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NICKEL-HYDROGEN BATTERIES FROM INTELSAT V TO SPACE STATION

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INTRODUCTION

The Ni-H_2 battery system has been under development for about 14 years and has been flying on several geosynchronous orbit (GEO) spacecraft since 1983, in configurations such as the Intelsat V battery assembly shown in Figure 1. It has been qualified as well for low earth orbit (LEO) applications but is not as yet flying in LEO. An application now being studied in detail is the Space Station, which may require very large Ni-H_2 batteries to meet the 75 kW power requirement cost-effectively.

This paper discusses the heritage of Ni-H_2 technology that makes the Space Station application feasible. It also describes a design for a potential Space Station Ni-H_2 battery system. Specific design values presented here were developed by Ford Aerospace as part of the Rocketdyne team effort on the Phase B Definition and Preliminary Design of the Space Station Power System in support of NASA Lewis Research Center.

SPACE STATION Ni-H_2 BATTERY SYSTEM OVERVIEW

The Ni-H_2 battery system is a current option for the Space Station Initial Operating Capability (IOC). The system consists of four batteries of 105 individual pressure vessel (IPV) cells. Each cell has a nominal 275 Ah capacity. The four batteries each consist of five battery assemblies with 21 cells. The assemblies contain heat pipes for heat tranport to a fluid loop interface. The total system consists of 20 battery assemblies held in two racks, one in each Power System utility center. Design details will be provided following some background discussion.

CELL DESIGN HERITAGE

While Ni-H_2 cells are currently flying in GEO only, there is a large body of work and data that provides confidence in the readiness of the system for a large-scale LEO application in the early 1990s. The key features of the design of the 275 Ah Ni-H_2 cell required for the Space Station have already been individually demonstrated. Figure 2 illustrates some of these important efforts, some completed and some still in process, along with their major background contribution to this program.

Intelsat V provides important background as the first and longest operational flight of $Ni-H_2$ batteries. Spacenet, G-Star, and Satcom K (RCA programs, not shown) demonstrate cell scale-up feasibility. The Air Force LEO cell and MANTECH programs provide LEO design and manufacturing data bases. The dual electrode stack design concept is being qualified on the MILSTAR program. While all these efforts involved 3.5-inch diameter cells, the 4.5-inch diameter required for high-capacity cells has been developed under Air Force sponsorship.

Component-level developments and life test programs are supporting these efforts. NASA-LeRC is funding electrode optimization studies for LEO, and has pursued other innovations such as vessel-wall-mounted oxygen recombination technology. The Air Force is initiating life tests at Naval Weapons Support Center in Crane, IN.

Ford Aerospace and Yardney are co-funding development of a 220 Ah $Ni-H_2$ cell which incorporates the necessary and best features of these other efforts. The cell is a 4.5-inch diameter, dual-stack LEO design, incorporating wall-mounted recombination sites, LEO-optimized components, and several new and upgraded features. Development of all components has been completed, and tests of the first cell will commence in December 1985. The cell is shown in Figure 3 next to a typical Intelsat V flight cell. This large-cell demonstration will establish readiness for future development of a specific Space Station size cell, in any capacity ranging up to 300 Ah. Current Space Station battery design calls for a 275 Ah cell, on which the discussion below is based.

CELL DESIGN

The 275 Ah $Ni-H_2$ cell is a 4.5-in diameter, tandem-stack LEO cell, based on a combination of proven features of already developed lower capacity cells.

The nickel electrode design for the 275-Ah LEO cell is based on design parameters developed by the space nickel battery industry over the last decade for long life electrodes, including sinter porosity, pore size distribution, and loading levels consistent with those derived in the NASA-LeRC funded research at Hughes Research Laboratories, as well as in U.S. Air Force development efforts. The hydrogen electrodes are based on a proven design that currently is flying on several spacecraft. The baseline separator system combines features of demonstrated separator materials to provide the necessary electrolyte reservoir and barrier characteristics.

The mechanical design of the cell is derived from the demonstrated Air Force 4.5-in cell technology. It also incorporates scaled-up features developed under the Air Force/Yardney MANTECH program and additional improvements to provide more uniform stack support. The stack components are supported on a central core which attaches to the weld ring. Each stack is held between two support/end plates, one of which can move with respect to the core against a Belleville washer to maintain constant compressive force over the life of the cell. Electrode tabs are fed through the central core.

The pressure vessel is made of Inconel 718 with a 0.035-in design thickness. The two hydroformed and age hardened shells are joined by electron-beam welding to the Inconel 718 weld ring. The vessel has demonstrated a 3900 psi burst pressure. Maximum operating pressure is expected to be 1100-1200 psi. The electrical feedthroughs incorporate hydraulic cold-flow teflon seals.

Oxygen management is achieved by recombining oxygen generated on overcharge on the vessel wall which is coated with porous zirconia (wall wick), on which platinum catalyst is deposited based on a design pioneered by NASA-LeRC. Heat generated during overcharge thus is removed very effectively without thermal burden on the stack. The water formed is returned to the stack by the wall wick via separator edges in contact with it. The wall wick also serves as electrolyte concentration and inventory equilibrator, and as a reservoir.

BATTERY SYSTEM DESIGN DISCUSSION

Electrical Design

The 75-kW power requirement of the station, plus allocations for user converter inefficiency and PMAD processors, is provided by the battery through a 0.90 efficiency chain for a total battery system output of 95.8 kW (see Table 1). Power peaks are supported during sunlight periods by reducing the charge current if required and during eclipse by the battery at 125.8 kW. With 105 cells in series per battery and an average EOL discharge voltage per cell of 1.25 V, delivered capacity per cell is about 110 Ah for a typical eclipse. Table 2 provides additional electrical design data.

Nominal battery DOD is 40%, which assures the capability for contingency support following a peak eclipse, and is consistent with a 5-year life expectancy for the battery system. Cell capacity required to meet this requirement is 275 Ah, well within the estimated minimum 300-Ah capability of the tandem stack 4.5-in cell design. The 275 Ah capacity is achieved by adding six electrode modules to each of the two stacks of the 220-Ah cell discussed above.

Any non-wearout failures observed in Ni-H_2 cells have typically been short circuits. Because of this and the maintainability of the station hardware, no individual cell bypass hardware is included in the design. Outage of a single battery during maintenance or reconditioning represents a temporary increase in DOD to 53% for the remaining batteries, which represents no life risk.

Charge management involves microprocessor-based coulometry during charge and discharge. Charge current and time are determined based on a programmable recharge ratio and end-of-charge current taper profile.

Mechanical Design

The overall battery rack concept for one Utility Center is shown in Figure 4. It has space for 10 battery assemblies which slide into the rack. On one side cold plates are provided which interface with the heat exchanger of the corresponding battery assembly. Cable harnesses are incorporated in the rack with connectors at each battery shelf. Each battery assembly, as shown in Figure 5, contains 21 cells and is an independent unit interchangeable with any other. It consists of a graphite/epoxy honeycomb panel on which graphite/epoxy support beams are bonded that carry heat pipes on their top surface. Cells are contained in aluminum sleeves, which provide mechanical support and transport heat away from the cell as well. A resilient insulator layer electrically isolates the cell and sleeve and provides good thermal contact. Flanges on the sleeve are mounted to the heat pipe saddles forming both mechanical and thermal interfaces. The cell mounting design is shown in cross-section in Figure 6.

Battery physical data are shown in Table 3. Based on an individual battery assembly mass of 220 kg, and a rack mass of 75 kg, the total system mass is 4550 kg. This is not necessarily the lowest-mass battery design, but represents the overall most cost-effective approach.

Thermal Design

Battery thermal design relies on the cell sleeve, primary and secondary heat pipes, and the utility center coolant loop as major elements in the heat rejection path. The cell sleeve surrounds the cylindrical portion of the cell over the length of the cell stack and is insulated from it by a conductive layer. The sleeves conduct heat to two sets of flanges which contact the primary heat pipes as shown in Figures 5 and 6. The primary heat pipes carry heat to one side of the battery panel where their condensers interface with the evaporators of secondary heat pipes. The latter terminate on part of the long side of the panel where they form a heat exchanger which contacts a coolant loop cold plate. Instead of secondary heat pipes a simple coolant conduit fitted with quick-disconnect couplings can be used, into which an external coolant loop is plugged.

Average heat dissipations of each battery assembly during discharge and charge are 995 W and 270 W, respectively. Nominal temperatures are 10 to 20°C. The area requirement for an Al/NH_3 heat pipe radiator system to support the battery heat load would be 94 m^2, taking advantage of heat load averaging by the battery heat capacity of 60 Wh/$^{\circ}$C per assembly.

Life and Reliability

Prediction of cycle life capability of $Ni\text{-}H_2$ batteries for LEO applications is more difficult than for Ni-Cd batteries. The latter have been tested extensively at Naval Weapons Support Center, Crane, IN (NWSC-Crane). A thorough analysis of this data base is represented by the model derived by McDermott and reported in various proceedings of the NASA Goddard Battery Workshop over the last four years.

Reported cycle capabilities for early developmental 50 Ah $Ni\text{-}H_2$ cells at 80% DOD equates to 33,000 to 40,000 cycles at 40% DOD, based on applying the McDermott Ni-Cd model, which should be conservative for the $Ni\text{-}H_2$ system. Sufficient progress has been made in $Ni\text{-}H_2$ cells since the mid-1970s, that a mean cycle life of 40,000 to 45,000 at 40% DOD in LEO appears to be a realistic projection for $Ni\text{-}H_2$ cells, particularly in view of the fact that even some Ni-Cd cells have achieved this (packs 1H, 1J, 8G at NWSC-Crane).

The large in-orbit data base shows that random failure probability for spacecraft batteries is extremely low on the many Ni-Cd and $Ni\text{-}H_2$ batteries that have been flown. Based on Ford Aerospace's in-orbit experience, Ni-Cd cells exceed 40,000,000 cell hours without random failures; industry-wide on $Ni\text{-}H_2$ the total is 7,000,000. Analysis yields an expected 0.6 random cell failures for the Space Station battery system over 5 years or an mean-time-to-failure of 68,000 hours.

Reliability analysis based on the Weibull distribution with a shape factor of 12 and a mean cycle life of 45,000 cycles was performed. The shape factor value is somewhat optimistic, but based on the smaller number of wearout mechanisms in $Ni\text{-}H_2$ cells compared to Ni-Cd (typical shape factor 8), and the tight control of operating conditions, not unrealistic. Table 4 shows the estimated system reliabilty based on these figures, an assumption that 3 shorted cell failures per battery string are allowed, and for shorted/open failure distributions of 98/2 and 80/20. Another variable is the possible presence of a spare assembly for every two batteries or 10 assemblies, which can be switched in on demand. Conclusions are:

- There is high probability (97%) that all four batteries in the system will be available for use at all times during a 5 year operational period

- Probability of uninterrupted power support for 5 years is 99.9%

- A single spare battery assembly per set of two batteries provides sufficient open cell protection over a wide range of open cell failure possibilities

The reliability analysis results indicate that it may be not be necessary to plan for replacement of individual assemblies, but to replace instead the entire battery as a package upon wearout.

SUMMARY AND CONCLUSIONS

The heritage of space $Ni-H_2$ batteries from Intelsat V, through many LEO-oriented cell and component development efforts and culminating in the Ford Aerospace/Yardney development of a 220-Ah LEO cell, has prepared the technology to a point of readiness where application on the Space Station can be seriously considered. Practical battery system designs have been derived that are compatible with the requirements of the Station. While these designs do not necessarily have the lowest possible mass, they are configured to provide a 5-year battery system capability with maximal cost-effectiveness.

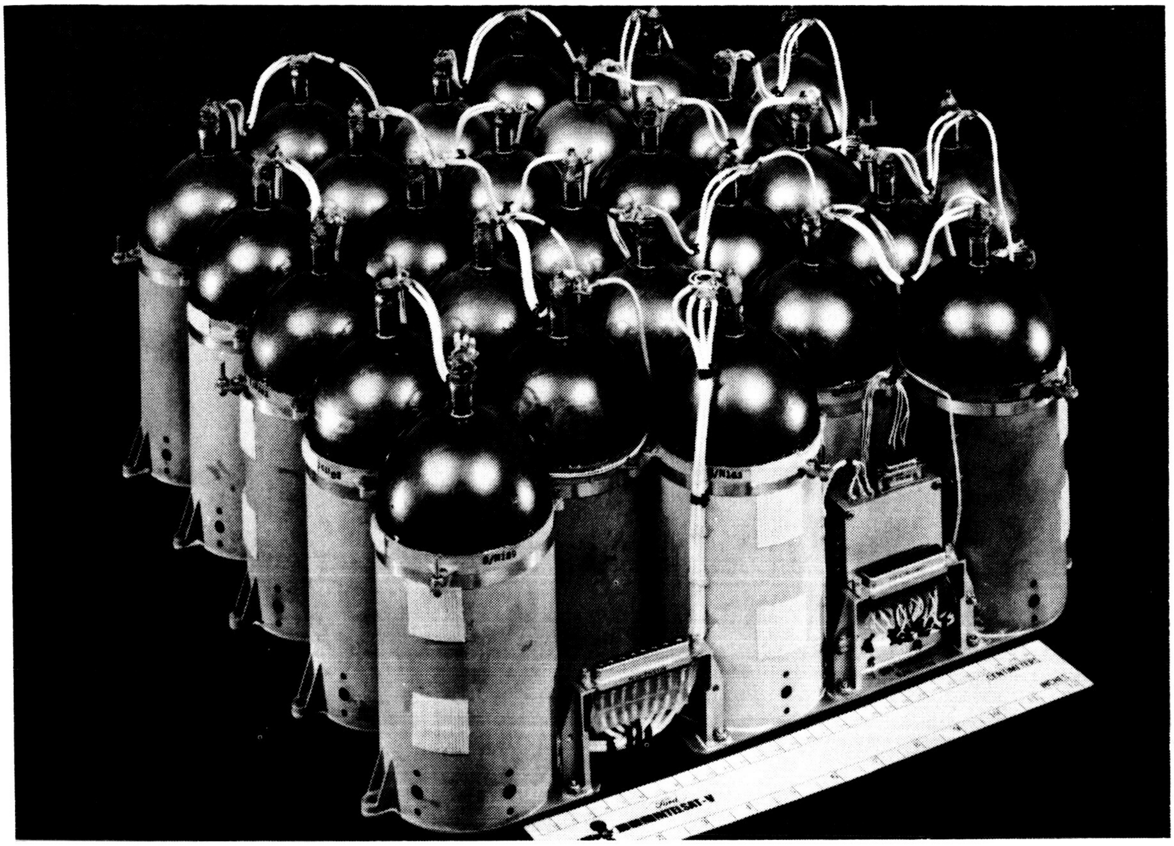

Figure 1. INTELSAT V NICKEL-HYDROGEN FLIGHT BATTERY

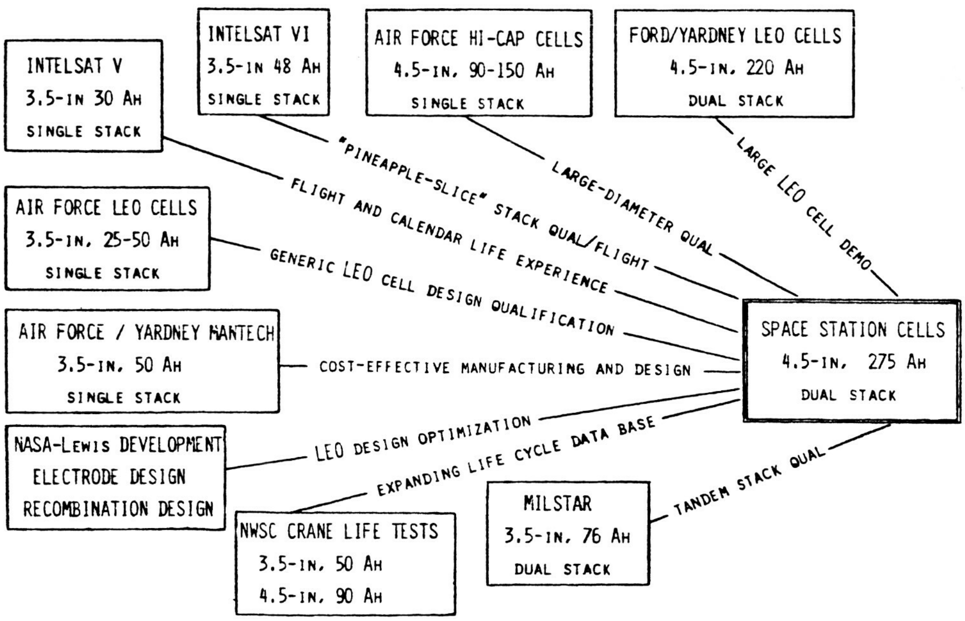

Figure 2. INTEGRATION OF DEMONSTRATED NICKEL-HYDROGEN TECHNOLOGIES FOR THE SPACE STATION

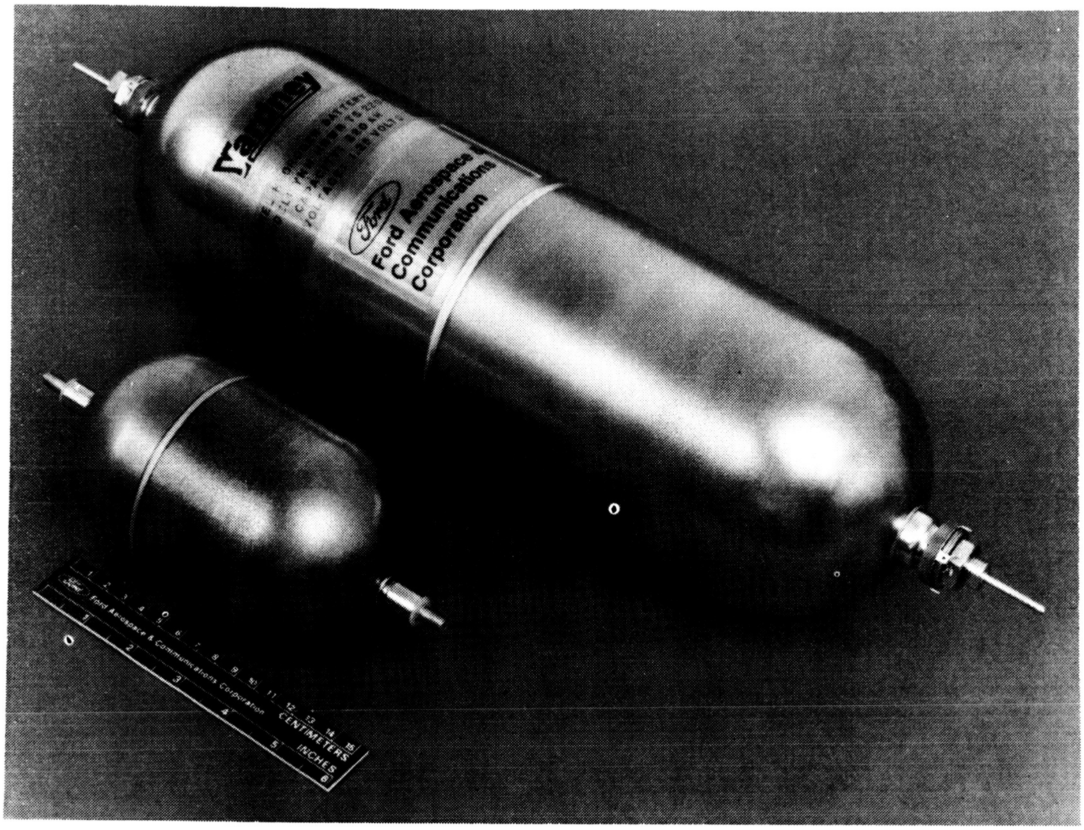

Figure 3. 220-Ah LEO NiH_2 CELL WITH 30 Ah GEO FLIGHT CELL

TABLE 1. SPACE STATION $Ni\text{-}H_2$ BATTERY SYSTEM OPERATING REQUIREMENTS

o NOMINAL DISCHARGE POWER	= 86.25 kW @ 0.90 EFF = 95.8 kW
o DISCHARGE DURATION	= 35.8 MIN
o PEAK POWER	= 113.25 kW @ 0.90 EFF = 125.8 kW
o PEAK DURATION	= 7.5 MIN
o RECHARGE DURATION - MAX	= 58 MIN
o DISCHARGE VOLTAGE	= COMPATIBLE WITH 160 V SOURCE BUS
o CHARGE VOLTAGE	= COMPATIBLE WITH 160 V SOURCE BUS
o CONTINGENCY CAPABILITY	= 50% OF LOAD FOR 1 ORBIT AFTER ECLIPSE

TABLE 2. SPACE STATION Ni-H_2 BATTERY SYSTEM DESIGN AND OPERATING CHARACTERISTICS

o NUMBER OF BATTERIES	4
o NUMBER OF IDENTICAL ASSEMBLIES PER BATTERY	5
o CAPACITY PER BATTERY	275 AH
o CELLS PER BATTERY	105
ECLIPSE	
o AVERAGE DISCHARGE VOLTAGE	131.3 V
o AVERAGE DISCHARGE CURRENT	182.5 A
o AVERAGE DEPTH OF DISCHARGE	39%
o PEAK ORBIT DOD	41.6%
o NON-PEAK ORBIT DOD	36.4%
o WORST-CASE CONTINGENCY DOD	97.9%
o AVERAGE HEAT DISSIPATION	19.9 kW
CHARGE	
o AVERAGE CHARGE VOLTAGE	154.4 V
o MAXIMUM CHARGE CURRENT	128.4 A
o AVERAGE HEAT DISSIPATION	5.4 kW

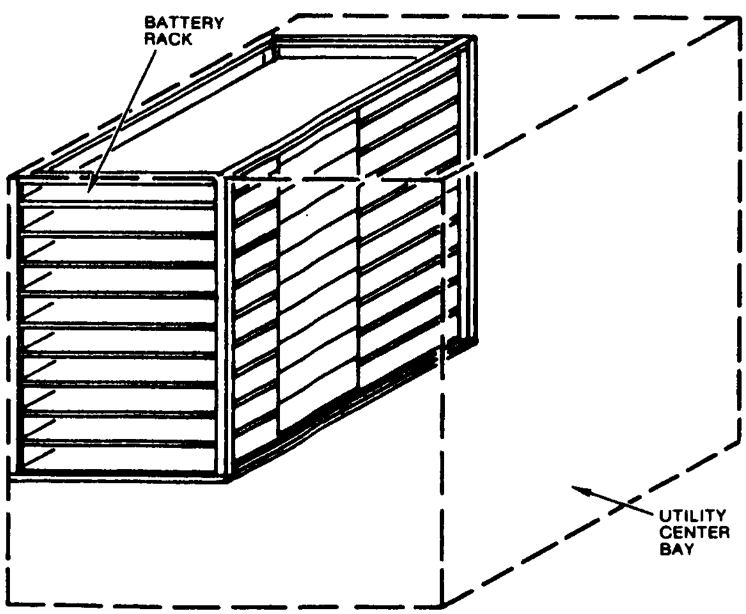

Figure 4. NiH_2 BATTERY RACK CONFIGURATION IN UTILITY CENTER BAY

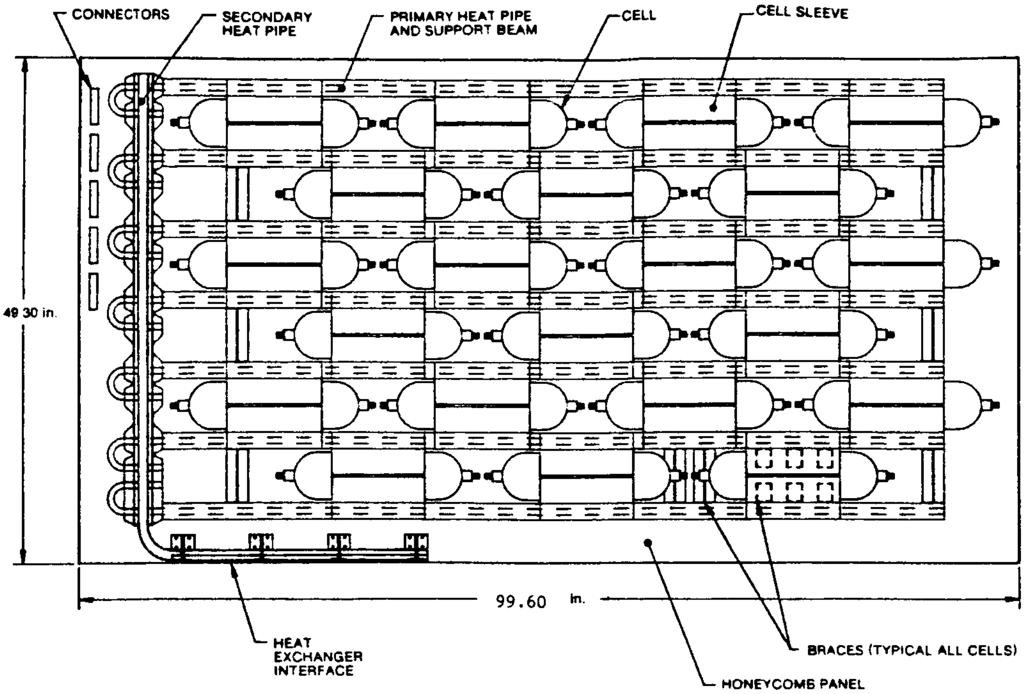

Figure 5. SPACE STATION NiH_2 BATTERY ASSEMBLY LAYOUT

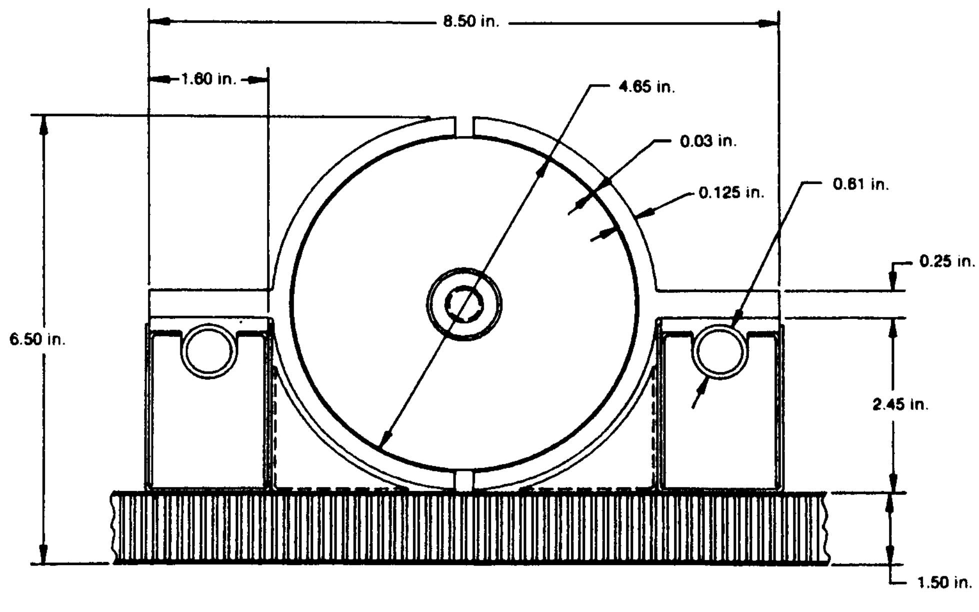

Figure 6. SPACE STATION NiH_2 CELL MOUNTING CONFIGURATION

TABLE 3. SPACE STATION $Ni\text{-}H_2$ BATTERY SYSTEM PHYSICAL CHARACTERISTICS

MASS PER CELL KG (LB)	6.99 (15.42)
MASS PER BATTERY ASSEMBLY KG (LB)	220 (485)
MASS PER BATTERY KG (LB)	1100 (2425)
TOTAL ESS MASS KG (LB)	4550 (10030)
CELL DIMENSIONS CM (IN)	55.1 x 11.8 DIA (21.7 x 4.65 DIA)
BATTERY ASSEMBLY DIMENSIONS M (FT)	2.52 x 1.25 x 0.17 (8.30 x 4.10 x 0.56)
BATTERY DIMENSIONS M (FT)	2.52 x 1.25 x 0.95 (8.30 x 4.10 x 3.12)
BATTERY SYSTEM DIMENSIONS (2 EA.) M (FT)	2.62 x 1.35 x 1.90 (8.60 x 4.43 x 6.23)
TOTAL BATTERY SYSTEM ENVELOPE VOLUME M^3 (FT^3)	13.4 (475)
THERMAL MASS WH/^oC	1210

TABLE 4. SPACE STATION NI-H2 BATTERY RELIABILITY ESTIMATES

Mission Time (years)	98% Short/2% Open				80% Short/20% Open			
	Without Spare Assembly		With Spare Assemblies		Without Spare Assembly		With Spare Assemblies	
	4 Batteries	3 of 4 Batteries	4 Batteries	3 of 4 Batteries	4 Batteries	3 of 4 Batteries	4 Batteries	3 of 4 Batteries
1	>0.9999	>0.9999	>0.9999	>0.9999	>0.9999	>0.9999	>0.9999	>0.9999
2	>0.9999	>0.9999	>0.9999	>0.9999	>0.9999	>0.9999	>0.9999	>0.9999
3	>0.9999	>0.9999	>0.9999	>0.9999	0.9993	>0.9999	>0.9999	>0.9999
4	0.9979	>0.9999	>0.9999	>0.9999	0.9790	0.9998	0.9999	>0.9999
5	0.9674	0.9996	0.9974	>0.9999	0.7340	0.9699	0.9777	0.9998
6	0.0839	0.3721	0.1086	0.4310	0.0165	0.1347	0.0934	0.3955