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High Energy Density Rechargeable Batteries for Aerospace Power Requirements

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This report has been reviewed by the Public Affairs Office (PAS) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

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The power requirements of Air Force Space Division (AFSD) space missions that expect to be in a request for proposal phase by the 1995-1996 time frame have been evaluated through discussions with AFSD and The Aerospace Corporation program offices. In light of these requirements the rechargeable battery and fuel cell technologies that are expected to be available for these missions are identified, and areas of technology development that will be required for each energy storage system are indicated. The general conclusions are that the nickel cadmium and nickel hydrogen battery systems will be able to satisfy the space power needs through the early 1990s, after which a significantly higher energy density system will be required, particularly for geosynchronous and mid-altitude orbit missions. The sodium sulfur battery is the only system projected to meet the requirements of the most power intensive missions that are expected to operate in higher orbits by the mid-1990s. For low earth orbit missions the nickel hydrogen battery system is expected to provide the required

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power levels, except in situations where very high peak power levels are required. The hydrogen oxygen regenerative fuel cell is best suited to satisfying the high peak power needs in large power systems, but must undergo significant development to obtain the needed system life.

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I. INTRODUCTION

The power requirements of orbital and space flight vehicles have been increasing since the inception of the space program. Power needs are expected to continue this trend, and appropriate energy storage technology to satisfy these power requirements must be developed and qualified for use in a timely manner. The objectives of the work reported here are:

- First, assess the currently established and future requirements of the Air Force Space Division (AFSD) in the area of space vehicle power. Requirements will be expressed in terms of the time frame when a fixed technology is required, which is typically about 5 to 7 years prior to initial operational capability.

- Second, project how battery technologies are expected to develop in the future and correlate the various technologies with the AFSD requirements. Part of this projection will indicate the areas of technology development that are needed if the various battery systems are to satisfy the AFSD requirements.

Assessment of power requirements and battery technologies likely to satisfy these requirements will be done through the time frame where technology is fixed by 1995 [or request for proposal (RFP) by 1995].

AFSD requirements for space vehicle power were assessed by contacting a wide cross section of Space Division (SD) programs, including both continuing programs and programs tasked with implementing advanced concepts, the latter programs sometimes being in an early conceptual state. The specific requirements that were evaluated as being pertinent to high energy density rechargeable batteries (HEDRBs) are:

- Time frame when fixed technology is needed
- Power levels (peak and average)
- Weight and volume constraints
- Mission life and reliability
- Anticipated ranges of orbits
- Autonomy level required

The assessment that has been done both evaluates the requirements and provides an indication of areas that tend to be mission constraints or design drivers for the various classes of programs.

The various HEDRB technologies have been previously reviewed in detail for their suitability in several advanced space vehicle concepts in an Air Force Wright Aeronautical Laboratories report[1] that includes technology development through early 1983. In the report herein, an update of battery technology progress in the past 2 years will be presented along with current technology projections out to 1995. A significant input in the technology projections will be the incremental advances that each technology has experienced in the past several years. Because of funding cutbacks during this period, a number of technology areas that have the potential to eventually provide power needs have not progressed rapidly and are therefore likely to entail a greater risk in terms of satisfying near-term (through 1995) power needs. The technologies considered in this report have been chosen specifically for their abilities to satisfy AFSD requirements, and are not necessarily chosen based on theoretical or long-term potential.

The technology areas that will be available to satisfy needs in the next 10 years are expected to be the NiCd, NiH_2, and NaS batteries, as well as the hydrogen oxygen regenerative fuel cell. These systems are all expected to go through incremental increases in energy density in the next 10 years; therefore, are all discussed in the context of HEDRB. A number of other battery systems may provide potential benefits, but are not expected to be available as a fixed and adequately developed technology by 1995. These include the silver hydrogen, lithium iron sulfide, hydrogen halogen, zinc bromine, and ambient-temperature lithium rechargeable systems. These latter systems are discussed briefly, but no correlations with AFSD needs are presented.

II. ASSESSMENT OF POWER REQUIREMENTS

The AFSD program requirements were identified by discussions with AFSD and Aerospace program offices, with particular emphasis on obtaining the currently available information for the categories listed in Table 1. This information was used as the basis for evaluating how the overall needs in the power area will be changing over the next decade.

Table 1. Areas of Power Subsystem Needs Used in HEDRB Assessment

1. Weight and/or volume limitations
2. Battery location (inside or outside vehicle)
3. Number of batteries if known
4. Time frame technology required
5. Subsystem bus voltage
6. Power required (peak and average) prior to deployment
7. Design and mean mission duration
8. Eclipse season duration and frequency
9. Eclipse durations and frequency (mean and max)
10. Nominal power required
11. Peak power required if significantly greater than nominal
12. Duration and frequency of peak power pulses

The weight and volume limitations for most programs were indicated to be imposed by the launch vehicle, which in most cases was expected to be the Shuttle. The volume constraint imposed by this launch system is that the vehicle, plus an upper stage booster, if needed, must fit into the Shuttle bay. For power systems exceeding about 10 kW, energy storage and thermal management systems will have to be incorporated into the vehicle structure to meet the volume constraints. This is particularly true for the nickel hydrogen system, which has a relatively high volume. Weight limitations imposed by the Shuttle are presently 40,000 lb, and are expected to increase to 65,000 lb by 1995. If the space vehicle is intended for a low earth orbit (LEO) that can be reached by the Shuttle, the Shuttle throw weight is the ultimate limitation on vehicle or platform weight. Programs planning LEO missions did not generally see weight as the primary limiting factor. If it is assumed that energy storage devices should be no more than 10% of the total LEO throw weight, then weights for these devices could be as high as 4000 lb, or 6500 lb by 1995. For these numbers, it is assumed that the total throw weight of the Shuttle is available. Additional weight and volume constraints are, of course, imposed if several vehicles are to be launched from one Shuttle flight, as is planned for a number of programs.

Vehicles launched into mid-altitude orbit (MAO) or geosynchronous orbit (GEO) from the Shuttle are typically limited by the weight that can be delivered into the higher orbit by an upper stage booster. This weight is expected to reach about 15,000 lb by 1995. With an inertial upper stage (IUS) booster, many programs plan on about a 7000-lb delivery into GEO. Again assuming that the energy storage system should be 10% of the vehicle weight, batteries should be limited to about 700 lb. Heavier batteries can of course be used at the cost of available payload weight for power intensive missions. Conversely, space programs generally desire to keep subsystem weights as low as possible without entailing a significant increase in risk, so that payload weight can be maximized.

The location of batteries in the space vehicle was determined to not be a constraint. No future programs have specified requirements for either internal or external battery placement at this time. Since battery placement can have significant impact on thermal design and thermal management, this variable appears to be available for system optimization.

The time frames in which advanced technology will be required fell into three general classes:

- The first class consisted of programs that either were currently involved in, or would be entering into, an RFP phase within the next few years. These programs generally had relatively firm requirements, and in some cases firm design concepts as well. Out of necessity these programs are constrained to use existing flight proven or qualified technology with incremental improvements where possible.

- The second class of programs anticipated the RFP phase to occur in a 1990-1992 time frame. These programs have reasonable ideas of their power requirements, although it should be recognized that these requirements may be subject to significant changes in the future. This class of programs is generally open to using new battery technology for high energy systems, and, in some instances, may also consider power subsystem options other than batteries.

- The third class of programs was primarily defined in terms of concepts that are expected to draw on technology that will be available in the 1995-1996 time frame. Power requirements cannot be defined closely in this class because the implementation of these concepts has not been defined in the necessary detail. However, the required power can generally be estimated accurately enough from the mission concepts to allow definition of the technology that will be required to provide the power needs.

The number of batteries in the subsystem and the bus voltage have not been defined by any but the most current programs. The only apparent constraint for the number of batteries results from the protection against single point failures that can be realized by having several parallel strings of cells or batteries to provide power. For programs requiring high power levels, it is likely that bus voltages significantly higher than those currently used will have to be employed to limit distribution losses. In this kind of high power system it may be desirable to employ hybrid battery operation, where different batteries are used to serve different power functions or needs. For example, a smaller battery system may be used for housekeeping functions, while a large HEDRB or other power source may be employed for supplying high voltage power to a load. The number of battery cells in a string is expected to impact the methods used for charge control, cell redundancy in the string, and the application of bypass circuitry to protect against possible open-circuit cell failures.

For most programs the power requirements prior to full mission deployment are not well defined. These requirements include power needed during transfer and insertion into orbit as well as power needed prior to solar panel deployment. Since these needs are mission specific, they are not specifically considered as part of the power needs presented in this report.

Mission durations for GEO orbits and for high earth orbits were generally 10 years, with up to another 2 years of orbital storage required in some cases. A need was not generally found for batteries that last well beyond the 10-12 year frame, primarily because other hardware items are expected to become life limiting beyond this time. LEO orbit missions generally have goals of 5 years, and MAO missions 5 to 7 years depending on the orbit involved. The types of orbits that are projected for future missions cover the range from 3× GEO to GEO, a wide range of MAO orbits, and LEO orbits. Eclipse frequencies and durations thus vary quite widely depending on orbit. In terms of battery capability most of these orbits are variations of either the LEO profile with many thousands of cycles over the mission life, or the GEO profile with 1000 to 2000 cycles expected. One exception is the high earth orbit (2× or 3× GEO) that is proposed for some missions, which would involve a small number of relatively long eclipses.

The mission power requirements were found to generally increase over the period out to 1995. Some programs were found to drive the power requirements, while a number of other programs expect to operate at lower power levels. The power requirements that are expected to drive the battery technology are summarized in Fig. 1, where each shaded block represents a given class of programs that are expected to have common needs. The size associated with each block in Fig. 1 thus indicates both the uncertainty associated with projected needs and the range of needs for the various programs within each block. Peak power needs, where they exist, are indicated in Fig. 1 by vertical arrows. The diagonal line drawn on Fig. 1 indicates a general trend of increasing maximum power needed to satisfy AFSD requirements. The classes of programs in the upper portion of Fig. 1 that require power up to 50 kW and above would require the use of HEDRB systems, as indicated in the example of Ref. 1 for a solar/battery power subsystem to be selected. For power levels of this magnitude, other power sources are also under consideration, primarily because of perceived limitations in solar panel technology. Missions that anticipated peak-power pulse requirements generally could not define these pulses any more closely than is indicated on Fig. 1. The dashed lines on Fig.

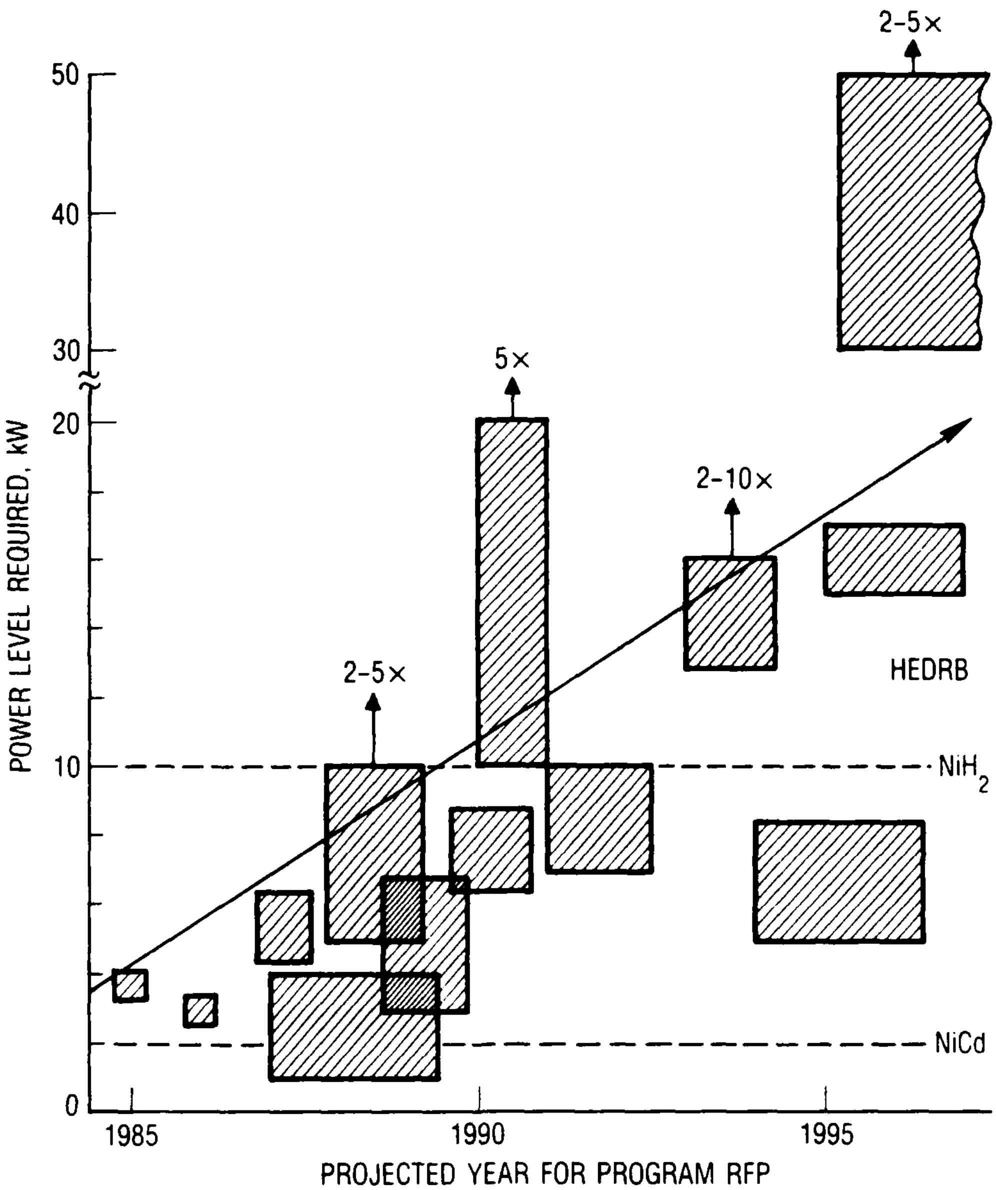

Fig. 1. Space Program Power Requirements through 1995

1 indicate the approximate power regions below which the NiCd, NiH_2, and HEDRB systems are expected to be satisfactory choices in meeting the power needs for orbits higher than LEO. For LEO orbits the nickel hydrogen system is expected to be used for power levels significantly above the 10-kW level. Programs requiring extremely high power levels, in the megawatt range, are not generally considering batteries for primary power needs. In these types of power systems, battery power has been considered for housekeeping power needs in Fig. 1.

Autonomy needs for many SD programs are increasing and are expected to continue increasing in the future. Autonomy requirements for present and near term (through 1987) missions generally do not exceed 6 months in terms of totally unattended battery operation. However, for missions that will be using 1992 battery technology, some requirements are expected for extremely high levels of autonomy that would include unattended power subsystem operation for many years. For the power subsystem and batteries, this means that the functions of charge control, dealing with degradation of the battery complement, and failure protection must be fully handled within the system. For emerging technology it is necessary that these autonomous functions be easily and reliably implemented for those missions in which they are required. Autonomy levels are expected to continue increasing for programs beyond the 1992 time frame. Although no specific requirements were found to have been formulated at this time, it is likely that more programs will be requiring high levels of power subsystem autonomy beyond the 1992 time frame.

III. HEDRB TECHNOLOGY ASSESSMENT

The objective of the assessment of battery technologies reported here is to provide an overview of recent advances in the various battery technologies that have the potential for satisfying AFSD space vehicle power needs. Technology development for each battery system will be projected through the 1995 time frame, in terms of the expected development based on present levels of effort and in terms of the development that is required for each system to be capable of meeting space power needs. The details of battery operation, chemistry, and development prior to about 1983 will not be discussed because this information has been previously presented for most of the advanced battery systems.[1] Background technology and development information for the NiCd, NiH_2, and regenerative fuel cell areas are presented in several publications.[2-4]

A. NICKEL CADMIUM

Nickel cadmium batteries have been the workhorse system in space vehicles until recent years when some of the programs have begun using nickel hydrogen batteries. However, nickel cadmium batteries will continue to be weight and cost effective for power levels below the 1-2 kW range.

- The primary advantages of the nickel cadmium system over other systems are in the areas of thermal management and supporting structures, and are due largely to the prismatic cell design and low operating temperatures.

- Another significant advantage is the sizeable data base that exists in terms of ground tests and flight data.

- The primary drawback of the presently used prismatic nickel cadmium cell designs involves the inability to maintain performance when this design is scaled up to a capacity more than 50 Ah.

- The main disadvantage of the NiCd system is its sensitivity to overcharge, particularly at elevated temperatures. For long life operation the degree of overcharge must be carefully limited and the cell thermal environment must be kept between -5 and 10 degrees C. The charge control methods required and the need for periodic reconditioning thus present some control problems that must yet be dealt with if fully autonomous operation is to be realized with NiCd batteries.

Nickel cadmium battery technology has been fixed for several decades: however, incremental design changes continue over the years to improve this system in terms of life and energy density. For example:

- Reductions in the electrode loading levels have been used in recent years to limit internal electrode stresses that are thought to cause cell degradation. Despite the improvement, nickel cadmium cells presently manufactured are not yet of a design that has been optimized for long life performance in space applications.

- A program recently undertaken by Hughes Aircraft Company[5] has employed optimized electrodeposited nickel and cadmium electrodes, advanced separator systems, and special charge control methods to realize 43,000 cycles at 40% depth of discharge (DOD) in LEO tests, and several thousand cycles at 80% DOD in accelerated GEO cycling tests. These results indicate that significant improvements are possible in the present NiCd cells, and that these cells are likely to remain competitive for energy storage requirements below 1-2 kW.

State-of-the-art usable energy densities should show incremental improvements from about 9.5 Wh/lb in 1986 up to about 12.5 Wh/lb by 1995 for GEO orbits, and from about 4 Wh/lb in 1986 up to about 6 Wh/lb by 1995 for LEO orbits. If the potential advances in technology demonstrated by the work at Hughes is implemented, DOD in GEO orbits should increase from the 60% presently used to about 75% in 1995, while DOD in LEO should increase from the 25% levels typical today to 35-40% by 1995. The comparisons that are presented in Table 2 (Section IV) use these values for projecting the performance of NiCd batteries relative to other systems.

The incremental advances in nickel cadmium battery technology that are expected in the next 10 years will require a continued effort in the test and verification areas. NiCd cell and battery tests must continue to be run with these advanced NiCd cells to verify the performance and to evaluate what the failure modes and life-limiting components are in the cells. Such test and data base generation must include real-time as well as accelerated testing for the types of orbits that the batteries are to be used in.

B. NICKEL HYDROGEN

Over the past several years nickel hydrogen batteries have been replacing nickel cadmium batteries in a number of space vehicle applications, particularly in geosynchronous and high earth orbits. The test data base that currently exists for nickel hydrogen cells is discussed in Reference 4e.

- The advantages of nickel hydrogen as opposed to nickel cadmium batteries that have driven this trend are projected long life, less sensitivity to overcharge or less-than-optimum charge control than NiCd batteries, higher usable energy density, and less need for reconditioning procedures.

- Disadvantages of nickel hydrogen relative to nickel cadmium are the greater volume of the cells, the larger and heavier supporting and thermal management structures that are needed, high self-discharge rates (up to 10% per day), less mature technology and lower manufacturability.

For the advanced high power subsystems required in the future by many programs, the energy density and long life make nickel hydrogen the system of choice. The lower sensitivity of nickel hydrogen to overcharge, overdischarge, and reconditioning makes this system somewhat easier to operate in an autonomous mode. However, nickel electrode failure, which appears to be the most likely end-of-life failure mode, is accelerated by overcharge and overdischarge at high rates. Therefore optimum cell life will require the use of appropriate charge control techniques to limit these stresses.

Several advanced concepts are possible to increase the energy density of the nickel hydrogen system. The first of these is a scale-up of the present 3.5-inch-diameter cell to a 4.5-inch-diameter cell. Development in this area is presently under way under the direction of AFWAL (Air Force Wright Aeronautical Laboratories). Life testing of these cells should begin in 1986-1987. It is likely that a sufficient data base will be available by the 1990 time frame to allow these cells to be used in flight programs. This program is described in a Space Power Workshop paper.[6]

A second advanced concept involves a common pressure vessel containing a number of nickel hydrogen cells connected either in series or in parallel. The major active development in this area is based on work pioneered at NASA-Lewis Research Center. This effort involves the design and construction of a bipolar unit that contains a large number of cells placed back-to-back in a series configuration and enclosed in a large common pressure vessel. This unit is intended for high power operation using multikilowatt modules. The program is presently in the development phase, with a small prototype test unit having been produced and placed into parametric testing. The unit is being developed by Ford Aerospace and Communications Corp., Western Development Laboratories (FACC-WDL) in conjunction with Yardney Battery Division. Since these design concepts have not been implemented previously, it is expected that some fundamental problems will be discovered during the ongoing development and scale-up of the bipolar unit. It is anticipated that this development effort will be completed to the point of producing fully developed modules for life testing in the 1988-1989 time frame. Assuming that no major problems or failure modes arise during life testing that would require additional iterations through the development and test cycle, and if the data base that is accumulated indicates acceptable or manageable reliability, this technology could be ready for potential application by the 1994-1995 time frame. If this technology is to be successfully applied to space vehicle power subsystems, the questions of reliability in the series string of cells and reliability of the active thermal management system that is required must be adequately addressed. Units of this type require an active cooling system that involves moving mechanical parts and plumbing that may not have the reliability typically required for satellite applications.

It is expected that incremental improvements in the existing nickel hydrogen cell technology will also occur over the next 10 years, particularly in the areas of separators, oxygen management, and nickel electrode fabrication. The nickel electrode is presently one of the life-limiting elements in the nickel hydrogen cell. Such incremental improvements will cause continued need for testing of nickel hydrogen cells and batteries, for the purposes of both verifying the effects of incremental changes and to accumulate more complete long-term data on which battery system designs may be based. Nickel hydrogen batteries currently have usable energy densities of about 15 Wh/lb for GEO missions, a value that is expected to increase to about 22 Wh/lb by the 1995 time frame. For LEO applications usable energy densities of 10-11 Wh/lb in 1986 are expected to increase to about 14 Wh/lb by 1995.

C. SODIUM SULFUR

Sodium sulfur battery technology has made major advances in the past 10 years, and is currently at the point where it is receiving practical consideration for space vehicle applications.[1]

- The primary advantage of the sodium sulfur battery is its extremely high energy density compared to other battery systems, about 40-50 Wh/lb.
- Other advantages include the wide operating temperature range, chemical simplicity (no parasitic reactions), zero self-discharge, and 100% coulombic efficiency.
- The main disadvantages of the system are related to the known failure mode due to breakage of the ceramic electrolyte, the high operating temperature (300-400 degrees C), internal cell component corrosion, increases in cell impedance with time, and manufacturability.

One of the principal historical problems with sodium sulfur technology has been the fracturing of the electrolyte either during temperature cycling between ambient and operating temperatures, or during electrical cycling. A major reason why sodium sulfur technology is presently being considered for space power applications is that significant progress has been made in alleviating the electrolyte breakage failure modes.[8] Cells currently produced by FACC-Aeroneutronic Division have shown the ability to go through a number of temperature cycles between ambient and operating levels without fracturing the electrolyte. Cells on electrical cycling tests at AFWAL have demonstrated cycle capability consistent with GEO requirements.[6] Further improvements in electrolyte strength are being made by changes in the electrolyte fabrication procedures and by more effective electrolyte screening methods. This is an area where additional effort can make a significant impact on the usability and reliability of this technology, particularly for projected LEO types of applications.

Charge control systems for sodium sulfur batteries have a number of requirements that are much different from those of batteries presently in use. Since the batteries have no self-discharge, they may simply be charged up to a preset voltage per cell and then open circuited until discharge begins. It is likely that the current which is normally used to trickle-charge present-design batteries could be used for heaters that would be needed to maintain the battery thermal environment. The primary functions of the charge control system are likely to consist of battery temperature maintenance and system protection against failed cells. The principal end-of-life failure mode that is anticipated for cells is electrolyte breakage, which causes a high impedance condition in the cell. To maintain battery operation when this takes place and to protect against single-point failure modes, cell bypass circuitry will be necessary. The charge control system will have to detect failed cells, activate the bypass circuitry, and adjust the recharge voltage limits to reflect a lower number of cells. A sufficient number of cells would have to be put in each battery string to allow for the loss of some cells at end of life while maintaining a sufficient system voltage. This is more easily done for systems operating at higher voltages than those that are presently used.

A number of reliability issues need to be answered for sodium sulfur batteries, versions of which have been recently proposed by FACC-WDL. Continued testing of the batteries and cells as they evolve is necessary to obtain a data base that is sufficiently extensive to predict reliability as determined by electrolyte breakage failure modes. Battery reliability may also be impacted by the reliability of the bypass electronics that are necessary, since bypass electronics that can operate reliably over long periods of time at 300-400 degrees C are at this point only conceptual. The bypass circuitry probably must be in the high-temperature battery environment to prevent the bypass wiring from causing large thermal leakage pathways, and to save weight for the bypass wiring. Other factors that must be considered in the reliability issue are concerned with the probability of cell failure during initial heat-up, and the reliability of the technique chosen for initial heat-up if the battery is launched in the cool state (generally desirable to minimize the risk of electrolyte fracture in the launch environment).

The manufacturability of the sodium sulfur cell in the quantities needed for the future power needs represents a concern that must be eventually addressed. Factors that are critical for current sodium sulfur cell fabrication are part tolerances, reliability of weld and seal techniques and assembly with minimal extraneous contamination to the system. While it has been demonstrated by FACC that a few cells can be constructed without major difficulty, problems in these areas are likely to become significantly more critical in a larger volume factory-type assembly facility.

Corrosion of case, seal, and electrode materials in the high temperature sodium sulfur cell environment is a concern over 10-12 year usage periods that must be addressed in real-time tests, primarily because accelerated testing can only be done at the materials level. Corrosion processes are generally accelerated by temperature for ground test evaluation. However, for a sodium sulfur cell, temperature cannot be increased significantly above 400 degrees C to accelerate these processes; therefore, accelerated testing for corrosion concerns is difficult in the cell environment. For long periods of operation, even a very slow corrosion process can cause performance problems, a situation that may dictate a lower or reduced range of operating temperatures for optimum life.

Sodium sulfur cells have a relatively high internal impedance compared to many other battery systems, which may limit their use in power systems where peak power requirements are more than 2-3 times the base load, since the battery must be designed for peak power rather than base power. Hybrid power system concepts may be useful in large systems to effectively satisfy high peak power requirements.

The data base on sodium sulfur cells that has been obtained recently in tests at AFWAL[6] indicate that these cells as currently produced are capable of providing the cycle life needed in GEO applications, but are not yet developed to the point where they can reliably satisfy the MAO or LEO applications. The AFWAL tests have demonstrated 500-600 accelerated GEO cycles at 80% DOD with no failures to date, and 2000-4000 cycles in MAO-type orbits at 60% and 80% DOD with two cells out of six having failed to date. The usable energy density for sodium sulfur batteries using current cells in GEO applications is projected at 32 Wh/lb, increasing to 40 Wh/lb by 1995. Development of sodium sulfur batteries for LEO applications could be completed by the 1992 time frame through a program proposed by AFWAL in conjunction with FACC, which is projected to provide sodium sulfur technology for LEO test and initial application by the mid-1990s. Usable energy densities for LEO application in 1986 are about 10 Wh/lb, while by 1995 usable energy density is expected to increase to about 25 Wh/lb.

D. HYDROGEN OXYGEN REGENERATIVE FUEL CELL (RFC)

The hydrogen oxygen fuel cell has been extensively developed for terrestrial and NASA space flight programs.[4] These space programs are typically of relatively short duration, and thus have different reliability considerations than do the long-term orbital missions. The primary difficulty with fuel cells is that the peripheral pumps and plumbing have not demonstrated the needed reliability for extended space missions. For a LEO mission of 5 years it may be possible to service a RFC system to assure the mission life; however, development and demonstration of pumps and plumbing that have long-term reliability would be a major step in enabling fuel cells to fill space power needs. In order to supply power for a 10-year GEO mission where on-orbit servicing is not easily done, tremendous improvements must be made in system reliability over that demonstrated to date. Other than the reliability question, the RFC is relatively well developed technology that has reasonable energy density. For LEO orbits where weight is not the driving consideration that it is in higher orbits, efficiency optimized RFC units are most likely to be used to alleviate the thermal management problems. These units would have efficiencies of 60-65% and usable energy densities of 10 Wh/lb in 1986, increasing to 14 Wh/lb by 1995. For GEO applications weight-optimized RFC units would be of most interest for high power systems. These units in 1986 are expected to provide usable energy densities of 42 Wh/lb, increasing to about 72 Wh/lb by 1995. These quite high energy densities for GEO orbits are largely due to the need for only a small electrolyzer unit because of the relatively long recharge time that is available. Energy densities significantly less than these numbers would be applicable to MAO orbits, for which recharge times decrease as the orbit altitude decreases. Energy densities were found to vary considerably depending on the various thermal and system design options that have been employed. However, since hydrogen oxygen RFC devices are much less efficient than batteries, a weight penalty for the low system efficiency would result from the increased solar array sizing that would be needed.

A feature of RFC devices is that they have good peak power capability, being able to provide at least 10 times the base power. This capability may be useful for augmenting sodium sulfur batteries in high power systems at times of power pulses, or for satisfying high peak-power system needs in LEO missions. In this way solar panel and radiator sizing may be kept down while meeting the peak power needs.

The major concern with using RFC devices in systems that require a significant degree of autonomous operation is the reliability of some of the supporting mechanical hardware. While redundancy in the plumbing and mechanical hardware may be possible to provide high reliability levels, this effort will require careful analysis, redesign of existing systems, and demonstration, and is likely to entail significant weight penalties. A study of the potential applications of RFC devices to space power needs is currently being conducted by Hughes for AFWAL.

E. LITHIUM IRON SULFIDE

The lithium iron sulfide battery system has been developed for terrestrial applications at Argonne National Laboratories and is currently under further development by workers at Gould Incorporated. The major problem with this system is that average cell cycle life has been typically 400-500 cycles, with energy densities of less than 40 Wh/lb at the battery level. These performance levels do not effectively compete with present sodium sulfur technology, a performance gap that does not appear to be narrowing, and in fact has apparently widened over the past 2 years. Some of the work that is presently taking place at Gould may improve the performance of this system. However intrinsic limitations to long-term operation appear to exist with current technology in the areas of separators, parasitic reactions, and electrode shape changes. It does not appear likely that this system will be able to meet the life and reliability requirements for space applications by the 1995 time frame.

While the lithium iron sulfide system does not appear likely to compete effectively with sodium sulfur based on cycle life and energy density, it is clearly the best battery system that presently exists in terms of ability to deliver high peak power. Gould is presently working on this system for production of very high power, with current densities up to hundreds of amperes per cm^2. Although this work is highly exploratory and aimed at the production of megawatt-level pulses, it is clear that this system is the best candidate battery for extremely high power, and low to moderate cycle life applications.

F. LITHIUM IRON DISULFIDE

Some work has been done in the lithium iron disulfide system since the review of Ref. 1, primarily at Gould. This system offers an energy density that is potentially as good as that of sodium sulfur, but which is largely conceptual, having not yet been demonstrated in long-term battery testing. Recent work has shown that iron disulfide is not stable under the high temperature conditions in lithium iron sulfide cells, making it necessary to significantly reduce the temperature and employ a different electrolyte. This is likely to substantially reduce the peak power capability of the system. Because the fundamental chemistry is not fixed and tested for this system at the present time, it appears unlikely that this battery system will be available by 1995 for the space power needs defined in this report.

G. SILVER HYDROGEN

The silver hydrogen battery system has been developed extensively for aerospace use in Europe,[7] and has provided excellent test results for the space power requirements of many of the European space programs. This system has somewhat better energy density than the nickel hydrogen system, but provides a much lower cycle life than does nickel hydrogen. This limitation is due to relatively fundamental problems with the physical stability of the silver electrode. There has been no indication of major advances in the silver hydrogen system in the past 2 years that would significantly advance the cycle life capability. Thus this battery system is not expected to be able to satisfy the future life requirements of space vehicle power needs with the required reliability levels.

H. HYDROGEN HALOGEN REGENERATIVE FUEL CELLS

The hydrogen bromine regenerative fuel cell has been proposed for space power applications, largely because it has the potential of energy efficiencies comparable to those obtained from the nickel cadmium and nickel hydrogen systems. Energy densities are projected as 22 Wh/lb, with improvements to 30 Wh/lb possible.[4] However, little test data related to how these fuel cells would be used in space vehicles have been obtained. To realize the efficiency advantages of the hydrogen bromine system, a reversible electrolyzer should be used. Such a unit has not been built and tested. Tests have been done using a system consisting of separate fuel cell and regeneration units, which was operated for 6 months and indicated that the electrodes were stable.[4] However, it is not clear that this test provides a reasonable indication of stability in a reversible cell. The problems with pumps, plumbing, and mechanical parts are also expected to be more severe for this system than for the hydrogen oxygen RFC, due to the highly corrosive nature of the bromine fuel. While the hydrogen bromine fuel cell has potential advantages over the hydrogen oxygen RFC based on efficiency, the concerns surrounding pump and plumbing reliability and the fact that this system is presently largely a paper concept make this fuel cell an unlikely candidate to provide a significant impact on space power usage by the 1995 time frame.

The hydrogen chlorine RFC is presently not as highly developed as the hydrogen bromine RFC, in that significant ground testing has not yet been done with separate fuel cell and electrolyzer units. This system is not projected to have as good efficiency as the hydrogen bromine RFC, and may have only slightly better energy density. It shares the problems due to the corrosive nature of the fuel and the poor reliability of the mechanical and plumbing hardware. This system is not expected to have a significant impact on space power usage.

I. ZINC BROMINE

This system, in spite of its rather low energy density, was projected in Ref. 1 as having possible applications in LEO where weight is not the overriding factor that it is in GEO. However, little progress has been made over the past 2 years in further developing this system, or in addresssing the reliability of the plumbing and mechanical hardware that are required. Most of the previous development of this system has been directed toward load leveling or electric vehicle applications. It does not appear that this technology will be developed to the point of being able to support space power needs through the 1995 time frame.

J. AMBIENT TEMPERATURE Li/MoS_2, Li/FeS_2

Ambient temperature rechargeable lithium molybdenum disulfide batteries have been developed recently by Moly Corporation.[9] These cells can achieve cycle lives on the order of hundreds of cycles, and have energy densities of about 35 Wh/lb. The development and improvement of these cells is continuing, particularly in the area of cathode improvement. However, fundamental limitations associated with the cycling ability of the lithium electrode do exist, and it is not clear that these kinds of cells will ever have the cycle life necessary to satisfy satellite power needs over the long-term missions defined by AFSD programs. These cells may have some potential applications in future space flight vehicle or transfer orbit vehicles with moderate cycle life requirements. They are not projected in this work to satisfy any of the known power requirements through the 1995 time frame.

Lithium iron disulfide cells, which were extensively developed by Exxon, have been produced in recent years by Jet Propulsion Laboratory and have shown cycling characteristics and energy densities similar to the lithium molybdenum disulfide cells described above. A battery composed of these cells has been placed in a real-time GEO test at Rockwell International, and has performed well through four eclipse seasons.[10] These results are too preliminary to indicate the feasibility of using the battery in a GEO application; however, it is expected that, for a 10-year operational period, additional development will be required. Again, these cells are not projected to satisfy the known power requirements through the 1995 time frame.

K. ADVANCED LITHIUM RECHARGEABLE SYSTEMS

Advanced lithium/sulfur dioxide rechargeable battery cells are under development by several companies; however, these at present should be characterized as being in the research stage. The concept of a lithium/polymer battery cell is also under active research level investigation and development. While some progress has been made in both areas over the past 2 years, it is expected that a competitive end product is many years away. This technology, the feasibility of which has not been fully established, is certainly beyond the 1995 time frame covered by this assessment.

IV. CORRELATION OF POWER REQUIREMENTS WITH PROJECTED TECHNOLOGY

The ranges of power that are required by SD programs through the 1995 time frame are indicated in Fig. 1, where each block represents a class of programs. There are a number of programs, generally at about 1-2 kW or lower, that are likely to continue to use NiCd batteries. However, the programs that require power levels much higher than this are being driven by weight considerations to the nickel hydrogen system. This trend is already occurring for programs requiring over 2 kW. At much higher power levels (about 10 kW) the nickel hydrogen system begins to be large and heavy, creating a need for a significantly higher energy density battery system. The dashed lines in Fig. 1 indicate the relative power regions below which NiCd, nickel hydrogen, and a HEDRB are expected to be most useful. The programs starting in the 1990 time frame will begin to push the capability of the nickel hydrogen system. By 1995 it is clear from Fig. 1 that a battery system having higher energy density than nickel hydrogen will be needed, particularly for the MAO and GEO classes of programs. These higher orbits have projected needs for power levels in excess of 10 kW by the 1994 time frame.

To correlate the battery technologies that appear most likely to be able to provide for program needs by 1995 with the needs in Fig. 1, projections of weight and life capabilities are presented in Table 2. The weight and life of batteries needed to satisfy the maximum power needs are indicated for the 1985-1986, 1991-1992, and 1995-1996 time frames. The energy densities used in Table 2 are usable energy densities that include battery packaging factors and the expected operating depth of discharge. Thermal control, charge control, and solar array systems are not included, since the details of these systems are in many cases mission-specific.

The projections in Table 2 clearly show that, for higher orbit applications, a battery system significantly higher in energy density than nickel hydrogen will be required at about 10 kW if battery weight is to be kept to about 10% of vehicle weight. For the classes of programs outlined in Fig. 1, this power level should be required between 1992 and 1995. The two high-energy-density systems that were projected in the previous section as being capable of providing flight-ready hardware prior to 1995 are the sodium sulfur

Table 2. Weight and Life Characteristics of Battery Systems

1985-1986 req.-4 kW	LEO			GEO		
	Wh/lb usable	Weight (lb)	Life (yr)	Wh/lb usable	Weight (lb)	Life (yr)
Nickel cadmium	4	600	5	9.5	505	10
Nickel hydrogen	11	218	5	15	343	10
Sodium sulfur	10	240	2	32	150	8
Hydrogen oxygen	10	240	2	42	114	2

1991-1992 req.-10 kW	LEO			GEO		
	Wh/lb usable	Weight (lb)	Life (yr)	Wh/lb usable	Weight (lb)	Life (yr)
Nickel cadmium	5	1200	5	11	1091	10
Nickel hydrogen	12.5	480	5	17	706	10
Sodium sulfur	15	400	4	36	333	10
Hydrogen oxygen	12	500	3	57	211	3

1995-1996 req.-20 kW	LEO			GEO		
	Wh/lb usable	Weight (lb)	Life (yr)	Wh/lb usable	Weight (lb)	Life (yr)
Nickel cadmium	6	2000	5	12.5	1920	10
Nickel hydrogen	14	857	5	20	1200	10
Sodium sulfur	25	480	5	40	600	10
Hydrogen oxygen	14	857	4	72	333	4

and the hydrogen oxygen RFC. Of these two systems, the RFC is not projected to be able to provide the 7-10 year life required in higher orbits. Significant development of the sodium sulfur system is needed for the lower mid-altitude orbits, while present technology looks promising for geosynchronous life requirements.

For LEO applications that employ Space Transportation System (STS) launch, the power system weight is not the design constraint that it is in higher orbits, except for the nickel cadmium system, which becomes prohibitively heavy at high power levels. Nickel hydrogen is expected to be adequate in terms of both weight and reliability for most LEO requirements. The requirement for a 5-year operating life (assumed to be without servicing) is a potential problem for both the RFC and the sodium sulfur system to meet. However, those missions that require very high peak power may require the hydrogen oxygen fuel cell capability. With an appropriate development program, RFC units may be able to approach the life that is required for LEO applications.

An area of need that is not clearly filled by any of the existing battery systems is the very high peak-power requirement. Sodium sulfur batteries must be designed for the peak power since the cells have significant internal impedance. RFCs have good peak power characteristics, but do not have the life and reliability that will be required for many missions. Although improved life and reliability may certainly be achieved through appropriate redundancy in life-limiting hardware, this will entail a significant weight penalty. Nickel hydrogen batteries can only supply peak power somewhat in excess of the base load. In the applications that require very high peak power levels, the nickel hydrogen system must be designed to handle the peaks. The RFC appears best able to handle the peak power requirements, although major development must be done to obtain the required life from RFC units.

The impact of the technologies presented in Table 2 on the space vehicle system in general becomes increasingly important as the power levels increase, and also because each energy storage technology has specific system impacts that must be considered. Thermal control and heat dissipation are critical in the high power systems that will be used in future space vehicles. It is likely that the power system must be integrated into the vehicle structure to improve thermal coupling and to minimize the supporting structures required for the batteries, particularly for nickel hydrogen batteries. It should be possible in many of these systems to use the battery system for shielding more critical components, since the batteries are quite insensitive to even quite large doses of radiation. Sodium sulfur batteries may be more isolated from the structure due to the high temperature operation. This poses a weight penalty from thermal insulation and packaging; however, this also means that heat dissipation and thermal control may be less critical for sodium sulfur since the thermal environment of the battery must be decoupled from that of the vehicle. RFC units, even in the efficiency optimized design, have much lower efficiencies than do the battery systems (see Table 3). Radiators and heat pipes will be a significant factor in these systems in terms of both weight and integration into the vehicle design. The charge/discharge controllers that are required for all of the systems are not considered in this report in terms of weight. The weight of bypass circuitry is a significant factor for the sodium sulfur system, and may be required for the nickel hydrogen system. The RFC configuration is not yet established to the point where equivalent systems to protect against single point failures have been defined or implemented. It is certain that such systems will be necessary, and that they will add significantly to the RFC system weight.

Table 3. Round-Trip Energy Efficiency of Battery and Fuel Cell Systems

Nickel cadmium	80-85%
Nickel hydrogen	75-82%
Sodium sulfur	82-86%
Hydrogen oxygen RFC wt. optimized (GEO)	49-54%
Hydrogen oxygen RFC eff. optimized (LEO)	60-64%

The considerations presented in Table 2 are based solely on battery weight, and do not include secondary effects of the different energy storage systems on the weight of the power system. The usable energy densities given in Table 2 do include the expected packaging factors for the different systems. With the exception of the RFC, which must include additional weight for solar arrays and radiator capability, the impact of the energy storage system on other aspects of overall system weight is not expected to alter the conclusions that are presented here. Detailed system studies for nickel hydrogen batteries and sodium sulfur battery concepts have been done,[1,8] and support the overall results presented here. A detailed study of how the RFC could be implemented in a spacecraft power system for reliable operation over a 5-year LEO mission, in which very high peak-power pulses are required, has not been done and is recommended if RFC units are considered for these specific applications.

Mission life requirements are compatible with the demonstrated or expected life of all of the battery systems presented in Table 2 except the RFC. Significant development is needed before RFC units can be expected to operate with high reliability over the 5-10 years that are required. If these systems are to impact space power before 1995, this development must be undertaken soon, since the testing that is necessary to demonstrate reliable long-term operation generally requires many years of real-time and accelerated testing.

Missions that require autonomous operation should be able to satisfy these needs with either the nickel hydrogen or the sodium sulfur systems. Although there are additional difficulties with autonomous operation of nickel cadmium batteries, such operation should be possible in the lower power systems that are expected to continue using NiCd batteries. Because it is relatively tolerant to environment and because charge control can be effectively accomplished with present systems, the nickel hydrogen battery system can be operated autonomously more easily than can the NiCd battery. The sodium sulfur system is particularly amenable to autonomous operation because its failure mode is relatively well understood, and the system response clear. The chemical simplicity of the sodium sulfur system allows for simple charge control without requiring adjustment to compensate for gradual degradation of performance. The RFC units are not at the developmental point where the failure modes and degradation characteristics have been clearly demonstrated. Based on system complexity and test results to date, these failure modes are expected to involve moving parts and plumbing, which could prove to be a significant problem for autonomous operation.

V. CONCLUSIONS

1. Nickel cadmium and nickel hydrogen batteries can satisfy SD program power needs through the early 1990s. Particularly for some geosynchronous and mid-altitude requirements, the sodium sulfur battery must be available for use by the early 1990s. The nickel hydrogen battery is expected to satisfy the majority of low-earth-orbit battery power needs through 1995.

2. In low earth orbits, regenerative hydrogen oxygen fuel cells have a unique capability to satisfy projected mission requirements that involve very high peak power pulses. Significant reliability issues must be resolved before these fuel cells will be available for 5-year missions. In higher orbits where very high peak-power levels are required, the fuel cell is an attractive alternative to either the nickel hydrogen or sodium sulfur systems, although the reliability issues for the fuel cell may preclude meeting the 7-10 year life requirements for missions by the mid-1990s.

3. The nickel hydrogen and sodium sulfur systems appear best suited for autonomous power subsystem operation, a requirement by the early 1990s for an increasing number of programs.

4. Development and testing of high energy density systems such as the sodium sulfur battery and hydrogen oxygen regenerative fuel cell should be implemented now if this technology is to be available by the mid-1990s when needed.

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The Laboratory Operations of The Aerospace Corporation is conducting experimental and theoretical investigations necessary for the evaluation and application of scientific advances to new military space systems. Versatility and flexibility have been developed to a high degree by the laboratory personnel in dealing with the many problems encountered in the nation's rapidly developing space systems. Expertise in the latest scientific developments is vital to the accomplishment of tasks related to these problems. The laboratories that contribute to this research are:

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