SPACE OPERATIONS CENTER

SYSTEMS ANALYSIS

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ANALYSIS OF REGENERATIVE FUEL CELLS

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FINAL REPORT

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FOR

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FOREWORD

This study was managed by the Lyndon B. Johnson Space Center. Hoyt McBryar was the NASA/JSC Study Technical Manager. This study was conducted by The Boeing Aerospace Company, Large Space Systems Group. The SOC study manager was Gordon W. Woodcock; the technical staff engineering manager was Dr. Richard Olson; the task manager was Sidney W. Silverman; and Sidney Gross was the principal investigator.

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TABLE OF CONTENTS

TABLE OF CONTENTS (CONT.)

1.0 INTRODUCTION

1.1 SUMMARY

This study analyzes and evaluates orbital energy storage systems for space stations, using the Space Operations Center (SOC) as a point of reference. Energy storage systems for spacecraft in the past generally have used nickel cadmium (Ni-Cd) batteries for rechargeable systems, or hydrogen-oxygen fuel cells for relatively short duration missions, such as Apollo or Shuttle. In this study, major attention is devoted to the concept of a rechargeable fuel cell (RFC) system (Fig. 1.1-1). A newer type of rechargeable battery, the nickel hydrogen ($Ni-H_2$) battery, is also evaluated.

To help resolve the question as to the potential of the RFC system, a review was made of past studies. These studies showed large variations in weight, cost and efficiency. However, the variations are much reduced when normalized. Operations cost is the most difficult to establish because ground rules varied considerably. However, the general conclusion in prior studies was that the RFC system has good potential for space stations, and this conclusion was found to be valid.

Hydrogen-bromine and hydrogen-chlorine regenerable fuel cells were studied, and were found to have a potential for higher energy storage efficiency than the hydrogen-oxygen system. A reduction of up to 15 percent in solar array size may be possible as a result. These systems are not yet developed, but further study of them is recommended.

Integration of the energy storage system with the reaction control system offers weight savings possibilities. Water can be resupplied, electrolyzed on board, and the product hydrogen and oxygen used as reactants for orbit makeup; this saves considerable weight over the use of hydrazine.

An additional opportunity with the regenerable fuel cell system is in the use of residual hydrogen and oxygen from the Shuttle. These fuels can be used in the fuel cell, thus reducing or eliminating the size of the energy storage system and the solar array. With 19 evenly spaced Shuttle flights per year to the SOC, the solar array size can be reduced by half; with 50 flights per year, no solar array is required.

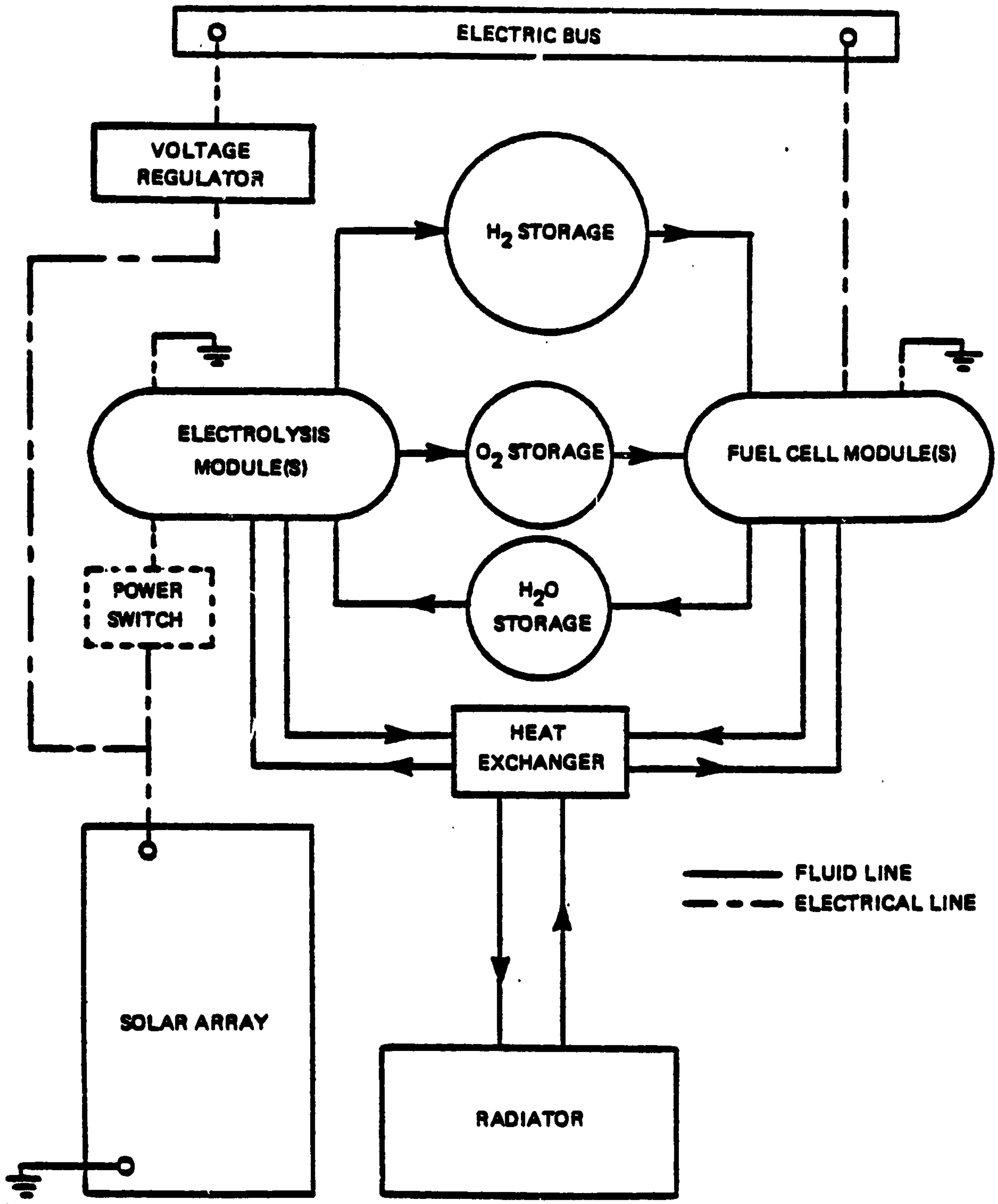

Figure 1.1-1: Regenerative Fuel Cell Orbital Energy Storage System – Block Diagram

1.2 BACKGROUND

The background upon which this study is cast is the Space Operations Center (SOC). Study of the SOC was conducted by Boeing in two parts: a Phase A Systems Analysis and a Phase A Extension. The Phase A study analyzed and defined a manned space station dedicated primarily to operational missions. It developed system design requirements, and design and operational concepts. The Phase A Extension concentrated on development of mission models and analysis of SOC utility. That phase of study considered applications science and technology missions as well as operational missions. The SOC study was managed by the Lyndon B. Johnson Space Center, with Sam Nassiff as the Study Technical Manager. The final report includes five documents:

D180-26785-1	Vol. I	Executive Summary
D180-26785-2	Vol. II	Programmatics
D180-26785-3	Vol. III	Final Briefing
D180-26785-4	Vol. IV	SOC System Analysis Report
D180-26495-2, Rev A		SOC System Requirements
D180-26495-3, Rev A		SOC System Definition Report

Regenerable fuel cell (RFC) systems are discussed at length in this study. They produce electricity during spacecraft occultation in a conventional fuel cell mode by combining reactants, such as hydrogen and oxygen, in an efficient electrochemical process to generate electricity and the product water. During sunlight, the process is reversed to convert the discharge product water electrochemically to the initial reactant state, typically hydrogen gas and oxygen gas. This regeneration mode can take place in a separate unit, called the electrolyzer, or in the fuel cell using bifunctional electrodes. The use of an electrolyzer is of the greatest interest at this time for space station applications.

The nickel hydrogen battery is also a promising candidate for the energy storage system. It is currently under development and is generally considered to have good promise for longer life and deeper depth-of-discharge capability than the conventional nickel cadmium battery system.

A number or studies have been conducted over the past years, comparing regenerative hydrogen-oxygen fuel cell systems with batteries to determine the applicability of regenerable fuel cell systems to future multi-kilowatt spacecraft. Ground rules and assumptions all differed, but the results generally showed a weight advantage for the regenerable fuel cell system. Weight alone is not a sufficient criterion, however, and other factors must also be considered. This study was intended to help resolve some of the questions with regard to the potential of this system.

1.3 PROGRAM OBJECTIVES

The general objective of this study program is to evaluate orbital energy storage systems for SOC. A principal element is to compare and evaluate the previously accomplished power studies together with their common conclusions as to the applicability of regenerable fuel cells within the framework of various SOC evolutionary design configurations. Study tasks for the program are as follows:

1. Review and define energy storage requirements for the SOC. Define a reference regenerative hydrogen-oxygen fuel cell system.

2. For the reference regenerative fuel cell system defined, determine the important engineering parameters.

3. Categorize results from prior studies to identify differences and commonalities.

4. Develop a method to adjust for the differing ground rules and assumptions in the prior studies to obtain a common comparative basis.

5. Determine technology advancements that could influence systems comparisons.

6. Assess H_2-Br_2 and H_2-Cl_2 regenerative fuel cell systems.

7. Compare results of prior studies and evaluate the impact of technology advancements.

8. Evaluate integration of regenerative H_2-O_2 fuel cell systems with other SOC subsystems.

9. Compare regenerative fuel cell systems with battery systems for SOC.

10. Document study results and prepare final report.

2.0 DEFINITION OF REQUIREMENTS AND PENALTIES

The following requirements and penalties are defined for the SOC energy storage system.

<u>Orbital Conditions</u>

Altitude	370 km (200 NM) to 450 km (243 NM)
Inclination	28.5 degrees
Solar Cycle	Sunlight duration - 55 minutes Occult duration - 37 minutes

<u>Bus Voltage</u>

Regen. Fuel Cells	200 +2%, -20% dc
Batteries	200 +10%, -30% dc
MIL 1539 (Ref.)	28 +21.4%, -21.4% dc

<u>Electric Power Requirements, Normal Operation</u>

See Figure 2.0-1. Load management results in less load during occultation than during sunlight.

<u>Electric Power Requirements -- Emergency Operation</u>

See Figure 2.0-2

<u>Equipment Cooling</u>

Cold Plate Mounting and Cooling (batteries & electronics)	11 percent of equipment weight
Radiator area for batteries (5°C)	14 W/ft^2 radiation surface
Radiator area for electronics (20°C)	19 W/ft^2 radiation surface
Radiator weight	1.27 lb/ft^2 of radiator (2 ft^2 radiation surface/ft^2 radiator in plan view)

		SUNLIGHT – W	OCCULTED – W
FULL SOC	ELECTRIC LOADS	50,000	39,230
	ELECTROLYZER FOR RECHARGE	AS REQUIRED	———
	INTEGRATED SUBSYSTEMS ELECTROLYZER	FIGURE 2.0-3	SUNLIGHT ONLY
HALF SOC	ELECTRIC LOADS	27,880	23,770
	ELECTROLYZER FOR RECHARGE	AS REQUIRED	———
	INTEGRATED SUBSYSTEMS ELECTROLYZER	FIGURE 2.0-3	SUNLIGHT ONLY
GROWTH SOC	ELECTRIC LOADS	50,000	39,230
	EXPERIMENTS	40,000	30,000
	ELECTROLYZER FOR RECHARGE	AS REQUIRED	———
	INTEGRATED SUBSYSTEMS ELECTROLYZER	FIGURE 2.0-3	SUNLIGHT ONLY

Figure 2.0-1: Electrical Power Requirements – Normal Operation

EMERGENCY MODE "A" – COMPLETE LOSS OF ONE SOLAR ARRAY WING. CAN LAST 60 DAYS. ARRAY CAPABILITY IS REDUCED 50%, BUT LOADS ARE REDUCED 80% (50 KW TO 10 KW). THEREFORE, REGENERABLE FUEL CELL MAY OPERATE IN A LESS EFFICIENT MANNER IF NEED BE.

EMERGENCY MODE "B" – LOSS OF ATTITUDE CONTROL/SOLAR ARRAY ORIENTATION. THIS RESULTS IN A PARABOLIC OUTPUT OF SOLAR ARRAY POWER WITH TIME, BUT WITH PEAK OUTPUT APPROACHING 50 KW. THE EFFECTIVE CHARGE DURATION IS REDUCED TO 38 MINUTES, AND THE EFFECTIVE DISCHARGE DURATION IS INCREASED TO 54 MINUTES. LOADS ARE REDUCED 80% (50 KW TO 10 KW). THE EMERGENCY CAN LAST 21 DAYS.

EMERGENCY MODE "C" – COMPLETE SHUTDOWN OF SOLAR ARRAY FOR ONE ORBIT (92 MINUTES). ALL ELECTRICAL POWER ENTIRELY OFF ENERGY STORAGE SYSTEM FOR ONE ORBIT AT A POWER LEVEL OF 3,000 W. THIS CAN OCCUR IMMEDIATELY AFTER A NORMAL-LOAD OCCULTATION DISCHARGE. THE EFFECT OF THIS REQUIREMENT IS TO INCREASE THE CONTIGUOUS LOAD ON THE ENERGY STORAGE SYSTEM BY 19.5% OF THE NORMAL LOAD.

	EMERGENCY DURATION	ENERGY STORAGE LOAD	
		FULL SOC OR GROWTH SOC	HALF SOC
EMERGENCY MODE "A"	60 DAYS	9,000 W AVE, 10,000 W PEAK	4,500 W AVE, 5,000 W PEAK
EMERGENCY MODE "B"	21 DAYS	9,000 W AVE, 10,000 W PEAK	4,500 W AVE, 5,000 W PEAK
EMERGENCY MODE "C"	92 MINUTES	3,000 W	1,500 W

Figure 2.0-2: Electrical Power Requirements – Emergency Operation

	WATER ELECTROLYSIS RATE – LB/DAY	NUMBER OF ELECTROLYZER SYSTEMS REQUIRED: CASE NO. 1 – NO INTEGRATION	NUMBER OF ELECTROLYZER SYSTEMS REQUIRED: CASE NO. 2 – INTEGRATION	GAS STORAGE CRITERIA
FUEL CELL ELECTROLYZER	PER ANALYSIS	3		EMERGENCIES A, B AND C
LIFE SUPPORT ELECTROLYZER	17.8 LB/DAY (1) (3)	2	3	EMERGEN[illegible] A, B A[illegible]
ORBIT MAINTENANCE ELECTROLYZER	18.0 LB/DAY (2)	2		EMERGENCIES A, B AND C
		TOTAL: 7	TOTAL: 3	

(1) PEAK REQUIREMENT IS 20.2 LB/DAY, WITH 27% AT 900 PSI

(2) FOR GROWTH SOC, REQUIRED 27.2 LB/DAY
FOR HALF SOC, REQUIRE 9.66 LB/DAY

(3) FOR GROWTH SOC, REQUIRED 26.7 LB/DAY
FOR HALF SOC, REQUIRE 6.7 LB/DAY

Figure 2.0-3: Electrolyzer/Storage Requirements for Integrated Subsystems – Full SOC

Radiator area for fuel cell	Temperature	Watts/ft^2 radiator surface
	60°C	37.2
	70°C	42.9
	80°C	49.0
	90°C	55.7

Power System Constraints on Regenerable Fuel Cell System

Number of fuel cell modules, full SOC	3 busses with minimum of 2 modules/buss, and minimum of 6 modules total Design to carry full load with 2 modules out, though efficiency may suffer Design to emergency load with 2 modules out.
Number of fuel cells modules, half SOC	3 busses with minimum of 1 module/bus Design to carry full load with 1 module out, though efficiency may suffer. Design to emergency load with 2 modules out.
Number of fuel cell modules, growth, SOC	No redundant modules required for science equipment. Design to carry full load with about 25% of the modules failed, though efficiency may suffer.
Number of Electrolyzer Modules	See Figure 2.0-3.

Power Supply/Controller Efficiency (including transmission loss)

Electrolyzer controller	99%
Battery Chargers	92%

Solar Array Incremental Weight Penalty (weight per unit array - generated power)

Half SOC	30.6 lb/kW
Full SOC	30.6 lb/kW
Growth SOC	30.6 lb/kW

Note: Penalty for solar array drag not included. This is a resupply penalty that is addressed separately.

3.0 EFFICIENCY CONSIDERATIONS

3.1 THE IMPORTANCE OF HIGH EFFICIENCY

Energy storage efficiency is a key factor in the optimization of any particular energy storage system, and also in the choice between one system and another. The importance of this appears to have been mostly overlooked, and as a result the minimum weight, or at least low weight designs, have often been favored in the past. This is not to say that minimum weight designs are not worthwhile. Some missions can be visualized where low weight is paramount. However, for the general purpose solar array-powered space station, high efficiency designs are compelling.

The reasons for underscoring the importance of high efficiency are: (1) Cost can be lowered by reducing solar array size for a given load, saving both on array cost and on fuel for orbit-makeup propulsion; (2) Space Station power capability can be effectively increased by permitting more electrical payload for a given size of solar array (alternative to item1); (3) Life of the energy storage system is increased due to the low current density designs needed for high efficiency; (4) Peak power and failure mode power capabilities are increased due to the low current density designs needed for high efficiency; (5) Attitude control performance is improved.

<u>Solar Array Size and Cost</u>

An efficient energy storage system reduces the size of the solar array. This is shown in Figure 3.1-1 for the SOC requirements. Costs of solar arrays are expected to be considerably greater than costs of energy storage systems, as shown in Figure 3.1-2. Note that there is a wide range of uncertainty on these costs. As a reference point on solar array costs, the cost of the Skylab solar array was $600. per Watt. Although there has been much interest in low cost solar arrays, it is questionable whether there is a sufficient market to allow large cost reductions. Large solar arrays possibly will also require complex, deployable structures to provide stiffness, and the cost of this would be significant. For these reasons, it is more important to try to reduce solar array costs than it is to try to reduce energy storage system cost. Thus, reduction of solar array size should give significant cost savings.

An alternative to solar array cost saving, due to improved efficiency, is to permit a greater electrical payload for a given solar array size. Solar arrays of specific sizes are likely to be built and qualified, and power could be rigorously limited. The

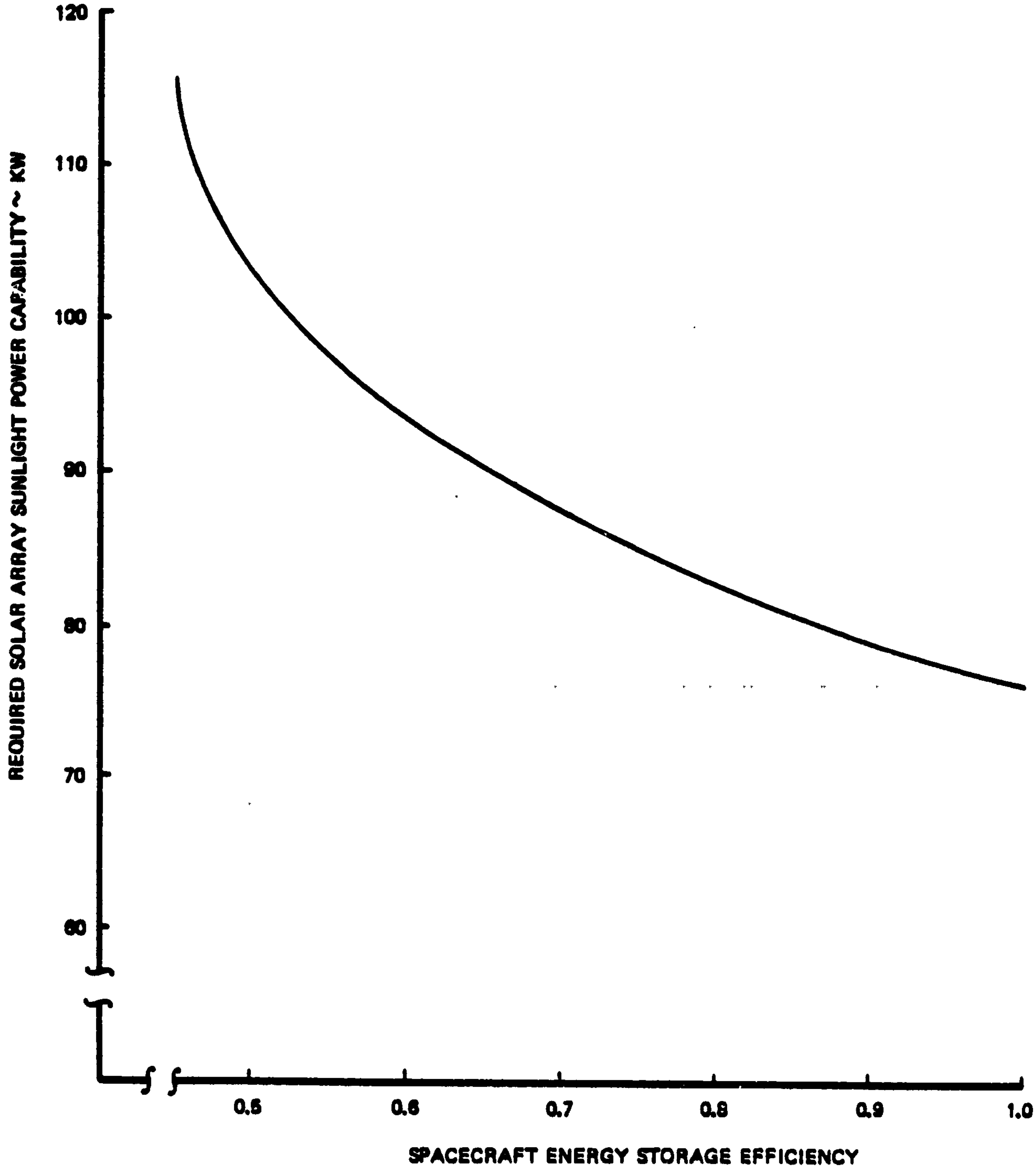

Figure 3.1-1. Effect of Efficiency on Solar Array Size

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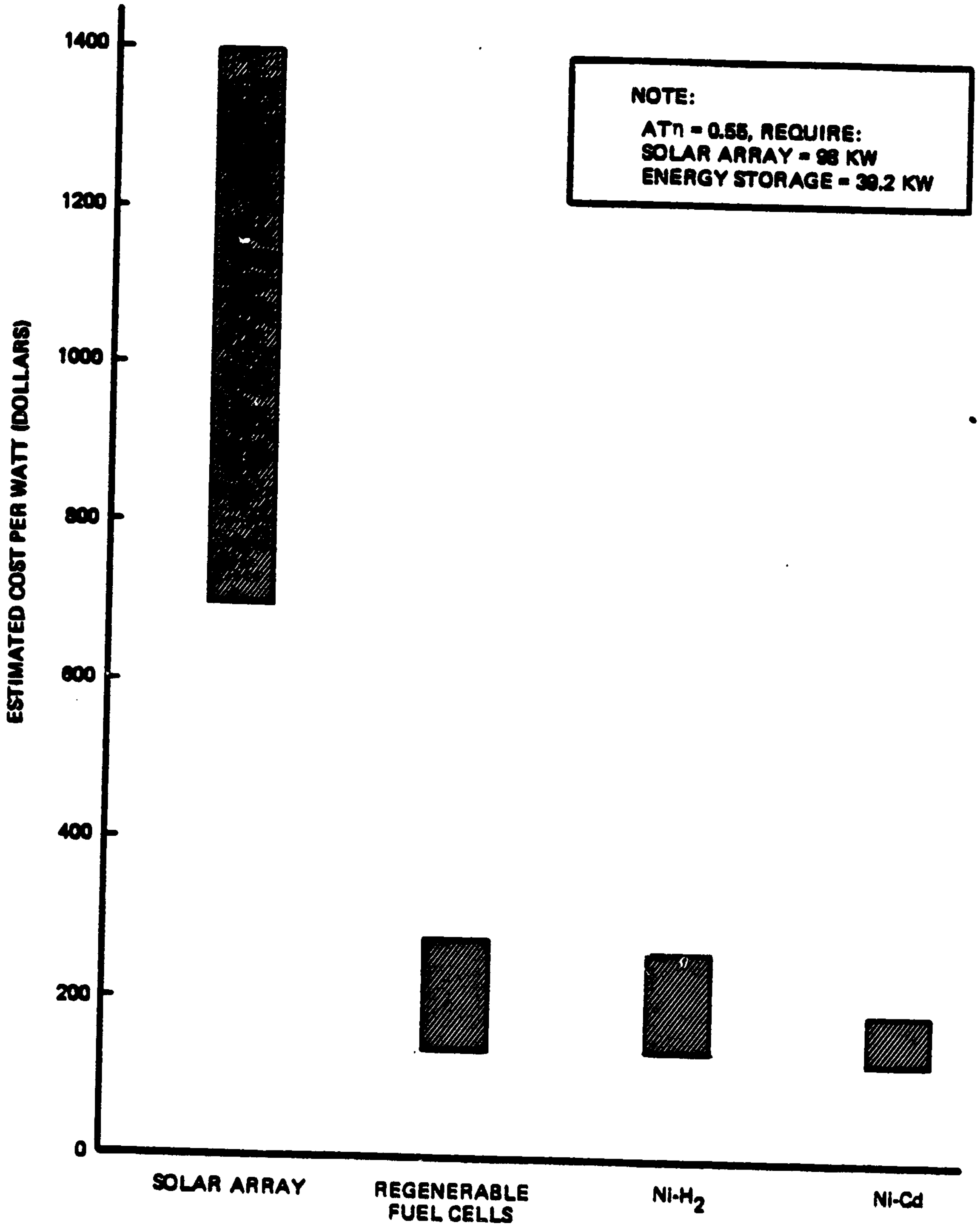

Figure 3.1-2: Estimated Power System Costs

problems of large sized solar arrays are well out of proportion to the modest weight involved.

Propulsion Resupply Due to Solar Array Drag

Significant quantities of propulsion fuel must be resupplied regularly to offset the effects of solar array drag, and maintain the space station within the selected orbit. Inefficient energy storage systems require greater solar area, and hence more propulsion fuel. This is shown in Figure 3.1-3 for both hydrazine and hydrogen-oxygen propellants. This penalty can be considerable over the life of the spacecraft.

Attitude Control Effects

Large solar arrays penalize the attitude control system in several ways (Figure 3.1-4). Of major concern is the fact that propellant weight consumption rises with array size increase. Also, if a control moment gyro system is used, then the time between desaturation events is decreased, which is an operational disadvantage. In addition, pointing accuracy is reduced, which can be critical with some payloads. All these attitude control penalties are related to energy storage system efficiency through its effect on solar array size.

3.2 REGENERABLE FUEL CELL EFFICIENCY CONSIDERATIONS

Contributors to Inefficiency

There are approximately ten possible contributors to energy storage system inefficiency with the RFC system: (1) Fuel cell voltage loss; (2) Fuel cell Faradaic inefficiency; (3) Fuel cell ancillary power; (4) Fuel cell discharge regulator power loss; (5) Electrolyzer voltage loss; (6) Electrolyzer Faradaic inefficiency; (7) Electrolyzer ancillary power (8) Electrolyzer input power regulator power loss; (9) Inefficient use of solar array charging area; (10) Power consumption for temperature control. These items are discussed below.

(1) Fuel Cell Voltage Loss. Typical discharge voltage for an alkaline fuel cell is shown in Figure 3.2-1. Voltage is highest at low current densities, hence high efficiency would be favored at such operating conditions. A completely efficient discharge would occur at the reversible voltage, which is associated with the Free Energy change, and is 1.23 V at room temperature and lower at higher temperatures. The enthalpy voltage, or thermoneutral voltage, is approximately 1.45 V at room temperature, so

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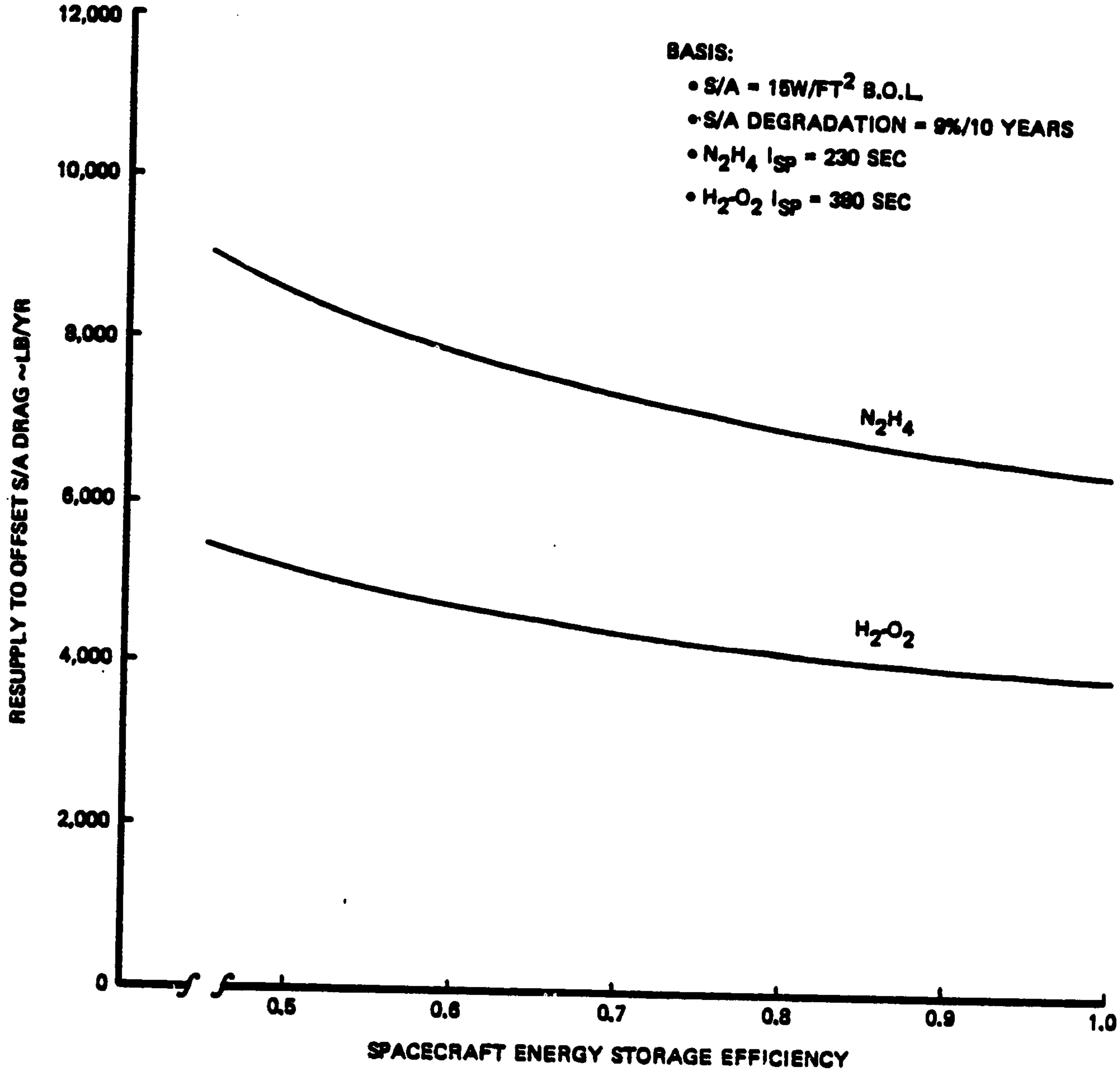

Figure 3.1-3: Propulsion Resupply Due to Solar Array Drag

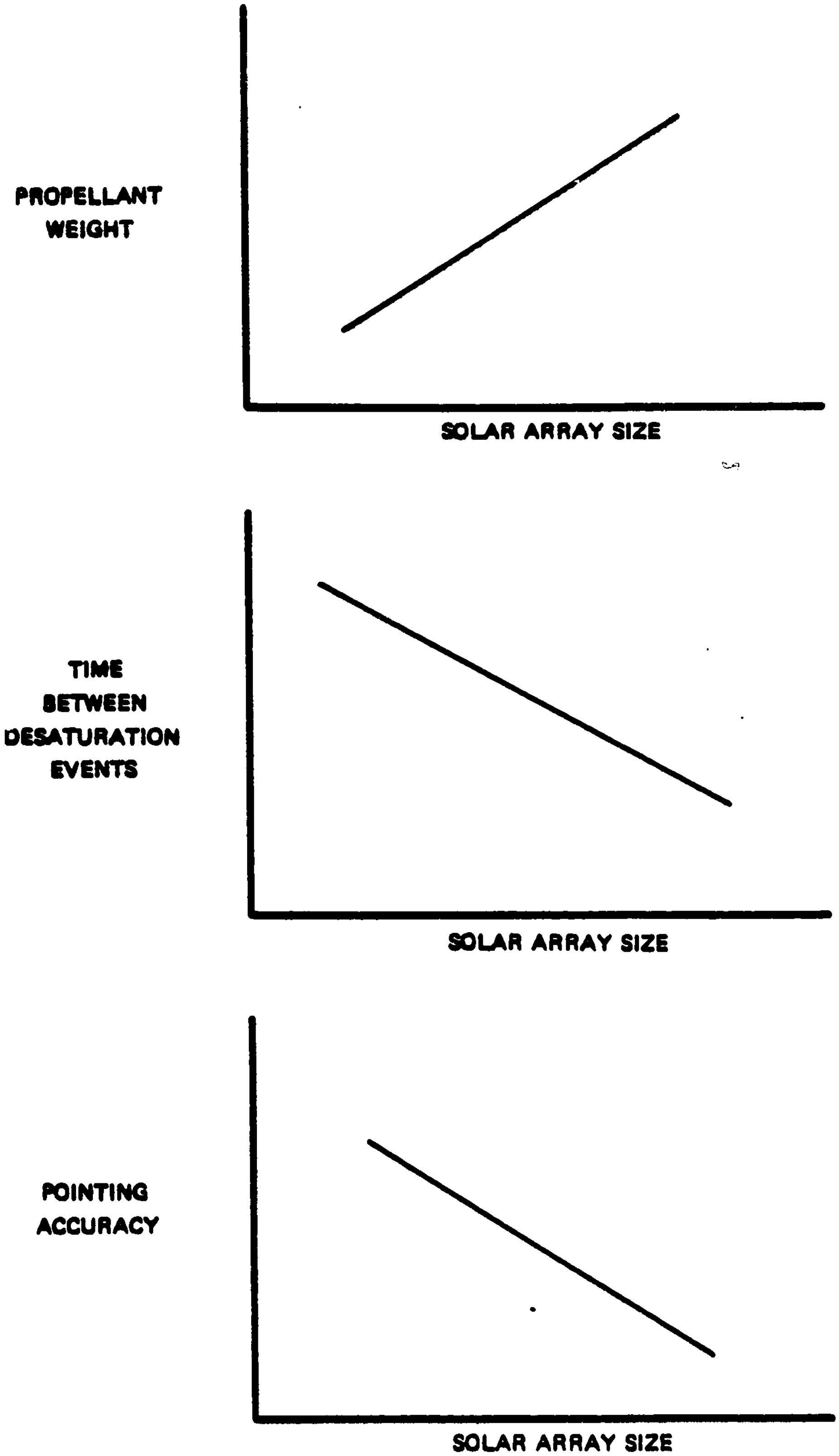

Figure 3.1-4: Large Solar Arrays Penalize the Attitude Control System

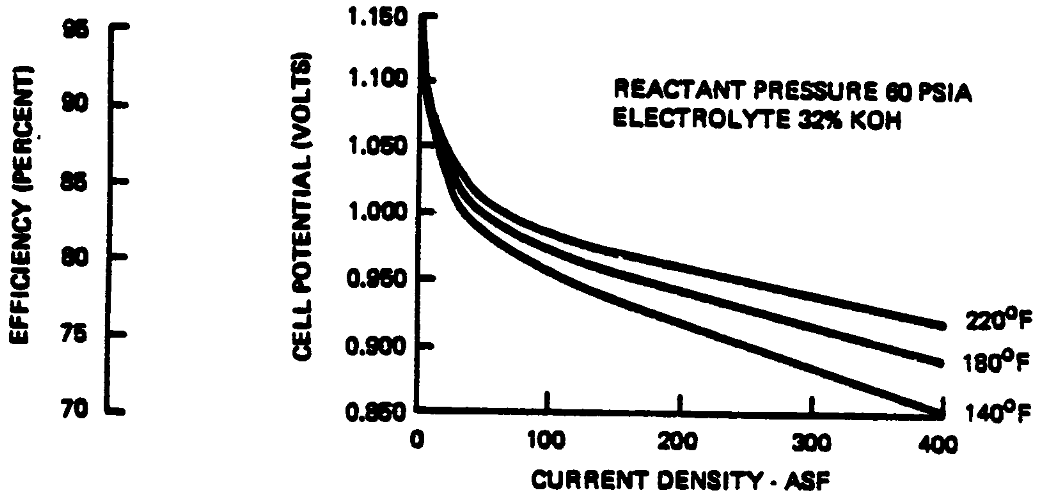

Figure 3.2-1: Typical Alkaline Fuel Cell Performance

even an ideal discharge at 1.23 V will generate heat. Some people prefer to use the enthalphy voltage as the voltage reference for determining efficiency, but it does not matter in the calculation of overall RFC system efficiency if a consistant basis is used.

Using the reversible voltage as the basis for ideal efficiency, the efficiency of fuel cells is shown in Figure 3.2-2. Actual measured open circuit voltage is approximately 1.15 V, so this sets a practical upper limit to the efficiency.

(2) Fuel Cell Faradaic Inefficiency. The Faradaic, or current efficiency, is essentially 100 percent in alkaline fuel cells. Losses are negligible, though at very high pressure these losses should be measurable. With solid polymer electrolyte fuel cells, there is always a current inefficiency, which is a self discharge due to cross diffusion of hydrogen and oxygen. This loss is shown in Figure 3.2-3, and is proportional to system pressure and inversely proportional to thickness of the solid electrolyte NAFION. This loss occurs at all times, irrespective of fuel cell discharge current, and it can become an important limitation in attempting to obtain maximum efficiency with solid polymer electrolyte fuel cells. Thus, to minimize this loss with the solid polymer electrolyte (acid electrolyte) system, oxygen and hydrogen gases to the fuel cell could be shut off during sunlight.

(3) Fuel Cell Ancillary Power. Ancillary power to operate pumps, motors, controls and other equipment varies with system size, but is on the order of 1.3 percent of the power output. Figure 3.2-4 shows the estimated ancillary power consumption. It is expected that most of the ancillary load will be off during sunlight; better definition is needed to distinguish between occulted and sunlight ancillary loads.

(4) Fuel Cell Discharge Regulation. A regulator is sometimes included to convert output voltage to within an acceptable range. This is often done as an outgrowth of other fuel cell applications where very tight voltage regulation was required. However, fuel cell voltage regulation is no worse than that of competing batteries, and thus generally need not have output voltage regulation. Special voltage regulation may be needed for special loads, such as voltage boosting for batteries, wherein this penalty would be legitimate.

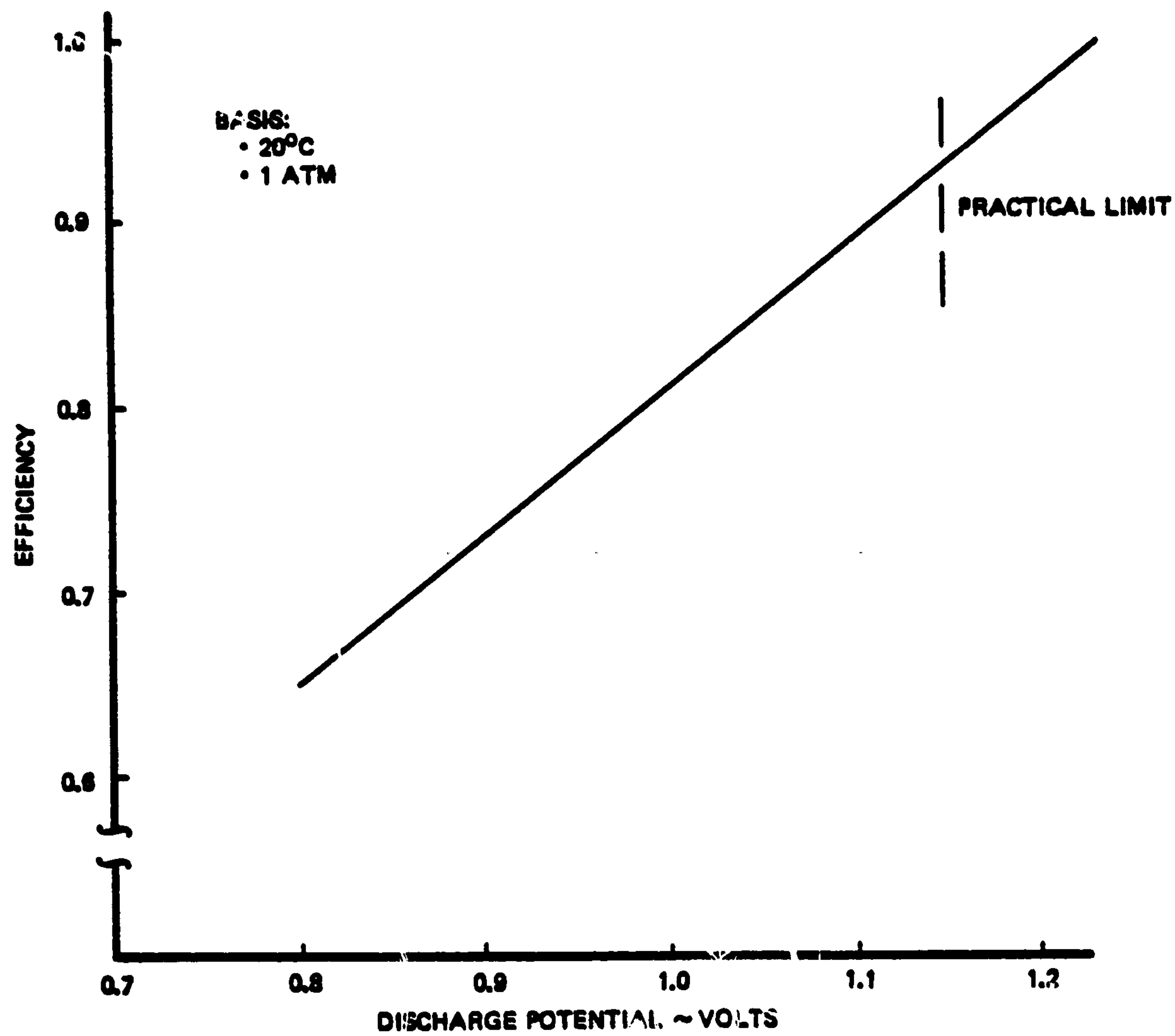

Figure 3.2-2: H_2-O_2 Fuel Cell Discharge Efficiency

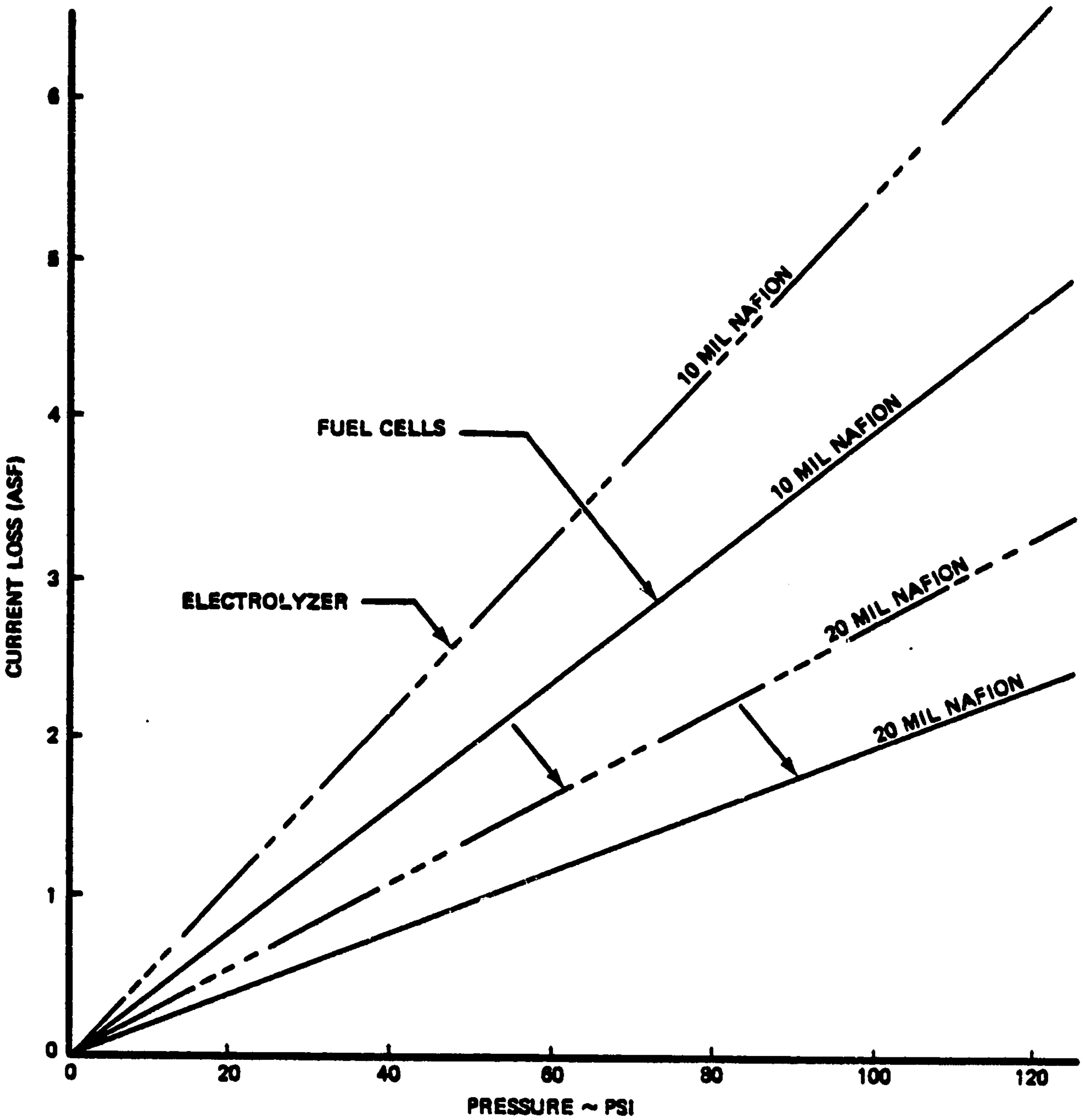

Figure 3.2-3: Cross Diffusion Losses from Solid Polymer Electrolyte Cell System

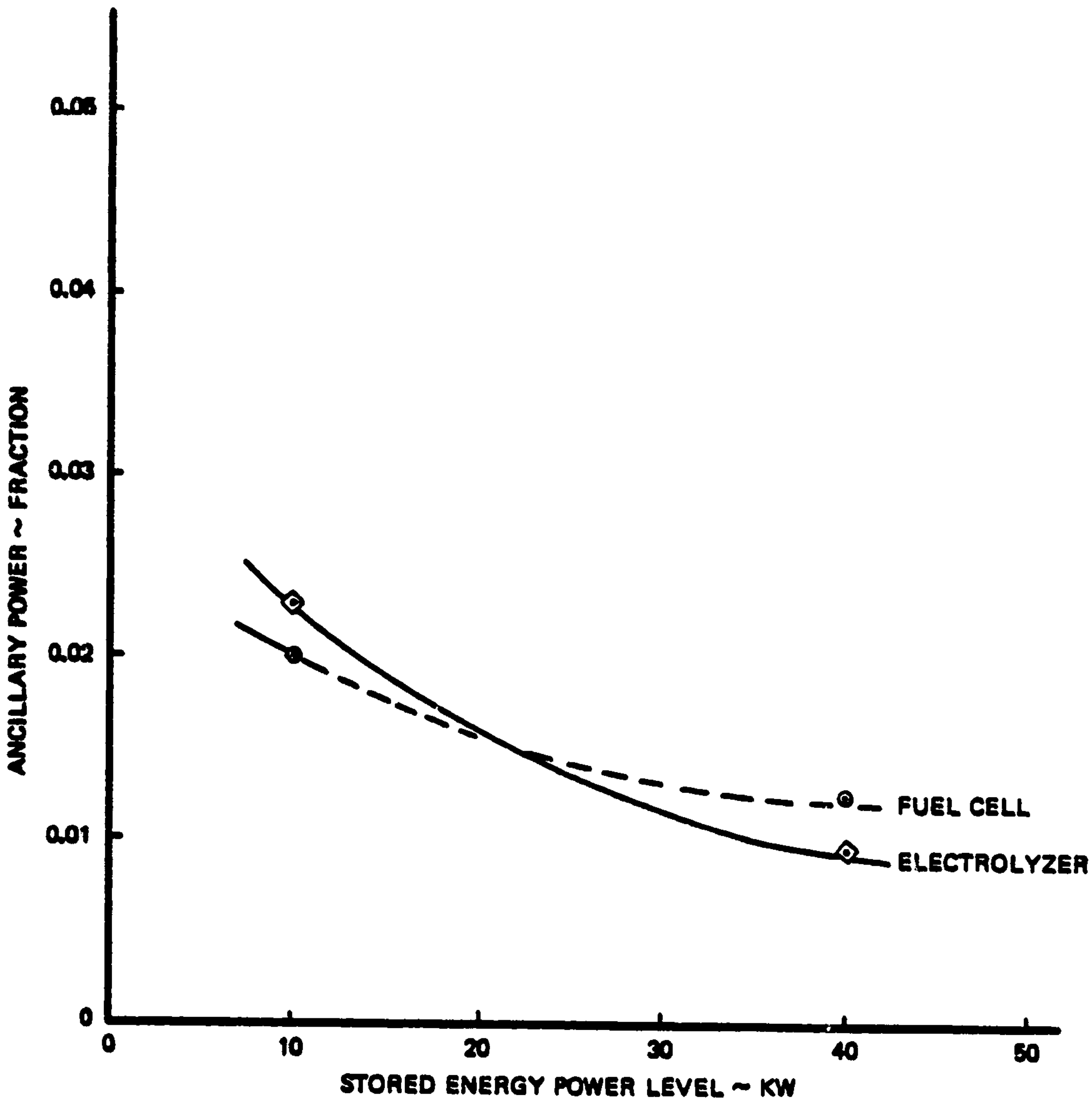

Figure 3.2-4: Ancillary Power in Alkaline Systems

(5) Electrolyzer Voltage Loss. An ideal electrolyzer at room temperature would operate at 1.23 Vdc. The higher voltage that must be used constitutes a loss. Typical voltage behavior for alkaline electrolyzers is shown in Figure 3.2-5. As with fuel cells, low current density gives the best voltage. Using the reversible voltage as the basis for ideal efficiency (rather than enthalpy voltage), the efficiency of electrolyzers is shown in Figure 3.2-6. The actual measured open circuit voltage is approximately 1.35 V, so this sets a practical upper limit to electrolyzer efficiency. As with the fuel cell, the enthalpy voltage (thermoneutral voltage) at room temperature is approximately 1.45 V; operation above 1.45 V will generate heat, whereas operation below 1.45 V will require that heat be added to the electrolyzer to maintain constant temperature.

(6) Electrolyzer Faradaic Inefficiency. The efficiency of alkaline electrolyzers is practically 100 percent, though there should be some small loss at very high pressures, (e.g., 3000 psi). Electrolyzers with solid polymer electrolyte are subject to Faradaic losses due to cross diffusion of hydrogen and oxygen, similar to solid polymer fuel cells.

(7) Electrolyzer Ancillary Power. Electrolyzer ancillary power to operate pumps, controls and other equipment varies with system size, but is on the order of 1.0 percent of the power level. Figure 3.2-4 shows the estimated ancillary power consumption. As with fuel cells, better definition is needed to distinguish between occulted and sunlight ancillary loads.

(8) Electrolyzer Input Power Controller. An input power regulator is sometimes included to control power to the electrolyzer. Though a controller is needed for switching functions and perhaps other purposes, it should not be necessary to regulate the supply voltage, for that already is closely regulated by the solar array regulator. With the advanced technology expected for the space station, it should be practical to vary the solar array control voltage, or to control bus voltage so as to obtain a desired current input to the electrolyzer. Also, all or part of the electrolyzer power can be from a separate section of the solar array, so that the electrolyzer may operate at a voltage different than bus voltage if there is an advantage to do so. Since the controller need provide only switching and control logic functions, losses will be slight, hence an efficiency of 99.5 percent is used.

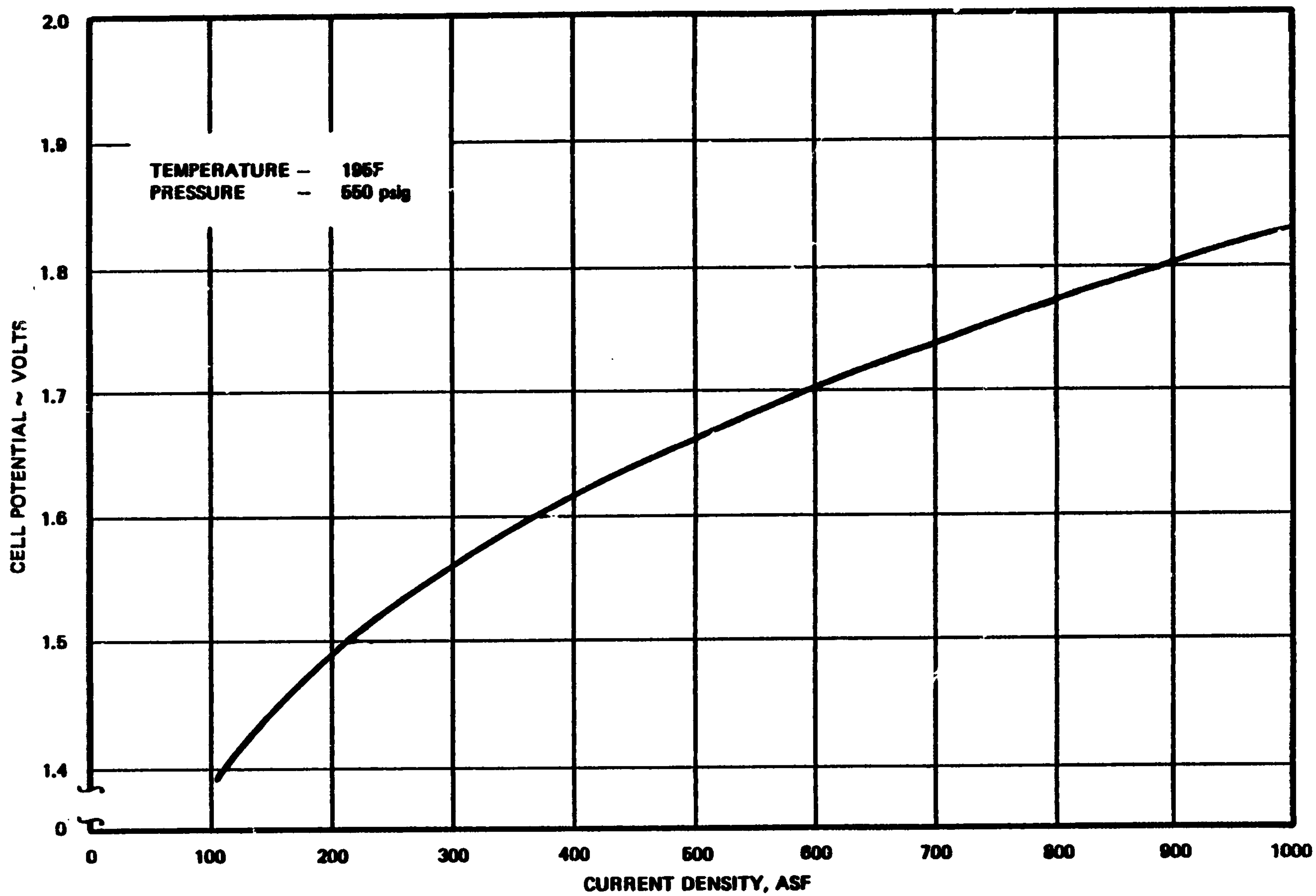

Figure 3.2-5: Typical Water Electrolysis Cell Performance

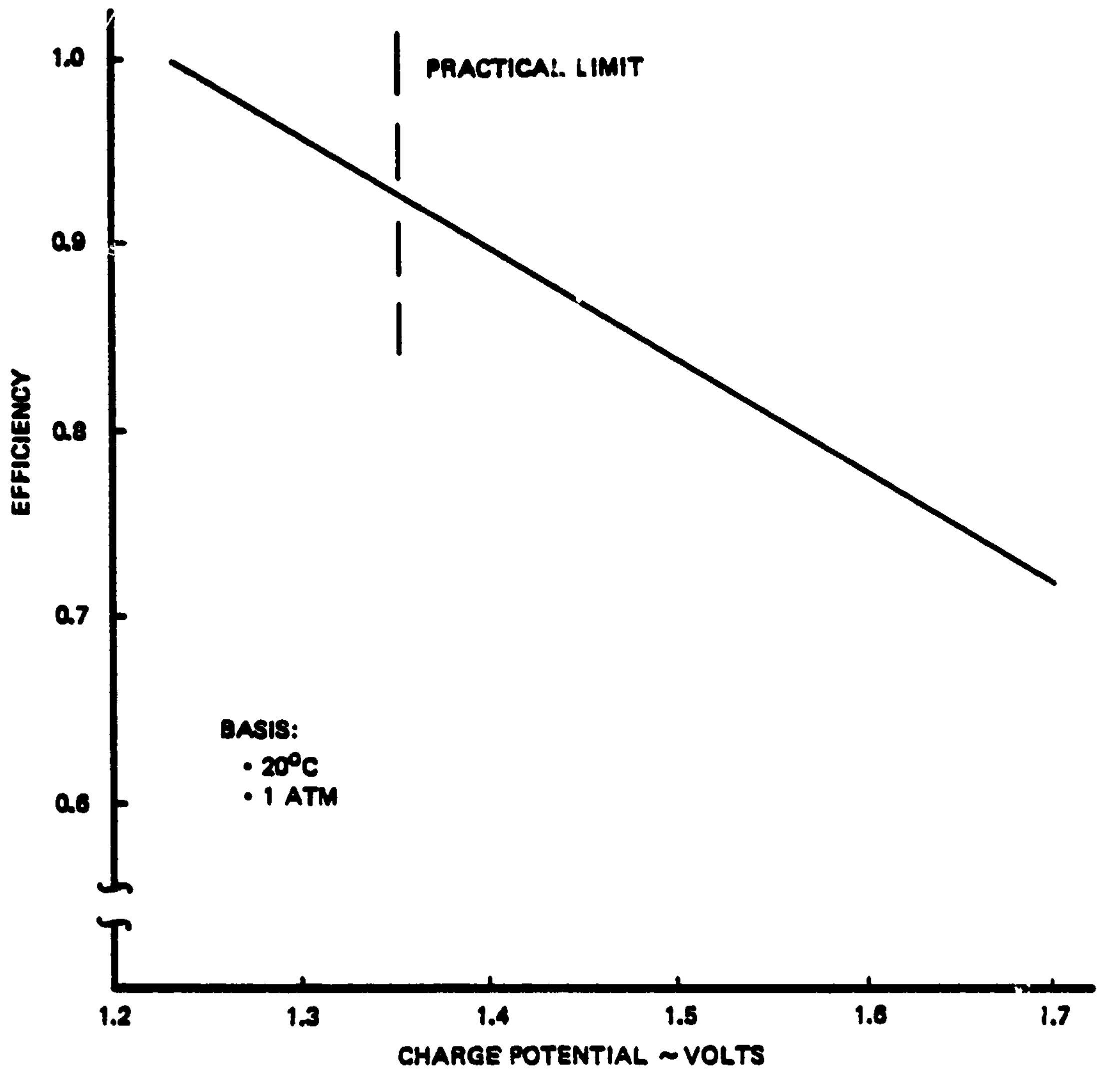

Figure 3.2-6: H_2 - O_2 Electrolyzer Efficiency

(9) Inefficient Use of Solar Array Charging Area. The solar array must be sized with a particular amount of area sized for or dedicated to charging batteries or, with a RFC system, powering the electrolyzer. If the energy storage system does not make maximum use of all that allocated power, then this becomes a loss chargeable to the energy storage system. Electrolyzers can be operated at constant current and constant voltage, and thus should obtain very little, if any, inefficiency from this cause.

(10) Power Consumption For Temperature Control. The electrolyzers and fuel cells are held at about 185°F. If the electrolyzer operates at voltages that are below the thermoneutral voltage or only a little above it, heat will have to be supplied for temperature control. Since the fuel cell and electrolyzer preferably are at the same temperature, they can be tied together thermally with a small phase change heat exchanger to maintain temperature control without comsumption of extra power. This concept is shown in Section 5.

Transfer of waste heat to the radiator requires energy, whether a pumped liquid loop is used, or heat pipes are used. Heat pipes appear to be favored at this time, and so their use has been assumed. To maintain the close control desired, variable conductance heat pipes will be required. These require electric heaters to control the gas front location, and this heat penalty increases with the heat transfer distance from the electrolyzer to the radiator. Because the heat load from the fuel cell and electrolyzer will be fairly predictable and at high temperature, the heater power is estimated to be 1.0 percent of the heat removed.

Voltage Range Effects

An inherent characteristic of secondary batteries is a relatively wide bus voltage spread due to the large difference between charge and discharge voltages. Since the fuel cell and electrolyzer are separate units, only that unit which has the greater voltage range need dictate bus voltage spread, this being the fuel cell. Thus, a typical fuel cell system will have about half the voltage spread of a Ni-H_2 battery. Since most equipment users require their own internal power supplies, this makes the design of those power supplies more efficient. An estimate of the typical improvement in efficiency of these loads is shown in Figure 3.2-7. It is seen that most of the loads could be reduced one third of one percent using the tighter voltage regulation attainable with fuel cells. It is believed that this potential saving would actually be

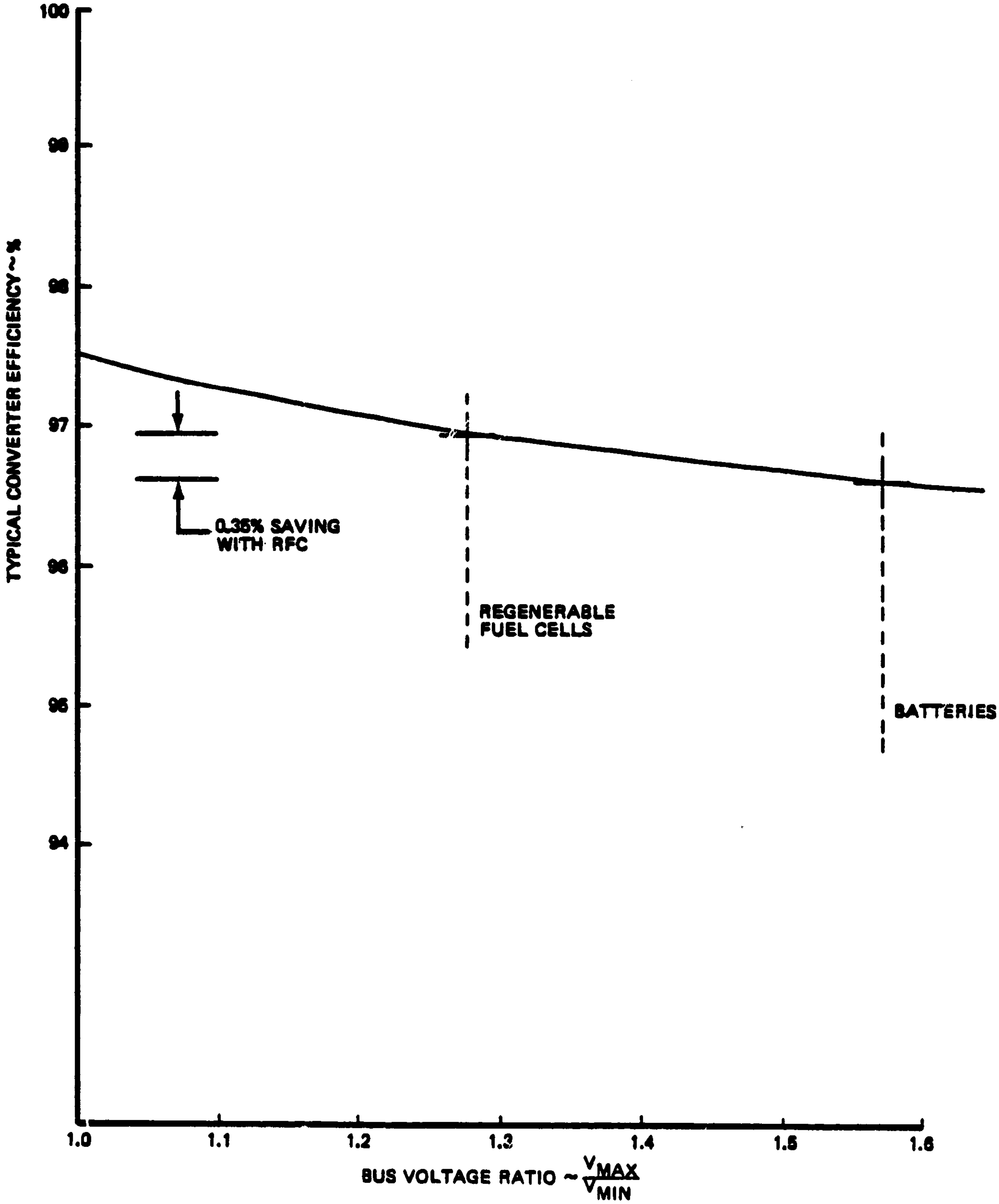

Figure 3.2-7: Effect of Bus Volt Regulation on Power System Efficiency

attained. However, it is considered very unlikely that commitments could be obtained to reduce loads, which would be necessary in order to reduce the size of the electrical power system. Therefore, it is concluded that this advantage of the RFC system is one that will show up as a performance improvement rather than as a saving in electrical power system size.

Efficiency Calculations

In the conduct of RFC system design trades for SOC, a system using the solid polymer electrolyte fuel cell was designed with an overall energy storage efficiency of 65 percent, and another system was designed with an alkaline electrolyte with an overall energy storage efficiency of 67 percent. For the condition of both systems weighing 4800 lb, the regenerative fuel cell efficiency was 64 percent for the solid polymer system, and 67 percent for the alkaline system. Neither of these data points may be considered optimized. Slightly higher efficiencies were considered possible, but were not pursued.

Allowing for 99.5 percent efficiency with the electrolyzer controller and 99 percent equivalent efficiency for the heat pipe controller, the overall energy storage efficiency on these two calculated points is reduced to 63.0 percent for the solid polymer electrolyte fuel cell, and to 66.0 percent for the alkaline fuel cell. Thus, we conclude that a design energy storage efficiency for the RFC system of 60 percent is possible without undue development risk using either fuel cell system. As is shown subsequently, this compares with an energy storage design efficiency of 55 percent with the Ni-H_2 battery.

3.3 BATTERY EFFICIENCY

Contributors To Inefficiency

There are approximately 9 possible contributors to energy storage system inefficiency with batteries. (1) Discharge voltage loss; (2) Charge voltage loss; (3) Charge current inefficiency; (4) Battery charger inefficiency; (5) Inefficient use of solar array charging area; (6) Battery discharge diodes; (7) Failed cell allowances (if designed for); (8) Cell bipass electronics (if used); (9) Power consumption for temperature control. These items are discussed below.

(1) and (2) Discharge/Charge Voltage Loss. These inefficiencies are best considered together, because the reversible voltage of the Ni-Cd and Ni-H_2 systems vary with the state of charge, and also because a large entropy effect on voltage adds to the complication. Figure 3.3-1 shows typical charge-discharge behavior of a 50 AH Ni-H_2 cell under cycle testing. The average charge potential is 1.55 V, and the average discharge potential is 1.19 V. This results in a voltage efficiency of 76.77 percent. End of life efficiency is expected to be worse. This voltage data, from Reference 8, is in agreement with other sources, for example, Reference 9.

(3) Charge Current Efficiency. The self discharge rate of Ni-H_2 batteries is much greater than with Ni-Cd batteries (Figure 3.3-2). As a consequence, a higher degree of overcharge is needed, resulting in a high charge current inefficiency. It is necessary to select the overcharge ratio (AH_{in}/AH_{out}) based on the needs of the weakest cell in the battery, and based on degraded characteristics near end of life. Tests of 50 AH Ni-H_2 cells in low earth orbit have shown recharge ratios ranging from about 1.05 to 1.34 with 1.06 being typical of new cells. A value of 1.08 is taken as being representative of the testing experience with mature cells, while discounting those examples judged to be excessive. A slightly higher design ratio of 1.09 is considered necessary for electrical power system design to allow for degradation, especially with large, 200 volt batteries.

(4) Battery Charge Efficiency. Battery charge efficiency is sensitive to system voltage, regulation complexity required, and to some degree, to power level. For high power battery chargers in a 200 volt system, a charger efficiency of 93 percent efficiency was determined to be reasonable.

(5) Inefficient Use of Solar Array Charging Area. Ni-Cd and Ni-H_2 batteries require a taper charge for long life. Subjecting the nickel electrode to high gassing rates is a high stress; in fact, this is even used sometimes as an accelerated life test. The consequence of the need to taper the charge is that the charging power level will not be constant. Since the energy storage system does not use all the allocated charge power of the solar array, this becomes a loss chargeable to the energy storage system. The efficiency of the charge can be taken as the ratio of the average charge power to the maximum charge power, with care taken in the evaluation not to include the overcharge losses twice. Even with constant current charging, without tapering, this efficiency element is only approximately 94 percent. Because there is not a commonly

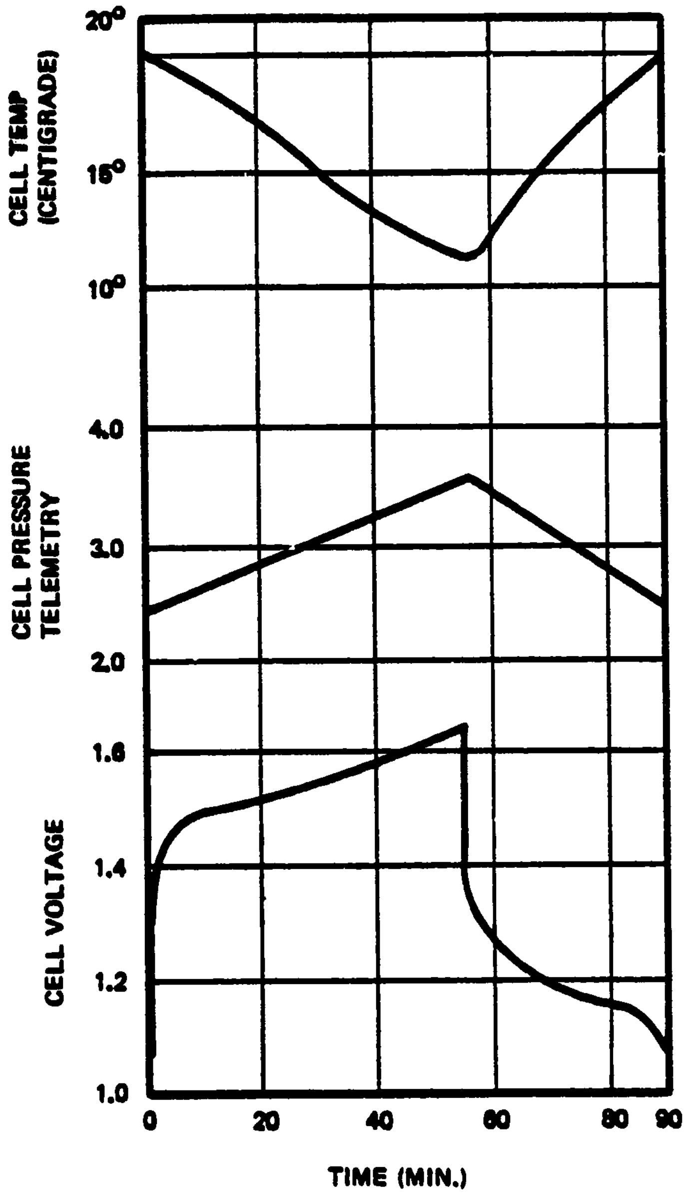

Figure 3.3-1: Typical Nickel Hydrogen Cell Performance

- SELF-DISCHARGE RATE IS HIGH
- HIGH SELF-DISCHARGE NOT IMPORTANT FOR NORMAL OPERATIONS
- HIGH SELF-DISCHARGE IS POSSIBLY IMPORTANT FOR SPECIAL CONDITIONS –
    - SHUTDOWN/STARTUP OF SOC
    - EMERGENCIES

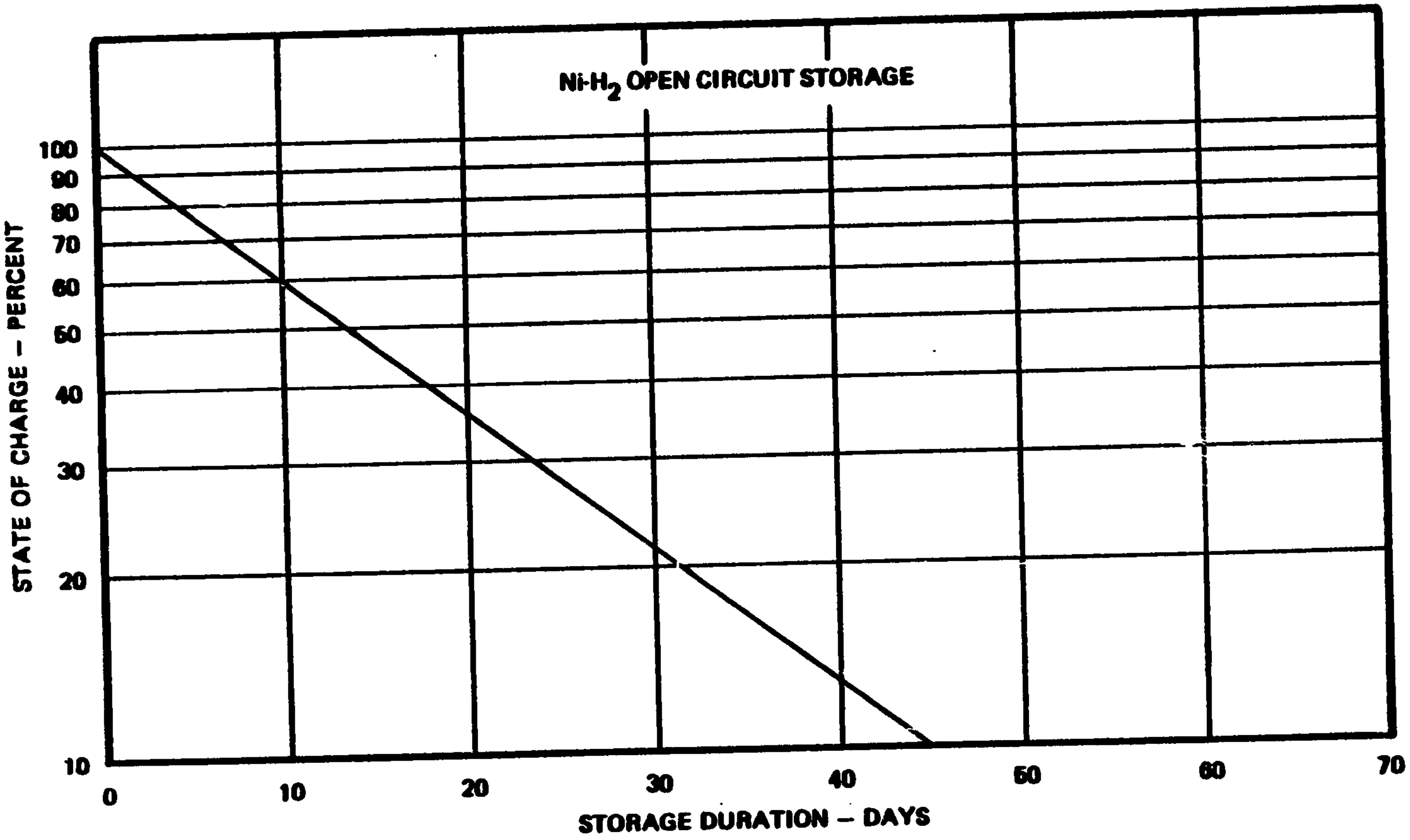

Figure 3.3-2: Nickel-Hydrogen Self-Discharge

accepted charge control law for $Ni-H_2$ batteries, experimental values of this efficiency vary widely, approximately 76 percent to 94 percent. The problem here is the need to compromise between battery life and system efficiency. Good end-of-discharge voltage has been obtained using a taper charge, which is beneficial but inefficient. Taper charge has also proved beneficial for Ni-Cd cells, but again this is obtained at the expense of efficiency. It is judged that a reasonable efficiency would be 90 percent, though an even lower efficiency could be used in the interest of promoting long life.

(6) Battery Discharge Diodes. Spacecraft power systems customarily provide protection with paralleled batteries by the addition of one or more diodes in series with each battery. For a one volt drop in a 200 volt system, this would be only a 0.5 percent loss.

(7) Failed Cell Allowance. Since a common premature failure mode of Ni-Cd and $Ni-H_2$ cells is by shorting, many times the system will be designed to accommodate about 4 or 5 percent of the cells failing shorted. For the space station, it would be worthwhile for the system to continue to function properly with some shorted cells, but it is considered unnecessary to levy an efficiency penalty for this.

(8) Cell Bypass Electronics. Electronic circuits are sometimes used to bypass failed cells in a battery string, allowing the battery to continue to function even though degraded. It is considered unnecessary to levy an efficiency penalty for this.

(9) Power Consumption for Temperature Control. Heat pipes appear to be favored for transferring waste battery heat from the cold plate to the radiator. Variable conductance heat pipes are appropriate for maintaining the close control of battery temperature needed. These will require heaters to control the gas front location. Because of the low temperature of these heat pipes (approx. $0^{\circ}C$), a relatively large amount of heat is required with today's technology (about 5 to 8 percent of the peak heat load). Since new, high capacity heat pipe technology will be needed for the space station, it is anticipated that these improvements will allow this heater load to be reduced to 3 percent of the peak heat load.

Efficiency Calculations

Overall energy storage efficiency expected with Ni-H_2 batteries is summarized in Figure 3.3-3. Typical performance is expected to result in an overall efficiency of 57.7 percent which would be reflected in a typical design allowance of 55.2 percent. Two thirds of the losses are attributable to the battery itself, whereas one third is due to the battery's effect on the spacecraft system. This latter loss is often neglected in system trade studies, and causes battery systems to project more favorably than is justified. As shown previously, this 55 percent efficient design compares with a selected design energy storage efficiency of 60 percent for the RFC system.

The Ni-H_2 system has the potential for improvement over the performance seen in existing test data. It can be assumed that the causes of the high premature failure incidence observed on low earth orbit tests will be found and corrected. Additionally, it will be necessary to reduce the voltage degradation rate. Figure 3.3-3 shows the estimated improvement potentiality, resulting in an overall design efficiency of 62 percent.

The data given in Figure 3.3-3 is more pessimistic toward nickel hydrogen cells than some of the published data, or other data which may be available to those concerned with this system. Indeed, the data taken early in cycling is much more favorable. However, cell degradation eventually sets in and performance becomes much worse with time. This may be illustrated by the test data obtained by McDonnell Douglas on LEO cells of AF/Hughes design. The initial report on the first 2000 test cycles suggested that the design was good, with stable performance and with end of discharge voltage of 1.21 V and above at 50% DOD (Ref. 12). The later McDonnell Douglas data shows the worsening effects of cycling (Ref. 13). End of discharge voltage has dropped to 1.13 V, with corresponding lowering of average discharge voltage. Also, one of the two cells at 50% DOD failed at near 10,000 cycles (1.8 years); such early failure is consistent with the results of other testers at LEO conditions. Degradation phenomena must be given adequate consideration in determining the expected efficiency after long-term cycling.

If the Ni-H_2 technology can be improved to eliminate early shorts and voltage degradation, then the efficiency of the Ni-H_2 system would be much improved. We have made the assumption in this study that the shorting problem would be solved. However, voltage degradation is a fundamental problem and requires a level of

		TYPICAL END-OF-LIFE PERFORMANCE	TYPICAL DESIGN	DESIGN POTENTIAL
BATTERY RELATED ITEMS	RECHARGE RATIO	1.08	1.09	1.075
	AVE CHARGE VOLTAGE	1.55 V	1.57 V	1.53
	AVE DISCHARGE VOLTAGE	1.19 V	1.17 V	1.21
	FAILED CELL ALLOWANCE	——	——	——
	CELL BYPASS ELECTRONICS	——	——	——
SYSTEM RELATED ITEMS	SOLAR ARRAY CHARGE AREA EFF.	0.90	0.90	0.91
	BATTERY DIODES EFF.	0.995	0.995	0.995
	BATTERY CHARGER EFF.	0.93	0.93	0.93
	BATTERY HEAT PIPE POWER EFF.	0.975	0.970	0.970
	OVERALL EFFICIENCY	0.577	0.552	0.686

Figure 3.3-3: Energy Storage Efficiency Determination with Ni-H_2 Batteries

understanding and research effort possibly beyond what is now being pursued. At this time, one can only speculate on the performance at the end of four to seven years of cycling, even if design improvements are found and implemented.

Ni-Cd batteries have a higher efficiency than Ni-H_2 batteries. This is due in part to greater design maturity, and in part to the fact that lower depths of discharge are more appropriate for Ni-Cd. Overall design efficiency is approximately 62.5 percent based on a recharge ratio of 1.06, an average charge voltage of 1.45 V, and an average discharge voltage of 1.19 V. Other factors are the same as with Ni-H_2.

4.0 ANALYSIS OF PAST REGENERABLE FUEL CELL STUDIES

4.1 CRITIQUE COMMON TO ALL STUDIES

The following observations apply to nearly all the studies, and thus are not cited individually in the discussions.

Efficiency

High efficiency is a key attribute of space station energy storage systems. The resulting reduction in solar array size has many benefits, so that except for short lived space stations or other special missions, it is advantageous to sacrifice some initial launch weight. Benefits from reduced solar array size are discussed in section 3.1, but include: (1) Large size in itself is a problem, well out of proportion to the modest weight involved; (2) Solar array costs are very high, especially the deployable structure for the panels; (3) Orbit makeup propulsion fuel due to solar array drag is a substantial resupply need. High efficiency was often sacrificed in order to minimize initial launch weight. An additional shortcoming was that the energy storage efficiency with batteries tended to be determined too high for the reasons discussed in Section 3.0.

Reliability

Reliability of spacecraft energy storage systems has been a continuous problem, and needs emphasis during the formative years of space station power system development. This needs to be an important consideration in system selection.

Life Cycle Cost

As several studies showed, the total life cycle cost associated with energy storage vastly exceeds the equipment purchase cost. Though it is difficult to quantize total cost, there should at least be qualitative life cycle cost comparisons of contending systems.

Dry Gas Electrolysis

The hydrogen and oxygen product gases from the electrolysis of water, as conceived in the various studies, will have a high water vapor content. If all components in the RFC system could be assured of long term isothermal operation, this would present no problems. However, temperature variability with occasional large excursions is commonplace in spacecraft. This can cause the condensation or even freezing of water. Where water electrolysis is used for reaction control fuel, the problem could be very severe due to the long piping runs required. Thermodynamically it should not require extra energy to electrolyze all the water vapor. The technology for dry gas electrolysis is not yet available, though some experimental work has been done.

Weight Items

Some weight items were omitted. Cold plates for mounting and cooling of the batteries, electronic equipment, and other heat generation equipment were universally omitted. This weight is expected to be approximately 11 percent of the equipment so mounted. Non-heat generating equipment or fluid-cooled equipment can generally be mounted directly to structure without the need for cold plates. Radiator weights for low temperature equipment, such as electronics and batteries, often was underestimated due to selection of operating temperatures which were too high for long life.

Tank Design

Varying design criteria were used for the sizing of the hydrogen and oxygen tanks. Tank weights of the older studies tended to be heavy, whereas the later studies reflect improved tank technology, resulting in much lighter weights. In some cases the requirement was imposed on the study contractor to use a safety factor of 1.5. This is the same factor of safety used on many of the shuttle pressurized tanks, such as the KEVLAR-over-aluminum gas bottles and the titanium propulsion tanks. These tanks have good cycling capability, but additional allowance is needed for design to many cycles. A fracture mechanics design approach is needed for tanks for the space station to account for the effect of many cycles. Also, in some cases the tanks appear not to have been sized with adequate consideration of ullage. Note the discussion in section 5.5.

4.2 NORTH AMERICAN ROCKWELL STUDY

Objectives

The energy storage part of this study (Reference 1) supports the Modular Space Station study of North American Rockwell (now called Rockwell). The purpose of this study segment was to prepare an electrical power system preliminary design and analysis, based on the selected solar array primary power source and a RFC energy storage system. This study was completed in January, 1972. That study did not provide data in a form amenable to analysis of the type required for this report. A discussion of the Phase B study is given at the end of Section 4.2.

Requirements

The Modular Space Station is a 6-man station with growth to 12 men. Orbit altitude is 240 to 270 nautical miles, with 270 nautical miles baseline. Inclination is 28° to 55°, with 55° as the baseline. Mission duration was 10 years, based on a 5-year initial station, with the growth version lasting another 5 years. The loads are nominally 11 to 28 kW, with a 24-hour average of 19.64 kW, and a "normal" requirement of 19.95 kW. An emergency mode is required at 1.63 kW for 96 hours. During space station buildup for 60 days, prior to solar array power being available, power must be provided by the energy storage system. This power level is 355 W average with peaks of 655 W, and is provided by operating the fuel cells continuously without electrolysis of the product water. Input voltage from either the solar array or the fuel cells is 112 Vdc, but power to users is 120/208 Vac, 400 Hz three phase, plus 240/416 Vac, 400 Hz three phase.

Major Findings

The major contribution of this study was the definition of a RFC system to a particular space station requirement. Figure 4.2-1 summarizes the major characteristics of the RFC system. Life Systems and Lockheed did a more detailed study of RFC systems for this particular space station, and their studies are discussed later in this report.

In Trades and Analysis, Volume 6 of Reference 1, background information is provided on energy storage systems for the space station. Nickel cadmium battery technology and regenerable fuel cell technology are discussed at length, including proposed solutions to some of the recognized problems. A trade study was conducted comparing Ni-Cd batteries and the RFC system, and the RFC system was much the lighter. The reported data for the electrical power subsystem (6-men) was: 22,932 lb using Ni-Cd batteries, and 16,351 lb using the RFC system. However, energy storage weight information is not broken out. The RFC system was also of lower cost: approximately $30 M vs. $37 M for Ni-Cd batteries. The conclusion was to select the RFC system. However, it was recognized that the designs traded were not optimum, and that more optimized concept comparison would be needed.

	RFC SYSTEM
LOADS –	
BUILDUP (60 DAYS)	355 W AVE, 655 W PEAK, 298 KW HR
OPERATION	19.95 KW
REPLACEMENT LIFE	2.25 YEARS
EFFICIENCY	52.5%
WEIGHT	4,896 POUNDS (NOTE: 995 POUNDS IS INCLUDED FOR BUILDUP REQUIREMENTS)
VOLUME	117.9 FT^3
SPECIFIC WEIGHT	250 LB/KW

Figure 4.2-1: North American Study – Selected Summary

Energy requirements during spacecraft buildup are 298 kW-hrs, compared with 163 kW-hrs for the 96 hour emergency. Thus, the high pressure (3000 psi) hydrogen and oxygen tankage is sized by the buildup requirement.

After the solar array and the RFC system are operating, it would be worthwhile to recharge the high pressure oxygen and hydrogen tanks. However, special high pressure electrolyzers are needed for this, since sizing the RFC electrolyzers to 3000 psi would be heavy. The addition of two very small 3000 psi electrolyzers might be a practical solution.

North American Rockwell Conclusions

Use of an RFC system is practicable for space station energy storage. The fuel cells are especially useful during buildup, when they can provide power prior to power being available from the solar array.

Critique

This is a pioneer application of RFC systems to space station energy storage. Electrolyzer technology was in its formative stages, so the weight information is not very reliable.

The power requirement of 355 watts during buildup appears to be very low. There is a question of whether the fuel cells can operate at such a low power level and maintain their own control. Much higher power levels are believed to be needed, even if only to maintain temperature control for the RFC system and critical spacecraft equipment.

Rockwell appears to have failed to see an opportunity to capatalize on their RFC design to improve emergency capability. Hydrogen and oxygen tankage are sized by the station buildup requirement. After buildup is completed, this tankage can be used for reactants for emergency power, and should allow nearly double the allowable emergency duration. However, if the emergency were to occur immediately after the buildup, the maximum quantity of reactants might not be available for the emergency.

Impact on North American Rockwell Conclusions

Further analysis would alter the system weight, but is not expected to change the conclusions that an RFC system is practicable for space station energy storage. If power during station buildup is required to be considerably larger than 355 watts, then it may be necessary to use cryogenic reactant gases, or deploy the solar arrays much earlier than 60 days.

4.3 UNITED TECHNOLOGIES, POWER SYSTEMS DIVISION, STUDY

Objectives

The objectives of this study (Reference 2) were to define alkaline regenerable fuel cell systems (RFC) for LEO space stations with power ranging from 35 kW to 250 kW. Required was a preliminary design concept and performance characteristics. This study was completed in December, 1981.

Main Requirements

Space station power levels to be considered were 35 kW, [illegible] kW, and 250 kW. System voltage was to be 120 Vdc ±10%. A 90 minute orbit with 36 minute occultation was postulated. A 2-hour emergency duration was required. Specific weight of the solar array was 45.15 lb/kW.

Major Findings

The major contribution of this study was the definition and analysis of RFC systems using state-of-the-art technology. Figures 4.3-1 to 4.3-3 summarize the significant results of the design and analysis. No cost information was provided.

One of the findings was that the specific weight did not change much with power system size (Fig. 4.3-1). Specific weights for the 35 kW and the 250 kW systems were 55.1 lb/kW and 51.1 lb/kW, respectively. With advanced technology, it was estimated that the specific weight for a 100 kW system would decrease from 52.6 lb/kW to 35.1 lb/kW. This projected weight saving is partitioned as follows: (a) Replace inconel oxygen and hydrogen tanks with filament-wound tanks: 19.9%; (b) replace porous nickel electrolyte reservoir plate in the fuel cell module with graphite: 5.5%; (c) improved space radiator: 6.4%; miscellaneous: 2%; Total: 33%.

Component replacement life on the fuel cell modules was determined to be 3.1 years. The critical life item identified was the pumps, with a replacement life of 1.1 years.

	35 KW	100 KW	100 KW ADVANCED TECHNOLOGY	250 KW
LAUNCH WEIGHT (LB) (NO S/A)	1,927	5,257	3,506	12,778
SPECIFIC WEIGHT (LB/KW)	55.1	52.6	35.1	51.1
RESUPPLY - 10 YRS (LB)	3,000	6,670	——	12,500
ENERGY STORAGE EFFICIENCY	0.50	0.504	——	0.50
FUEL CELL TEMP (°F)	140°	140°	200°	140°
ELECTROLYZER TEMP (°F)	180°	180°	180°	180°
FUEL CELL CURRENT DENSITY (ASF)	323	308	308	286
FUEL CELL V.	0.901	0.908	——	0.902
ELECTROLYZER CURRENT DENSITY (ASF)	310	317	——	358
ELECTROLYZER V.	1,603	1,607	——	1,629
SYSTEM PRESSURE (PSI)	70 - 200	70 - 200	70 - 200	70 - 200

Figure 4.3-1: United Technology Study – Selected Summary

TANKS AND REACTANTS	25.0%
FUEL CELL SYSTEM	25.3%
ELECTROLYZER SYSTEM	17.8%
POWER CONDITIONER	12.4%
RADIATOR	18.7%
MISCELLANEOUS	0.8%
	100.0%

Figure 4.3-2: United Technology Study – Weight Breakdown (100 KW)

FUEL CELL MODULES	3.1 YEARS
ELECTROLYSIS MODULES	4.0 YEARS
VALVES	5.2 YEARS
PUMPS	1.1 YEARS

Figure 4.3-3: United Technology Study – Component Replacement Life

Overall energy storage efficiency was approximately 50.4 percent. The fuel cell system was designed to be fairly efficient (approx. 0.898 V/cell), but the water electrolysis system had low efficiency (approx. 1.60 V/cell). Overall energy density was calculated to be 38 W-Hr/lb, or 55.8 W-Hr/lb excluding the radiators and power conditioning equipment.

United Technologies Conclusions

Regenerable fuel cell systems for space stations are practicable and lightweight. Technology advancements show the potential of reducing weight 33 percent.

Critique

The United Technolgies design is a low weight design, though not the minimum weight design. Though some missions would prefer close to the minimum weight, this is not universally preferable. High efficiency designs, though heavier, are judged as preferred for general space station needs.

One of the systems losses shown is the power conditioner for the electrolyzer, with an efficiency of 94 percent. Raw solar array power is seldom provided to the spacecraft bus, for the power is usually regulated to constant voltage by a shunt regulator or other type of controller. Though a controller to do switching and control functions to the electrolyzer is desirable, this need not be a regulating power type of unit.

The fuel cell module is designed to 140°F (200°F advanced design), and the electrolyzer is designed to 180°F. It would be useful if both modules could be designed to the same temperature. A common radiator could then be used, and excess heat from the one module could be used for temperature control of the other when needed.

Pumps were identified as the critical life item, with a replacement life of 1.1 years. This is misleading. The basis for this was that 1.1 years is the longest duration for which there are life test data on fuel cell module pumps. Since industrial pumps of many kinds can give long service without replacement, there is no reason to believe that a long life pump cannot also be designed for aerospace use.

The hydrogen and oxygen weights were based on the requirement that they be designed to a safety factor of 1.5. This is the same design factor used for many of the shuttle tanks, but may not be sufficient for the large number of pressure cycles required for space stations. Note the discussion in section 4.1 on tank weights, and in section 5.5 tank optimization.

The projected weight savings with advanced technology are large, and much dependent on tank weight analyses. The analyses of the metal and composite tanks were apparently done separately, and different design criteria may have been used. It is suggested that if interest develops in very lightweight systems, then tank weights should be redetermined in enough detail to eliminate any doubt, using fracture mechanics design criteria. Also, though it is true that fuel cell weight can be reduced by using graphite electrodes instead of nickel electrodes and by operation at higher temperature (200°F), these measures would require additional research and development; even then, it is likely that there will be some sacrifice to life and possibly also to performance. Nevertheless, the potential weight savings with the advanced, light-weight technology are of great interest for applications which must be optimized to low initial weight, for example, synchronous orbit.

Impact on United Technology's Conclusions

The design provided in this study is a light-weight, medium efficiency design. This design philosophy is appropriate where minimum launch weight is paramount, perhaps when a solar array of more than ample size is used, and when resupply cost is only a minor consideration. A higher efficiency, though heavier, energy storage system (about 60% efficient) is judged to be preferred for general space station needs. This would increase the w ight and alter the performane of the described design. Also, due to the resulting lower current density with the fuel cell modules and electrolyzer modules, a longer replacement interval should result.

The power conditioner for the electrolyzer need not perform power regulation functions, since this is accomplished by the solar array power regulator. The efficiency of the power conditioner should therefore increase from 96 percent to greater than 99 percent.

Operation of the fuel cell modules and the electrolyzer modules at the same temperature will eliminate one of the two radiators plus accessories. Total radiator size will not change much, but system reliability will be improved. Minor changes in operating performance of the RFC system will also result.

An evaluation should be made of the expected pump replacement life, and that value should be used even if not fully verified by life testing. Extra redundancy should be added, if necessary, to bring pump replacement life compatible with other components.

Tanks probably need to be designed to a higher safety factor. This will increase weight a small amount.

4.4 LOCKHEED STUDY

Objectives

The principal objective of this study (Reference 3) was to develop technical materials and methods for evaluation of regenerable fuel cells for the Modular Space Station. The main output of the contract was a Design Data Handbook, LMSC-D159786, which was intended to be a working document for use by electrical power system designers. A secondary objective was to compare regenerable fuel cells with nickel cadmium batteries, and also to assess the effects of integrating the electrical power system with the environmental control/life support and reaction control systems. This study was performed in 1972 prior to the selection of the Shuttle fuel cell supplier.

Requirements

The main electrical power system requirements were for a power level of 10 to 35 kW, with 25 kW selected as the nominal level. Output power was selected as 112 Vdc (+18 Vdc, -22 Vdc). Another requirement was the need to provide electrical power at a 355 Watt level during a 60-day space station buildup without the availability of a solar array.

Major Findings

The main output of this contract was a data handbook. Equations were formulated defining weight relationships, and these were programmed into a computer. One set of output data was generated, with total system weight given for regenerable fuel cells and nickel cadmium batteries. Total equivalent weight penalty includes the solar array and drive, inverter, shunt regulator, charge controller or power controllers, batteries, tankage, hydrogen and oxygen, fuel cells, electrolyzers, and ancillaries.

Results based on a continuous 25 kW system are summarized in Figure 4.4-1. The complete electrical power system with regenerable fuel cells is 25% lighter than with nickel cadmium batteries. Subtracting out the weight of the solar array and drive system, the relative weight difference is even greater. The energy storage system specific weight is very high compared to today's technology, calculated to be 384 and 631 lb/kW for regenerative fuel cells and nickel cadmium batteries, respectively; it should be recognized however that these values include inverters and power controllers.

One finding of the Lockheed study was that the Lockheed electrolyzer was proposed as the best one of the available options. This concept requires electrolyzer units circulating electrolyte with pumps and bubble separator; two absorbent matrices, one being for gas-liquid separation; differential pressure controllers to maintain electrolyte equilibrium; a system to sense gas in the liquid KOH electrolyte; a heat exchanger; a closed electrolyte reservoir; a water deionizer; a nitrogen purge system; valves; and instrumentation and control with sensors and transducers. This system operates at about 10°C, which is not compatible with the 60°C fuel cell temperature; this low electrolyzer temperature would also require larger radiators for heat removal. Thus, it is evident that this is a complex system. This system is no longer a viable candidate, for its development never has materialized.

Lockheed Conclusions

Lockheed concluded that a regenerable fuel cell electric power system offers up to a 26% weight saving over nickel-cadmium batteries. Development of the water electrolysis system was determined to be the pacing item, and a development program was recommended. The Shuttle fuel cell was deemed appropriate, with modification to 115 Vdc design.

Critique

The Lockheed study was done in 1972, and should be viewed as a precursor study with many formative concepts. Thus, the electrolyzer system is complex with a large number of ancillaries. The weight model given is no longer valid, resulting in weights considerably heavier than those obtained in current analyses. For example, the weight difference between regenerative fuel cells and nickel cadmium batteries (6174 lb for 25 kW) is more than twice the weight of current regenerable fuel cell systems.

	REGENERABLE FUEL CELL SYSTEM	Ni-Cd BATTERY SYSTEM
WEIGHT OF CONTINUOUS 25 KW SYSTEM WITH SOLAR ARRAY	8,400 KG	11,200 KG
WEIGHT OF SOLAR ARRAY SYSTEM	4,043 KG	4,043 KG
WEIGHT OF ENERGY STORAGE SYSTEM	4,357 KG	7,157 KG
ENERGY STORAGE SPECIFIC WEIGHT	384 LB/KW	631 LB/KW
DEVELOPMENT COST	$19.1M	——

Figure 4.4-1: Lockheed Study — Selected Summary

One shortcom of the study is the lack of weight breakdown information or sample calculations. Calculations were done by computer, and only total system weight was reported.

Impact on Lockheed Conclusions

The energy storage system given in this study was an early design effort, and thus is heavy compared with the more mature technology available today. The major conclusion was that a RFC system for a space station would be lighter than a Ni-Cd battery system, and that conclusion still appears to be valid. Comparison of the RFC system and Ni-H_2 batteries was not made, however. The Design Data Handbook is considered too much out of date to be useful today.

4.5 LIFE SYSTEMS STUDY

Objectives

The objectives of this study (Reference 4) were to evaluate the Modular Space Station and the application of a regenerable fuel cell (RFC) system. An RFC energy storage system was to be defined, the RFC technology reviewed and characterized, and the pacing technologies identified. Ni-Cd batteries were to be traded with the RFC system. This study was completed in December, 1972.

Main Requirements

The Modular Space Station, defined by North American Rockwell, is a 6-man station with growth to 12 men. Orbit altitude is 240 to 270 nautical miles, with 270 nautical miles baseline. Inclination is 28° to 55°, with 55° baseline. Mission duration was 10 years, based on a 5 years initial station with the growth version lasting another five years. The loads are nominally 15kW to 30 kW. The initial station has a nominal load of 18.7 kW, a peak load of 21 kW and a 24 hour average load of 17.4 kW. An emergency use of expendables is required at 1.75 kW for 96 hours. Voltage is 240/416 Vac, 400 Hz, 3 phase, with 112 Vdc input from the solar array.

Major Findings

The major contribution of this study was the review and characterization of regenerable fuel cells, and their application to a particular space station requirement. Characterization of RFC systems is done thoroughly enough that the report still functions as a useful reference source, limited to 1972 technology. The pacing technology identified in the study was the water electrolysis subsystem.

Figures 4.5-1 to 4.5-3 show the major characteristics of the RFC system design, and tabulate some of its key attributes. Since the power output is 240/416 Vac, 400 Hz, 3-phase, inverters are required from the output of the fuel cells, which degrades overall energy storage efficiency. To permit efficiency comparisons with dc systems which do not require inverters, Figure 4.5-1 also shows energy storage efficiency with and without inverters.

In the cource of this study, a number of trades were conducted. Figure 4.5-1 summarizes the trade between Ni-Cd batteries and a RFC system. It was concluded from this trade study that the RFC system is the lowest cost, has the lightest launch weight, and requires the least amount of solar array. When one compares Ni-Cd vs RFC designs sized for the peak load (Figure 4.5-1), it is seen that the RFC system requires 9 percent larger solar array, but is 4680 pounds lighter. When both systems are sized for the 24 hour average, they both are able to show a reduction in solar array size with a concomitant increase in electrical power system weight. With such a 24-hour sizing criteria, the RFC system requires a solar array 8 percent larger than does the Ni-Cd battery system, but the RFC system is 9800 pounds lighter. On this basis, it was reasoned that it is practicable to design the RFC system to the 24 hour average, with capability provided for peak loads, but it was judged that the Ni-Cd battery system should be sized for the peak load. It is this rationale that resulted in the conclusion that the RFC was best in all major respects.

One of the trade studies conducted was a determination of the best water electrolysis design approach for an RFC system. This was the weakest technology area in that time period, and there were a number of competing technical approaches. The competing water electrolysis concepts differed in these major respects:

1. Nature of the electrolyte -- alkaline was preferred because weight was least and there is less sensitivity to contamination.

2. Method for electrolyte incorporation within the cell -- the selected method was to hold the electrolyte in a porous matrix.

	NI-Cd SYSTEM	RFC SYSTEM
LOADS – PEAK 24 HR AVE	21 KW 17.4 KW	21 KW 17.4 KW
SOLAR ARRAY – SIZED FOR PEAK SIZED FOR 24 HR AVE	7,790 FT^2 6,980 FT^2	8,500 FT^2 7,540 FT^2
ENERGY STORAGE WEIGHT – SIZED FOR PEAK SIZED FOR 24 HR AVE	9,172 LB (12,012 LB REFERENCE)	(4,482 LB REFERENCE) 2,818 LB
ENERGY STORAGE EFFICIENCY	0.626 (0.694 W/O INVERTER)	0.526 (0.582 W/O INVERTER)
COST – DEVELOPMENT HARDWARE OPERATIONS TOTAL	\$12.7M \$7.5M \$10.9M \$32.2M	\$14.7M \$5.3M \$7.8M \$27.7M
SPECIFIC WEIGHT	436 LB/KW	134 LB/KW

Figure 4.5-1: Life Systems Study – Selected Summary

	ORIGINAL MSS	REVISED DESIGNS	
		OPTIMISTIC	MAINTAINABLE
WATER ELECTROLYSIS SUBSYSTEM	1,288	1,608	4,016
FUEL CELL SUBSYSTEM	808	808	808
H_2 STORAGE TANK	748	784	784
O_2 STORAGE TANK	360	360	360
H_2O STORAGE TANK AND PUMP	80	80	80
REACTANT	40	40	40
PLUMBING, REGULATOR AND VALVES	262	262	262
MOUNTING AND SUPPORTS	366	366	366
INVERTERS, SEQUENCERS, WIRING	92	184	184
TOTAL	4,044 LB	4,492 LB	6,900 LB

Figure 4.5-2 Regenerative Fuel Cell Subsystem Weight

MAXIMUM SUSTAINED POWER	7.0 KW	
MAXIMUM POWER WITHIN VOLTAGE LIMITS	10.0 KW	
VOLTAGE LIMITS	112 VOLTS (+5 -11%)	
MINIMUM POWER	200 WATTS	
MINIMUM REACTANT SUPPLY PRESSURE	60 PSIA	
MAXIMUM COOLANT TEMPERATURE (TO FUEL CELL)	120°F	
SPECIFIC REACTANT CONSUMPTION	0.82 LB/KW-HR	
CELL AREA	0.508 FT^2	
NUMBER OF CELLS	32/STACK	
NUMBER OF STACKS/7 KW	4	
ELECTROLYTE	KOH	
CURRENT DENSITY	123 (100 - 350) ASF	
OPERATING TEMPERATURE	190 (190°F - 250°F)	
OPERATING LIFE	10,000 HR (ADV. SHUTTLE FUEL CELL)	
OVERLOAD	2 TIMES NOMINAL RATING	
	PER UNIT	TOTAL OF 4 UNITS
WEIGHT, LB	202	808
UNIT DIMENSIONS (L x W x H)	13 x 13 x 55 IN	——
VOLUME, FT^3	5.4	24
ACCESSORIES WT, LB		
BATTERIES	10	40
PLUMBING, REGULATOR AND VALVES	16	64
MOUNTING AND SUPPORTS	22	88
INVERTERS	5	20
SEQUENCERS	3	12
WIRING	15	60

Figure 4.5-3: MSS Fuel Cell Subsystem Characteristics

3. Waste heat removal -- conduction to cooled fins was selected because it is simple and avoids the use of pumps and phase separators associated with circulating liquid systems.

4. Makeup water addition -- a static feed gas phase method was selected to eliminate gas-liquid separators and to minimize the effects of contamination.

Because the selected baseline was a 55° inclined orbit, there are cyclic variations in the dark/light ratio. Since the electrolyzer must be sized for the highest dark/light ratio, there is excess electrolyzer capability much of the time. Though this was identified, no use was made of this capability in the study. It may be possible to exploit this unique capability of the RFC system, particularly for electrolysis of water for orbit makeup propulsion fuel.

An additional item looked at briefly was whether or not it would be worthwhile to integrate the RFC system with other systems. It was concluded that integration of the hydrogen and oxygen systems is worthwhile for power, reaction control, and life support. The system was sized based on 24-hour averages.

Life Systems Conclusions

Life systems concluded that the RFC system is the best energy storage system for the Modular Space Station. It was found to be superior to Ni-Cd batteries in weight, solar array size, and cost. It was also concluded that development of water electrolysis systems is needed for RFC systems.

Critique

The RFC system was determined to be better than the Ni-Cd battery system because it was judged that it would have been impractical to design the battery system for a 24-hour average. The assumption made was that if the Ni-Cd battery were designed for a 24-hour average, the large weight increase needed for the battery system would not offset the saving in solar array size. However, no trade was made to verify that this is a correct conclusion. Fortunately, this is a moot point, for we know today that the efficiency of RFC systems can be comparable to that of batteries, approximately 60 percent to 67 percent.. Refinement in energy storage efficiency calculations would result in a modest reduction in efficiency of the Ni-Cd battery system (shown to become 69.4 percent without inverters) and a modest increase in efficiency of the

RFC system (shown to become 58.3 percent without inverters). Thus, it would not be possible for battery systems to have any advantage with respect to a smaller sized solar array.

The cost estimates developed did not play a big role in the selection of the RFC system. However, the estimates given do not appear to be valid. Assuming a shuttle fuel cell as developed, development cost was $14.7 M for the RFC system, and $13.7 M for the Ni-Cd system. Considering that Ni-Cd technology is relatively mature, the cost differential is too narrow. No substantiating detail was provided for this or the other costs shown in Figure 4.5-1.

Not considered in this study was the nickel hydrogen (Ni-H_2) battery system, which was not available at that time. If the expectations for higher allowable depth of discharge and longer life are realized, then this battery system could be better than the Ni-Cd battery system, which would affect the results of this study. The omission of Ni-H_2 batteries from the life systems study was not an oversight, but merely a reflection of the state of technology ten years ago.

To lower the dew point of the product gases, the design involves throttling of the gases from 20.4 atm. to 1.0 atm. This results in efficiency loss for the system; also, the dew point reduction to 36°F may not be sufficiently low.

One of the design decisions was to integrate the hydrogen and oxygen system used for the RFC with the hydrogen and oxygen systems used for reaction control and life support. It was expected that this would result in advantages in cost, reliability and logistics. It is true that use of common gases for these systems would have important advantages, but there also are significant disadvantages to full integration of three major subsystems, namely, (1) the life support system requires high pressure oxygen for extra vehicular activity, and this possibly is not compatible with the optimum pressure for RFC; (2) the several subsystems will likely have separate contractors, and interface definition would be a serious obstacle throughout the program; (3) subsystem testing would be compromised and more costly.

Finally, it may be emphasized that progress has been made in the technology of RFC systems in the ten years since this study was done. Reanalysis today in this, as well as all the other contractor studies, can be expected to result in improvements in all phases of the system.

Impact on Life Systems Conclusions

The conclusion that an RFC system is lighter than a Ni-Cd battery system is expected to be reinforced by any further analysis. $Ni-H_2$ batteries were not considered, so it is not fair to say the RFC system is best until those two systems are properly traded.

Whether or not all hydrogen and oxygen systems are integrated should have little effect on system weight, for integration does not save in weight of the major components for a low inclination orbit, such as 23°. Integration or cross-coupling is an excellent idea for use in the event of failures or emergencies for such orbits, but the decision should have little impact on weight or cost. For high inclination orbits such as 55°, however, there can be a weight saving, for the periodic excess capacity of the electrolyzer can be used for electrolysis of water for orbit makeup propulsion fuel. Also, when the dark/light ratio becomes low, the excess available power may be planned upon for experiments.

Life support systems should not be integrated with the electrical power system unless this is shown to be worthwhile by an in-depth study. However, there is little weight impact of such a decision to integrate or not integrate.

4.6 McDONNELL DOUGLAS STUDY

Objectives

The energy storage part of this study (Reference 5) supports a Space Station Systems Analysis Study to evaluate alternatives for the Space Construction Base. The purpose of this study segment was to evaluate energy storage alternatives to the nickel cadmium battery system, operating with a solar array. This study was completed in September 1977.

Requirements

The space station has an electrical power level of 100 kW average. A peak power of 450 kW is required for 15 minutes several times each day. Emergency power required is 5 kW for 180 hours. The space construction base was required in 1985, using technology available in 1980. Mission life was 10 years. The power system guidelines were for 400 Hz, 115 Vac, though the energy storage section was considered to be dc power.

Major Findings

Ni-Cd, Ni-H_2, and RFC systems were compared. The RFC system was found to be the lightest, having the longest life, and requiring the least amount of resupply. Cost of the RFC system was 8 percent lower than the battery system, but the efficiency was also lower. Although the RFC system appeared to be the most attractive, it did not meet the requirement of technology readiness in 1980, needed for space construction base operation in 1985.

Comparisons between the competing energy storage systems are summarized in Figure 4.6-1. In comparing Ni-Cd and Ni-H_2 batteries, no clear advantage of one over the other is apparent, for cost and life were equal. The Ni-H_2 battery system was lighter, with resulting lower resupply weight, but its efficiency was a little less than Ni-Cd. The RFC system was also found to be best for satisfying the emergency power requirement of 5 kW for 180 hours. Both the alkaline and solid polymer fuel cell technology appeared to be adequate for the RFC system.

Meeting the peak power requirement of 450 kW for 15 minutes several times each day had a big impact on the battery energy storage systems, forcing discharge at very high rates. It was assumed that the batteries could tolerate the high discharge rates without additional weight.

McDonnell Douglas Conclusions

1. A solar array power source is better than other approaches.

2. Ni-Cd batteries are best for energy storage within schedule restraints.

3. Ni-H_2 batteries are also attractive, but are handicapped by lack of test data.

4. The RFC system would be the best system, except that it could not be fully developed by 1980.

	Ni Cd	ADVANCED Ni Cd	Ni H_2	REGENERATIVE FUEL CELL SYSTEM
WEIGHT (KG)	17,470	10,730	7,233	2,748
SPECIFIC WEIGHT (LB/KW)	385	237	159	61
10-YEAR RESUPPLY (KG)	41,919	25,746	17,356	2,994
RESUPPLY DOUBLING TIME (YEARS)	4.2	4.2	4.2	9.2
EFFICIENCY	62%	65.7%	60.8%	54.1%
DEPTH OF DISCHARGE	14.5%	14.5%	18.6%	(33%)
LIFE (YEARS)	3.3	3.33	3.33	5
COST –				
DEVELOPMENT	$18M	$19M	$20M	$40M
HARDWARE	$32M	$34M	$31M	$20M
OPERATIONS *	$56M	$42M	$33M	$9M
10-YEAR COST	$349M	$337.5M	$335.2M	$316.7M

* OPERATIONS COSTS OBTAINED FROM TOTALS BY RATIOING ENERGY STORAGE FRACTION LESS DRAG PROPELLANT TRANSPORTATION

Figure 4.6-1: McDonnell Douglas Study – Selected Summary

Critique

Energy storage efficiency was established at 62 percent for Ni-Cd, 65.7 percent for advanced Ni-Cd, 60.8 percent for Ni-H_2, and 54.1 percent for the RFC system. Because of the low depth of discharge of the batteries (14.5 to 18.6 percent), the Ni-Cd and Ni-H_2 efficiencies reported are believed to be realistic. The improvement in performance expected for advanced Ni-Cd batteries is unlikely, for, although some research is continuing, there is very little emphasis today on the development of advanced Ni-Cd batteries. However, the RFC system efficiency of 54.1 percent is too low, since overall efficiencies in excess of 62 to 65 percent are possible.

The effect of high peak power requirements on the choice of space station energy storage systems is important to determine, for variable power demands are more typical of spacecraft than are constant power demands. This study included a peak power requirement of 450 kW for 15 minutes several times each day. This would impact the selected Ni-Cd battery in the following ways:

1. The discharge rate is at least four times greater than normal, which would produce low voltages, probably lower than the allowable limit;

2. Maximum depth of discharge on the batteries would be increased, at least double. This increased depth of discharge in combination with the high discharge rate would be expected to impact battery life;

3. Heavier batteries or more frequent resupply would be required. The RFC system, designed to low current density for high efficiency, is much better suited to such peak loads than are batteries.

A conservative depth of discharge (18.6 percent) was selected for the Ni-H_2 batteries due to the lack of test data. Although even today there are not sufficient test data to justify selection of Ni-H_2 batteries, the premise should be made that this system will eventually permit longer life and greater depth of discharge than Ni-Cd batteries. Otherwise, there is no reason to consider Ni-H_2. This would make the Ni-H_2 system more attractive with respect to weight and resupply. Tentative rejection of Ni-H_2 batteries would still be justified on the basis of insufficient test data, however.

A trade study was conducted on emergency power systems to meet the requirement of 5 kW for 180 hours. The normal battery compliment is not adequate, for the capacity is exceeded. The study showed that a RFC system is very attractive for this need. However, although the Ni-Cd battery was selected for spacecraft energy storage, no extra weight increment can be identified for emergency power.

The choice of a relatively low battery depth of discharge is judged to be a wise one in principle. The choice of the best DOD is not entirely one of that is amenable to analysis, but depends also on judgement. The reason is that the data on mean cell life are not adequate to determine when the first cell failure is most likely to occur in a battery. Low DOD is also consistant with the need for high reliability, and helps reduce the high risk of failure due to the large number of cells in series.

The above general argument for low battery DOD also applies to the RFC system in the form of low current density. However, with the RFC system, the low current density has additional benefits, particularly higher efficiency. The RFC system designed in this study is much lighter than batteries, and it would be appropriate to increase RFC system weight and obtain efficiencies equivalent to those obtained by batteries.

Total 10-year cost for energy storage ranged from $316 M to $349 M for all energy options. Care must be used with these cost estimates, because they contain other power system elements which are not strictly energy storage. The objective was to allow cost comparisons, rather than obtain absolute costs.

<u>Impact on McDonnell Douglas Conclusions</u>

1. The Ni-Cd batteries appear to be undersized for the peak power requirement. The peak power requirement makes the energy storage selection much more favorable to the RFC system.

2. Although some research is continuing on the Ni-Cd system, development of advanced Ni-Cd batteries is currently receiving relatively little emphasis, and the projected improvements are unlikely. Therefore, Ni-Cd batteries of advanced design cannot be considered a viable option.

3. An RFC system redesigned for efficiency comparable to that of batteries would require a weight increase, but the RFC system weight should still be less than that of batteries.

4. The RFC system apparently would have been selected if the schedule had permitted it. Since there is not now a schedule which must be met, the choice of Ni-Cd batteries would not continue to apply.

4.7 TRW STUDY

<u>TRW Study Status</u>

A final report has not yet been released on the TRW study. Therefore, this review of that study is based on the progress report relating to energy storage, the mid-term and final oral reviews, and a published technical paper. These are identified respectively in references 6a, 6b, 6c, and 6d.

<u>Objectives</u>

The objectives of this study were to define and assess multi-hundred kW power system concepts and technology development requirements. Energy storage was one of the items under the electrical power system design; this review is limited to that item.

<u>Main Requirements</u>

Task I requires that an electrical power system reference design be established. This requires an analysis of energy storage selection and definition of battery costs. The electrical power system has seventeen 16.2 kW channels to support 250 kW of payload power plus 25 kW of housekeeping equipment. TRW refers to this as a 250 kW system, whereas in this report it is taken to be a 275 kW system. Each channel includes one 160-cell, 150 ampere-hour $Ni\text{-}H_2$ battery for energy storage. The orbit is 160 nautical miles, 28.5° inclination, with an occult duration of 36 minutes. Bus voltage is 220 Vdc $\pm$20 Vdc. Solar array costs are based on a manufacturing cost of $30./Watt, which reflects a prior solar array costing exercise.

<u>Major Findings</u>

An electrical power system was developed using seventeen 16.2 kW channels to support the loads. One battery is devoted to each channel. This was done to avoid paralleling high voltage batteries, and precludes the need for battery voltage matching regulators.

Also, the isolation switch gear need not operate at high voltage and high current. Additionally, it is claimed that a higher efficiency system will result.

Ni-Cd, Ni-H_2, and RFC systems were compared, and Ni-H_2 batteries were found to be the lightest and cheapest overall for a 30-year mission (Figures 4.7-1 to 4.7-5). For short missions, less than five years, the three approaches were very close in both respects. The RFC system would be the lightest approach except for the propulsion fuel to preclude orbital decay.

The cost of the electrical power system was dominated by the cost of Ni-H_2 batteries. Initially, these cost half as much as the solar array ($22.5 M vs. $50.7 M), but by the end of 30 years the battery cost was double that of the solar array ($118.6 M vs. $50.7 M). It was concluded that significant economic benefits remain in reducing electrical power system cost, but that this requires considerable investment.

A 40 percent reduction in Ni-H_2 battery cost is projected for 1986 by increasing cell size from 50 AH to 150 AH. A 75 percent cost reduction is projected by the 1990's by increasing cell size to 250 AH with a common container design, with accompanying improvements in life. It is concluded that a greater reduction in energy storage system cost is possible by reducing battery cost through improved technology than by extending battery life.

The optimum depth of discharge for Ni-Cd and Ni-H_2 batteries was calculated to be 30 percent. This value was used in the systems analyses.

<u>TRW Conclusions</u>

1. A power system with 17 separate channels is considered best. Each channel would have its own battery.

2. Ni-H_2 batteries were found to be the lightest and cheapest for a 30 year mission.

3. Batteries are the biggest power system cost driver for a 30-year mission.

4. A greater reduction in battery cost is possible by technology improvements than by extending battery life.

PARAMETERS	NICKEL CADMIUM	NICKEL HYDROGEN	FUEL CELL PLUS ELECTROLYSIS
SYSTEM COSTS			
ENERGY STORAGE (M$)	243	101	101
SOLAR ARRAY (M$)	18	18	35
ALTITUDE MAINTENANCE (M$)	53	51	99
THERMAL SUPPORT (M$)	6	5	6
DEVELOPMENT (M$)	1	5	50
TOTAL (M$)	321	180	291
SYSTEM WEIGHT (30 YEARS)			
ENERGY STORAGE (LB)	364,600	95,000	44,500
SOLAR ARRAY (LB)	14,700	14,100	27,600
ALTITUDE MAINTENANCE (LB)	108,800	94,500	214,700
THERMAL SUPPORT (LB)	3,100	2,600	5,200
TOTAL (LB)	491,200	216,200	292,000

Figure 4.7-1: TRW Study – Energy Storage Comparisons

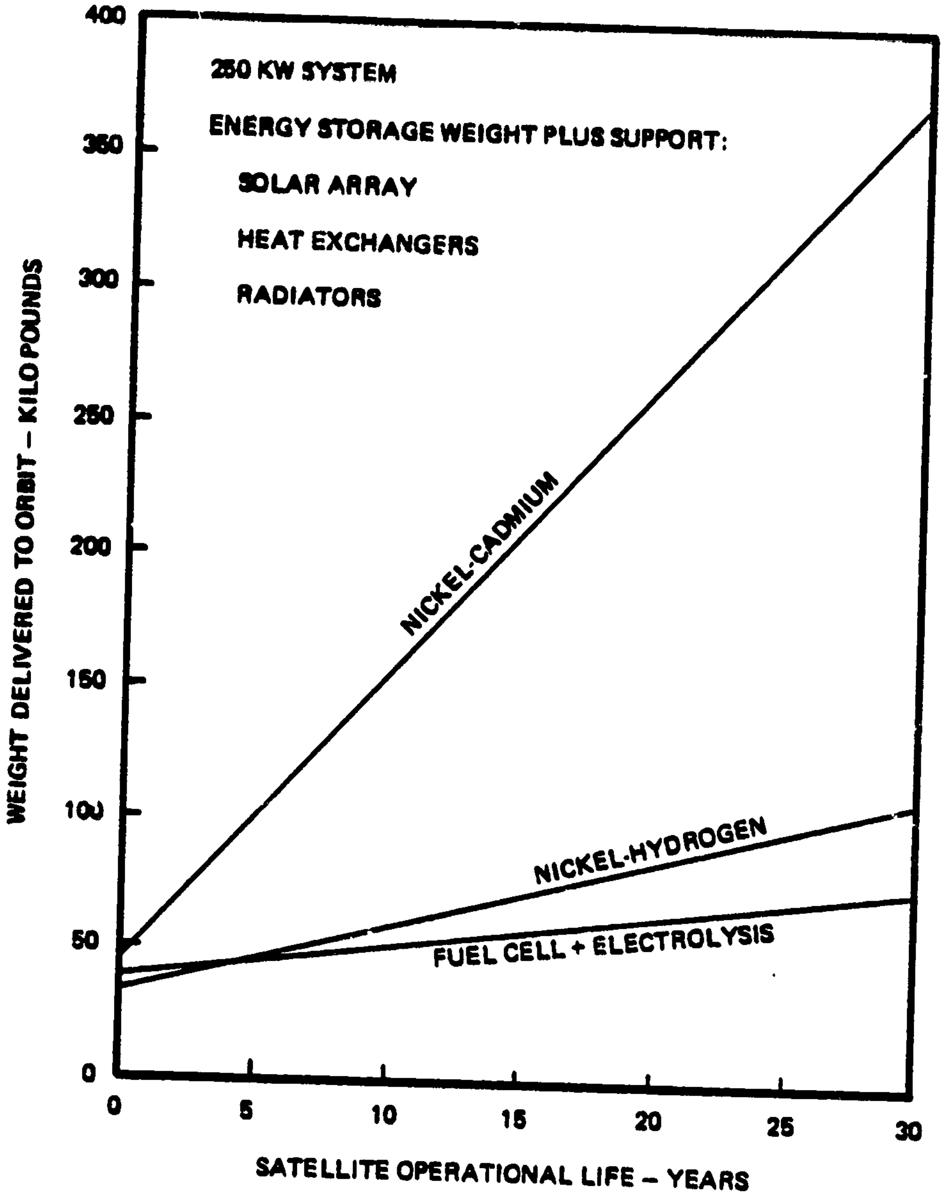

Figure 4.7-2: TRW Study – Comparison of Weight Into Orbit

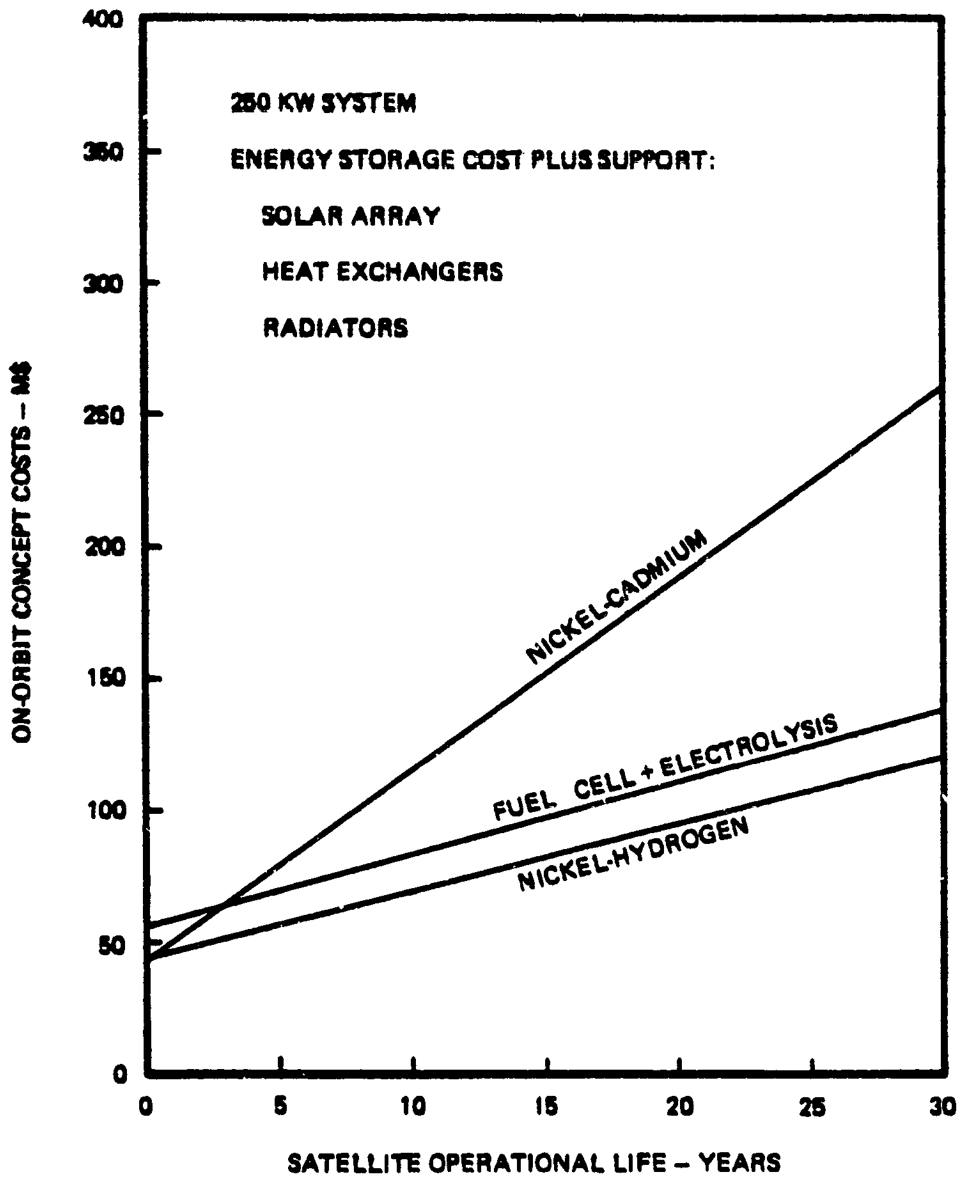

Figure 4.7-3: TRW Study – Cost Comparison

PARAMETER	NICKEL CADMIUM	NICKEL HYDROGEN	FUEL CELL PLUS ELECTROLYSIS UNIT
ENERGY STORAGE (WH)	306,000	450,000	200,000
DEPTH OF DISCHARGE (%)	49	33	75
AVERAGE LIFE (YR)	2.75	7	4.6 (STACKS) 1.1 (PUMPS)
CELL SIZE	100 AH	150 AH	270 AMPERES (FUEL CELLS) 353 AMPERES (ELECTROLYSIS UNITS)
CELLS/UNIT	170	160	308 FUEL CELLS 135 ELECTROLYSIS UNITS
UNIT QUANTITY	17	17	5 FUEL CELLS* 6 ELECTROLYSIS UNITS*
HEAT LOSSES (KW)	38**	32**	79 (SUNLIGHT) 231 (ECLIPSE)
TEMPERATURE (°C)	0	0†	40/75
INPUT POWER (KW)	229	220	430
SPECIFIC WEIGHT (WH/LB)	10	25	35††
WEIGHT			
INITIAL (LB)	30,600	18,000	5,775
REPLACEMENTS (LB)	334,000	77,000	38,709
COSTS			
INITIAL (M$)	20.4	19.1	14.3
REPLACEMENTS (M$)	223	82	87
DEVELOPMENT (M$)	1	<5	>50

* ONE UNIT ADDED FOR RELIABILITY
** 90-MINUTE AVERAGE
† NOT OPTIMIZED
†† NOT SCALABLE

Figure 4.7-4: TRW Study – Energy Storage Sizing Parameters (250-Volt System, 250-KW Payload)

PARAMETER	NICKEL CADMIUM	NICKEL HYDROGEN	FUEL CELL PLUS ELECTROLYSIS UNIT
SOLAR ARRAY			
POWER * (KW)	301	289	586
MFG COST (M$)	9.0	8.7	17.0
LAUNCH COST ** (M$)	9.4	9.1	17.7
AREA (SQ FT)	21,600	20,700	40,600
WEIGHT *** (LB)	14,700	14,100	27,600
HEAT EXCHANGERS			
WEIGHT (LB)	800	680	513
MFG COST †	2.4 M$	2.4 M$	220 K$
RADIATOR			
WEIGHT †† (LB)	2,300	1,940	4,646
MFG COST (M$)	1.8	1.5	3.6
ALTITUDE MAINTENANCE (PROPULSION FUEL)			
WEIGHT (LB)	108,800	104,500	214,700
LAUNCH COST (M$)	53	51	99

* BEGINNING OF LIFE, BASED ON 20% DEGRADATION OVER 30 YEARS
** BASED ON VOLUME REQUIREMENTS (958 KW/SHUTTLE)
*** AT 45 W/KG (20.5 W/LB)
† AT $20,000 PER UNIT
†† PUMPED LIQUID RADIATORS, 5.53 KG/M^2

Figure 4.7-5: TRW Study – Energy Storage Support Parameters

Critique

It is not clear that the seventeen separate power channel system is the best approach. Unless the typical load is relatively small, it will not be practical to divide the loads evenly between the seventeen channels. That will result in some batteries being discharged shallow, and others being discharged deeper than designed for. Also, since each energy storage unit is a single-thread design -- one charger and other battery-related equipment -- it is not clear how reliable the system will be, especially in view of the use of 160 cells in series. For the trade study using the RFC system, only four fuel cell stacks were used; it is not clear how this could be consistent with the seventeen channel concept.

Much of the energy storage system results are closely associated with cost projections. This is a difficult task, and it is difficult for people to believe in large projected cost savings from improved technology, which often is counter to their experience. Part of the problem is the need to distinguish between the potential cost saving and what might realistically be expected. This problem is made worse by the fact that, at least in the preliminary reports available so far, there is inadequate support for some of the conclusions.

If we first address the question of what is possible, then it is certainly possible for a 40% reduction in Ni-H_2 battery cost for 1986 by increasing size from 50 AH to 150 AH, for there are real cost savings obtainable with increased size. This is also a reasonable expectation, with the qualification that such a battery could be built in 1986, but such batteries could not be used until several years later when life would be verified. A 75% reduction in Ni-H_2 battery cost by the 1990's using a common pressure vessel design is also possible, for projections have been made of cost reductions up to 85%. What may be considered a reasonable expectation is another question, and must consider many factors. Solar array costs of $30 per watt does not even seem possible, but that item is beyond the scope of this evaluation.

The major cost emphasis in this study was placed on the initial manufacturing cost of the batteries. This is very important in many spacecraft applications. However, for space stations, like the 30-year station evaluated, initial purchase cost of batteries is small compared to the total life cycle cost, on the order of 6 percent. For example, Ni-Cd batteries are relatively inexpensive, but the total life cycle cost is high because battery life is short relative to the envisioned cycle life of Ni-H_2 batteries or the RFC system. Thus, technology advancements must not only include those factors relating to low manufacturing cost, but must also result in significantly improved cycle life. Life improvement is a much more difficult undertaking; it is a topic the industry could never come to grips with on the Ni-Cd system, and it is risky to depend on breakthroughs in cycle life with the $Ni-H_2$. In fact, the emphasis on large cells can run counter to life improvement, for large cells are expected to have higher failure rates than smaller cells. Consequently, if the assigned life of 7 years at 33 percent DOD with a 160-cell battery does not also materialize (in addition to the 75% cost reduction), the total life cycle cost of the $Ni-H_2$ system will increase.

There are a number of cost-related items which appear to be questionable or deserving of comment in the TRW study. These are not central to the general cost conclusions, but are worthwhile to identify:

a) Battery costs are projected to be 1.52 times the cell cost. This compares with 3.05 times the cell costs for the NASA standard Ni-Cd 60 AHr battery.

b) Dependence on cost reduction by development of large cells may not be workable if a 250 kW space station must evolve from a much smaller size, or if a much smaller size is ultimately selected as the baseline. Assume the TRW choice of a 150 AH cell is appropriate for a 250 kW system with seventeen channels; if then a 50 kW system were required with 8 channels, the cell size required would be 64 AH. This size is essentially state-of-the-art; major cost savings expected from increased cell size should be negligible, but some cost savings from a common design approach should be expected.

c) TRW experience of $2300 per cell for 50 AHr laboratory $Ni-H_2$ cells was used as part of the basis for cost estimates, whereas the current budgetary price for the AF-designed 50 AHr LEO cells is currently $5000 per cell.

d) The optimum depth of discharge for the batteries was determined to be 49 percent for Ni-Cd and 33 percent for $Ni-H_2$. This was based on analysis of Ni-Cd data and $Ni-H_2$ projected cycle life data. This results from the calculation that the product of mean cycle life and DOD is greatest at those discharge depths. The problem is that we must consider not merely when the average cell fails, but when the first few cells fail in a battery. The average cell life information does not help much in this regard, because sample sizes are too small to give good statistics. A lower depth of discharge must be used to minimize the incidence of early cell failures in a battery. This is especially true when there is a large number of cells in series in the battery. Also, lower DOD is consistent with the need for high reliability. As a further point, it should be noted that 49% DOD on Ni-Cd batteries is marginal with respect to recharging in low earth orbits; the cells cannot be charged quickly enough, especially when degraded, unless specially designed with a sacrifice in energy density. This unjustifiably high DOD for Ni-Cd batteries is in part responsible for the very low weights calculated for the Ni-Cd system.

This critique does not take the position that costs cannot be reduced dramatically, but merely that insufficient evidence has been provided to support that conclusion. We do disagree, however, with the conclusion that technology improvements will result in greater cost reductions than will improvements that extend battery life.

Costs of the RFC system are very difficult to estimate. The hardware costs appear to be low, but there are no better data available to make comparisons. The solar array and altitude maintenance cost penalties are high because of the low RFC system efficiency used; these costs would be equal to those of batteries if the RFC system were designed to the same overall efficiency. Perhaps the costs will also even out. It must be recognized that cost estimates of RFC systems will always be soft relative to battery costs because of limited applications and therefore the lack of a data base.

Though the RFC system was analyzed to be the lightest in-orbit energy storage system, the lower efficiency assumed for the RFC system resulted in a greater amount of orbit makeup fuel, making the total weight heavier than for Ni-H_2 batteries. Though energy storage system efficiency data are not given, this can be inferred from the associated solar array penalty (Figure 4.7-5), which is 20,700 ft^2 for Ni-H_2 and 40,600 ft^2 for the RFC system. These are measures of relative inefficiency. Thus, if the Ni-H_2 system efficiency were 70 percent, then the RFC system efficiency would be 41 percent. We now know that the energy storage efficiency of battery systems and RFC systems can be comparable, though that does not result in the minimum initial launch weight design for the RFC system. Thus, the RFC system weight data of Figure 4.7-1 is not optimized to minimum total weight for 30-year life.

Even though the TRW predicted battery costs are very low, they still are more costly than the solar array prediction. This is a consequence of a low assumed solar array manufacturing cost of $30 per watt. Comparing this with the $600 per watt cost for the Skylab solar array, and with $900 per watt for more recent arrays, it is apparent that this is an unusually low cost, and would require a major breakthrough to achieve.

Impact on TRW Conclusions

1. The use of a seventeen-channel electric power system would appear to be usable for battery energy storage, but not practical for RFC system energy storage. No important impact is seen by reducing the number of channels were the RFC system to be used.

2. Cost and weight of the battery systems appears to be too low. Refined analysis, including revised assumptions, should cause batteries to look less favorable, and RFC systems to look more favorable.

3. Solar array costs apear to be too low. Cost refinement should cause the entire electrical power system to be more costly.

4.8 PRC SYSTEMS STUDY

Objectives

The purpose of this study (Reference 7) was to develop computer models which are used to determine the total life cycle cost of electrochemical energy storage systems for space stations. The effect of design variables on cost was also to be determined, as well as system weight. This study was completed in September, 1981.

Requirements

Requirements for this study are defined in a specification given in Appendix B of their final report. Analyses were to be made for both LEO and GEO orbits. The LEO orbit was at 444 km with 56° inclination, with power levels ranging from 25 kW to 250 kW at end of life. Mission duration was 30 years, with resupply and maintenance provided. The GEO mission was for 5 years operation without overhauls or replacement of hardware, and required autonomous deployment. Electrical power system voltage was 120 Vdc nominal for all missions.

Major Findings

The significant findings of this study are summarized in Figures 4.8-1 to 4.8-3. The major output of this contract was the generation of two sets of computerized performance/cost models, one for battery subsystems, and one for regenerable fuel cell subsystems. These models permit analysis of the effect of design variations on life cycle costs. A large number of runs was made and the results plotted, showing the affects of many design variables. No other study has attempted such a comprehensive analysis. One result of these analyses is that the cost of both Ni-Cd and Ni-H_2 batteries is more sensitive to design variables than is the cost of the regenerable fuel cell system.

For LEO missions, Ni-Cd battery systems cost more than Ni-H_2 battery systems; this appears to be related in part to the deeper depth of discharge assumed for Ni-H_2 batteries. Cost of the regenerable fuel cell system was found to be approximately the same as for Ni-H_2 batteries. Weight of the LEO energy storage system was lightest for RFC systems, being 4100 kg compared with 4500 kg for Ni-H_2 and 8200 kg for Ni-Cd.

Cost data generated show that the production or manufacturing cost of the energy storage systems is almost insignificant compared to the total life cycle cost. The LEO data summarized in Figure 4.8-1 shows that the production cost is on the order of one twentieth the total cost, but it is even a smaller fraction than that because production cost in this study also includes prelaunch and integration costs, space transport costs, and space deployment and checkout costs: these costs are not conveniently separable, however. The Ni-H_2 battery and the RFC system have nearly equal energy storage subsystem life cycle costs ($131 M and $138 M respectively for 50 kW), but the Ni-H_2 battery has lower total life cycle cost ($554 M vs. $775 M). This is due to the lower calculated efficiency of the RFC, resulting in a much greater solar array cost.

For GEO missions, total subsystem life cycle cost is about one sixth that of the LEO missions, and so the total life cycle cost is also less (Figure 4.8-2). The RFC has the least cost, especially at the production and energy storage subsystem levels, with only

	NI Cd	Ni-H_2	RFC
DOD	24.8%	43%	(80%)
EFFICIENCY	63.5%	62.1%	41.3%
ESS WEIGHT (KG)	8,231	4,488	4,102
LIFE (RESUPPLY)	7.1 YR	7.1 YR	7.1 YR
SPECIFIC WT (LB/KW)	363	197.9	180.9
COSTS ($M)			
DDT&E	14.38	10.79	23.95
PRODUCTION	32.78	20.47	36.16
OPERATION AND MAINTENANCE	238.99	99.44	77.98
ELECTRICAL POWER SUBSYSTEM LIFE CYCLE COST	286.15	130.70	138.10
COST INTERFACE			
SOLAR ARRAY	405.19	412.04	587.83
THERMAL	9.29	9.55	6.78
PWR COND	3.17	1.99	1.99
TOTAL LIFE CYCLE COST ($M)	703.71	554.27	744.70

Figure 4.8-1: PRC Systems Study — Selected Summary, 50 KW, LEO

	LEO (30 YEARS)			GEO (5 YEARS)		
	Ni-Cd	Ni-H_2	RFC	Ni-Cd	Ni-H_2	RFC
DOD	24.8%	40%	(80%)	55.2%	78.7%	(80%)
ESS WEIGHT	4116 KG	2178 KG	2057 KG	2726 KG	1796 KG	446 KG
COST (MILLIONS)						
PRODUCTION *	$18.69	$12.59	$20.96	$44.88	$31.40	$16.31
ESS LIFE CYCLE	$152.57	$77.42	$81.04	$54.29	$39.86	$23.68
TOTAL LIFE CYCLE	$393.77	$318.28	$422.49	$72.21	$60.78	$50.69

* INCLUDES SPACE TRANSPORTATION

Figure 4.8-2: PRC Systems Study, Comparison of LEO and GEO (25 KW)

BATTERIES – TOTAL LIFE CYCLE COST, LEO

1. COST IS INSENSITIVE TO DOD UP TO 30% DOD
2. OPTIMUM DESIGN LIFE IS APPROXIMATELY 7 YEARS FOR Ni-Cd AND 9 YEARS FOR $Ni\text{-}H_2$
3. COST DECREASES WITH INCREASING CELL SIZE (ALSO DISCHARGE CURRENT), AT LEAST UP TO 280 AH

BATTERIES – TOTAL LIFE CYCLE COST, GEO

1. OPTIMUM CAPACITY FOR 25 KW IS 75 AH
2. OPTIMUM DOD IS GREATER THAN 50% FOR Ni-Cd, AND IS 70% FOR $Ni\text{-}H_2$

REGENERABLE FUEL CELLS – TOTAL LIFE CYCLE COST, LEO

1. COSTS ARE RELATIVELY INSENSITIVE TO CURRENT DENSITY OR ACTIVE AREA
2. COSTS ARE RELATIVELY INSENSITIVE TO DESIGN LIFE
3. OPTIMUM DISCHARGE VOLTAGE IS 0.7 V/CELL

REGENERABLE FUEL CELLS – TOTAL LIFE CYCLE COST, GEO

1. COSTS ARE RELATIVELY INSENSITIVE TO CURRENT DENSITY OR ACTIVE AREA
2. OPTIMUM FUEL CELL CURRENT DENSITY IS 350 MA/CM^2
3. OPTIMUM DISCHARGE VOLTAGE IS 0.7 V/CELL

Figure 4.8-3: PRC Study, Design Trends for Lowest Total Cycle Life Cost a small advantage at the total life cycle cost level. The weight advantage calculated for the RFC system is spectacular for GEO missions, 450 kg vs. 1800 kg for Ni-H_2.

Hardly any analysis was made of the data generated. In our review of the PRC report, a number of important trends were observed, and are summarized in Figure 4.8-3.

Conclusions of PRC

PRC elected to draw a minimum of conclusions, choosing rather to let the generated data speak for itself. The conclusions they drew were: 1) Energy storage system life cycle costs for Ni-Cd are about twice those for Ni-H_2; 2) Ni-H_2 and RFC life cycle costs are comparable; 3) Battery parameters are more sensitive to life cycle costs than are fuel cell parameters.

Critique

As PRC pointed out in their report, the effectiveness of the cost model prepared is somewhat limited at this time due to the absence of good emperical data on performance, physical characteristics, and costs for Ni-H_2 batteries and regenerable fuel cell systems. The fact that the data base is thin for those two key systems is no fault of the study, but is an inherent limitation that must be recognized in using the study results.

One characteristic of this study is that in an effort to account for all the factors relating to cost, a highly detailed and complex model was generated. As a result, much of the data and assumptions used in the model are buried within the computer program and are not readily accessible for scrutiny by potential users. Thus, it is not practical to check on many of the weight and cost elements or obtain breakdowns of the results. For example, the Ni-H_2 weights calculated for GEO are high, but the cause is unknown.

One of the important results is that the total life cycle costs are considerably greater thn the purchase price of the hardware. Costs for operations and maintenance have a dominant influence on subsystem costs, yet it seems not to be possible to determine why the operations and maintenance cost for Ni-Cd exceeds that for Ni-H_2.

Solar array costs have an overwhelming importance in the total life cycle cost, dwarfing energy storage hardware costs. This is qualitatively correct, though the unit cost information is either not given or is difficult to find. Solar array/size and cost are directly tied to energy storage system efficiency. Thus, greater emphasis on system efficiency would have been warranted. The calculated efficiency of the regenerable fuel cell system of 41.3 percent is especially low. An independent analysis of energy storage efficiencies shows that battery and RFC efficiencies can be comparable. Assuming the RFC efficiency to be equal to that of the $Ni\text{-}H_2$ battery for the 50 kW mission, the RFC total life cycle cost is reduced from $744 M to $548 M, which is comparable to the $554 M cost of the $Ni\text{-}H_2$ system.

Solar array drag has a big impact on the need for resupply of orbital makeup propellant. This was not considered in the PRC study. However, since the efficiencies of the contending energy storage systems should all be comparable, this should not be a large consideration in the comparison of energy storage systems.

It would have been preferable if the PRC study had included an analysis of the data generated. Interpretation of the data has largely been left to the reader. The design trends we observed for lowest total cycle life cost are given in Figure 4.8-3. Comments on some of these observed trends are as follows:

1. The finding that very large battery cell sizes are best (at least 260 AH for LEO) is questioned. This critique does not take the position that the conclusion is wrong, but merely that the arguments and analyses to support it are insufficient to justify the conclusion. The finding stems from the expected large reduction in operations and maintenance cost with large size cells, and is derived on the assumption that failure rates, preventative maintenance, and overhaul are directly related to the number of modules, and not dependent on module or cell size. This finding is questioned on the basis that (a) large cells are expected to have higher failure rates than smaller cells; (b) the question is not yet resolved whether it is best to promote reliability by redundancy at the cell level or at the battery level; use of large cells tends to lead to redundancy at the cell level; (c) excessively large cells will reduce the number of batteries below the minimum needed for safety; assuming a 50 kW system having three busses with a minimum of two batteries per bus, a minimum of six batteries is needed, with maximum cell size of approximately 85 AH. Recent events which lend some support to the conclusion favoring large cell sizes are: a) development is being started on the common pressure vessel $Ni\text{-}H_2$ multi-cell; and b) NASA-Lewis is showing good success in their development of a novel, large capacity $Ni\text{-}H_2$ cell.

2. The finding of an optimum fuel cell discharge voltage of 0.7 V/cell is questioned. Low voltage results from high current density, which promotes low efficiency and shorter life, and requires a larger solar array. Voltages in the range of 0.85 to 0.90 are considered to be more appropriate.

3. The finding that cost is relatively insensitive to fuel cell current density or active area is questioned. The argument is similar to that of item 2 above.

<u>Impact on PRC Conclusions</u>

1. Caution must be exercised in the use of the cost information from the PRC report. Some of the findings are important and should be followed up. However, where these findings are used as the basis for future R&D, the conclusions should be corroborated by a separate analysis.

2. The conclusion that Ni-Cd battery systems are ultimately more costly than Ni-H_2 hinges on the expectation that Ni-H_2 batteries can be discharged to deeper depths and will be longer lasting. This has not yet been proven, but probably it will eventually be proven. With that qualification, this conclusion appears to be valid.

3. The conclusion that Ni-H_2 and RFC life cycle costs are comparable appears from other work to be valid, with the provision that both systems be designed with comparable efficiency.

4. The conclusion that battery parameters are more sensitive to life cycle costs than are fuel cell parameters cannot be refuted, but does not appear to be reasonable. Considerable cost leverage is associated with operations and maintenance cost, and with solar array cost, both of which should be sensitive to RFC design parameters.

5. The general finding that equipment purchase costs represent only a small fraction of the total associated cost appears to be valid.

6. The finding that RFC systems are of lower cost and considerably lighter than batteries for GEO missions is significant and appears to be reasonable. Followup study should be made to verify and quantify this conclusion.

4.9 COMPARISON OF STUDY RESULTS

Analysis Method

Analyses were made on the results of the studies by the seven contractors. Considerable difficulty was met with in trying to find common bases to make comparisons. The main problems were: 1) the energy storage requirements differed, not only in power levels and mission duration, but also in considerations such as power for station buildup, peak power and emergency power; 2) the contractors had differing views on what items should be included as part of each penalty; 3) data breakdowns usually were not provided.

It was decided not to attempt to manipulate the data to compensate for all the differences. Instead, it was determined that a few key parameters would be established to normalize some of the data. Then, if important differences showed up in the results, the reasons for those differences could be sought out independently in terms of differing requirements, differences in definition of an item, or simply as differences in a design or its expected cost.

The following normalizing parameters are used: 1) Energy Storage Specific Weight (lb/kW). This consists of the launch weight of the energy storage system, divided by the system rated power in kW; no associated penalties are included in this definition of the energy storage system weight; 2) Resupply Doubling Time (years). This is the duration for the energy storage resupply weight to equal the energy storage system launch weight; 3) Energy Storage Hardware Specific Cost ($/kW). The energy storage system production cost for one space station is divided by the system rated power in kW; 4) Operations Cost, 10 years ($/kW). The cost of operations and maintenance is divided by the system rated power in kW, and pro-rated for a 10-year duration.

In addition to the normalizing parameters, the reported energy storage efficiency is used. Where the inefficiency included dc to ac power losses, an adjustment was made to exclude that loss, since it is not truly an energy storage loss. Development cost was also included without adjustment on the reported results.

Results of Analysis

The energy storage system selected as best by each of the seven contractors is given in Figure 4.9-1. PRC did not make a choice of the best system, but indicated that Ni-

	NICKEL CADMIUM BATTERY	NICKEL HYDROGEN BATTERY	REGENERABLE FUEL CELL SYSTEM
NORTH AMERICAN ROCKWELL	O		X
UNITED TECHNOLOGIES			X
LOCKHEED	O		X
LIFE SYSTEMS	O		X
McDONNELL DOUGLAS	X	O	O
TRW	O	X	O
PRC SYSTEMS	O	*	*

X = SELECTED APPROACH

O = OTHER APPROACHES EVALUATED

* TWO TOP CONTENDERS; NO SELECTION MADE

Figure 4.3-1: Energy Storage System Selected

H_2 batteries and the RFC system had comparable life cycle costs. Rockwell and United Technology studied the RFC system, and Lockheed did not study the Ni-H_2 system.

Results of studies by the seven contractors are compared in Figures 4.9-2, 4.9-3, and 4.9-4 for RFC systems, Ni-Cd batteries, and Ni-H_2 batteries, respectively. It is seen that the attempt to normalize some of the data has been fairly successful, with most of the parameters falling into a range of two-to-one or three-to-one. Operations cost for each of the three systems is seen to be the most significant cost item, but this is also the parameter with the greatest variation. This is attributed to the fact that there were important differences in the ways this cost was determined. Even so, the reduced data give some idea on the costs that may be expected. It also points out that the biggest cost saving opportunity is in designing the systems for minimum operations and maintenance activity.

The specific weight of the RFC systems also has high variability. Systems designed long ago tend to be heavy, reflecting the early stage of RFC system technology.

Results of the NASA-sponsored studies should be viewed as information which will assist in making a decision on the best energy storage system for space stations. The studies alone are not a sufficient basis upon which to decide this question. This can be seen in Figure 4.9-5 showing the attributes that govern the selection of energy storage systems for space stations. The NASA sponsored studies examined some of the important attributes, but some others, which could be more important, were for good reason not part of the NASA studies. The comparison between RFC systems and batteries is discussed further in Section 8.0.

	ROCKWELL	UNITED TECHNOLOGIES	LOCKHEED	LIFE SYSTEMS	McDONNELL DOUGLAS	TRW	PRC SYSTEMS
SPECIFIC WT (LB/KW)	250	52.6	384	134	61	145.5	181
EFFICIENCY	52.5%	50.4%	52.5%	58.3%	54.1%	——	41.3%
SPECIFIC HDWR COST ($/KW)	——	——	——	$252K	$200K	$200K	$241K
RESUPPLY DOUBLING TIME	*	7.9 YR	——	>5.0 YRS	9.2 YRS	4.5 YRS	7.1 YRS
DEVELOPMENT COST	——	——	$19.1M	$14.7M	$40M	$50M	$24M
OPERATIONS COST - TOTAL	——	——	——	$7.9M	$80.7M	$100M	$78.0M
OPERATIONS COST - $/KW, 10 YRS	——	——	——	$378K	$807K	$120K	$520K
ELECTRICAL LOAD	20 KW	100 KW	25 KW	21 KW	100 KW	275 KW	50 KW
MISSION DURATION	10 YRS	——	——	10 YRS	10 YRS	30 YRS	30 YRS

* 2.5 YEARS ON MAJOR COMPONENTS

Figure 4.9-2: Comparison of Study Results on RFC Systems

	ROCKWELL	UNITED TECHNOLOGIES	LOCKHEED	LIFE SCIENCES	McDONNELL DOUGLAS	TRW	PRC SYSTEMS
SPECIFIC WT (LB/KW)	——	——	631	436	385	181	383
EFFICIENCY	——	——	64.0%	62.5%	62.0%	——	63.5%
RESUPPLY DOUBLING TIME	——	——	——	——	4.2 YRS	2.75 YRS	7.1 YRS
HARDWARE SPECIFIC COST ($/KW)	——	——	——	$357K	$320K	$164K	$655K
DEVELOPMENT COST	——	——	——	$13.7M	18M	$1.0M	$14.4M
OPERATIONS COST - TOTAL	——	——	——	$10.0M	$56M	$260M	$239M
OPERATIONS COST - $/KW, 10 YRS	——	——	——	$476K	$580K	$315K	$1593K
ELECTRICAL LOAD	20 KW	100 KW	25 KW	21 KW	100 KW	275 KW	50 KW
MISSION DURATION	10 YRS	——	——	10 YRS	10 YRS	30 YRS	30 YRS

Figure 4.9-3: Comparison of Study Results on Ni-Cd Batteries

	ROCKWELL	UNITED TECHNOLOGIES	LOCKHEED	LIFE SYSTEMS	McDONNELL DOUGLAS	TRW	PRC SYSTEMS
SPECIFIC WT (LB/KW)	——	——	——	——	159	130.9	197.9
EFFICIENCY	——	——	——	——	60.8%	——	62.1%
RESUPPLY DOUBLING TIME	——	——	——	——	4.2 YRS	7.0 YRS	7.1 YRS
HARDWARE SPECIFIC COST ($/KW)	——	——	——	——	$320 K	$164 K	$136 K
DEVELOPMENT COST	——	——	——	——	$18M	$5M	$10.7M
OPERATIONS COST - TOTAL	——	——	——	——	$33M	$80M	$78M
OPERATIONS COST - $/KW, 10 YRS	——	——	——	——	$330K	$97K	$520K
ELECTRICAL LOAD	20 KW	100 KW	25 KW	21 KW	100 KW	275 KW	50 KW
MISSION DURATION	10 YRS	——	——	10 YRS	10 YRS	30 YRS	30 YRS

Figure 4.9-4: Comparison of Study Results on Ni-H_2 Batteries

MANDATORY ATTRIBUTES	LONG LIFE (CELL LEVEL)	NOT PART OF NASA STUDIES
	RELIABILITY (SYSTEMS)	
POSSIBLY MANDATORY ATTRIBUTES	LARGE EMERGENCY POWER CAPABILITY	
	HIGH PEAK POWER CAPABILITY	
	BASE BUILDUP CAPABILITY	
IMPORTANT ATTRIBUTES	HIGH EFFICIENCY	
	INTEGRATION ADVANTAGES	
	LOW WEIGHT	SUBJECT OF NASA STUDIES
	LOW COST	
	LOW RESUPPLY	

Figure 4.9-5: Attributes for Selection of Energy Storage Systems for Space Stations

5.0 SOC REFERENCE FUEL CELL SYSTEMS

5.1 SYSTEM DESIGN

Regenerative fuel cell systems were studied for the SOC to provide a point of reference. In order to be sure the design would be credible, we obtained the assistance of both General Electric Co. and United Technologies in the design and optimization of this system. Their help is gratefully acknowledged. General Electric's technology is based on the solid polymer electrolyte fuel cell with a separate solid polymer electrolyte electrolyzer. United Technologies' approach is based on the alkaline electrolyte fuel cell. A separate alkaline electrolyzer made by Life Sciences would be used with the alkaline fuel cell. We consider both the solid polymer and the alkaline electrolyte systems to be well suited to the space station, and believe that either one would give the needed life and performance. Both General Electric Co. and United Technologies have documented their contributions to this study (References 10 and 11), and these reports provide additional analysis detail.

Rather than produce a single design, a large number of designs were established in order to investigate a number of different objectives. One design of interest is one which would be interchangable with nickel hydrogen batteries. Our analysis showed that the energy storage efficiency with a nickel hydrogen system should be approximately 55 percent, so we configured a fuel cell design specifically to that efficiency. Actually, the regenerative fuel cell efficiency is 55.25 percent, but the energy storage efficiency is slightly lower at 54.4 percent. This difference of 0.6 percent is minor and still permits a valid comparison.

The 55 percent efficiency design with solid polymer electrolyte weighs 2418 lb, with the following weight breakdown:

Radiator	453 lb
Tanks and Reactants	187
Fuel Cell System	1223
Electrolyzer System	555
Total	2418 lb

Operating conditions and design data are summarized in Figure 5.1-1. For example, the design consists of six fuel cell modules, based on the concept of three buses with two modules per bus. This arrangement is heavier than a design with fewer modules, but tolerates failures better.

A second design produced is a minimum weight design. This is not suggested as the appropriate design for SOC, for the low weight is obtained at the expense of efficiency. However, a minimum weight design may be useful for some missions, and this design data provides a useful comparison with the high efficiency designs.

The minimum weight design the solid polymer electrolyte weighs 1744 lb, with the following weight breakdown:

Radiators	548 lb
Tanks and Reactants	204
Fuel Cell Subsystem	646
Electrolysis Subsystem	346
Total	1744 lb

This system has a regenerative fuel cell efficiency of 48.1 percent, and a slightly lower energy storage efficiency of 47.4 percent. Operating conditions and design data are summarized in Figure 5.1-2.

As was discussed in Section 3, designs were established with regenerative fuel cell efficiencies of 65 percent and 67 percent for the solid polymer and alkaline electrolyte systems, respectively, which would have energy storage efficiencies of 64 and 66 percent, respectively. It was concluded that a design energy storage efficiency of 60 percent is possible without undue development risk using either fuel cell system. This compares to an energy storage efficiency of 55 percent with the nickel hydrogen battery based on existing cell performance, or 62 percent based on potential design improvements. To implement this philosophy, a third design produced was a high efficiency design. This has a regenerative fuel cell efficiency of 62.8 percent, and an energy storage efficiency of 61.9 percent.

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NORMAL BUS POWER REQ'D	39.23 KW	
BUS VOLTAGE	180.00 VOLTS	
SOLAR ARRAY SPEC WEIGHT	13.88 KG/KW	30.60 LBS/KW
LIGHT PERIOD IN ORBIT	55.00 MIN.	
DARK PERIOD IN ORBIT	37.00 MIN.	
ENERGY STORAGE CAPACITY	44.04 MIN.	

FUEL CELL OPERATING CONDITIONS

MEAN CELL PRESSURE	206.85 KPA	30.00 PSIA
MEAN CELL TEMPERATURE	355.37 K	180.00 F
CELL CURRENT DENSITY	64.58 MA/SQCM	60.00 ASF
CELL VOLTAGE	.898 VOLTS	
NO. OF CELLS PER MODULE	201	
NUMBER OF MODULES	6	
MEMBRANE THICKNESS	.254 MM	.010 IN
INDIVIDUAL CELL AREA	.057 SQ M	.613 SQFT
MODULES OUTPUT POWER	39.83 KW	
MODULE OUTPUT VOLTAGE	180.44 VOLTS	
CELL CURRENT,PARAL MODS	36.79 AMPS	
CELL CURRENT EFFICIENCY	98.07 %	
MODULES HEAT GEN. RATE	26.75 KW	

ELECTROLYZER OPERATING CONDITIONS

MEAN CELL PRESSURE	827.40 KPA	120.00 PSIA
MEAN CELL TEMPERATURE	355.37 K	180.00 F
CELL CURRENT DENSITY	215.28 MA/SQCM	200.00 ASF
CELL VOLTAGE	1.481 VOLTS	
NO. OF CELLS PER MODULE	135	
NUMBER OF MODULES	3	
MEMBRANE THICKNESS	.254 MM	.010 IN
INDIVIDUAL CELL AREA	.036 SQ M	.388 SQFT
MODULES INPUT POWER	47.29 KW	
MODULE INPUT VOLTAGE	199.94 VOLTS	
CELL CURRENT,PARAL MODS	77.67 AMPS	
CELL CURRENT EFFICIENCY	96.77 %	
MODULES HEAT GEN. RATE	1.80 KW	

SYSTEM OPERATING CONDITIONS

SOLAR ARRAY OUTPUT POWER	47.77 KW	
IDEAL REGEN FUEL CELL EFF.	57.52 %	
SYSTEM ENERGY STORAGE EFF.	55.25 %	
WATER PRODUCED-MODE C	11.16 KG	24.60 LBS
H2 STORAGE TANK VOLUME	2.75 CU M	97.04 CUFT
O2 STORAGE TANK VOLUME	1.37 CU M	48.52 CUFT

WEIGHT SUMMARY

SOLAR ARRAY	663 KG	1462 LBS
SPACE RADIATORS	205 KG	453 LBS
H2,O2 AND WATER TANKS	85 KG	187 LBS
FUEL CELL SUBSYSTEM	555 KG	1223 LBS
ELECTROLYSIS SUBSYSTEM	252 KG	555 LBS
SYSTEM VARIABLE LAUNCH WEIGHT	1760 KG	3879 LBS

Figure 5.1-1: Regenerative Fuel Cell System Summary – 55% Efficiency Design

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NORMAL BUS POWER REQ'D	39.23 KW	
BUS VOLTAGE	180.00 VOLTS	
SOLAR ARRAY SPEC WEIGHT	13.88 KG/KW	30.60 LBS/KW
LIGHT PERIOD IN ORBIT	55.00 MIN.	
DARK PERIOD IN ORBIT	37.00 MIN.	
ENERGY STORAGE CAPACITY	44.04 MIN.	

FUEL CELL OPERATING CONDITIONS

MEAN CELL PRESSURE	206.85 KPA	30.00 PSIA
MEAN CELL TEMPERATURE	355.37 K	180.00 F
CELL CURRENT DENSITY	161.46 MA/SQCM	150.00 ASF
CELL VOLTAGE	.810 VOLTS	
NO. OF CELLS PER MODULE	223	
NUMBER OF MODULES	6	
MEMBRANE THICKNESS	.254 MM	.010 IN
INDIVIDUAL CELL AREA	.023 SQ M	.245 SQFT
MODULES OUTPUT POWER	39.83 KW	
MODULE OUTPUT VOLTAGE	180.66 VOLTS	
CELL CURRENT,PARAL MODS	36.74 AMPS	
CELL CURRENT EFFICIENCY	99.29 %	
MODULES HEAT GEN. RATE	33.04 KW	

ELECTROLYZER OPERATING CONDITIONS

MEAN CELL PRESSURE	827.40 KPA	120.00 PSIA
MEAN CELL TEMPERATURE	355.37 K	180.00 F
CELL CURRENT DENSITY	484.38 MA/SQCM	450.00 ASF
CELL VOLTAGE	1.584 VOLTS	
NO. OF CELLS PER MODULE	126	
NUMBER OF MODULES	3	
MEMBRANE THICKNESS	.254 MM	.010 IN
INDIVIDUAL CELL AREA	.018 SQ M	.199 SQFT
MODULES INPUT POWER	54.36 KW	
MODULE INPUT VOLTAGE	199.64 VOLTS	
CELL CURRENT,PARAL MODS	89.42 AMPS	
CELL CURRENT EFFICIENCY	98.56 %	
MODULES HEAT GEN. RATE	4.53 KW	

SYSTEM OPERATING CONDITIONS

SOLAR ARRAY OUTPUT POWER	54.91 KW	
IDEAL REGEN FUEL CELL EFF.	50.03 %	
SYSTEM ENERGY STORAGE EFF.	48.07 %	
WATER PRODUCED-MODE C	12.22 KG	26.93 LBS
H2 STORAGE TANK VOLUME	3.01 CU M	106.21 CUFT
O2 STORAGE TANK VOLUME	1.50 CU M	53.11 CUFT

WEIGHT SUMMARY

SOLAR ARRAY	762 KG	1680 LBS
SPACE RADIATORS	249 KG	548 LBS
H2,O2 AND WATER TANKS	93 KG	204 LBS
FUEL CELL SUBSYSTEM	293 KG	646 LBS
ELECTROLYSIS SUBSYSTEM	157 KG	346 LBS
SYSTEM VARIABLE LAUNCH WEIGHT	1553 KG	3425 LBS

Figure 5.1-2: Regenerative Fuel Cell System Summary — Minimum Weight Design

The third design with solid polymer electrolyte weighs 4797 pounds, with the following weight breakdown:

Radiators	372 lb
Tanks and Reactants	177
Fuel Cell Subsystem	3107
Electrolysis Subsystem	1141
Total	4797 lb

Operating conditions and design data are summarized in Figure 5.1-3.

Additional supporting analysis for the three designs is provided in Reference 10. For example, it is shown that voltage regulation can be maintained with two of the six fuel cell modules failed, and ability to survive the three emergency conditions is shown. The Half SOC operates with three of the six fuel cell modules, but since the electrical load is greater than half the full SOC (60 percent of full SOC), there is a small reduction in system efficiency using equipment optimized for the Full SOC.

It was not practicable in this report to show the results of all the analyses made on the RFC system for SOC. Data on the alkaline fuel cell system were in many ways comparable to that generated for the solid polymer electrolyte system. The alkaline system estimates were in fact a little lighter, or viewed in another way, the alkaline system was a little more efficient for the same weight. For example, for the condition of both systems weighing 4800 lb, the regenerative fuel cell efficiency of the solid polymer system was 63 percent, compared with 67 percent for the alkaline system.

5.2 THERMAL DESIGN

It can be seen in Figure 5.2-1 that the heat generated by the fuel cells is considerably greater than the heat generated by the electrolyzer, on the order of 15 to 1. This is a consequence of the thermodynamics of these reactions, as is illustrated in Figures 3.2-2 and 3.2-6. Heat generation with fuel cells is always relatively high, but is reduced as the cell operates more efficiently, at the higher voltages. Heat generation with

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NORMAL BUS POWER REQ'D	39.23 KW	
BUS VOLTAGE	180.00 VOLTS	
SOLAR ARRAY SPEC WEIGHT	13.98 KG/KW	30.60 LBS/KW
LIGHT PERIOD IN ORBIT	55.00 MIN.	
DARK PERIOD IN ORBIT	37.00 MIN.	
ENERGY STORAGE CAPACITY	44.04 MIN.	

FUEL CELL OPERATING CONDITIONS

MEAN CELL PRESSURE	137.90 KPA	20.00 PSIA
MEAN CELL TEMPERATURE	355.37 K	180.00 F
CELL CURRENT DENSITY	21.53 MA/SQCM	20.00 ASF
CELL VOLTAGE	.974 VOLTS	
NO. OF CELLS PER MODULE	185	
NUMBER OF MODULES	6	
MEMBRANE THICKNESS	.508 MM	.020 IN
INDIVIDUAL CELL AREA	.171 SQ M	1.843 SQFT
MODULES OUTPUT POWER	39.83 KW	
MODULE OUTPUT VOLTAGE	180.12 VOLTS	
CELL CURRENT,PARAL MODS	36.85 AMPS	
CELL CURRENT EFFICIENCY	98.34 %	
MODULES HEAT GEN. RATE	21.39 KW	

ELECTROLYZER OPERATING CONDITIONS

MEAN CELL PRESSURE	551.60 KPA	80.00 PSIA
MEAN CELL TEMPERATURE	355.37 K	180.00 F
CELL CURRENT DENSITY	80.73 MA/SQCM	75.00 ASF
CELL VOLTAGE	1.422 VOLTS	
NO. OF CELLS PER MODULE	140	
NUMBER OF MODULES	3	
MEMBRANE THICKNESS	.508 MM	.020 IN
INDIVIDUAL CELL AREA	.085 SQ M	.914 SQFT
MODULES INPUT POWER	41.58 KW	
MODULE INPUT VOLTAGE	199.12 VOLTS	
CELL CURRENT,PARAL MODS	68.58 AMPS	
CELL CURRENT EFFICIENCY	97.23 %	
MODULES HEAT GEN. RATE	-.25 KW	

SYSTEM OPERATING CONDITIONS

SOLAR ARRAY OUTPUT POWER	42.00 KW	
IDEAL REGEN FUEL CELL EFF.	65.45 %	
SYSTEM ENERGY STORAGE EFF.	62.84 %	
WATER PRODUCED-MODE C	10.26 KG	22.62 LBS
H2 STORAGE TANK VOLUME	4.04 CU M	142.76 CUFT
O2 STORAGE TANK VOLUME	2.02 CU M	71.38 CUFT

WEIGHT SUMMARY

SOLAR ARRAY	583 KG	1285 LBS
SPACE RADIATORS	169 KG	372 LBS
H2,O2 AND WATER TANKS	80 KG	177 LBS
FUEL CELL SUBSYSTEM	1409 KG	3107 LBS
ELECTROLYSIS SUBSYSTEM	517 KG	1141 LBS
SYSTEM VARIABLE LAUNCH WEIGHT	2758 KG	6081 LBS

Figure 5.1-3: Regenerative Fuel Cell System Summary — 62% Efficiency Design

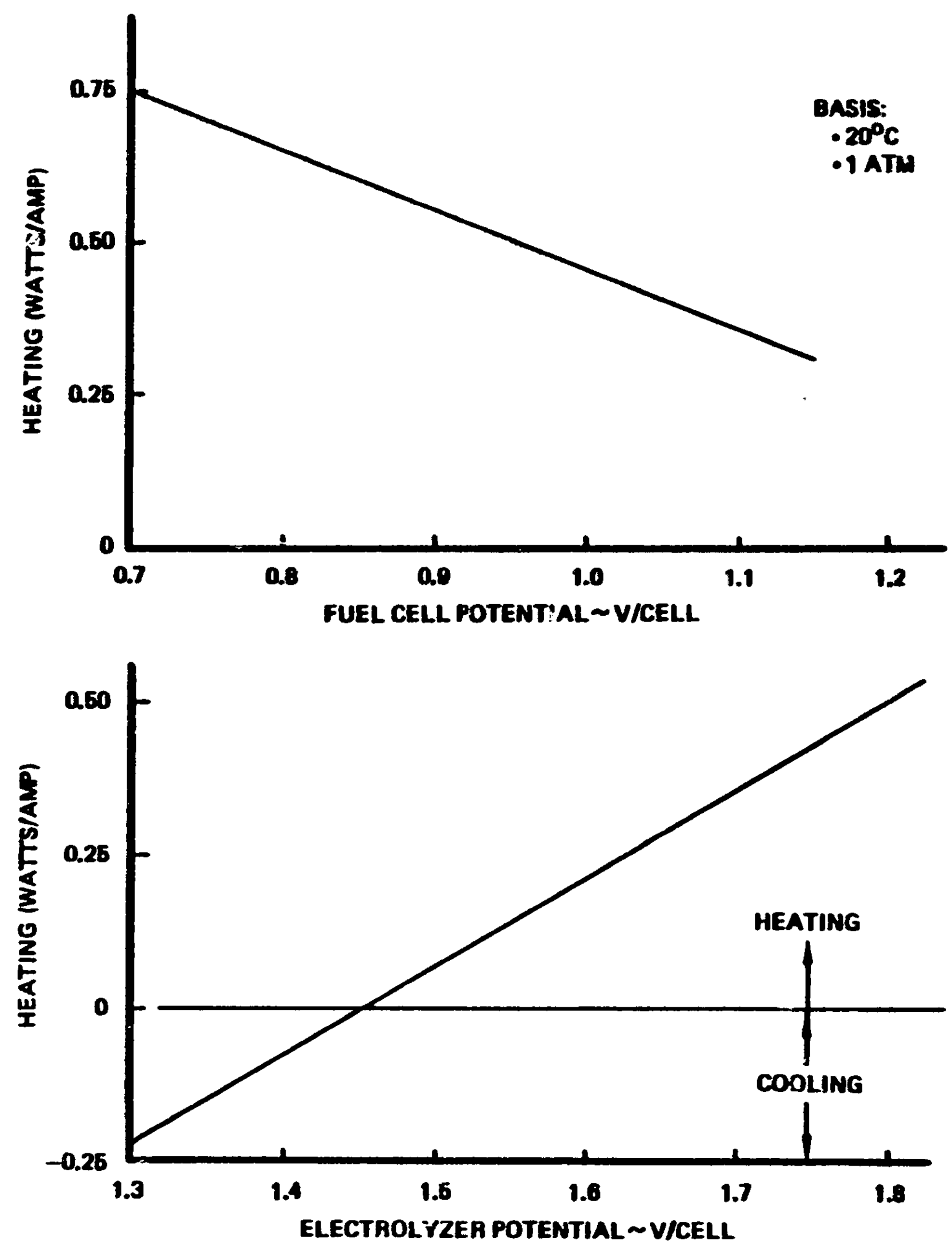

Figure 5.2-1: Heat Generation in Regenerable H_2 - O_2 Fuel Cells

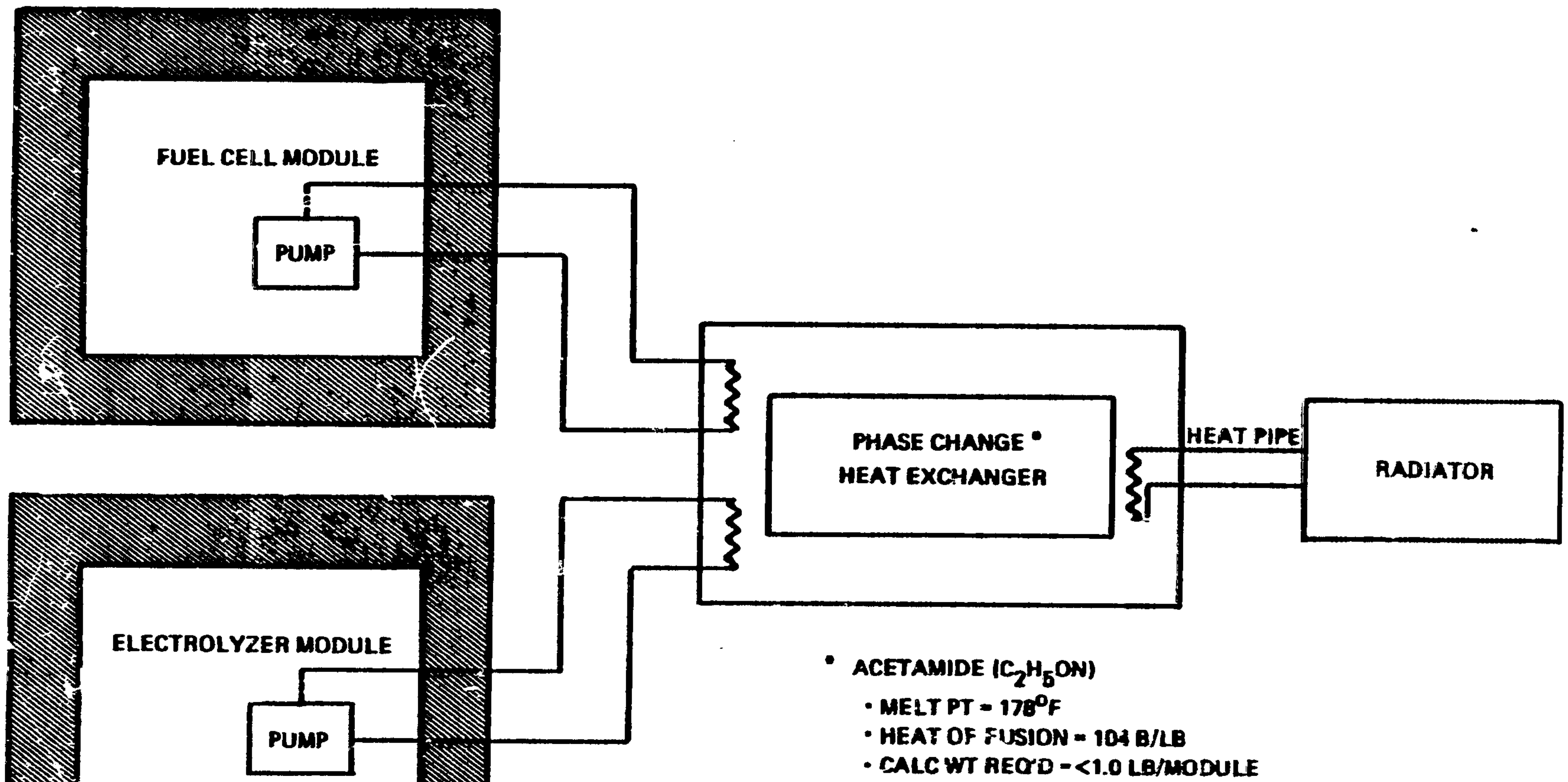

Figure 5.2-2: Fuel Cell/Electrolyzer Temperature Control

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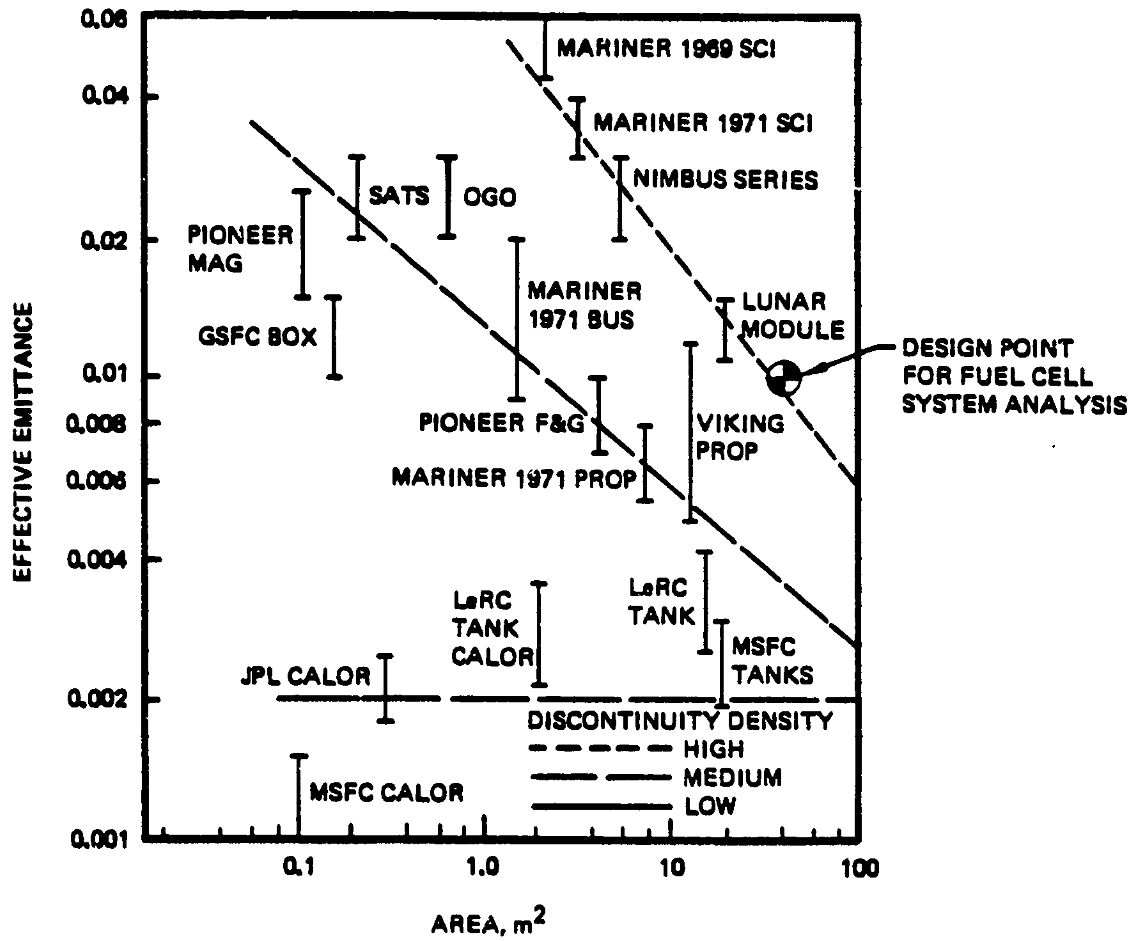

Figure 5.2-3: Multilayer Insulation Performance

Electrolyzers generate a lesser amount of heat, even crossing into the cooling regime when the electrolyzer operates at very high efficiency, corresponding to low voltage.

This imbalance in heating behavior could cause problems with high efficiency designs. In fact, some electrolyzer designs in the past have used relatively high voltages in part to assure sufficient self-generation of heat to maintain proper temperature control. The approach we have taken to this problem is illustrated in Figure 5.2-2. Both the fuel cell and electrolyzer modules dissipate heat to the radiator via a common phase-change heat exchanger. If the electrolyzer requires the addition of heat, it is obtained from the heat storage capacity of the phase change material. Acetamide, having the formula C_2H_5ON, is a good heat transfer material for this purpose, with a melting point of 178°F and a heat of fusion of 104 BTU/lb. Only a few pounds would be required per heat exchanger.

The regenerative fuel cell system is located outside the pressurized compartment in the current packaging concept. Since the units operate at aproximately 185°F, they must be insulated to prevent overcooling, especially the electrolyzer. The insulation concern is not the multilayer insulation itself, which has superb thermal properties, but the effects of penetrations, mountings and other discontinuities. Figure 5.2-3 gives a correlation of the performance of a wide variety of prior multilayer insulation applications, and shows that in the worst case the RFC system may expect to have an effective emittance of 0.01. For a typical system operating at 185°F, this will result in a heat loss of approximately 325 watts. This loss is small compared with the typical system heat dissipation rate of 20 to 30 kW. However, it is comparable to the heat deficit of the electrolyzer for the high efficiency design, which is approximately 250 watts. Though this is entirely manageable, it does point out the need to insulate the electrolyzers especially well to minimize thermal difficulties.

5.3 DRY ELECTROLYSIS GAS

The hydrogen and oxygen product gases from the electrolysis of water will be nearly saturated with water vapor unless steps are taken to reduce its level. If all components in the RFC system could be assured of long term isothermal operation, a high water content in the gases would present no problems. However, variable temperatures in spacecraft are common, and could cause condensation or even freezing of water. Where water electrolysis gases are used for reaction control fuel, the problem could be very severe due to the long piping runs required.

One concept for drying the gases is shown in Figure 5.3-1. Both the wet hydrogen and the wet oxygen gases are cooled in a heat exchanger which is coupled to a radiator by a heat pipe. The condensed water is removed by water separators, and the dried gases are then routed to gas storage tanks via a regenerable heat exchanger to improve the thermal efficiency of the process. The water collected will be saturated with oxygen and hydrogen gases, so a catalytic deoxidizer unit is provided to combine these gases.

Though removal of water by condensation should be feasible, the process is somewhat complex. An alternative approach is shown in Figure 5.3-2. Water is electrolyzed into wet oxygen and wet hydrogen. These gases then continue into a water vapor electrolyzer, which may either be a separate unit or a final stage of the electrolyzer. Though it is feasible to electrolyze water vapor, this technology is not yet available. The major problem expected is not the ability to do electrolysis itself, but proper control of the process.

The RFC system studied for the SOC presumed the use of a condensation system for water removal. A water vapor electrolyzer would have been preferable, but the technology is not available. Hopefully this technology will be developed in the near future.

5.4 EMERGENCY POWER

The designs previously described meet the e ergency requirements defined in Section 2.0. In emergency mode "A" the loss of one of the two solar array wings was hypothesized. In Emergency mode "B", it was hypothesized that the solar array orientation control was damaged, resulting in cyclic power input from the array. In emergency mode "C", full solar array power loss was presumed for one full orbit.

Total loss of solar array power for durations much longer than one orbit is considered extremely remote. Nevertheless, the SOC would have provisions for an all-out survival emergency of 21 days. Electrical loads have not been determined for this emergency, but would be an absolute minimum and are expected to have a total energy

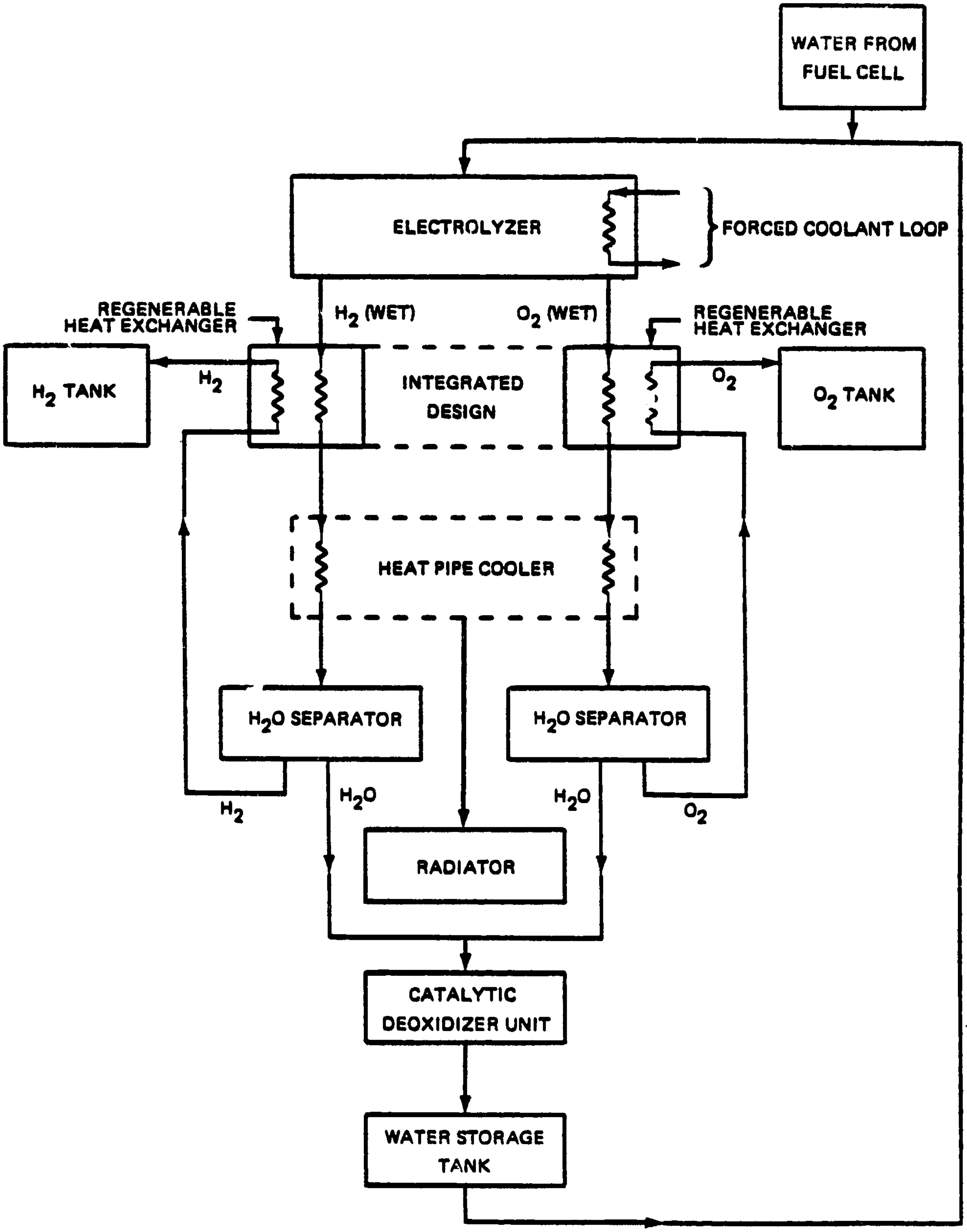

Figure 5.3-1: Concept for Water Removal by Condensation

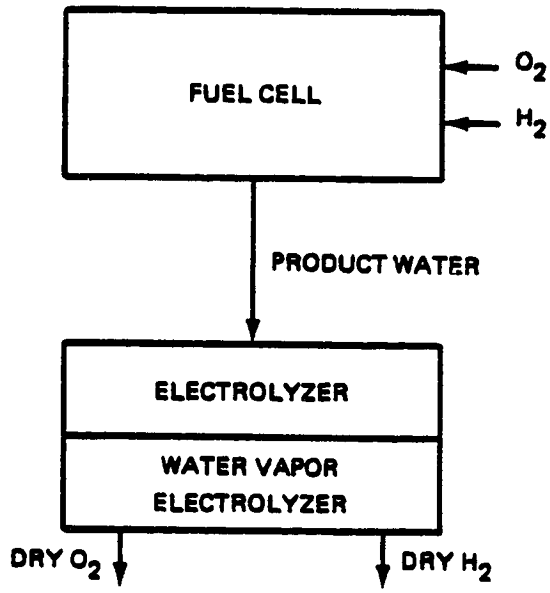

Figure 5.3-2: Electrochemical Concept for Water Removal

demand less than the stored energy for the other emergencies defined. The 21 day duration is based on the expected time required to effect a rescue.

Because of the emphasis required on safety, it may be worthwhile to provide additional stored energy that would either extend the all-out emergency duration beyond 21 days, or require a higher power level than that for an extended time. It is judged that it would be appropriate to provide an additional 10-day emergency supply of continuous power at 1.5 kW. The RFC system has excellent capability for such emergency power, especially when integrated with the orbit makeup reactant system. Orbit makeup can be delayed up to 60 days, so the hydrogen and oxygen gas for orbit makeup can be available for emergency power use. Tankage weight is the major penalty required.

High pressure gas storage on the order of 2000 psi is preferred to minimize tank volume. This will require use of an electrochemical oxygen pump, which is needed anyway for life support oxygen, and an electrochemical hydrogen pump, which would weigh about 65 lb. Based on the requirements shown in Figure 8.1-2 the design for this additional emergency would require approximately 965 pounds, as follows:

Gases Required	Oxygen	Hydrogen	Sub Total
Reactants for fuel cells	350	50	400 lbs
Oxygen for life support	173	—	173
Total	523	50	573

Weight Penalty	Power	Life Support
Oxygen tank — power	420	—
Oxygen tank — life support	—	208
Hydrogen tank	480	—
Hydrogen gas compressor	65	—
Total	965 lbs	208 lbs

5.5 ENERGY STORAGE INSTALLATION COMPARISON

An installation configuration was developed to show the main features of a regenerable fuel cell energy storage system as compared to a nickel-hydrogen battery system. Figures 5.5-1 and 5.5-2 compare the two installations on the service module design that comprised a part of the SOC space station concept. This service module was one of two in the complete SOC configuration and supplied half of the total electric power used by the SOC - 25 kW on the sunlit portion of the orbit and 20 kW on the dark side. The reference SOC configuration is shown in Figure 5.5-3.

The battery version of the system utilized large numbers of individual Ni-H_2 cells organized into batteries. Details of the battery installation were not developed. The battery boxes shown represent the volume required for the battery installation.

The fuel cells and electrolyzers can be either of new design or derivatives of the shuttle systems. Two RFC packages are installed on each service module, one on each side. Gas and water storage tanks and a box representing the appropriate power electronics volume are also shown.

The gas tanks shown are low-pressure tanks with a maximum pressure of about 100 psia. The mass-optimum pressure for tank design is about 500 psia (3500 kpa) as shown in Figure 5.5-4. The configuration was drawn with low-pressure tanks to emphasize that packaging considerations will not force the use of high pressures.

5.6 DESIGN SUMMARY

Three regenerable fuel cell designs were prepared for the SOC because each design has its own special merit. It is judged that the high efficiency design is the most worthwhile, so that design is used in this summary. Note that engineering data on that design is provided with in Figure 5.1-3. The weight summary is as follows:

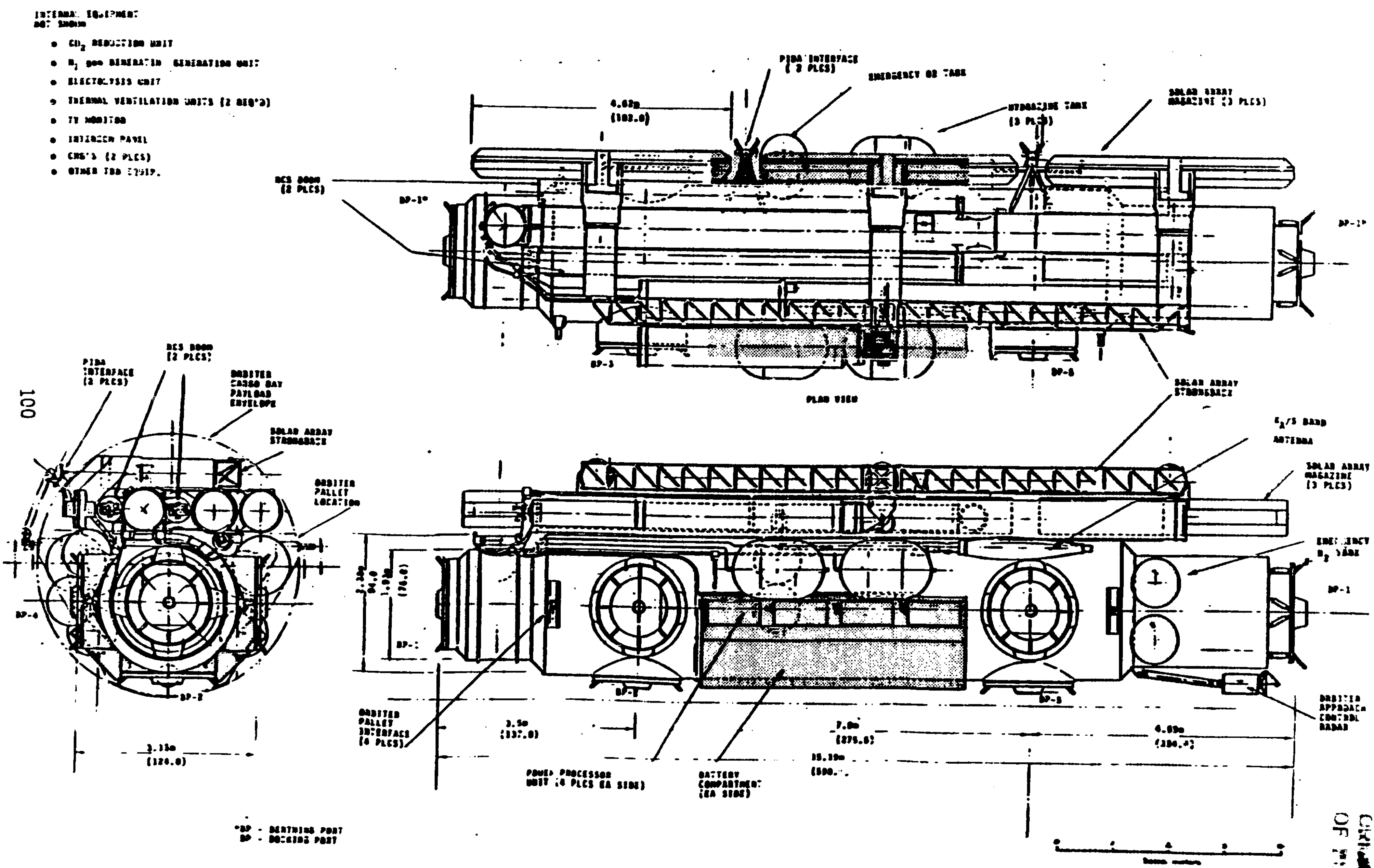

Figure 5.5-1: Service (Packaged Configuration)

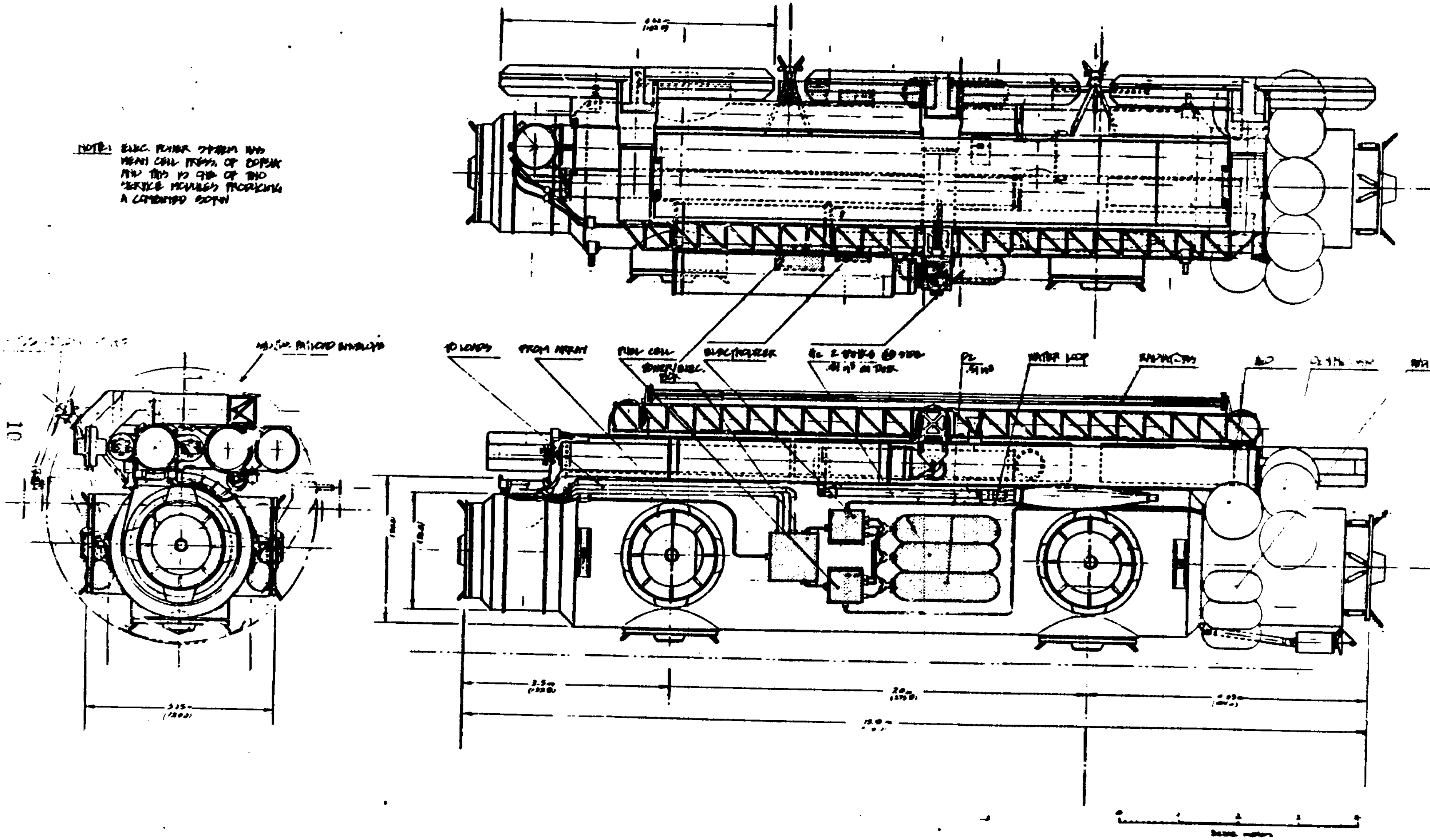

Figure 5.5-2: Electrolyzer Fuel Cell

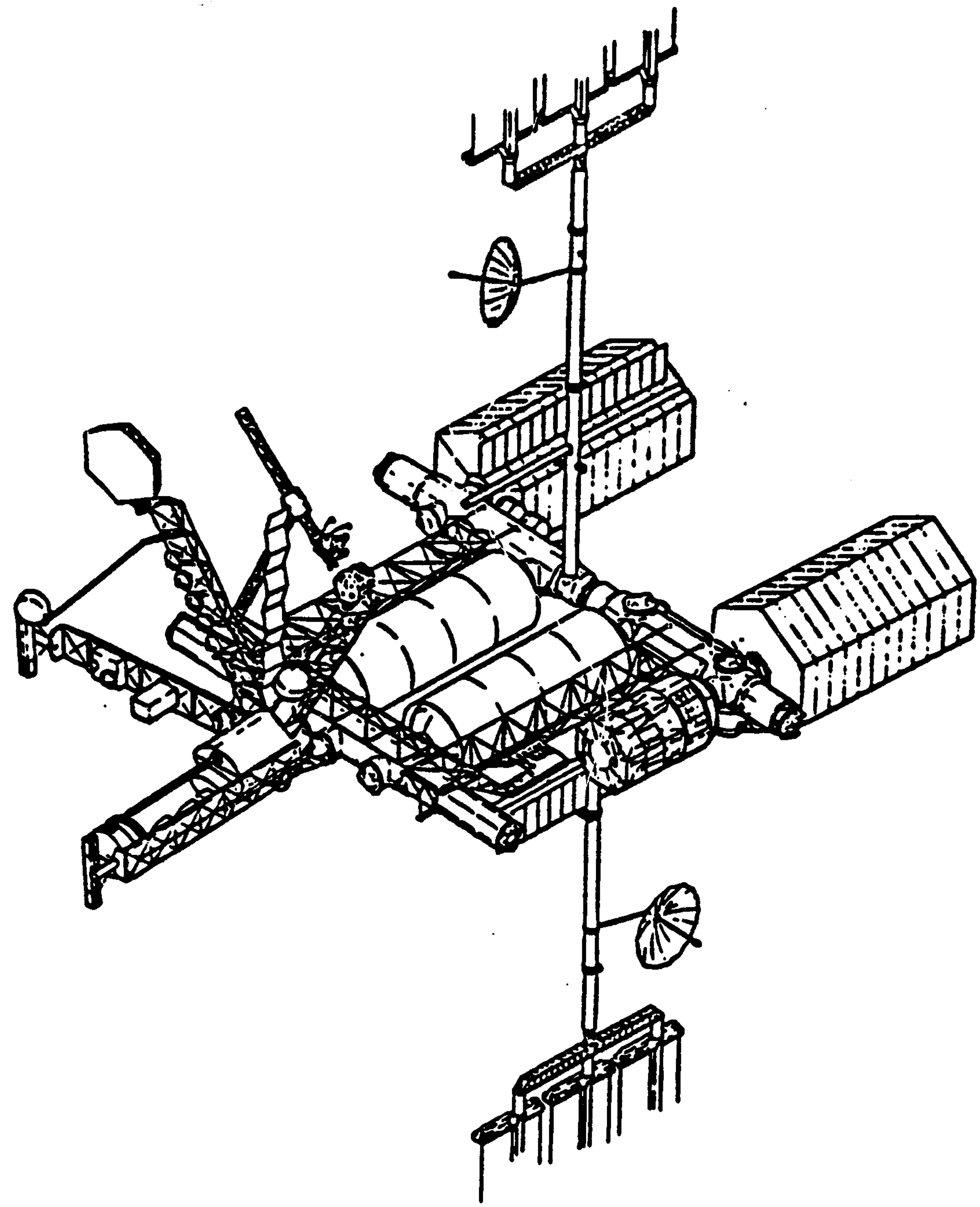

Figure 5.5-3: Reference SOC Configuration (2 Service Modules)

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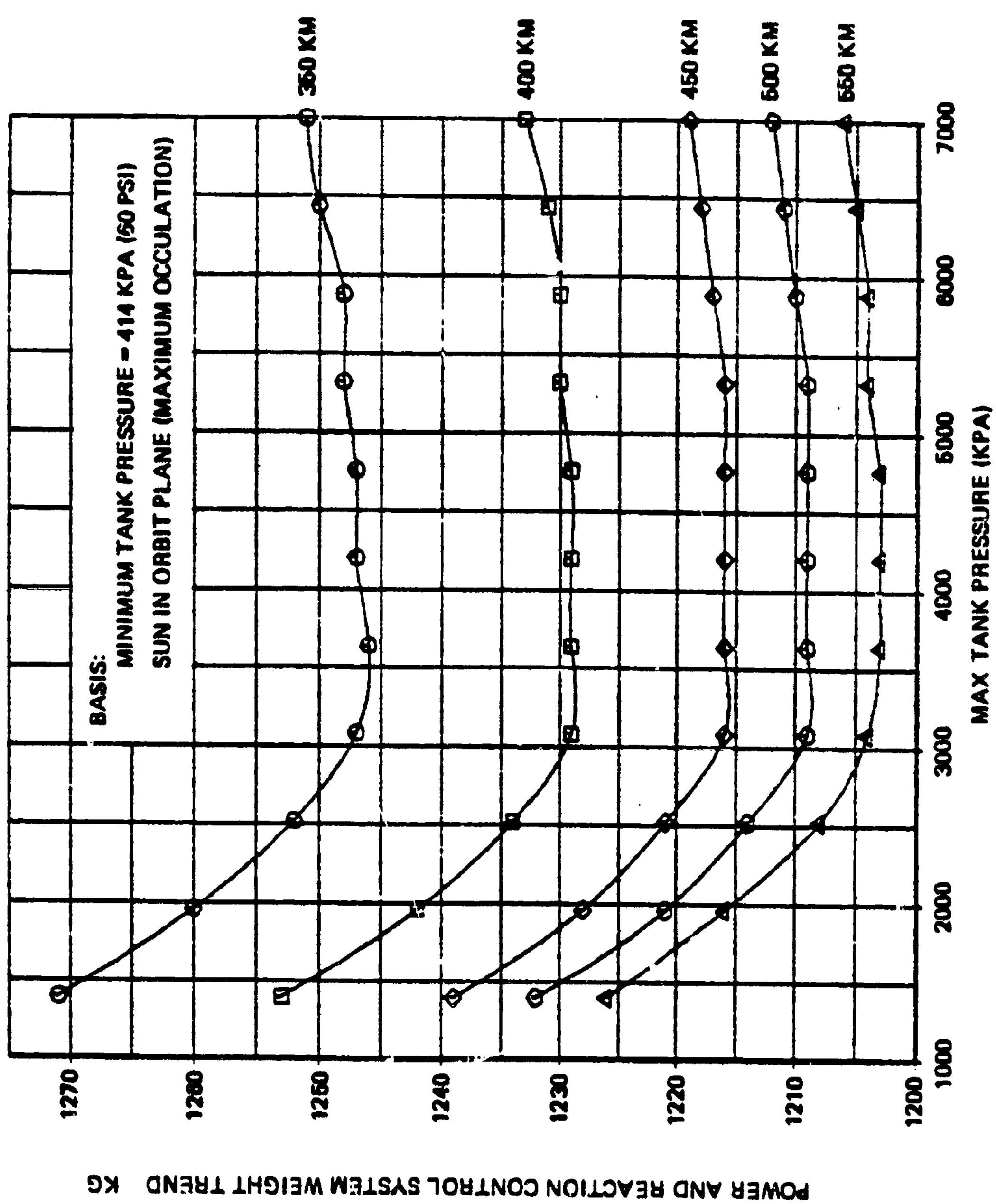


Figure 5.5-4: Typical Optimization of Initial Tank Pressure

62% efficiency regenerable fuel cell system (without solar array)	4796 lb
10-day emergency power and life support oxygen system	965
Total	5761 lb

Due to the low current density used, a fuel cell manufacturer has estimated fuel cell life to be about 10 years; electrolyzer life is assumed to be comparable. Life of ancillaries is estimated at 3 to 7 years, based on the range of life estimates made in recent studies of the RFC system, and discounting the 1.1 year pump life value as discussed previously.

A weight comparison with $Ni\text{-}H_2$ batteries is of interest. These batteries, without the 10-day emergency power system, based on a system energy storage efficiency of 55 percent, and a 35 percent depth of discharge, results in a total weight penalty of approximately 5865 lb. This compares with 2418 lb for a 55 percent efficient RFC system, or 4796 lb for a 62 percent efficiency RFC system.

6.0 ASSESSMENT OF HYDROGEN-HALOGEN REGENERATIVE FUEL CELL SYSTEMS

6.1 INTRODUCTION AND SUMMARY

Relatively little serious consideration has been given to the possible role of hydrogen-halogen regenerative fuel cell systems in future spacecraft. Contending systems are the hydrogen-bromine system and the hydrogen-chlorine system. Because of the toxicity of bromine and chlorine, our first impression was that these systems could not survive the strict requirements on personnel hazards. However, space station studies on the SOC showed that it would be preferable for any energy storage system, whether batteries or fuel cells, to be installed outside the manned compartments. A second concern was that suitable materials might not be available for use with these highly corrosive materials, especially bromine. However, we determined that carbon-fiber composites and other composites appear to be suitable. Thus, toxicity and materials are much reduced as concerns, and so these systems can be given serious consideration.

The natural competitor to hydrogen-halogen systems would be the hydrogen-oxygen system, which has a long successful history and has useful integration advantages. The question then arises as to where might the hydrogen-halogen system have a useful advantage? Possible answers are in the improvement of weight, efficiency, life, or reliability. As it turns out, it is the efficiency which offers a principal advantage, and this is reflected primarily as saving in solar array size. In this respect, the hydrogen-halogen systems are unique, for with a few exceptions, no other fuel cell or battery system has the potential for as high an efficiency as do the hydrogen halogen systems. Whether this unique advantage is significant to warrant R&D on these systems then becomes the key question with these systems.

6.2 ANALYSIS OF HYDROGEN-HALOGEN SYSTEMS

The good reversibility of the hydrogen-bromine system has long been known. Development had been hampered by the lack of suitable membrane separators, however. With the development of solid polymer membranes such as those from the NAFION family, laboratory work has been performed which characterizes these systems, and their development for aerospace applications can be entertained. The hydrogen-chlorine electrolyzer has been applied commercially, and full system demonstration tests have been conducted on both systems. However, other commercial applications have not appeared. General Electric is the developer of these systems.

Hydrogen-bromine cells use a solid polymer electrolyte which can function either in the discharge mode or the electrolysis mode. The conservative design approach, however, would be to use a separate discharge module and electrolysis module. Figure 6.2-1 shows the electrolysis/discharge characteristics of these cells. The significant difference between this behavior and that of the hydrogen-oxygen system is that the electrolysis/discharge voltage difference approaches zero at zero current density for hydrogen-bromine. It is this voltage difference which gives rise to system inefficiency (other than ancillary power). Thus, the ideal system efficiency approaches 100% as current density approaches zero.

Figure 6.2-2 shows the electrolysis/discharge characteristics of the hydrogen-chlorine system. The behavior is similar, being linear with current density and approaching zero voltage drop as current density approaches zero. The reversible voltage (voltage at zero current density) is a little higher, however.

The efficiency of these systems, excluding ancillaries, is shown in Figure 6.2-3. The significant feature is that extremely high efficiency is attainable at low current densities. It is not known whether there is any significant cross-diffusion of hydrogen and halogen through the solid electrolyte; this would cause a current inefficiency and reduce overall efficiency. Also shown for comparison on this figure is some typical performance of the advanced high temperature hydrogen-oxygen fuel cell using solid ceramic electrolyte, under development by Westinghouse. This system also approaches 100 percent efficiency as current density approaches zero, and is one of the few other systems to do so.

With all battery systems, the reversible voltage varies a little with concentration of the electrolyte, the temperature, and variations in other constituents in the cell. With most systems, the voltage sensitivity to those effects is so slight that it is usually is of secondary importance. With the hydrogen-halogens, however, these are major effects and show up strongly in voltage regulation for any application. Figure 6.2-4 shows the dependence on acid concentration; as the cells are discharged, more acid (HCl or HBr)

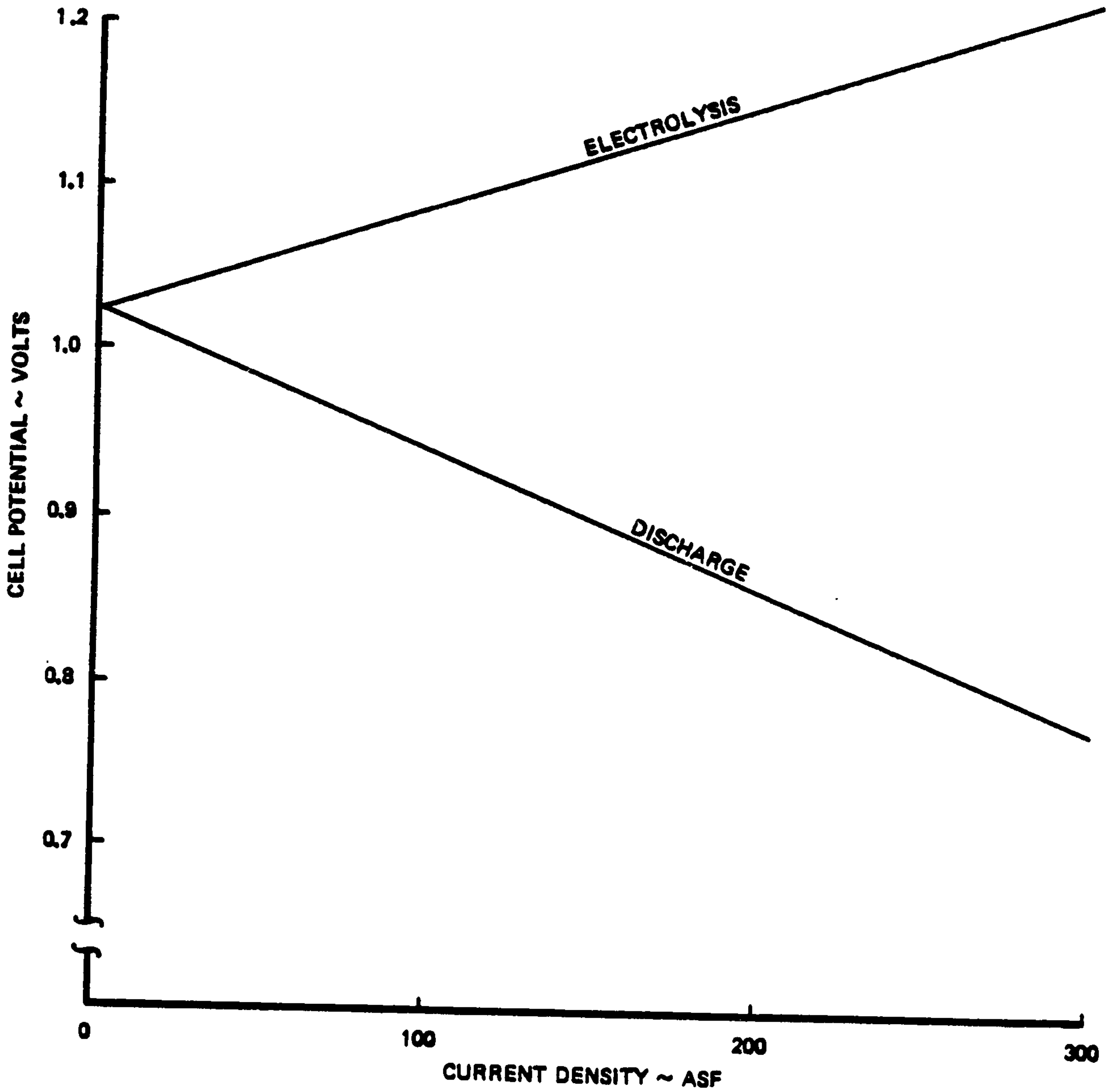


Figure 6.2-1: Performance of Regenerable Hydrogen-Bromine Fuel Cell

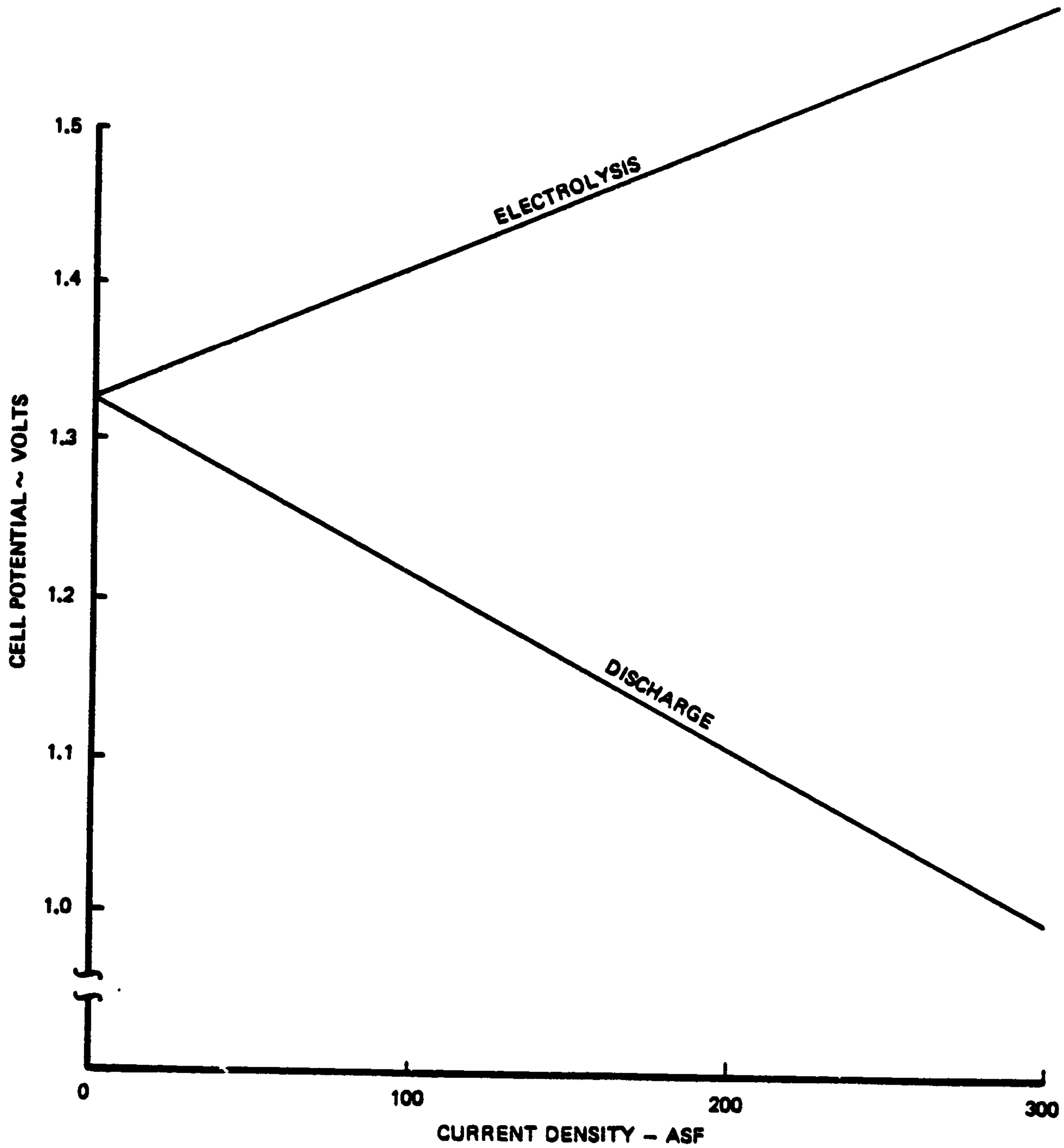


Figure 6.2-2: Performance of Regenerable Hydrogen-Chlorine Fuel Cell

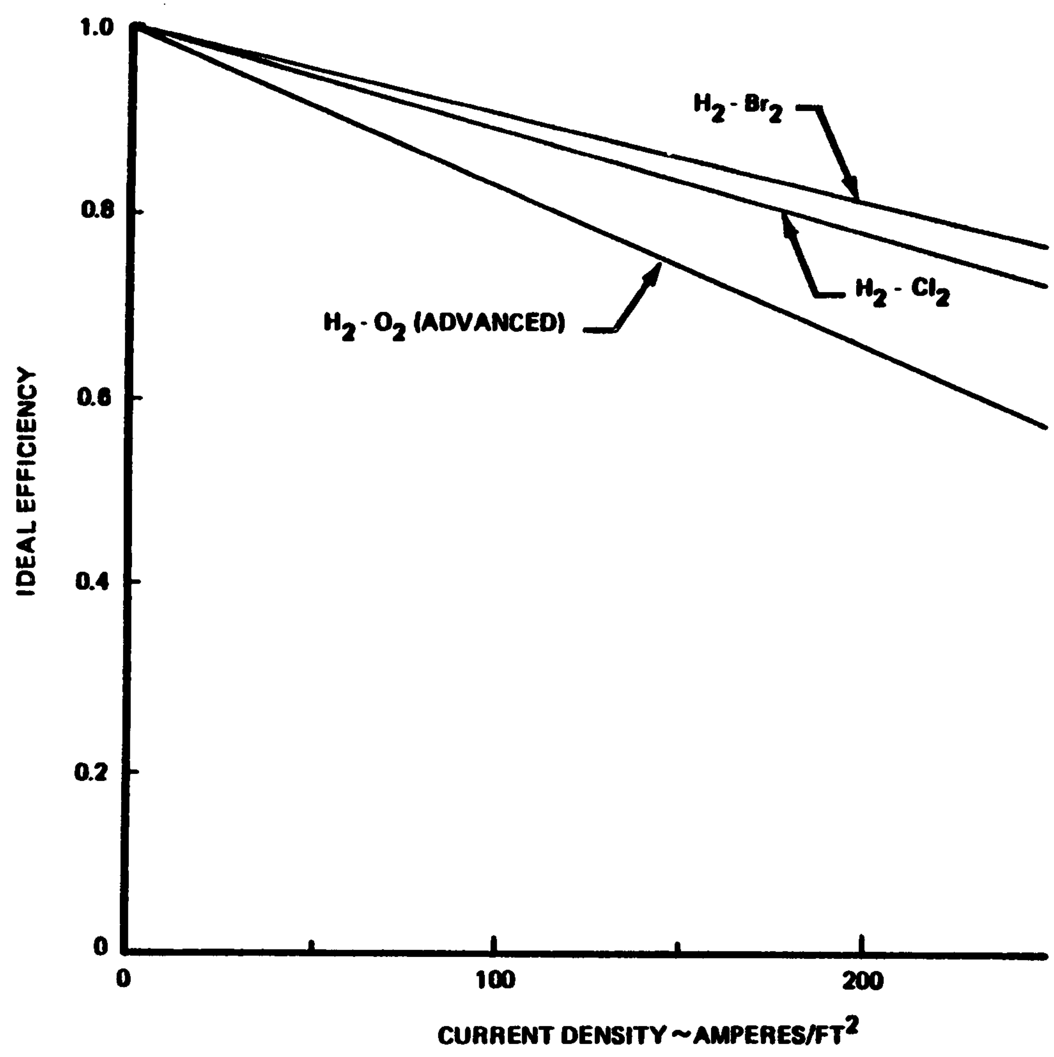


Figure 6.2-3: Efficiency of Regenerable Fuel Cell Systems

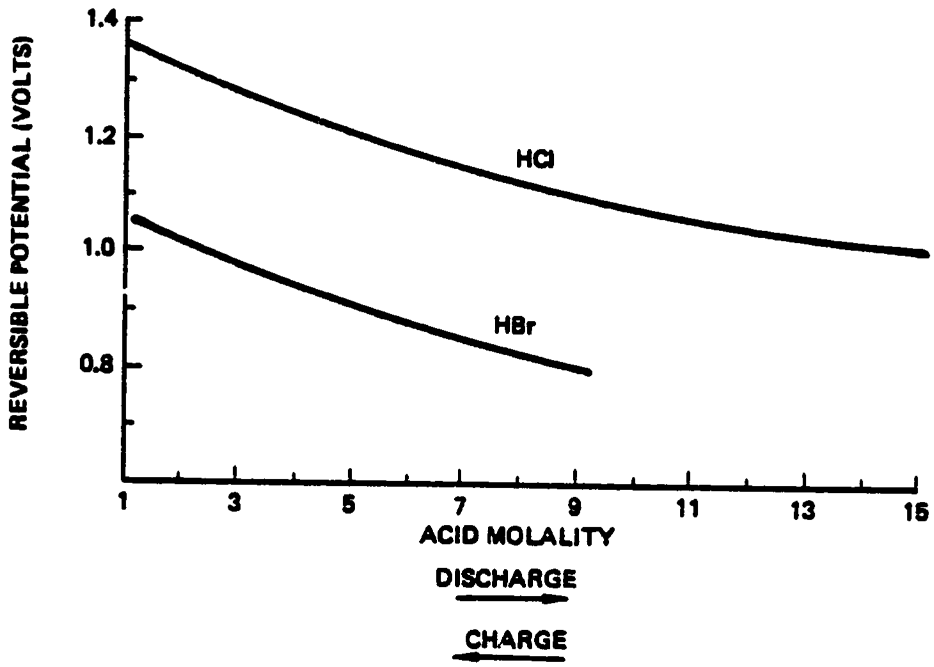


Figure 6.2-4: Halogen Fuel Cell Voltages Depend on Acid Concentration

is formed, increasing its concentration, and lowering the reversible voltage. The hydrogen-chlorine cell is especially sensitive to temperature as well, as shown in Figure 6.2-5. Since temperature will typically rise during discharge, the lowering of voltage with increased temperature intensifies the lowering of voltage with increasing acidity, which also occurs during discharge. However, the strong sensitivity of temperature and voltage can lend itself to an apparant increase in efficiency if enough heat is added during electrolysis to raise the temperature. This is shown in Figure 6.2-6, and is a concept that can be considered only where thermal energy is readily available or surplus. Of course, this extra heat energy must be removed during discharge, so a good heat sink must also be available. This unique property might be exploited in certain special applications, but is unlikely to find general use for spacecraft.

One approach that has been tested with hydrogen-bromine regenerable fuel cells is the use of hydride storage for the hydrogen. This allows low volume for the hydrogen, and has proved to be satisfactory during Boeing tests of this system. An analysis was therefore made of the effect of hydride storage on system efficiency, since system efficiency is known to be very important for the space station. The results of the analysis are shown in Figure 6.2-7 for hydrogen-bromine. With gas storage of hydrogen, the major loss (ancillary losses were not considered) is due to electrode polarization, which increases with current density. With hydride storage, there is always an additional loss because energy must be applied to the hydride bed to drive out the hydrogen. A further loss with hydride storage is the fact that the hydride bed efficiency is not 100 percent, in that all of the heat provided does not go into the hydrogen molecules, but some goes into the bed material. Hydride storage with the hydrogen-chlorine system is shown in Figure 6.2-8 and shows behavior similar to that of the hydrogen-bromine system. It is concluded from this analysis that hydride storage is not worthwhile for space stations because of the significant reduction in efficiency that results.

6.3 ASSESSMENT

Hydrogen-halogen systems offer the possibility of obtaining higher energy storage efficiency than with batteries or regenerable hydrogen-oxygen fuel cells. Theoretically, these systems could save up to about 20 percent of the solar array size compared to a high efficient (60%) battery or RFC system. The practical upper limit

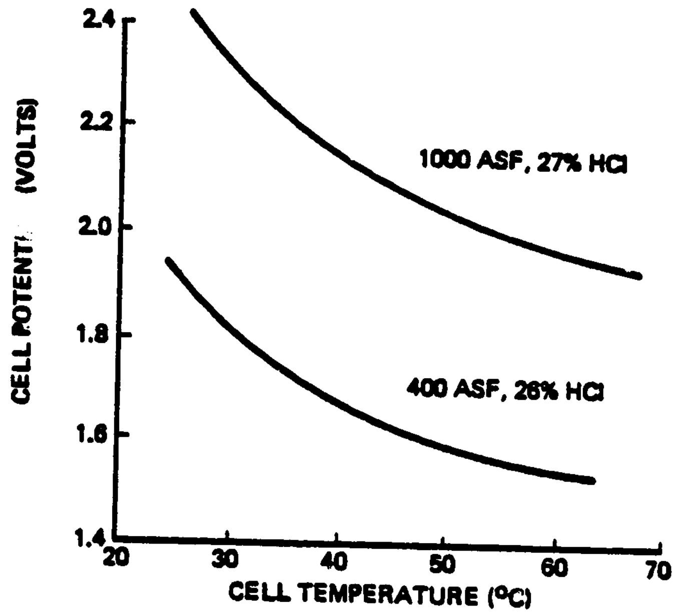


Figure 6.2-5: H_2-Cl_2 Fuel Cell Voltages Depend Strongly on Temperature

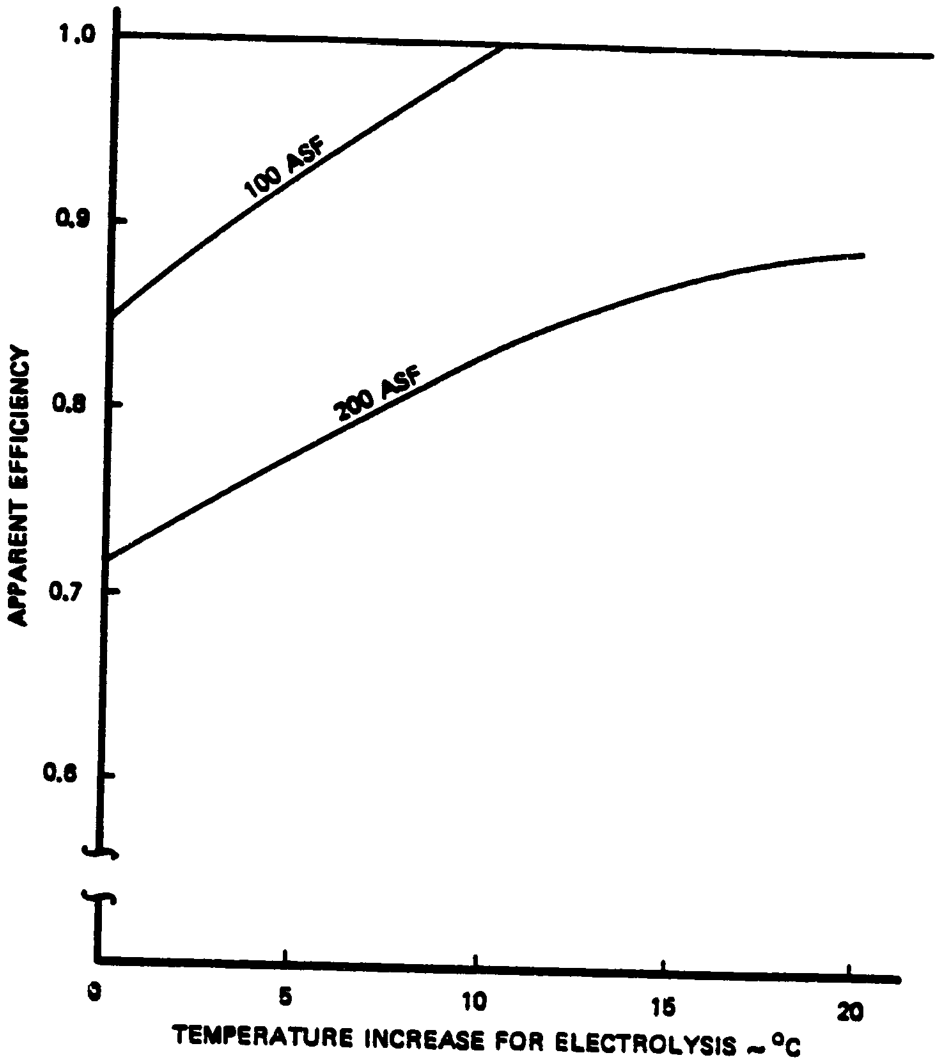


Figure 6.2-6: Efficiency Improvement by Heat Addition in Regenerable $H_2 - Cl_2$ Fuel Cells

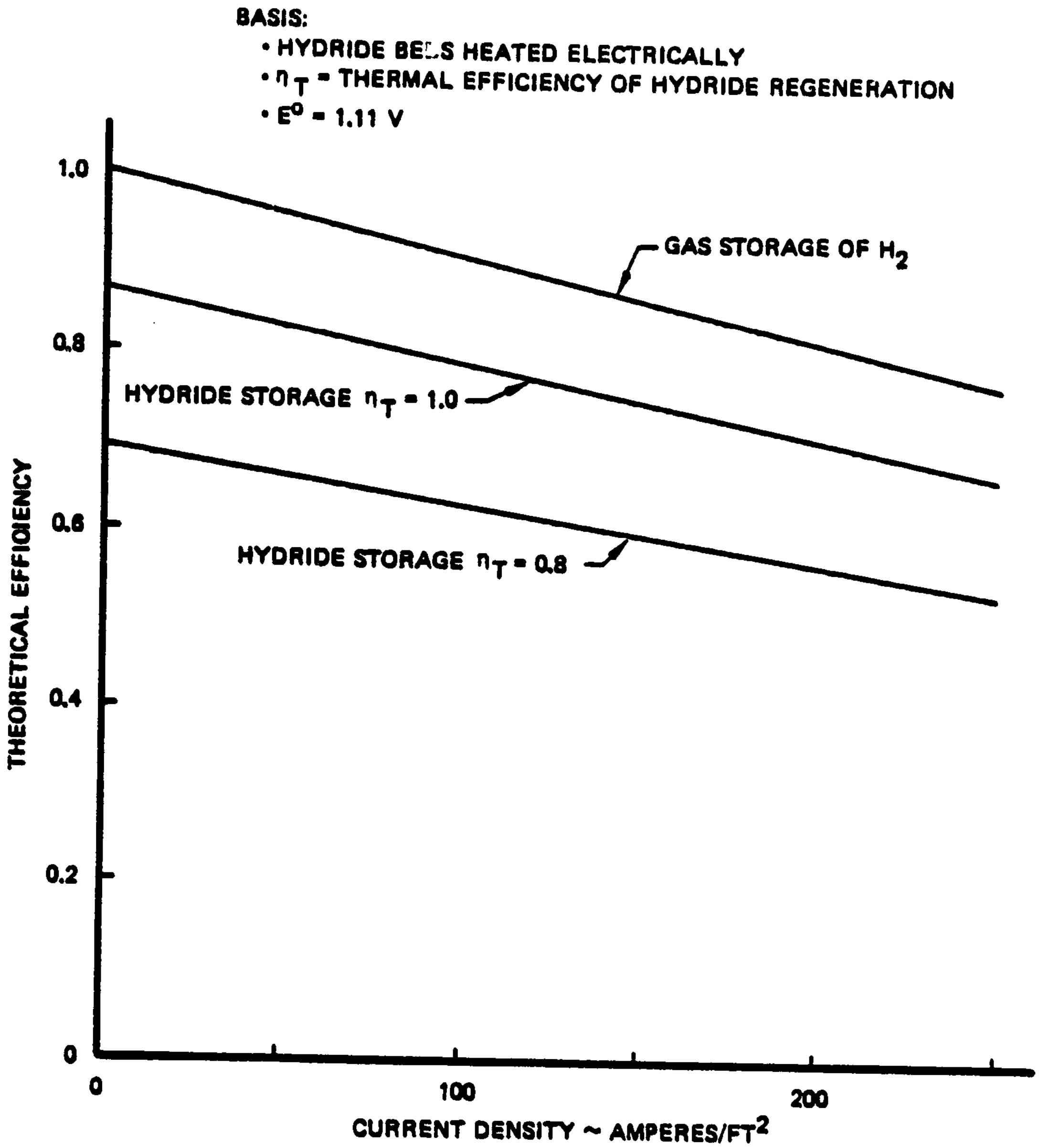


Figure 6.2-7: Efficiency of $H_2 - Br_2$ Regenerable Fuel Cell Systems with Hydride Storage of H_2

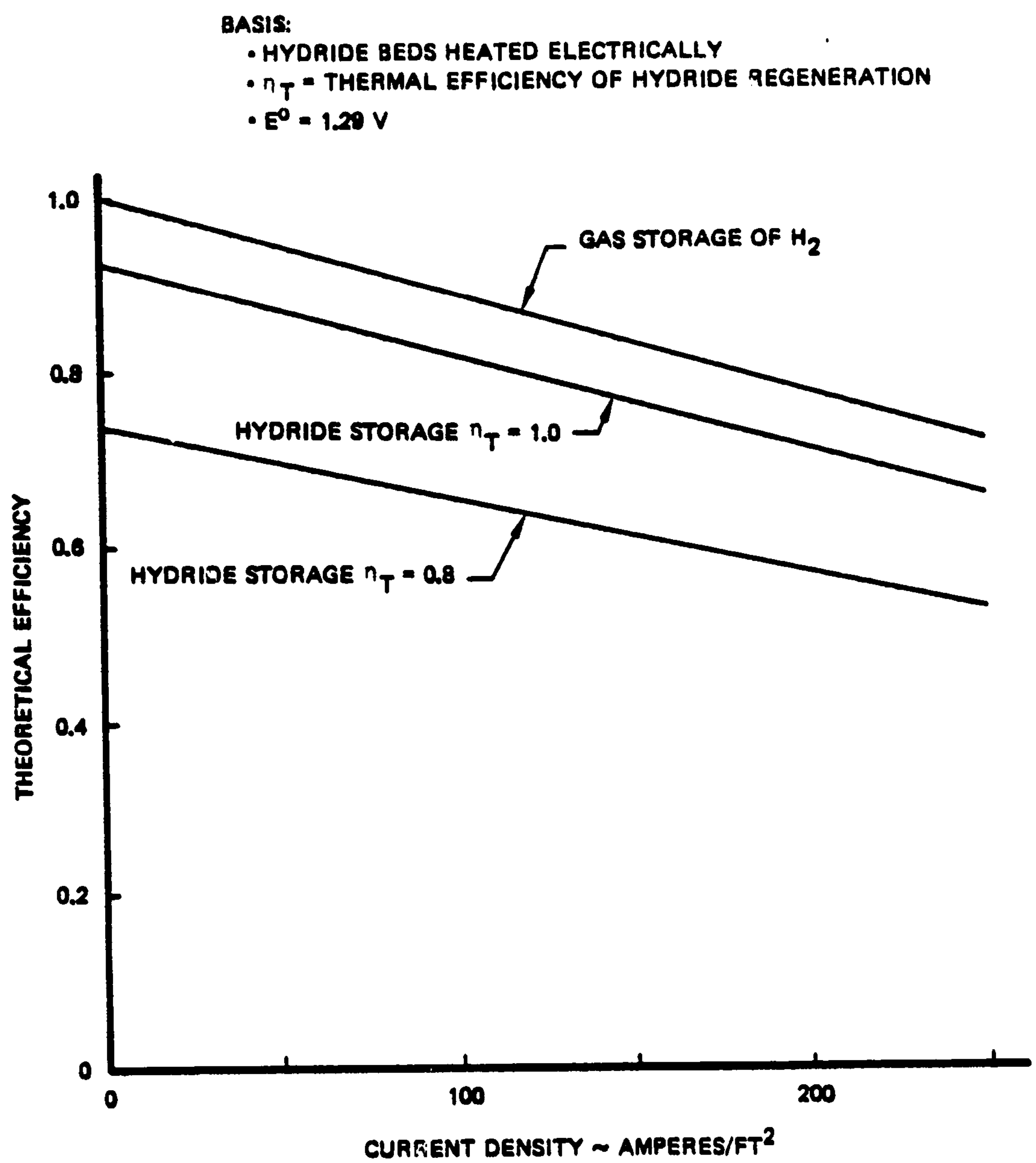


Figure 6.2-8: Efficiency of $H_2 - Cl_2$ Regenerable Fuel Cell Systems with Hydride Storage of H_2

is expected to be a 15 percent saving. Low current density designs are needed to obtain the high energy storage efficiencies to permit such savings in solar array size. It is unknown what weights might be required, what realistic efficiencies might be obtainable, and what serious technical problems, if any, there might be with such new systems. The fact that successful tests have been run on both systems shows that at least the systems do work; in the case of the hydrogen-chlorine system, the electrolyzer portion is highly successful, and this technology has been reduced to commercial practice.

It is concluded that the potential for high energy storage efficiency is sufficiently important that some follow-through should be carried out with these systems. This work should include attempts to better define realistic overall efficiency. There is not sufficient information now to make a good judgement as to which of the two systems holds the most promise. An answer to that question should also be obtained on any future work done with these systems.

7.0 TECHNOLOGY ADVANCEMENTS

This section summarizes the technology advancements foreseen in the near future which could affect the choice of the energy storage system for SOC.

7.1 NEW SYSTEMS

The number of new battery systems under investigation and development is considerable. However, the requirements for low earth orbit spacecraft batteries are very demanding — many cycles, high charge and discharge rates, and high energy density. Thus, the number of candidates with promise is very much reduced.

A serious problem with new undeveloped systems that show promise is the very long amount of time needed to develop a system to the point that it is usable. Fifteen years is typical for commercial practice, and longer time is often required for aerospace applications. The nickel hydrogen battery was invented in 1958, and development in the U.S. started in the late 1960's. This concept was based on the use of existing nickel electrodes from nickel cadmium technology, and existing hydrogen electrodes from fuel cell technology. Yet, the system is only now just beginning to be ready for aerospace use for GEO, which is much less demanding than LEO.

Because of long lead times needed, existing battery and fuel cell systems will command the most attention. The principal competitors are nickel cadmium batteries, nickel hydrogen batteries, and hydrogen-oxygen fuel cells. Before dismissing all other systems, however, brief mention should be made of ambient temperature lithium batteries and high temperature batteries, both categories of which have attracted much interest as possibly the next generation of high performance secondary batteries for aerospace.

In the case of secondary ambient temperature lithium batteries, there is little to support these hopes except the strong desire based on the good energy density of primary lithium batteries. We need 5800 cycles per year, and the lithium electrode is capable of about 250 cycles. We need high charge and discharge rates, and the ambient temperature lithium systems are low rate systems. We need one single data point or analysis that shows promise, and we have none.

In the case of the high temperature systems, there is more chance of success, but even that is problematic. The basic problem is that the weaknesses and failings of the high temperature systems coincide precisely with those criteria which are of the greatest importance in aerospace energy storage: long life, high reliability, high charge and discharge rate capability, and high efficiency. The geo-synchronous application feels the pressure of weight much more than does the LEO case, and many fewer cycles are needed. Thus, the GEO application is more likely to be developed and used first, as has been the case with nickel-hydrogen batteries. After success has been achieved for GEO, then we may expect greater interest in applying this to LEO.

7.2 NICKEL HYDROGEN BATTERIES

The status and problems of nickel hydrogen batteries are discussed in other sections of this report. In general, they have good promise, but the demonstrated life has not yet been satisfactory for LEO, and the demonstrated energy storage efficiency after long cycling is not high. Work is continuing on improvement of this system, with efforts focusing primarily on development of large cells or multiple cells in one container in order to reduce weight and cost. Greater concentration on the life problem will be needed for space station use, for the system will see little use until the life issue is settled.

The Air Force has a program on nickel hydrogen cells (Ref. 14) that is multi-faceted, and this is improving the Ni-H_2 technology in several areas Computer programs have been developed to examine design variables, and these permit rapid focusing on the best designs. Yardney Corp. has a manufacturing technology program, one of the objectives of which is to develop cost reduction approaches. A common pressure vessel design program with Hughes should improve weight energy density about 20 percent over the conventional individual pressure vessel, and will also reduce volume; capacity will be extended to 150-AH, and there are expectations that cost will also be reduced.

A novel development underway at NASA Lewis Research Center has taken a fresh approach to the problems of nickel hydrogen cell design, and initial results show very good promise (Ref's. 15 and 16). This design uses bipolar construction in a common pressure vessel, and has a projected energy density of 20-24 W-hr/lb. It resembles a fuel cell system more closely than a conventional battery, having active cooling, a separate catalyst surface for oxygen recombination, and an electrolyte management design which gives excellent electrolyte volume tolerance. This modular concept has been tested, resulting in exceptionally uniform cell-to-cell voltage, and a watt-hour efficiency of 81 percent. The internal resistance is very low, and permits very high peak power. This unique approach with bipolar construction has improved thermal and oxygen management, and shows promise for low weight, good electrical performance, and low cost.

With the nickel hydrogen system there is the possibility that the present life and reliability uncertainties will soon be resolved and verified by life tests. It is possible that would happen before verification could be obtained on the RFC system. When the time for decision comes, the system that is ready and has demonstrated life could easily win out over other systems that are not ready.

7.3 REGENERABLE FUEL CELL SYSTEMS

No major technology advancements in the RFC system are visualized in the near future that would affect the choice of an energy storage system for SOC. Technology improvement programs are underway with both the alkaline electrolyte and the solid polymer electrolyte systems, but these are expected to result in gradual improvements rather than large jumps. It is expected that a full systems test of the RFC system will be conducted in the near future, and this will provide data needed for confidence in the system. Proof is needed that the major components can be made to work together as a system.

Advances are being made in understanding the life-limiting effects with the alkaline system. The identification of carbonate build-up with time as being a life-limiting cause is a significant finding. Initial tests on potassium titanate as a substitue matrix material have shown no loss of performance with time so far, thus suggesting that this material has the potential for very long life.

Another area that could be meaningful would be the development of reliable static methods for control of water, humidity, and perhaps other processes, thus placing less reliance on dynamic equipment. Ancillaries probably are more prone to fail than the fuel cells or the electrolyzers, and improvement of ancillaries could make a significant improvement in overall system life and reliability.

7.4 NICKEL CADMIUM BATTERIES

No major technology advancements in the nickel cadmium battery technology are visualized in the near future that would affect the choice of an energy storage system for SOC. Very little research is being devoted to this system, although the knowledge that is being gained on the nickel electrode for nickel hydrogen batteries should eventually have a beneficial effect on nickel cadmium batteries.

There are two additional developments gradually being implemented that will improve nickel cadmium battery performance over what has been seen in the past. The first of these is the development of variable conductance, heat pipe-cooled battery mounting plates. This will allow batteries to be cooled to a constant temperature nearly irrespective of the environment, degradation with time, or changes in battery load. Temperature control has often been a problem for batteries in the past, for nickel cadmium batteries are highly temperature sensitive.

The second development, especially with large power systems, is in the use of sophisticated, computer-based control and diagnosis, including charge control. Sophisticated logic and large memory can be readily available at low weight, and there will be little need to compromise the design or system operation in large power systems of the future.

Although the Ni-Cd battery system is not expected to make major technology advances, it still has attributes that could prove significant in selection of the energy storage system for space stations. First, it is available and proven, and considerable data are accessible on its life and performance. Second, the initial cost of the system is low, and depending upon possible funding constraints and mission duration, this could be more important than the total life cycle cost. If the life of the Ni-Cd system could be significantly improved, using, for example, advanced nickel electrode technology, then it is possible that the Ni-Cd system could be a formidable competitor to the Ni-H_2 and RFC systems for space station energy storage.

8.0 EVALUATION OF INTEGRATION WITH OTHER SUBSYSTEMS

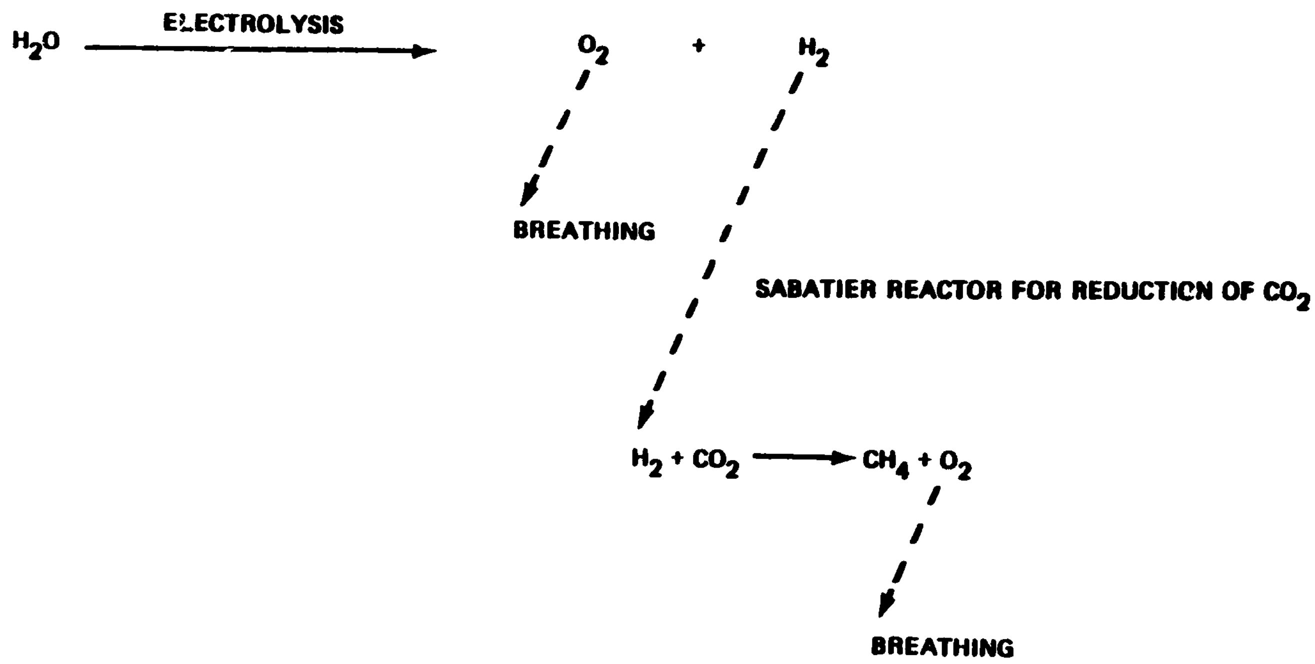
8.1 INTEGRATION OPTIONS AND REQUIREMENTS

The baseline SOC reaction control system for orbit makeup uses hydrazine. An alternative to this is to use hydrogen-oxygen propellant either as separate gases or as transported water which would be electrolyzed on board. The life support system also uses water, oxygen and hydrogen, and these gaseous systems can be integrated with the hydrogen-oxygen regenerable fuel cell system. An additional possibility is the use of primary fuel cells for power, using hydrogen and oxygen from shuttle residuals; this fuel system can be integrated with the reaction control system.

The life support system can employ water electrolysis to provide oxygen needed for breathing and hydrogen needed for reduction of CO_2 in a Sabatier reactor. The requirements for this are summarized in Figure 8.1-1. Typically 17.8 lb/day of water will be electrolyzed, but this can increase during extra-vehicular activity (EVA) to 20.2 lb/day. High pressure oxygen is also needed intermittently for EVA use.

The Full SOC vehicle without a solar array is large and requires 19.35 lb/day of electrolyzed water for orbit makeup, compared with 9.1 lb/day for the Half SOC. The solar array requires an additional 13.65 lb/day, for a total of 33 lb/day for the Full SOC. This compares with approximately 324 lb/day of water electrolysis for the energy storage system. Thus, the energy storage requirement dominates the orbit makeup requirement.

Power needs during emergencies are expected to be between 1500 W and 3000 W. The fuel cells would be very efficient at this low power level, but we have assumed that the fuel cell ancillaries, which are on the order of 600 W, should not be cut back in power. Assuming the worst case condition where the fuel cell must provide power continuously during light and dark, the hydrogen and oxygen consumption, given as the equivalent pounds of water, is 68.5 lb/day for a 3000 W electrical load (plus the 600 W load for fuel cell ancillaries); for a 1500 W electrical load (plus the 600 W load for fuel cell ancillaries) 40 lb/day are consumed. In addition, the life support consumption of oxygen will be 15.8 lb/day, which is equivalent to the electrolysis of 17.8 lb/day of water. Hydrogen and oxygen consumption during emergencies is summarized in Figure 8.1-2, based on I_{SP} = 380 sec. It should be noted that some emergencies will be of a



	H_2O REQUIREMENTS	
	NORMAL USE (8 MEN)	EVA ACTIVITY
LOW PRESSURE (< 20 PSI)	17.8 LB/DAY	14.7 LB/DAY
HIGH PRESSURE (900 PSI)	------	5.5 LB/DAY

Figure 8.1-1: Life Support Water Electrolysis Requirements

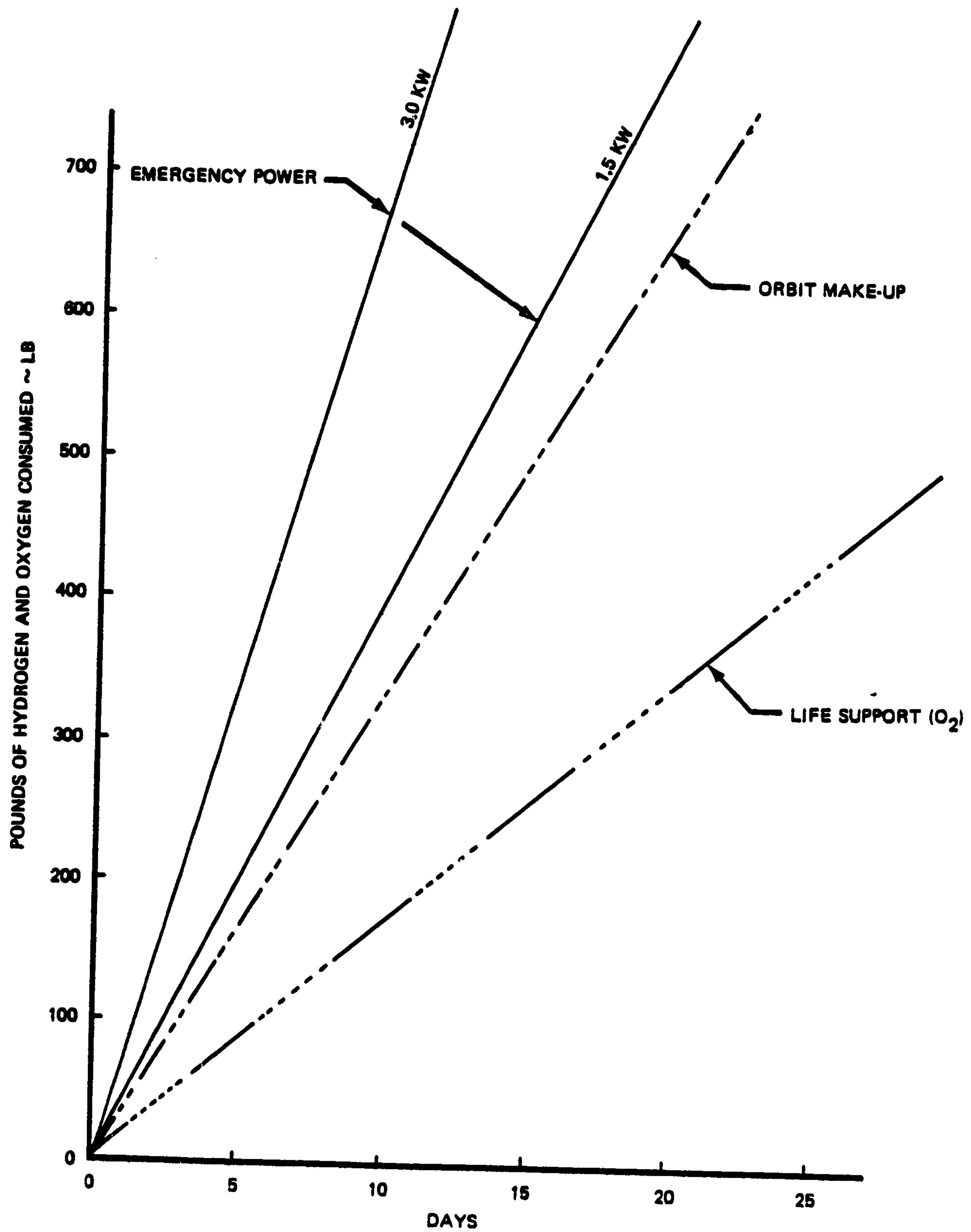


Figure 8.1-2: H_2 and O_2 Consumption for Emergencies

type where electrolysis of water during sunlit operation is possible, and others where it is not possible. That distinction has not been made in this analysis, and the worst case was assumed.

8.2 INTEGRATION WITH REACTION CONTROL SYSTEM

Reactants for orbit makeup are 33 lb/day using hydrogen and oxygen in stoichiometric ratio, based on electrolysis of water. The I_{SP} assumed was 380 sec. This results in 12,045 lb/year of water transport to the SOC. Hydrazine, with an I_{SP} of 230 sec. would total 19,900 lb/year. Thus, the use of electrolyzed water would save 7855 lb/year in resupply for orbit maintenance.

System pressure compatibility with the integrated approach should not be a problem. Hydrogen-oxygen thrusters have operated with rocket chambers at 100 psia and 50 psia and with a blow down to one third of these values. The minimum electrolysis gas pressure we have considered for integrated systems is 120 psia.

In addition to the 7855 lb/year weight saving, it is worthwhile to avoid the shipping, handling and storage of hydrazine from the standpoint of safety. Hydrazine lines must be heated, and though that is normally not an important consideration, the long external line lengths required with the SOC exacerbates the problem, especially during power emergencies.

Another feature of the hydrogen-oxygen system is the ability to provide very small impulse bits, as compared with the hydrazine system; this obtains by gas release without combustion. Factors in favor of hydrazine are (1) the thruster technology is well developed; (2) hydrazine is a good source of nitrogen and hydrogen needed for life support; and (3) fuel processing is not required.

The required electrolysis for orbit maintenance may be attained either by dedicated units or by integrating with the electrolyzers of the energy storage system. Integration would increase the normal 324 lb/day of water electrolysis by an additional 33 lb/day, or 10.2 percent. Maintaining the same current density, the increased weight of the 55 percent efficient energy storage system would be 56.5 lb., and for the 62 percent efficient system would be 116.2 lb. Integration in this way gives redundancy from the multiple electrolyzers.

With dedicated electrolyzers there is the need to provide suitable redundancy. A typical design would be one scaled up from the 18.0 lb/day unit described in Reference 10, p. 27. Three units would be provided so that two failures could be endured. Capacity would be increased from 18.0 lb/day to 33.0 lb/day, and current density would be reduced to result in 500 ASF after the second failure, that is, 166.7 ASF initially. The unit weight would scale up from 142 lb to 221.3 lb, and there would be three units, for a total of 663.8 lb.

Since the current densities would be designed to be similar, electrolyzer module power consumption by the electrolyzer cells would be no different whether the system were integrated or not. However, ancillary power will be much increased for the dedicated units because of the relatively low power level. We expect ancillary power to increase from approximately 1.5 percent with the energy storage system to about 5.0 percent with the small, dedicated units. With dedicated electrolyzers, power consumption would be 6.33 kW. Integrating with the energy storage system would save about 220 watts.

8.3 INTEGRATION WITH LIFE SUPPORT

The life support system requires the electrolysis of 17.8 lb/day. The trades and rationale on integration of this with the RFC energy storage system are similar to that of electrolysis for orbit maintenance reactants. Thus, three dedicated electrolyzers would weight 383 lb versus 30.8 lb for integration with the 55 percent efficient energy storage system, or versus 63.4 lb for integration with the 62 percent efficient system. Whether or not the life support system were integrated with the energy storage system, means must be provided for the 900 psia needed for EVA. This can best be done either by direct electrolysis to that pressure, or by means of an electrochemical oxygen compressor. The electrochemical oxygen compressor has an advantage in that it can be used also as a backup method for obtaining high pressure starting with either the energy storage oxygen or the reaction control oxygen. This compressor weighs 65 lb.

A more attractive integration system is exploitable if hydrogen and oxygen reactants are used for orbit makeup. The concept, as shown in Figure 8.3-1, is to use non-stoichiometric combustion in the thrusters and thus obtain a higher specific impulse for propulsion. The oxygen that is saved can be used for life support. Thus, if water

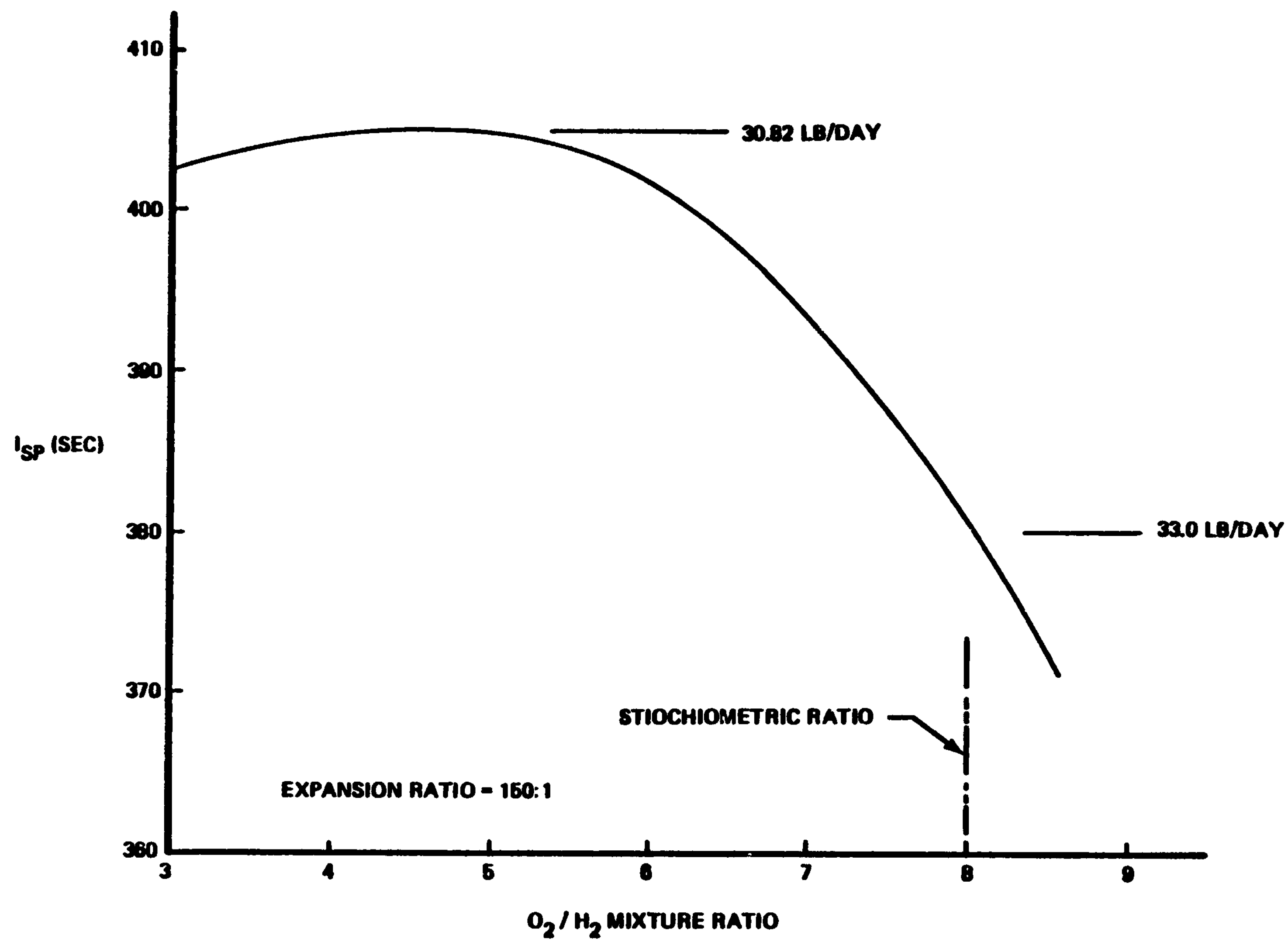


Figure 8.3-1: Expected Performance of H_2 - O_2 Thrusters

were electrolyzed and the product hydrogen and oxygen used as is for reaction control, 33 lb/day would be required. By operating at an oxygen/hydrogen mixture ratio of 5 to 1, the specific impulse is increased from 380 sec. to 405 sec. and the reactant requirement reduces from 33 lb/day to 30.82 lb/day.

The excess oxygen electrolyzed in the non-stoichiometric concept is 10.3 lb/day and meets much of the daily oxygen need of 15.8 lb/day (based on 17.8 lb/day of water). It should be noted that the weight saving is 33.0 minus 30.82, that is, 2.18 lb/day or 795.7 lb/year. Note must be made of the fact that in this concept there is litle excess hydrogen that would be available for reduction of CO_2 in a Sabatier reactor. However, there are other approaches to CO_2 reduction, such as a Bosch reactor.

An attractive approach for integration of the life support, energy storage, and reaction control systems is the opportunity to provide especially long duration emergency capability. Since large amounts of oxygen and hydrogen are needed for orbit makeup, a reserve of these gases can be maintained at high pressure and be available during emergencies for all three systems. Electrochemical pumping is a simple, lightweight way to obtain the desired high pressure, and oxygen compression is needed anyway for EVA. Tankage is the main penalty. For example, using the data in Figure 8.1-2, a 10-day emergency supply of all the gases needed for orbit makeup, 1.5 kW electric power, and life support would require approximately 1900 lb of tanks; also required would be 65 lb for a hydrogen compressor. Postponing orbit makeup until after the emergency would cut the tankage weight in half. Following an emergency or temporary use of these gases, the high pressure reserve can be replenished on board.

8.4 INTEGRATION SUMMARY

A summary of the benefits and penalties of the several integration options is given in Figure 8.4-1. Conclusions with regard to these options are as follows:

1. Electrolysis of orbit makeup water to hydrogen and oxygen is preferable to the use of hydrazine. The weight of equipment and the electric power required are modest compared to the weight saving obtainable.

2. Electrolysis integration of orbit makeup water with the energy storage system saves 550 lb and appears to be worthwhile.

A) H_2-O_2 VERSUS N_2H_4 FOR ORBIT MAKE-UP

	N_2H_4	H_2-O_2
WEIGHT	13.900 LB/YR	12,045 LB/YR (DELTA = 7,855)
POWER	0	6.3 KW

B) H_2-O_2 FOR ORBIT MAKE-UP – DEDICATED UNITS VERSUS INTEGRATE WITH ENERGY STORAGE

DEDICATED	INTEGRATED (DELTA)
663.8 LB	55% SYSTEM: 56.5 LB, SAVE 220 W
	62% SYSTEM: 106.2 LB, SAVE 250 W

C) H_2-O_2 FOR ORBIT MAKE-UP – NON-STOIC BURN WITH INTEGRATION WITH LIFE SUPPORT AND ENERGY STORAGE VERSUS STOIC BURN

	STOIC BURN	NON-STOIC BURN AND INTEGRATION
ELECTROLYZER:	6.3 KW	5.9 KW (DELTA = 0.4 KW)
WATER:	12,045 LB/YR	11,249 LB (DELTA = 795.7 LB/YR)

D) H_2 AND O_2 FOR LIFE SUPPORT – DEDICATED UNITS VERSUS INTEGRATION WITH ENERGY STORAGE

	DEDICATED	INTEGRATED (DELTA)
POWER:	3.4 KW	3.4 KW
ELECTROLYZER WEIGHT:	383 LB	55% SYSTEM: 30.8 LB
		62% SYSTEM: 63.4 LB (SAVE 0.2 KW)
O_2 COMPRESSOR WEIGHT:	65 LB	65 LB

Figure 8.4-1: Summary of Integration Trades – Weight and Power

3. Non-stoichiometric combustion of hydrogen and oxygen saves nearly 800 lb/yr and appears to be worthwhile. This saving may be contingent on development of an atmospheric CO_2 reduction process such as the Bosch reactor.

4. Integration of life support water electrolysis with the electrolysis of the energy storage system offers a weight saving of approximately 330 lb. It is judged that this is not sufficient a weight saving to offset the advantages of a fully self-contained life support system. However, water electrolysis by the energy storage system should be a backup to the life support system.

5. An on-board replenishable high pressure reserve of hydrogen and oxygen is a worthwhile opportunity for an integrated emergency gas system for life support, energy storage, and orbit makeup. Ten days emergency can be provided for with a weight penalty of 920 lb for tanks; if orbit makeup propulsion can be delayed until after the emergency, the penalty is halved.

9.0 ASSESSMENT OF FUEL CELL VS. BATTERIES

9.1 COMPARISON OF ATTRIBUTES

Results of the NASA-sponsored studies should be viewed as information which will assist in making a decision on the best energy storage system for space stations. The studies alone are not a sufficient basis upon which to decided this question. This can be seen in Figure 4.9-5 showing the attributes that govern the selection of energy storage systems for space stations. The NASA-sponsored studies examined some of the important attributes, but some others, which could be more important, were for good reason not part of the NASA-sponsored studies.

Figure 9.1-1 gives a qualitative evaluation of attributes for the three candidate energy storage systems. Low cost and low resupply weight were not evaluated because they were considered to be closely linked to long life and low weight. Comments on the items in this figure are as follows:

Long Life. Long life is mandatory. The Ni-H_2 battery is regarded as having good long life potential. Both the nickel electrode and the hydrogen electrode have the intrinsic capability of long life, but the principal attempt to prove long life in low earth orbit gave many early failures. This development is continuing, and is expected to succeed. For the present, however, the Ni-H_2 is not yet credible for LEO. Fuel cells and electrolysis cells have shown a potential for long life at the cell level. The solid polymer electrolyte fuel cell is especially long lived, showing hardly any degradation after five years of operation. Lifetimes of both the solid electrolyte and alkaline electrolyte fuel cells will be much extended by the low current density, which is preferred for space station needs. Lack of full system tests remain a major deficiency of the RFC system. It is clear that for both the Ni-H_2 battery and the RFC system a better data base is needed drawn from long duration tests at real time duty cycles.

Reliability. Both the Ni-H_2 and RFC reliability are unkown. Early failures in LEO tests raise concern with Ni-H_2 reliability; the chief concern with the RFC system is its complexity. A detailed reliability analysis of the RFC system appears not to have been attempted, and full-up tests are lacking.

		Ni-Cd	$Ni\text{-}H_2$	RFC
MANDATORY ATTRIBUTES	LONG LIFE (CELL LEVEL)	FAIR	TESTS UNDERWAY	TESTS UNDERWAY
	RELIABILITY (SYSTEM)	FAIR	UNKNOWN	UNKNOWN
POSSIBLY MANDATORY ATTRIBUTES	LARGE EMERGENCY POWER CAPABILITY	POOR	POOR	GOOD
	HIGH PEAK POWER CAPABILITY	FAIR	FAIR	GOOD
	STATION BUILDUP CAPABILITY	POOR	POOR	GOOD
IMPORTANT ATTRIBUTES	INTEGRATION ADVANTAGES	NONE	NONE	GOOD
	HIGH EFFICIENCY	FAIR/GOOD	FAIR/GOOD	FAIR/GOOD
	~~LOW COST~~	———	———	———
	LOW WEIGHT	POOR	FAIR	FAIR/GOOD
	~~LOW RESUPPLY~~	———	———	———

Figure 9.1-1: Evaluation of Energy Storage Systems for Space Stations

Large Emergency Power Capability. Modest requirements have generally been set for space station emergency power. This would be needed whenever primary power is lost. If there were a need or strong desire for a large emergency power capability, then the RFC system would have a decided advantage.

High Peak Power Capability. Both the $Ni-H_2$ and the Ni-Cd battery systems have good peak power capability provided the peak load is brief. The H_2-O_2 fuel cell has an advantage in that it can be designed for quite high rates for fairly long durations with only a modest weight penalty. This could be a significant attribute if the peak power requirements were similar to those defined in the McDonnell Douglas study, or if provisions were required for special high peak power military payloads.

Base Buildup Capability. The need for power during base buildup hinges on whether the solar array can be deployed early, or whether deployment must be deferred for a long time, such as the 60-day duration in the North American Rockwell study.

Integration Advantages. The RFC system is the only one which has the option of integration. Oxygen and hydrogen tankage can be integrated with the reaction control or life support system, and the RFC electrolyzer can be used with the reaction control system. Integration may be either for the purpose of saving weight, or as a backup operating mode.

High Efficiency. High energy storage efficiency is very important in reducing solar array size and cost, and in minimizing resupply of reactants to compensate for solar array drag. All three candidate energy storage systems can be designed for comparable energy storage efficiency.

Low Weight. The RFC system is lighter than batteries. However, this advantage may not be sufficient if the $Ni-H_2$ is able to provide outstanding long life at deep depth of discharge, as has been envisioned for it.

9.2 ASSESSMENT

In assessing batteries vs. regenerative fuel cells for the space station, the objective at this time is not to choose the best system, but to define which ones have the best potential and should be developed.

The importance of long life and high reliability cannot be emphasized too strongly. If the nickel hydrogen battery had proved out the early expectations and could provide say 7 years of trouble-free life, it would be extremely attractive for the space station. We have actually moved backwards with the nickel hydrogen system, however, for now there is a fair amount of poor performance data to attempt to overcome. Nevertheless, the system has the potential for long life, and this potential should be exploited. More emphasis on the fundamentals seems to be needed, aimed at improving life, rather than engineering advancements to improve energy density.

Several comments are deserved in defense of the Ni-Cd system. This system generally took third place in the various space station energy storage studies, and was discussed relatively little in this analysis. The reason for this is that the Ni-H_2 and the RFC systems are regarded as having greater potential. The fact remains, however, that if a commitment had to be made today, it would have to be to the Ni-Cd system. It is the only one proven credible for LEO. We have a lot of experience with it, and though it has limitations, we know how to deal with them. The sooner the commitment must be made, the more likely it will be to the Ni-Cd system. There are at least two other conditions whereby the Ni-Cd system might prove the best choise. One is the case where, due to funding restraints, low first cost is much more important than total cost. The second is the case where either the space station or the power module is designed for only a few years.

The regenerative fuel cell system has some advantages in addition to weight saving which are very attractive and make this system worthwhile of development. One important advantage is the ability to function as a primary fuel cell as well as in the normal RFC mode. This gives it the capability to: a) provide a large amount of emergency power on the order of days or weeks; b) operate temporarily (hours or days) at power levels well above that of the solar array; and c) take advantage of the opportunity to use the large residuals expected from the shuttle. For example, with 19 evenly spaced shuttle flights per year and use of the shuttle residuals, the solar array can be reduced to 50 percent of its normal size.

Low current density designs are best for the fuel cell and electrolyzer in order to obtain high efficiency. In this way, the RFC system efficiency can equal or exceed that of batteries. Moreover, the low energy density gives the capability to handle very large peak current, or high steady-state loads if other units fail, and still remain within voltage limits.

One of the most important advantages of the low current density fuel cell designs is the opportunity for long life. Tests on electrodes suggest that fuel cells have an inherent capability to outlive either the nickel cadmium or the nickel hydrogen system. The life situation with ancillaries is not clear, but that is much less a fundamental problem than the problem of electrode life.

When faced with the question of whether or not to develop the RFC system, an important issue is whether or not such a development would be worthwhile for applications other than the space station. Here the RFC system has a potential that is most enticing, and that is as an energy storage system for high power synchronous orbit spacecraft. With low current density there is the potential to far exceed the life of battery systems, and a 15-year system could be reasonable. Whereas the RFC system is noticably lighter than batteries for LEO, there is a much greater weight advantage for geo-synchronous orbit, and weight for that orbit is paramount. This weight saving results from the fact that the electrolyzer can be sized quite small because of the long recharge time available. Some indication of the weight saving can be seen from the PRC study which showed that the RFC system would weigh 25 percent of the Ni-H_2 battery. Preliminary Boeing estimates confirm that the RFC system is by far the lighter.

In summary, it is concluded that the RFC system has the best potential in a variety of areas and is deserving of development. Realization of this potential lies in developing and testing full systems, with emphasis on life and reliability. The nickel hydrogen battery also has good potential and is deserving of development; realization of its potential lies in fundamental work aimed at understanding and addressing the failure and degradation mechanisms in the system.

10.0 ASSESSMENT OF PRIMARY FUEL CELLS USING SHUTTLE RESIDUALS

10.1 ANALYSIS

The shuttle is required to carry a greater amount of hydrogen and oxygen propulsion fuel than is normally used on each mission. This results from the need to design for worst-case conditions of engine performance, wind shear, trajectory error, and all other factors that contribute to fuel consumption. As a consequence, the typical shuttle will arrive at the SOC with an excess of hydrogen and oxygen fuel. This fuel is of high enough quality for use in fuel cells, for orbit makeup propulsion, or for life support needs. Use of this fuel gives opportunities to save weight and cost of the electrical power system, and is a further argument to eliminate hydrazine from the resupply cycle. In the following analysis, it is recognized that the propulsion system also competes for this fuel.

The hydrogen and oxygen in the Shuttle are in cryogenic form. This presents problems in propellant transfer, especially in zero-G. A principal disadvantage of this approach is in the present lack of technology for zero-G transfer of cryogens. This could be a costly development.

We have looked at two approaches for the application of residuals to the SOC electrical power system. The first concept is to use the hydrogen and oxygen residuals for all power needs, both sunlit and occulted. This eliminates the need for either a solar array or an energy storage system; a large quantity of fuel is required, however, except for initial, short duration flights possibly used in the evolution of a space station. The second concept is to use a primary fuel cell for the occulted period only. This eliminates the need for an energy storage system, and also reduces the solar array size significantly.

The analysis was based on Rockwell data for the expected quantity of scavengable cryogens. The mean weight of available LO_2 is 6270 lb with a one sigma of ± 1582 lb. The mean weight of available LH_2 is 3078 lb with a one sigma of ± 634 lb. Reactant consumption of the fuel cells was based on 0.85 lb/kW-Hr, based on a stoichometric ratio. Excess delivered hydrogen is used for orbit makeup, and is not exploited in this analysis.

Figure 10.1-1 shows the continuous steady power (concept #1, no solar array) available as a function of the frequency of Shuttle flights. Since the SOC has a 50 kW load in sunlight and a 39.2 kW load in the dark, the average load is 45.9 kW. At that power level, approximately 50 Shuttle flights per year to the SOC are required to meet all the power needs with fuel cells. Also, it is seen that after about 6 to 10 flights per year, the statistical deviations from the mean are insignificant.

For concept #2, in which the fuel cell provides only the nighttime power, the energy requirement is reduced to 38 percent of the continuous level. Thus, only 19 flights per year to the SOC are required for this condition. Since approximately half the solar array is devoted to recharge of the energy storage system, there is a considerable saving in array development and hardware cost.

Figure 10.1-2 gives a comparison of the energy storage systems weights, with component weight breakdowns. This analysis is based on 50 kW continuous power, and does not reflect the nighttime power reduction to 39.2 kW as is the present SOC baseline.

The significant result from Figure 10.1-2 is the impressive reduction in weight attained by either of the two fuel cell concepts, based on free fuel. Also shown is the weight comparison between batteries and the RFC system, with the result that the RFC system is two thirds the weight of the Ni-H_2 battery system.

It is concluded from this analysis that use of Shuttle residuals is very attractive for SOC. Weight is reduced significantly, there is less hardware to be developed, and the solar array size is reduced by a factor of two. Large cost reductions should be possible if the technology for scavaging and transferring cryogen residuals can be made feasible.

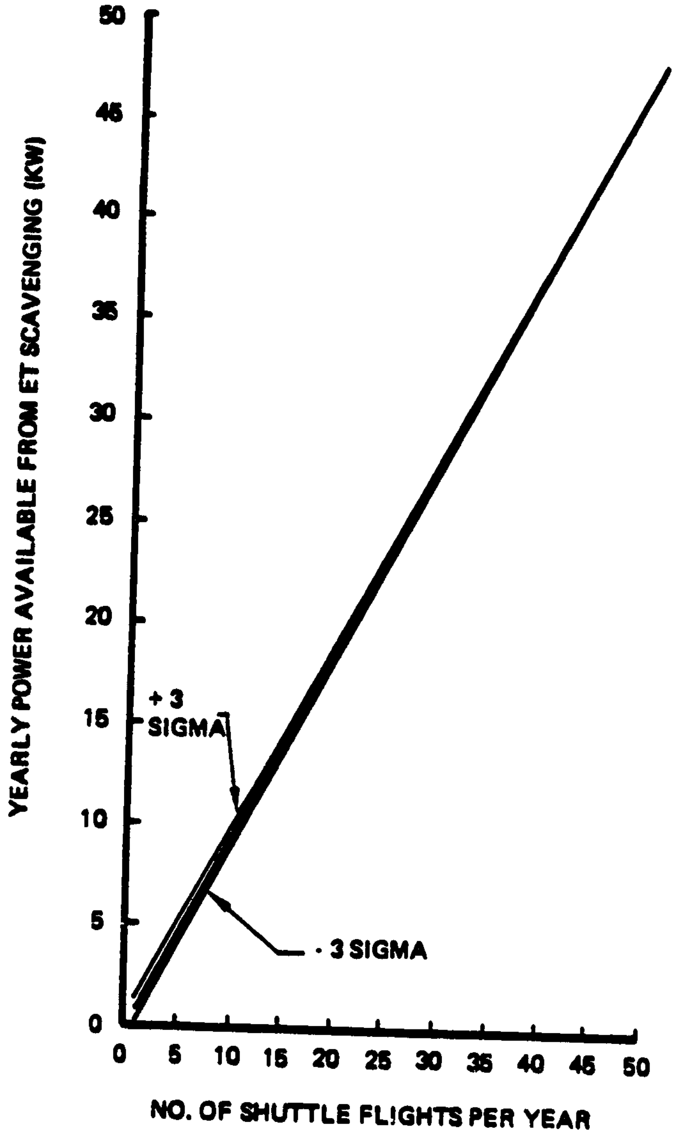


Figure 10.1-1: Fuel Cell Power Capability Using Scavenging Cryogens

	BATTERIES			REGENERATIVE FUEL CELLS		PRIMARY FUEL CELLS[1]	
	NiCd (25% DOD)	NiH_2 (35% DOD)	NiH_2 (30% DOD)	WT OPT	EFF OPT	FUEL CELLS PLUS SOLAR ARRAY	FUEL CELLS ONLY
SOLAR ARRAY WEIGHT	3,245	3,401	3,245	3,817	3,245	1,530	——
(SOLAR ARRAY POWER, KW)	(108.1)	(111.2)	(108.1)	(124.8)	(108.1)	(50)	(–)
RADIATOR	960	1,047	960	521	395	395	395
FUEL CELLS[4]	——	——	——	860	1,630	1,720	1,720
ELECTROLYSIS CELLS[4]	——	——	——	365	635	——	——
BATTERIES[4]	8,769	5,796	6,762	——	——	——	——
PROPELLANTS[5] ($H_2 \cdot O_2$ ANNUAL REQMT)	3,281	3,439	3,281	3,860	3,281	1,547	——
COLD PLATES	965	638	744	——	——	——	——
HEAT EXCHANGERS	——	——	——	50	40	40	40
TANKS	——	——	——	282	240	(OPN. DEP)[2]	(OPN. DEP)[3]
TOTAL, LBS	17,220	14,321	14,992	9,735	9,466	5,232	2,155

1 DEPENDENT UPON LAUNCH RESIDUAL PROPELLANT SALVAGE AND TRANSFER

2 REQUIRES ~ 156K LBS REACTANTS PER YR.; 8.2 K LBS PER VISIT; 19 VISITS/YR.

3 REQUIRES ~ 388 K LBS REACTANTS PER YR.; 20.4 K LBS PER VISIT; 19 VISITS/YR.

4 ASSUMES 5-YEAR BASIC LIFE

5 ALTITUDE MAINTENANCE TO COUNTERACT SOLAR ARRAY DRAG ONLY

Figure 10.1-2: Weights for SOC Energy Storage Systems — 50 KW Continuously

11.0 CONCLUSIONS

The conclusions from this study are as follows:

1. High energy storage efficiency should be an important objective in selection and design of spacecraft power systems. This minimizes solar array size and cost, and reduces resupply for orbit makeup from solar array drag.

2. Regenerable fuel cell systems can be designed with energy storage efficiency that is equal to or higher than present nickel hydrogen batteries.

3. Evaluation of prior studies on space station energy storage systems show large variations in weight, cost, and efficiency. These variations are much reduced when normalized. Operations cost is the most difficult to establish because ground rules varied considerably.

4. Prior studies on space station energy storage systems generally resulted in preference for the regenerable fuel cell system because of a weight advantage. Although those studies optimized the regenerable fuel cell (RFC) systems at too low an efficiency, the RFC system still will be lightest.

5. A high bus voltage (200 Vdc) may not be best for reliability of batteries, and possibly also fuel cells, due to the limited number of modules and the large number of cells in series. Further evaluation of the optimum voltage is needed with regard to energy storage reliability.

6. Hydrogen-halogen regenerable fuel cells have the potential for higher energy storage efficiency than either batteries or hydrogen-oxygen fuel cell systems. This can result in a reduction of up to 15 percent in solar array size. This is sufficiently worthwhile that further study should be conducted of those systems.

7. Electrolysis of water to yield H_2 and O_2 for propulsion fuel offers major weight savings over the use of hydrazine fuel.

8. Electrolysis integration of orbit makeup water with the RFC energy storage system saves weight and appears to be worthwhile.

9. Non-stoichiometric combustion of hydrogen and oxygen saves resupply weight and appears to be worthwhile. This saving may be contingent on development of an atmospheric CO_2 reduction process such as the Bosch reactor.

10. Integration of life support water electrolysis with the electrolysis of the energy storage system offers a possible weight saving, but it is judged that this is overshadowed by the disadvantages of integration.

11. Both the $Ni\text{-}H_2$ and the RFC systems are at a point in their development where there is no clear superiority of one over the other in the key areas of long life and reliability. Both have unique and worthwhile attributes, and both are worthy of development. The $Ni\text{-}H_2$ system has the expectation for achieving long life without the complexity of ancillaries, and engineering developments are being carried out in several areas that could apply to space stations. The regenerable fuel cell system can be designed for high efficiency or low weight, and has the potential for long life. Attributes of the RFC system which are clearly superior to the $Ni\text{-}H_2$ system are: good emergency capability, potential for weight saving by integration with other subsystems, the ability to take advantage of reactant residuals from the shuttle, and the ability to service customer payloads at temporary, high power levels.

12. Energy storage equipment purchase costs for space stations represent only a small fraction of the total associated cost. Therefore, in selecting systems for R&D, manufacturing cost differences between candidate energy storage systems should be secondary to system life and other performance attributes.

13. Use of hydrogen and oxygen residuals from the Shuttle is very attractive for use in the RFC system. With 19 flights per year to the SOC, the solar array size can be reduced by half; with 50 flights per year, no solar array is required, provided the residuals can be committed to the fuel cell.

12.0 RECOMMENDATIONS

The following recommendations are made:

1. The regenerable fuel cell system has been found to have good potential for space stations. Therefore, emphasis should be given to properly develop the technology. Some of the appropriate tasks are:

   a) Perform systems analyses and design studies, with identification and study of the interfaces and spacecraft system interrelationships.

   b) Develop energy-efficient dry gas electrolysis for both the alkaline and solid polymer electrolyte systems.

   c) Develop technology for improved reliability. Objectives should be to develop passive operation as much as possible, reduce the complexity and parts count of the ancillaries, and develop long life components with suitable redundancy.

   d) A test program should be established to explore component and system behavior over a full range of environments and operating conditions. A data base should be established for operating life and failure modes both at the component and system levels.

2. A water electrolysis/propulsion system should be developed. This should include integration with the power system. Non-stoichiometric operation should be evaluated, especially from the standpoint of mass balance over a wide range of space station conditions.

3. Hydrogen-halogen systems should be evaluated to determine if a high efficiency system can be produced. An assessment should be made of the weight and technical problems involved with these systems.

4. The high temperature (ceramic electrolyte) hydrogen-oxygen system should be evaluated to determine if a high efficiency RFC system is practicable. An

assessment should be made of the technical problems involved with these systems.

5. Regenerative fuel cell systems should be studied for the GEO application. Evaluations to be made should include realistic weight and efficiency improvement obtainable over batteries.

6. Water electrolysis/propulsion systems should be studied for the GEO application for weight-saving potential. Both dedicated electrolyzers and electrolyzers integrated with the power system should be evaluated.

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