BATTERIES FOR DIRECT BROADCASTING SATELLITES

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NADIAN ASTRONAUTICS LIMITED

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TABLE OF CONTENTS

TABLE OF CONTENTS

TABLE OF CONTENTS

LIST OF FIGURES

TABLE OF CONTENTS

Section **Title** **Page**

LIST OF TABLES

APPENDICES

1 SCOPE

This report describes the results of a study of the battery requirements for a possible Canadian Direct Broadcasting Satellite (DBS). The study was conducted by Canadian Astronautics Limited (CAL) according to a Department of Communications Statement of Work, which in abridged form was as follows:

- Assemble data on the design, performance, operational constraints and cost of spacecraft batteries assuming a 1985-1995 launch date.
- Conduct a critical assessment of both Nickel-Cadmium and Nickel-Hydrogen battery systems.
- Perform an analysis of the inter-relationships between the following parameters, assuming eclipse loads between 500 W and 5 kW:
    - Ampere-hour capacity of the battery
    - Mass and volume (including mounting hardware)
    - Rate of charge
    - Depth of discharge
    - Operating temperature range
    - Battery and bus voltage
    - Estimated cost
    - Predicted reliability (based on a life requirement of eight to nine years).

- Evaluate the importance of various battery management concepts and calculate the mass, volume, cost and reliability of systems based on each concept.

- Visit such manufacturers, agencies and laboratories as are deemed necessary to obtain information required for the study.

- Critically assess, with consultant assistance, the electrical, electrochemical and thermal parameters that must be considered in optimizing a satellite battery system.

- Prepare and submit a report summarizing the findings of the study.

For the puposes of the study, the DBS was assumed to be either a 3-axis or spin-stabilized spacecraft in geosynchronous earth orbit (GEO). Although the inter-relationship and constraints between the batteries and the spacecraft power system are covered in the study, no attempt has been made to match the batteries to a particular power system.

2 INTRODUCTION

2.1 OVERVIEW OF THE DBS BATTERY APPLICATION

Although a Canadian DBS has yet to be designed or built, its configuration, especially in regard to the batteries and power system, can be expected to be similar to that of a large communications satellite, of which more than 10 have already been launched. Thus the experience gained both in the U.S.A. and Europe in the design, manufacture and operation of communications satellite batteries is directly applicable to a DBS. The power levels of presently operating communications satellite and those to be launched in the next few years are at the low end of the projected levels (500 W to 5 kW) at which a DBS might operate, but useful extrapolations can be made; although as shown later in this report, power levels (during eclipse) of greater than 3 kW are not realistically achievable with present day or projected battery technology. Figure 1 is a plot of power levels against launch date for several typical state-of-the-art communications satellites, and shows the continuing trend toward higher powers.

The prime requirement for batteries on board a DBS is to provide power during the periods the spacecraft (S/C) is in eclipse and the solar arrays supply no power.

The load on the batteries during eclipse is the sum of the S/C housekeeping loads required in eclipse and the payload (broadcasting equipment) load. The housekeeping load is in the order of a few hundred watts, but the payload load will be much higher (equal to the normal sunlit power if service is not to be interrupted). For the study, total loads of from 500 W to 5 kW were used.

There are two seasons each year when the sunline to the S/C is obscured by the earth for a short period each day at midnight (S/C time). These seasons are centred on the spring and autumn equinox dates and last for 45 days each. The eclipse duration varies from a few minutes to 72 minutes maximum at the mid-point of the season (see Figure 2). As long as the battery system can supply the total load throughout the longest eclipse, then it will meet the load demands for all other eclipses and for other periods in the mission (launch, eclipses during transfer orbit, array deployment and sun-moon eclipses) when the S/C requires battery power.

Even though the eclipse period is short compared to the period in which the S/C is in sunlight, the batteries required to maintain full service are a substantial proportion of the S/C on-orbit mass. For present day S/C, which have eclipse load requirements of 500 W to 1 kW, the batteries form approximately 6% of the S/C on-orbit mass. This percentage is high enough to make the batteries a critical item in the spacecraft design. The design problems is more acute in projected S/C with higher power levels and lifetime requirements, since present and projected propulsion systems have limited capabilities for injecting mass into synchronous orbit.

The S/C batteries are a substantial proportion of the S/C mass for two main reasons:

1) At present the only qualified battery type for this application is based the Nickel-Cadmium electrochemical system, which is used in all existing communications satellites. The maximum energy density attainable from this system is limited.

2) The Ni-Cd system is subject to several degradation and failure mechanisms that are dependent both on the age and the amount of use of the battery. Because of this, batteries have to be designed with significant initial over-capacity (typically 100%) and practical energy densities of only about 17.6 W.h/kg are realized.

Another problem with Ni-Cd batteries is that the degradation and failure mechanisms are still imperfectly understood and flight experience is limited to on-orbit battery lifetimes of about seven years.

Although improvements can be expected in Ni-Cd batteries they will not be substantial.

Other battery systems have been studied for GEO S/C applications. Of these, only the Nickel-Hydrogen (Ni-H_2) System has any immediate promise, and several communications satellites (e.g., INTELSAT V flights 5 through 9) with Ni-H_2 systems are soon to be launched. Practical energy densities of 39 W.h/kg are expected to be achieved. Even though this is an improvement over Ni-Cd systems, it is not great enough to make the battery design task much easier. Also, as the technology is new and flight experience very limited compared to Ni-Cd systems, which have been used since the 1960s, there is some uncertainty over the long-term performance of Ni-H_2 cells. Nevertheless, the absence of identifiable degradation processes gives good grounds for optimism concerning their long-term lifetime expectation.

A DBS application will have to use batteries to the limits of their capabilities, and the battery system must be optimized to meet tight mass and reliability requirements. Later sections of this report will show the effect of various design and operational parameters on the battery system and the performance (i.e., primarily energy density) that may be achieved.

2.2 CONDUCT OF THE STUDY

The study activity can be divided into four main areas:

1) Literature Search

Although CAL has a considerable amount of battery related literature from its involvement in other S/C battery related programs, it was considered worthwhile to use the NRC/CISTI literature search service to obtain further citations. Approximately 270 citations on Ni-Cd and Metal-Hydrogen batteries and S/C power systems were received, and copies were obtained of those articles that were pertinent to this study and not already in-house. Over 50 references are now available at CAL. Most of these are listed in Appendix A.

It is evident that there are three major sources of information on S/C battery systems:

a) NASA Battery Applications Manuals. These give good general information on all types of cells and their application to GEO and Low Earth Orbit (LEO) S/C.

b) Proceedings of the Intersociety Energy Conversion Engineering Conferences. These give good data on S/C battery and power systems design and performance.

c) Proceedings of the NASA-Goddard Space Flight Center (GSFC) Battery Workshops. These, to some extent, parallel the IECEC papers (often the same paper is presented at both conferences), but there is more emphasis on cell design and testing. The most current data is presented at the workshops, but unfortunately the proceedings are not published until several months later.

2) Visits

During the course of the study, CAL personnel attended the 1980 GSFC Battery Workshop, a presentation at DREO by SAFT on Ni-H_2 and Silver-Hydrogen cells, and visited the following battery manufacturing and user organizations:

- Eagle Picher Inc., Joplin Mo.
- Ford Aerospace, Palo Alto, Ca.
- Hughes Aerospace, El Segundo, Ca.
- TRW Inc., Redondo Beach, Ca.

Trip Reports from these visits are included in this report as

Appendix B. Also included in Appendix B is a trip report for the 1980 IECEC, which was attended in the course of another CAL program.

3) Review and Analysis

The data obtained from the literature search and visits was reviewed and analyzed as was necessary to complete the study. During this phase a computer model of a spacecraft battery system was developed and used to predict battery performance as affected by varying parameters. Section 4 of this report contains a detailed description of this computer model.

As the internal properties of the cell are an important factor in the overall battery performance, and as CAL does not have extensive experience in this area, consultant advice was obtained from Dr. T. E. King, who was formerly Head of Power Systems at DREO and who is still active in the battery field.

4) Final Report

The final phase of the program was to prepare this final report.

2.3 OBSERVATIONS

Several factors became apparent during the course of the study, particularly in regard to Ni-Cd systems. These are:

- There are significant differences between Low Earth Orbit (LEO) and Geosynchronous Earth Orbit (GEO) applications.
- Performance of a battery (or cell) is heavily dependent on its previous treatment (i.e., depth and number of discharge cycles, storage temperature, etc.)
- There are few firm guidelines or design formulae for designing S/C battery systems.

- Although there is a great deal of published data, differences in cell construction and applications render accurate comparisons difficult.

- Some advice and experience is contradictory.

- Cell manufacturers do little research and development and therefore S/C contractors and their customers heavily influence the cell design. Each contractor and customer has his own preferences, and thus there are currently several different cell designs and operating practices.

In view of the above, the approach taken throughout the study was to concentrate on recent flight experience and on published data on modern cell and battery designs.

2.4 ACKNOWLEDGEMENTS

Several persons from other organizations assisted CAL in the course of this study by discussion, advice, and assistance in arranging and participation in visits. The assistance of the following is therefore hereby acknowledged:

Dr. M. Bouchard	CRC
Mr. J. Lackner	DREO
Dr. T. King	Consultant
Mr. G.H.C. Mackie	CRC

2.5 LIST OF ACRONYMS

DBS	Direct Broadcasting Satellite
GEO	Geosynchronous Earth Orbit
S/C	Spacecraft
LEO	Low Earth Orbit
IUS	Inertial Upper Stage
DET	Direct Energy Transfer
BDR	Battery Discharge Regulator
DOD	Depth of Discharge
EOD	End of Discharge
SOC	State of Charge
IOTV	Interim Orbital Transfer Vehicle
CPV	Common Pressure Vessel

3 OVERALL CONCLUSIONS

The major conclusions of the study are listed below. More details of each conclusion and supporting material will be found in later sections of this repoort.

1) The S/C power system configuration has neglible effect on the type or size of battery used. (Reference Section 4.)

2) Battery mass considertions limit the continuous power that can be supplied during eclipse to about 1.5 kW if Ni-Cd batteries are used, and to about 3 kW for Ni-H_2 batteries, assuming a shuttle IUS launch vehicle. (See Figure 3).

3) Ni-Cd cells are a feasible choice for eclipse power demands up to about 1 kW. They are simpler to package but require careful handling to meet a 8-9 year on-orbit life requirement.

4) Careful handling of a Ni-Cd cell involves:

- Choice of cell construction
- Proper pre-launch treatment
- Low temperature operation
- Continuous trickle charge during non-eclipse periods
- Periodic deep reconditioning (i.e., periodic controlled complete discharge).

5) A design limit of 50% (for Ni-Cd cells) should be used as the depth of discharge for the maximum eclipse period.

6) A long-life Ni-Cd cell should be constructed from:

- Electrochemically impregnated positive electrodes, without PQ treatment
- Teflonated negative electrodes

- Polypropelene separators (Nylon is acceptable)
- Electrolyte without Lithium Hydroxide additive.

7) General Electric is the best source of Ni-Cd cells.

8) $Ni-H_2$ cells should be baselined for applications involving eclipse power demands greater than 1 kW.

9) Although there is little flight experience with $Ni-H_2$ cells, results to date are excellent and the cells have an inherent long-life capability.

10) A design limit of 70% should be used as the maximum depth of discharge for $Ni-H_2$ cells.

11) The COMSAT $Ni-H_2$ cell design is optimum for DBS applications. COMSAT, Yardney and Eagle Picher should be considered as suppliers. Development of SAFT cells should be monitored, but at the moment they are a year or so behind North American suppliers.

12) Silver-Hydrogen cells have a significantly greater energy density than Ni-Cd or $Ni-H_2$ cells, but are not sufficiently developed for S/C use at present. Developments in this area should be closely monitored.

13) Battery management systems will extend useful battery life in long-term missions.

14) Battery (particularly cell) technology is still evolving and should be continually monitored.

15) The performance over the next few years of communications satellite that are presently in service (especially RCA SATCOM and NTS-2) will yield valuable data on the reliable long-term (greater than 5 years) performance of Ni-Cd and $Ni-H_2$ systems.

16) Proper application of any battery type requires an informed customer or prime contractor.

17) A computer model is available at CAL that can accurately predict the performance of a S/C battery, including effects due to age and reconditioning.

4 SPACECRAFT POWER SYSTEMS

4.1 CURRENT DESIGNS

A S/C power system must in general perform the following functions:

- Transfer power from the solar array to the S/C loads when the array is sunlit.
- Transfer power from the batteries to the loads when the S/C is in eclipse.
- Recharge the batteries after eclipses.
- Condition (i.e., voltage regulate) array and battery power as it is being transferred.

Unconditioned array and battery voltages can vary over a 2:1 range while loads generally require voltage regulation in the 1% range. Also, to be charged, the batteries require a voltage greater than they provide when open-circuited or discharging.

Most modern communications satellites use a variant of the Direct Energy Transfer (DET) system to fulfil the above requirements. Three such variants are:

a) INTELSAT V, (Figure 4)[78-1].

b) TDRSS, (Figure 5)[78-3].

c) DSCS-III, (Figure 6)[78-2].

Note: The figures in this report are very much simplified, full details of these systems can be found in the cited references.

The choice of power system configuration has little effect on the battery requirements. For example, if a regulated bus is used, then there are power losses in the Battery Discharge Regulator (BDR); but if an unregulated bus is used, there are similar losses in the additional power conditioning associated with the loads to accomodate a wide input voltage variation. Similarly, there is little to choose between dedicated charge arrays and charge controllers. The charge currents produced and mass requirements are similar.

For the purposes of this study, the DET power system configuration described below has been chosen.

A shunt controlled array feeds into a regulated bus, which supplies the spacecraft load. During eclipse, a set of batteries feeds the bus through a boost regulator. In sunlight, the batteries are charged from the regulater bus via a buck charge controller. Figure 7 shows this configuration, and specific details are given in the following Section which describes the computer model.

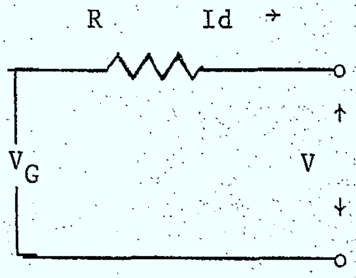
The bus voltage was chosen to be 50 V, as this value will likely be commonly used in the next generation of communications satellites. (This value has been chosen for L-SAT.)

4.2 COMPUTER SIMULATION

The simulation programs used to provide some of the information in this report were based on the model of a Ni-Cd battery developed by COMSAT Laboratories and presented in the paper "LONG-TERM PREDICTION OF POWER SYSTEM PERFORMANCE FOR GEOSYNCHRONOUS SPACECRAFT" by W. J. Billerbeck.[79-9]

It has been found that Ni-Cd batteries used in geosynchronous spacecraft do not fail in any catastrophic manner but generally degrade in performance as they age. Data collected from approximately seventy orbit years of geosynchronous battery operation have pointed to a number of factors that significantly affect battery performance.

A model and equations developed from the above data are given below.



$$V = V_G + V_T - Id.R$$

$$V_G = 1.3597 - 0.83986\ DOD + 3.6972\ DOD^2 - 8.6476\ DOD^3 + 9.8953\ DOD^4 - 4.4239\ DOD^5$$

$$V_T = 0.00072\ (T_C - 32.2) \quad (T_C \text{ in } °C)$$

$$R = R_0 + kR_F\ t^2 \quad (t \text{ in years})$$

Simple circuit analysis shows that the output voltage depends on a number of factors. The generated voltage of the battery (V_G) is a function of the extent to which the battery has been depleted, or Depth of Discharge (DOD). It is a fifth order polynomial representing the characteristics apparent in past performance. A simple linear temperature correction factor, V_T, incorporates the end of discharge temperature measured in degrees Celsius.

The resistor in the model has two components. One is constant and can be said to equal the initial internal resistance of the battery. The other varies with cell age and past use. It has been found that the effects of age on a battery can be minimized if it is drained and recharged when not in use. This procedure, termed reconditioning, is incorporated into the second resistive component as a factor, R_F, based on empirical data. The effect of reconditioning on the battery increases with the depth to which the battery is drained during the reconditioning cycle. The reconditioning factor for a discharge of 1.0 V per cell was taken from Figure 5 of the Billerbeck paper to be 0.37. A factor of 0.13 was calculated for a 0 V per cell reconditioning discharge by matching the discharge data from the SATCOM S/C, which are reconditioned to that level.

Figure 7 shows the system model composed of the battery, a battery discharge regulator (BDR), the load, and resistances to simulate wiring losses.

To facilitate comparison with INTELSAT IV data, the battery was usually modelled as containing 28 cells with variable characteristics as previously described.

The BDR model assumes a constant 98.5% efficiency to reflect inductor losses, together with battery and bus voltage dependent factors to reflect switching losses.

Line voltage drops are taken into account by resistors that are set to give approximately constant voltage drops of 0.5 V (BDR to load) and 0.2 V (battery to BDR) as these are the values to which S/C harnesses are typically designed. Total losses, BDR and wiring, usually turn out to be about 10% when the program is run.

The heart of the program is the generation of the battery voltage during a 72 minute discharge. Such a run is shown in Figure 9 which simulates both a constant current (to compare with INTELSAT IV data) and a constant power curve (to be compatible with the study requirements).

This basic program has been expanded into several iterative configurations, up to five nested loops, to provide data for this report. For example, Figure 10 shows curves that are based on repetitions of Figure 9 for increasing cell age.

4.3 SIMULATION RESULTS

1) Constant Current versus Constant Power Loads

Figures 9 and 10 show that a constant power load is a more severe load on the battery than a constant current. Although with a constant power load the initial discharge current is lower, the fall in battery voltage causes the current to increase sharply near the end of the discharge, producing a substantially lower end-of-discharge (EOD) voltage. The final depth of discharge (DOD) is about the same in the two cases, but it is decreasing at a faster rate at the discharge end in the constant power case.

2) Effect of Cell Age

Figure 10 also shows the effect of the cell aging factor. This becomes quite significant after about 5 years.

3) Bus Voltage

It is clear from Figure 11 that the bus voltage has little effect on battery sizing. (The curve shows the initial battery capacity required to give a 50% DOD with a fixed load and varying bus voltage.) The reasons for this are that the BDR efficiency is not strongly dependent on either bus or battery voltage and because wiring is sized to meet voltage drop requirements. It should be noted, however, that increasing bus voltages can substantially reduce wiring mass.

4) Temperature

The cell model has a EOD discharge temperature term in the equivalent cell resistance. The effect of this is small (see Figure 12) and reflects the effect of temperature on the discharge curve. Lower temperatures increase the (negative) slope of the curve and lead to lower EOD voltages for a given

DOD[79-2]. It should be noted, however, that lower temperatures lead to increased usable capacity from the cell, which will lead to lower DODs and compensate for the effect that has been modelled. Future versions of the simulation should account for both effects.

5) Reconditioning

The simulation clearly shows the dramatic effects of deep reconditioning (see also Section 5.6). Figure 13 shows discharge curves for three cell ages with reconditioning to 1.0 and 0 V per cell, showing that a 10 year old cell with 0 V reconditioning is in far better shape than a 5 year old cell that has been reconditioned to 1.0 V only. (Reconditioning is assumed to be performed prior to each eclipse season.) Figure 14 shows the initial cell capacity required to maintain a 50% DOD at EOD for three reconditiioning regimes. For a 9-year lifetime, more than 50% extra initial capacity is required if no reconditioning is performed, 13% for reconditioning to 1.0 V and only 3% if reconditioning is carried out to 0 V per cell.

6) Conclusion

The computer simulation is a flexible, easy to use instrument that can quantify the qualitative knowledge on battery performance obtained by reading the existing literature. When applied to an existing design it is a powerful predictive tool, and when used for study purposes it is a useful modelling aid.

5 NICKEL-CADMIUM SYSTEMS

5.1 DEFINITIONS

The following are the definitions of several terms that are used extensively in battery literature and in this report:

- Rated capacity (sometimes termed Nominal, Reference or Standard capacity). This is the manufacturer's value for the cell ampere-hour (A.h) capacity. It corresponds to the guaranteed minimum capacity available from the cell under the most adverse temperature conditions in which the cell is specified operable. The capacity is usually measured at a C/2 (see below) discharge rate.

- Measured Capacity. This is the actual capacity determined by test (e.g., during acceptance test). Measured capacity is generally measured at a C/2 discharge rate and usually is 10 to 20% greater than the Rated capacity.

- Charge and Discharge rates. These are expressed as a fraction of the normalized rate C, which is the rate equal to the cell's rated capacity (in A.h) divided by 1 hour. For example, a C/10 rate for a 20 A.h (rated) cell is 2 A.

- Depth of Discharge (DOD). Defined as the percentage of capacity that has been discharged, it is usually based on the rated capacity of the cell.

- State of Charge (SOC). The percentage of (usually Rated) capacity remaining in the cell.

- Reconditioning. This is a procedure by which the capacity of a degraded cell (or battery) may be substantially restored. The procedure essentially consists of a deep (close to 100%) discharge followed by a full recharge.

5.2 CELL DESCRIPTION

The NASA Sealed-Cell Nickel-Cadmium Battery Applications Manual[79-2] gives an excellent account of the construction and manufacture of sealed nickel-cadmium cells, and thus only a brief description will be given here so that the terminology used in this report may be readily understood.

The cell is based on the reaction:

$$2N\text{:}\ \ OOH + Cd + 2\ H_2O \underset{\text{Charge}}{\overset{\text{Discharge}}{\rightleftharpoons}} 2N\text{:}\ (OH)_2 + Cd(OH)_2$$

and consists of positive and negative electrodes between which is a porous separator holding electrolyte solution. These components are housed in a stainless steel case, as shown in Figure 15.

The electrodes (or plates) are manufactured from a porous sintered nickel plaque (the sinter is attached to a nickel grid or perforated screen for support and to conduct current to the cell terminal) that is impregnated ("loaded") with electrochemically active material (nickel hydroxide for positive plates, cadmium hydroxide for negative plates). Plates are loaded using either a chemical or an electrochemical process. The plate edges are strengthened by being stamped ("coined") before being impregnated.

Additives are generally introduced during loading of the positive plate: these are cobalt (to increase the use of the positive active material) and/or cadmium (to act as an anti-polar material). Addition of cadmium is termed the PQ treatment.

Negative plates are often coated or wrapped with teflon ("Teflonation") after impregnation. The effect of this is to reduce the wetability of the surface and hence reduce electrolyte distribution; also, migration of negative material into the separator is reduced by this process. An alternative treatment for negativea plates is the addition of a small quantity of silver.

Separators are usually manufactured from the polyamide (nylon) material Pellon 2025, although polypropelene is also used.

The electrolyte is an approximately 30% solution of KOH and normally fills approximately 85% of the cell volume. Care is taken to limit the amount of carbonate (K_2Co_3) in the solution. Lithium hydroxide (1%) may be added.

Cells are made with a ratio of negative to positive plate capacities of 1.5 to 2.0. This, together with a "precharge" that is introduced during manufacture, stabilizes initial capacity, minimizes capacity fading during cycling, and provides overcharge protection.

5.3 EFFECTS OF OVERCHARGE AND OVERDISCHARGE

It is important that the cell be fully charged following each discharge period and for this reason it is normal to overcharge the cell to about 105-110% of its actual capacity. Continued overcharge must be avoided, however, for three principal reasons:

1. Internal cell pressure increases because of internal oxygen evolution. The final cell pressure is a function of internal cell parameters such as the electrolyte volume; an aerospace cell can tolerate continuous 0.1 C overcharge.

2. All electrical energy going into the cell is dissipated as heat.

3. Continued overcharge has been shown to be a significant factor in cell deterioration[80-13].

The effects of overdischarge (cell reversal) are even more serious. The H_2 generated can increase cell pressure until the case ruptures.

Rupture is a possibility unless the rate is very low (around C/100) or the cell voltage is held below 0.2 V[79-2].

5.4 FAILURE MECHANISMS

The major identified failure mechanisms in Ni-Cd cells are:

1. Loss of Electrolyte through leakage. Earlier problems with the terminal seals have been overcome and now the only likely cause for leakage is rupture of the cell due to overpressure caused by overdischarge (cell reversal).
2. Separator degration. It is known that nylon is attacked by the electrolyte, although the reaction is slow and may not be significant until 10 years or so if the cell is kept cool (0 to 10°C). It should be noted, however, that Hughes specify polypropelene separators in cells for their S/C to avoid this known failure mode.
3. Cadmium migration. The negative electrode undergoes morphological changes during each charge/discharge cycle. After repeated cycles plate material may penetrate the separator and cause full or partial short circuits. Teflonation of the plate is said to reduce this effect.
4. Expansion of the positive electrode. As with the negative electrode, morphological changes occur as the cell is cycled. Severe swelling of the plate will drive electrolyte from the separator and produce a "high-resistance" cell. Electrochemically impregnated plates show reduced swelling compared with those that are chemically impregnated. Lowering the plate loading also reduces electrode swelling.

5.5 CELL MASS

Figure 16 summarizes the mass information available from manufacturers and in the literature. The Hughes 24 and INTELSAT V cells are current state-of-the-art cells and can be used as a basis for DBS battery mass calculations. A point to note is that current 50 A.h cells do not achieve the energy density of the INTELSAT V cells.

5.6 RECONDITIONING

5.6.1 RECONDITIONING PROCEDURES

Although the subject of much controversy in the past, reconditioning has now been accepted as an essential procedure in the operation of long-life GEO (Ni-Cd) batteries. Reconditioning is usually carried out prior to each eclipse season, but may also be performed at the end of an eclipse season or at other times when cell degradation is suspected or detected.

The basic reconditioning procedure is a deep discharge followed by a full recharge. In most S/C the discharge is implemented by switching a resistive load across the battery to give a discharge rate of about C/5. Although this implementation method is simple, and to a certain extent effective, it suffers from two significant disadvantages:

1. The discharge rate is too high for maximum effectiveness. TRW have demonstrated[79-11] that discharge rates of C/100 or less are required for the optimum reconditioning effect. An explanation for this effectiveness being that the degradation in performance is due to small volumes of the active plate material becoming disconnected from the bulk of the material and remaining charged and being unable to be discharged at normal rates. A slow discharge will discharge these volumes and restore their connection to the bulk of the material. At these low discharge rates most of the cell capacity is removed by the time the cell reaches 1 V, but continued discharge, even to the point of cell reversal, will not damage the cell, as the internal pressure increase is minimal at these rates. It is recommended[79-11] that about 10% more than the rated capacity of the cell must be removed

for maximum reconditioning effectiveness. This can only be achieved at low discharge rates.

2. At this rate, cell reversal must be avoided at all costs, because of the danger of rupture due to excessive pressure. Thus the discharge must be terminated when the first cell is discharged to 0 volts, and the remaining cells will then not be completely discharged. The advantage of low rates is that the discharge can be carried out on the complete battery, as cell reversal will not be damaging.

5.6.2 FLIGHT EXPERIENCE

Two major programs, INTELSAT IV[80-7] and RCA SATCOM[80-6, 76-3], have reported their flight experience, which includes reconditioning operations, extensively.

For the INTELSAT S/C, the batteries become the life limiting factor at about six years of on-orbit operation[80-7], at which time loads must be shed in order to maintain sufficient end of discharge (EOD) voltage. This is the culmination of a gradual degradation in EOD voltage that has been observed throughout the mission life of each S/C in this series.

The RCA SATCOM S/C (F1 and F2), on the other hand, have shown very little degradation in EOD voltage over the present five years of mission life, as shown in Figure , which compares the results from these two programs. A point to be noted is that the initial power performance of the SATCOM F2 was due to operational problems that resulted in the battery being insufficiently recharged. These were converted around the 7th eclipse season.

There are factors in both cell construction and S/C battery on-orbit operations that could account for these differing results. Pertinent information on the batteries in the two programs can be summarized as:

Factor	INTELSAT IV	SATCOM
Cell capacity	15 A.h rated 20 A.h actual	12 A.h rated 14 A.h actual
Manufacturer	GE	GE
Launch dates	1971 onwards	1975 onwards
Max DOD	53-57% rated 40-43% actual	54-65% rated 46-46% actual
Plate impregnation	chemical	chemical
Separator	nylon	nylon
Negative plate treatment	$Li(OH)_2$ in electrolyte	Teflonated
Electrolyte quantity	2.25 cc/A.h	2.50 cc/A.h
Solstice storage mode	open-circuit	trickle charge
Recondition EOD voltage	1 V/cell	.1 V/cell
Temperature range	2 to 17°C	0 to 15°C

Reconditioning on INTELSAT is carried out to a battery voltage that corresponds to an average of 1 V/cell (with the proviso that it is terminated if a sudden voltage drop is observed, to obviate cell reversal). On the SATCOM S/C, the reconditioning is carried out by shorting individual cells with 1 ohm resistors[76-3]. Thus, discharge starts at about C/10, dropping to C/120 by the time the discharge is terminated at 0.1 V. The discharge takes about 21 hours, being interrupted for a few hours early on to prevent temperature limits being exceeded.

The better performance of the SATCOM batteries can be attributed to:

- Reconditioning to 0.1 V/cell
- Trickle charge during storage periods (non-eclipse season)
- Increased electrolyte quantity
- Teflonated negatives, which make the increased electrolyte quantity possible.

5.6.3 CONCLUSIONS

Support for the importance of "deep" reconditioning, i.e., to close to 0 V/cell or at a low rate until the cell is almost fully discharged, is provided by the FLTSATCOM program, which uses a deep, low rate recondition, where no EOD voltage degradation has been observed after 3.5 years operation[81-2], and by TRW accelerated tests, which show no EOD degradation after more than 40 simulated eclipse seasons at 75% DOD[78-4, 81-2].

The long-term effects of deep reconditioning are still a somewhat open question. It is obvious from the SATCOM and TRW experience that its use will maintain EOD voltages for at least five years. RCA project this to nine years for SATCOM. Keeping a high EOD voltage will tend to increase cell life as DOD then remains low, with constant power loads. Nevertheless, reconditioning may have little effect on long term failure modes, such as cadmium migration, which causes cell shorts as have been observed on INTELSAT[79-11]. It has been shown[80-14] that reconditioning will only produce short-term remission in the event of cell shorts. On the other hand, it is possible that deep reconditioning may slow the formation of cadmium crystals.

In summary, deep reconditioning appears to be essential if battery lifetimes of greater than 5 or 6 years are required. Such reconditioning should extend the battery lifetime to 8 to 10 years or more, although there is as yet no direct flight experience at these lifetimes. The performance of the SATCOM's in the next few years should provide this experience and merits close attention.

Deep reconditioning is best carried out at a high rate initialy (C/10 to C/5), with the final 20% or so of capacity being withdrawn at a low rate (around C/100)[77-4].

5.7 THERMAL AND PACKAGING CONSIDERATIONS

5.7.1 THERMAL

The optimum temperature range for operation of Ni-Cd cells is 0° - 10°C. In this range factors such as charge efficiency and discharge capacity are optimum, and most importantly, long term degradation rates are low.

Heat evolution from the cell varies with the cell state of charge and the value of the charge or discharge current flowing.

During discharge, heat is evolved at 14 to 18% of the electrical output rate [79-14]. During charge, at typical (C/10) rates, the reaction is initially slightly endothermic but progresses rapidly to an exothermic region towards the end of charge. All the electrical input power is converted to heat in the overcharge region.

Thermal design and simulation techniques [77-3] are well established. Thermal coupling from individual cells is achieved by aluminum shims between them; these are in turn connected to the battery baseplate or radiating surface, which is conductively or radiatively connected to the S/C surface. Heaters, about 1 W per cell, are used for thermal control; these can be supplemented by control of the trickle charge rate.

Thermal data can be found in the NASA Application Handbook [79-2], which should be updated with the information in reference 80-12.

5.7.2 PACKAGING

Packaging is primarily governed by the thermal requirements and by the need to restrain the cell walls against the internal pressure. Cells are therefore stacked in rows with thermal shims between them and with stiffened plates connected by tie rods to apply pressure to the cell faces. Figure 18 shows a typical battery pack.

Cell protection diodes and heaters are also mounted on the pack.

About 10 to 20% of the total battery mass is required for the mounting hardware, wiring, etc. Typically 18% is used for planning purposes [79-10]. Table 1 gives data on some state-of-the art Ni-Cd batteries.

Application	INTELSAT V	TDRSS	LEASAT	NASA - MPS	NASA - MPS
Manufacturer	Ford Aerospace	TRW	Hughes	McDonnell Douglas	McDonnell Douglas
Launch date	1980 onwards	1982	1982	1980 onwards	1980 onwards
Battery data:					
Batteries per s/c	2	2	3	3 max	3 max
No of cells	28	36	32 (4x8)	22	22
Overall dimensions			30 x 13 x 16.5(pack)	34.6x19.8x24.9 cm	47.9x29.7x22.9 cm
Total mass/battery	31.59 kg	62.91 kg	8.85 kg (pack)	24.0 kg	50.8 kg
Total to cell mass ratio	1.100	1.211	1.123	1.224	1.139
	1014 kg	2000 kg			
% of s/c mass	6.23	6.29		na	na
Design life	7 yr		7 yr	7 (Geo)	7 (Geo)
Eclipse power requirement	960 W	1440 W	1047 W	250 ———	—1200 W
Design temperature range		0-5°C		0-20°C	0-20°C
Cell data					
Manufacturer	General Electric	General Electric	General Electric	General Electric	General Electric
Nominal capacity	34 A.h	40 A.h	25 A.h	20 A.h	50 A.h
Measured capacity	35-38 A.h	46.6 (min req.)		22-25 A.h	54-62 A.h
Nominal DOD	55%	50%	43%	50%	50%
Overall dimensions		6.24(5) x 3.404 x 1.314 in.			
Mass	1025.4 g	1482 g max	985 g	891	2027

Table 1 Ni-Cd Battery Data, Sheet 1 of 3

Case					
Material	304L stainless	304L			
Thickness	.30 mm (12 mil)	.48 mm (19 mil)	.38 mm (15 mil)(7)	Conventional(.48?)	(25 mil)?
Mass	80 g				
Terminals	Low profile double ceramic aluminate metal				
Positive Electrodes					
No of plates	13	16	27		
Theoretical capacity	40 ± 2 A.h				
Impregnation	Chemical		Electrochemical	Electrochemical	Electrochemical
Loading	13.7 ± .6 g/dm^2		11.4 g/dm^2		
Area Thickness	10.4 x 9.8 cm	5.4 x 3.2 in.			
Thickness	.069 cm	.026/8	.61		
Capacity density	25.7 mA.h/cm				
Treatment	ns				
Mass	767 g				

Table 1 Ni-Cd Battery Data, Sheet 2 of 3

Negative electrodes				
Negative-positive ratio	1.60:1.00		1.5:1	
No of plates	14	17	27	
Theoretical capacity	66 ± 6 A.h			
Impregnation	Chemical			
Loading	16.0 ± .6 g/dm^2		15.9 g/dm	
Area/thickness	10.4 x 9.8/.074	ns /.031	/.069	
Capacity density	ns			
Treatment	Teflonated	Silver		
Mass	767 g			
Separator				
Material	Pellon 2505		Polypropelene	
Thickness	.30 mm			
Treatment	ns			
Mass	17			
Electrolyte				
KoH	31 wt.%	31.0 ± .5 wt.%	31 wt.%	
Carbonate	≤2 g/l		Low	
Nitrate	≤1 mg/l			
Mass	117			
References	80-1 79-6	78-3 79-7	80-2 78-5	80-3

Table 1 Ni-Cd Battery Data, Sheet 3 of 3

5.8 SYSTEMS ASPECTS

Although, as has been previously discussed, the type of power system used in the S/C has little effect on the battery, there are several systems aspects that must be considered in each design.

1) Charge control. It is important that the battery be fully recharged, yet not overcharged. Some systems use temperature-dependent voltage settings to determine the point at which charging should be terminated, but a better method for DBS use is to measure the ampere-hours discharged and to replace a set percentage (around 105%). The ampere-hour integration can be done autonomously on the S/C or via telemetry to the ground, which normally is continuously available in these applications.

   Charge currents are normally in the C/20 to C/10 range as this enables charging to be complete within the 22 hour period before the next eclipse without increasing the solar array size required by too much. There may be some advantage to cell performance in charging at somewhat higher rates, e.g., C/5. There will be solar array capacity available for this at beginning of life, but the charge controller must be appropriately sized.

2) Reconditioning provisions. As discussed in Section 5.6, provisions for deep reconditioning must be made if 8-9 years life is required.

3) Cell protection. Open-circuit cells are rare occurrences, but they are catastrophic since the entire battery could be lost, therefore it is customary to provide protection against them with diodes, as shown in Figure 19. The single diode also reduces the voltage across a cell if it should become overdischarged and lessens the chance of cell rupture.

4) Trickle charge. A continuous trickle charge (C/50 to C/100 range) is required to prevent loss of charge due to thermal decomposition

of the positive electrode. The necessary trickle charge rate increases with the battery temperature.

5) Cell Matching. Cells in each battery are generally matched to ±3%, based on cell acceptance test results.

5.9 RELIABILITY

Data on cell reliability exists[79-2], and it generally shows failure rates in the order of 100 x 10^{9} and which increase with cell age. This data has little validity, however, because of the wide variations in cell types and operating conditions.

The most common approach to achieving reliability is shown in Figure 20, which appears in several places in the literature. This approach is to add one or two extra cells per battery, primarily to maintain battery voltage in the event of a cell failure, to use nominal DODs of 50% or less, and to use diodes for cell protection. DODs can be increased if cells fail or degrade.

5.10 BATTERY MANAGEMENT SYSTEMS

A battery management system, such as is under development at CAL, will provide all of the following functions:

1) Individual cell voltage monitoring.

2) Individual cell protection (See Figure 19). Relays are preferred over diodes as they dissipate less heat, cause no voltage drop, and guarantee protection against cell rupture if overdischarged. They can also be used to produce 0 V per cell during the last stage of a recondition discharge.

3) Provisions for "deep" reconditioning.

4) Bypassing of overcharge current on an individual cell basis so that incompletely charged cells continue to charge.

5) Continuous monitoring and integration of charge and discharge currents.

6) Control of battery heaters.

7) Control of charge controllers and discharge regulators.

Most S/C incorporate some of these functions, e.g., cell voltage monitoring and protection (using diodes), but none has yet incorporated all functions under the control of an autonomous microprocessor.

A complete system would add in the order of 5 to 10 kg plus 0.1 to 0.2 kg per cell to the S/C mass, but the microprocessor would be able to perform other S/C functions such as power management and thermal control.

As modern communications satellites usually incorporate some battery management system features, such as cell voltage monitoring, the choice to be made is more how much of a system is required rather than is one to be used or not. Modern S/C (e.g., SATCOM) probably incorporate all that is needed for a 5 to 7 year lifetime. Where a complete system, with individual cell switching relays and overcharge bypass circuits, etc., might be justified is when longer lifetimes are required and cell deterioration becomes significant. JPL have shown[77-5] that individual cell switching will greatly extend useful battery life when many cell failures are present. LEO applications, where battery life is limited by the number of charge/discharge cycles are also attractive candidates for battery management systems. The autonomous approach has the great advantage of being substantially independent of S/C-ground command and telemetry links.

5.11 BATTERY SIZING

The number of cells and their capacity required for the S/C batteries can be determined by carrying out the following procedure:

1. Determine total watt-hours required. It is generally sufficient to use the average eclipse load (including conversion losses, typically 10%) multiplied by 1.2 h (the maximum eclipse period).

2. Determine the power system constraints on the number of series cells in each battery. For power systems using a regulated bus and a discharge regulator (as in Figure 7) a maximum limit on the number of cells is set so that the charge controller will operate at the maximum on-charge battery voltage, which thus must be about 2 V less than the bus voltage in sunlight. The maximum number of cells is thus:

   $$(V\ \text{bus} - 2) \div 1.55$$

   For systems using unregulated buses, a lower limit on the number of cells is set by the minimum bus voltage allowable. An end-of-discharge voltage of 1.15 V per cell is commonly used. It is then usual to add one or two cells to ensure that the minimum bus voltage is maintained in the event of a cell failure.

3. Determine maximum DOD. The NASA curve (Figure 21)[76-4] can be used, but "engineering judgement" must be applied to this[79-2]. The present practice, for 5 to 7 year missions, appears to be to use 55 to 60% (of rated capacity) if one or two extra series cells have been used and to use 50% or less if not. Using these figures will result in DODs in the 40 to 50% range based on actual capacity, which gives some margin for cell degradation.

   Computer simulation (see Figure 14) shows that these DOD figures are valid (strictly should be decreased by 2%) for 8 to 10 year missions, provided that deep reconditioning is performed.

4. Determine total A.h required from the formula:

$$\text{Total A.h} = \frac{\text{W.h}}{\text{Max. DOD x Average Battery Voltage}}$$

An average battery voltage of 1.15 V is commonly used.

5. Determine number of batteries and cell capacity required to provide required total A.h. The constraints used in this phase are:

- Maximum or minimum number of series cells (from 2.)
- Minimum number of batteries, which is two so that all capacity is not lost in the event of a catastrophic failure in one battery.
- Maximum individual cell capacity. To be taken as 50 A.h with present cell designs.

Curves such as shown in Figure 22 can be used to aid this phase of the calculation. The curves shown were based on the assumptions used above e.g.:

- conversion losses 10%
- Max. DOD 50%
- Average cell voltage on discharge 1.15

The CAL battery simulation program can be used to provide a somewhat more accurate figure for cell capacity as it models conversion losses and cell voltage accurately. The results using the approximations will, however, be quite good, as can be seen by comparing Figures 14 and 21. Figure 14, which is the computer simulation, shows that a single 31 A.h, 28-cell battery will support a 400 W load at 50% DOD. Figure 21, which uses average conversion losses and cell voltages also gives a 31 A.h/28 cell requirement for the equivalent load (1600 W from four batteries).

6. Determine cell and battery mass from known cell masses (see section 5.5) and an allowance of 10 to 20% for hardware (see section 5.7.2).

Figure 3 shows the net result of battery mass versus power demand calculations using the above procedure and assumptions.

5.12 LAUNCH VEHICLE CONSTRAINTS

Historical evidence (see Table 1) and reference 79-10 shows that the battery will traditionally form 6.3% of the S/C mass. This percentage figure thus gives a quick method of determining whether or not a given eclipse load requirement is feasible for a S/C launched by a particular launch vehicle. Figures showing 6.3% of the capability to GEO for projected launch vehicles are shown in Table 2. The IUS referred to is the standard version, and the IOTV is the spin stabilized version whose development has been recently halted.

Launch Vehicle	GEO Capability (kg)	6.3% (kg)
Atlas-Centaur	1048	66
Ariane 2	1098	69
Ariane 3	1322	83
Ariane 4	1824	115
Shuttle SSUS-A	936	59
Shuttle IUS	2118	133
Shuttle IOTV	4536	286

Table 2 Battery Mass vs Projected Launch Vehicles

It will clearly be difficult to design an IUS-launched DBS with more than about 2 kW eclipse capacity if Ni-Cd cells are used or 3 kW with $Ni-H_2$ cells.

The battery limitation only applies to eclipse power demands and sunlight operating modes can use higher power levels provided they are reduced during the eclipse. Housekeeping loads will be in the 100-200 W range and therefore most eclipse battery power can be used for the payload.

5.13 CELL AND BATTERY PROCUREMENT

5.13.1 PROCUREMENT

Manufacturers offering aerospace quality Ni-Cd cells are:

SAFT (France)
Yardney
Eagle Picher (EP)
General Electric (GE)

SAFT cells are primarily procured by European contractors [79-8], and North American contractors use EP or GE cells. Problems have been experienced with EP cells [79-15] and all recent communications satellites have used GE cells.

Cells must be procured to a comprehensive specification, such as reference 81-6, with extensive quality control requirements. The major S/C contractors with extensive experience will go as far as defining the internal cell construction in detail.

Completed batteries can be purchased from any major S/C contractor (Ford Aerospace, GE, RCA, etc.), but could be manufactured by any contractor with high-reliability aerospace, particularily thermal, design and manufacturing experience, and access to good environmental test facilities.

5.13.2 COSTS

Figure 23 gives an indication of cell costs. To cover requirements for engineering model, flight spare, and test cells, about three times the number of cells required for the flight batteries should be procured (for a single S/C). Battery development costs would be in the $1M region, and are large compared with the cell costs. As an example, total costs for a 1 kW system (56 x 40 A.h) would be around $1.2M.

5.14 PRE-LAUNCH TREATMENT

As the behaviour of Ni-Cd cells is considerably influenced by their history and as cell degradation can be accelerated by improper environments or operating conditions, it is important that tightly controlled storage and handling procedures be implemented in the year or more that will elapse between cell manufacture and S/C launch. Standard guidelines for storage and handling in this period are[78-4]:

1. The cell temperature during long-term storage should be maintained at no greater than 0°C.
2. Open circuit storage periods of greater than 5 days must not be allowed. (Cells are normally stored short circuited.)
3. Open circuit stands of more than 2 hours should be followed by a shallow discharge before recharging.
4. Short discharges, such as might occur during S/C integration tests should be avoided, but if they do occur they must be followed by a proper recharge.
5. Trickle charging at elevated temperatures (above 23°C) should be avoided.

The object of the above procedures is to preserve cell overcharge protection, minimize separator degradation, and to maintain the stability of the negative electrode morphology. The problems of high temperature and non-optimum operations during S/C integration can be lessened by designing the S/C so that the batteries need only be integrated at a late stage (ideally, just before launch).

5.15 ACCELERATED TESTING

Accelerated tests on aerospace Ni-Cd cells have been carried out for a number of years, primarily at the Naval Weapons Support Center, Crane, Indiana. Unfortunately for DBS purposes, these tests have been mainly applicable to LEO applications and "interpretation of the Crane data has not yet led to a predictive model for synchronous orbit".[80-13] The tests have, however, given strong evidence that the trickle charge period plays a major role in the degradation of the cell in synchronous orbit.

With several S/C now having been in service for periods in excess of 5 years, on-orbit experience is now providing the major data source for GEO applications.

It is often customary to have a few cells on continuous ground test whereby they simulate the S/C conditions a year or two in advance. This practice gives operations planners a preview of the future performance of the S/C batteries and provides a test bed for new operational procedures.

5.16 FUTURE PROSPECTS

The recent developments in Ni-H_2 cells has undoubtedly taken some of the pressure off the development of lighter Ni-Cd cells (and reduced funding in this area), but some progress can be expected in coming years. Some developments that might have promise are use of perforated metal screen electrodes and carbon-fibre cases.

The requirements for long-life is now as, or more, important than initial energy density. There are indications that customers are demanding simpler cells, e.g., without PQ treatment[79-16]. It appears, however, that electrochemically impregnated plates and, probably, teflonated negatives are here to stay. The performance of the Hughes cell with polypropelene separators bear close watching.

6 NICKEL-HYDROGEN SYSTEMS

6.1 INTRODUCTION

Metal-hydrogen systems have been intensively studied for several years because of their intrinsically high energy densities. Of metal hydrogen systems, only nickel-hydrogen (Ni-H_2) has been developed sufficiently to be considered for satellite applications at this time. Silver-Hydrogen (Ag-H_2) cells, which have greater energy densities than Ni-H_2, are being developed (see section 6.15), but not sufficiently for consideration at the moment.

Although all Ni-H_2 cells are basically similar, three major design variants have emerged in the last few years. These types of Ni-H_2 cell are named after their prime sponsors:

- COMSAT
- Air Force/Hughes

and
- SAFT

A comparison among these types is made in section 6.5, but the following description of construction and operation is based on the COMSAT design, as this has been specifically designed for communication satellite applications.

6.2 BASIC PRINCIPLES AND CONSTRUCTION

In their internal construction, Ni-H_2 cells resemble Ni-Cd cells: i.e., they are built from a stack of positive and negative electrodes, with separators between them that are impregnated with electrolyte. But, because of the high pressure generated during operation, the electrode stack is housed in a steel pressure vessel (see Figure 24).

The positive electrodes are sintered nickel in which nickel hydroxide is deposited by electrochemical impregnation (as in Ni-Cd cells).

The negative (hydrogen) electrodes consist of teflon-bonded platinum blocks supported by a nickel screen. The separator is asbestos and the electrolyte is a potasium hydroxide solution.

The plate stack is housed within an Inconel 718 pressure vessel and the leads are brought out through plastic compression seals.

The basic chemical reactions are:

a) at the positive electrode:

$$Ni(OH)_2 + OH^- \overset{\text{charge}}{\underset{\text{discharge}}{\rule{4em}{0.4pt}}} NiOOH + H_2O + e^- \qquad (1)$$

b) at the negative electrode:

$$H_2O + e \overset{\text{charge}}{\underset{\text{discharge}}{\rule{4em}{0.4pt}}} \tfrac{1}{2} H_2 + OH^- \qquad (2)$$

c) total reaction:

$$Ni(OH)_2 \overset{\text{charge}}{\underset{\text{discharge}}{\rule{4em}{0.4pt}}} NiOOH + \tfrac{1}{2} H_2 \qquad (3)$$

d) on overcharge:

$$4\ OH^- \rightarrow 2H_2O + 4e + O_2 \qquad (4)$$

The hydrogen generated while charging (see equation 1) causes the cell pressure to vary from about 100 psi when the cell is discharged to about 600 psi when it is fully charged.

As with Ni-Cd cells, Ni-H2 cells are designed to be positive limiting. The excessive negative capacity required is achieved by introducing hydrogen into the discharged cell.

6.3 EFFECTS OF OVERCHARGE AND OVERDISCHARGE

Oxygen is generated on overcharge (Section 6.2, equation 4) by electrolysis at the positive electrode, but this is electrochemically and chemically reduced by the hydrogen produced at the negative electrode. The cell pressure and electrolyte concentration remains stable.

A similar effect occurs on over-discharge when hydrogen evolved at the positive electrode is consumed by the negative plate (equation 2). The cell voltage stabilizes at -0.2 V, which means that a weak cell will not be damaged by current from good cells in a battery undergoing a deep discharge.

Tests have shown[75-1] that continuous over- or under-discharge at a C/2 rate have no apparent effect on the cells.

6.4 COMPARISON WITH NICKEL-CADMIUM SYSTEM

The advantages of the Ni-H_2 system can be summarized as:

1) Absence of cadmium negative. The hydrogen negative electrode is chemically inert and the problems in Ni-Cd cells due to changes in morphology and cadmium migration are eliminated

2) Inert separator. The asbestos separator is unaffected by the electrolyte

3) No change in electrolyte concentration or quantity during operation. Shown by equation (3) which demonstrates that no change in H_2O quantity occurs

4) Higher energy density. Up to 55 W.h/kg compared with 33 W.h/kg for Ni-Cd

5) Tolerance to overcharge. On overcharge, oxygen evolves at the positive electrode (equation 4) but is reduced at the hydrogen electrode and does not cause a pressure increase. The cell is unaffected provided the heat produced can be dissipated

6) Tolerance to cell reversal. There is no pressure build up when a cell is overdischarged and the voltage limits at about -0.2 V

7) Ability to determine state of charge. A fair measure of the state of charge of the cell can be obtained by measuring the cell pressure

8) Potential for operation at high DODs. Although more data is needed to make precise recommendations, indications are that 60 - 80% DODs are feasible for long-life GEO missions.

The disadvantages of the Ni-H_2 system are:

1) Lower volumetric energy density. About 60 W.h/dm^3 compared with 100 W.h/dm^3 for Ni-Cd

2) Greater cost and lead time

3) Harder to package because of cylindrical configuration

4) Poor charge retention. 50% lost in 8 days compared with 10% for Ni-Cd

5) Potential for open-circuit if pressure is lost

6) Little flight experience.

6.5 COMPARISON OF CELL TYPES

As mentioned previously, the all Ni-H_2 cells are basically the same, but compared with the COMSAT cells, other designs show the following differences:

1) The Air Force/Hughes cell. This is optimized for low earth orbit (LEO) applications and designed as a rugged cell with a high cycle life. It is thus somewhat heavier than the COMSAT cell. Detailed differences are:

   - Separator is brought out to the container wall, to maximize heat transfer
   - Leads are taken down the centre of the stack and are sized for high currents (5C)
   - Interior of container is sprayed with zirconium oxide, which acts as a "wall wick" and ensures good electrolyte distribution
   - Positive plates are electrochemically impregnated using the "Pickett" process; COMSAT plates are by the "Bell" process
   - Vessels are internally electrochemically milled, leaving thicker material in weld region
   - Terminals use teflon seals.

2) SAFT Cells.

   - Terminals extrude from the same end in a "rabbit-ear" configuration (see Figure 25).

- Separator is two layers of non-woven polyamide felt.
- Terminals are ceramic, as in Ni-Cd cells.

6.6 FAILURE MECHANISMS

Potential failure mechanisms in Ni-H_2 cells are:

1) Loss of hydrogen through leakage. This does not appear to be a problem. Measured leak rates are low enough for operation of 10 years and more.

2) Cell rupture due to hydrogen embrittlement and/or KOH attack. This, too, does not appear to be a problem[81-5].

3) Separator degradation. Although possibly a problem in the long term with SAFT cells, which use a polyamide separator, degradation is not forseen as a problem with the asbestos or zircon separators used in the COMSAT and Air Force cells.

4) Degradation of the negative electrode. As this electrode acts only as a catalyst and current carrier, there are no significant failure mechanisms in this electrode.

5) Expansion of the positive electrode. As with nickel-cadmium cells, the positive electrode will swell as the cell is cycled. Severe swelling of the electrode will drive electrolyte from the separator, and earlier Hi-H_2 cell designs, which used chemically impregnated electrodes did suffer failures from this cause[80-10]. Modern cells with electrochemically impregnated electrodes have, however, shown neglible loss of EOD voltage after 34 simulated eclipse seasons.

6.7 FLIGHT EXPERIENCE

The only flight experience with COMSAT cells is the NTS-2 battery

(14 x 35 A.h cells). As of July 1980, the battery had been in-orbit for 3 years (7 eclipse) seasons and had accumulated approximately 420 cycles[80-5]. Because of operational factors, DODs ranging from 25 to 60% had been used. There had been no noticeable degradation in EOD voltage. On one occasion in the seventh eclipse season, due to failure of the satellite to execute a solar orientation maneuver, the battery was completely discharged. Its capacity then was 40.3 A.h, compared with 40.0 A.h measured prior to launch.

6.8 CELL MASS

The 30 A.h COMSAT cell manufactured by Eagle-Picher weighs 890 g[80-9] and Yardney quotes 953 g for a similar cell. Yardney quotes 1300 g for a 50 A.h cell and a similar COMSAT development cell weighs 1200 g. SAFT cells are a little heavier (see Figure 26). It is reasonable for planning purposes to use 890 g as the mass of 30 A.h, and 1250 g for 50 A.h cells.

6.9 CELL AND BATTERY VOLUME

Both 30 and 50 A.h cells are housed in 88.9 mm (3.5 in.) diameter cylinders (a diameter chosen as optimum for 50-70 A.h cells) and the overall lengths are approximately 198 mm (7.8 in.) and 241 mm (9.5 in.) respectively. Volumetric energy densities are 57 and 64 $W.h/dm^3$

The cylindrical configurations renders the $Ni-H_2$ cell harder to package than the prismatic Ni-Cd cell. Volumetric energy densities drop to 20 (30 A.h cell) and 25 (50 A.h cell) $W.h/dm^3$. The higher volume of $Ni-H_2$ batteries compared with those using Ni-Cd cells is not expected to be a problem in large Direct Broadcasting Satellites, particularly those designed for a shuttle launch (max. payload diameter is 4.4 m (14.5 ft), although it might pose a problem for smaller S/C using expendable launch vehicles.

6.10 THERMAL AND PACKAGING CONSIDERATIONS

The thermal characteristics and operating conditions are very similar to those of Ni-Cd cells. Cell capacity is greatest between 0 and 10°C and batteries should be designed to operate in this temperature range. As heat is generated in the cell stack, the common practice [80-9] is to mount the cell in a cylindrical sleeve (about 0.04 in. thick) that provides both mechanical support and a conductive heat transfer path to the S/C deck or radiating surface. Figure 27 shows a typical configuration.

Cell heaters of approximately 1 W per cell will be required to maintain the battery at its low temperature limit, and overcharge must be limited to prevent upper temperature limits being exceeded.

Heat generation is somewhat higher on discharge than in Ni-Cd cells, but this is balanced by less during charge so the net heat output over a charge-discharge cycle is about the same as for a Ni-Cd cell.[79-13]

As the cylindrical configuration is not as optimum for packaging as the prismatic configuration, mounting hardware will comprise about 20% of the total battery weight.

6.11 SYSTEMS ASPECTS

In general, Ni-H_2 batteries behave similarily to and require the same operational treatment as Ni-Cd batteries, i.e.:

- Charge rates. Normal, between C/25 (INTELSAT V) and C/10 (NTS-2); trickle, between C/73 and C/60.

- Charge termination. By ampere-hour integration, termination when cell temperature rise shows that the cell is in the overcharge region, or by measurement of cell pressure (using strain gauge sensors). Evidence to date is that the pressure measurement is a "fair" measure of state-of-charge; there being a tendency for cell pressures to increase with cycling[79-13].

- Discharge Voltage. As the discharge voltage is slightly higher in Ni-H_2 cells than Ni-Cd, one fewer cell (in 20 to 30) is required in each battery.

- Depth of Discharge. The INTELSAT specified limit is 70% (of rated capacity). Allowing for one cell failure, gives a beginning of life value of 57%.

- Cell Protection. Although unlikely, open-circuit cells, due to hydrogen leakage, are a possibility. Ford uses diodes for cell protection on the INTELSAT batteries, whereas Hughes use relays on theirs. The extra mass of relays (which each weigh 45 to 65 g) and circuitry required to close them must be traded against the voltage drop and thermal dissipation of diodes (which each weigh 10 to 20 g).

- Cell Matching. The current practice[79-13, 81-3] is not to match cells. As manufactured cell capacities are within about ±3%, which is considered close enough.

- Reconditioning. Provisions for reconditioning are normally provided although it has not yet been proved to be a necessary procedure. Considerable operational experience must be obtained before this point can be settled one way or another.

6.12 BATTERY SIZING

As Ni-H_2 batteries are very similar to Ni-Cd types, battery size can be determined by using the procedure outlined in Section 5.11. Two factors should be changed, however:

1) Because of the slightly higher discharge voltage of the Ni-H_2 cell, 1.2 V should be used as the average discharge voltage.

2) Depths of discharge can be greater, and 60% of rated capacity is a reasonable figure.

Carrying out this procedure, and factoring cell masses from Figure 26, gives the predicted mass versus eclipse power relationship shown in Figure 3. Launch vehicle constraints apply as for Ni-Cd cells.

6.13 CELL AND BATTERY PROCUREMENT

6.13.1 PROCUREMENT

As $Ni-H_2$ cells are generally manufactured by the same manufacturers and using similar processes as Ni-Cd cells, procurement practices should be similar (see section 5.13).

Several manufacturers now produce $Ni-H_2$ cells:

SAFT (France) are developing cells under ESA sponsorship[79-8], and have an excellent reputation for first-class quality control. Nevertheless, their cell design and qualification program appears to be a year or so behind those in North America. SAFT cells can be expected to be on the expensive side. SAFT also appear to be putting some considerable effort into $Ag-H_2$ development, and are probably the leaders in this field.

Hughes Aircraft build Air-Force type cells for classified programs but are primarily S/C contractors rather than cell manufacturers[81-3,81-5].

Yardney build COMSAT type cells, though probably not yet in significant quantities. They plan to open a new facility later this year. EIC Corp. are building development model Common Pressure Vessel Cells.

Eagle-Picher are the largest $Ni-H_2$ manufacturer at present. They build both Air-Force and COMSAT cells. At the moment they are in a production run of 800+ COMSAT cells for the INTELSAT V program. Although their manufacturing and quality assurance provisions might leave something to be desired, with close monitoring and comprehensive documentation of requirements, they are surely capable of producing acceptable cells.

Two other factors to be considered when purchasing $Ni-H_2$ cells are:

1) The necessity to obtain an export licence ($Ni-H_2$ cells are on the munitions list)

2) Long delivery times, in the order of one year, can be expected. This is primarily because of the long lead time required by the manufacturers to obtain Inconel 718 pressure vessel material.

6.13.2 COSTS

The 1981 quotations for $Ni-H_2$ COMSAT cells (in quantities of about 30 cells) are U.S. $3,000 each for 35 A.h and U.S. $3,500 each for 50 A.h.

The cost of cells for a flight program (one S/C) will therefore be in the U.S. $500,000 region.

6.14 FUTURE PROSPECTS

The COMSAT 30 A.h cell is a mature, "3rd generation" design and little change can be expected to occur to it. It is likely that a COMSAT-type 50 A.h cell will be produced and used in quantity for future satellites, e.g., L-SAT or INTELSAT VI. Higher capacities, e.g., 100 A.h cells will require development of larger pressure vessel designs, (137 mm, 4.5 in. diameter) which will probably be first used in LEO applications. For lower capacities, it is advantageous to series connect two or more cell stacks in a common pressure vessel (CPV). EIC Corp. are actively developing CPV cells, with encouraging progress being made so far.

The future will see DODs being increased to a forecast 80% as flight experience becomes available.

6.15 SILVER-HYDROGEN CELLS

Silver-hydrogen cells are constructed similarly in most respects to nickel-hydrogen cells, the most basic difference being that the positive electrode is formed from sintered silver on a silver grid. The outstanding advantage of silver- versus nickel-hydrogen cells is their energy density: values of 70 to 80 W.h/kg having been achieved. Unfortunately these cells are still in the development stage, they have not been qualified for space use, and there is no flight experience. Although test cells have completed more than 500 cycles[78-1] there are still concerns over long term degradation modes, particularly silver migration (although SAFT claim to have overcome this). Their advantages and disadvantages compared with nickel-hydrogen and nickel-cadmium cells can be summarized as:

Advantages:

- High energy density (e.g., 77 A.h/kg compared with 55 A.h/kg for nickel-hydrogen and 33 A.h/kg for nickel-cadmium).
- Good charge retention (95% over 8 days, compared with 50% and 90% for Ni-H_2 and Ni-Cd, respectively).
- Tolerance to cell reversal and overcharge (similar in this respect to Ni-H_2 cells).

Disadvantages:

- Still in development stage
- Lower discharge voltage and higher charge voltage than Ni-H_2 or Ni-Cd. (This complicates the power system design.)

At present, SAFT[80-1,81-1] and NASA-Lewis[79-3] are working on silver-hydrogen cells. The SAFT program aims at a first generation cell having an energy density greater than 80 W.h/kg and a second generation cell having an energy density of 80 - 90 W.h/kg with a 10 year GEO life. In view of the high energy density potential of silver-hydrogen systems, progress in this area merits close monitoring.

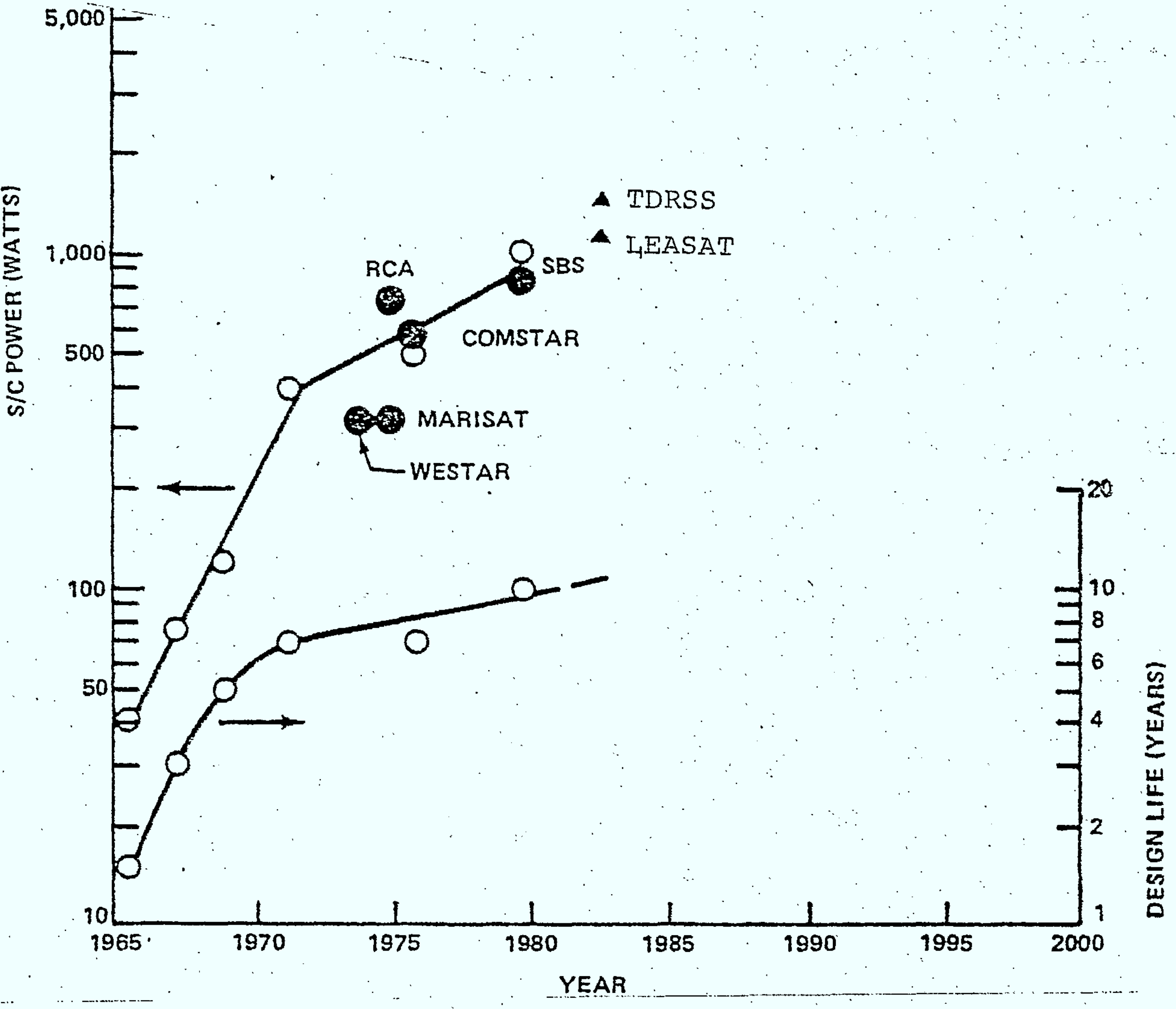


Figure 1 Typical Growth of Spacecraft Power and Design Life

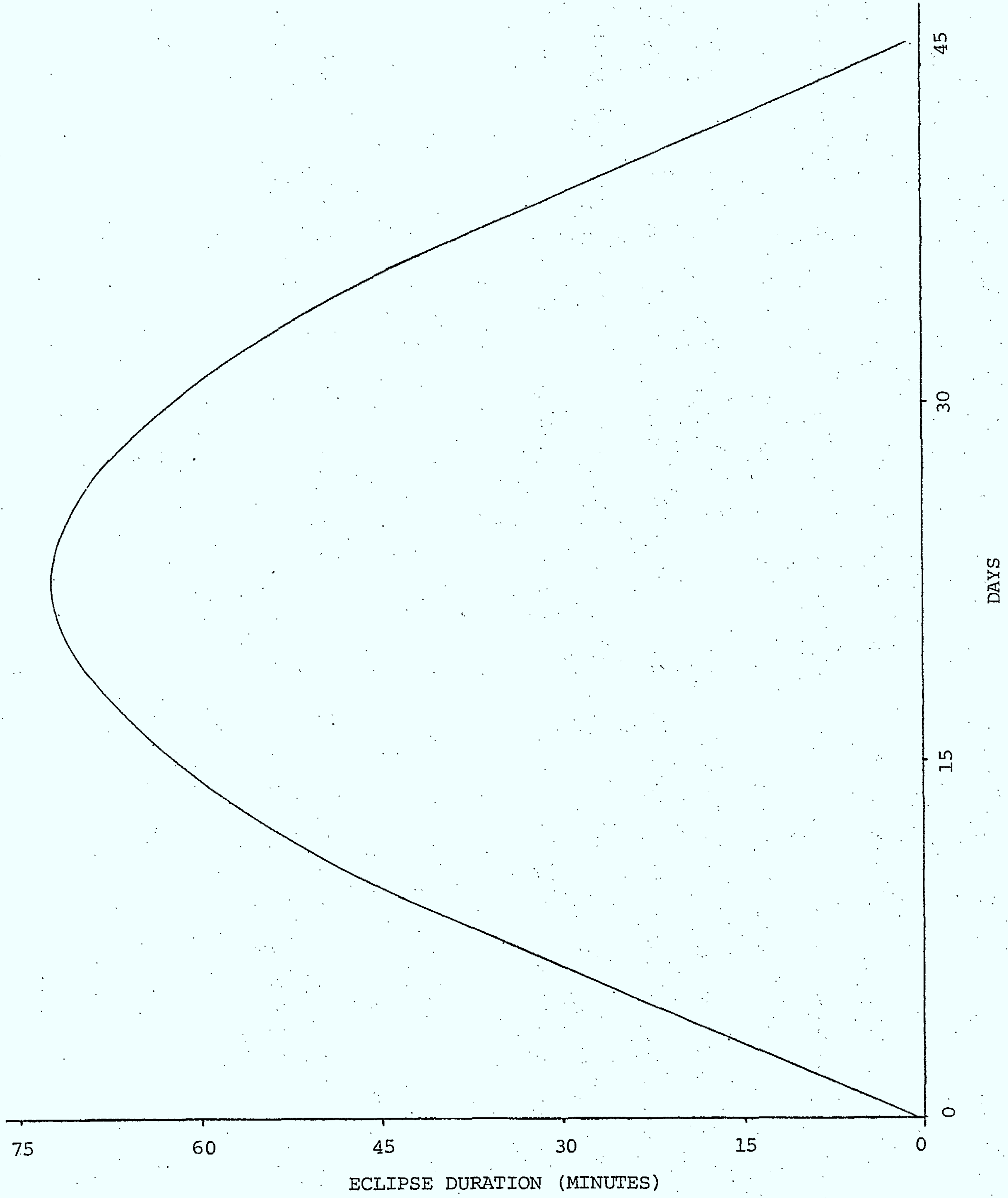


Figure 2 Eclipse Duration vs Days in Eclipse Season

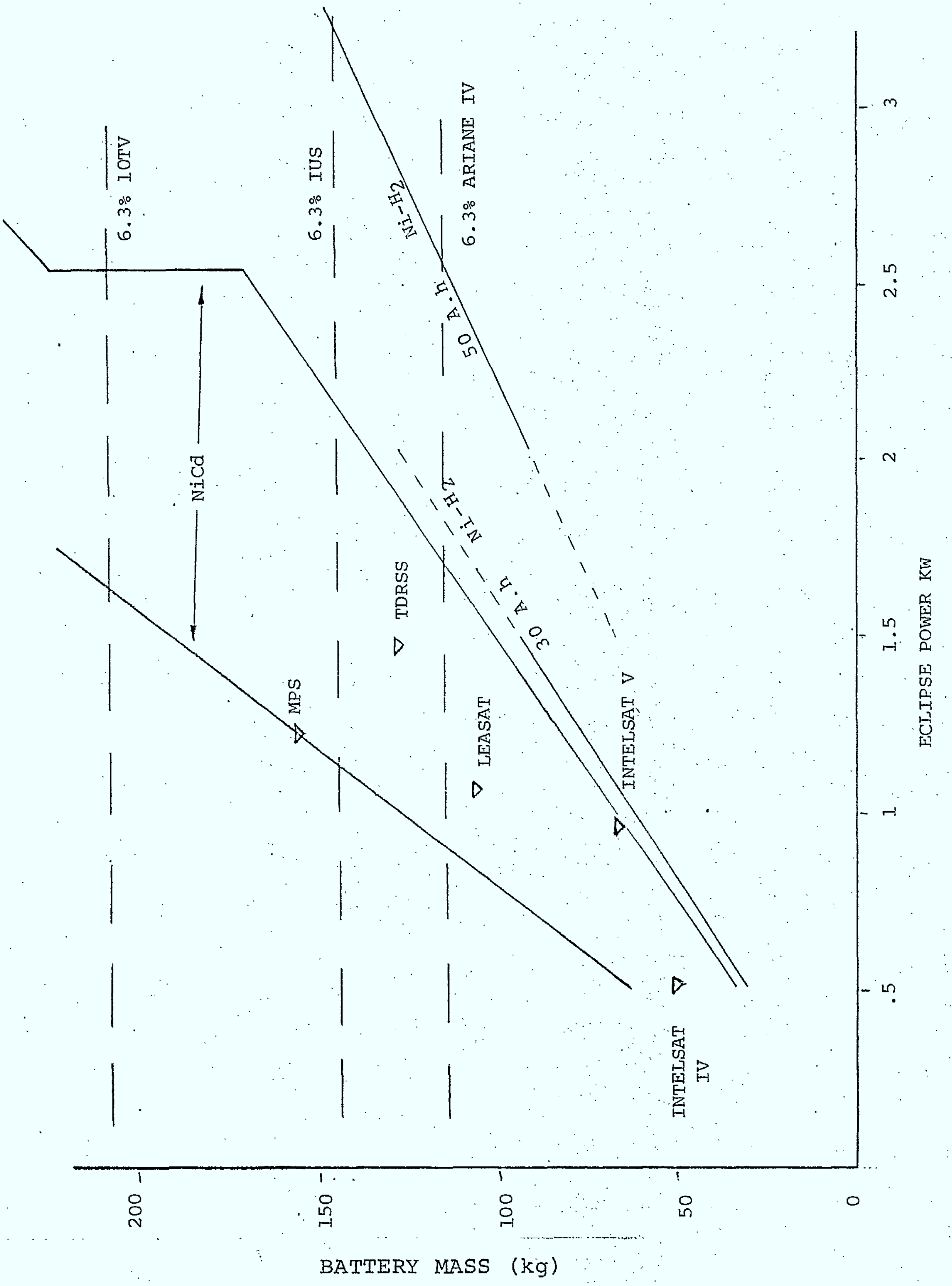


Figure 3 Battery Mass as a Function of Eclipse Power Availability

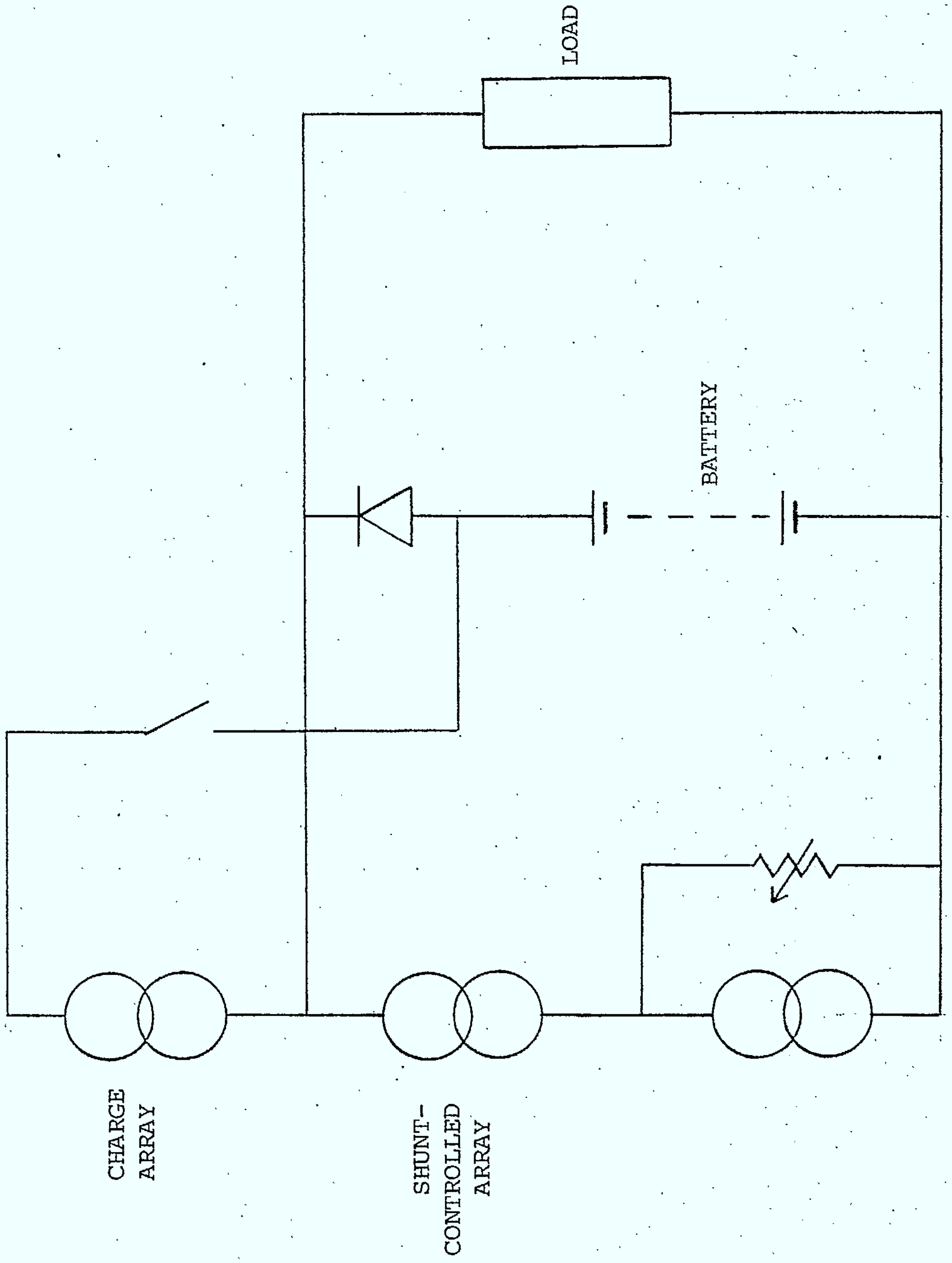


Figure 4 INTELSAT V Power System (One of two identical halves)

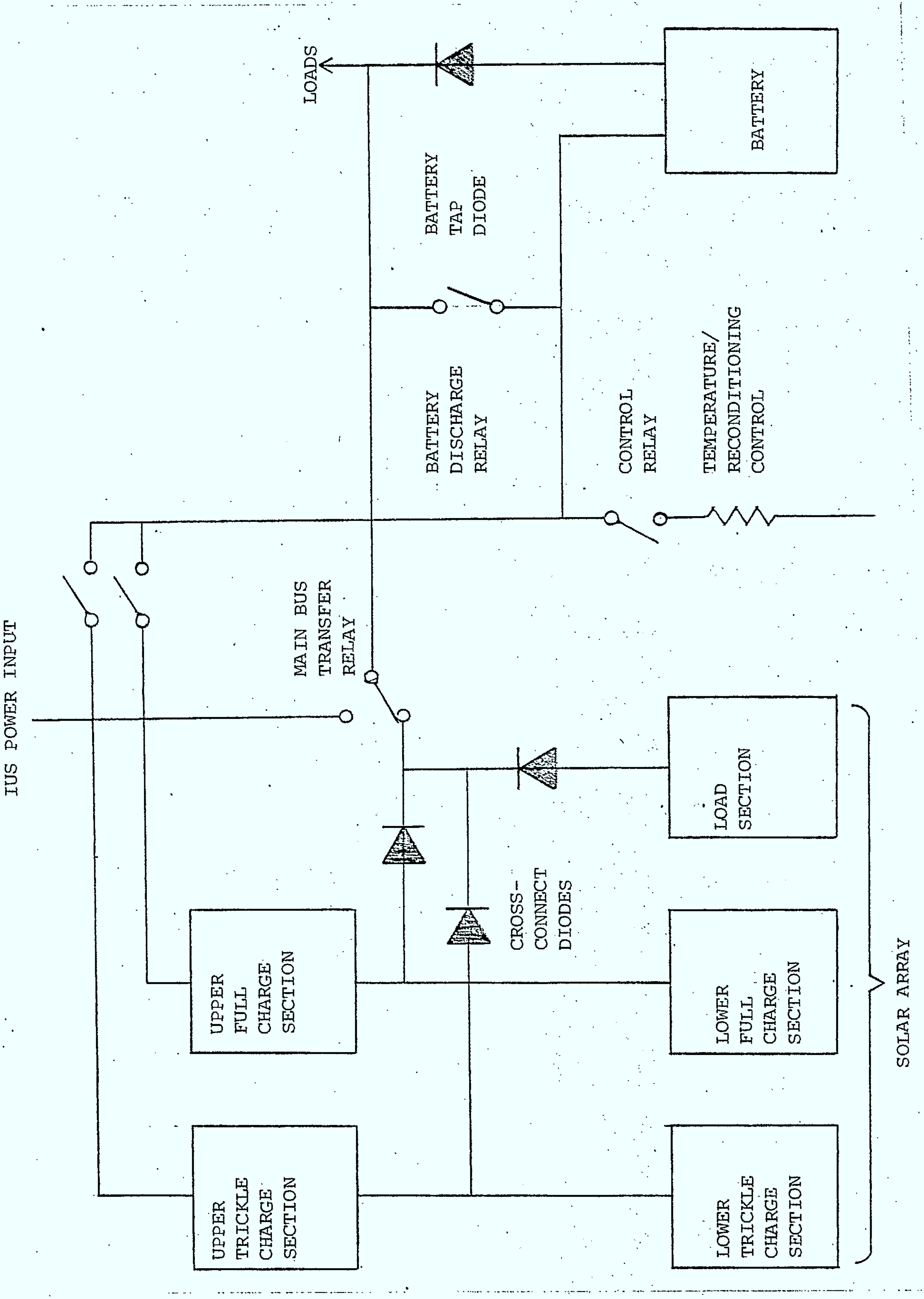


Figure 5 TDRSS Power System

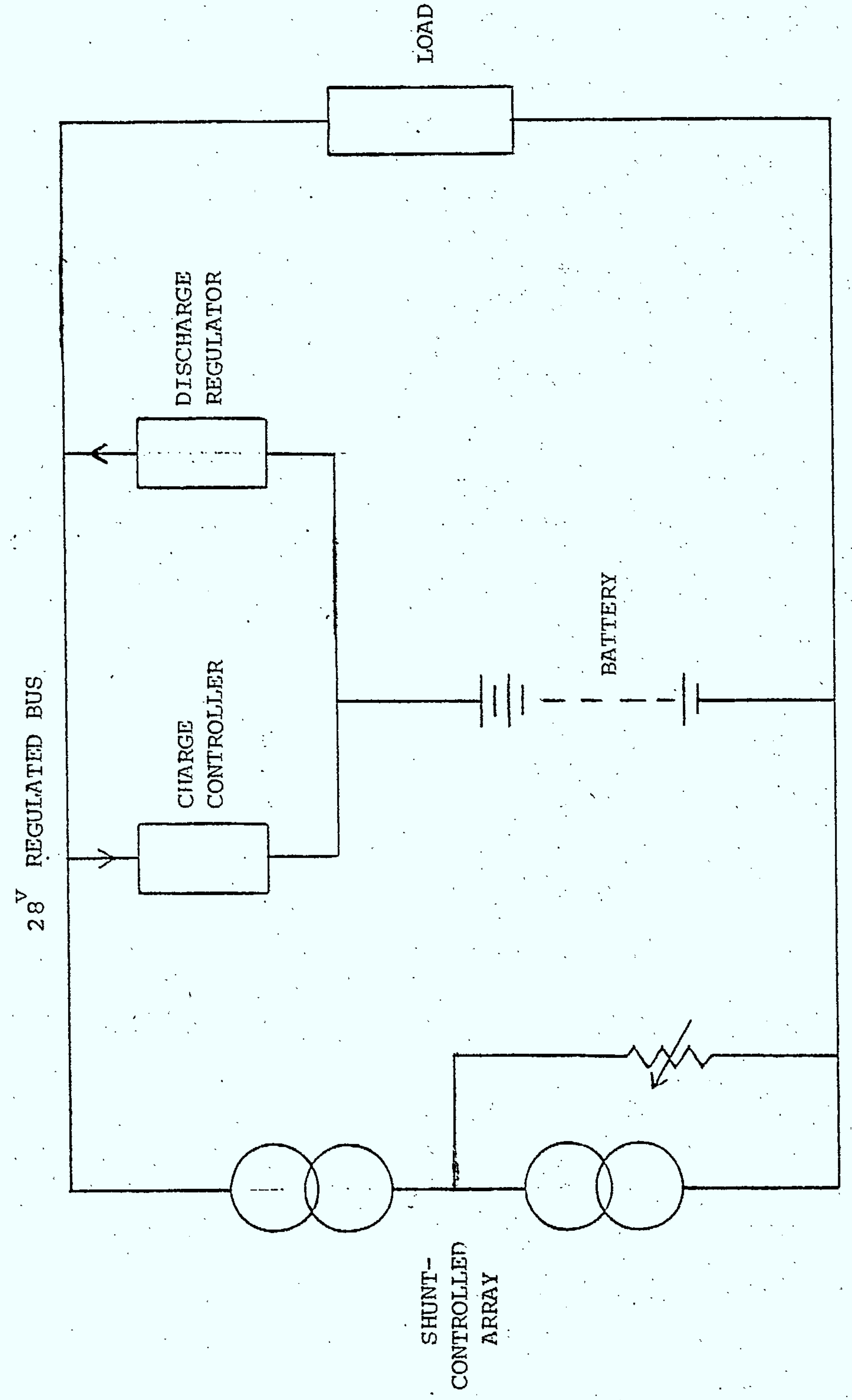


Figure 6 DSCS-II Power System

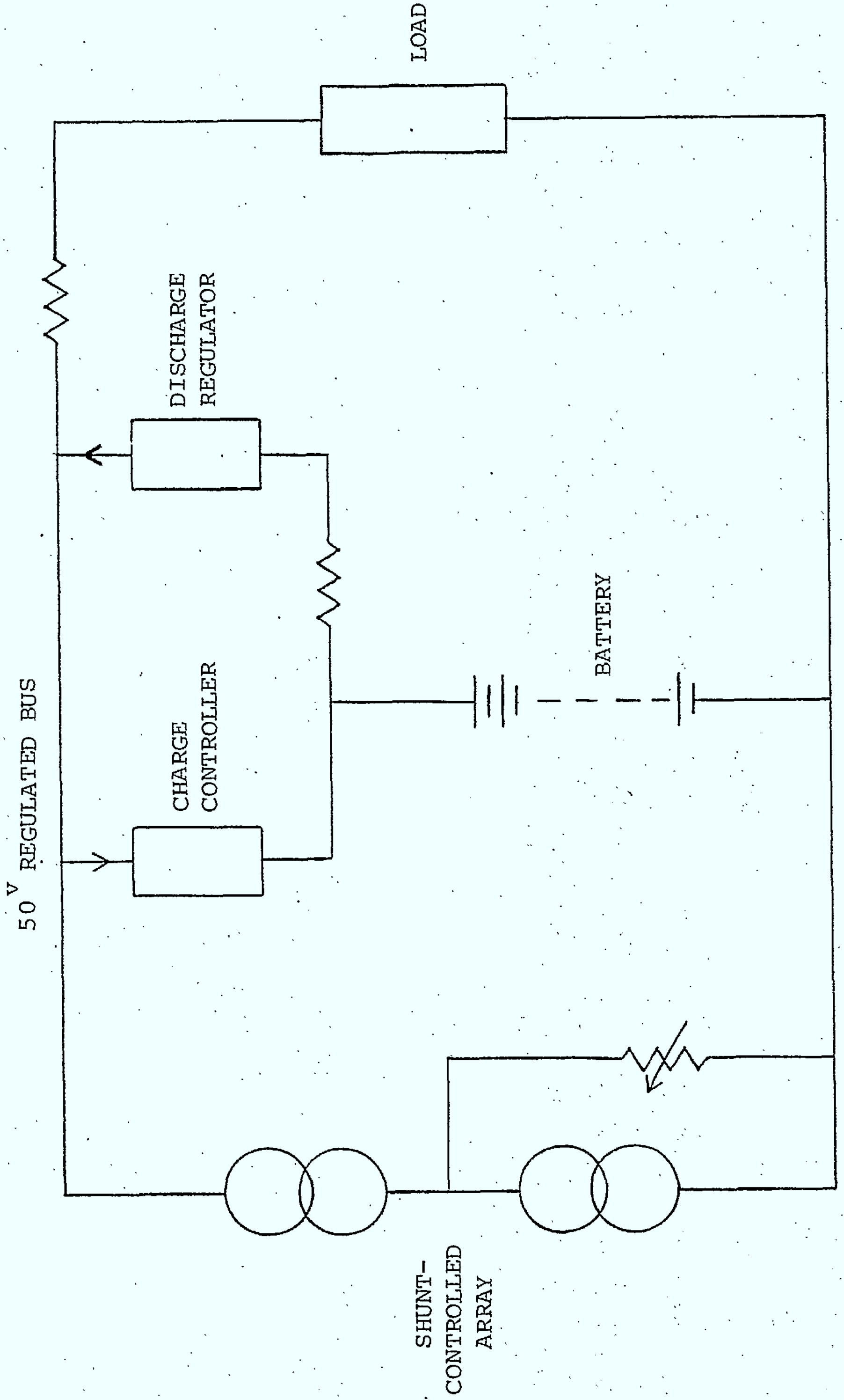
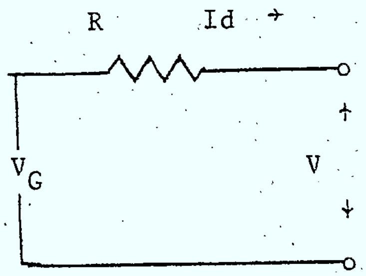


Figure 7 Power System Model Used for Computer Simulating



$$V = V_G + V_T - Id.R$$

$$V_G = 1.3597 - 0.83986\ DOD + 3.6972\ DOD^2 - 8.6476\ DOD^3 + 9.8953\ DOD^4 - 4.4239\ DOD^5$$

$$V_T = 0.00072\ (T_C - 32.2) \quad (T_C \text{ in } °C)$$

$$R = R_O + kR_F\ t^2 \quad (t \text{ in years})$$

Figure 8 Nickel Cadmium Cell Model

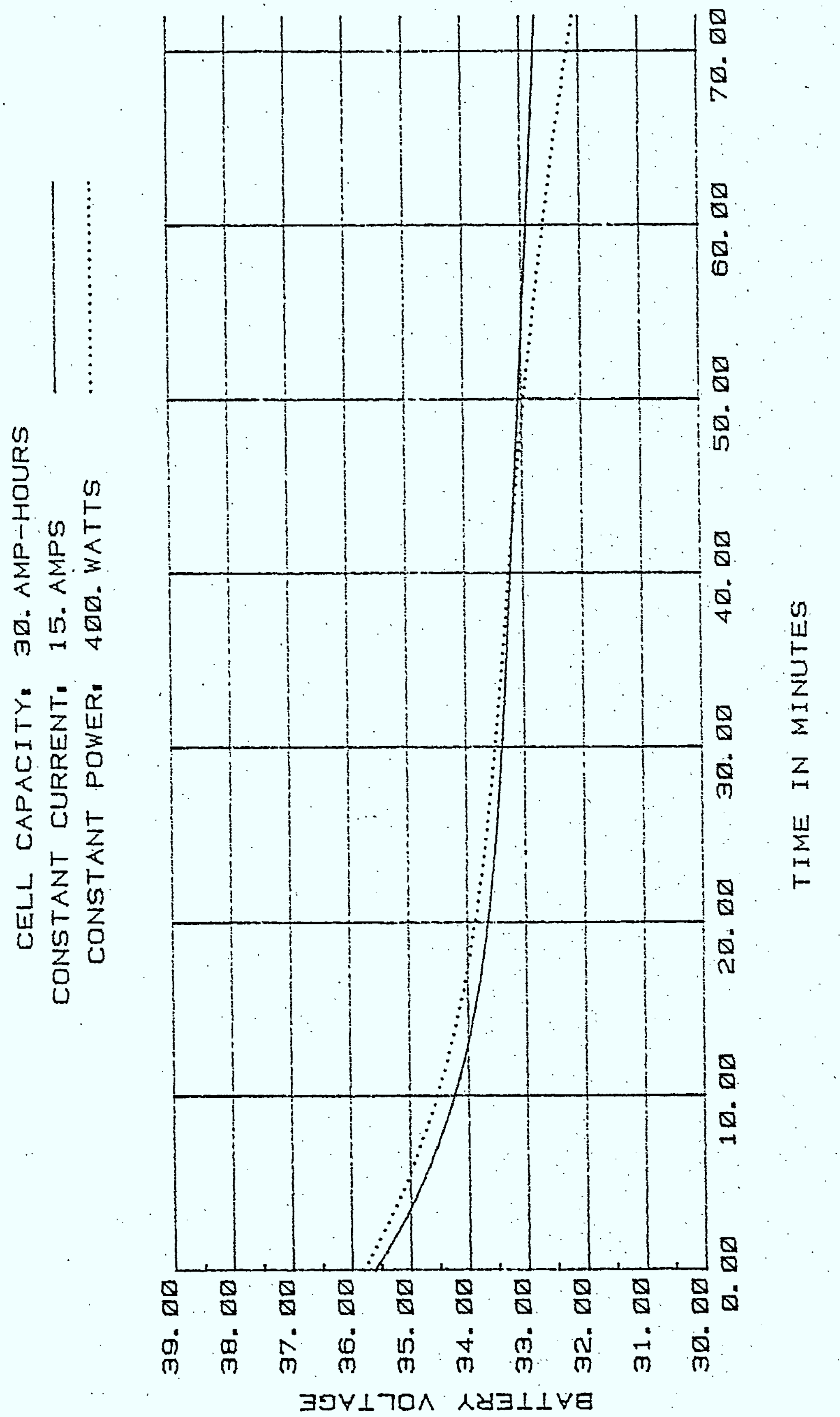


Figure 9 Battery Voltage vs Time During First Eclipse

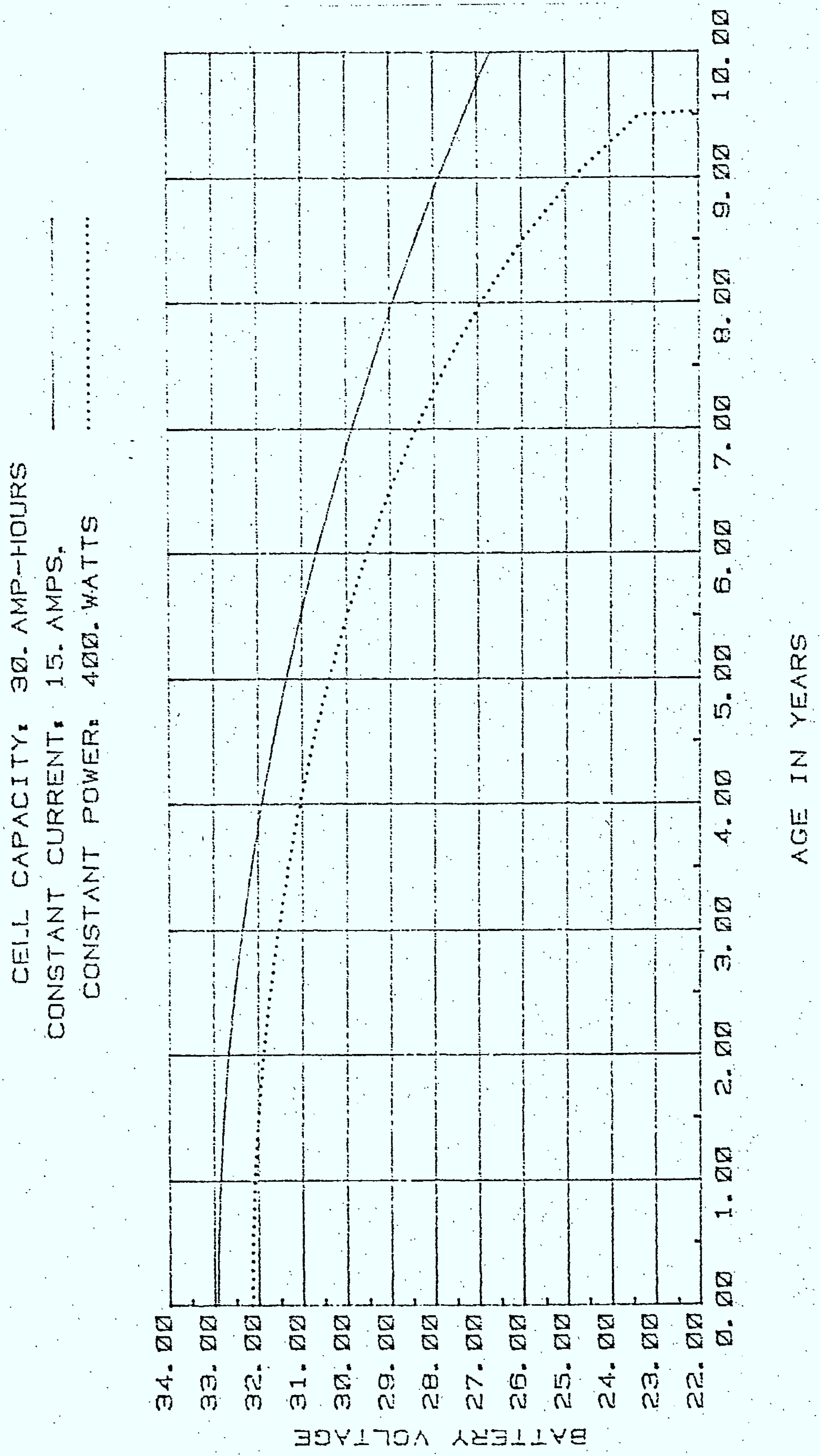


Figure 10 End of Eclipse Voltage vs Battery Age

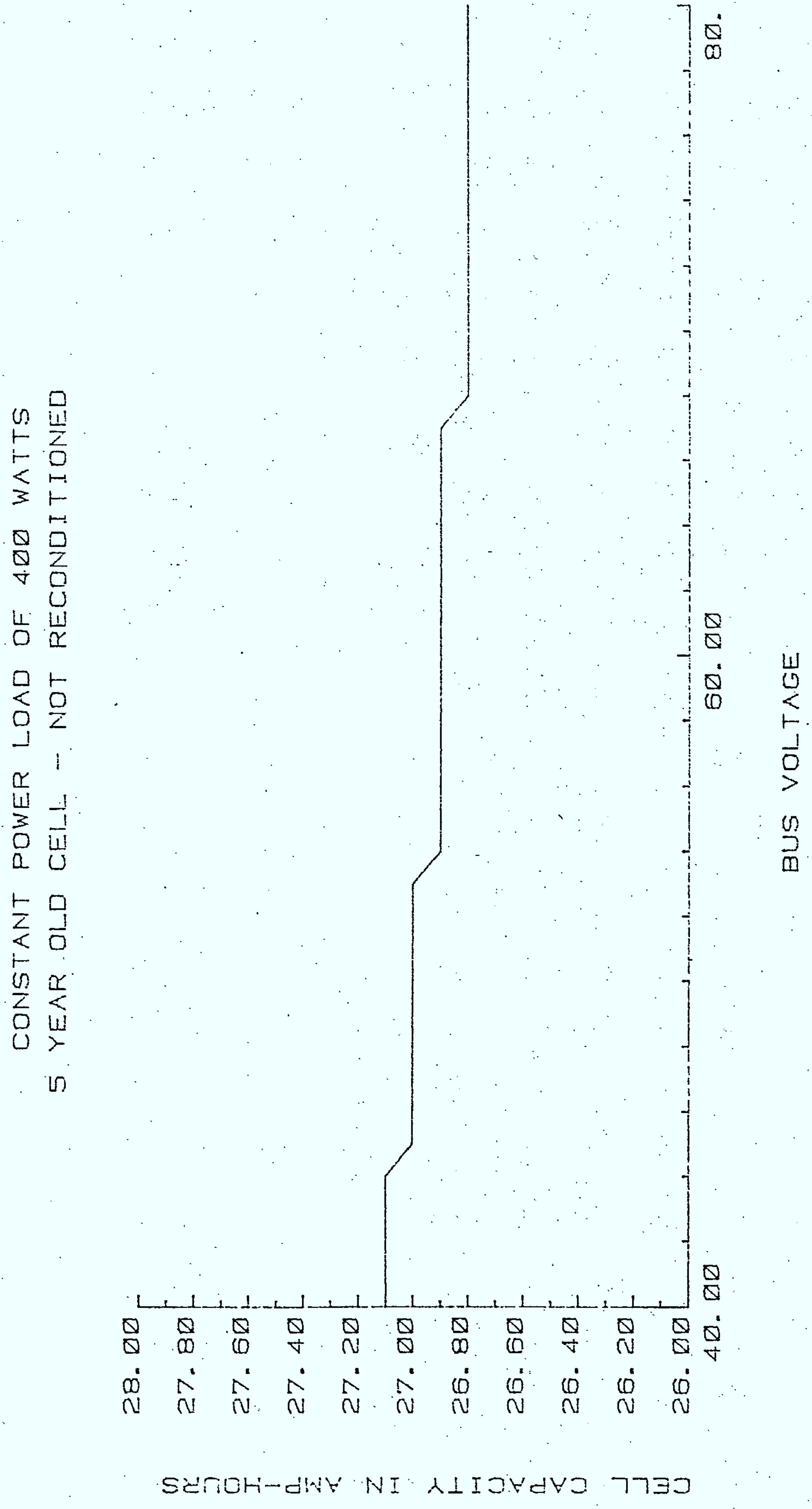


Figure 11 Effect of Bus Voltage

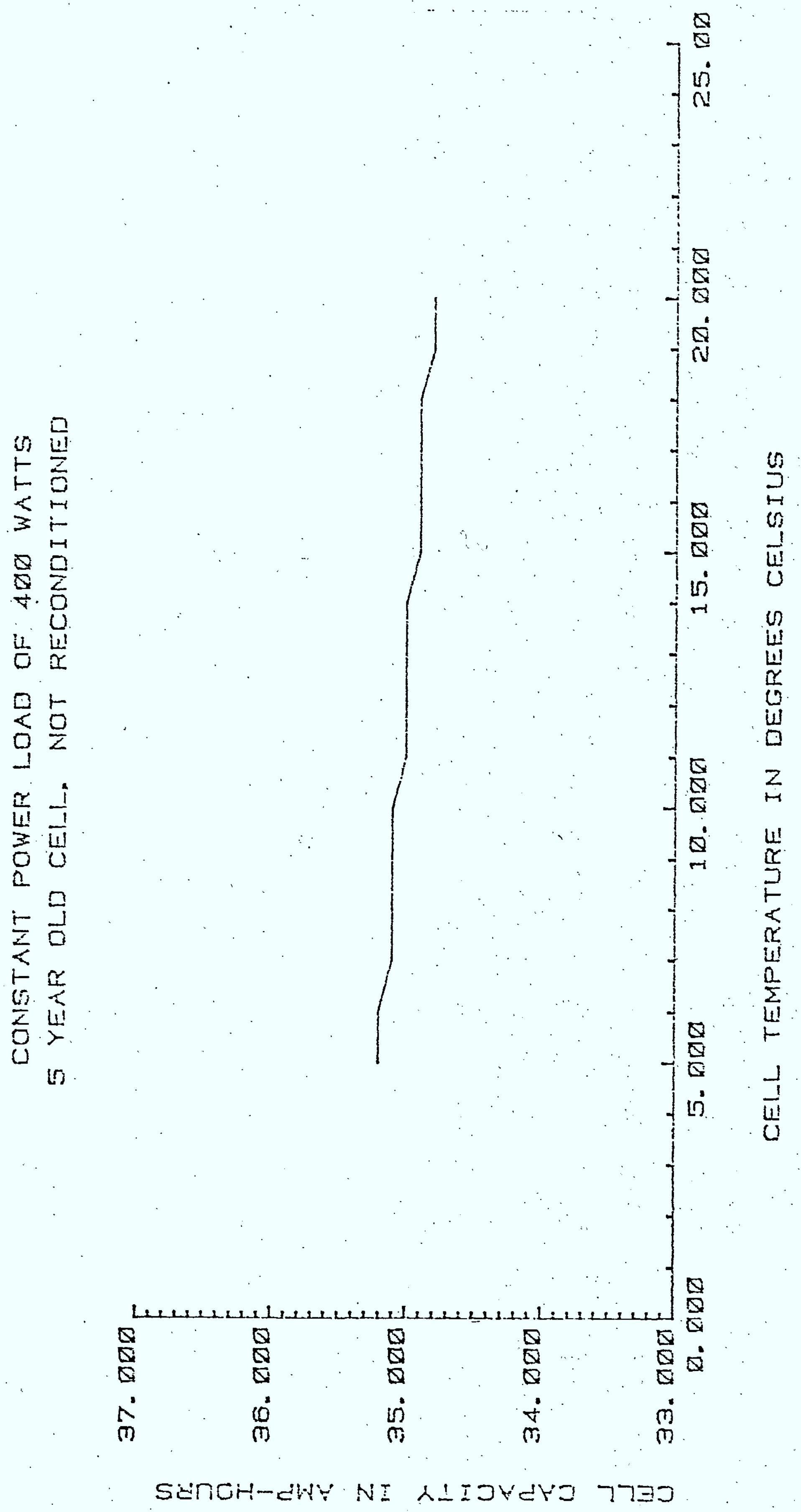


Figure 12 Cell Capacity vs EOD Temperature for 50% DOD

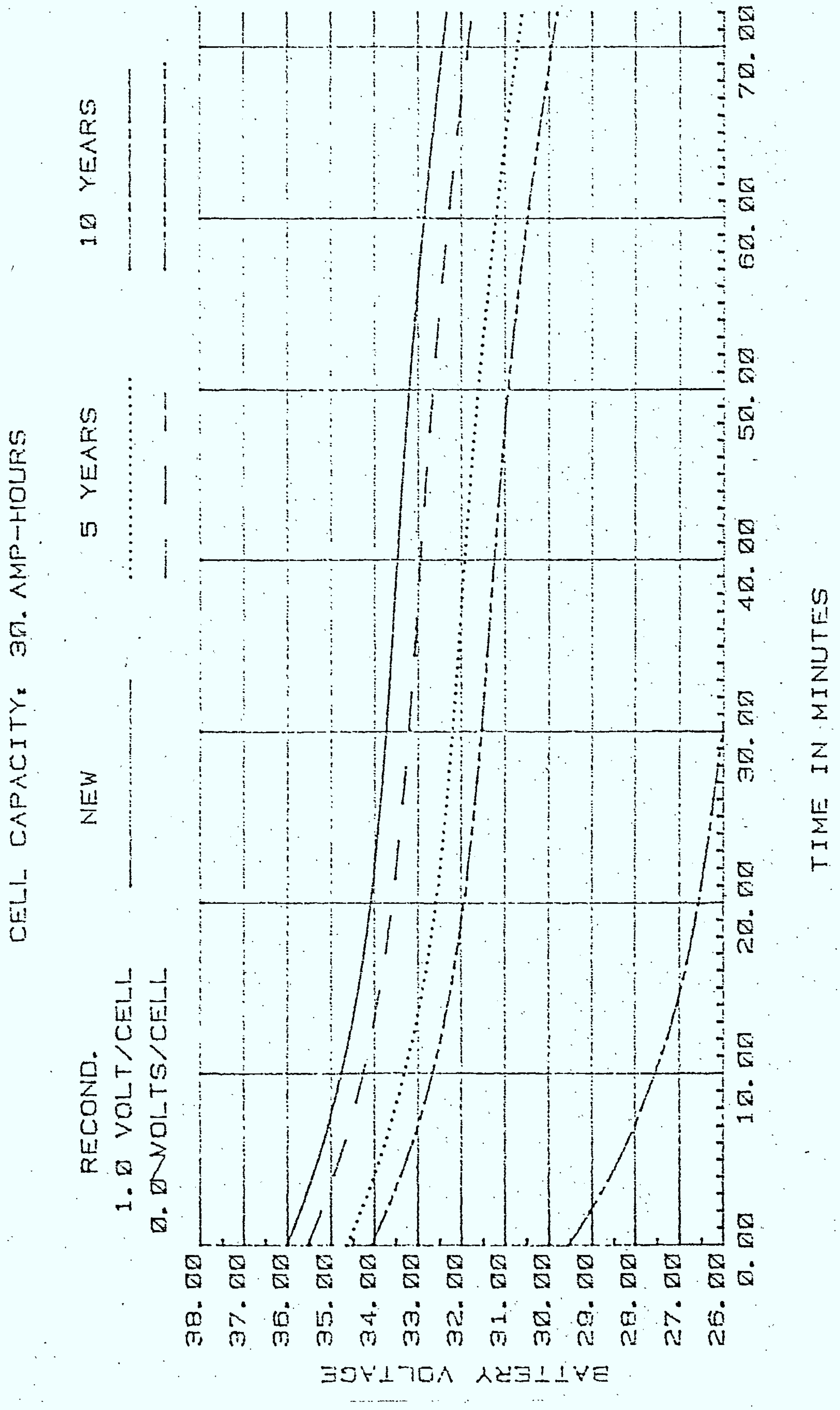


Figure 13 Battery Voltage vs Time During Eclipse

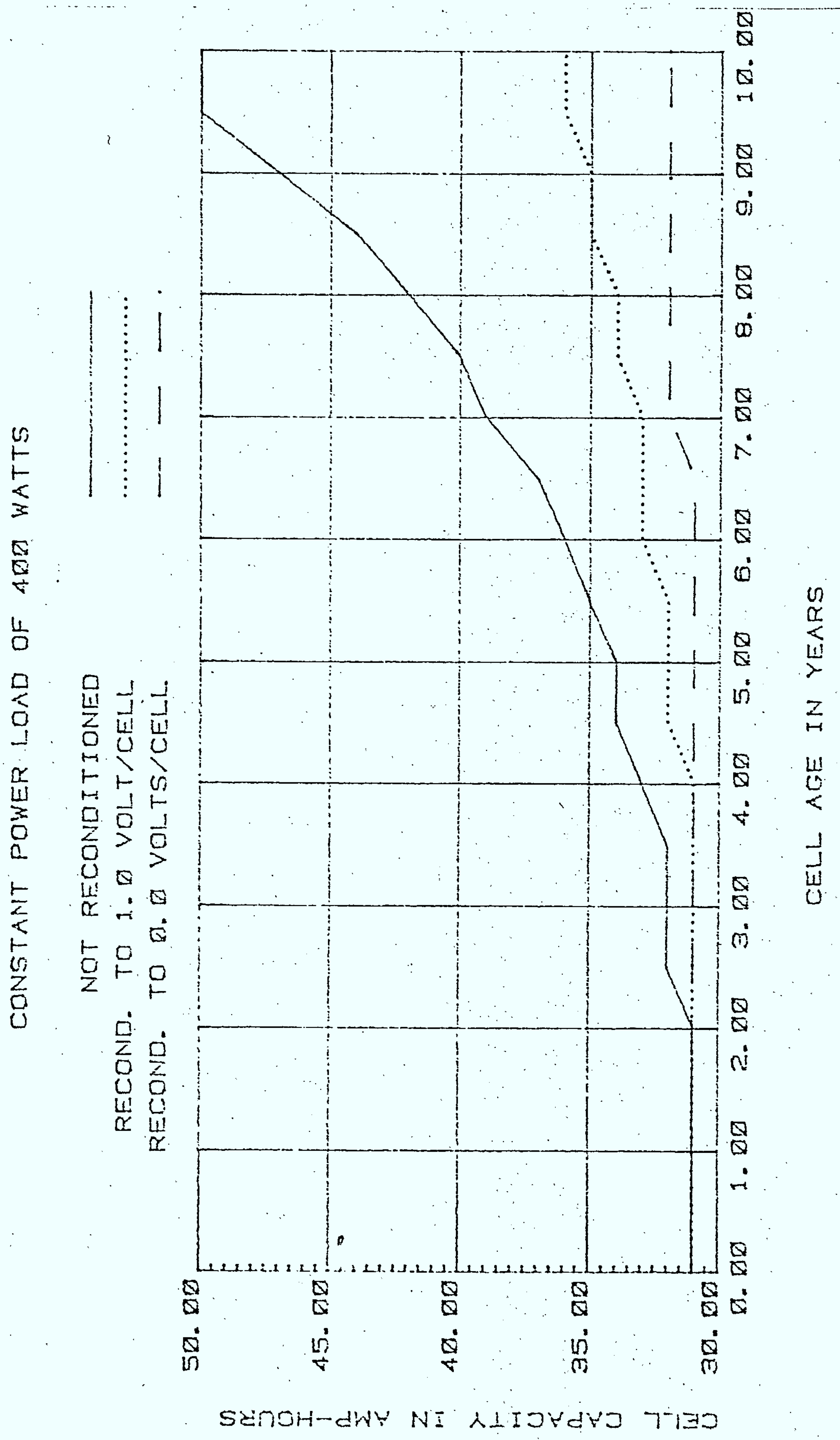


Figure 14 Cell Capacity vs Cell Age for 50% DOD

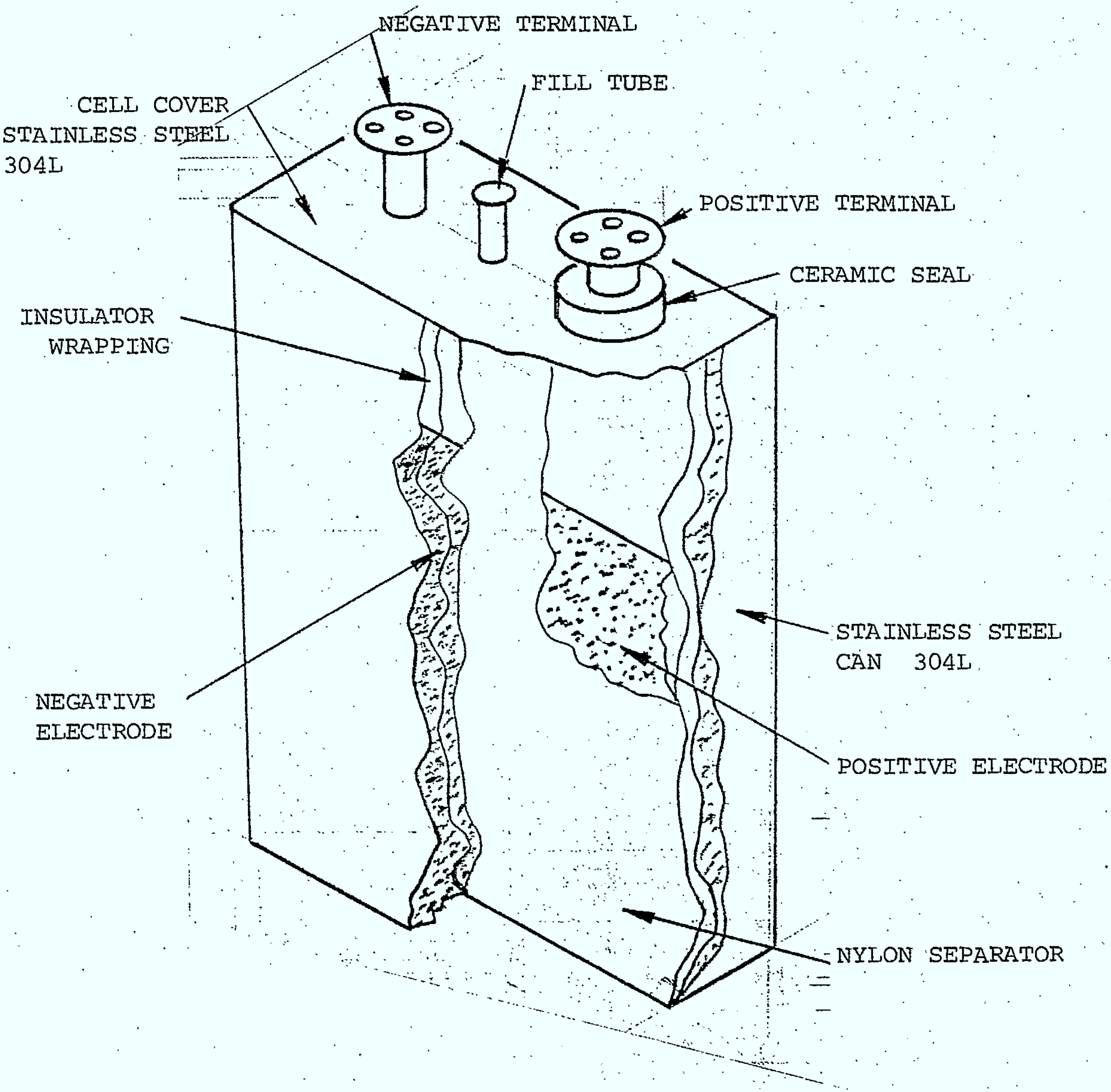


Figure 15 Ni-Cd Cell Construction

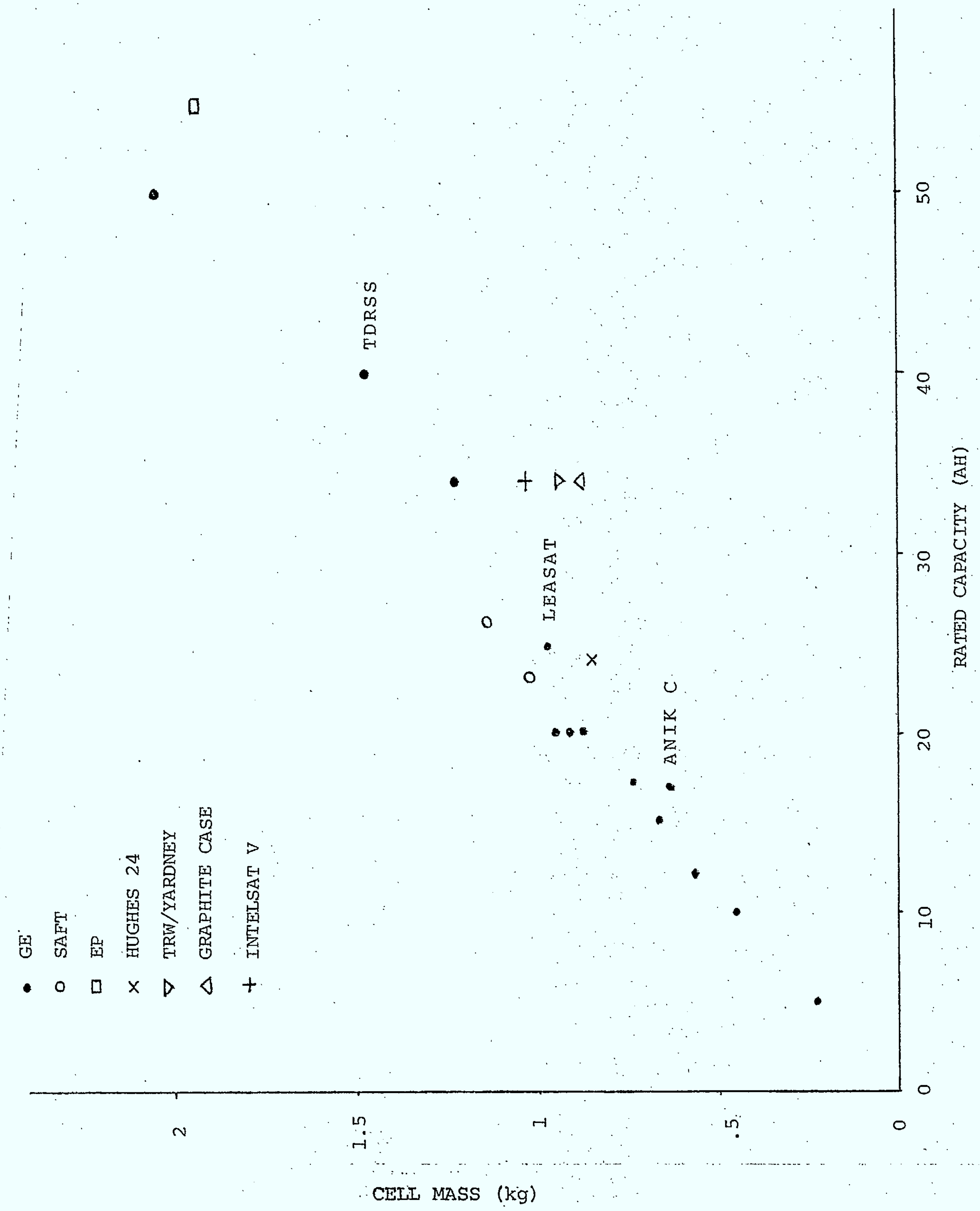


Figure 16 Ni-Cd Cell Mass

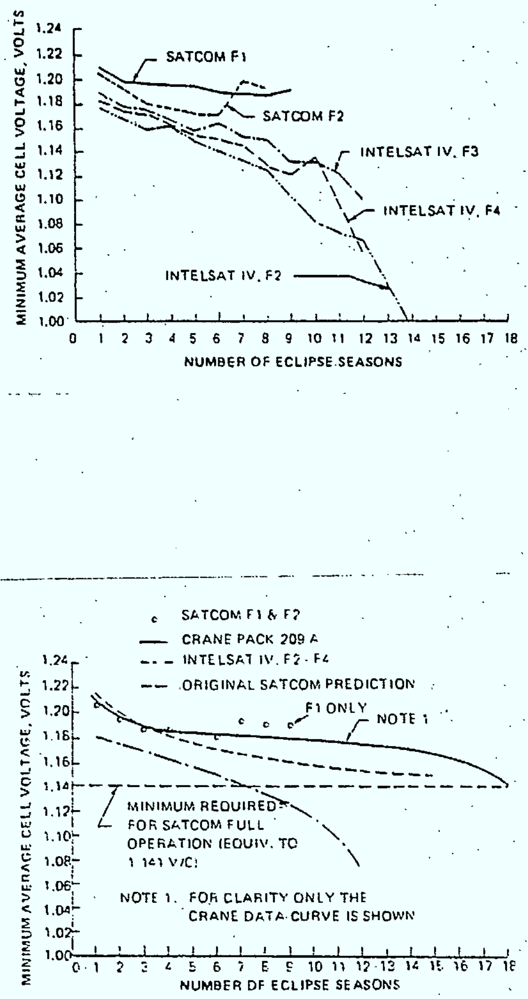


Figure 17 SATCOM and INTELSAT IV Flight Data

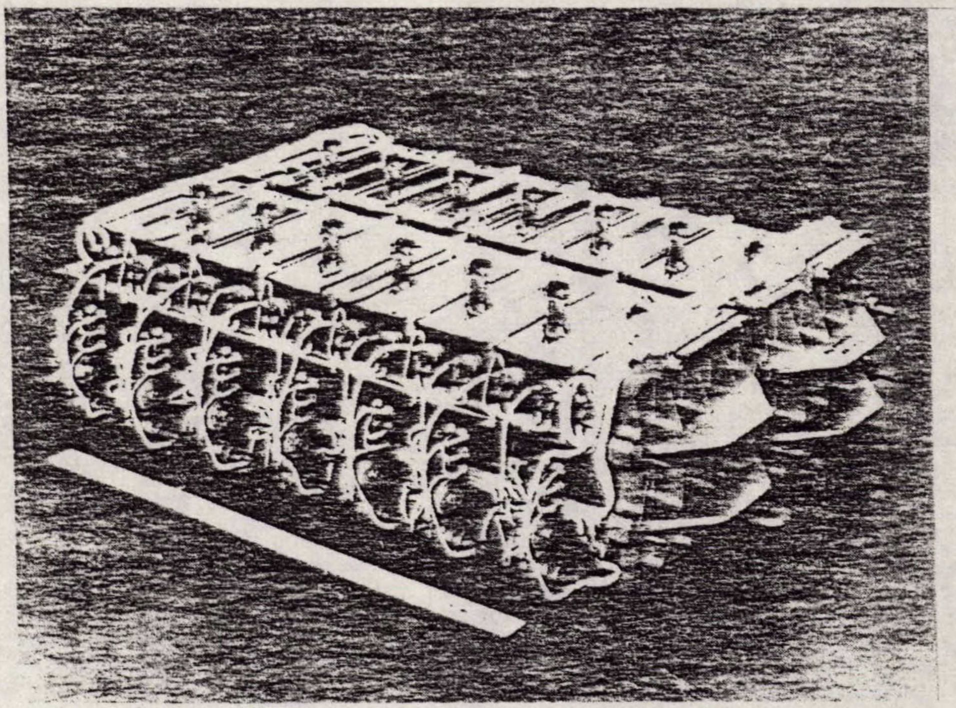


Figure 18 INTELSAT V Battery Pack

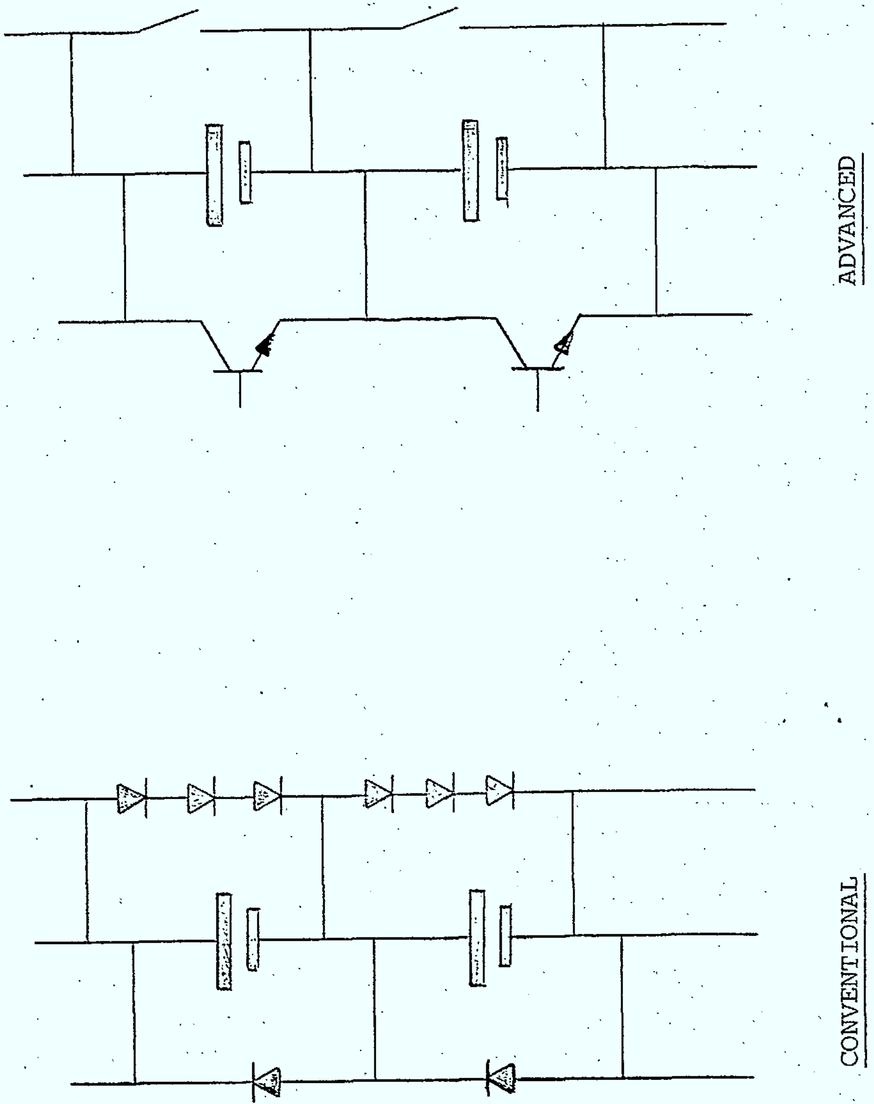


Figure 19 Cell Protection Schemes

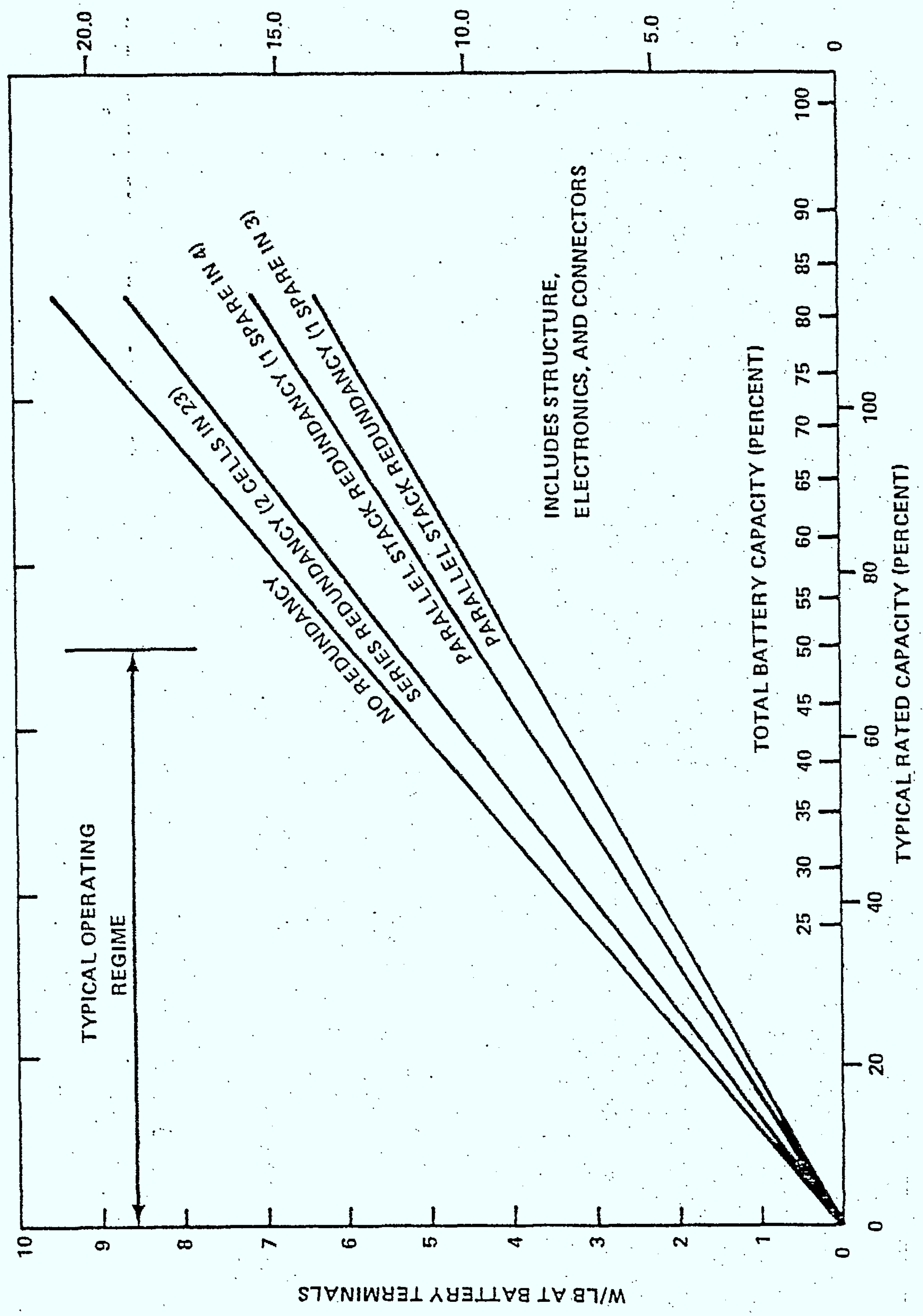


Figure 20 Ni-Cd Battery Energy Density vs Depth of Discharge

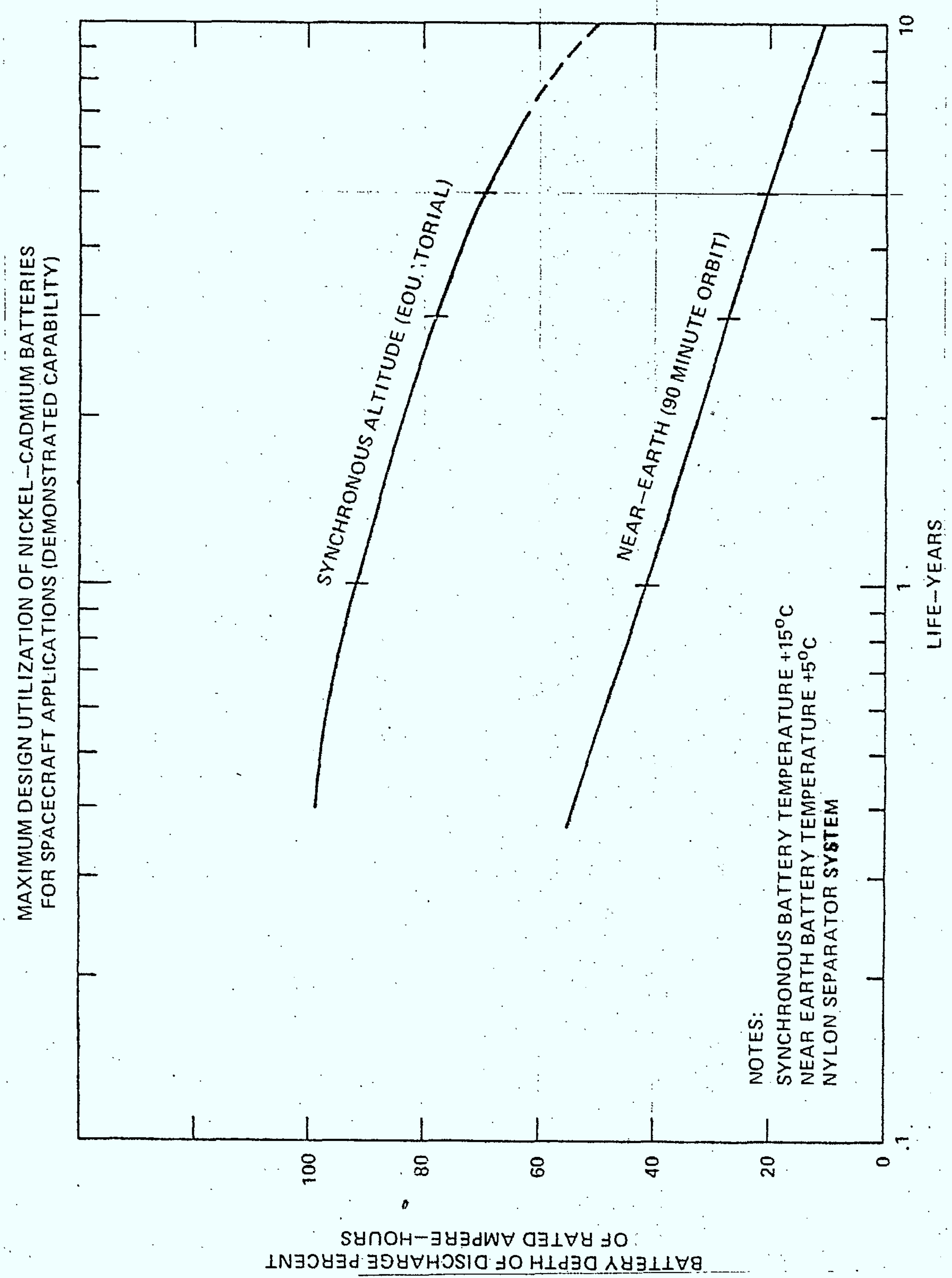


Figure 21 Maximum Design Utilization of Nickel-Cadmium Batteries for Spacecraft Applications

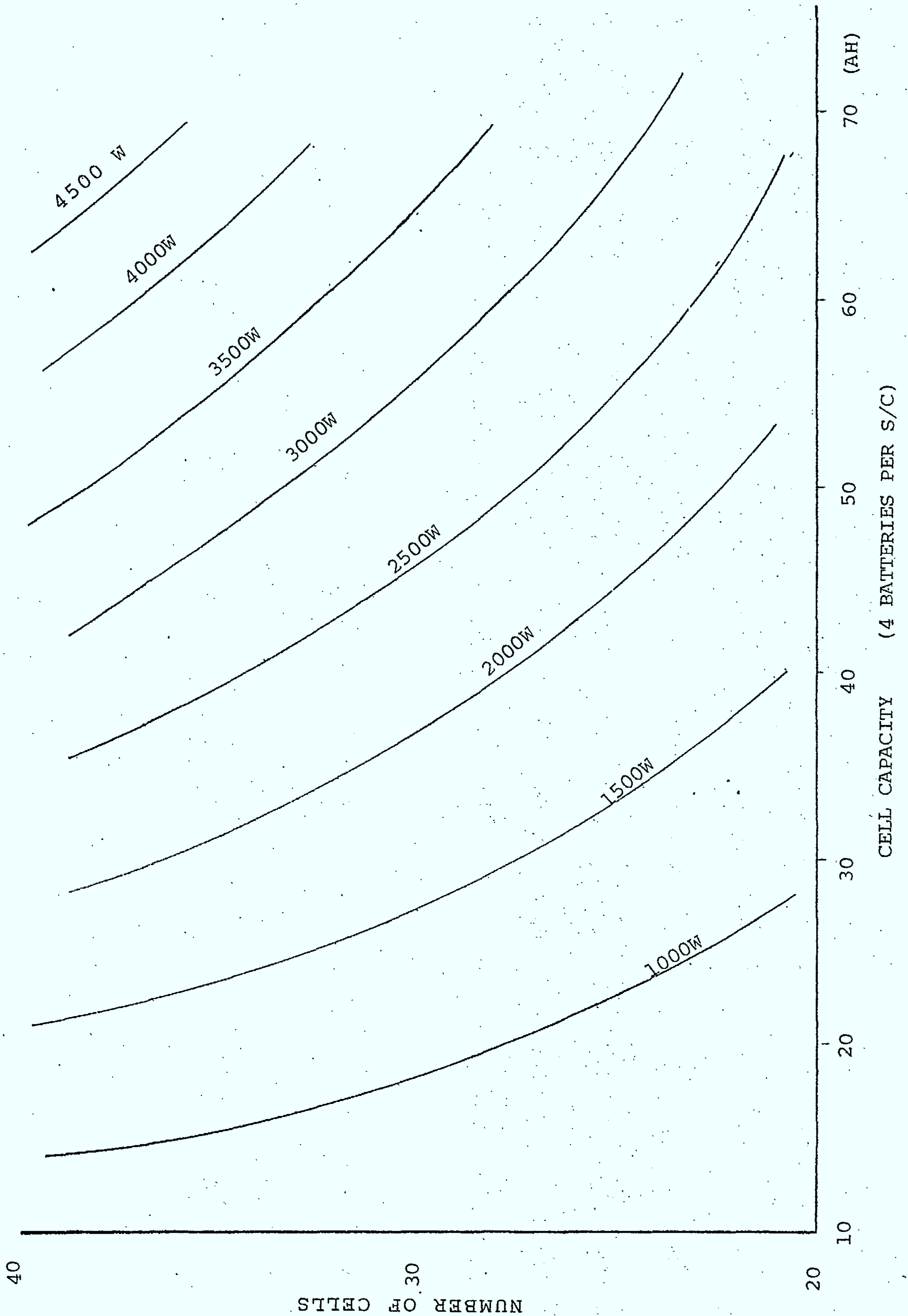


Figure 22 Number of Cells vs Capacity for Increasing Eclipse Loads

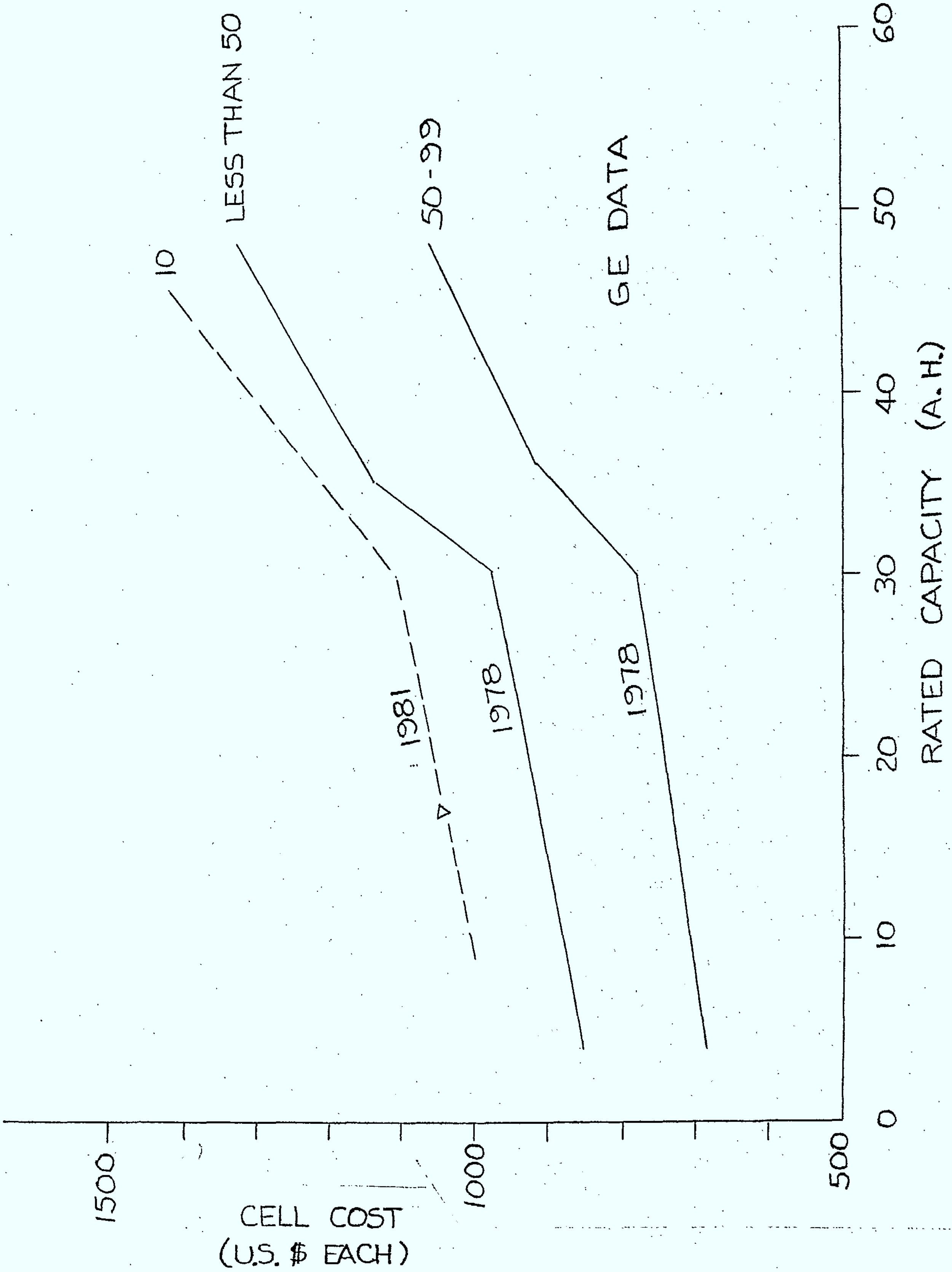


Figure 23 Ni-Cd Cell Costs

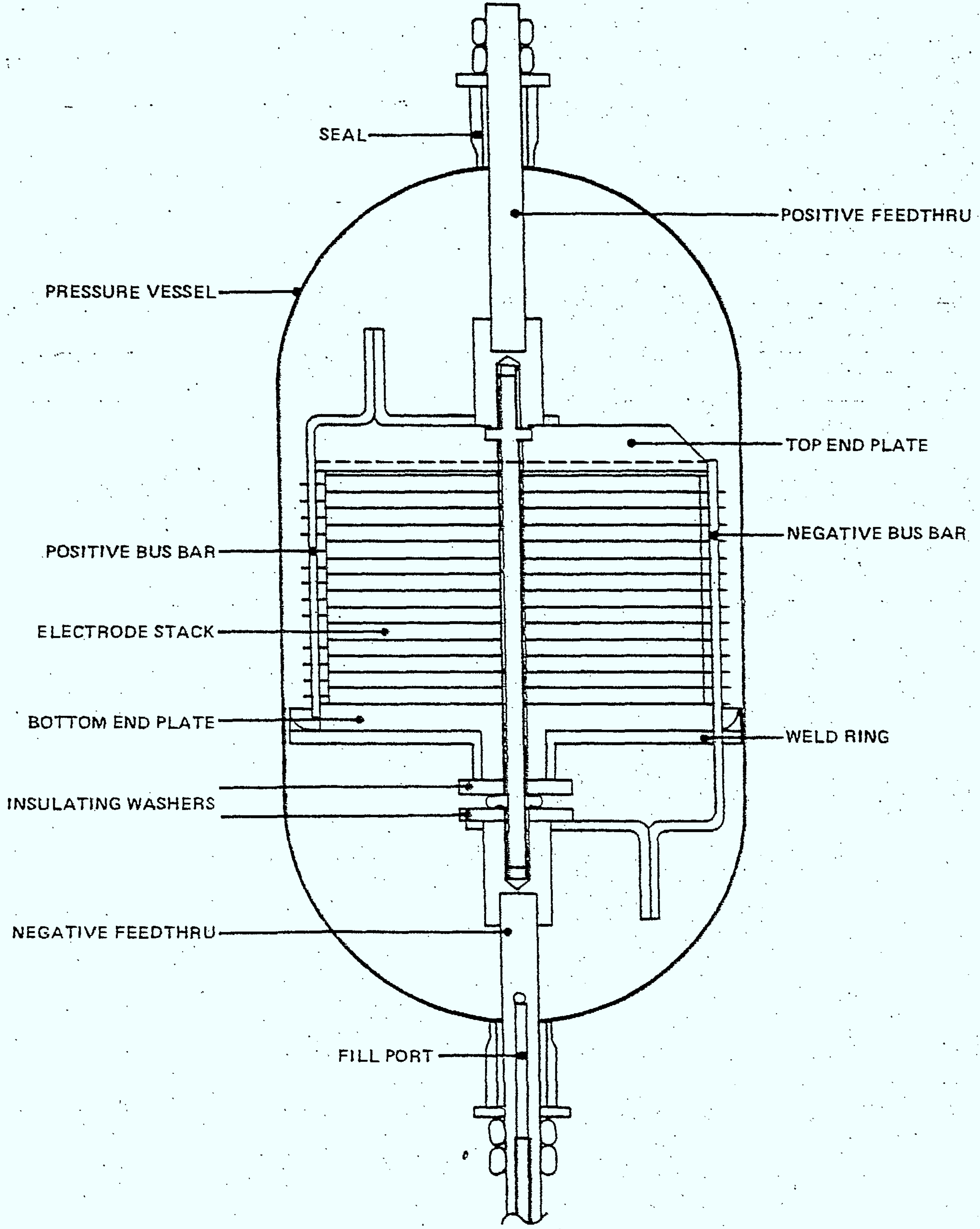


Figure 24 Nickel-Hydrogen Cell

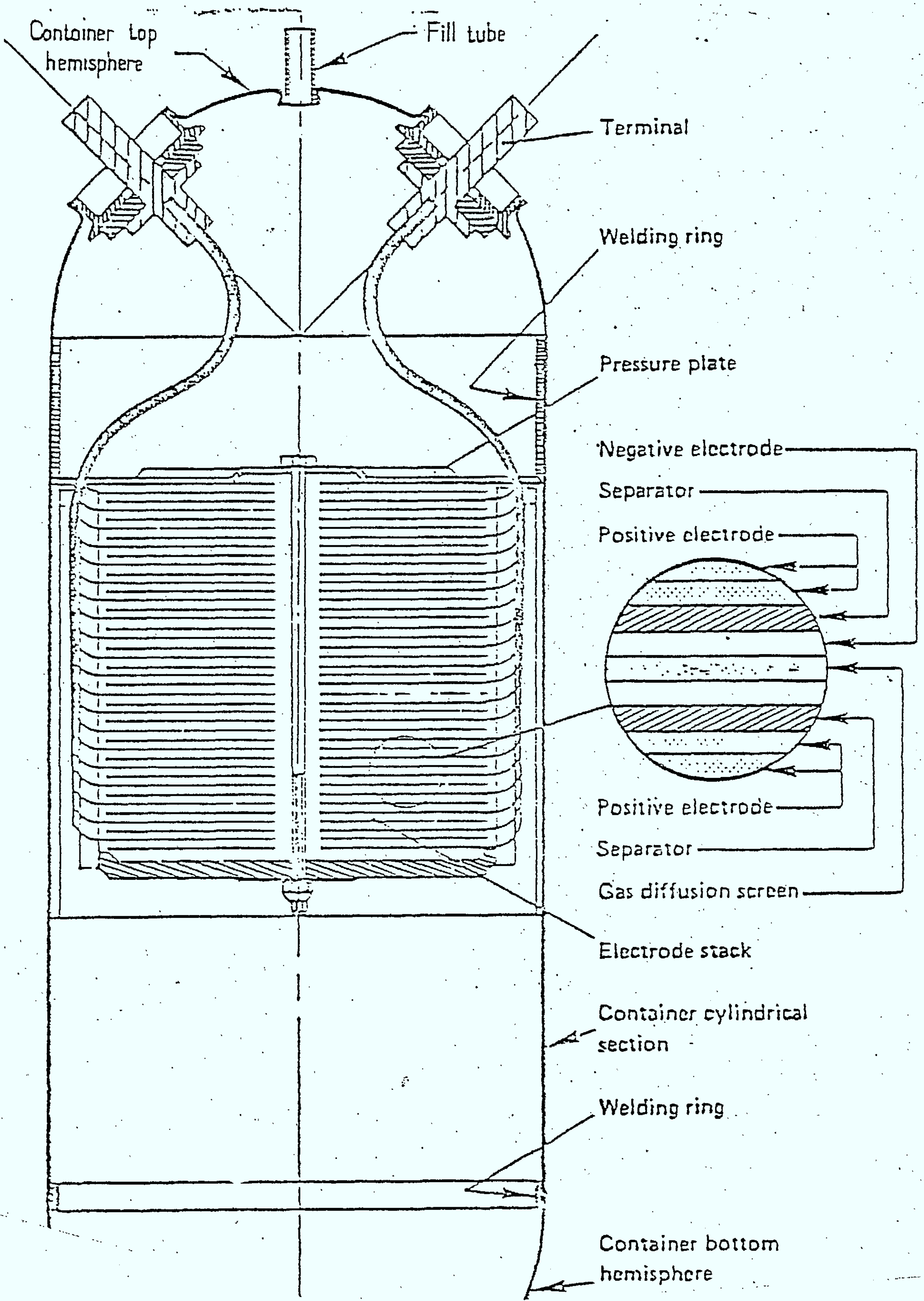


Figure 25 SAFT Ni-H_2 Cell

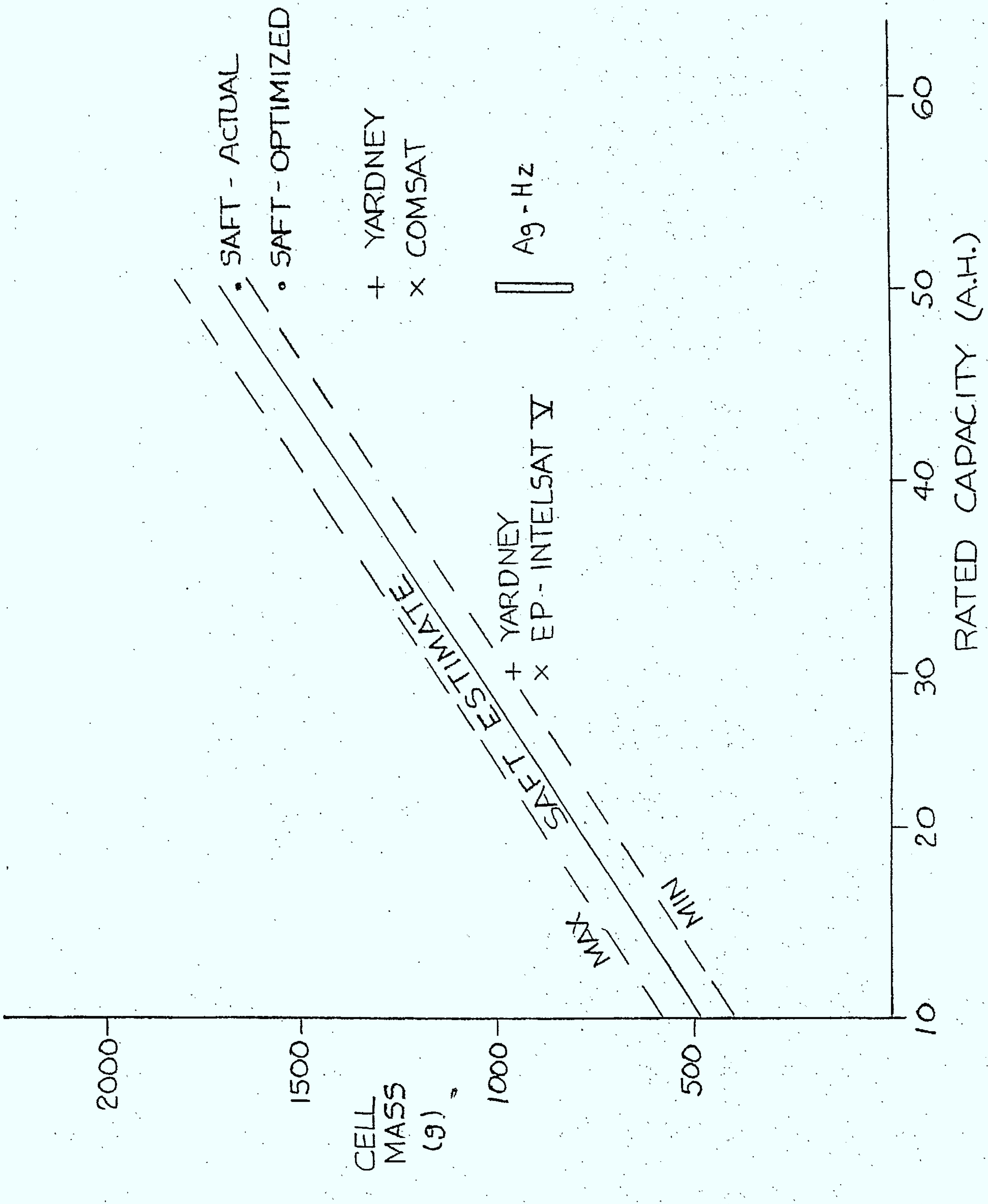
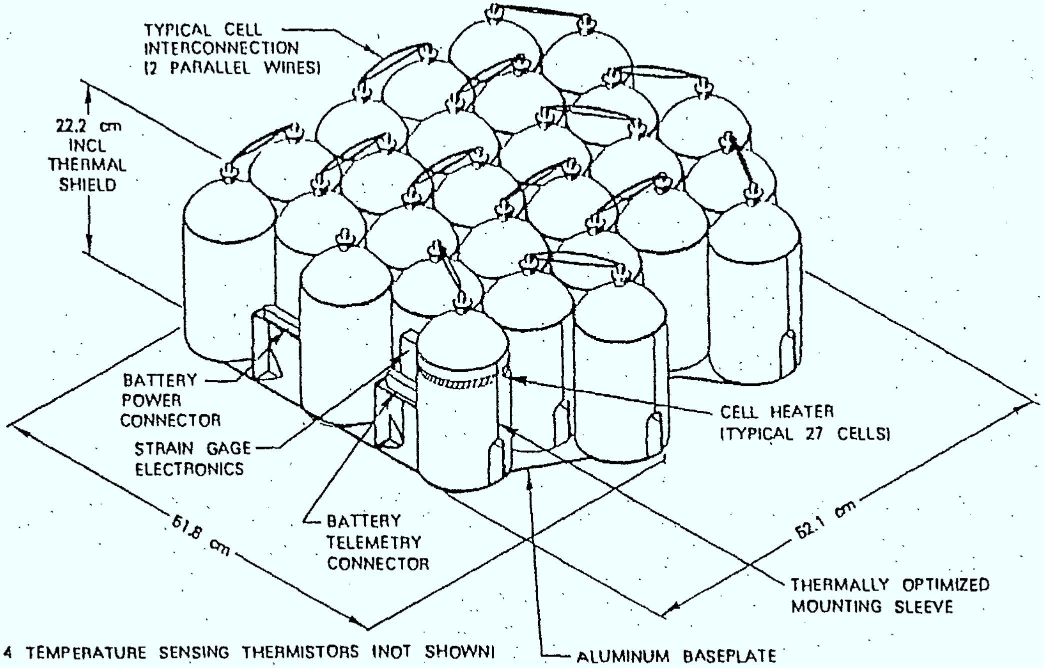


Figure 26 Mass of Nickel-Hydrogen Cells



- 4 TEMPERATURE SENSING THERMISTORS (NOT SHOWN)
- EACH CELL DIODE PROTECTED (NOT SHOWN)
- PRESSURE SENSING STRAIN GAGES ON ONE CELL (NOT SHOWN)
- BATTERY WEIGHT - 30.1 kg

Figure 27 INTELSAT V Ni-H_2 Battery

APPENDIX A

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81-3	J. Beck, CAL. Trip Report, visit to Hughes Aerospace
81-4	J. Beck, CAL. Trip Report, visit to Eagle Picher
81-5	G. H. C. Mackie, CRC, Trip Report, TRW/Hughes/Ford Aerospace
81-6	Product Specification, Hermetically Sealed Nickel-Cadmium Cell 35 A.h, CAL document BATT-II-2-001

APPENDIX B

TRIP REPORTS

The Trip Reports listed below are included on the following pages.

1) 4 March 81
   Hughes Aircraft, El Segundo, 28 Jan. 81.

2) 6 March 81
   Eagle-Picher Inc., Joplin, Mo., 29 Jan. 81.

3) 4 March 81
   TRW, Inc., Redondo Beach, 27 Jan. 81.

4) 18 February 81
   G. H. C. Mackie; TRW, Hughes Aircraft and Ford Aerospace.

5) 3 September 80
   15th IECEC

CANADIAN ASTRONAUTICS LIMITED
1024 Morrison Drive, Ottawa, Ontario K2H 8K7
(613) 820-8280 Telex: 053-3937

March 4, 1981

TRIP REPORT

HUGHES AIRCRAFT, EL SEGUNDO, 28 JANUARY 1981

1. With G. Mackie (CRC) and W.F. Payne, visited Steve Stadnick to discuss Ni-H_2 cells. Dr. Howard Rodgers was present part of the time.

2. Points from the discussion:

- The large volume of Ni-H_2 cells is not a constraint for shuttle launched S/C but may be for expendable e.g. Ariane types.

- The battery Hughes are developing is for a 10 year mission life at 40% DoD. Design is for 5 year wet shelf life, 2.5 year LEO operation followed by 7.5 year unspecified mission operation.

- Cells are mounted on 6.1 lb/ft^3 Al honeycomb. Cells (9) weigh 21.83 lb., total pack is 31.80 lb. Protection relays (Leach) weigh 1.63 lb.

- These are LEO cells. Leads are good for 5C (.4C is normal rate). Plates are lightly loaded. 10 cc excess electrolyte.

- Battery has thermal end cap (10 ml, .15 lb/cell) for radiation and shorting protection. May not be necessary for GEO, though cells must be protected from case shorts. 32-70°F baseplate temperature is predicted. 2 strain gauges per pack.

- Will use electronic integration to give 120% recharge ratio (EOL high temp. figure, based on parametric tests). Cells are not matched. Charge rate should be greater than C/10 at temperatures greater than 20°C.

- Hughes have had very good experience with regard to safety. Shorting tests have shown current is limited to 6C and pressure drops. Typical cell pressures are 500 psi EOC, 100 EOD.

- Recondition capability of C/60 is provided. Cells show pressure increase with cycling, from 70 to 80 psi over 3 years, due to charged but unavailable material. Can be returned by C/100 discharge or short for 2 months.

- H_2 leak tests are difficult but rates can be reduced from the tests. Rates of 22 psi over 10 years have been found, due to diffusion through the terminal seal. The Inconel 718 is unaffected by the H_2/KoH environment (30,000 + cycles).

- Ni-H_2 cells are preferred for long-term use. -ve electrode is stable for long period. Separator is inert. Surface tension drives excess electrolyte into tight spots (where it is needed). GEO cells don't need wall wick. Seal is very reliable with 2000 psi hydrostatic pressure. No problems experienced with brittleness of separator or flaking of

.../3

wall ceramic coating. Cells have passed 34 g.

- EP make +ve plates to Hughes procedure and "watch every move" during acceptance test. Hughes visited EP last December and were somewhat critical of their process control, etc.

- Hughes prefer to sell satellites rather than cells. Present max. capability is 25/50 cells/month. Could expant to 100/month if demand existed. Cost would be twice EP's, because of QA and conservative approach.

- Miscellaneous points: Latest design of Shottky diodes with guard rings are not susceptible to transients; PQ treatment gives Ni-Cd cells good charge efficiency at room temperature; we saw qualification pack in battery laboratory, which seems to be well set up.

J.R. Beck

c.c. W.F. Payne
G. Mackie (CRC)

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1024 Morrison Drive, Ottawa, Ontario K2H 8K7
(613) 820-8280 Telex: 053-3937

March 6, 1981

TRIP REPORT

EAGLE - PICHER INC., JOPLIN, MISSOURI

29 JANUARY 1981

1. Visited Jack N. Brill, Product Manager, Nickel Cadmium and Nickel Hydrogen batteries, and (briefly) Lee E. Miller, Marketing Manager, Battery Systems.

2. The EP plant developed from a lead mine, and appears to have been in existence for a considerable time. The Joplin area has a population of about 1 million, based mainly on light industries. EP prefer to hire locally as the wage rates, especially for engineers, are unattractive to outsiders, although living costs are low. EP obviously sell a good many space- or mil- qualified batteries of many types, primarily Silver-zinc for launch vehicle and missile applications, Nickel Cadmium and Nickel Hydrogen.

3. EP are enthusiastic about Nickel Hydrogen cells. At present they are manufacturing both Air Force and Comsat types. They quoted costs of $4500 - 6000 for Air Force 50 AH cells (30 - 40 quantity) with Comsat cells being 10 to 15% cheaper. Unless order can be combined with an existing purchase, delivery times of greater than one year can be expected, due to the long lead time required for Inconel 718 procurement.

4. The Air Force cells use positive plates that are electrochemically impregnated at their Colorado Springs

facility, using the Air Force (Pickett) process. The Air Force cells have internally shaped (electrochemical machining) cases that are thicker in the weld area. They are electron beam welded (by a local company). They are harder to make than Comsat cells. Hughes are reputed to have had trouble making them.

5. The Comsat cells use positive plates that are electrochemically impregnated at Joplin using the EP (based on Bell) process. Cases are TIG welded by EP. At least 800 Comsat cells (rated 30 AH) are being manufactured in batches of 74/75 every six weeks. The cell capacity is 35 AH at 30°C, 37 to 38 at 10°C, less at 0°C.

6. Up to 75 AH cells could be made in the present case size if higher pressures were used, but the factor of safety would be reduced below 4:1. I was shown a light weight Nickel Cadmium 50 AH cell (1928 gm) and told a 100 AH version was in work, but one year away.

7. Cell assembly was being carried out under what appeared to be industrial (rather than clean room) conditions, although the person assembling Comsat plates was wearing a white coat and sitting at a laminar flow bench. The battery test equipment looked quite antiquated, though they plan to upgrade it. Other than the attached, I was refused a copy of a Ni-H_2 cell specification on the grounds that they were the customer's property.

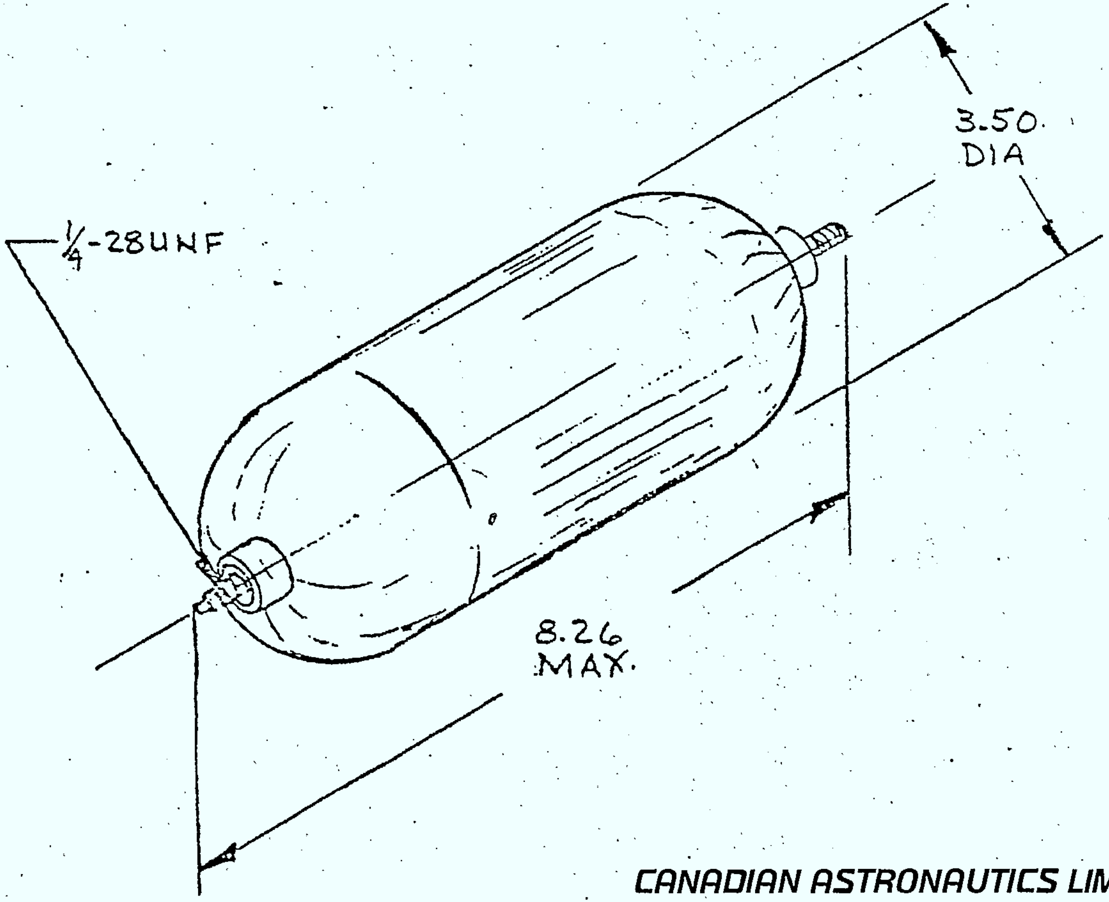
J.R. Beck

c.c. W.F. Payne
G. Mackie (CRC)

MANUALLY-ACTIVATED NICKEL-HYDROGEN SYSTEMS

TECHNICAL DATA

Model	RNH-30-1
Program Use	Satellite
Voltage	1.21 V Min
Capacity (amp-hrs)	30 Nominal
Rate (amps)	15
Weight (lbs)	1.96 Average
Volume (in^3)	44.54 + Boss & Terminal
Temperature	0°C to 30°C
Heater	N/A
Max. Heater Time	N/A
Max. Activation	N/A
Charge Retention (72 Hours @ 10°C)	70%



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March 4, 1981

TRIP REPORT

TRW, INC., REDONDO BEACH, 27 JANUARY 1981

1. With G. Mackie (CRC) and W. Payne, visited Dr. Willard Scott Jr. (and H. Cohen) to discuss spacecraft batteries, particularly Nickel-Hydrogen types.

2. Points from Ni-H_2 discussion with W. Scott:

- The Hughes/AF Ni-H_2 cell is an expensive cell that has been optimized for LEO applications, by including features such as a wall wick and increased electrolyte. Other designs should be good for 1000 to 2000 cycles. EP are the only qualified source. Hughes are doubtful and expensive. For evaluation cells he would buy to a rudimentary TRW specification.

- EP can make EI plates and negatives but can't make cadmium negatives or chemically deposited positives. They have an "independent attitude". For a flight program Scott would go to EP with massive contractual documentation.

- Ni-H_2 cells appear today to be good for a 5 year mission. He would commit today to their use. Drawbacks are:
  - there is no life test or reliability data available

- thermal performance (can be estimated)
- charge control (unknown)

- DoD should be 70% for 8/9 year life, 80% for less. Main failure mode is redistribution of the electrolyte. At higher DoD's the +ve material comes out of the plate.

- The situation re reconditioning is confused. At this time, it is not possible to judge whether it is required or not.

- Bypass circuits are too costly. Ni-H_2 characteristics are more predictable than Ni-Cd. Jury is still out on asbestor versus zircon separators. No traces of hydrogen embrittlement have been found.

- Ni-H_2 cells must be kept cool to reduce self discharge, which is orders of magnitude higher than for Ni-Cd. It is prudent to terminate overcharge because of the heat generated. If the case temperature is too low (10°C) water is distilled out of the electrolyte. If Ni-H_2 cells are reversed, the only problem is the heat generation, as the H_2 generated recombines.

3. Discussion on Ni-Cd cells:

- FLT SATCOM has shown no EOD degradation after 3.5 years with 73% DoD.

- Tests have shown good results for 45 seasons with OV reconditioning.

- Reconditioning is carried out at C/80 rate until

.../3

28 AH removed (this was the C/2 capacity at launch) or battery reaches 18V. This corresponds to 1.1V/cell. Probably possible to get 32 AH out at C/80 if cell completely drained. This reconditioning method completely discharges all the active material, and locks the cells together.

- Pellon separators are good for 10 years below 10°C. Effects of carbonate are not understood. Proper reconditioning, etc. may eliminate effects. Have seen perfect cells with 25% carbonate.
- TDRSS 40 AH cells are similar to '68 GE design but with thinner walls. These have shown 9 yr. life on ATS(?). Plates are chemically deposited, cell is heavily loaded and has silver treated negatives.
- Teflonation is preferable in LEO cells to impede cadmium migration.
- Customers heavily influence battery design, and won't buy real-time tests. For HEAO NASA-MSFC directed use of SAFT (America) 20 AH cells.

J.R. Beck

c.c. W.F. Payne
G. Mackie CRC

Government of Canada Gouvernement du Canada

MEMORANDUM NOTE DE SERVICE

TO / À: Distribution

FROM / DE: George H.C. Mackie

SECURITY - CLASSIFICATION - DE SECURITE:

OUR FILE/NOTRE RÉFÉRENCE:

YOUR FILE/VOTRE RÉFÉRENCE:

DATE: 18 February, 1981.

SUBJECT / OBJET: Trip Report

During the week of 26 January 1981, and as part of a study contract in support of DBS, W.F. Payne and J. Beck of CAL and G. Mackie of CRC visited the U.S. companies identified below for the purpose of obtaining information on nickel-hydrogen spacecraft batteries.

J. Beck, in the same period, also visited the Eagle Picher manufacturing facility located in Joplin, Missouri. This company is being set up as a "second source", for the USAF designed nickel-hydrogen cell, hitherto made exclusively by Hughs Aircraft. Eagle Picher is also the main supplier of the COMSAT version of the nickel-hydrogen cell which is being used on Intelsat V. This visit will be described in a separate report.

During the visit to TRW Systems, discussions were also held with TRW antenna specialists working on computer modelling of antenna patterns and configurations. This discussion will be described by W.F. Payne in a separate report.

1. TRW Systems, Redondo Beach
   Visited 27 January, 1981 by W.F. Payne, J. Beck and
   G. Mackie
   Discussions held with H. Cohen and W. Scott

A meeting with Dr. Willard Scott the TRW battery consultant was arranged at short notice by H. Cohen.

The discussions with Dr. Scott covered a wide range of topics affecting both NiH_2 and NiCd cells. What follows is a summary of some of the interesting and or important points arising from the meeting:

- Scott feels that the NiH_2 system is not effective (as compared with NiCd batteries) for battery power requirements of <1 KW.

- The USAF NiH_2 cell is he says a general purpose development with emphasis on LEO applications. However, he admits that in comparison with the COMSAT cell it is very expensive typically costing $2,000-$8,000 more per cell.

- Dr. Scott said he would never buy NiH_2 cells from Eagle Picher without generating massive control documentation and monitored procedures.

- The COMSAT cell configuration, he said, was satisfactory although he felt that the lack of a re-circulation system for the electrolyte was a significant drawback. A common failure mode in NiH_2 cells he said, was unfavourable redistribution of the KOH electrolyte within the cell.

- With regard to reconditioning he maintains that no one is sure of the advantages or disadvantages; although TRW do have data which show an improvement with reconditioning provided discharge is carried out at a low rate.

- There have been no identified problems due to hydrogen embrittlement.

- Contrary to the findings of others in the field, he said that the effects of reversal of NiH_2 cells were not yet fully understood.

- Electrochemical impregnation of NiCd cell plates makes the NiCd cell more reliable than chemical impregnation. However, the former are less efficient.

- Teflonated negative plate is superior for LEO applications since Cd migration is slowed down.

Operational Experience

On FLEETSATCOM reconditioning was done to the point where the lowest capacity cell went to zero volts. The NiCd batteries are working well after 45 eclipse seasons in accelerated ground tests.

2. Hughs Aircraft, El Segundo, California
Visited on 28 January, 1981 by W.F. Payne, J. Beck and G. Mackie
Discussions held with Steve Stadnick and Howard Rodgers

There was some initial resistance by Hughs to discuss NiH_2 batteries with representatives of Canadian Astronautics. This was due to U.S. government constraints on the "export of technology" and the fact that NiH_2 cells are included on the U.S. "munitions list". Efforts by G. Mackie to arrange the visit through official CJS and CRAD channels were unsuccessful due to insufficient lead time, and the discussions with Hughs were ultimately arranged with the help of J. Lackner of DREO who was able to get clearance for the visit through a personal contact at Wright-Patterson AFB.

Until recently when steps were taken to set up Eagle Picher as a "second source", Hughs was the sole manufacturer of the USAF design of NiH_2 cell; although the plate material used in the Hughs cell was supplied by Eagle Picher.

A mock up of a 9 cell 25 AH spacecraft battery was shown to the visitors. Cells are flange mounted on 3/4" Hexel material, fitted with a 20 mil facesheet to improve lateral thermal conductivity. A thermal end cap is mounted over each of the cell terminals which are located on the hemispherical extremities at opposite ends of the cell. This cap not only increases the area of heat radiating surface but also serves to guard against accidental shorts during ground handling. The weight of a single battery pack assembly is 31.80 pounds.

Operating Environment

The planned operating conditions for a 10 year life which includes a possible 5 year prelaunch delay is as follows:

Operating temperature	+32° F to +70° F	
DOD	40%	
Charge at BOL	$\frac{C}{7}$	120% return measured using a VCO temperature compensated coulometer system
Charge at EOL	$\frac{C}{10}$	
Trickle charge on stand	$\frac{C}{80}$	

A bi-metallic temperature sensor is fitted to each battery which terminates the charge at 95°C ± 5°C. A ground controlled override is provided.

Vibration

The battery pack has been designed to withstand vibration levels of 34g in all 3 axes.

Miscellaneous Observations

- Hughs say that although they record all cell capacities at the $\frac{C}{60}$ discharge rate it is not necessary to match cells when assembling a battery.
- Failure mode tests have included placing a short circuit across a fully charged cell. Except for an unspecified temperature increase there was no apparent effect on the tested cells which exhibited no change in charge efficiency or capacity.
- Cells have been run in reversal at a continuous 0.73C rate without damage.

- The presence of excess electrolyte does not degrade cell performance and typically cells are assembled with 10 millilitres of excess electrolyte.

Pressure Vessel

The pressure vessel is made by hydroforming INCONNEL 718 sheet which is unaffected by KOH.

The pressure vessel including the seals at the cell terminals is capable of withstanding internal pressures of > 24,000 psig. Tests show rupture occurs at pressures of approximately 30,000 psig.

Pressure Seal at Terminals

The USAF NiH_2 cell uses teflon insulation at the seal. The teflon is passed over the threaded terminal rod and compressed against the walls of the pressure vessel by compressing the ends of the teflon cylindrical insert between nuts and washers on the terminal rod. An identified problem with this arrangement is that the terminal rod tends to rotate (and thus displace the plate interconnect strips) when the clamping nuts used to attach the external wiring to the cell are tightened.

3. Ford Aerospace, Palo Alto, California
Visited on 29 January, 1981 by W.F. Payne and G. Mackie
Discussions held with G. Van Omering - Manager of battery development and applications

Background

As a result of the very encouraging performance of NiH_2 cells on NTS 2 a decision was made in the spring of 1978 to plan for the use of NiH_2 cells on the INTELSAT V program. Therefore, beginning with the fifth INTELSAT V S/C NiH_2 cells will replace the NiCd cells originally specified. The INTELSAT V power subsystem design was required to be compatible with the use of either NiCd or NiH_2 batteries with any change from the former to the latter involving the minimum impact on the S/C configuration. However, the following adjustments to accommodate the NiH_2 battery subsystem are required:

- higher voltage on charge
- reduced number of cells
- reduced battery capacity (from 34 AH to 30 AH)
- DOD increased to 60%
- The increased volume of the NiH_2 battery is relatively easy to accommodate, however the footprint requires some repositioning of other packages within the S/C.

The COMSAT NiH_2 Cell

Before joining Ford Aerospace G. Van Omering worked at COMSAT where he was one of the principals responsible for the design of the COMSAT NiH_2 cell. He was thus able to provide interesting details on the development of the cell which are discussed below:

Pressure Vessel

Like the USAF cell the pressure vessel for the COMSAT NiH_2 cell is hydroformed. As a result of the forming process the surface of the INCONNEL 718 material develops a rough pitted appearance which mainly for cosmetic reasons was removed on the early cells by liquid honing. It was subsequently discovered that the liquid honing process causes local high stress areas, and this practice has now been discontinued.

Also during the development phase the wall thickness of the pressure vessel was increased where the two halves of the pressure vessel are welded together. This too was found to result in high stress regions and is no longer adopted.

Mounting Sleeve

The mounting arrangement for the cell consists of an aluminum mounting sleeve which is cast and then machined to the required mechanical tolerances. This sleeve is in the form of a hollow cylinder with integral machined mounting brackets that allow the cell to be mounted in any position in the battery pack. The mounting sleeve is insulated from the cell wall by a 12 mil layer of RTV. An interesting feature of the mounting sleeve is an integral mechanical mounting bracket and heatsink for a 25 Amp diode for discharge open-circuit protection, and three series 6 Amp diodes for open-circuit charge protection. These are mounted on the inside of the sleeve so as to utilize an otherwise unused volume between the cell dome and mounting sleeve.

Terminal Seal

The COMSAT cell uses a ZEIGLER type seal. This consists of a nylon plug, which is moulded in situ to fill the void between the terminal post, and the hollow cylinder protruding from the top of the container dome. A compression seal is then formed by crimping the wall of the protruding cylinder. Van Omering claims that this terminal configuration is considerably more resistant to rotation of the terminal post than the teflon seal used on the USAF NiH_2 cell.

Filter Tube

One of the two cell terminal posts is drilled, and acts as a filter tube which is pinched off after the electrolyte is put into the cell.

Thermal

The cells are mounted on a 70 mil thermal spreader. Heat loss is mainly by conduction; there being very little loss from the dome ends. by radiation. The designed temperature limits are 0^oC to $+25^oC$. Ford prefer to operate at $+10^oC$ even though max capacity occurs at 0^oC. This higher operating temperature results in a 3-4% loss of capacity.

Redundancy and Safety Precautions

- Wiring within the battery pack including interface connectors employs 3 wire redundancy.
- A polyurothane conformal coating is applied to the cell dome ends to minimize the possibility of accidential short circuits to the adjacent terminals.

For ground operations, a safety cover is placed over the entire battery assembly. This is replaced by a different cover for thermal control immediately before launch.

Vibration

Qualification is done at the battery level. However sin sweeps are also done with single mounts. The levels used are:

5g sin
20.6g RMS in the Z axis

Leak and Pressure Tests

The filter tube is used for a helium leak test at 600 psi. In addition a hydrogen proof test at 1000 psi is done on each assembled cell.

Permitted leakage rate is based on a loss of <10 psi in 7 years. The burst pressure of the container is 29,000-32,000 psi.

Performance Tests

- A qualification battery has begun life testing at Ford Aerospace.
- A second qual battery is undergoing real time life testing at COMSAT.
- Ford have for 2 years been cycling a prototype 7 cell NTS 2 battery in series with a nickel cadmium battery. After "considerable abuse" the EOD voltage of the NiH_2 cell is approximately 30 mV greater than the NiCd cells. Between eclipse seasons reconditioning to just over 1V/cell is being carried out. The test batteries have experienced an accidental high rate discharge to 1 volt/cell.

Cell Matching

Ford select cells for a given battery on the basis of in-house test data. These include:

a) capacity

b) peak charge voltages at $0^{\circ}C$, $10^{\circ}C$ and $20^{\circ}C$.

Reconditioning

It is planned to recondition batteries between eclipse seasons.

Trickle Charging

Trickle charging will be done between eclipse seasons but it has not yet been decided whether this will be on a 50% time basis or at a continuous $\frac{C}{50}$ rate. If the interrupted trickle charge regime is adopted the average charge rate will be $\frac{C}{50}$ to $\frac{C}{60}$.

Availability of NiH_2 Batteries

Ford are currently supplying batteries to Boeing and would consider supplying batteries for Canadian use subject to U.S. government approval.

4. Summary

It is evident that the nickel-hydrogen battery has not completely excaped the "black art" approach which has characterized the production and application of the nickel-cadmium system for so long. Nevertheless, there can be no doubt that the NiH_2 battery is displacing the NiCd battery for both GEO and LEO missions during the 80's.

The unfavourable energy/volume ratio of NiH_2 batteries has thus far not introduced serious compatibility problems due to the large unused interior volume typical of so many current S/C configurations. As techniques for the use of common pressure vessels now under investigation are developed, the volume of NiH_2 battery subsystems should not only be reduced but it should be possible to better utilize available volume within the S/C without significant changes in the S/C centre of mass.

It is generally accepted that the nickel-hydrogen system is significantly more tolerant to excessive overcharge and to cell reversal. This should simplify the design of battery management systems in terms of first failure protection.

The increasing requirements for NiH_2 cells as well as the limited number of reliable sources will almost certainly increase the already long procurement lead time, and our planning for the use of such cells must reflect this important consideration.

G.H.C. Mackie

Distribution List Attached

Distribution

J.N. Barry	
M. Palfreyman	
R.H. Hum	
H.R. Raine	
M. Bouchard	
T. Nishizaki	
R. Wojcik	
W.F. Payne	CAL
J. Beck	CAL
J. Lackner	DREO

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September 3, 1980

TRIP REPORT

15th INTERSOCIETY ENERGY CONVERSION ENGINEERING CONFERENCE, 18-22 AUGUST 1980

1. GENERAL

The conference appeared reasonably well attended, with 800+ registered, although some speakers were unable to attend because of travel budget restrictions. It was disappointing that there was no European representation.

A total of 410 papers were presented, of which 80 were in the Aerospace Power category; an increase of 33% over last year. George Mackie (CRC) and I attended the majority of the Aerospace Power presentations, missing only those that were presented concurrently and Friday's session (Aircraft, Missile and Launch Facility Batteries). Attendance at these presentations was in the 40 to 100 range.

The papers have been published in a 3-volume set of proceedings, which I have. The index is attached to this report.

The following comments reflect what I think are the interesting and relevant points from the Aerospace Power sessions and also some of the answers to questions. The references are to paper identification numbers in the proceedings.

2. POWER SYSTEM REQUIREMENTS AND ISSUES

Papers (809015,809016) by Lyn Randolph of NASA HQ and T. Mahefkey from the Air Force showed a clear trend towards requirements for 10-50 kW spacecraft power levels in the next decade, with even higher levels projected thereafter.

Since NASA has launched only about 120 kW of solar power in total to date, considerable development work is required in the next few years. Solar power is expected to be used for most civilian needs, which include projections of 100-250 kW low-earth orbit (LEO) applications, whereas military systems may use nuclear reactor systems for 50 kW and higher requirements.

The NASA Space Power Research and Technology program aims at advancing the U.S. technology base to meet the requirements outlined above, with two main directions: very high power levels at low cost, and low power, high-performance systems such as are required in geosynchronous (GEO) or planetary missions. Areas of development are:

- Photovoltaic Energy Conversion
- Chemical Energy Conversion
- Thermal-to-Electric Conversion
- Power systems Management and Distribution
- Advanced Energetics.

An unpublished paper by Bob Finke of NASA-Lewis described the NASA/DOD High Orbit Spacecraft Energy Technology program (SET), which is in its initial phases. A "strawman" mission was developed and discussed by working groups earlier this year. The mission parameters were:

- Shuttle/IUS launched, GEO orbit
- 25 kW EOL required by payload in sunlight
- 2.5 kW hr battery capacity
- Dissipate 25 kW of heat from payload and 3 kW from power system
- 10 year life
- Technology available in 5 years.

The working group conclusions were:

- Photovoltaics: 350 W/Kg is expected to be achieved by 1985, focus on SET goals would require minimum impact on present technology.

- Energy Storage: Full power is required in eclipse, not 1/10th as baselined. Although there is a potential for 40 Whr/lb, 200-250 AH cells being available, 60 Whr/lb is required. Present advanced energy storage technology programs are not focussed on SET requirements, and energy storage is a major technical constraint.

- Thermal Management: Another major driver, thermal management must be established as a technological discipline. 100 W/Kg dissipation is required. A program focussed on SET goals is required.

- Power management: High-voltage, high-frequency distribution systems with integrated autonomous fault protection are required. The on-going technology program addresses most SET requirements.

NASA-Lewis plans to contact industry and the universities in the near future regarding contract work toward the SET program plan.

A related paper (809134) by L. Slifer of GSFC discussed the recommendations of the Power Subsystem Panel at the NASA Flight Technology Improvement Workshop held last year. The panels prioritized list of areas that require development was:

- Analytical Modelling of the Power System
- Power System Monitoring and Degraded System Management
- New Component Development
- High Voltage ((Kilovolt) Technology
- Reliable Solar Cell Interconnections
- Nickel-Cadmium Battery Manufacturing and Application Technology
- Substorm and Plasma Design Data
- Engineering Data Base
- Rotary Joints for Power and Signal Transfer
- On-array Power Management.

For their part, DOD have instigated a High-Voltage High-Power Solar Power Systems Study (809137) to provide the technology base for the development of a 6-12 w/lb, 10-50 kW power module for late 1980's DOD missions.

3. POWER SYSTEM MANAGEMENT

A breadboard power system with autonomous microprocessor control has been developed by JPL (809135) for planetary missions. A preliminary evaluation of the system has shown significant advantages to the concept:

- Reduced failure detection and response time
- Reduced inter-system wiring
- Reduced mission analysis manpower requirements
- Increased power system data handling capability
- Reduced pre-launch testing manpower requirements.

A NASA-sponsored study (809273) shows that high-frequency AC distribution systems using resonant converters would be superior to DC systems in high-power (100 kW) space platform applications.

4. POWER SYSTEM SIMULATION

At the converter level, a CAD model for a saturating transformer was described (809020). The model gives an accurate simulation with low computational requirements, which was previously not possible.

At the spacecraft level, simulations of complete power systems are now routinely used to optimize designs and predict on-orbit array and battery performances, as described by Lockheed (809021), Hughes (809022) and Intelsat (809023).

Bill Billerbeck's (Intelsat) paper was particularly interesting. Intelsat have used data from 36 GEO spacecraft batteries, covering over 70 orbit-years, to develop a statistical model that will predict battery performance for several years in advance. The model takes into account both cell ageing and the effects of reconditioning.

Although Intelsat have experienced a couple of open-circuit (attributed to abuse of the cells with a continuous c/10 overcharge) and some random short-circuited cells, the predominant failure mechanism is a gradual decay in cell voltage. Existing Intelsat spacecraft recondition to 1 v/cell and lifetimes of up to 10 years are predicted. Reconditioning to lower voltages and possibly implementing intensive reconditioning of poor performance cells can be expected to give improved performance in future spacecraft. A potential need for adaptable telemetry systems that would have the capability of altering channel allocations, during fault diagnosis, for example, was mentioned.

5. NUCLEAR POWER SOURCES

Technically, nuclear reactors are promising candidates for supplying the 100 kW and greater demands of space-based radars and other advanced systems, but the safety and political issues remain to be resolved. (Paper 809139, D. Buden, Los Alamos Scientific Laboratory).

At a lower power level, results from a 1.3 kW ground demonstration dynamic isotope power system (DIPS) were presented (809138). The DIPS (809201) offers the potential of:

- Increased user power
- Extended mission life
- Improved thermal control
- Improved orbit stability and predictability (because of reduced solar pressure)

But work on this program has ceased.

Other papers (809202, -203, -204) described Radioistope-heated Thermoelectric Generator RTG's that will be used, for example, on the Solar Polar Mission.

6. HIGH VOLTAGE AND CONVERTER TECHNOLOGY

Mike Glass of Lockheed described a 6 kW converter for the Shuttle Power Extension Package (809146). The converter consists of two 3 kW converters operating in parallel and which convert 130 V (nominal) from the array to 32 VDC. Features of the converter are:

- Transformer coupling to reduce losses inherent in a bucking regulator design at this voltage ratio
- Incorporation of a peak power tracker
- Efficiency of 92%
- 65 lb mass
- Use of the D60T "snowflake contact" 50A, 500V bipolar transistor that NASA has developed.

A paper by Boeing (809149) showed that accumulation of cosmic dust can be expected to create problems on high-voltage arrays.

The use of heatpipes to achieve a 40% reduction in the mass of a 3 kVA transformer was described by M. Chester of TRW (unpublished paper, NASA Technical Memorandum 79270).

7. PHOTOVOLTAIC APPLICATIONS

The papers in this group were divided into two major categories: concentrator arrays and descriptions of current spacecraft power systems.

Concentrator arrays appear to hold promise for lower cost designs than planar arrays in high power applications. Since the field is fairly new, a wide variety of concepts was discussed, with concentration ratios (CR) varying from 2 to 1000.

JPL (809074) showed that concentrator arrays have advantages over RTG's in deep space applications out to 10 AU from the sun. The Air Force (809073) are also interested in them because of their potential cost savings and enhanced survivability to natural and artificial environments.

NASA (809067) and Lockheed (809271) showed that GaS solar cells have the potential for substantial advantages over Si cells in the areas of efficiency, elevated temperature operation and radiation damage stability. CR's of 4-6 appear optimum for GaS arrays, compared with 2-3 for Si.

Other papers described more exotic systems - a CR=1000 system with a dichroic beam splitting mirror to direct portions of the solar spectrum to cells with matched energy bandgaps (809071) and a thermovoltaic space power system (809072).

General descriptions of several spacecraft power systems were given:

- Pioneer Venus Multiprobe and Orbiter (809076). The solar arrays for both these spacecraft were the first to use Spectrolab K-6 solar cells in space. Both arrays exceeded their design objectives. The orbiter array is producing 365 W at 29.6V after 492 days in Venus orbit compared with a design objective of 329W at 28V after 243 days.

- Leasat (809206). Four Leasat communications spacecraft will be leased from Hughes Communications Services by the Navy. Cost and reliability were prime drivers in the program and as a result decision making has been rapid and formal documentation kept to a minimum. Proven space components were used wherever possible. The spacecraft (a GEO spinner) is 15 ft diameter and designed specifically for a "frisbee" launch from the shuttle orbiter. Internal heaters (2 kW) are used to maintain the array temperature while in the cargo bay, rather than using a shroud. The array is designed for 1047 W EOL and, to save costs, uses "K6-3/4" solar cells (18.78 mW/cm^2) that are about 6% lower in output than the state of the art. The batteries consist of three 32 cell 25 AH packs. The cells are scaled up from flight-qualified SBS 22 AH cells, and maximum DOD is 43%. Reconditioning will initially be terminated at 1.1V/cell and is limited to .7V/cell by zener diodes.

- ISEE-A, C (809207). The requirements for low electrical and magnetic fields from the spacecraft (International Sun-Earth Explorer) dictated the use of Ag-Cd batteries and a conductive coating of Indium Oxide over the solar cells. Performance of both spacecraft has been as expected.

- INSAT-1 (809208). The INSAT is a 3-axis stabilized multi-payload spacecraft. Because of the thermal requirements of the Radiometer payload, the array consists only of a single 5-panel wing on the South face, balanced by a solar sail on the North face. Batteries consist of two 28-cell 12 AH packs. Cell protection diodes are incorporated, maximum DOD is 55%, and individual cell voltage monitoring is provided.

- SBS (809209). The SBS is similar to Anik-C. The array uses 20 mW/cm^2 K7 cells and 10 lb was saved by using micro-balloons in the cell-bonding epoxy. The batteries (two, 32 cell-22 AH) are sized for 55% maximum DOD. The cells have been improved over previous designs by:

  - Low carbonate level to reduce cadmium migration

  - Increased interelectrode spacing to increase electrolyte volume

  - Thinner, more lightly loaded plates to reduce current density.

  The batteries are reconditioned until the first cell reaches .5V. Cell voltage monitoring is provided by a multilayer thick/thin film hybrid multiplexer which is accurate to +/- .25% over a 0 to 1.6V cell voltage range.

8. NICKEL-CADMIUM BATTERIES

Papers in this group generally covered the application of Ni-Cd cells rather than going into details of cells themselves.

A paper by Dr. Scott of TRW (809318) give new values for charge efficiencies of 50 AH cells. The new values are greater than those presently in use, but are considered more accurate as they are based on measurements of heat output during charge rather than being derived from discharge data. The new curves are given for various temperatures and would be particularly useful for GEO applications.

Hughes (809319) have determined that plate expansion, which may be an important life limiting factor, varies as $DOD^{2.2}$.

RCA (809320) described the excellent performance being exhibited by Satcom 1 and 2 batteries (I was told Anik B experience is comparable). The Satcom end-of-discharge voltages, after 8 or 9 eclipse seasons, are significantly greater than those in Intelsat IV series spacecraft, and exceeds voltages from a Crane test pack under similar conditions. The good performance is attributed to:

- Use of teflonated negative electrodes
- Increased electrolyte quantity
- Individual cell reconditioning to .1V
- Use of continuous trickle charge
- Provision for low temperature operation.

Following anomalous battery behaviour on DSCS spacecraft during the third eclipse season and thereafter, TRW launched an intensive investigation into the cause and possible cure for the problems (809323). Their conclusions were that the battery degradation was caused by cell shorting due to penetration of cadmium bearing material into the separator. The amount of cadmium increases during the charge/overcharge period in the eclipse season and decreases during eclipse discharge and reconditioning. The early shorts were produced by excessive overcharge at c/10 and shorted cells could be temporarily (hours or weeks) put into remission by deep recondition cycles.

Based on Crane data, McDermott (809327) has produced a set of curves which predict cell life in GEO as a function of temperature and overcharge rate, during non-eclipse seasons. It is probable that the trickle charge period may be the major degrading factor, particularly in applications with less than 40% DOD during eclipse.

Other papers described the INTELSAT V (809321) and Modular Power System (809324) battery packs, and the (Japanese) NASDA 8 AH prismatic cell (809325).

Eagle Pitcher (809322) described their electrode process facility, which has been specifically designed for the production of high-quality nickel and cadmium electrodes for aerospace use.

9. NICKEL-HYDROGEN CELLS

$Ni-H_2$ technology is becoming well established; later INTELSAT V spacecraft will use $Ni-H_2$ cells, with a first launch projected for late 1981. Although the design is not optimal, a battery weight of 60.3 kg has been achieved, compared with 65 kg for the equivalent Ni-Cd system. An optimized design, using a higher DOD (70% v-60%) is predicted to weigh 46 kg. COMSAT (809381) recommend that the following generation of $Ni-H_2$ batteries for space use should have a goal of 48 Wh/kg compared to the 39 Wh/kg achieved for INTELSAT. This will require a cell size larger than the INTELSAT 30 AH or multiple stacks in one pressure vessel.

The use of multiple stacks in common pressure vessels gives a good weight advantage for capacities less than about 50 AH. Work on these designs is continuing (809386, 809391).

Hughes (809384), McDonnell Douglas (809385) and Ford Aerospace (809382) described their $Ni-H_2$ battery designs, which are generally designed to be replacements for existing Ni-Cd designs. Hughes take particular care with the electrical insulation of the cell containers, due to the large exposed area, and use relays for open-circuit cell protection.

Air-force testing of a 21 cell (809387) battery at 51% DOD for a LEO application has reached 8000 cycles with one cell failure (short-circuit) at 6800 cycles.

TRW (809388) have tested several generations of $Ni-H_2$ cells under GEO conditions. Present-day (fourth generation) cells have been tested over 10 accelerated and 2 real-time eclipse seasons. The improvement in performance over earlier cells is attributed to the use of electrochemically rather than vacuum impregnated positive electrodes. The Air-Force design gives a higher end-of-discharge voltage than the COMSAT/INTELSAT type cell, but is slightly heavier.

10. CONCLUSIONS

The current trends in spacecraft power systems appear to be towards:

- Higher powers
- Higher voltages and AC systems (possibly)
- Use of $Ni-H_2$ cells
- Increased requirements for thermal engineering support
- Autonomous management
- Careful treatment of batteries during overcharge and reconditioning
- Use of simulations for design optimization and predicition.

The CAL Advanced Battery Management System is compatible with these trends.

John R. Beck

Enclosure

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Table of Contents

Advanced Concepts

Advanced Power Cycles for Fusion

Aerospace Power: Aircraft Electrical Power Systems I

Aerospace Power: Aircraft Electrical Power Systems II

Aerospace Power: Aircraft, Missile, & Launch Facility Batteries I

Aerospace Power: Aircraft, Missile, & Launch Facility Batteries II

Aerospace Power: High Voltage Technology

Aerospace Power: NiCd Space Batteries I

Aerospace Power: NiCd Space Batteries II

Aerospace Power: NiH_2 Space Batteries I

Aerospace Power: NiH_2 Space Batteries II

Aerospace Power: Power System Requirements & Issues

Aerospace Power: Power System Simulation

Aerospace Power: Space Power Electronics II

Aerospace Power: Space Photovoltaics & Solar Arrays I

Aerospace Power: Space Photovoltaics & Solar Arrays II

Aerospace Power: Space Power Satellites & Platforms I

Aerospace Power: Space Power Satellites & Platforms II

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APPENDIX C

PROGRAM LISTING

```
&PLTC2 T=00004 IS ON CR00036 USING 00005 BLKS R=0000

FTN4,L
      PROGRAM PLTC2
C
C   THIS PROGRAM CALCULATES THE END OF ECLIPSE VOLTAGE FOR A S/C
C BATTERY POWER SYSTEM IN THE CASES OF CONSTANT CURRENT AND
C CONSTANT POWER LOADS OVER A TEN YEAR LIFETIME.  THE DATA IS THEN
C GRAPHED USING THE H.P.9872A PLOTTER.
C
      DIMENSION IGCB(192),PLOT(3,21)
C
C CONSTANT VALUES
C
      VT=-0.015984
      RO=0.0072
      RF=0.0006
      DOF=18.0
      RECONV=0.37
      NCELLS=28
      VBUS=50
      IFLAG=0
C
C ASK FOR DATA FROM TERMINAL.
C
      WRITE(1,101)
  101 FORMAT(1X,"CELL CAPACITY, BATTERY CURRENT,"
     1" AND CONSTANT POWER LOAD, PLEASE ?")
      READ(1,*)NPCAP,BATTI,PLOAD
C
C CALCULATE CONSTANT CURRENT DATA
C
      CONSTI=BATTI
      ROC=20.0*RO/NPCAP
      RFC=20.0*RF/NPCAP
      DOD=72/60*BATTI/NPCAP
      AGCELL=-0.5
      DO 20,I=1,21
      VG=1.3597-DOD*(0.8398-DOD*(3.6972-DOD*(8.6476-DOD*
     1(9.8953-DOD*4.4239))))
      AGCELL=AGCELL+0.5
      R=ROC+RFC*RECONV*AGCELL*AGCELL
      VC=VG+VT-BATTI*R
      BATTV=VC*NCELLS
      POW=BATTV*BATTI
      WRITE(18,307)AGCELL,POW
  307 FORMAT(1X,"AGCELL=",F7.3,"  POWER=",F7.3)
      PLOT(1,I)=AGCELL
      PLOT(2,I)=BATTV
   20 CONTINUE
```

```
C
C CALCULATE CONSTANT POWER DATA
C
C
C      CALCULATE LOAD LOSSES
C
       PWO=.5*PLOAD/(VBUS-.5)
       RWI=.316*NCELLS/PLOAD
C
C CALCULATE THE DATA VALUES OVER A PERIOD OF TEN YEARS
C AT HALF-YEAR INTERVALS
C
       AGCELL=-0.5
       DO 50,I=1,21
~~       AGCELL=AGCELL+0.5~~
       DOD=0.
       TIME=0.
C
C CALCULATE DATA VALUES FOR EACH MINUTE OF LONGEST
C ECLIPSE
C
       DO 30 K=1,72
C      INITIAL BATT V
C
       CN=NCELLS
       BATTV=1.3597*CN
       BATTI=10.0
C
C ITTERATE TO FIND VOLTAGE AND CURRENT VALUES
C
       DO 40 J=1,50
       T=BATTV
       VC=1.3597-DOD*(.83986-DOD*(3.6972-DOD*(8.8476-DOD*(9.8953-
      1DOD*4.4239))))
       VD=T-32.2)
       R=ROC+RECONV*RFC*AGCELL*AGCELL
      BATTI
       BATTV=CN*VC
       PWI=RWI*BATTI*BATTI
       PIN=((PLOAD+PWO+2.+(PLOAD/150.))*(VBUS+1.)*(BATTV+.5)
      1*1.015/(VBUS*BATTV))+PWI
       EFF=PLOAD/PIN
       BATTI=PIN/BATTV
       T2=T-BATTV
     IF(T2.LT.0.01) GO TO 22
 40    CONTINUE
 22    CONTINUE
       TIME=TIME+.016667
       DOD=DOD+.016667*BATTI/
 30    CONTINUE
       POW=BATTV*BATTI
       WRITE(18,102)AGCELL,BATTI,POW,DOD
  102  FORMAT(1X,"AGCELL=",F6.2,"  BATTI=",F6.2,"  POWER=",F7.3,
      1"  DOD=",F6.4)
       IF(BATTV.LT.22.0)IFLAG=1
       IF(IFLAG.EQ.1)BATTV=0.0
       PLOT(3,I)=BATTV
 50    CONTINUE
```

```
C
C THE FOLLOWING PORTION PLOTS THE CONTENTS OF PLOT(3,73)
C
      LU=24
      ID=2
      CALL PLOTR(IGCB,ID,1,LU)
      CALL LIMIT(IGCB,5.0,255.0,5.0,200.0)
      CALL PEN(IGCB,3)
      CALL SETAR(IGCB,1.5)
      CALL FXD(IGCB,2)
      CALL FRAME(IGCB)
      CALL VIEWP(IGCB,20.,140.,20.,70.)
      CALL WINDW(IGCB,0.,10.,22.,34.)
      CALL LGRID(IGCB,-.5,.5,0.,22.,2.,2.,1.)
C
C DRAW PLOTS OF DATA
C
      CALL MOVE(IGCB,PLOT(1,1),PLOT(2,1))
      DO 70,J=2,21
      CALL DRAW(IGCB,PLOT(1,J),PLOT(2,J))
   70 CONTINUE
      CALL LINE(IGCB,1)
      CALL MOVE(IGCB,PLOT(1,1),PLOT(3,1))
      DO 60,J=2,21
      CALL DRAW(IGCB,PLOT(1,J),PLOT(3,J))
   60 CONTINUE
      CALL LINE(IGCB,0)
C
C DRAW LABELS
C
      CALL VIEWP(IGCB,0.,150.,0.,150.)
      CALL WINDW(IGCB,0.,150.,0.,150.)
      CALL MOVE(IGCB,75.,135.)
      CALL CPLOT(IGCB,-20.,0.,0)
      CALL LABEL(IGCB)
      WRITE(LU,200)
  200 FORMAT("END OF ECLIPSE VOLTAGE VS. BATTERY AGE")
      CALL MOVE(IGCB,75.,125.)
      CALL CPLOT(IGCB,-18.,0.,0)
      CALL LABEL(IGCB)
      WRITE(LU,302)NPCAP
  302 FORMAT("      CELL CAPACITY: ",F3.1,"AMP-HOURS")
      CALL MOVE(IGCB,75.,120.)
      CALL CPLOT(IGCB,-15.,0.,0)
      CALL LABEL(IGCB)
      WRITE(LU,303)CONSTI
  303 FORMAT("CONSTANT CURRENT: ",F3.1,"AMPS.   ")
      CALL CPLOT(IGCB,30.,0.25,0)
      CALL DRAWI(IGCB,20.,0.)
      CALL MOVE(IGCB,75.,115.)
      CALL CPLOT(IGCB,-13.,0.,0)
      CALL LABEL(IGCB)
      WRITE(LU,304)PLOAD
```

```
304 FORMAT("CONSTANT POWER: ",F4.1,"WATTS   ")
    CALL CPLOT(IGCB,28.,0.25,0)
    CALL LINE(IGCB,1)
    CALL DRAWI(IGCB,20.,0.)
    CALL LINE(IGCB,0)
    CALL MOVE(IGCB,70.,15.)
    CALL CPLOT(IGCB,-4.,0.,0)
    CALL LABEL(IGCB)
    WRITE(LU,300)
300 FORMAT("AGE IN YEARS")
    CALL MOVE(IGCB,10.,80.)
    CALL CPLOT(IGCB,-1.,-8.,0)
    CALL LDIR(IGCB,+1.57)
    CALL LABEL(IGCB)
    WRITE(LU,400)
400 FORMAT("BATTERY VOLTAGE")
    CALL LDIR(IGCB,0.0)
    CALL PLOTR(IGCB,ID,0)
    END
    END$
```