NICKEL-HYDROGEN SPACECRAFT MODULE CONFIGURATIONS STUDY

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ABSTRACT

The incorporation of nickel-hydrogen technology into spacecraft power system designs for LEO vehicles offers significant power system weight reductions by increasing the power storage watt-hour efficiency. Several possible module configurations exist for the power system. The module configurations were compared utilizing reliability, weight, volume and load capability as evaluation parameters. This paper summarizes the results of this study.

INTRODUCTION

The NASA Standard Multi-Mission Spacecraft (MMS) module was the baseline volumetric constraint for the energy storage system for this study. The MMS module has the following dimensions:

LENGTH - 44"
WIDTH - 44"
HEIGHT - 16"

For the Low-Earth-Orbit (LEO) application pertaining to this study, the entire MMS module was allotted for batteries. The battery chargers, shunt banks, power control units and power control and distribution units will be located outside the MMS module. The Electrical Power Subsystem Design Criteria for the LEO application specifies a 24 volt minimum battery voltage. Twenty-two series connected nickel-hydrogen cells could support this minimum battery voltage requirement. The conventional battery would thus consist of 22 series connected nickel-hydrogen cells. The 22 cell battery could be divided into submodules which could be series connected to comprise the battery. The one-cell module configuration would differ from the conventional 22 series connected cells in that each one-cell module would have the capability for bypass in the event of a failure. Important considerations relative to module size determination are reliability, weight and load growth capability. Volume was not considered a critical selection parameter due to the allocation of the entire MMS module for cells/batteries.

The basic ground rules and assumptions for this study were:

1) The nickel-hydrogen cell specified in this report is the 50 Ampere-Hour, Air Force design cell per Hughes Aircraft Company specification PS32014-031.

2) Battery discharge current was limited to a 1.3 C rate, or 65 amps.

3) Battery System Operational Life is 3 years.

4) The battery shall utilize redundancy so that a single module or component failure does not reduce the capability of the battery to support mission requirements.

5) The reliability allocation for the Electrical Power Subsystem is 0.946. It is assumed for this study the reliability of the battery system must be at least 0.99.

6) There will be only one module configuration for the battery system. This will simplify design and structural requirements.

7) The maximum number of 50 Ampere-Hour cells, depicted in Figure 1, that will fit in the NASA MMS module is 126.

DESCRIPTION OF SELECTION PARAMETERS

Selection parameters considered for the nickel-hydrogen battery system application included weight, reliability, safety, charge/discharge characteristics and requirements, maintainability, support requirements and load growth capability. Three parameters have been selected from this list in which a significant difference exists among the module configuration candidates. The other parameters, while important, are not significantly impacted by the module configuration selected. The three selection parameters utilized for this study are reliability, weight and load growth capability.

Battery reliability is quantitatively described as the probability that the system reliability will deliver rated power for the required mission duration. The main factors affecting battery reliability are cell reliability, pressure vessel reliability and the quantities of cells per module and per battery. The two main failure modes for a nickel-hydrogen cell are the short-circuit and open-circuit conditions. The short-circuit failure mode usually affects only one cell in a module, and the module or battery may still be capable of supporting loads at a lower voltage. The open-circuit failure mode will affect the entire module and generally arises from mechanical damage within a battery or from the loss of electrolyte within the cells. The capability of bypass protection circuitry can enhance the overall system reliability and alleviate the failure modes of short-circuit and open-circuit. For this study reliability is considered the most important of the selection parameters. If the total battery system does not provide a reliability of at least 0.99, then the battery system is considered unacceptable and does not even deserve further consideration. A cell reliability number for a 50 ampere-hour nickel-hydrogen cell does not exist due to the absence of a LEO data base. For this study, a cell reliability of 0.99 is assumed. It should be noted that a 0.99 cell reliability is somewhat optimistic based on the lack of an adequate data base.

Weight is considered an important selection parameter due to its impact on life cycle costs. The overall significance of weight has been reduced by the fact the entire MMS module may be utilized. For this study however, weight has also been evaluated for each module as a function of the available power. This allows a comprehensive weight evaluation of each module.

The average electrical load of successive iterations of a spacecraft design normally increases. The capability of a battery system for load growth would be advantageous for future missions. The load growth capability of each module configuration with associated weight and reliability factors were evaluated for the load capability parameter.

NICKEL-HYDROGEN MODULE CONFIGURATIONS

A twenty-two cell nickel-hydrogen battery may be constructed by use of submodules in numerous ways. The requirement that the nickel-hydrogen battery system will utilize only one module configuration reduces the possible module candidates to four:

1) Twenty-Two Cell Module - The most simplistic approach to a battery configuration is to have the module level equivalent to the battery. The maximum number of identical twenty-two cell modules that could fit in the NASA MMS module is five (5). The following paragraphs evaluate the twenty-two cell module configuration for reliability, weight and load capability.

The LEO application defines the operational life for Electrical Power Subsystems as three (3) years. If time t is assumed to be three years, and the cell reliability (P_C) is assumed to be 0.99, then the reliability of a twenty-two cell module (P_B) may be expressed as:

$$P_B = (P_C)^N = (0.99)^{22} = 0.802$$

If k batteries out of m total batteries in the system must survive for the system to survive, and P_B is the battery reliability, then the overall system reliability may be expressed as:

$$S_R = \sum_{x=k}^{m} \frac{m!}{x!(m-x)!} (P_B)^x (1-P_B)^{m-x}$$

Table 1 illustrates the battery system reliability when the module reliability is 0.802 and the total number of modules is five. Table 1 shows the twenty-two cell module configuration is unacceptable for meeting the reliability requirement of 0.99 when three or more operational batteries are required for load support. In order for the overall battery system reliability to be above the Electrical Power Subsystem reliability requirement, only two batteries out of the five total can be required for mission success. If only two of the five total batteries are required, the overall system reliability would be 0.9935.

The weight of a 50 Ampere-Hour nickel-hydrogen cell is assumed to be approximately 3.0 pounds. If a 1.35 weight packaging factor is assumed for wiring, structure and thermal control, then the weight of a 22-cell module would be:

(22 Cells)(3.0 Lbs/Cell)(1.35) = 89.1 Lbs

Each battery would require two relays to permit switching the battery on and off the Bus. A 1.3 C rate limit for the nickel-hydrogen cell dictates a possible charge/discharge current of 65 amps. If the relays are sized based upon a maximum contact rating of 65 amps, then 100 amp relays (derated) weighing approximately 0.75 lbs each would be required for switching. Smaller and lighter relays would suffice if the contact rating of the relays was reduced to 25 amps or less. For this study, a 25 amp relay weighing 0.3 lbs is utilized. The total battery weight would then be approximately 89.7 pounds. The total battery system weight for the five, 22-cell module battery system would be 448.5 pounds.

Table 1 shows the twenty-two cell module configuration is capable of meeting the Electrical Reliability Subsystem reliability requirement only if two operational modules are required out of the five total. A redundancy requirement of operation with one unit failed results in a design usable energy from only a one battery system. Using 1.2 volts as the end-of-life, end-of-discharge voltage for a nickel-hydrogen cell, the energy available from one battery from full charge to 100% DOD is:

(1 battery)(26.4 V/battery)(50 A-Hr) = 1320 Watt-Hours

For a three year mission, the maximum allowable DOD for the nickel-hydrogen battery is 60%. The usable available energy for the MMS module based upon the 22-cell module configuration would be:

(1320 Watt-Hours)(.60 DOD) = 792 Watt-Hours

A 1.3 discharge rate limit dictates a peak load capability of 65 amps. The peak load capability for a twenty-two cell module configuration based upon a one battery system would be:

(1 battery)(65 amps)(26.4 V/battery) = 1716 Watts

The twenty-two cell module configuration has the design capability to support a maximum load of 1716 watts for a maximum time of 27.7 minutes or until 792 watt-hours have been removed.

2) Eleven Cell Module - An eleven cell module consisting of eleven series connected cells is another viable nickel-hydrogen battery module configuration candidate. Two of the eleven cell modules electrically series connected would comprise a battery. The maximum number of eleven cell modules that could fit in the NASA standard MMS module is eleven. The following paragraphs evaluate the eleven cell module configuration for reliability, weight and load capability.

The reliability of the eleven cell module may be expressed as:

$$P_B = (P_c)^N = (0.99)^{11} = 0.895$$

If k modules out of m total in the system must survive for the system to survive, and P_B is the module reliability, then the overall battery system reliability, S_R, with the eleven cell module configuration may be expressed as:

$$S_R = \sum_{x=k}^{11} \frac{11!}{x!(11-x)!} (.895)^x(1-.895)^{11-x}$$

Table 2 summarizes the battery system reliability for k operational modules out of eleven total modules when the eleven cell module reliability is 0.895. Table 2 shows that the eleven cell module configuration is capable of meeting the battery system reliability requirement of 0.99 if seven of the total eleven modules are required for operational support. Seven modules could be connected to comprise a three battery system with one spare. The spare would meet the redundancy requirement of operation with one unit failed. From a reliability standpoint, the eleven cell module configuration would be acceptable if the load requirements do not exceed a three battery system capability.

If the weight of a 50 Ampere-Hour cell is assumed to be 3.0 pounds and a weight packaging factor of 1.35 is utilized, the weight of an eleven cell module would then be:

(11 Cells)(3.0 Lbs/Cell)(1.35) = 44.55 lbs

The switching configuration of relays required to connect eleven cell modules into various pairs to comprise a battery is rather complex. A minimum number of 144 relays are estimated to allow the independent switching to comprise 3 batteries out of 11 total modules. The total weight of the 11, eleven cell modules plus switching relays would be:

(11 modules)(44.55 lbs/module) + (144 relays)(0.3 lbs/relays)
= 533.3 lbs

The minimum acceptable battery system reliability requirement of 0.99 and the redundancy requirement of operation with one unit failed results in a maximum design load capability based upon a three battery system. The energy available from three batteries from full charge to 100% DOD would be:

(3 Batteries)(26.4 V/Battery)(50 AHr) = 3960 Watt-Hours

For a three-year mission, the maximum allowable DOD is 60%. The usable available energy from a three battery system comprised of eleven cell modules is:

(3960 Watt-Hours)(.60 DOD) = 2376 Watt-Hours

The battery system peak load capability would be:

(3 Batteries)(65 amps)(26.4 V/Battery) = 5148 Watts

The eleven cell module configuration battery system has the capability to support a maximum load of 5148 watts for a maximum time of 27.7 minutes or until 2376 watt-hours have been removed.

3) Two Cell Module - A two cell module consisting of two series connected cells is another possible module configuration. Eleven, two cell modules connected in series could comprise a battery. The following paragraphs evaluate the two cell module configuration for reliability, weight and load capability.

The reliability of a two cell module may be expressed as:

$$P_B = (P_c)^N = (0.99)^2 = 0.9801$$

The maximum number of modules that could fit in the NASA MMS module is 63. Eleven modules would be required per battery, thus a maximum number of five batteries are available. The reliability of a 22 cell battery consisting of eleven series connected two cell modules may be expressed as:

$$P_B = (P_c)^N = (0.9801)^{11} = 0.8016$$

This is unacceptable for a battery reliability. If, however, in each battery there is a spare two cell module, then the battery system reliability would be enhanced. Table 3 summarizes the battery reliability for k operational modules out of m total modules when the two cell module reliability is 0.9801 and the total number of modules is 12, 13 and 14. The 13 and 14 module concepts provide a battery reliability greater than 0.99. However, the overall battery system reliability has not yet been calculated. Table 4 summarizes the overall battery system reliability for the battery configurations reviewed in Table 3. The 14, two cell module configuration per battery provides a high overall battery system reliability of 0.9992. The redundancy requirement of operation with one unit failed has been met through the additional modules per battery. From a reliability standpoint, the two cell module configuration is an excellent candidate if the load requirements do not exceed a four battery system capability.

The weight packaging factor for a two cell module configured battery will be significantly greater than the twenty two or eleven cell module configurations due to the extra connections and cabling. For the two cell module configuration, a 1.50 weight packaging factor has been assigned. The weight of a two cell module would then be:

(2 Cells)(3.0 Lbs/Cell)(1.50) = 9.0 Lbs

The switching configuration of relays required to comprise a twelve, thirteen or fourteen module battery would involve the capability to series connect various two cell modules or place the two cell modules in an open circuit condition. The advantage to this configuration is, off-line charging is probably not necessary if the capability to periodically switch modules in and out of the string exists. Twenty-six total relays (including redundancy) would be required for a 13, two cell module battery. The relays would be rated at 25 amps and weigh 0.3 lbs each. The total weight of a a twelve, thirteen or fourteen module battery would be:

(12 modules)(9 lbs/module) + (24 relays)(0.3 lbs/relay) = 115.2 lbs

(13 modules)(9 lbs/module) + (26 relays)(0.3 lbs/relay) = 124.8 lbs

(14 modules)(9 lbs/module) + (28 relays)(0.3 lbs/relay) = 134.4 lbs

The NASA MMS module can accommodate five, 12 module batteries or four, 13 or 14 module batteries. The total battery system weight for the two cell module configuration is summarized in Table 5.

Five batteries consisting of twelve modules each would have a maximum available capacity of 250 ampere-hours. The energy available from full charge to 100% DOD would be 6600 Watt-hours. The redundancy requirement of operation with one unit failed has been met at the module level. The usable energy available from five batteries based upon a maximum allowable DOD of 60% would be:

(6600 Watt-Hours)(.60 DOD) = 3690 Watt-Hours

Four batteries consisting of thirteen or fourteen modules each would have a maximum available capacity of 200 Ampere-hours. The energy available from full charge to 100% DOD would be 5280 Watt-hours. The usable energy based upon a maximum allowable DOD of 60% would be:

(5280 Watt-Hours)(.60 DOD) = 3168 Watt-Hours

The 1.3 C discharge rate limit would dictate a peak load capability of 65 amps per battery. The battery system peak load capability of a four or five battery system would be:

(4 batteries)(65 amps)(26.4 V/battery) = 6864 Watts

(5 batteries)(65 amps)(26.4 V/battery) = 8580 Watts

Table 6 summarizes the load capabilities of the two cell module configurations.

4. One Cell Module - A one cell module is the smallest possible configuration candidate. Twenty-two, one cell modules connected in series would comprise a battery. The following paragraphs evaluate the one cell configuration for reliability, weight and load capability.

The reliability of a one cell module would simply be the cell reliability, or 0.99. If 22 one cell modules were series connected, the battery reliability would be:

$$P_B = (P_C)^N = (0.99)^{22} = 0.802$$

This is an unacceptable battery reliability. The battery reliability may be enhanced by having additional one cell modules per battery. The addition of spare modules would require the capability to switch cells in or out of the series. Table 7 summarizes the battery reliability for k operational modules out of m total modules for a cell reliability of 0.99. Table 8 summarizes the overall battery system reliability for the one cell module candidates. Five batteries consisting of 23 cells will fit in the MMS module, while four batteries consisting of 24 or 25 cells will fit in the MMS module. The redundancy requirement of operation with one unit failed has been met at the cell level within a battery. From a reliability standpoint, the one cell module configuration is an excellent candidate if the load requirements do not exceed a four battery system.

The weight packaging factor for the one cell module is assigned the same value as the two cell module, 1.50. The weight of a one cell module would then be:

(1 Cell)(3.0 Lbs/Cell)(1.50) = 4.5 Lbs

The switching configuration of relays required to comprise a 23, 24 or 25 cell battery would involve the capability to series connect 22 total modules and place the spare cells in an open circuit condition. A total of 50 relays are required for such a configuration for a 25 cell battery. The total weight of 23, 24 and 25 cell battery would be:

(23 cells)(4.5 lbs/cell) + (46 relays)(0.3 lbs/relay) = 117.3 lbs

(24 cells)(4.5 lbs/cell) + (48 relays)(0.3 lbs/relay) = 122.4 lbs

(25 cells)(4.5 lbs/cell) + (50 relays)(0.3 lbs/relay) = 127.5 lbs

The NASA Standard MMS module can accommodate five 23 cell batteries or four 24 or 25 cell batteries. The total battery system weight for the one cell module configurations is summarized in Table 9.

The load capabilities of a five or four battery system were calculated in the two cell module configuration paragraph. Table 10 summarizes the load capabilities of the one cell module configurations.

CONCLUSION

Table 11 summarizes the results of this study for a battery system with a minimum reliability of 0.99. The twenty-two and eleven cell module configurations require a large number of spare modules in order to meet the reliability requirements, resulting in poor specific energy densities for the configurations. The redundancy requirement of operation with one unit failed also significantly reduces the available design capacity for the twenty-two and eleven cell module configurations. The two and one cell module configurations provide the highest reliable battery system and appear to be the optimum configuration candidates for the NASA Standard MMS module.

It should be noted that this study was the initial investigation of nickel-hydrogen module configurations. Many system components of the Electrical Power System were not evaluated as to the impact of nickel-hydrogen modular implementation. The reliability of the relays for switching cells in or out of the series was assumed to be very high (1.00 for the study) and was not evaluated any further. The study does indicate, however, that the one cell module configuration is the optimum candidate for a nickel-hydrogen energy storage system.

INDIVIDUAL PRESSURE VESSEL NICKEL-HYDROGEN CELL

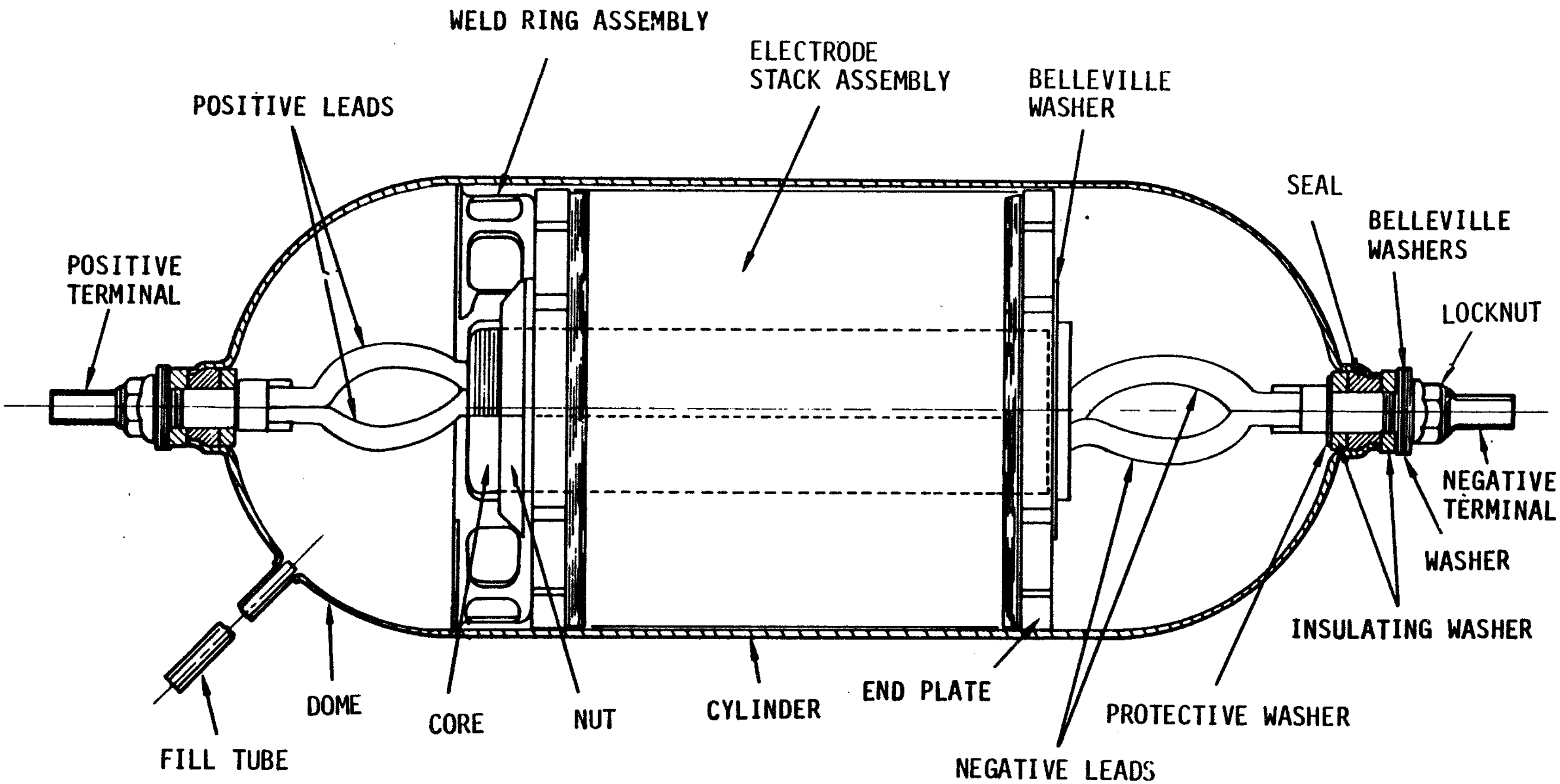

Figure 1. Individual Pressure Vessel Nickel-Hydrogen Cell

Table 1. TWENTY-TWO CELL MODULE OVERALL SYSTEM RELIABILITY

Number of Operational Batteries (k) Required Out of m Total (5) for Mission Success (0.95 Cell Reliability)	Overall Battery System Reliability
5	0.3310
4	0.7414
3	0.9436
2	0.9935
1	0.9997

Table 2. ELEVEN-CELL MODULE OVERALL SYSTEM RELIABILITY

Number of Operational Batteries (k) Required Out of m Total (11) for Mission Success	Overall Battery System Reliability
11	0.2952
10	0.6761
9	0.8995
8	0.9781
7	0.9966
6	0.9996
5	0.9999

Table 3. TWO-CELL MODULE BATTERY RELIABILITY

Number of Operational Modules (M) Required Out of N Total for a Battery k	m	Battery Reliability
11	12	0.9771
11	13	0.9980
11	14	0.9998

Table 4. TWO-CELL MODULE OVERALL BATTERY SYSTEM RELIABILITY

Number of Two-Cell Modules per Battery	Battery Reliability	Number of Batteries per MMS Module	Battery System Reliability
12	0.9771	5	0.8906
13	0.9980	4	0.9920
14	0.9998	4	0.9992

Table 5. TWO-CELL CONFIGURATION BATTERY SYSTEM WEIGHT PROFILE

Number of Two-Cell Modules per Battery	Number of Batteries per MMS Module	Total Battery System Weight (Lbs)
12	5	576.0
13	4	499.2
14	4	537.6

Table 6. TWO-CELL MODULE LOAD CAPABILITY

Modules per Battery	Number of Batteries per MMS Module	Load Capability (Watt-Hours)	Peak Load Capability (Watts)
12	5	3960	8580
13	4	3168	6864
14	4	3168	6864

Table 7. ONE-CELL MODULE BATTERY RELIABILITY

Number of Operational Modules (M) Required Out of N Total for a Battery		Battery Reliability
k	m	
22	22	0.8016
22	23	0.9780
22	24	0.9983
22	25	0.9999

Table 8. ONE-CELL OVERALL BATTERY SYSTEM RELIABILITY

Number of One-Cell Modules per Battery	Battery Reliability	Number of Batteries per MMS Module	Battery System Reliability
23	0.9780	5	0.8947
		4	0.9149
24	0.9983	5	0.9915
		4	0.9932
25	0.9999	5	0.9995
		4	0.9996

Table 9. ONE-CELL CONFIGURATION BATTERY SYSTEM WEIGHT PROFILE

Number of Cells per Battery	Number of Batteries per MMS Module	Total Battery System Weight (Lbs)
23	5	586.5 Lbs
23	4	469.0 Lbs
24	4	489.6 Lbs
25	4	510.0 Lbs

Table 10. ONE-CELL MODULE LOAD CAPABILITY

Cells per Battery	Number of Batteries per MMS Module	Load Capability (Watt-hours)	Peak Load Capability (Watts)
23	5	3960	8580
24	4	3168	6864
25	4	3168	6864

Table 11. BATTERY CONFIGURATION EVALUATION SUMMARY

Module Configuration	Battery System* Reliability	Battery System Weight (Lbs)	Capacity (Watt-Hours)	Peak Load Capability (Watts)
22 (Five, 22-cell batteries)	0.9935	448.5	792	1716
11 (Eleven, 11-cell modules; five batteries total)	0.9966	533.3	2376	5148
2 (13, 2-cell modules/battery; 4 batteries total)	0.9920	499.2	3168	6864
1 (24, 1-cell modules/battery; 4 batteries total)	0.9932	489.6	3168	6864

* Minimum acceptable reliability for battery system is 0.990. All module configurations listed in this table were based on this minimum acceptable battery system reliability. Redundancy requirement of operation with one unit failed also included in this table.