I don't think so.



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MODULE DESIGN REQUIREMENTS

ELECTRICAL CHARACTERISTICS

- . 7.2 AHR. MINIMUM CAPACITY
- . 28.05 TO 39.0 VOLTS
- . CAPACITY WITHIN 5% WHEN DISCHARGED TO 28.05 V
- . VOLTAGE DELAY <100 MICROSECONDS
- . SINGLE POINT FAILURE PROTECTION VIA BY-PASS DIODES
- . PYRO TAP FOR 14-24 VOLTS

STORAGE

- . 5.4 YR. LIFE
- . 2.5% PER YEAR MAXIMUM CAPACITY LOSS

RELIABILITY

- . 0.99 FOR COMPLETING THE MISSION

Figure 2-13



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MODULE DESIGN REQUIREMENTS (CONT'D)

MODULE

- CASE - RIGID VENTED
  - MAXIMUM DEFLECTION - 0.050 INCHES
  - FINISH 0.1

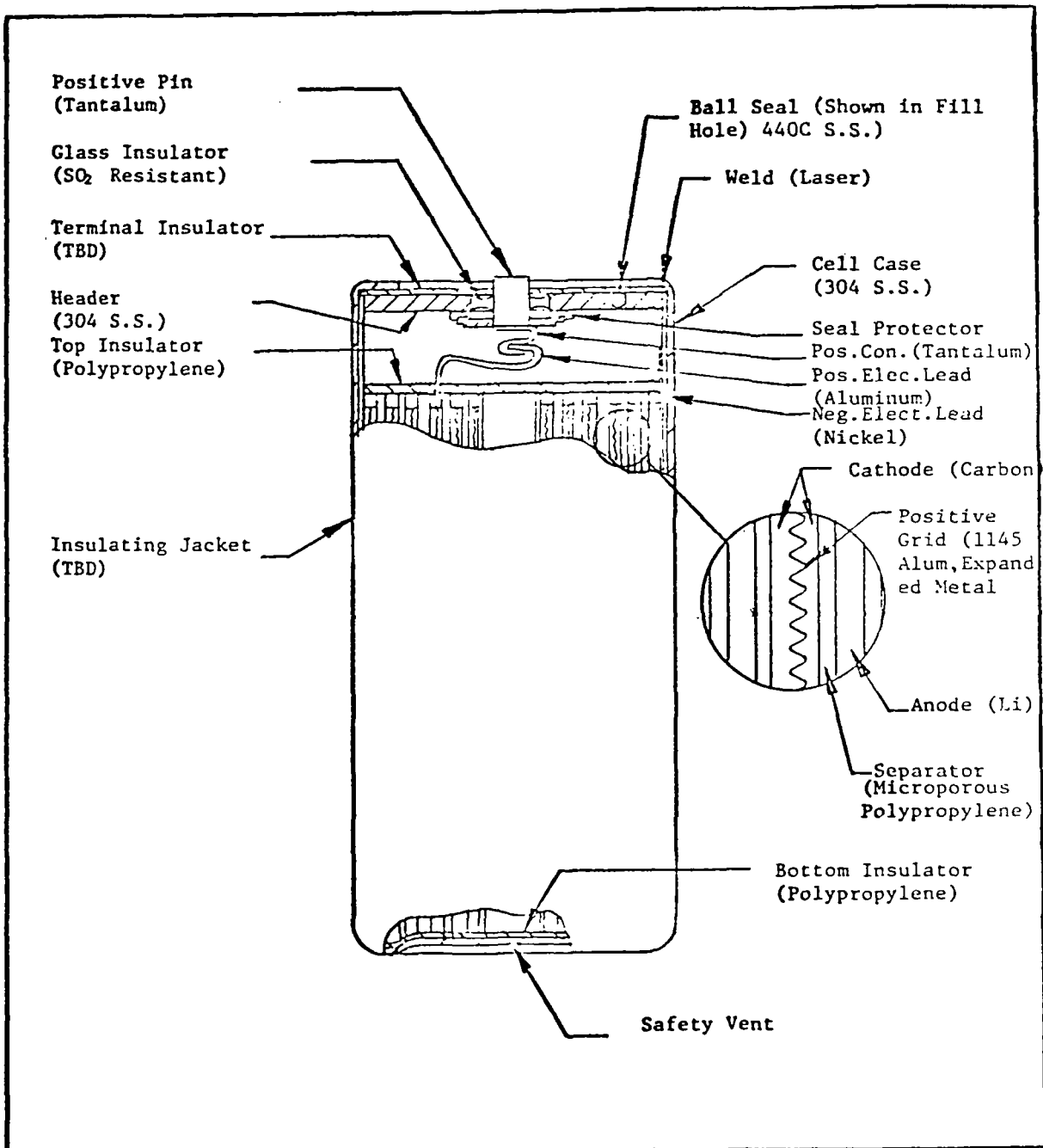
MASS - 2.5 Kg MAX.

ENVIRONMENTS

- . VIBRATION - SINE AND RANDOM VIBRATION
- . DECELERATION, 410 G's
- . 150 G's LATERAL, 30 RANDOM VIBRATION
- . SPIN 10-15 RPM, 2.5 - 5 RPM
- . RADIATION 200 KILORADS Co<sup>60</sup>
- . PRESSURE, 16 BARS QUAL; 13 BARS ACCEPTANCE

Figure 2-14





FOHM FM-100

PARTIAL CROSS SECTION OF HONEYWELL  
BASELINE CELL

Figure 2-15

GALILEO PROGRAM

MODULE CASE & CELL ASSEMBLY

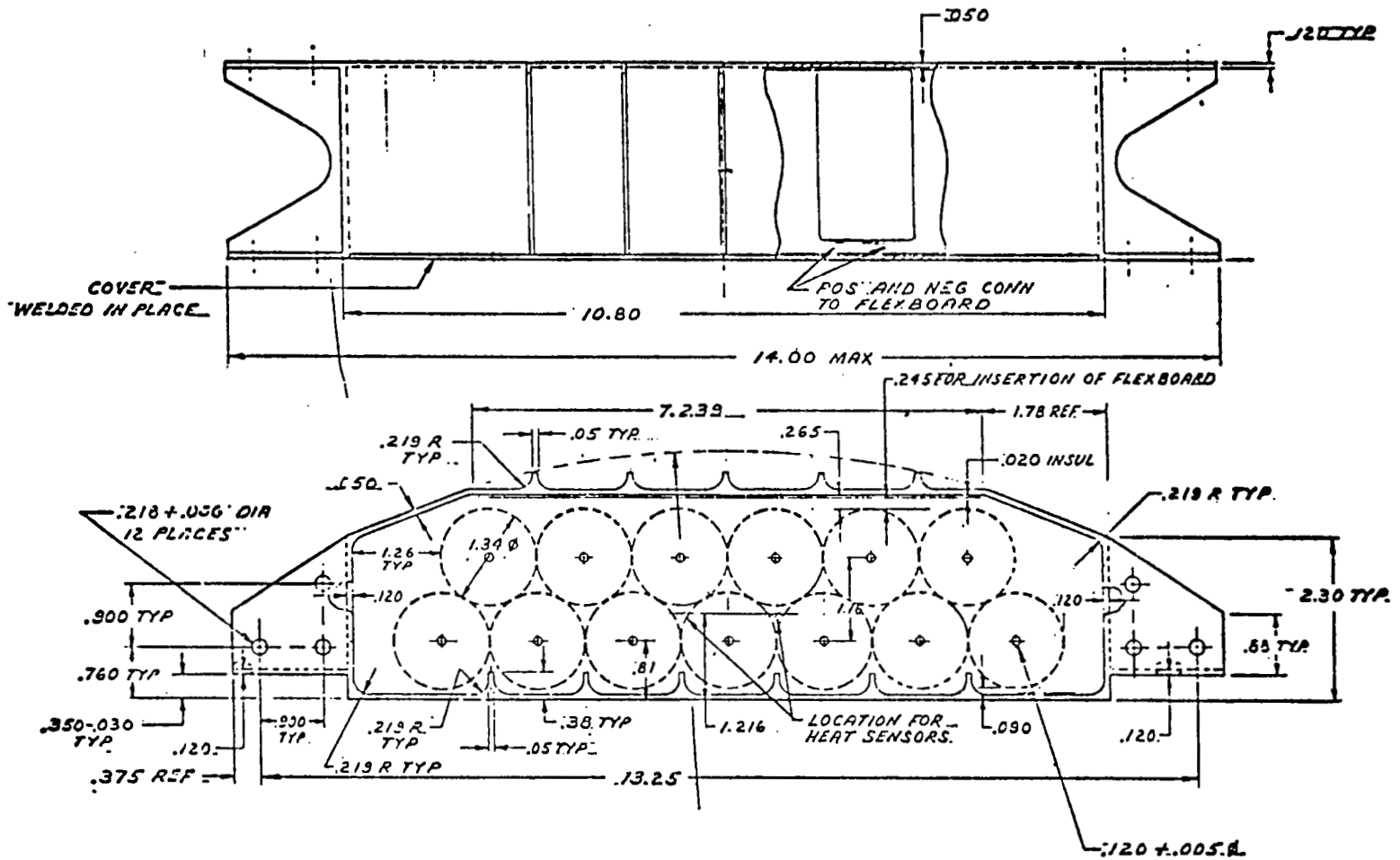


Figure 2-16



ELECTRICAL PERFORMANCE

- DEMONSTRATED CAPACITY TO 28,05 VOLTS BASED ON DISCHARGES OF 5 CELL STACKS:

<u>MISSION TEMP. PROFILE</u>	<u>CAPACITY (AHRs)</u>
MINIMUM	7.26
NOMINAL	7.73
MAXIMUM	7.79

- MINIMUM PYRO-PULSE VOLTAGE AT 6.65 AHRs (END OF MISSION):

<u>MISSION TEMP. PROFILE</u>	<u>VOLTAGE (VOLTS)</u>
MINIMUM	31.3
NOMINAL	32.0
MAXIMUM	33.0

- VOLTAGE DELAY - MET BY APPLYING A CONDITIONING LOAD WHICH REQUIRED AN ELECTRICAL SYSTEM CHANGE.

Figure 2-17



STORAGE -

- 450 CELLS TO BE STORED AT 0 °C CONFIRMING THE EFFECTS OF ORIENTATION AND BY PASS DIODE LEAKAGE CURRENT, ON TEST Nov. 1979.
- PROTECTIVE CAP OVER CELL GTM SEAL HAS MINIMIZED EFFECTS OF ORIENTATION (OR 0 G ENVIRONMENT) BASED ON 70°C INVERTED STORAGE TEST RESULTS.

RELIABILITY

- 0.99 PROBABILITY OF COMPLETING MISSION (6.65 AHRs.) HAS BEEN PREDICTED.

Figure 2-18



MODULE

- FIRST PROTOTYPE MODULE COMPLETE 7 Nov. 1979
- ACTUAL WEIGHT OF FIRST MODULE - 2.22 KILOGRAMS.
- FIVE ADDITIONAL MODULES IN PROCESS TO BE ENVIRONMENTALLY TESTED.

ENVIRONMENTS

- GALILEO CELLS (PHASE I) HAVE PASSED THE FOLLOWING SPECIFICATION ENVIRONMENTS:
  - RANDOM VIBRATION
  - SINUSOIDAL VIBRATION
  - DECELERATION
- NON-GALILEO CELLS (SIMILAR CONSTRUCTION) HAVE PASSED THE RADIATION REQUIREMENTS.

Figure 2-19



SAFETY

- BATTERY DESIGNS SHOULD BE VENTED
- ISOLATION DIODES SHOULD BE USED IF PARALLEL CONFIGURATIONS ARE REQUIRED.
- BATTERIES SHOULD BE FUSED.
- CELL DESIGNS SHOULD BE LITHIUM LIMITED.
- DEFINE OPERATION HANDLING AND TRAINING PROCEDURES.
- BATTERY MODULAR CONCEPTS SHOULD BE INCORPORATED FOR HIGH ENERGY REQUIREMENTS.

Figure 2- 20



### RELIABILITY

- OPTIMIZED BATTERY VOLTAGE/CAPACITIES TO WITHSTAND SINGLE CELL FAILURE.
- SINGLE POINT FAILURE CAN BE PRECLUDED WITH BY PASS DIODES.

### PERFORMANCE

- CELL MANUFACTURING TOLERANCES MUST BE TIGHTLY CONTROLLED.
- BATTERY CONDITIONING SHOULD BE CONSIDERED IF VOLTAGE DELAY IS CRITICAL.

### STORAGE

- CONTROLLED (LOW TEMPERATURE) ENVIRONMENTS ARE CRITICAL IF LONG TERM STORAGE IS REQUIRED.

Figure 2-21