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Sodium-Sulfur Batteries For Spacecraft Energy Storage

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Abstract

Power levels for future space missions will be much higher than are presently attainable using nickel-cadmium and nickel-hydrogen batteries. Development of a high energy density rechargeable battery is essential in being able to provide these higher power levels without tremendous weight penalties. Studies conducted by both the Air Force and private industry have identified the sodium-sulfur battery as the best candidate for a next generation battery system. A two to three-fold increase in energy density is possible with the sodium-sulfur battery when compared to the nickel-hydrogen battery.

Nickel-cadmium batteries have been a part of our nation's space program since its inception in the 1950's. Their reliability and lifetime have enabled them to endure throughout the years. Development of nickel-hydrogen batteries began in the 1970's and today they are available for use. Lifetime and weight advantages are gained by going to nickel-hydrogen batteries, but the increased capabilities are not enough to meet the requirements of future high power missions.

Future space missions will require much higher power levels than the 0.5 - 5 kW we need today (Figure 1). Directed energy weapons, ultrahigh resolution radar, and direct broadcast communications are three missions that will require multikilowatt to multimegawatt levels of power. Scale up of present battery system technology to these high power levels is not practical due to tremendous weight penalties. A real need exists now for batteries with much higher energy densities capable of achieving these high power levels without unacceptable weight penalties. In this paper, the advantages of the rechargeable sodium-sulfur battery are discussed in light of the shortcomings of current spacecraft battery technology.

The responsibility for providing electrical power aboard spacecraft is shared between the solar array and the battery. During the time a spacecraft is illuminated by the sun, electrical power is provided by the solar array. When an eclipse period occurs, the burden of supplying power to the payload shifts to the battery. The battery recovers its spent energy by recharging from the solar array during the following sunlight periods.

Depending upon the orbit, these sunlight periods may be fairly continual throughout the year or they may occur at certain intervals of the day. A possible cycling regime for low earth orbit (LEO) requires the battery to partially discharge in approximately 30 minutes and fully recharge in 60 minutes. This cycle will be repeated 16 times in a 24 hour day and 5840 times a year. By moving to higher orbits, the number of cycles decreases due to a lessening in the frequency of eclipse periods. When geosynchronous earth orbit (GEO) is reached, the eclipse periods occur only during two 45 day periods per year. Discharge times in this orbit vary from 12 - 72 minutes during each eclipse period, which results in a total battery discharge requirement of 90 cycles a year.

Apparent from the characteristics of the various orbits is the significant decrease in required cycles as the orbit moves from low altitude to high altitude. LEO is much more demanding in terms of the frequency of cycles required from a battery than is GEO. As a result, calendar lives of batteries in the lower orbits are shorter than those in higher orbits. Average lifetimes of nickel-cadmium batteries in LEO run 3-5 years, while lifetimes in GEO average 7-10 years. Nickel-hydrogen batteries are expected to last longer on the average, but still are life-limited by the same nickel electrode used in nickel-cadmium batteries.

The sodium-sulfur battery is different in that both the anode and cathode are liquids instead of solids (Figure 2). As such, they do not experience the fatigue and degradation problems associated with the continuous cycling of solid electrodes. Conceivably, the sodium and sulfur could continue to cycle forever in an ideal cell. The life limiting factor in this case is not the electrode, but the solid ceramic electrolyte and the cathode container. Shaped in the form of a tube, the electrolyte serves as both an ion conductor and a separator in the cell. The cells commonly fail by breakage of the tube resulting from flaws in the ceramic. This allows the sodium and sulfur to mix, causing irreversible failure of the cell. Restriction of the flow of sodium available for reaction is necessary to prevent the occurrence of a large temperature increase when the liquid sodium contacts the liquid sulfur through the crack in the electrolyte. The current Air Force cell design, based upon the Ford Aerospace terrestrial cell, uses a stainless steel protection tube equipped with a restrictive device to limit the sodium flow from the anode compartment. In the event of electrolyte failure, the amount of sodium from the reservoir able to react with the sulfur is limited by the flow rate through the restrictive device.

Corrosion of the cathode container is the other factor presently limiting cell lifetime. Terrestrial cells use chromium coated stainless steel to contain the sulfur/sodium polysulfide catholyte and transport the current. Sodium polysulfides slowly react with the chromium to form corrosion products which deposit on the electrolyte surface (Figure 3). These harmful deposits appear to contribute to cell resistance rise over the life of a cell. Evidence also exists for the corrosion of the electrolyte by the sodium chromium polysulfides, possibly resulting in strength degradation of the tube's wall.[1]

Still, substantial reduction in flaw sizes in the ceramic electrolyte and the use of corrosion resistant container materials will be necessary before sodium-sulfur cells are ready for space. Development of the components for terrestrial cells has been driven by the need for relatively inexpensive starting materials and low cost fabrication methods. Commercialization goals for terrestrial sodium-sulfur technology set energy storage costs of the battery at between $50 and $100 per kilowatt-hour. Compare these values with the average $50,000 per kilowatt-hour cost for a spacecraft battery and one can see a great deal of improvement can be made. Higher quality starting materials, better fabrication techniques, and higher quality assurance standards will improve the lifetimes of the cell components. Goals of 30,000 cycles and 10 years life should be achievable through advancements in research by the year 2000.

A second factor to consider in regard to spacecraft batteries is efficiency. Efficiency is the amount of energy withdrawn from the battery during discharge divided by the amount of charging energy put into the battery during one typical electrical cycle. The energy storage efficiency directly affects the power level of the accompanying solar array. Increased efficiency of the energy storage system equates to more efficient use of solar array power and a subsequent reduction in the size of the solar array. Efficiency is important in all orbits, but is especially critical in the low altitude orbits where the recharge time is short. Short recharge times imply high solar array power and high battery efficiency can reduce the size of these large solar arrays. Improved energy storage efficiency decreases the energy losses during this stage and results in better utilization of solar array power, as well as reduced thermal management requirements to radiate waste heat. Both nickel-cadmium and nickel-hydrogen batteries have efficiencies of 75%, while sodium-sulfur is 85-90% efficient.

The advantage of switching to more efficient batteries is decreased solar array size, resulting in a weight reduction of up to 10%. A decreased solar array size benefits not only the increased weight allocable to the payload, but also results in reduced drag, smaller radar signature and reduced altitude maintenance propellant requirements. The magnitude of these individual benefits is small, but it becomes significant when they are combined.

A third major factor for spacecraft batteries is the trade-off between power and weight. Missions outlined in the Military Space

[1] J.A. Smaga and J.E. Battles, "Post-Test Examination of Na/S Cell ADA23," Private Correspondence to Air Force Wright Aeronautical Laboratories, 1985.

Systems Technology Plan (MSSTP) project power levels for future spacecraft at 50 kilowatts and above. Present spacecraft batteries supply power up to 5 kilowatts and comprise on the average about 10 - 15 percent of the total satellite weight. As spacecraft power levels rise and spacecraft weights approach the payload limits of boosters and orbital transfer vehicle capabilities, the allowable battery weight will place limits on the power available to the spacecraft (Figure 4). The percentage of spacecraft weight occupied by batteries is determined not only by battery technology, but by the technology of the other subsystems. This percentage can be reduced by improving battery technology through the development of more advanced systems. Increases in the percentage of satellite weight allocated to the batteries at this time must come at the cost of either reduced capabilities of other subsystems or improved technologies in those subsystems or the payload. For spacecraft using advanced nickel-hydrogen batteries, power in mid-altitude orbits will be limited to about 12 kilowatts using the Inertial Upper Stage (IUS) and 22 kilowatts using the High Energy Upper Stage (HEUS). In geosynchronous orbit the power drops to 7 kilowatts with the IUS and 14 kilowatts with the HEUS. When requirements for hardening and autonomy of the entire spacecraft are considered, the available power levels will be reduced further.

In order to achieve the power levels required by the MSSTP and overcome the adverse weight effects of hardening and autonomy, the sodium-sulfur battery must be developed. Present nickel-hydrogen batteries supply approximately 20 watt-hours (Wh) of energy per pound of battery weight in GEO and less than 10 Wh/lb in LEO. Further improvements in nickel-hydrogen will yield only modest increases in these energy density values.

A significant improvement in the energy density can be made through the development of sodium-sulfur batteries. Separate studies performed by AFWAL, Hughes Aircraft and Ford Aerospace predict the energy density of the sodium-sulfur battery to be 50 Wh/lb in GEO and 35 Wh/lb in LEO. These predictions represent over a two-fold increase in energy density when compared to nickel-hydrogen. For GEO using sodium-sulfur batteries with the HEUS, 50 kilowatt power levels will be attainable. This value assumes the battery will still comprise only about 15% of the total satellite weight.

Part of this reduction in weight can be realized when considering the thermal management system of a battery. Hughes Aircraft performed a system design of a mid-altitude orbit radar satellite. The system design called for a 50 kilowatt, 47 kilowatt-hour rechargeable battery. Radiators were sized for both a nickel-hydrogen and a sodium-sulfur battery. Results showed the nickel-hydrogen's radiator having a total area of 490 ft^2 while the radiator for sodium-sulfur was 47 ft^2 (Figure 5). The large disparity is the result of the different operating temperatures of the two batteries. Nickel-hydrogen's low operating temperature (10-20°C) requires a large radiator to dissipate waste heat. Sodium-sulfur, on the other hand, can discharge its waste heat through a smaller radiator at the battery's operating temperature of 350°C. Reductions in size and complexity would yield a highly reliable thermal management system with greater survivability from future threats in space.

Other lesser factors also deserve consideration when comparing characteristics of spacecraft batteries. Depth-of-discharge (DOD) is expressed as a percentage of the rated energy capacity removed from a battery in a single discharge. Depending on orbit and desired lifetime, nickel-cadmium DOD is limited to about 25% in the lower orbits, while at GEO the value can increase to 60%. The reason for utilizing only a fraction of the rated capacity is to extend the battery's lifetime. Greater than recommended depth-of-discharge results in declining battery performance and premature failure. Advances in nickel-cadmium and nickel-hydrogen batteries may extend DOD to 40% in LEO and 80% in GEO.

Sodium-sulfur cells again will make an improvement over nickel-hydrogen and nickel-cadmium. Cells on test in simulated mid-altitude orbit (MAO) and GEO at the Aero Propulsion Laboratory have been discharged to 80% DOD with no apparent adverse effect on lifetime. The deeper discharge would be a more effective use of available energy for low altitude orbit mission, but consideration will have to be given to the end of life requirements for battery capacity in determining the system's optimum DOD. Since a final cell design has not been selected at this time, performance degradation with time is unknown.

The problem of self-discharge by spacecraft batteries on open circuit will also be eliminated by the use of sodium-sulfur. Charging systems on present satellites are required to perform trickle charging to maintain the batteries at full capacity and account for small differences in charging efficiencies. Also, complicated individual cell controls are required. Sodium-sulfur is unlike present spacecraft batteries in that no self-discharge occurs while it is an open circuit, as Faradaic efficiency is 100%. Transport of sodium ions through the ceramic electrolyte can happen only when a load is placed on the system. Once a battery is charged to a predetermined voltage limit, the capacity will be retained until energy is required.

Problems, however, do exist with the sodium-sulfur battery in its present state. Sufficient lifetime and reliability of the cell for GEO and MAO are questionable. Cells on test at AFWAL have demonstrated the necessary cycle lifes for GEO and are approaching those needed for MAO (Figure 6). Nonetheless, the calendar life goal of 10 years is yet to be attained and will not be known for several years. Cell reliability is also unacceptable due to the percentage (less than 10%) of cell failures still occurring within the first 200 cycles. The keys to solving this particular problem will be improvement of the quality of ceramic electrolyte tubes and cathode containers used in the design.

In the area of battery design, several other problems must be solved before use in spacecraft can begin. Design of the thermal management system will require a lightweight battery container capable of isolating the battery's heat from the rest of the spacecraft. During discharge the battery generates more heat than it requires to remain at the operating temperature. Radiation of excess heat at 350°C could be a significant problem for the spacecraft's delicate instrumentation if the heat is not directed outwards into space. At the same time, sufficient insulation must be used to keep the battery at its operating temperature. Operation of the battery below this temperature would result in decreased efficiency and possible damage to the cells. Internal heaters in batteries for GEO will have to be used to maintain temperature during solstice periods.

Advancements in high temperature cell bypass technology is also necessary for the development of the sodium-sulfur battery. The diodes and relays used for cell bypass in nickel-cadmium and nickel-hydrogen are designed to function in these batteries' operating temperature range of 10-20°C. Placement of the bypass electronics external to the sodium-sulfur battery would result in large thermal losses through the connections to the container. New technology will be needed to withstand the rigors of a 350°C environment with the same reliability as before.

The sodium-sulfur battery is a developing technology with a tremendous potential to expand Air Force operational capabilities in space. This paper has discussed its benefits over existing technology, as well as the genuine need for it in the future. Sodium-sulfur is not just an enhancing technology like nickel-hydrogen, it is an enabling technology which is required for the performance of future high power space missions. Development of the technology must begin now in order for it to be available by the mid 1990's. Several issues concerning the system still must be addressed and technology problems solved before it will be ready for space use. Nonetheless, the advantages this system offers when compared to batteries we have now are so attractive and essential that we cannot afford to delay development any further. Space power is a key enabling technology in the accomplishment of the total space mission. Neglect of it would undoubtedly result in our failure to achieve important future mission objectives in space.

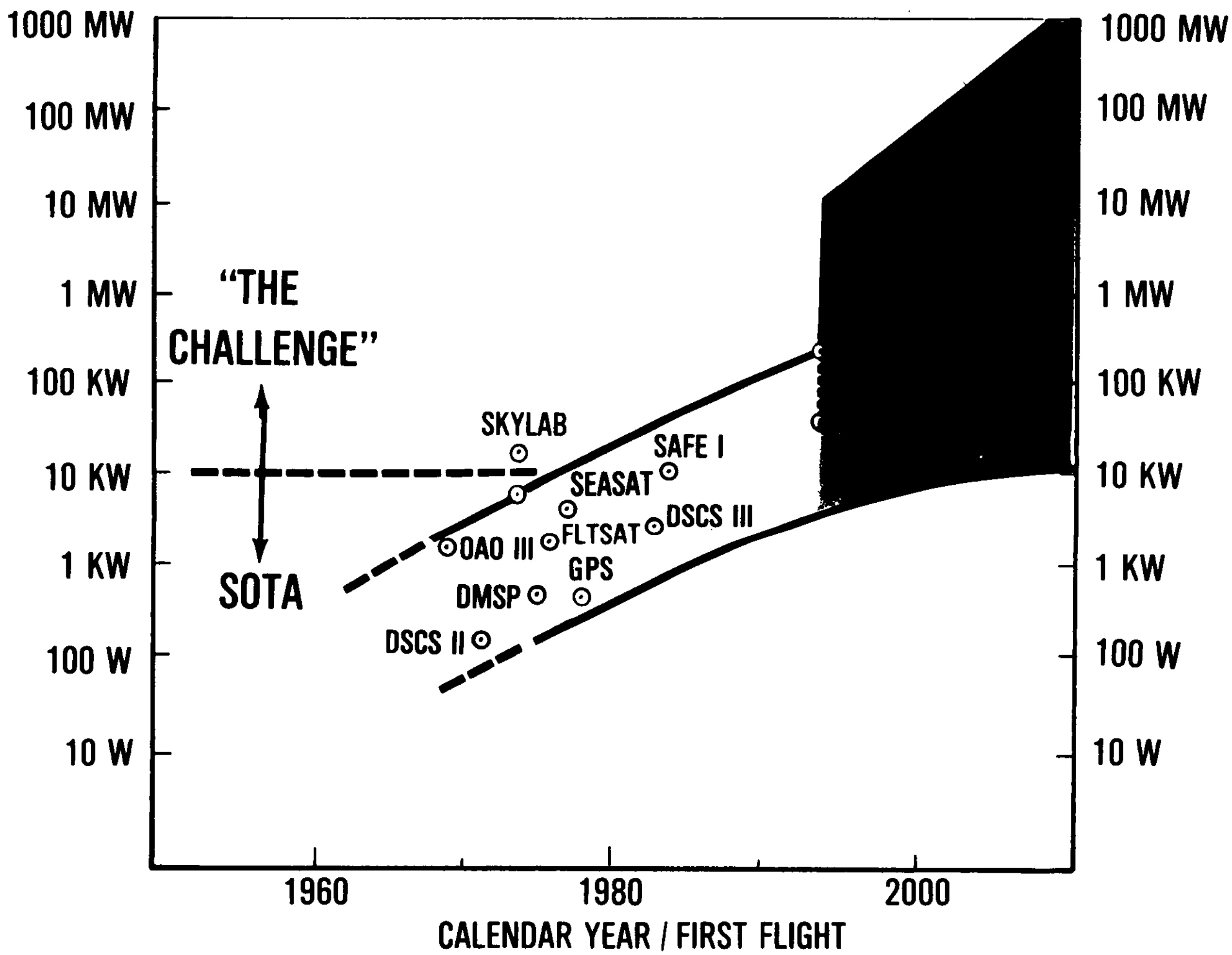

Figure 1. ELECTRICAL POWER TRENDS SPACECRAFT

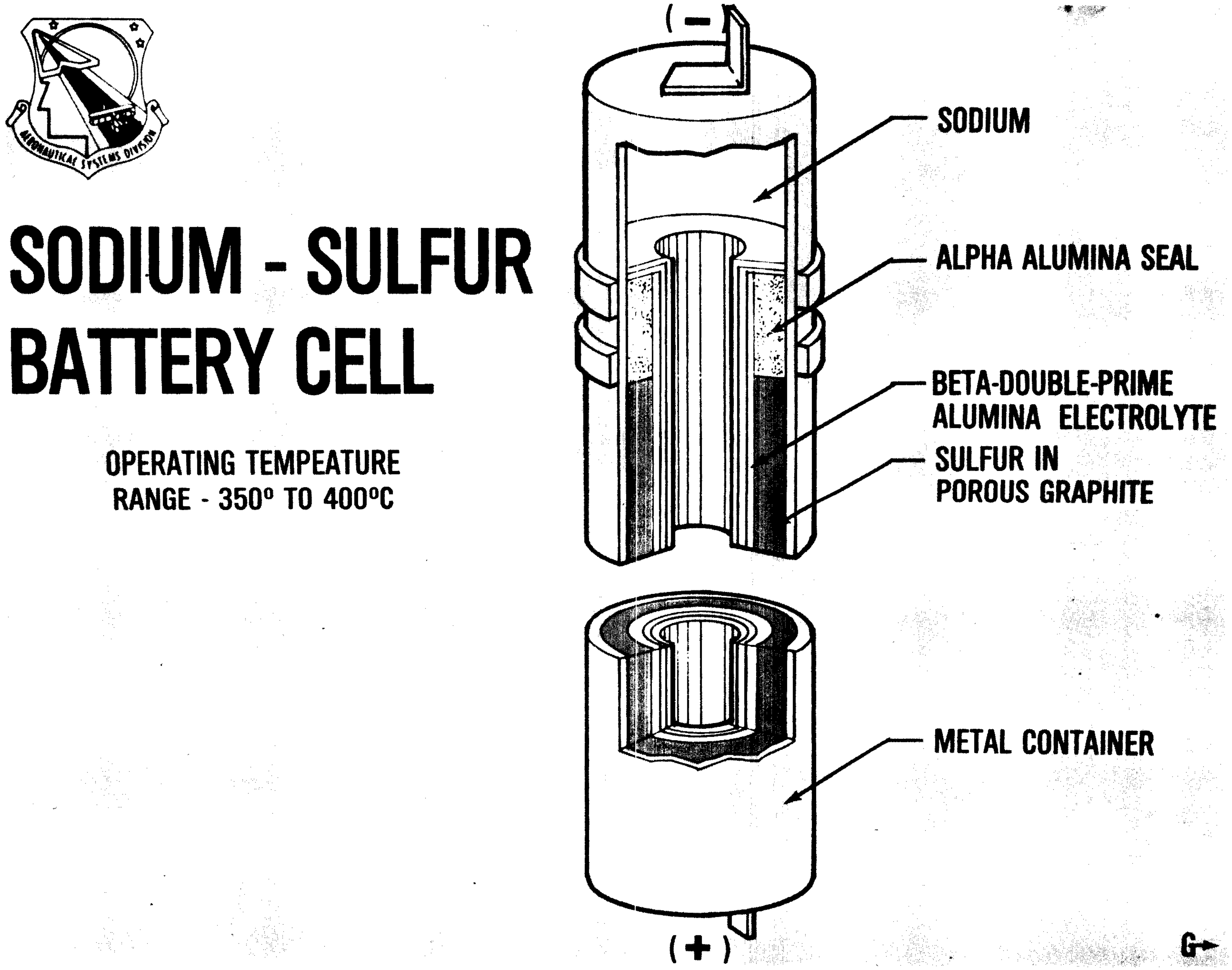

Figure 2. SODIUM—SULFUR BATTERY CELL

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Figure 3. $NaCrS_2$ CRYSTALS ATTACHED TO THE ELECTROLYTE SURFACE

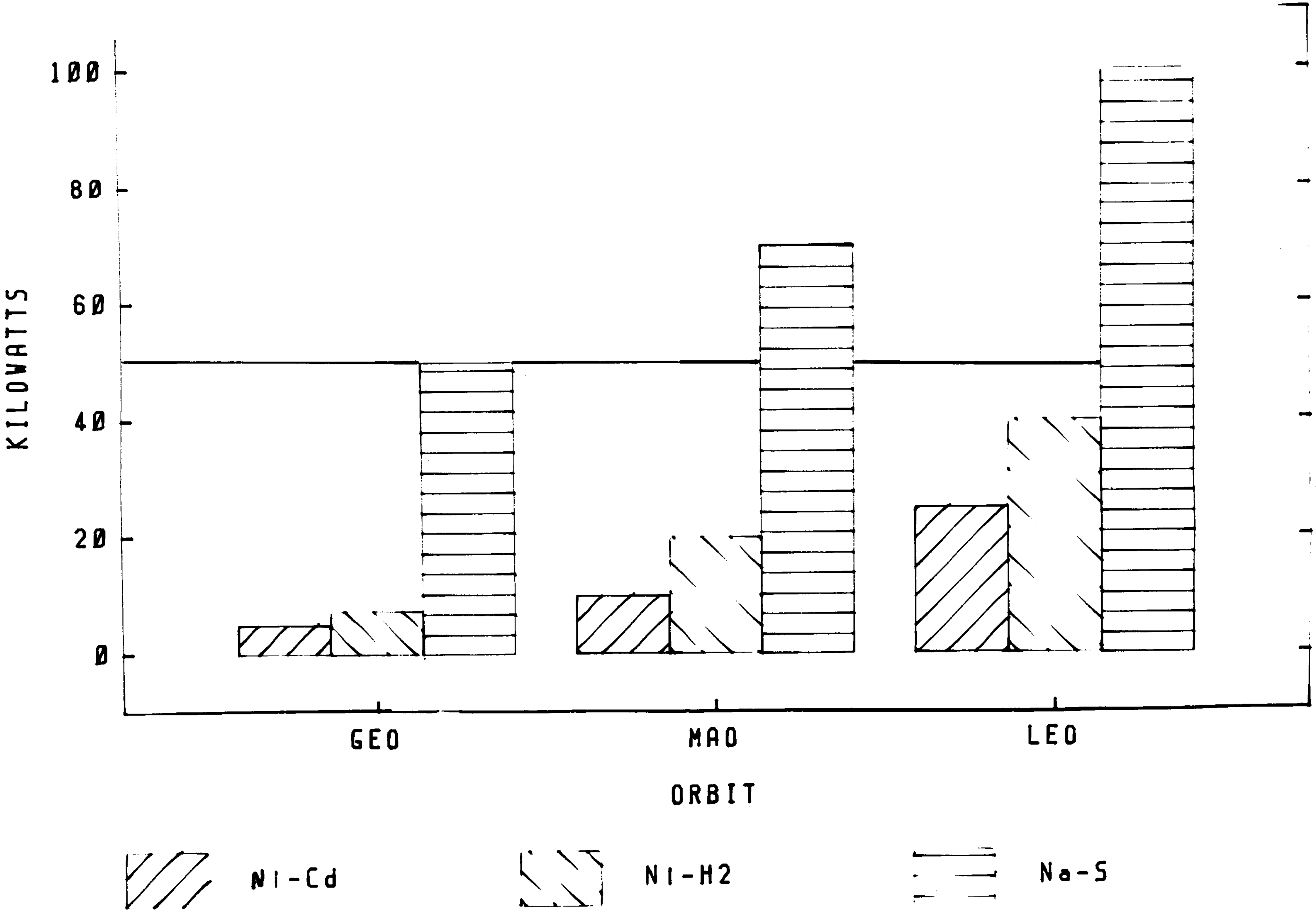

Figure 4. ELECTRICAL POWER SYSTEM OUTPUT CAPABILITY (SHUTTLE-HEUS)

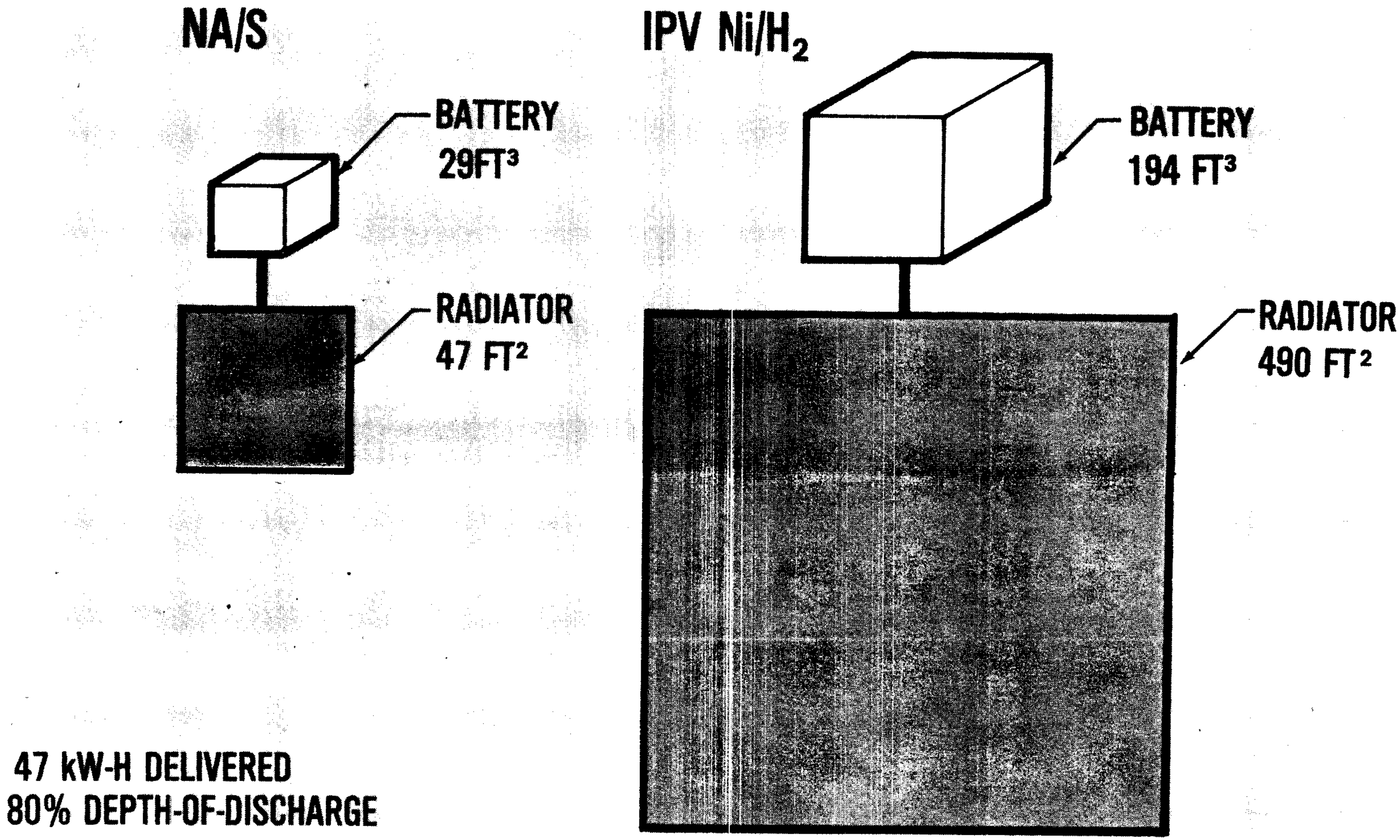

Figure 5. BATTERY SYSTEM SIZE

CELL	CYCLES	DAYS ON TEST
1	2204	601
2	3055	829
*3	2350	650
4	3055	829
5	5407	737
**6	3364	557
7	775	829
8	683	737

* FAILED 25 DECEMBER 1984
** FAILED 4 APRIL 1985

Figure 6. CYCLE LIFE DATA (AS OF 1 OCTOBER 1985)