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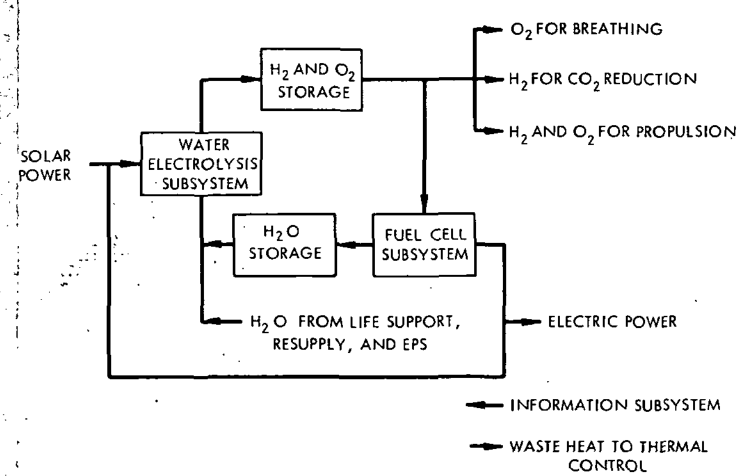
REGENERATIVE FUEL CELL STUDY

FINAL REPORT

by

R.A. Wynveen and
F.H. Schubert

December, 1972



Prepared Under Contract No. NAS9-12509

by

Life Systems, Inc.
Cleveland, Ohio 44122

for

MANNED SPACECRAFT CENTER
National Aeronautics & Space Administration

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FOREWORD

The present document summarizes the work carried out by Life Systems, Inc. under NASA Contract NAS9-12509. F. H. Schubert was a major contributor to the Water Electrolysis Subsystem efforts. Dr. R. A. Wynveen directed the integration of the water electrolysis, fuel cell, and gas and water storage technologies into a Regenerative Fuel Cell Subsystem. The overall Program Manager and Contract Administrator was R. M. Serabin.

The contract Technical Monitor was H. McBryar, Power Generation Branch, Propulsion and Power Division, NASA Manned Spacecraft Center, Houston, Texas.

The concept for the Regenerative Fuel Cell Subsystem was based almost entirely upon the excellent work presented by the North American Rockwell technical team defining and preparing the "Preliminary System Design of a Modular Space Station," Phase B Extension in Volume IV, Subsystem Analyses, and Volume VI, Trades and Analyses, NASA Contract NAS9-9958, January, 1972.

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1.0 INTRODUCTION

A Regenerative Fuel Cell Study was completed for the Modular Space Station (MSS) application. The program resulted in the preparation of

1. Regenerative Fuel Cell Subsystem Design Handbook, ER-151-3 and

2. Regenerative Fuel Cell Study Recommendations, ER-151-7

in addition to this Final Report.

1.1 Study Objectives

The objectives of the study were to evaluate the MSS energy storage requirement and the application of the Regenerative Fuel Cell Subsystem (RFCS) to it. This involved identifying the pacing technologies which turn out to be the Water Electrolysis Subsystem (WES) and the hydrogen (H_2)-Oxygen (O_2) Fuel Cell Subsystem (FCS). The expression "fuel cell" as used in this report always refers to the H_2-O_2 fuel cell.

1.2 Study Scope and Approach

The study covered the following subjects:

1. The Modular Space Station design requirements and constraints, environment, configuration, and build-up sequence;

2. The integrated Electrical Power Subsystem (EPS), and Environmental Control and Life Support Subsystem (ECLSS);

3. The MSS energy storage requirement, approaches to it, selection of the RFCS, and energy storage sizing considerations;

4. The WES technology including requirements, theory, history, WES classifications, state-of-the-art, design trade-off areas, impact of operating conditions, subsystem comparisons and selection of a specific subsystem for RFCS application.

5. The FCS technology including requirements, theory, history, state-of-the-art, desgn trade-off areas, impact of operating conditions, and technology deficiencies; and

6. The RFCS synthesized for MSS application including description, requirements, and characteristics.

1.3 Approaches to Regenerative Fuel Cell Subsystems

Two distinct and different approaches to synthesizing a RFCS exist:

1. Integrated modular fuel cell subsystem and modular Water Electrolysis Subsystem
    (A) Based on existing equipment currently being developed

(B) Based on advanced technology and optimized as an Energy Storage Assembly

2. Unitized Regenerative Fuel Cell Subsystem

The integrated approach uses a primary FCS to provide electrical power during the eclipse period operated from separate gas storage tanks. A separate WES is used to regenerate the reactant gases from the fuel cell product H_2O.

The unitized approach employs a FCS and a WES housed in a common container. The container also provides volumes for H_2O storage and gaseous reactant storage. The cells are individually packaged and can operate in either the fuel cell or electrolysis cell mode, with each cell consuming or regenerating its own reactant gases, depending on whether it is in the fuel cell or electrolysis cell mode, respectively.

The integrated approach was considered baseline for the current study due to:

1. The ground rule of minimum development cost;

2. The greater ease for maintenance; and

3. The greater flexibility in optimizing each of the modular subsystems when they are not unitized.

The latter consideration permits component design flexibility which allows optimization of both the FCS and WES for the most favorable operating condition and design configuration for each portion of the duty cycle.

1.4 Acknowledgment

Most, if not all, of the concepts related to the MSS were taken from the results of the North American Rockwell (NAR) MSS, Phase B Study referenced in the following section.

2.0 ANALYSIS RESULTS

2.1 MSS Mission Requirements

2.1.1 Guidelines

The MSS Program Definition is presented in Table 2-1. The MSS was designed to consist of a semi-permanent cluster of modules, each of which can be transported to and from orbit using the Space Shuttle to minimize launch cost. Total cost was a primary consideration requiring that developmental, production, and operational costs be considered in trade-offs.

For study purposes, the Space Station Program Phase C go-ahead was assumed to be in 1975 based on a launch date of mid-1981 for the first space station module. This implied that only concepts currently under development could be considered. This same guideline was used in evaluating the subassemblies that made up a RFCS.

2.1.2 MSS Operational Guidelines

Men were to be used in the build-up of the MSS with almost all manned operations to be performed within a pressurized volume. Safety and operational considerations dictated there was to be a minimum of two separate, pressurized, habitable volumes with independent life support capability, provisions, and other essential services, including energy storage and secondary fuel cell power. The second volume was to be a place into which the crewman could escape during an emergency (e.g., meteoroid penetration, contamination by experiment, accident or equipment failure).[1]

The MSS was designed to provide for on-board maintenance requiring accessibility for equipment repair by the crewman. It was to be able to operate independently for 120 days without resupply of consumables or spares. The normal resupply period was defined as 90 days maximum. The 30 days additional time was defined as the maximum time necessary to launch a resupply vehicle in the event the launch of the normal resupply vehicle was delayed. (Space Shuttle flights in support of the MSS's experimental program were to occur no greater than one every 30 days so that the frequency of resupply could be decreased from 90 days to 30 days at a launch-cost-penalty.)

2.1.3 MSS Power Supply Guidelines

The NASA guidelines required that a solar array concept be used for the MSS primary power source. Some form of energy storage was needed to be charged during the light portion of each orbit and discharged during the dark portion of an orbit or during peak demands of the light portion. Of the methods considered[2], the

---

(1) This required dividing the total energy storage requirement into a minimum of two modular RFCS units, one in each volume. It was eventually divided into four modular units so that each WES could be compatible with the requirements for the ECLSS and the FCS compatible with the Space Shuttle requirements.

(2) North American Rockwell, "Modular Space Station Phase B Extension, Preliminary System Design," Vol. IV, Subsystems Analyses, SD 71-217-4, NASA Contract NAS9-9953, DRL No. MSC T-575, Line Item 68, Jan., 1972.

TABLE 2-1 MODULAR SPACE STATION PROGRAM DEFINITION

Phase C Go-Ahead	Fiscal Year 1975
Initial Station	
Launch Year	1981
Crew Size	6 men
Resupply Period	90 days nominal; 120 days on-board capacity
Mission Duration	10 years (initial station, 5-6 years)
In-Orbit Completion (IOC)	February, 1982
Growth Station	
Launch Year	1986
Crew Size	12 men
Resupply Period	90 days nominal; 120 days on-board capacity
Mission Duration	5 years
Orbit	
Altitude	240 to 270 nautical miles (270 nautical mile baseline)
Inclination	28 to 55 degrees (55 degree baseline)
Flight Mode	X axis perpendicular to orbit plane
Initial MSS Build-up	
Module Delivery Frequency	1 per 30 days
Shuttle Visit Duration for Checkout	2 men, 5 days
Power Supply	19.3 kw, solar array, initial MSS (1.0 lb/watt penalty) 30.0 kw, growth station
Emergency Reserve of Expendables	96 hours
External Environment	The MSS will operate in zero gravity
Vehicle Environment	14.7 psia nominal, space vacuum in emergency
Vehicle Configuration	Cruciform, 14 ft dia by 38 ft modules
Vehicle Total Interior Volume	22,400 ft^3 (excluding RAM's,[a] cargo modules, power boom)
Vehicle Leakage (O_2/N_2)	10 lb/day, initial MSS 15 lb/day, growth MSS

Low initial cost was a primary design goal (minimum program, IOC and subsystem development costs).

(a) Research Application Modules.

nickel-cadmium (NiCd) secondary batteries and RFCS were found to be the most attractive.

The RFCS was finally selected because it required:

a. Lower overall cost (in orbit completion plus five years of operation);

b. Less solar array area;

c. Lower launch weight; and

d. Fewer Information Subsystem (ISS) interfaces.

2.1.4 MSS Configuration

The six-man initial station is shown in Figure 2-1. It utilized a cruciform configuration concept consisting of one central core module, one power module, four Station Modules (SM) located on the Z axis berthing ports, and accommodations for up to four cargo or Research Application Modules (RAM's) located on the Y axis berthing ports. The initial MSS program assumed two RAM's and one cargo module for on-orbit accommodations.

2.1.5 Energy Storage Sizing

Table 2-2 lists the conditions that influence the sizing of the RFCS, i.e., the MSS energy storage requirement.

TABLE 2-2 ENERGY STORAGE SIZING CONSIDERATIONS

1. Eclipse period and daylight peaking power requirements
2. Orbit parameters
3. Solar array utilization
4. Charge-discharge efficiency
5. Required operational life
6. Safety

Section 4.8 of the RFCS Design Handbook[1] reviews the quantitative impact of these sizing considerations.

Table 2-3 summarizes the reactant production rate required for the MSS.

2.1.6 Operational Life

Operational life required by the fuel cell and H_2O electrolysis subsystems are summarized in Table 2-4.

2.2 Regenerative Fuel Cell Subsystem Description

(1) Wynveen, R. A. and Schubert, F. S., "Regenerative Fuel Cell Subsystem Design Handbook," NASA Contract NAS9-12509, LSI-ER-151-3, November, 1972.

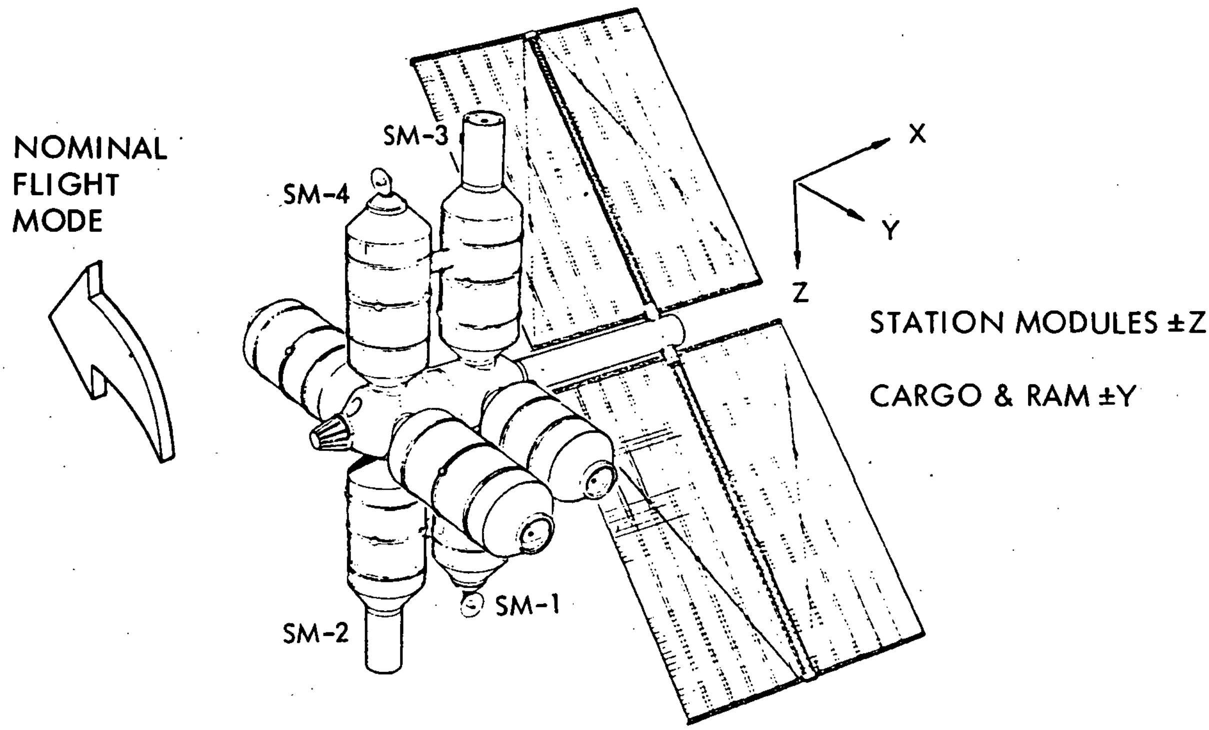

FIGURE 2-1 INITIAL MSS CRUCIFORM CONFIGURATION[1]

(1) Ibid., page 1-2.

TABLE 2-3 FUEL CELL REACTANT PRODUCTION REQUIRED TO MEET DAYLIGHT PEAKING AND ECLIPSE PERIOD STATION POWER REQUIREMENTS

Orbit Period[a]	14-hr Work	10-hr Rest	24-hr Avg.
Energy Requirements, kw-hr[b]			
Daylight Peaking	1.68	0.84	1.33
Eclipse	11.78	8.38	10.36
Total (kw-hr orbiter)	13.46	9.22	11.69
Reactant Requirements[c]			
Total lb reactant/orbit (59 Min)	11.04	7.56	9.60
Total lb reactant/hr	11.23	7.69	9.76
Lb reactant/hr/WES[d]	2.80	1.92	2.44
Lb reactant/hr/WES[e]	2.25	2.80	2.46
Total lb reactant/hr[e]	9.02	11.20	9.93

(a) Orbital 270 nautical miles, 55 inclination, dark/light ratio of 0.6

(b) Energy requirements shown include a 12% allowance for conditioning and distribution losses. This was increased to 17% for the final EPS mechanization which has a small effect on RFCS sizing

(c) Based on a fuel cell specific reactant consumption of 0.82 lb/kw-hr

(d) Four units with one per primary bus

(e) Optimized for solar array utilization and approach selected

TABLE 2-4 REQUIRED OPERATIONAL LIFE, HOURS

Initial MSS

(A) Replace after 2.5 years

(B) Application life time

30-day burnin x 24 hours	=	720	
365-day x 2.5 years x 24 hours	=	21,900	
10% contingency	=	2,260	
Total required application life:		24,880	hours

(C) Operational life time (dark/light ratio of 0.6)

FCS	9,950	hours[a]
WES	14,930	hours

Growth MSS

(A) Replace after 5 years

(B) Application life time

30-day burnin x 24 hours	=	720	
365-day x 5 years x 24 hours	=	43,800	
10% contingency	=	4,450	
Total required application life:		48,970	hours

(C) Operational life time (dark/light ratio of 0.6)

FCS	19,590	hours[a]
WES	29,380	hours

(a) Minus time operating in support of peaking loads during sunlight periods

2.2.1 Regenerative Fuel Cell Subsystem Requirements

Table 2-5 summarizes the RFCS requirements. It indicates the total and the requirements for each one of the four modular RFCS's that satisfy the MSS energy storage requirements.

2.2.2 Functional Description

Figure 2-2[1] shows a functional block diagram of the MSS RFCS. It consisted of a WES, gaseous reactant storage tanks, FCS, a H_2O storage tank, and pump.

During the daylight portion of the orbit solar array power was used to operate the WES which produced gaseous H_2 and O_2 from the H_2O feed. The WES operated at a pressure sufficiently high to force the H_2 and O_2 into their respective storage tanks.

2.2.3 RFCS Block Diagram

Figure 2-3 presents a block diagram of the modular RFCS (one-fourth of the MSS Energy Storage Assembly).[2] It also cites the weights of reactants resulting from the NAR studies.

2.3 Integrated EPS/RCS/ECLSS

The following sections describe the integrated EPS/RCS/ECLSS identified during the MSS studies.[3]

2.3.1 Electrical Power Subsystem (EPS)

The EPS provided for:

1. Primary power generation for normal operations;
2. Secondary power generation for station build-up, emergency, and solar array replacement operations;
3. Energy storage for orbital dark periods;
4. Power transfer, conditioning, and distribution; and
5. Spacecraft lighting.

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(1) North American Rockwell, "Modular Space Station Phase B Extension, Preliminary System Design," Vol. IV, Subsystems Analyses, SD 71-217-4, NASA Contract NAS9-9953, DRL No. MSC T-575, Line Item 68, page 4-9, Jan., 1972.

(2) North American Rockwell, "Modular Space Station Phase B Extension, Preliminary System Design," Vol.VI: Trades and Analyses, SD 71-217-6, NASA Contract NAS9-9953, DRL No. MSC 7-575, Line Item 68, page 241, Jan., 1972.

(3) North America- Rockwell, "Modular Space Station Phase B Extension, Preliminary System Design," Vol. IV, Subsystems Analyses, SD 71-217-4, NASA Contract NAS9-9953, DRL No. MSC T-575, Line Item 68, Jan., 1972.

TABLE 2-5 REGENERATIVE FUEL CELL SUBSYSTEM REQUIREMENTS

	Total	Per Unit
WATER ELECTROLYSIS SUBSYSTEM		
Reactant Generation Rate, lb/hr		
Nominal	11.2	2.80
Maximum Sustained		3.90
Overload Capability (Time Limit TBD)		5.5
FUEL CELL SUBSYSTEM		
Power, kw-hr		
Maximum Sustained	28.0	7.0
Maximum Within Voltage		10.0
Minimum Power		0.2
GAS ACCUMULATORS		
Total Reactants, lb		
10-hr Surplus	22.05	5.51
11.78 kw-hr Requirement	9.75	2.44
Residual at 60 psia	8.46	2.11
WATER ACCUMULATORS		
Total Reactant, lb		
Nominal	80	40
Maximum	644	322

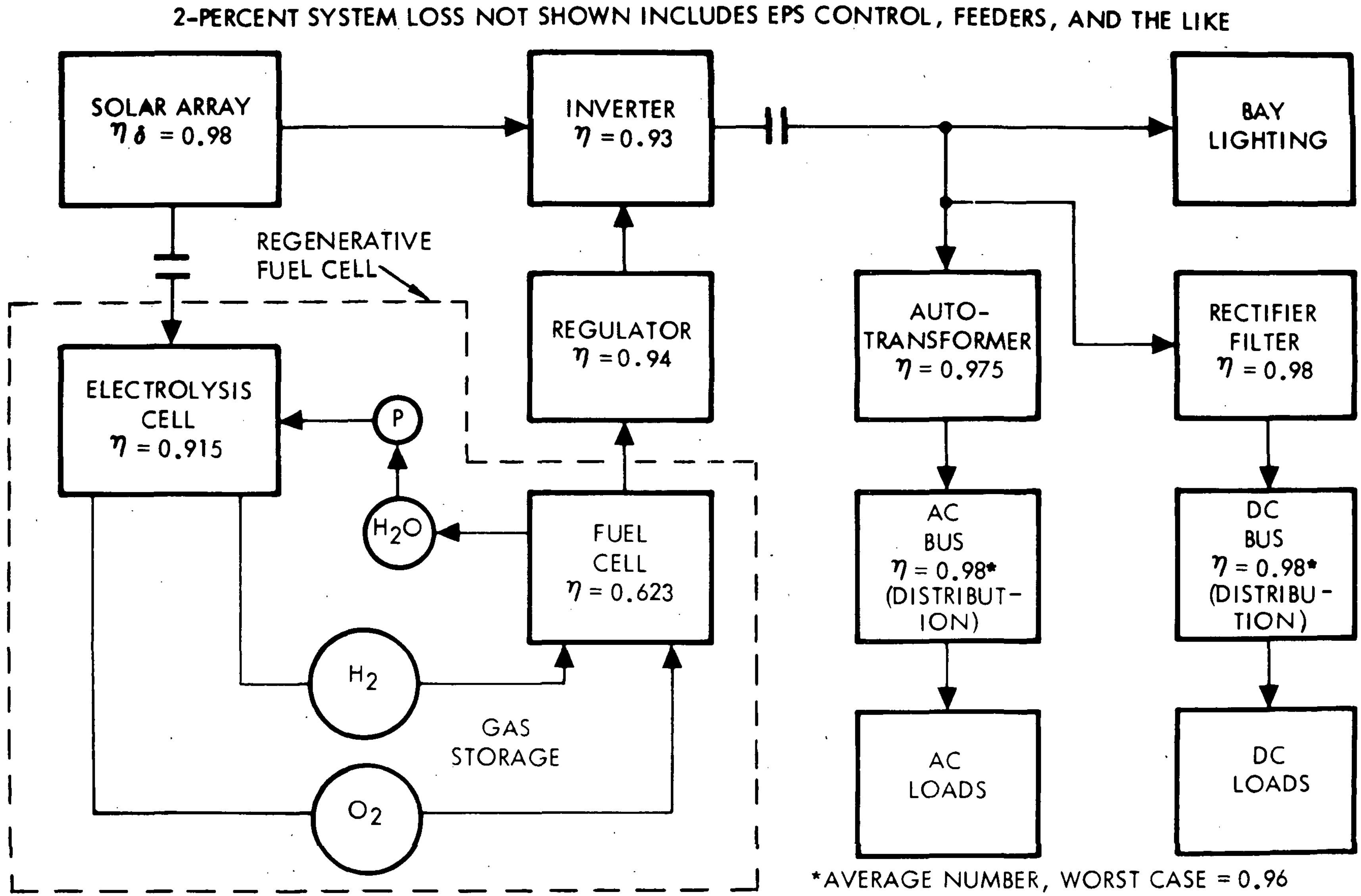
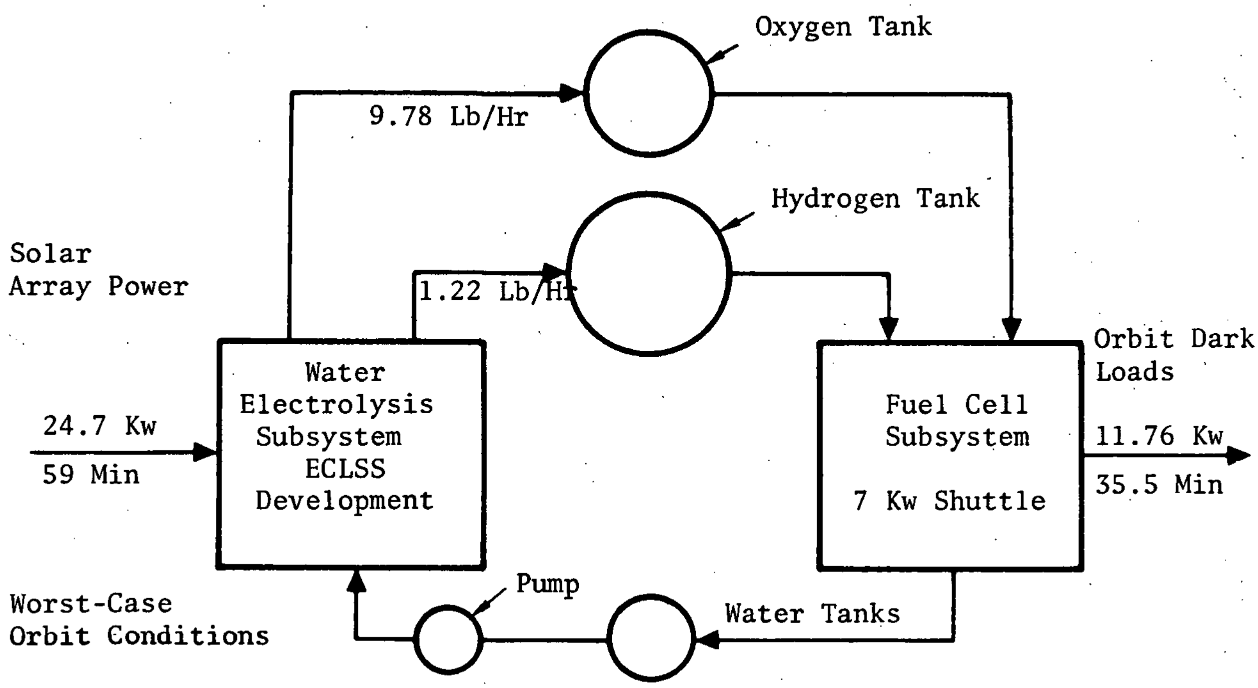


FIGURE 2-2 EPS POWER CONDITIONING SCHEMATIC(30)



(One Of Four Units To Satisfy Requirements)

FIGURE 2-3 MODULAR REGENERATIVE FUEL CELL SYSTEM

The EPS major requirements which influenced the selection trades and sized the equipment are identified in Table 2-6.

2.3.1.1 Primary Power

The solar array primary power generation selection was established by a NASA guideline while the sizing was based on the normal operations power level of 18.7 kw (excluding distribution and conditioning losses). This power level included 4.5 kw as the experimental operational requirement. Other major power requirements were:

1. 290 watts average for the MSS build-up power before solar array deployment (60-day duration); and
2. 1.75 kw emergency power (loss of solar array primary power generation) for 96 hours.

The fail/degrade requirement of 13.4 kw was primarily a driver on power conditioning, distribution, and control equipment sizing and redundancy rather than selection. The independent and separate Emergency Power Assembly is a requirement based on failure analyses of MSS subsystems while the 1.75 kw power level and the 96-hour duration (170 kw-hr) drove the selection.

The primary power generation assembly was a 7000 ft^2 solar array using the Lockheed technology concept. Power switching on the solar array was incorporated to improve power regulation, power management, and to provide power deadfacing at the interface for maintenance purposes.

2.3.1.2 Energy Storage

Energy storage was accomplished by four regenerative fuel cell assemblies (one per primary bus). The fuel cells also serve the function of secondary (emergency) power generation when supplied by the high-pressure stored gases.

2.3.1.3 Functional Block Diagram

Figure 2-4 presents a functional block diagram of the EPS. It illustrates the four channels, two per each solar array wing, and the interfaces with the RFCS, the primary buses, and the core and module loads.

2.3.1.4 EPS Preliminary Design

Figure 2-5 identifies the EPS selection and preliminary design for the MSS.

The initial station core module was compartmentized into a V_1 and V_2 volume. The primary and secondary buses, two regenerative fuel cell assemblies, and two inverters were located in each pressurized volume. Each Station Module contained two secondary buses, one from each primary bus of the associated volume. Critical loads were supplied from either secondary bus while non-critical loads were supplied from only one bus.

TABLE 2-6 EPS MAJOR REQUIREMENTS

- Solar array primary power generation (2 degrees of orientation)
- Separate & independent emergency (secondary) power assembly
- 5-year operational life initial & growth station
- 55 degrees inclination by 240-270 nautical mile altitude
- Failure criteria

Nominal Operations	One Failure
Degraded Operations	Two Failures
Emergency Operations	Three Failures (96 hours)

- In-flight maintenance without primary power shutdown
- Power requirements*

Buildup	290 watts	60-day intervals
Normal Oper.	18.7 kw (4.5 kw experiments)	Continuous
Fail Degrade	13.4 kw	Continuous
Emergency	1.75 kw	96 hours

*(Does not include distribution or conditioning losses)

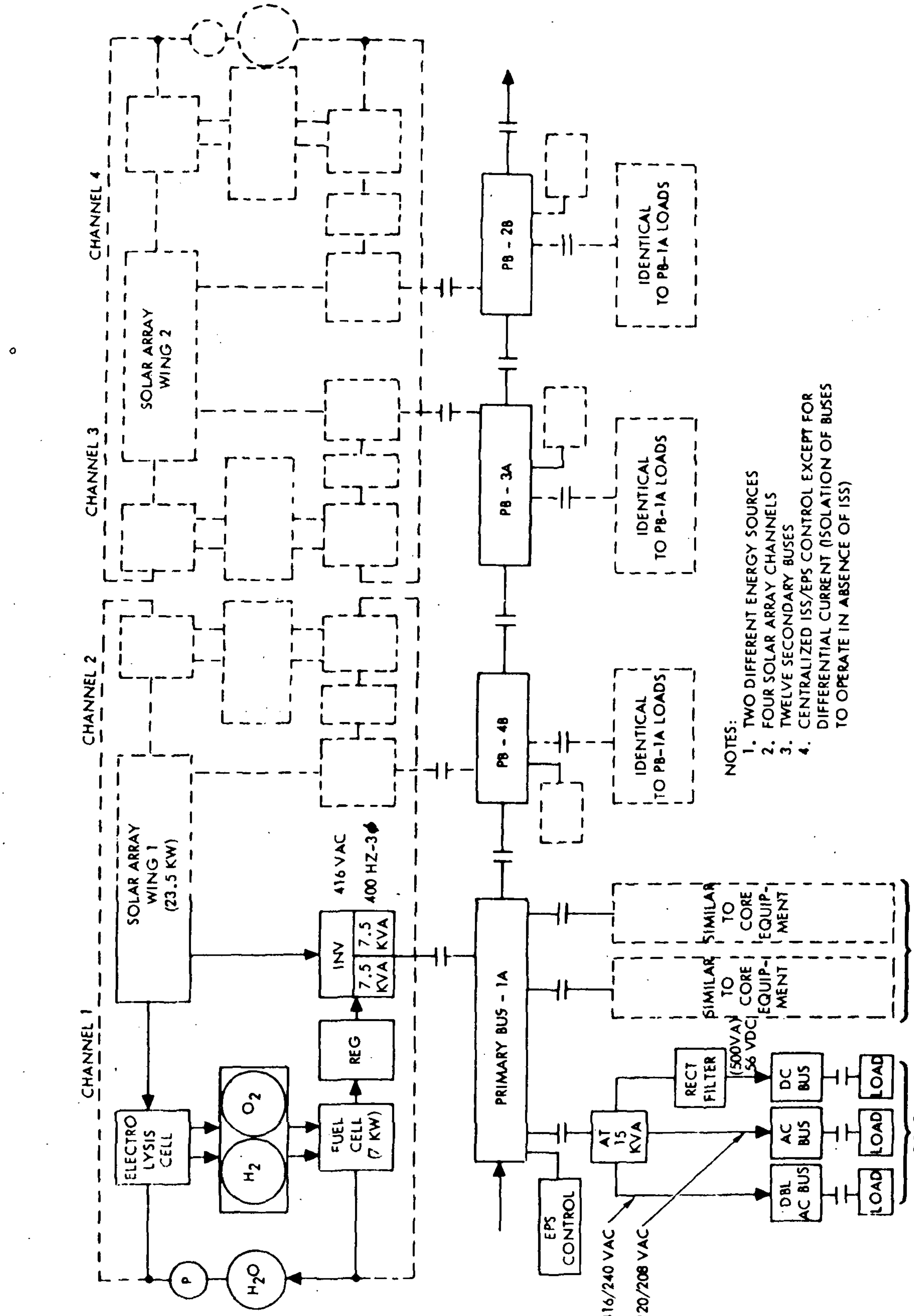


FIGURE 2-4 EPS FUNCTIONAL BLOCK DIAGRAM

SOLAR ARRAY
9.5 W / FT^2
0.617 LB / FT^2

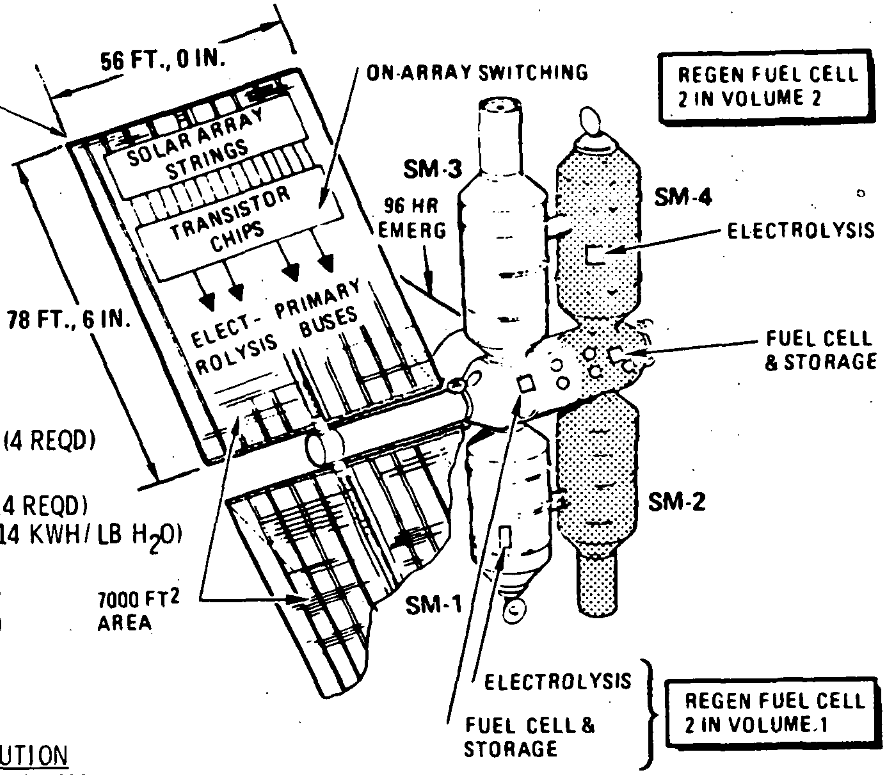
PRIMARY POWER GENERATION
7000 FT^2 SOLAR ARRAY
LOCKHEED TECHNOLOGY

ENERGY STORAGE
REGENERATIVE FUEL CELLS
FUEL CELL (SHUTTLE)
RATED POWER = 7.0 KW/FC (4 REQD)
ELECTROLYSIS (ECLSS)
REACTANT RATE = 3 LB / HR (4 REQD)
SPEC PWR CONSUMPT = 2.14 KWH / LB H_2O)
ACCUMULATORS
H_2 = 33 IN. DIAM (4 REQD)
O_2 = 26 IN. DIAM (4 REQD)

SECONDARY POWER GENERATION
ENERGY STORAGE FUEL CELLS
HIGH PRESSURE STORAGE

POWER CONDITIONING & DISTRIBUTION

PRIMARY BUSES	240/416 VAC, 400 Hz
SECONDARY BUSES	240/416 VAC, 400 Hz
	120/208 VAC, 400 Hz
	56 VDC



ODAPT 0.30 LB / FT^2
(ORIENTATION, DRIVE
AND POWER TRANSFER)

FIGURE 2-5 ELECTRICAL POWER SUBSYSTEM PRELIMINARY DESIGN

2.3.2 Reaction Control Subsystem (RCS)

The RCS provided thrust for:

1. stabilization,
2. docking,
3. orbit maintenance,
4. CMG desaturation, and
5. maneuvers.

In addition, under the integrated subsystem concept the RCS was responsible for providing the H_2 and 0_2 accumulators which stored all the gases provided by the ECLSS electrolysis. This included the orbital dark period H_2 for the Sabatier and the H_2 and 0_2 for the electrochemical CO_2 concentrator. Water storage was integrated into the ECLSS (cargo module storage) and the EPS (on-board storage).

2.3.2.1 Requirements and Sizing

The major requirements and hardware sizing influence are identified in Table 2-7.

The atmospheric model was a driver on the RCS. The impulse numbers identified in Table 2-8 were based on a 240-nautical mile, 55-degree orbit, and a Jacchia 2-sigma mean atmosphere. This model, in conjunction with an initial station IOC of February, 1982, formed the basis for RCS equipment sizing of electrolysis units, accumulators, and H_20 storage tanks. A 240-nautical mile nominal atmospheric model was used to define the solar array area penalty associated with the RCS electrolysis. The nominal mission of 270-nautical mile, 55-degree orbit with nominal atmosphere was used to define the RCS logistics resupply and the RCS average power requirements. The 12-hour no-venting requirement imposed by the experiments was also a driver on RCS accumulator sizing.

2.3.2.2 RCS Preliminary Design

The RCS preliminary design is shown in Figure 2-6.

2.3.3 Environmental Control and Life Support Subsystem (ECLSS)

The ECLSS provided for:

1. gaseous storage,
2. CO_2 management,
3. atmospheric control,
4. thermal control,
5. water management,
6. waste management,
7. hygiene, and
8. special life support.

In addition, the electrolysis units of the CO_2 management assembly were used to supply the RCS propellants.

TABLE 2-7 RCS MAJOR REQUIREMENTS

- Failure Criteria

  Buildup - after two failures capability to stabilize/dock

  Normal - after one failure

  Degraded - after two failures

  Emergency - after three failures capability to stabilize/dock

- 55-degree orbit altitude between 240 and 270 miles
- 120-day on-orbit propellant supply
- Jacchia (2 sigma mean) 240-nautical mile atmosphere for equipment sizing and impulse requirements
- Logistics requirements based on 270-nautical mile nominal atmosphere (IOC February 1982)
- CMG desaturation and orbit makeup at 12-hour intervals (experiment requirements)

TABLE 2-8 RCS IMPULSE REQUIREMENTS, LB. SEC.

Impulse Requirements	Initial	Growth
Orbit makeup	166,000	236,000
CMG desaturation		
Maneuvers	48,000	48,000
Shuttle docked	28,000	28,000
Contingency	48,000	62,000
120-day Total	290,000	374,000

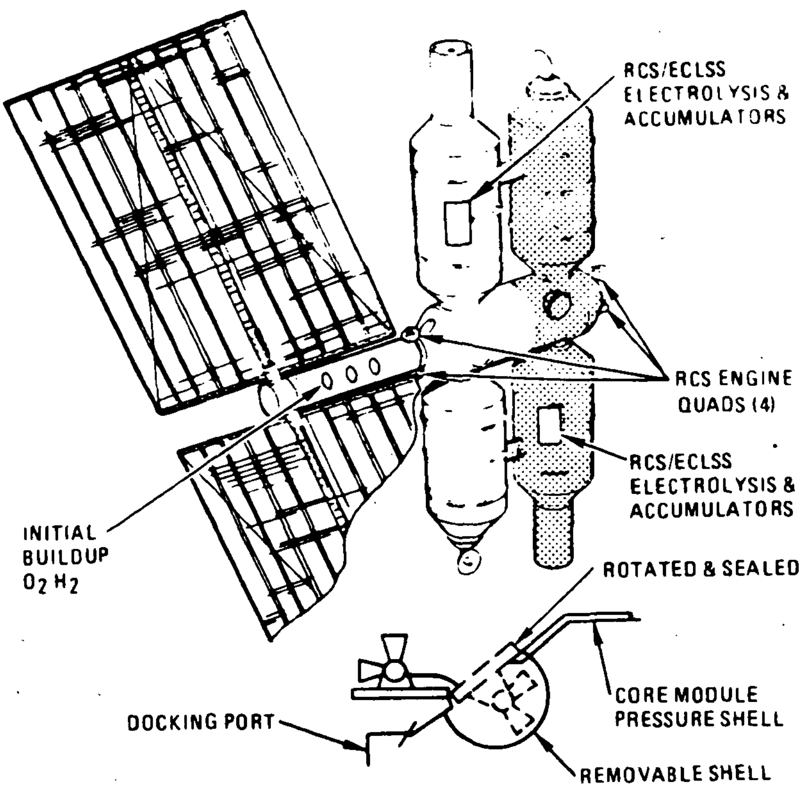


FIGURE 2-6 RCS PRELIMINARY DESIGN

2.3.3.1 Requirements

The ECLSS major requirements which influenced selection and sized equipment are identified in Table 2-9.

2.3.3.2 ECLSS Preliminary Design

Figure 2-7 identifies the ECLSS selection and preliminary design for the MSS. The dual pressure volume (V_1 and V_2) requirement, in conjunction with the failure criteria for the MSS, established the ECLSS redundancy and equipment sizing requirements for dual six-man equipment. The 3.0 mmHg pCO_2*requirement in conjunction with the 12-hour experimental no-venting requirement and minimization of electrical power drove the CO_2 removal selection to an electrochemical CO_2 concentrator concept. The ECLSS also had several requirements to provide experiment support. These included thermal control, waste and H_2O management, and atmospheric makeup.

2.3.4 Integrated Subsystem Schematic

Figure 2-8 illustrates the integrated EPS/RCS/ECLSS schematically.

* pCO_2 = partial pressure carbon dioxide.

TABLE 2-9 ECLSS MAJOR REQUIREMENTS

. 6-man crew with growth to 12-man crew	
. 120-day expendable storage capacity	
. 14.7 psia $0_2/N_2$; shirtsleeve atmosphere	
. 96-hour emergency	
. Dual-pressure volume	
. Repressurization of one pressure volume	
. Water vapor: 8-12 mm Hg	
. CO_2 concentration: 3.0 mm Hg	
. Thermal control	
Independent of orientation as design goal	
No condensation	
. Crew metabolic	11,900 Btu/man-day
O_2 consumption	1.84 lb/man-day
CO_2 production	2.25 lb/man-day
. Water usage	24 lb/man-day
. Thermal control	
Module loss-gain.	2,000 BTU's per hour-1,000 BTU's per hour
. Station leakage	10 lb/day initial
	15 lb/day growth
. Experiment support	
O_2 consumption	1.2 lb/day
RAM leakage	1.0 lb/day
Water usage	35 lb/day
Thermal control	7000 watts max.
Waste disposal	2.2 lb/day

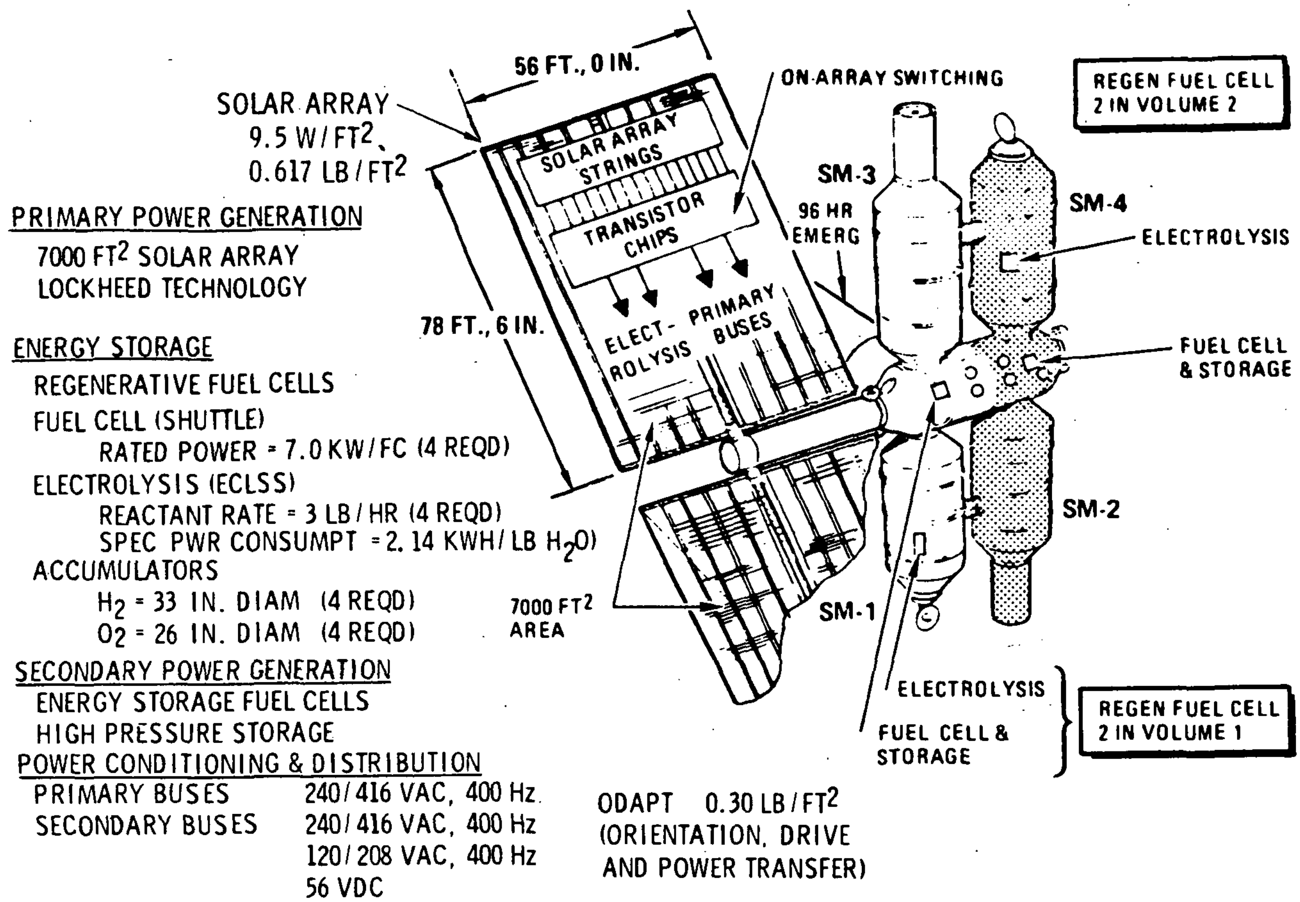


FIGURE 2-7 ECLSS PRELIMINARY DESIGN

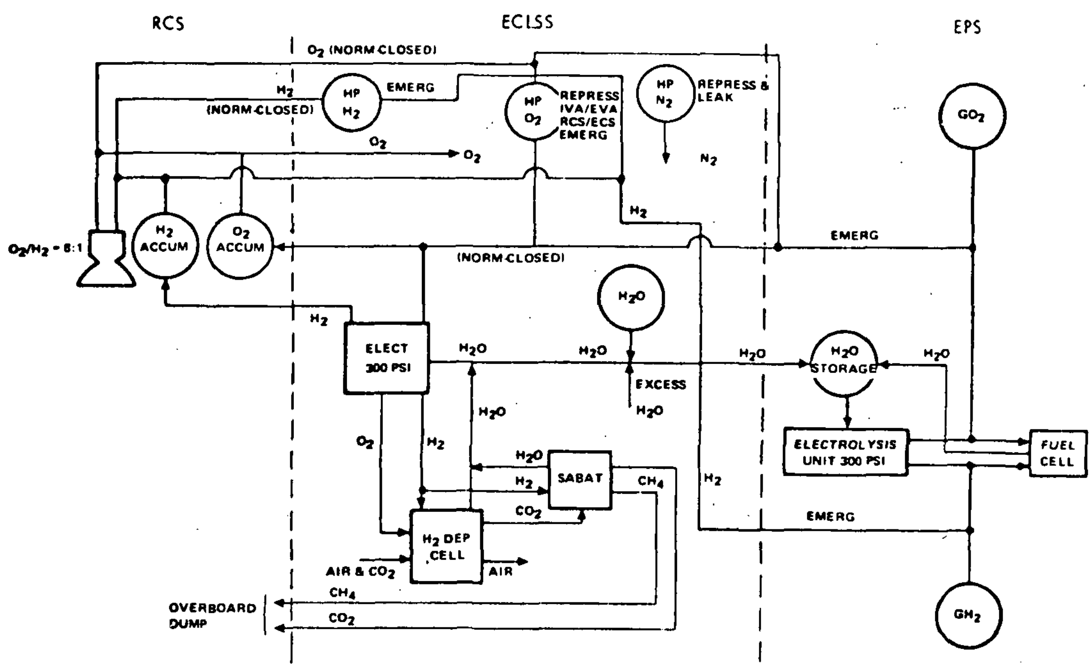


FIGURE 2-8 EPS/RCS/ECLSS INTEGRATED SUBSYSTEM

3.0 REGENERATIVE FUEL CELL SUBSYSTEM DESIGN DISCUSSION

The RFCS design description includes the requirements, subsystem block diagram, weight, and specific energy summary.

3.1 RFCS Requirements

The MSS energy storage requirements were summarized in Table 2-5. As noted previously, these were met by dividing the requirement into four modular RFCS's.

3.2 RFCS Block Diagram

Figure 3-1 presents a block diagram of the RFCS. It also summarizes the flow, power and weight characteristics evolved during the MSS studies.[1] The weight of the WES will probably increase as noted in the next section.

3.3 RFCS Weight Characteristics

Table 3-1 presents a summary of the RFCS weight that satisfies the total MSS energy storage requirement. It includes three different weight versions of the WES.

1. That referenced in the original MSS studies;[1]
2. An optimistic design based on the current studies; and
3. A more maintainable design based on the current studies.

Table 3-2 presents the weight and total equivalent weights for the latter two RFCS WES designs for both the modular version and the total group of four.

3.4 RFCS Specific Energy

The maximum usable stored energy is 38,400 watt hours. The specific energy calculated for the MSS study results in 9.4 watt-hours per pound (38,400 watt-hours/4,044 pounds).

The specific energy for the revised optimistic and maintainable designs (Table 3-1) are 8.5 and 5.6 watt-hours/pound, respectively.

The RFCS offers much greater specific energies than reflected in the 5.6 to 9.4 range cited above. Only through the expenditure of development time and funds, however, will the larger values become a reality.

3.5 Characteristics of RFCS's

The four units that make up the RFCS are the FCS, WES, Gas Accumulator Subassembly, and Water Tank Subassembly. They are detailed in the following sections.

3.5.1 FCS Characteristics

The characteristics of the MSS FCS are summarized in Table 3-3. The alkaline matrix fuel cell was assumed.

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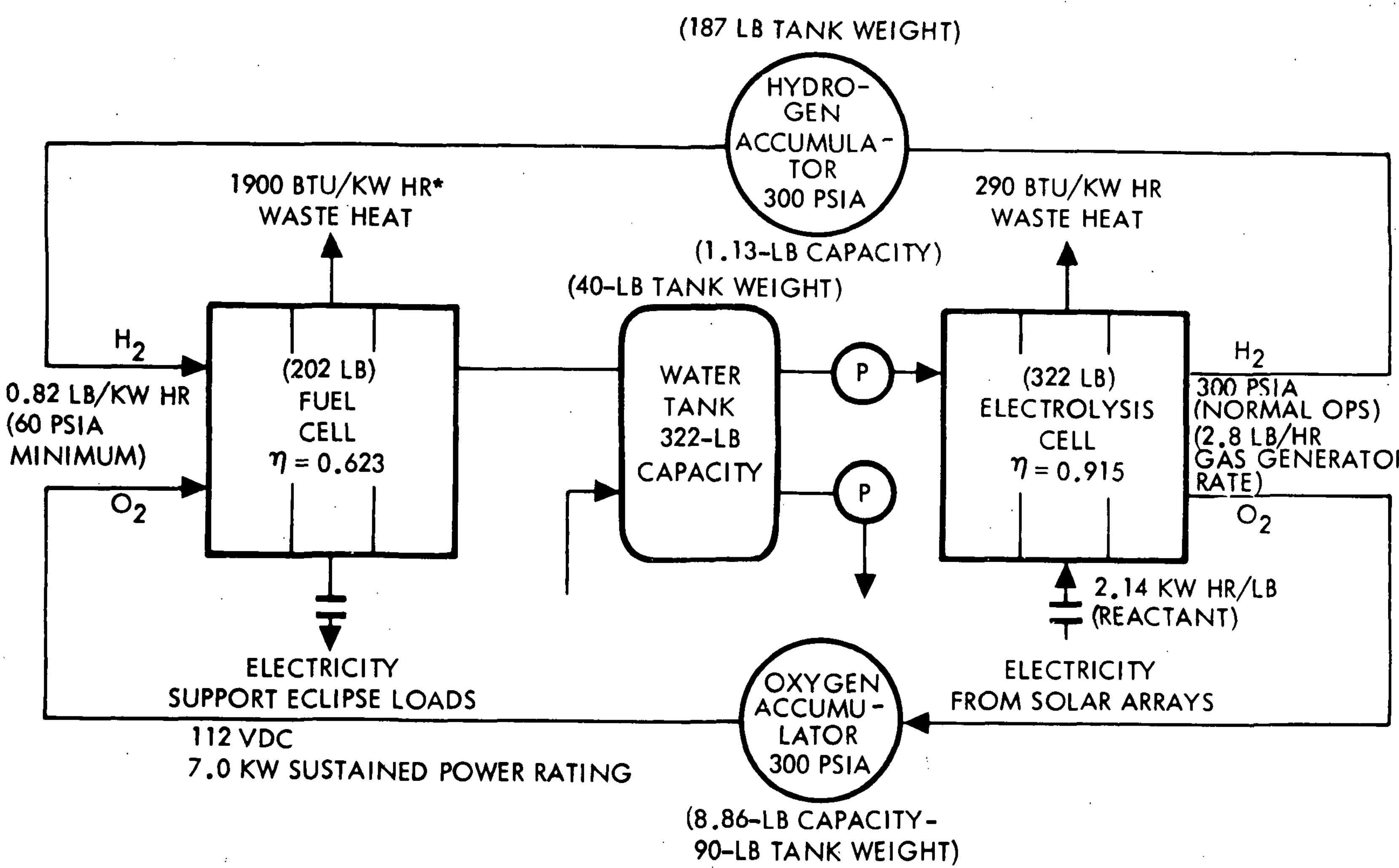
(1) North American Rockwell, Space Division, "Modular Space Station Phase B Extension," NASA Contract NAS9-9953, MSC 02471, T-575, Jan., 1972.



*AT SUSTAINED POWER RATING

FIGURE 3-1 RFCS BLOCK DIAGRAM(127)

TABLE 3-1 REGENERATIVE FUEL CELL SUBSYSTEM WEIGHT (POUNDS)

	Original MSS[b]	Revised Designs	
		Optimistic	Maintainable
Water Electrolysis Subsystem	1,288	1,608[a]	4,016[a]
Fuel Cell Subsystem	808	808[b]	808[b]
H_2 Storage Tank	748	784	784
O_2 Storage Tank	360	360	360
H_2O Storage Tank & 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[c]	184	184
Total	4,044 lb	4,492 lb	6,900 lb

(a) Taken from Table 5-18
(b) May increase due to in-flight maintenance requirements.
(c) Fuel Cell Subsystem quantities only.

TABLE 3-2 TOTAL EQUIVALENT FLIGHT WEIGHT FOR THE ENERGY STORAGE WES

	Per Unit	Per 4 Units
Reactant Weight, lb/hr	2.80	11.23
O_2 Rate, lb/hr	2.49	9.96
Power Required, kw @ 1.6V per Cell[(a)]	6.056	24.22
Power Penalty, lb @ 270 lb/kw	1,635	6,540
Heat Load, btu/hr @ 1.6V per Cell[(a)]	1,551	6,204
Heat Rejection Penalty, lb @ 0.054 lb/btu/hr[(b)]	84	336
Spared System Weight, lb		
Optimistic	402	1,608
Maintainable Design	1,004	4,016
Subtotal Equivalent Weight, lb		
Optimistic	2,121	8,484
Maintainable Design	2,723	10,892
Accessory Power, kw @ 20%[(c)]	0.606	2.422
Accessory Power Penalty, lb	164	656
Accessory Heat Load, btu/hr	2,069	8,276
Accessory Heat Load Penalty, lb	118	472
Total Equivalent Weight, lb		
Optimistic System Hardware	2,403	9,612
Maintainable System Hardware	3,005	12,020

(a) Not considering power conversion, power conditioning penalties nor the approximately 120 watts of 400 Hz, 115 VAC power used by the instrumentation.
(b) Assuming rejected directly to the liquid coolant.
(c) Assuming current controller efficiency of 92% and 120 watts of instrumentation power.

TABLE 3-3 MSS GAS ACCUMULATOR SUBASSEMBLY CHARACTERISTICS

Nominal Tank Pressure		300 psia
Maximum Tank Pressure		3000 psia
Gas Capacity @ 300 psia, lb	Per Tank	Total (4 Tanks)
H_2	1.10	4.40
O_2	8.88	35.52
Reactant Storage Tank Weight, lb		
H_2 Tanks	187	748
O_2 Tanks	90	360
Plumbing, Regulator, Valves[(a)]	14	52
Mounts and Supports[(a)]	29	116
Inside Tank Diameter, Inches		
H_2 Tanks	33	
O_2 Tanks	26	
Tank Volume, Ft^3		
H_2 Tank	10.9	43.6
O_2 Tank	5.3	21.3
Reactants, lb		
10-Hour Surplus	5.51	22.05
11.78 kw-hr Requirement	2.44	9.75
Residual at 60 psia	2.12	8.46
Total Reactants, lb	10.07	40.26

(a) Prorated

3.5.2 WES Characteristics

The characteristics of the MSS WES are summarized in Table 3-4. The Static Feed Water Electrolysis Subsystem (SFWES) design was assumed. As noted in Section 3.3, the weights should be increased from 374 lb to the range 402 to 1,004, depending upon the degree of maintainability and development level.

3.5.3 MSS Gas Accumulator Subassembly Characteristics

No changes are recommended in the MSS-designed RFCS Gas Accumulator Subassembly. The design approach was to size the reactant storage accumulators in accordance with normal energy storage requirements and to use this size tank at increased pressure for build-up requirements. This approach imposed a tank weight penalty on the Energy Storage Assembly, but additional tanks in the power module became available for energy storage. An increased safety factor was also involved in this approach since the tanks designed for 3,000 psia are normally operated at 300 psia.

Table 3-5 presents the Gas Accumulator Subassembly characteristics.

3.5.4 MSS Water Tank Subassembly Characteristics

No changes are recommended in the MSS-designed RFCS Water Tank Subassembly. One water tank services two WES's and two FCS's. Table 3-6 presents the subassembly characteristics.

3.6 RFCS Mounting Design Considerations

An evaluation was made of the location for mounting the RFCS. As shown in Figure 2-5, two WES's are located in SM-1 and SM-2. This was done to avoid exceeding core module weight limits. Two FCS's are located in each volume of the core module. Half of the gas and H_2O accumulators (two tanks of both O_2 and H_2 and one tank of H_2O) are located in each volume of the core module.

Figure 3-2 illustrates the RFCS mounting locations. Two possible changes might be:

1. Keep the WES closer to the solar array to minimize line losses; and
2. Separate the H_2 and O_2 storage tanks so they are not all located in the core module.

3.6.1 Personnel Safety

The subsystems are located within manned compartments but any other location would not allow convenient in-flight maintenance.

3.6.2 Redundancy

The concept of dividing the total energy storage requirement into four modular RFCS's provides adequate redundancy. Not only are there redundant subsystems in each volume and each volume is redundant, but the WES and FCS hardware for the ECLSS/RCS and secondary power generation, respectively, serve as RFCS backups. (See Sections below).

TABLE 3-4 REVISED MSS WATER ELECTROLYSIS SUBSYSTEM CHARACTERISTICS

Nominal Reactant Generation Rate	2.80 lb/hr
O_2	2.49 lb/hr
H_2	0.31 lb/hr
Maximum Sustained Reactant Generation Rate	3.9 lb/hr
O_2	3.46 lb/hr
H_2	0.44 lb/hr
Maximum Overload Capability (Time Limited TBD)	5.5 lb/hr
O_2	4.88 lb/hr
H_2	0.62 lb/hr
Nominal Operating Pressure	300 psig
Operating Pressure Range	60-400 psia
Nominal Cell Operating Temperature	160F

			Revised Total	
	Per Unit	Total (4 Units)	Optimistic	Maintainable
Weight	322 lb	1,288 lb	1,608 lb	4,016 lb
Plumbing, Regulator, Valves[(a)]	22 lb	88 lb	(b)	(b)
Mounts and Supports[(a)]	30 lb	120 lb	(b)	(b)
Unit Dimensions (LxWxH)	24x24x28 In	---	---	---
Volume	16 ft^3	64 ft^3	---	---
Density	20.1 lb/ft^3	---	---	---

(a) Prorated
(b) Included in weight members

TABLE 3-5 MSS FUEL CELL SUBSYSTEM CHARACTERISTICS[a]

Maximum Sustained Power	7.0 kw	
Maximum Power Within Voltage Limits	10.0 kw	
Voltage Limits	112 volts (+5-11%)[b]	
Minimum Power	200 watts[c]	
Minimum Reactant Supply Pressure	60 psia	
Maximum Coolant Temperature (to Fuel Cell)	120F	
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) Amp/Ft^2	
Operating Temperature	190(190-250F)F	
Operating Life	10,000 (Adv. Shuttle FC)	
Overload	2 times nominal rating	
	Per Unit	Total of 4 Units
Weight, lb	202	808
Unit Dimensions (LxWxH)	13x13x55 In (approx.)	--
Volume, Ft^3	5.4	24
Batteries	10	40
Plumbing, Regulator & Valves[d]	16	64
Mounting & Supports[d]	22	88
Inverters	5	20
Sequencers	3	12
Wiring	15	60

(a) Alkaline Matrix Fuel Cell
(b) Voltage level does not appear to have a large effect on power plant weight or program cost.[128]
(c) Power generated will probably be higher to sustain the operating temperature.
(d) Prorated

TABLE 3-6 MSS WATER TANK SUBASSEMBLY CHARACTERISTICS

Nominal Tank Pressure	60 Psia	
Maximum Tank Pressure	400 Psia	
Tank Capacity, Lb	Per Tank	Total (2 Tanks)
Nominal Requirement	40	80
Maximum Requirement	322	644
Weight, Lb	40	80
Spherical Volume Diameter	26 In	
Volume, Ft^3	5.3	10.7
Water Pump	TBD	TBD
Plumbing, Regulator & Valves[a]	29	58
Mounts and Supports [a]	21	42

(a) Prorated

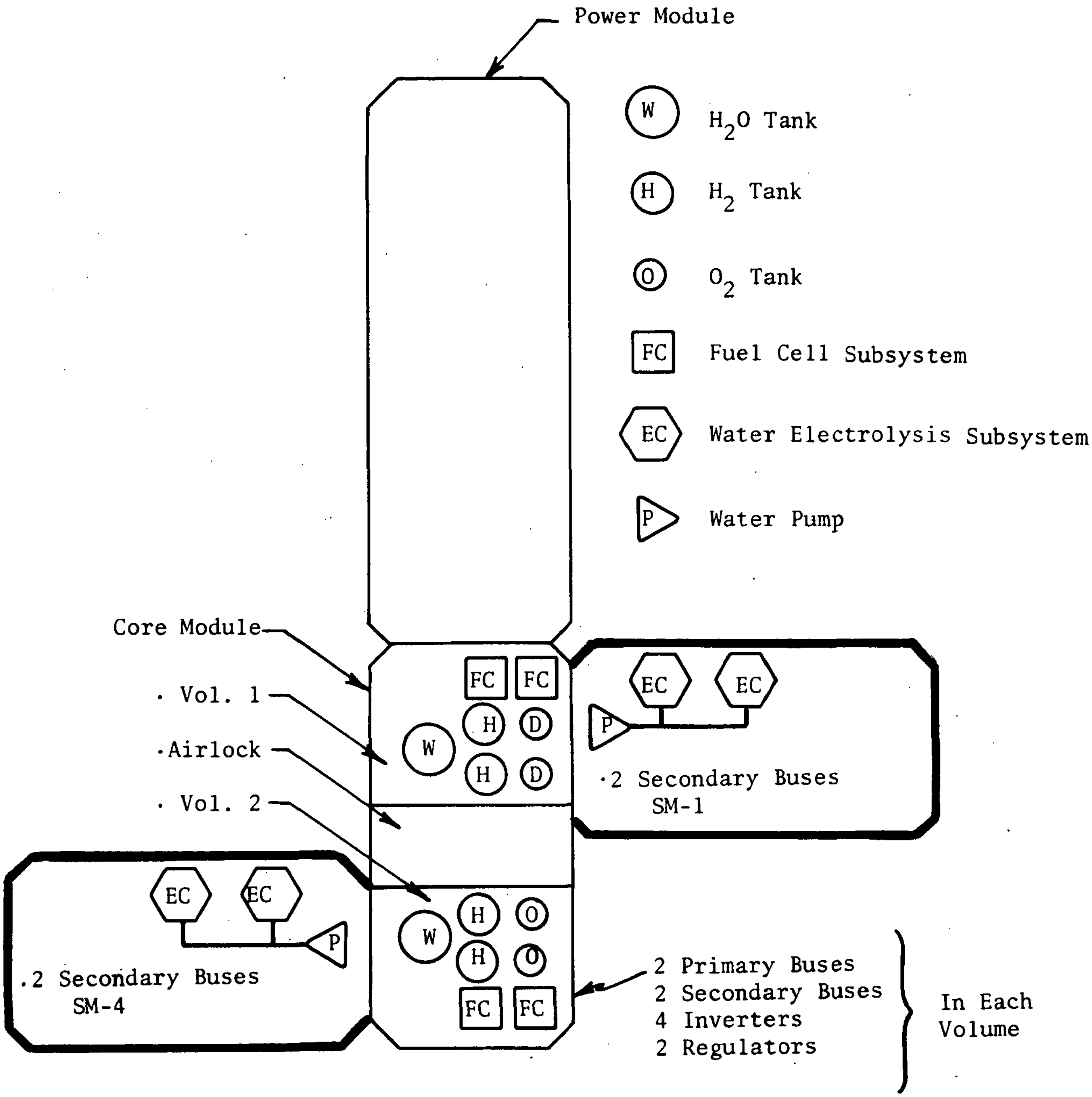


FIGURE 3-2 RFCS MOUNTING LOCATIONS

3.7 Gas Distribution

Figure 3-3 shows the gas distribution for the integrated EPS/RCS/ECLSS. It illustrates how the EPS electrolysis units in SM-1 and SM-4 can back up the ECLSS electrolysis units in SM-2 and SM-3.

3.8 Water Distribution

Figure 3-4 shows the H_2O distribution for the integrated EPS/RCS/ECLSS. It illustrates the backup possibilities.

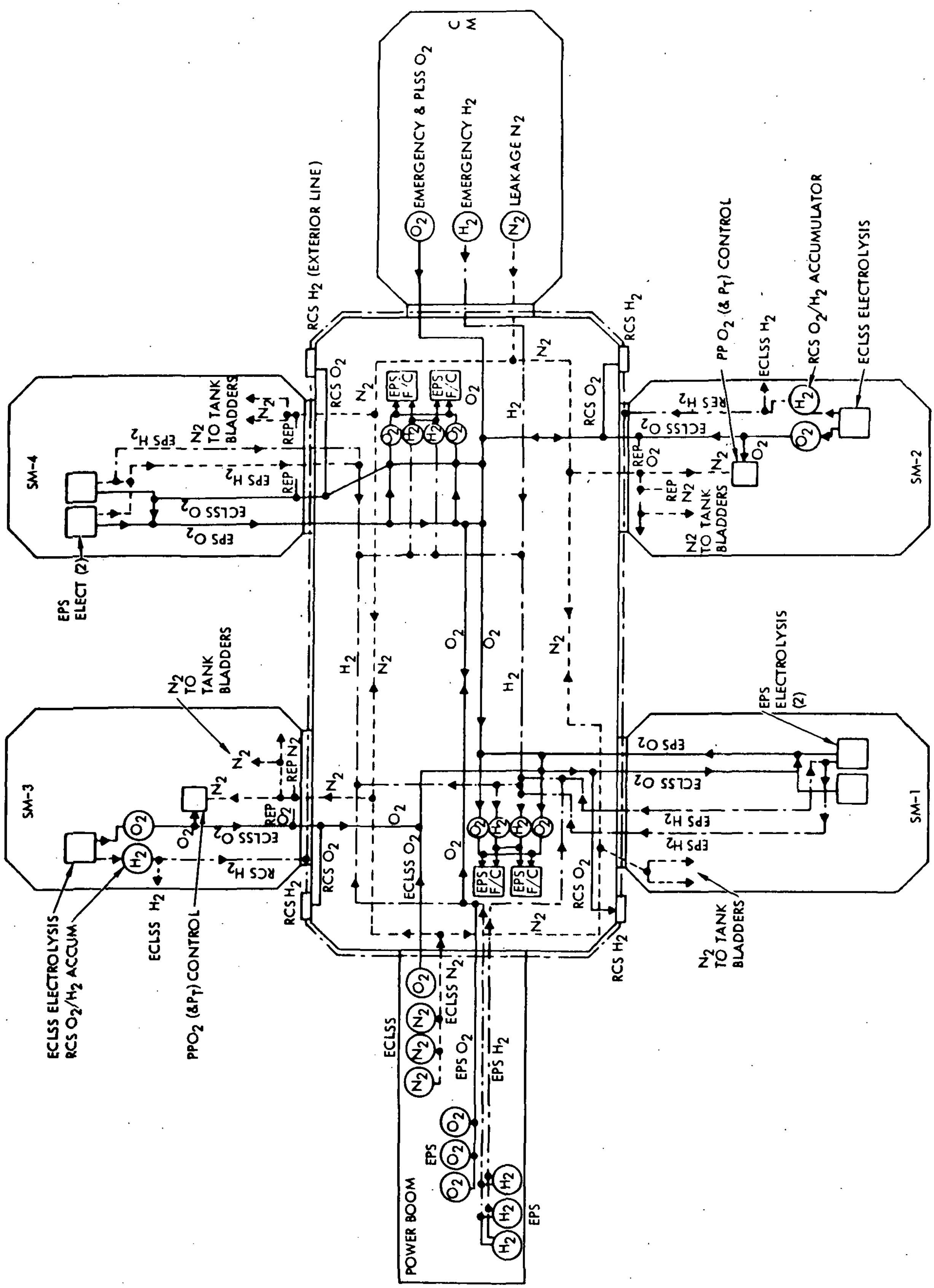


FIGURE 3-3 EPS/ECLSS/RCS INTEGRATED GAS DISTRIBUTION

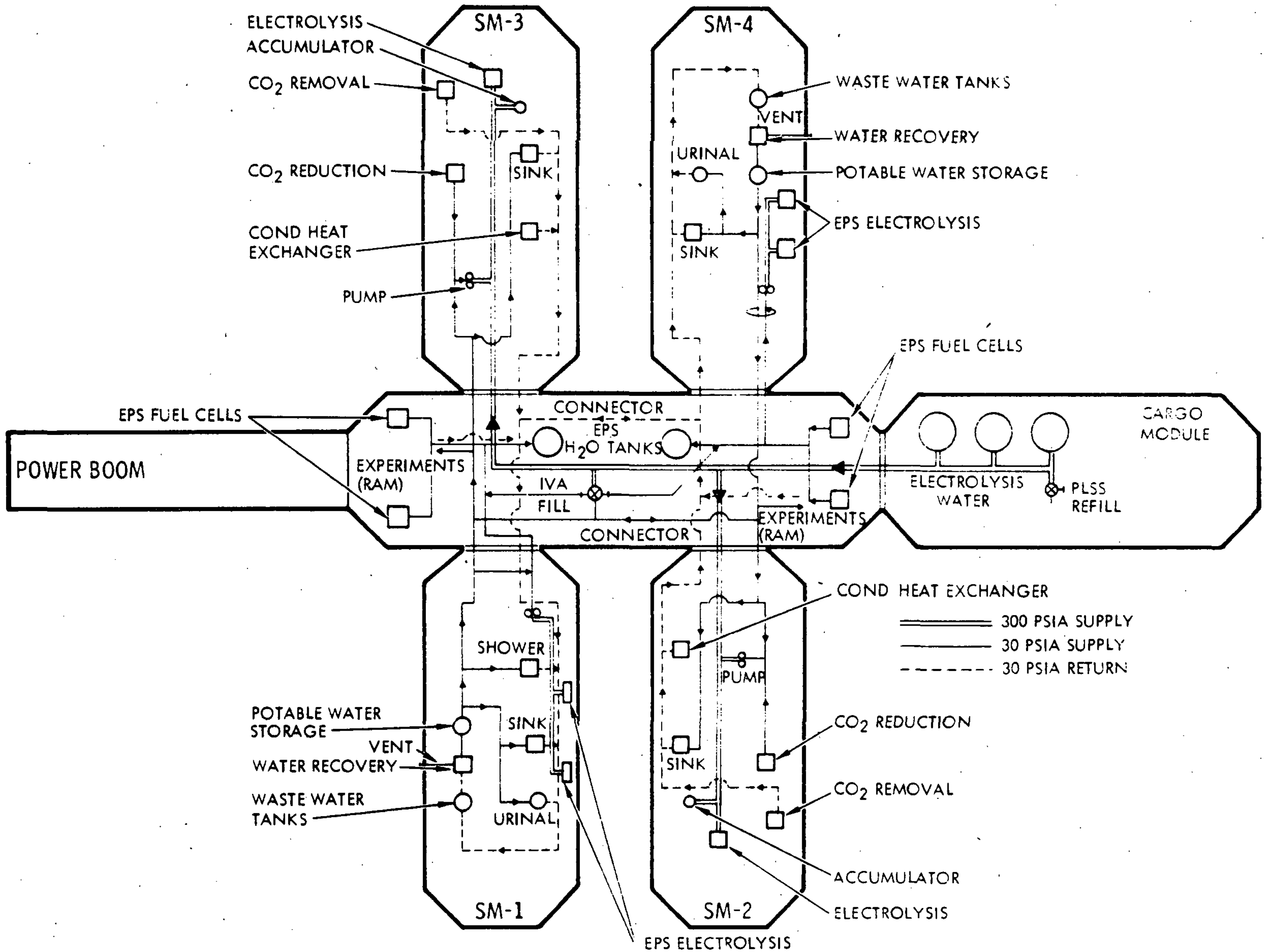


FIGURE 3-4 EPS/RCS/ECLSS INTEGRATED WATER DISTRIBUTION

4.0 REGENERATIVE FUEL CELL SUBSYSTEM VERSUS NiCd BATTERY SUBSYSTEM

The NASA Guidelines and Constraints document provided the basic requirement that a solar array concept should be used for the MSS primary power generation assembly. Figure 2-5 illustrated the preliminary design of EPS for the MSS.

The Energy Storage Assembly supports the MSS operations during sun eclipse portions of each orbit and also supports peaking loads during sunlight periods. Based on the efficiencies used, 1.9 kw-hr of primary solar array energy were required to provide 1.0 kw-hr of stored energy.(1)

4.1 Approaches to Energy Storage

Of the methods considered for energy storage,(2) only the NiCd batteries, regenerative fuel cells, and a hydrazine auxiliary power unit were retained by NAR for evaluation during the Phase B Extension studies. The latter was rejected because:

1. Excessive design and development cost, and
2. Large fuel weight requirement.

Both the RFCS and NiCd battery approaches had merit.

4.2 Trade Study Evaluations

It is worth noting the NiCd Battery option always has to be penalized for the FCS because of the requirement for a H_2-O_2 fuel cell as the emergency and secondary power source. Other significant technical advantages found for the RFCS energy storage concept are summarized below.

4.2.1 Thermal Control

The battery concept imposed an additional development requirement on the thermal control assembly due to its low temperature demands (i.e., 40F). The development of dual thermal control loops to provide 130F and 40F resulted in a cost penalty estimated at $4.8 million for the latter loop.

4.2.2 Solar Array Area

Effective utilization of solar array was a major consideration. The battery approach was more efficient on a charge-discharge comparison based on a per orbit cycle. This resulted in a savings of 720 ft^2 of solar array area. The regenerative fuel cell concept, however, was more adaptable to a combination

(1) To reduce the array area requirement, the energy storage assembly was sized to operate on a two lb-per-orbit fuel cell reactant (2.43 kw-hr) deficit during maximum crew activity, an amount which was made up during crew rest periods at a rate of 3.5 lb per orbit (4.25 kw-hr).

(2) North American Rockwell, "Modular Space Station Phase B Extension, Preliminary System Design," Vol. VI: Trades and Analyses, SD 71-217-6, NASA Contract NAS9-9953, DRL No. MSC 7-575, Line Item 68, page 197, Jan., 1972.

of per orbit and 24-hour cycling. Since the load profile had a 14-hour high-power demand and a 10-hour relatively low-power demand, excess gas generation during the 10-hour low-demand period could be stored and used during the 14-hour high-power demand period. In this way, the load demand was averaged out and solar array area requirement reduced. The same approach was recognized to be possible for batteries but at excessive weight and complexity increases.

4.2.3 ISS/EPS Interface Complexity

The battery approach used in the NAR comparison consisted of 84 cells per battery with battery charging provided for each 20-24 cells. Each primary bus was supported by two batteries or a total of eight batteries. The ISS interface consisted of battery charging at a 20-24 cell module level with the ability to switch four-cell modules and instrumentation on an individual cell basis.

The regenerative fuel cell approach essentially replaced two complete batteries on a primary bus with a single FCS and WES set. Power and monitoring was achieved on the modular level with complexity considered reduced by a factor of eight (or greater). The cost savings to the ISS was estimated to be a minimum savings of two preprocessors at roughly $0.52 million.

4.2.4 Battery Charge/Charge Control Constraint

Available battery charging energy from the solar array was limited to about 13.6 kw. Using a conventional four-step charge scheme, it was only possible to fully charge one battery per orbit and partially charge the remaining batteries. Considerable technology improvements were felt necessary to satisfy battery charging and control to obtain efficiency and life characteristics assumed for the MSS battery concept.

4.2.5 Initial Launch Weights

The regenerative fuel cell concept was felt to have a decided weight advantage (16,351 lb regenerative fuel cell versus 22,932 lb batteries).

4.2.6 Cost

A review of NAR's cost comparisons shows a lower cost (approximately $7 million) for regenerative fuel cells based on savings attributed to shared development (i.e., shuttle fuel cells and ECLSS electrolysis). This cost advantage improves with operating time by about an additional $1 million because of lower resupply weights.

4.3 Advantages of the Regenerative Fuel Cell Subsystem

Table 4-1 summarizes the advantages cited for the RFCS. Probably the most significant advantage is the fact that the RFCS can function both as an energy storage device and as a Space Station "utility." Figure 4-1 illustrates how the modular WES serves as this utility.

The selection of the RFCS approach to energy storage over the battery approach was sensitive to:

TABLE 4-1 ADVANTAGES CITED FOR THE RFCS

1. The RFCS can function as a battery and as a space station utility (especially the WES).

2. The RFCS is able to use the space shuttle fuel cell subsystem and ECLSS WES developments to minimize development costs.

3. The RFCS approach resulted in a 6,000 lb weight savings over NiCd battery subassembly.

4. The RFCS was the only single assembly that offered potentially great weight reduction of solar array electrical power systems in near-earth orbit. The RFCS had a smaller solar array area requirement: 7,540 ft^2 based on 24 hour cycling versus 7,780 ft^2 based on the per orbit cycling needed by the battery.

5. The RFCS has extensive growth potential because of the large theoretical fuel cell energy density.

6. The RFCS avoided the large ISS complexity for monitoring and fault isolation of the 672 cells in the batteries.

7. The RFCS avoided a $4.8 million development associated with a second, 40 F low temperature coolant load need only for the battery.

8. The RFCS was better able to use the excess power available during the 10 - hour low demand period to generate reactants for later use than was the battery.

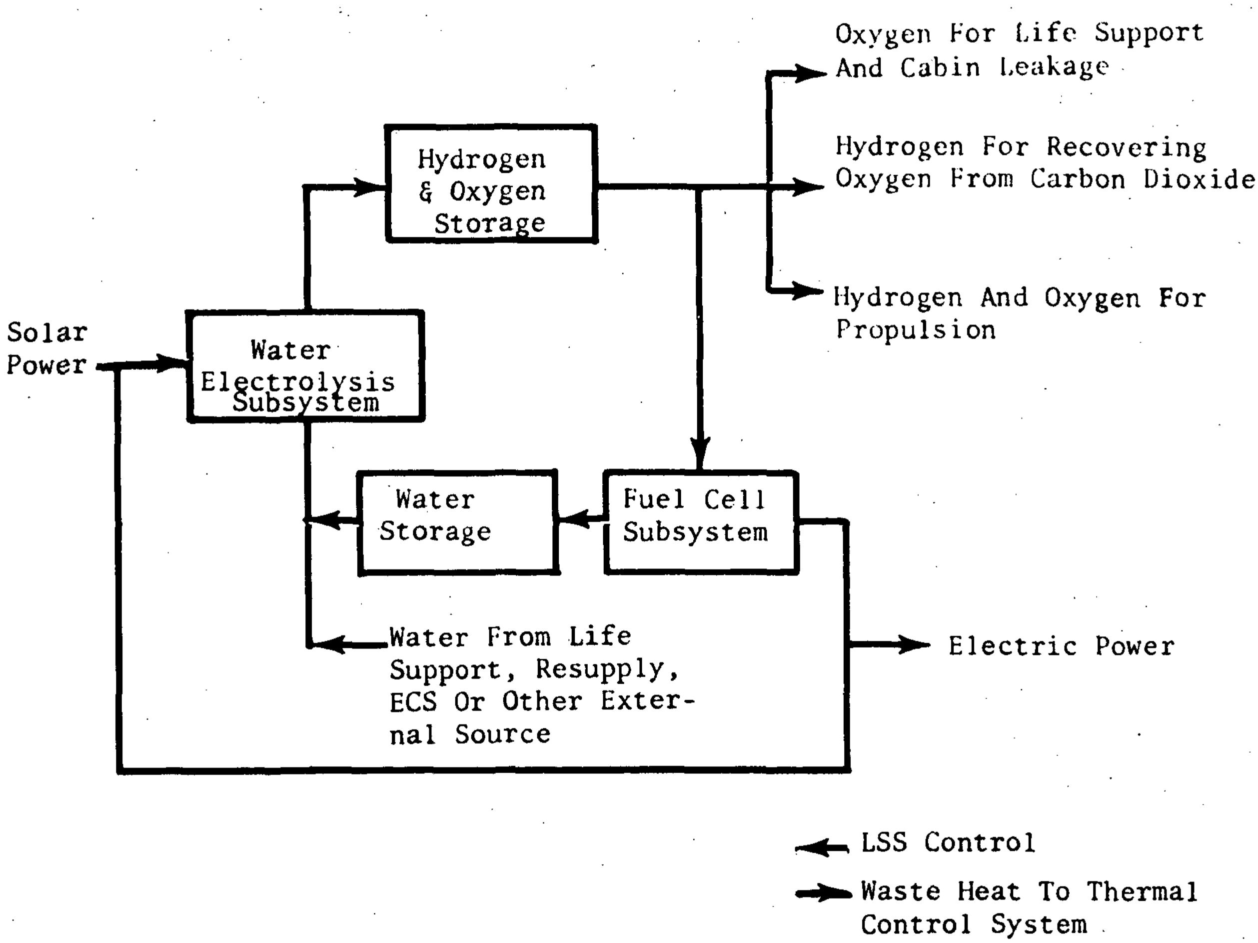


FIGURE 4-1 WATER ELECTROLYSIS SUBSYSTEM AS A MSS UTILITY SUPPLY

1. The sharing of development costs with the ECLSS WES and Space Shuttle FCS;
2. Fuel cell lifetimes of 10,000 hours;
3. Water electrolysis cell lifetimes of 15,000 hours; and
4. Twenty-four-hour cycling of energy storage instead of per-orbit cycling.

4.4 Advantages of the Battery Subsystem

Table 4-2 summarizes the advantages cited for the NiCd Battery Subsystem. The major advantages being the lower development risk.

4.5 Trade Study Assumptions

Several assumptions made in comparing a RFCS with the NiCd Battery Subsystem must be as noted:

1. Assumed 2.5 year lifetime is for both the RFC and battery. (The data supporting this is more extensive for batteries than for the WES or FCS. The 17,000-hour lifetime basis for the WES was obtained on approximately 2-inch x 2-inch cells and on cells operated at conditions not comparable to the operating conditions required for the RFCS application.)
2. Assumed a regenerative fuel cell is simpler than one Modular NiCd Battery. (A modular battery consisted of 168 cells, 8 battery chargers and instrumentation. An energy-comparable modular RFCS consists of approximately 100 fuel cells, 72 electrolysis cells, O_2, H_2, and H_2O storage tanks, power conditioner, associated valves, regulators and fluid lines, water pump, and instrumentation.)
3. Assumed the RFCS is safer than a battery. (The fuel cell and H_2O electrolysis cells both involve H_2 and O_2 in close proximity to each other, however.)
4. Assumed a RFCS storage efficiency of 0.525. (The more probable value is 0.47 or below, i.e.,
   RFCS efficiency = (current controller efficiency) (WES efficiency) (FCS efficiency) (inverter efficiency) or

$$\text{RFCS} = (0.92)(0.915)(0.623)(0.9) = 0.472^{(1)}$$

(1) In addition, as noted in Section 5.6.1.2 and Table 5-13 of the RFCS Design Handbook (see reference 1 on page 2.3), the WES efficiency may not be 0.915 but could be closer to 0.74.

TABLE 4-2 ADVANTAGES CITED FOR THE NiCd BATTERY SUBSYSTEM

1. The battery has better charge-discharge efficiency: 0.625 vs 0.525.
2. The battery has less heat rejection: 8 kw vs 10.5 kw.
3. The battery technology is more established with only new battery charging techniques to be developed.
4. The battery development has lower risk.
5. The battery design had a 29% pad against power degradation (672 cells included vs 520 cells required) because of configuration constraint.
6. The battery has demonstrated life time voltage characteristics (e.g., 1.25 to 3.5 years of continuous cyclic operation at the 20% depth of discharge) and amp-hour lifetimes beyond the target life of 2.5 years.

4.6 Comparison Conclusions

The RFCS is selected as the preferred energy storage concept because:

1. It integrates better with the MSS and provides a reliability, backup operating flexibility, and commonality of subsystem hardware not possible any other way.
2. It shares development cost minimizing number of development programs.
3. It integrates better with the primary solar array power source by allowing 24-hour cycling for solar area reduction.
4. It makes possible a WES "utility" based on common fluids: H_2O, O_2, and H_2.

5.0 DEVELOPMENT PLAN CONSIDERATIONS

5.1 MSS Projected Development Cost

Table 5-1 summarizes the projected development cost for the RFCS.

TABLE 5-1 MSS PROJECTED COST[1]

	Energy Storage
Development	$14,700,000[2]
Hardware	5,300,000
Operations	7,900,000[3]
Total (IOC + 5 Yr Ops)	$27,900,000

5.2 Major Near-Term Cost Items

Major near-term cost items are associated with the FCS and WES. These include:

1. Development of the cell stacks (modules);
2. Demonstration of operating life;
3. Incorporation of maintainability; and
4. Development of Subsystem Accessories:
   a. Power Conversion (conditioning), $\eta = 0.92$
   b. Phase Separation Devices
   c. Water Feed Control
   d. Gas Generation Rate Controller
   e. Gas-Gas and Gas-Liquid Pressure Differential Regulators

5.3 Techniques to Minimize Development Costs

Techniques to minimize cost include:

1. Minimize the number of subsystem components;

(1) Costs associated with the gas storage tanks and water storage tanks are not included.

(2) Shared WES development with ECLSS and FCS with Space Shuttle and Secondary Power Generation.

(3) Assumes launch items at $250/Lb.

2. Accept higher electrolysis cell and lower fuel cell operating voltages;
3. Select an approach that has room for growth;
4. Target a portion of the development fund to components required by both competitive approaches; and
5. Concentrate funds on life-limiting components.

5.4 Examples of Cost Trade Study Possibilities

Various approaches can be used to trade cost versus development objectives. Generally, the more funds expended, the greater the optimization, although each increment of funding does not contribute the same percentage improvement. The last 10 percent improvement can often take 90 percent of the development funds. Examples are contained in the following sections.

5.4.1 Effect of Development Level on Equivalent Weight

The final WES configuration and its equivalent weight is a function of the funds expended. This can be seen by illustrating how the WES power penalty varies with development level. The same holds true for all other areas of subsystem optimization. Figure 5-1 presents a comparison of the RFCS WES power penalty assuming

1. No power conversion penalty (this does not seem likely but included as a reference point);
2. A 10 percent power conversion penalty (development needed); and
3. A 20 percent power conversion penalty (no development needed) as a function of three levels of electrode performance:

   a. With the best projected electrodes (1.5 volts per cell at 150 amp/sq ft);
   b. With advanced electrodes (1.6 volts per cell at 150 amp/sq ft); and
   c. With existing electrodes derated for reliability and scale-up factors (1.9 volts per cell at 150 amp/sq ft).

Data such as that contained in Figure 5-1 is useful in evaluating how development funds should be expended to result in the greatest equivalent weight savings. This is further illustrated in Table 5-1, using the data from Figure 5-1. It includes consideration of equivalent weight for a 2.49 lb O_2/hr WES based on state-of-the-art and three levels of development:

1. With development of power conversion equipment having a 10 percent efficiency;
2. With development of advanced electrodes yielding End of Life (EOL) cell voltages of 1.6 volts at 150 amp/sq ft; and
3. With the ultimate in electrode performance yielding EOL cell voltage of 1.5 volts at 150 amp/sq ft.

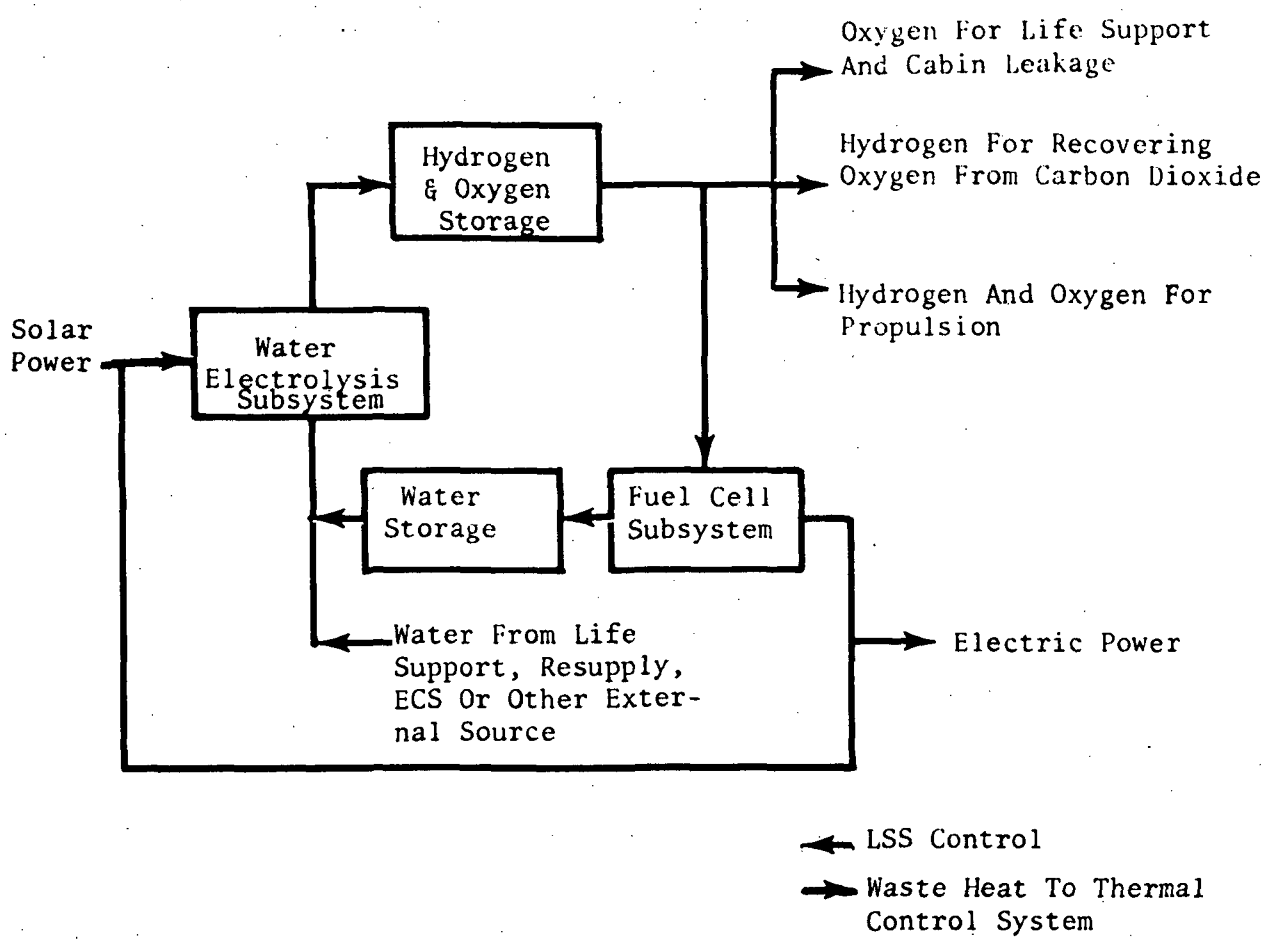


FIGURE 5-1 WATER ELECTROLYSIS SUBSYSTEM AS A MSS UTILITY SUPPLY

TABLE 5-2 SAVINGS IN WES'S EQUIVALENT WEIGHT (POUNDS) DUE TO POWER AND HEAT REJECTION PENALTIES

	Power[a] Weight Penalty	Liquid Heat Rejection Penalty[b] or		Air Heat Rejection Penalty[c]		All Liq. Cooling	Air Cool Module & Liq. Cool. Pwr. Conversion	All Air Cooling
		Power Conversion	Module or	Power Conversion	Module			
0. State-of-the-Art	2330	264	288	629	684	2882	3278	3643
1. Develop Power Conversion Equipment with 10% Inefficiency	(194)[d]	(132)	0	(315)	0	(326)	(326)	(509)
2. Decrease Module's Avg. EOL Cell Voltage to 1.6 Volts	(337)	(21)	(209)	(50)	(495)	(567)	(853)	(882)
Subtotal	1799 Lb	111	79	264	189	1989	2099	2252
Percent Savings						31	36	38
3. Decrease Module's Avg. EOL Cell Voltage to 1.5 Volts	(113)	(7)	(69)	(16)	(166)	(189)	(286)	(295)
Total	1686	104	10	248	23	1800	1813	1957
Percent Savings						38	44	46

(a) Power equivalent weight for 2.49 Lb O_2/Hr, 1.9 Volts/Cell; 20% power conversion inefficiencies, and 270 Lb/Kw.

(b) Penalty for heat rejection directly to liquid coolant of 0.184 Lb/Watt (0.0128 Lb/Btu/Hr).

(c) Penalty for heat rejection to cabin air of 0.437 Lb/Watt (0.054 Lb/Btu/Hr).

(d) The numbers in parenteses indicate pounds saved with development.

Steps 1, 2 and 3 all require research and development funds and each step will take more funds than the prior step. The comparison is now made for three cases:

1. Both cell stack (module) and power conversion heat rejected to a liquid coolant;
2. Cell stack heat rejected to ambient air and power conversion heat rejected to liquid; and
3. Both cell stack and power conversion heat rejected to a liquid coolant.

If development is taken through Steps 1 and 2, the equivalent weight savings for the two power and heat penalties [1] amounts to 31 percent to 38 percent, depending upon source of cooling. If the third step is taken, the equivalent weight saved is 38 percent to 46 percent or an additional 7 percent to 8 percent. Examples of conclusions that can be drawn include:

1. The difference in equivalent weight between a subsystem employing air cooling of the module (only) is significant if the average cell voltage is at the 1.9 volt level (684 lb) but is insignificant at the 1.5 volt level (10 lb).
2. Decreasing power conversion inefficiency from 20 percent to 10 percent results in an equivalent weight savings of 326 lb or 11 percent, if liquid cooling assumed (509 lb or 10 percent, if air cooling assumed).
3. Decreasing the module's average EOL cell voltage from a low risk 1.9 volt level to 1.6 volt results in an equivalent weight savings of 567 lb or 20 percent, if liquid cooling assumed (882 lb or 24 percent, if air cooling assumed).

(Note - the 2.49 lb O_2/hr design is only one-fourth of the total WES required for the MSS RFCS.)

5.4.2 Effect of Electrode Cost

A second cost trade-off example trades WES electrode cost against subsystem weight or power savings. Table 5-3 presents the data for four cases:

1. A baseline design;
2. An advanced, higher current density design;
3. An advanced, higher current density design using lower catalyst loadings; and
4. The Water Vapor Electrolysis Subsystem limited in current density.

It is assumed that the complete development will require 21 subsystems with an area electrode determined from the current density and reactant generation rate. A common approach to electrode cost is used with the high catalyst loading electrode costing four times the low catalyst loading electrode. The total cost is then expressed as pounds (based on two levels of Space Shuttle costs) and as power at a penalty of 270 lb/kw.

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[1] Cell and power conversion.

TABLE 5-3 EFFECTS OF ELECTRODE COST (2.80 Lb H_2O/Hr DESIGN)

Design	Catalyst Loading	Current Density	Total Electrode Cost For 21 Modules [a,b]	Savings Possible Over Baseline: Weight @[c] $250/Lb	Weight @[c] $500/Lb	Power @ 270 Lb/Kw[d] $250/Lb	Power @ 270 Lb/Kw[d] $500/Lb
Baseline Design	40 Mg/Cm^2	100 ASF[e]	$ 744,920	0	0	0	0
Advanced Design	40 Mg/Cm^2	300 ASF	$ 248,300	1987	993	7.40	3.7
Advanced Design (Higher Risk)	10 Mg/Cm^2	300 ASF	$ 62,075	2731	1366	10.1	5.1
WVES[f]	40 Mg/Cm^2	30 ASF	$2,483,000	(6952)[g]	(3476)[g]	(25.8)[g]	(12.9)[g]

(a) Assumes:

	Modules
Laboratory Breadboard	5
Subsystem Breadboard	1
Pre-Engineering Prototype	1
Prototypes	2
Flight Qualifiable Units	8
Flight Units	4
Total No:	21

(b) Assumes $6 per Gm catalyst, three times catalyst cost for electrode fabrication, and 5% allowance for quality control testing and scrap.
(c) Shuttle launch cost range $250 to $500/lb
(d) Assuming dollars saved converted into solar array power on basis of 270 lb/kw
(e) ASF - Amp/Sq Ft
(f) Water Vapor Electrolysis Subsystem
(g) The parenthesis indicates penalty over baseline.

6.0 RECOMMENDATIONS

A summary of the Contractor's recommendations were presented elsewhere.[1] The major near term recommendations are reiterated below.

6.1 Regenerative Fuel Cell Subsystem Recommendations

- Carry out a more detailed study comparing RFCS with nickel-cadmium batteries. Evolve a better set of design evaluation criteria.
- Initiate a study to establish what design areas to emphasize for maximum return on development funds.
- Carry out testing to point where failure is due to inability to perform the function and to, thereby, establish minimum design compatible with the required operating life. Avoid trying to reach such high performance levels that testing is prematurely terminated thus preventing the establishment of some actual technology base.
- Establish the technology dividend the RFCS development has for terrestrial problems.

6.2 Water Electrolysis Subsystem Recommendations

- Expand the study on the influence of WES design factors on total equivalent weight versus cost to develop.
- Test characterize operation of a Static Feed Water Electrolysis Module at the elevated pressures required for RFCS integration and verify:
  - Absence of feed H_2O degassing.
  - Absence of aerosols.
  - Elimination of condenser/separators.
- Obtain technology on RFCS related design subjects:
  - Loss of reactants during standby at design pressure.
  - Tolerance to unregulated source voltages of 130 VDC.
  - Selection of 112 or 56 VDC as the power source.
- Fabricate a self-contained, zero gravity applicable WES capable of cyclic operation.
- Complete the next generation current controller (92% efficient versus 86%).
- Carry out a study to establish penalties associated with using common WES's for ECLSS and the RFCS.

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(1) Life Systems, Inc., Engineering Report ER-151-7, "Regenerative Fuel Cell Study Recommendations," November 25, 1972.

- Evolve a better set of subsystem design evaluation criteria.

- Continue to improve the performance of the O_2 evolving electrode so that higher current densities are obtainable at lower cell voltages.

6.3 Fuel Cell Subsystem Recommendations

- Incorporate in-flight maintainability considerations into the hardware design including fault detection/isolation analysis. This is being done for the WES under SSP Program guidelines.[1,2]

- Drop emphasis on increasing energy density and begin emphasis on reliability through maintainability.

- Test full size modules to establish minimum design compatible with the required operating life (lower current densities, lower voltages, etc. with emphasis on life rather than on energy density, Lb/Kw).

- Complete an evaluation study to determine the real similarities between a Space Shuttle Fuel Cell Subassembly and one needed to fit the requirements of a MSS/RFCS (especially in areas of operating duty cycle, reactant purities, maintainability, etc.)

- Continue the development activities started on NAS3-13229 to establish effect of design and operating factors on life and performance of alkaline matrix fuel cells.[3]

- Establish answers to such technology questions as:
  - The allowability of alkaline matrix type fuel cell coolant within the manned portions of the MSS;
  - How to avoid the dry O_2 reactant problem;
  - Method(s) to keep the electrolyte invariant
  - Relaxation possible in fuel cell voltage regulation (changing from $\pm 5\%$ to $\pm 10\%$ could have a 30% impact on baseline weight)

6.4 Gas Accumulator Subassembly

No development activity is recommended. The tank weights are determined by another requirement. The design approach was to size the reactant storage accumulators in accordance with normal energy storage requirements and to use this size tank at increased pressure level for MSS buildup needs of secondary fuel cell requirements. This approach imposed a tank weight penalty, but

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(1) Willis, N. C., Jr., Samonski, F. H., Jr., Flugel, C., and Tremblay, P., "System Features of a Space Station Prototype Environmental Thermal Control and Life Support System," ASME Paper No. 71-Av-22, Life Support and Environmental Control Conference, San Francisco, Calif., July 12-14, 1971.

(2) Willis, N. C., Jr. and Neel, J. M., "Space Station Prototype Environmental Thermal Control and Life Support System - A Current View," ASME Paper No. 72-ENAv-35, Life Support and Environmental Control Conference, San Francisco, Calif., Aug., 14-16, 1972.

(3) Bell, W. F. and Wood, K. O., "The Effect of Design and Operating Factors on Life and Performance of Matrix Fuel Cells," NASA CR-72906, Contract NAS3-13220, Feb., 28, 1971.

additional tanks in the power module became available for energy storage. An increased safety factor was also involved in this approach since tanks designed for 3000 psia are, therefore, normally operating at only 300 psia.

A total tank weight of 1,108 lb was used to obtain baseline EPS weights. These weights were based on a station buildup gaseous storage pressure of 3000 psia and as such are not representative of the true penalty for 24-hour reactant generation averaging. Tank weight sized for the maximum 300 psia pressure and a safety factor of four were estimated to weigh 592 lb. If the tanks were sized for the orbit-to-orbit requirement for the 14-hour work period, the total amount of gas required including residuals was 13.5 lb (tank weight equaled 128 lb). These options are summarized in Table 6-1. Thus, a substantial reduction in tankage weight could be made by operating on an orbit-to-orbit basis. This would be largely offset, however, by a required increase in solar array weight. For a fixed charge-discharge efficiency, an approximate 10% reduction in solar array power (proportional to area) results if excess solar array power available during the 10-hour rest period is stored and used during the 14-hour work period.

TABLE 6-1 GASEOUS REACTANT STORAGE TANK WEIGHT

Tanks Sized For	Tank Weight, Lb
Baseline EPS Weight	1108 (a)
Maximum 300 psia Pressure and a Safety Factor of 4	592
Orbit-to-Orbit Requirement of the 14-Hour Work Period (b)	128 (c)

(a) Based on using station buildup gaseous storage tanks designed for 3000 psia operation.
(b) Total amount of gas required is 11.02 lb plus 2.48 lb of residuals.
(c) This substantial reduction in tankage weight is offset, however, by a required increase in solar array weight.

6.5 Water Accumulator Subassembly

The water storage tanks are sized so one tank services two fuel cells and two electrolysis cell units. The tank weight of 40 lb, with a 26 in. diameter (5.3 ft^3) is reasonable since each has a capacity of 322 lb H_2O or approximately 5.2 ft^3 of H_2O (322 lb x 454 g. x 1 cm^3 x 3.531 x 10^{-5} ft^3 = 5.2 ft^3). Little savings in weight can result so no additional development is being recommended.

6.6 RFCS Location

The selected locations for the major RFCS components are good. They provide the redundancy needed and avoid vulnerability to single failures. The WES, located in SM-1 and SM-4, are far enough from the power supply, however, to warrant caution in selecting the electrolysis load current. Assuming the solar array directly powers the cell stack, the weight penalty for transmission of the power can be unexpectedly high when cell stack current levels exceed 50 amps.

6.7 Product Assurance Recommendations

- Incorporate maintainability starting with the establishment of maintainability specifications to the same level as RFCS life or capacity is eatablished.

- Increase demonstrated operating reliability and begin emphasis on subsystem concept simplification especially in the WES area.

- Establish safety penalties and complete a Safety Hazard Analysis Study.

- Monitor nonmetallic materials for acceptability. Metallic materials are not pacing item.

- Delay activity on quality control.

7.0 CONCLUSIONS

A study has been completed of the Regenerative Fuel Cell Subsystem (RFCS) as an energy storage process for use aboard the Space Shuttle launched, Modular Space Station (MSS). The RFCS consists of a Water Electrolysis Subsystem (WES), a Fuel Cell Subsystem (FCS), a Gas Accumulator Subassembly, and a Water Accumulator Subassembly.

The present report reviews the MSS including configuration and module mounting locations. It reviews the manner in which the Electrical Power Subsystem, Reaction Control Subsystem, and Environmental and Life Support Subsystem (ECLSS) integrate. Specific mounting locations are given for the WES, FCS, and the gas and H_2O distribution networks.

The characteristics of the complete RFCS and its subsystems are presented. This includes weight, requirements, and description.

The Static Feed Water Electrolysis Subsystem was identified as being preferred. It consists of an alkaline electrolyte held in a porous matrix. Water is statically fed to individual electrolysis cells from water feed compartments located adjacent to the cells. Process heat is removed by passing air over external or internal fins.

The alkaline matrix Fuel Cell Subsystem was selected to illustrate the fuel cell interface. Final decision will depend upon the fuel cell selected for the Space Shuttle.

The comparison between RFCS and a Nickel-Cadmium Battery Subsystem was reviewed. The RFCS was selected because it enables considerable design flexibility in the MSS operation. Other reasons included lower launch weight, smaller solar array area requirements, and lower design and development costs. The lower cost results from sharing the FCS development cost with the Space Shuttle FCS development and sharing the WES development cost with the ECLSS WES development.

Additional work is required in study and technology areas. The WES technology is a pacing one. The FCS technology, however, is also characterized by a lack of extended operating time on the advanced fuel cell concepts needed for the RFCS application.