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ENGINEERING MODEL SYSTEM STUDY FOR A REGENERATIVE FUEL CELL

STUDY REPORT

by

B. J. Chang, F. H. Schubert, A. J. Kovach
and P. A. Wynveen

September, 1984

Prepared Under Contract NAS 3-21287

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Life Systems, Inc.
Cleveland, OH 44122

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LEWIS RESEARCH CENTER
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FOREWORD

The work described herein was conducted by Life Systems, Inc. for the National Aeronautics and Space Administration, Lewis Research Center in accordance with the requirements of Contract NAS 3-21287. The period of performance for the program was October, 1983 to September, 1984.

The overall Program Manager for the contract was F. H. Schubert. Dr. B. J. Chang was a major contributor to the Engineering Model System Design Definition effort. Technical support for the Regenerative Fuel Cell System Study was provided by A. J. Kovach and Dr. R. A. Wynveen.

The contract Technical Monitor was Mr. Mark A. Hoberecht, Electrochemistry Systems Section, Lewis Research Center, Cleveland, Ohio.

The authors wish to acknowledge the important technical contributions and program guidance offered by M. A. Hoberecht and D. Sheibley of Lewis Research Center, and D. Denais and L. Murgia of Johnson Space Center.

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LIST OF ACRONYMS

ASF	Amperes per Square Foot
CCA	Coolant Control Assembly
C/M I	Control/Monitor Instrumentation
ECLSS	Environmental Control Life Support System
EMS	Engineering Model System
EPS	Electrical Power System
EOL	End of Life
FCA	Fluids Control Assembly
FCS	Fuel Cell Subsystem
2-FPC	Two-Fluids Pressure Controller
3-FPC	Three-Fluids Pressure Controller
GC	Growth Capability
IOC	Initial Operating Capability
LEO	Low Earth Orbit
RCS	Reaction Control System
RFCS	Regenerative Fuel Cell Subsystem
SFE	Static Feed Electrolyzer
UTC	United Technologies Corporation
WES	Water Electrolysis Subsystem

SUMMARY

The Regenerative Fuel Cell System is the most promising energy storage concept for the Space Station. This study effort defined and resolved key design issues of the Regenerative Fuel Cell System concept and completed a design definition of an Alkaline Electrolyte Based Engineering Model System having a 10 kW output power capacity for Low Earth Orbit missions. Definition and resolution of key design issues for a Regenerative Fuel Cell System resulted in the following.

The gaseous reactants are to be stored in their moist state by keeping equipment and plumbing above their dew point temperature. A shared heat exchanger will allow exchange, i.e., sharing, of heat between the Fuel Cell Subsystem and the Water Electrolysis Subsystem. A high pressure pump will transfer the water from the fuel cell to the electrolyzer. Other regenerative fuel cell design issues were also addressed and resolved culminating in a detailed mechanical schematic based on the recommended approaches to the various regenerative fuel cell design issues.

A power flow diagram for the 75 kW initial Space Station was defined and the impact of different regenerative fuel cell modular sizes on the total five-year-to-orbit weight and volume determined. The performance characteristics of both the fuel cell and the electrolyzer were compiled from the existing data base as established by Power Systems Divion of United Technologies Corporation and Life Systems, Inc., respectively. An optimization computer program for the cell size of the static feed electrolyzer verified that a 1.0 ft^2 cell is within the optimum cell size range for a 10 kW regenerative fuel cell. The five-year-to-orbit weight of a 10 kW Regenerative Fuel Cell System was minimized by optimizing the operating conditions, component sizes and packaging.

An optimized 10 kW Engineering Model System requires a Water Electrolysis Module containing 45 cells and a Fuel Cell Module having 120 cells. System characteristics, an isometric drawing, component sizes, and mass and energy balances were determined for the 10 kW Engineering Model System. The projected Engineering Model System weighs 636 lb, has a volume of 18.4 ft^3, operates at an electrical-to-electrical efficiency of 61.7%, has a specific energy of 63.6 lb/kW and has an energy density of 29.43 W-h/lb (with a two hour continuous power output capability).

The Control/Monitor Instrumentation requirements for the Regenerative Fuel Cell System were defined. A Life Systems' 200 Series controller was proposed for the Engineering Model System. The reactant storage assembly (hydrogen and oxygen) design was based on state-of-the-art technology.

An open loop regenerative fuel cell concept was considered as a way of integrating the energy storage system with the life support system of the Space Station. A 12 kW regenerative fuel cell unit can meet the total water requirements of four persons, providing water with proven potability, i.e., proven aboard the Shuttle Orbiter.

Technical problems and their solutions, pacing technologies as well as required developments and demonstrations for the Regenerative Fuel Cell System were defined. Recommendations to address these issues were made to ensure a successful and timely development of a flight version regenerative fuel cell.

INTRODUCTION

The National Aeronautics and Space Administration requires an energy storage system for the Space Station operating in a Low Earth Orbit (LEO). The initial power level of the Space Station is projected to be 75 kW with an Initial Operating Capability (IOC) time in the year 1991. The Growth Station is projected to require 300 kW of power. A Regenerative Fuel Cell System (RFCS) based energy storage concept is the most promising system to meet projected Space Station requirements.

The basic concept of a RFCS is shown in Figure 1. Input power to the RFCS is supplied by a solar array during the sunlight portion of the orbit while power is provided by the RFCS for the Space Station during the occult portion of the orbit. Throughout the electrochemical processes of the RFCS, waste heat is dissipated to space through the radiator and conditioned parasitic power (less than 1.5%) is provided to the RFCS for its ancillary components. The reactants, namely, water, O_2 and H_2 are essentially conserved in the RFCS.

The RFCS in the Space Station will be modularized. Each modular unit incorporates a Fuel Cell Subsystem (FCS), a Water Electrolysis Subsystem (WES) and Reactant Storage Assemblies. A block diagram of the RFCS for the Space Station application is shown in Figure 2.

A study program was successfully completed by Life Systems, Inc. (Life Systems) to define the regenerative fuel cell concept and to define a 10 kW, alkaline electrolyte-based Engineering Model System (EMS) prototype. This report presents the results of the RFCS study and of the EMS design definition.

RFCS STUDY

The RFCS study was conducted to determine the best approaches to the various RFCS design issues. The results of this study formed the basis on which the EMS space prototype design definition was completed. The analyses performed as part of this study were based on the work performed under the NASA sponsored contract of which this study is part (NAS3-21287), NASA Contract NAS9-16659 and on relevant information available in the open literature.[a]

RFCS Concept Assumptions

A list of RFCS concept assumptions was first formulated that either defined the operating conditions or specified the technologies/approaches acceptable to a RFCS. Table 1 sets forth these assumptions. These assumptions were reviewed at a Study Review Meeting prior to the commencement of the EMS design. Mutual acceptance and agreement to the assumptions are important because of their impact on the final EMS configuration.

(a) References 1-5, pages 77 and 81.

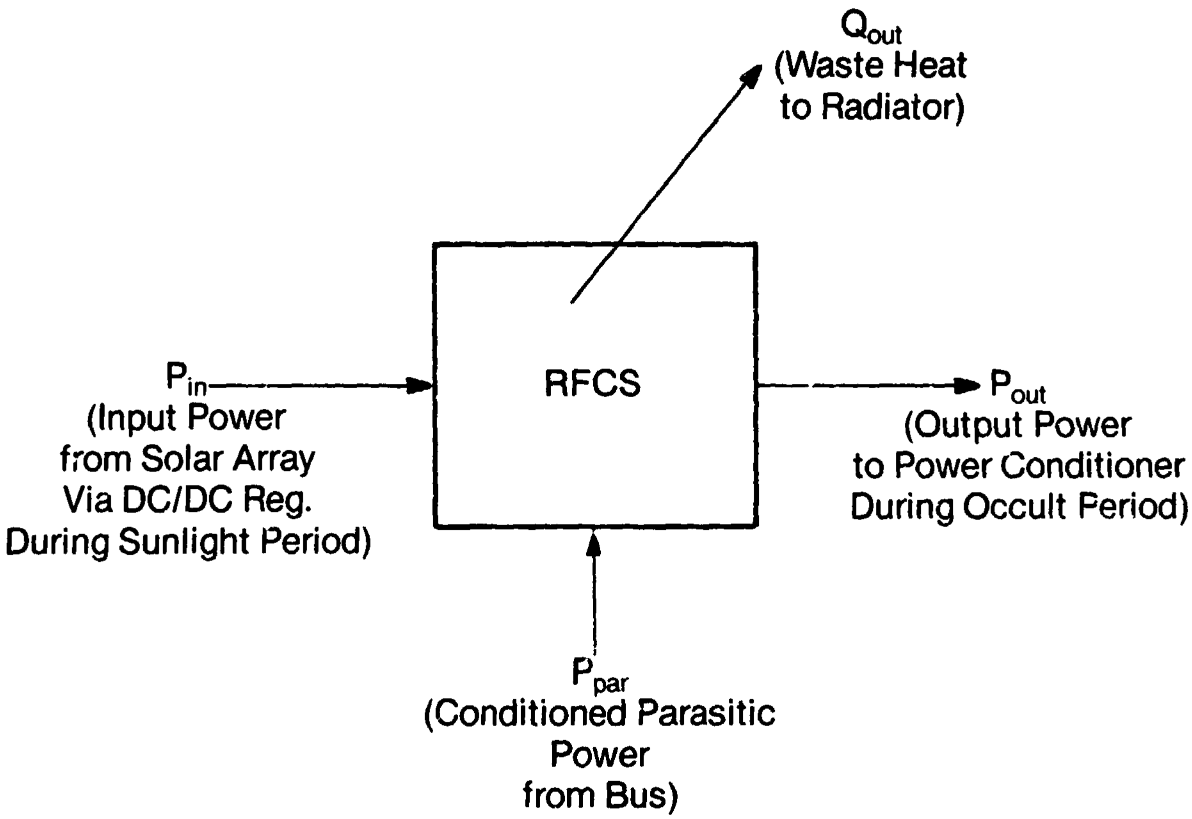


FIGURE 1 BASIC REGENERATIVE FUEL CELL CONCEPT

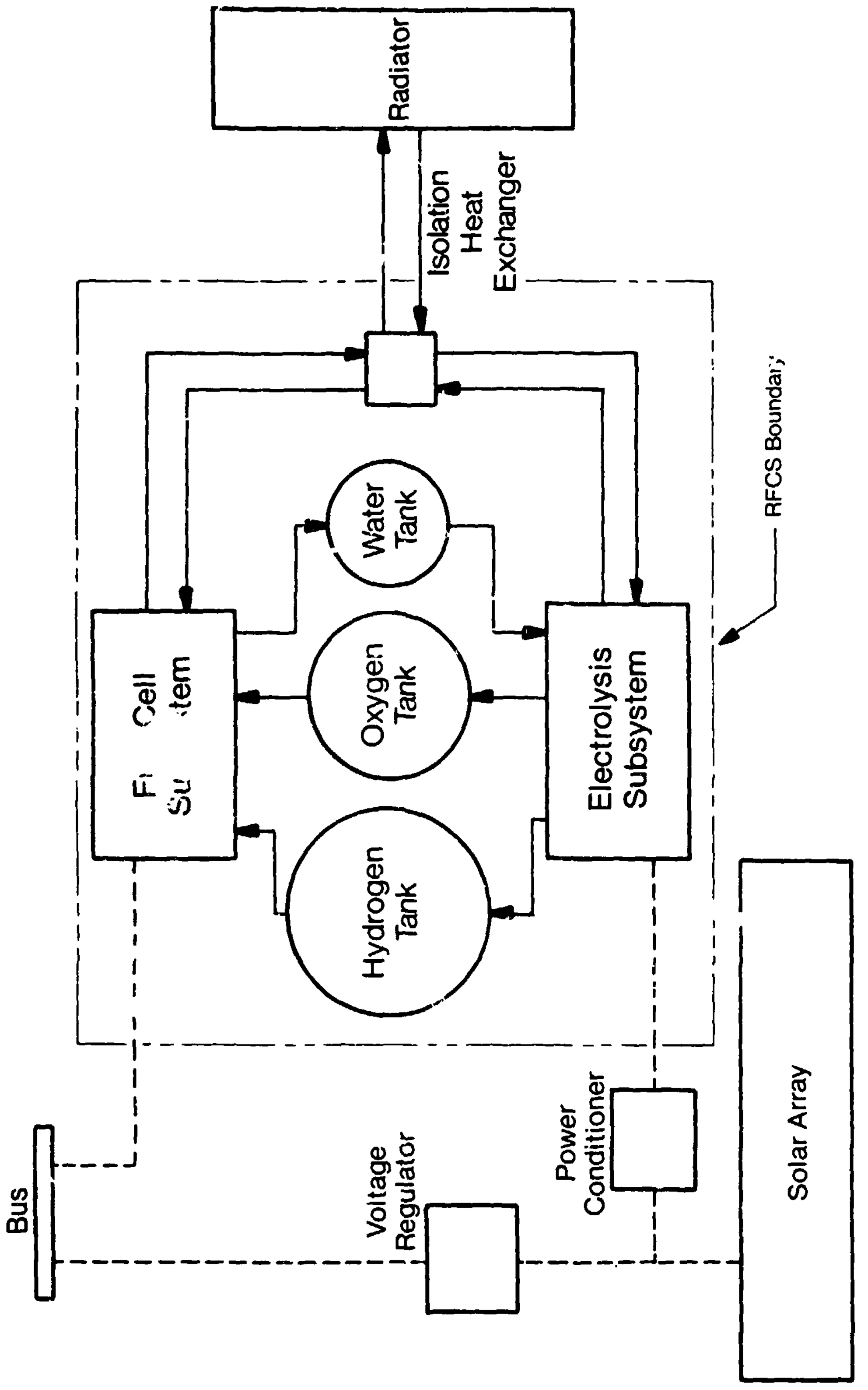


FIGURE 2 RFCS BLOCK DIAGRAM

TABLE 1 RFCS CONCEPT ASSUMPTIONS

No.	Assumption
1	RFCS nominal power output is 10 kW (per modular unit)
2	RFCS output voltage is $120V^{+10V}_{-20V}$
3	Dark/light solar cycle ratio is 35.7 minutes/58.8 minutes (0.607)
4	No loss of RFCS process fluids from 10 kW modular unit (Final analysis must address reactant losses)
5	Use existing Life Systems WES performance data
6	Use existing UTC Power Division FCS performance data
7	Peak power requirements are yet to be defined and hence have not been addressed (but 10 kW FCS is capable of 32.5 kW output, maximum)
8	Emergency power requirements (10 kW for 21 days) will be met by a separate RFCS unit.
9	System weight estimates include power conditioning
10	FCS and WES current efficiencies equal to 100% - cell matrices designed to prevent O_2 and H_2 cross-diffusion
11	FCS and WES cell efficiencies based upon 1.23V
12	No redundant FCS and WES cells per modular unit - additional demand handled by redundant RFCS modules
13	Modularity approach will be used to achieve 75 kW initial Space Station power needs and 150 kw or greater power needs for Growth Station
14	WES three compartment cell technology will be ready for incorporation into Engineering Model System (EMS) RFCS; however, this technology is not critical for EMS development
15	RFCS location will be external in unpressurized environment (though pressurized environment is not excluded)
16	Operation of the RFCS will be totally automated

continued-

Table 1 - continued

No.	Assumption
17	Maintenance approach will include Orbital Replacement Units (ORU), but zero gravity liquid line maintenance disconnects are needed
18	Replacement of a 10 kW RFCS modular unit is an acceptable approach to maintenance
19	Thermal insulation exists to maintain RFCS components above fluid dew points/freezing temperatures for deep space thermal sink (11 K)
20	Reliability goals will be met by "sizing" for End-of-Life (EOL) performance, derated operation (lower current densities) and redundancy (at modular and component, i.e., rotating components, level)
21	Nitrogen purge may be required to perform in-orbit maintenance or to condition a RFCS modular unit for dormancy if dictated by Space Station operational procedures
22	H_2/O_2 purge is required to return a RFCS modular unit to the power bus upon completion of in-orbit maintenance
23	Electric heating is required to prevent condensation/freezing during transient operation

RFCS Design Issues

Key RFCS design issues involve the management of water and the management of heat. These are discussed in the following sections. The methodology for the RFCS mass and energy balance is shown in Figures 3 and 4, respectively. These methodologies were used in this study to determine water, oxygen (O_2) and hydrogen (H_2) mass flow rates as well as waste heat generation rates. Other RFCS design issues considered included: operating conditions, reactant losses and make-up, dissolved H_2 in the fuel cell product water, packaging of components, zero-g maintenance and changeout, operating mode transitions and interface requirements.

Water Management

Water Transfer from the Fuel Cell to the Electrolyzer

The options considered for transferring product water from the FCS to the WES were: (1) high differential pressure (320 psid) pump; (2) low differential pressure (30 psid) pump with venting of the water storage tank reference gas in the WES; and (3) no pump but maintaining the FCS H_2 compartment pressure higher than that of the O_2 compartment pressure and venting the water tank. Because of ease of operation and fewer number of components involved, the high differential pressure pump is recommended for the RFCS. It should be pointed out that the high differential pressure pump is to be operated during the sunlight portion of the orbit when the weight penalty for the power is less. Also, the pump is sized for an 80% duty cycle to ensure that a small capacity pump can meet the water transfer requirements and that the size of the high pressure water tank can be minimized.

Water Vapor in Product Gases

The water vapor in the product gases represents a major challenge to the RFCS designer. Recycling the water vapor is mandatory because loss of large quantities of water are unacceptable. Several ways of recycling the water vapor exist. One way is to condense the water vapor and separate the condensate from the gas streams using either dynamic or static gas/liquid separation techniques. Each separation technique employs two or three devices or components that are available and have already been proven in zero-g applications. In the dynamic separator category, centrifugal separators, vortex separators or elbow separators are the available devices. Hydrophobic/hydrophilic screens and wick materials are their counterparts in the static separation category. After the water is separated from individual gas streams, it can be added to either the WES water feed or the FCS product water.

Another method of recycling the water vapor is to deliver wet gases to the FCS. In order to prevent condensation in the storage tanks and plumbing, heat tracing or regenerative adsorption with some heat tracing is necessary. Another method of recycling the water vapor is to electrolytically dry the product gases with either phosphoric acid or sulfuric acid electrolytic cells.

Evaluation of all of the aforementioned techniques was conducted using Life Systems' in-house data and available literature. Based on this evaluation,

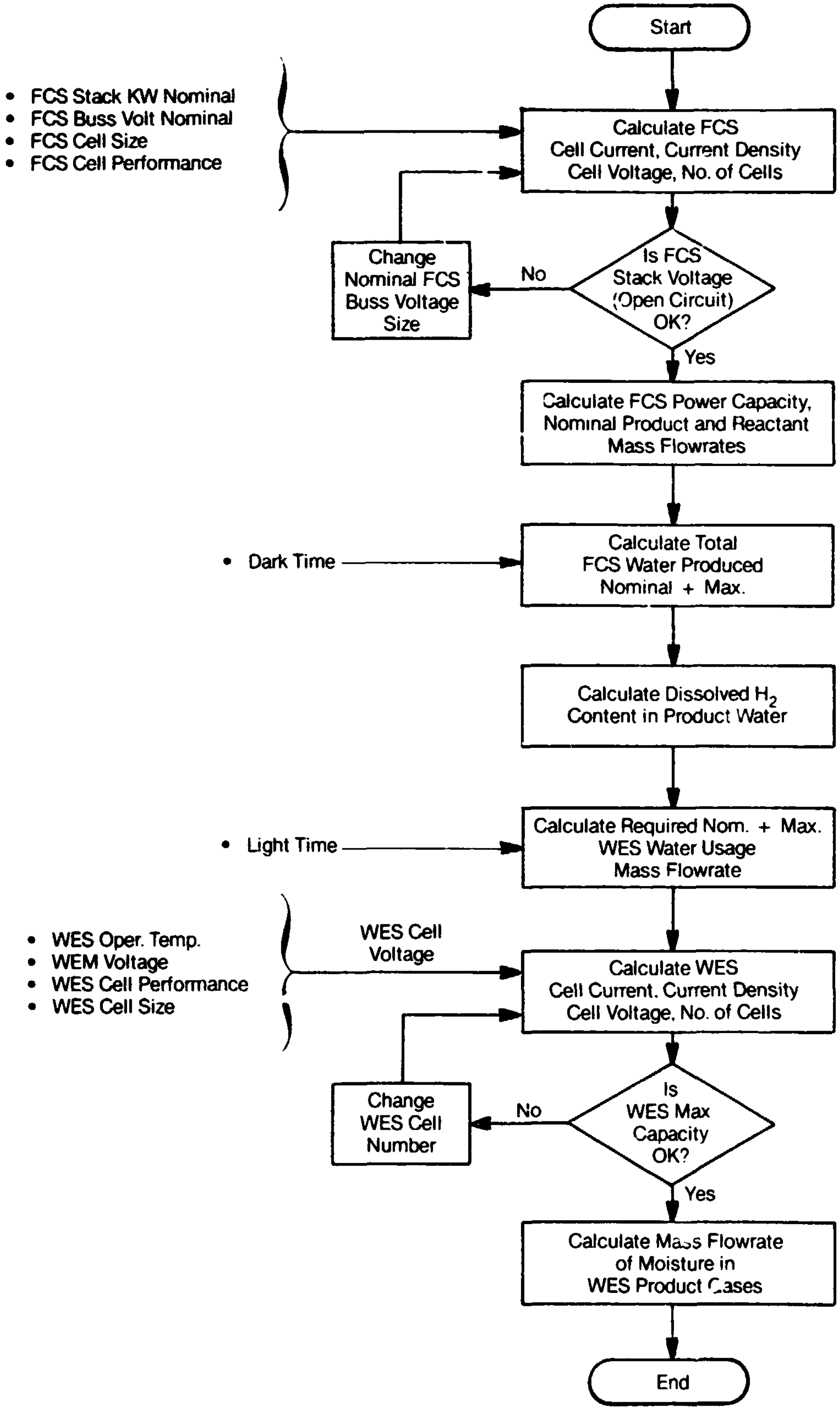


FIGURE 3 RFCS MASS BALANCE METHODOLOGY

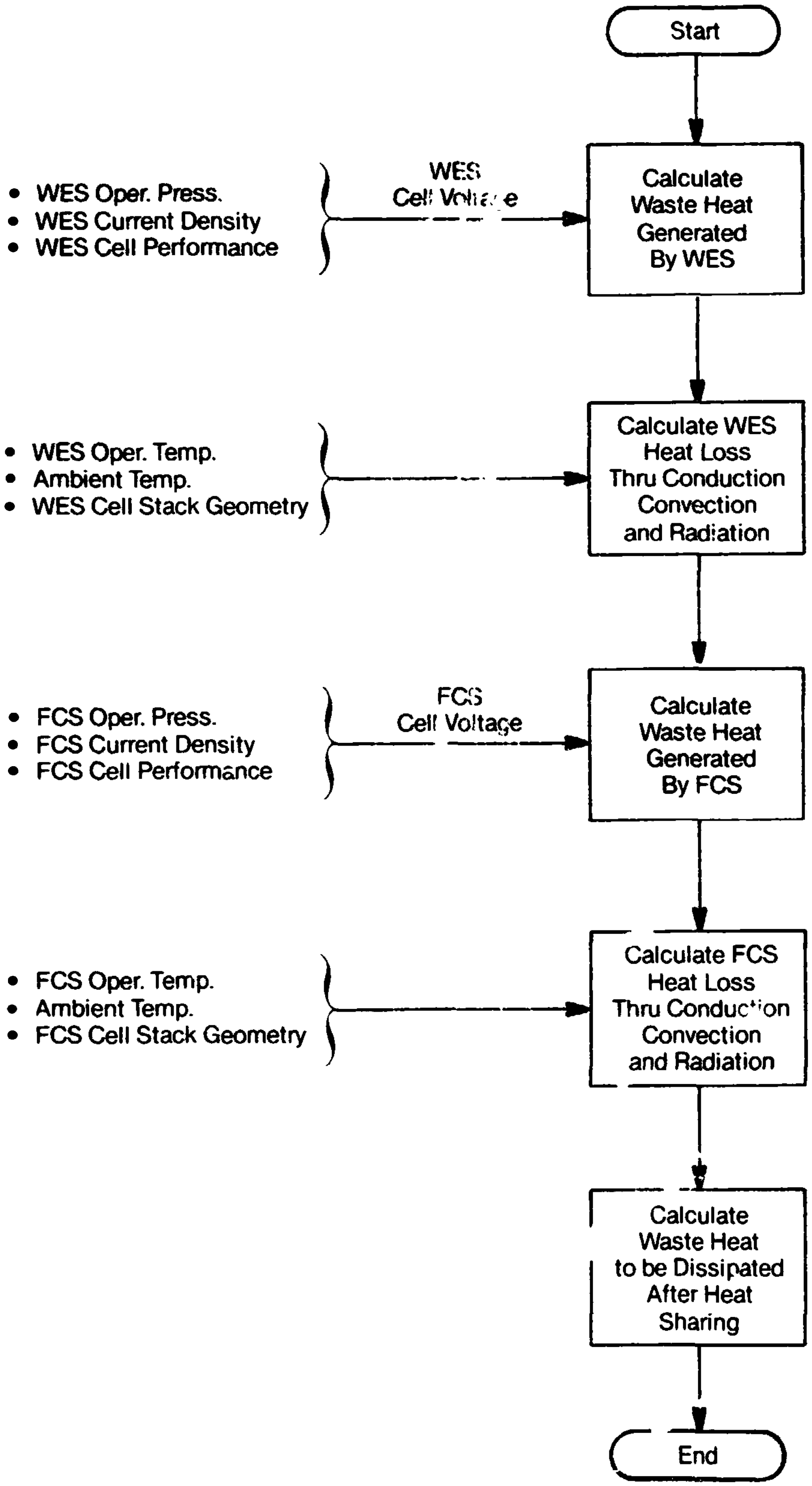


FIGURE 4 RFCS ENERGY BALANCE METHODOLOGY

the selected approach is to recycle the water vapor in the product gases by delivering wet gases to the FCS and maintaining system components and plumbing above the dew point temperatures. One overriding factor in arriving at this conclusion is that some sort of external heating is required even if other water vapor handling techniques were selected, since transient operation, low power mode and a backup for maintaining temperature would always be required. In any case, all water carrying lines and components must be kept above 32 F at all times (operating, stand-by or dormant) to prevent freezing.

The results of a trade between circulating FCS coolant and electric heating for keeping the storage tanks above dew point is shown in Figure 5. If the storage tanks are located in close proximity to the rest of the RFCS, circulating FCS coolant is recommended. If the storage tanks are remotely located, the weight penalty for electric heating would remain practically the same; however, the weight penalty associated with circulating coolant would increase proportionally with the distance. Depending on the location of the storage tanks in relation to the rest of the RFCS, electric heating may become advantageous.

Heat Management

Waste Heat Generation

The amount of waste heat generated by the FCS is in general much greater than that by the WES. This is a consequence of the thermodynamics of the respective electrochemical reactions. Based on the projected operating temperature of 180 F and a current density of 180 ASF for the FCS, the waste heat generated by the FCS is 6,110 W. A negligible amount of waste heat (less than 150 W) is generated by the WES when it is operated at 150 ASF and 180F. These initially projected operating conditions were later found to be close to optimum when minimizing the system weight of the RFCS.

Thermal Sharing and Heat Rejection

The waste heat generated in the FCS can be used to minimize temperature loss of the WES when the WES is idle during the darkside of the orbit. In addition, the waste heat can aid in the start up of the WES and in keeping system components and plumbing above dew point. Due to its high efficiency, the WES can not be used to maintain the FCS temperature but can minimize the temperature drop of the FCS during period of non-use of the FCS, i.e., during the 58.8 minutes of the sunlit portion of the orbit. One-way thermal sharing, however, is still recommended over thermally isolating the two subsystems. A shared heat exchanger has been incorporated into the RFCS to allow exchange of heat between the FCS and WES. An alternate consideration is to have one common coolant loop for the WES and FCS, thus eliminating one heat exchanger and one coolant pump, while maximizing thermal sharing efficiency. The loss in operational flexibility [illegible]dered minor. Also, in the unique three-compartment static feed [illegible]rolysis cell design, water is used as the coolant for the WES. Unless the material of the fuel cell separator plates is changed from currently used magnesium to a dielectric material, water cannot be used as the coolant in the FCS if a three-compartment WES is employed. Consequently, a common coolant loop for both subsystems is not possible. This restriction does not apply to a four-compartment WES module.

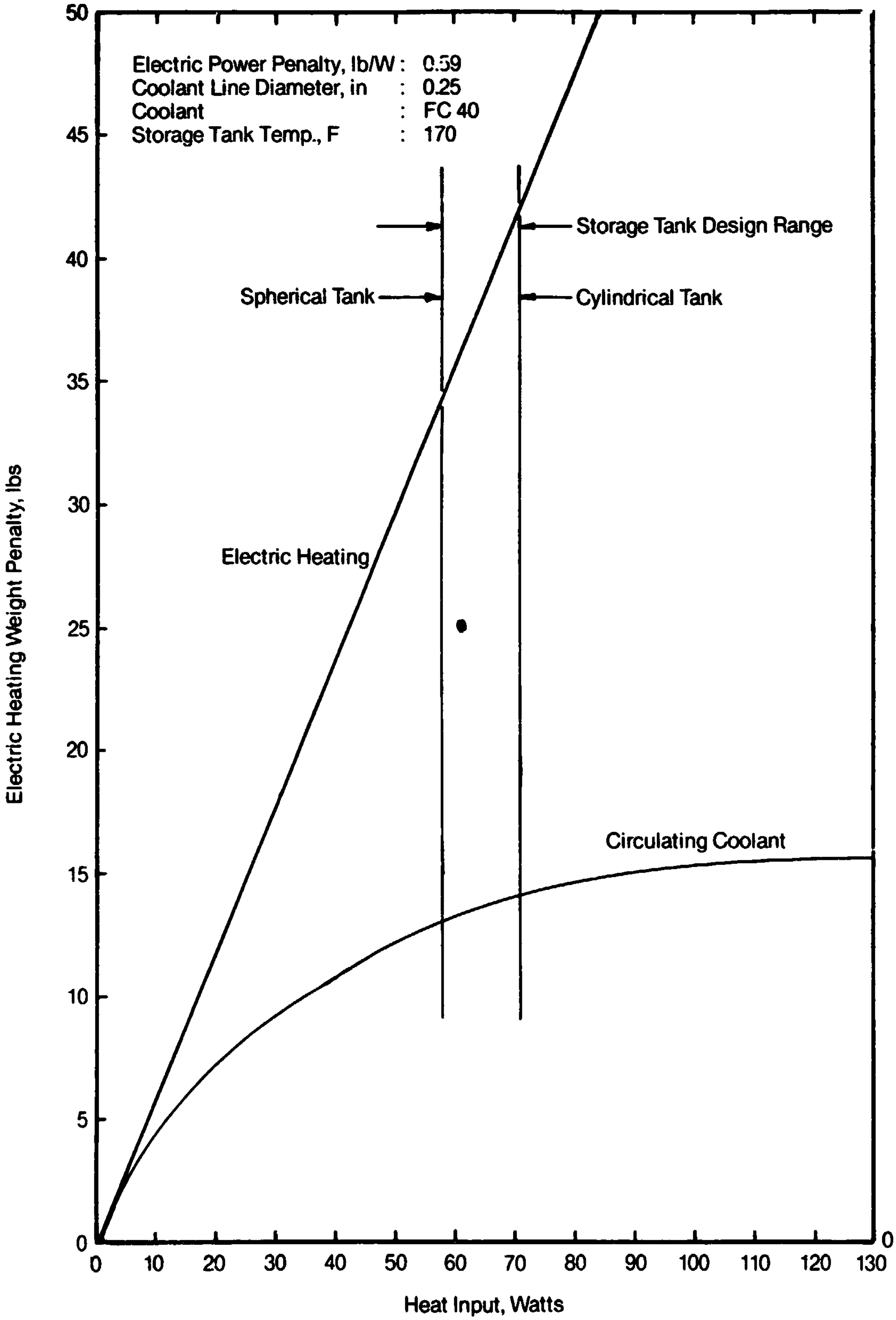


FIGURE 5 WEIGHT PENALTY FOR H_2 and O_2 STORAGE TANK HEATING

The overall heat balance indicates that heat is to be rejected from the RFCS to deep space. To accomplish this the waste heat generated by the RFCS is dissipated through an isolation heat exchanger. The isolation heat exchanger in turn transfers the heat to the radiator through a 150 F coolant loop which can be either a heat pipe or a pumped coolant loop.

Because the FCS and WES are projected to be operated at the same temperature level, a small phase change thermal storage heat exchanger may be employed to maintain temperature control of both subsystems. This concept was identified during the end of the study program and was not defined in detail. A trade between this concept, the shared heat exchanger concept or combination of both is recommended as a follow-on task. The shared heat exchanger is recommended for the RFCS at this time.

RFCS Study Results Summary

In addition to the key design issues of water and heat management in the RFCS, other issues were also addressed and resolved as part of this study. A summary of the recommended approaches to all of the design issues is presented in Table 2. Based on these recommendations to the RFCS design issues, the mechanical schematic shown in Figure 6 was developed. This mechanical schematic reflects the trades and analyses made under the RFCS study and serves as the starting point for the EMS design definition.

EMS DESIGN DEFINITION

The design guidelines for the EMS design are presented in Table 3. These guidelines reflect currently available information. As new data become available as part of Pre-Phase B and Phase B Space Station activities, these guidelines must be reviewed and upgraded, if required, before the commencement of the EMS hardware design.

Overview of the RFCS in the EPS

The RFCS provides power for all Space Station needs during darkside operation. It is the energy storage portion of the Electrical Power System (EPS). The power generation portion of the EPS is the solar array which during lightside provides power for the station needs and also recharges the RFCS. A solar array/RFCS power flow diagram for a 75-kW space station is shown in Figure 7. Also shown in Figure 7 are the efficiencies assigned to the various elements of the EPS power transmission and conditioning components.

The required solar array size for any given power level at the Space Station bus can be determined by the following equation:

$$P_{SA} = \frac{P_{BUS}}{(\eta_{CAB})^2 \eta_{INV} \eta_{BUS} \eta_{REG/F} \eta_{PT} \eta_{D/CAO} \eta_{HARN}} \left(1 + \left(\frac{t_D}{t_C}\right) \frac{E_E}{\eta_{CAB/F} \eta_{REG/E} E_F}\right) \quad (1)$$

TABLE 2 SUMMARY OF RECOMMENDED APPROACHES TO DESIGN ISSUES

Design Issue	Recommended Approach
Humidity Control	Maintain system components and plumbing above dew points
Thermal Management	Shared heat exchanger with heat flow from: a. (light side), WES to components to FCS to space, b. (dark side), FCS to components to WES to space
Reactant Loss Make-up	Via water (common tank for all 10 kW modular units) or gases (O_2 and H_2) as a back-up
Dissolved H_2 in FCS Product Water	Use of a three-compartment WES cell or a "ruggedized" four-compartment cell (Shuttle H_2 Separator as back-up)
Projected EMS Operating Conditions	WES current density of 150 ASF, WES temperature of 180 F, FCS current density of 180 ASF, FCS temperature of 180 F
Water Transfer from Fuel Cell to Electrolyzer	Use of high differential pressure pump (operated at 80% duty cycle light side only)
RFCS Inerts Purging	Purge while Resource Module still in shuttle bay prior to charging
Space Station Start-up or Emergency Power via Fuel Cell	Expendable cryogenic or gaseous reserves, Shuttle resupplied
Shutdown of RFCS	Insure fail safe operation of the RFCS by depressurizing and purging with N_2 prior to RFCS repair or replacement if required by Space Station operating procedures
Operating Modes	Unpowered, Shutdown, Purge (if needed), Standby, Normal
Allowable Mode Transitions	All transitions allowed except purge to standby, purge to normal, normal to purge, standby to purge
Cycle Time Adjustments	Cycle time adjustments dictated by Space Station power management
Zero-g Maintenance and Changeout	Zero-g liquid line maintenance disconnects needed on RFCS external liquid interfaces and Orbital Replacement Unit (ORU) interfaces

continued-

Table 2 - continued

Design Issue	Recommended Approach
Packaging of Components	Separate packaging of gaseous reactant storage tanks, separate package for rest of RFCS
RFCS/Solar Array Interface	Power-Programmed DC/DC regulator (95% efficient, pulse width modulation)
RFCS Interface with Other Space Station Systems	O_2, H_2 and H_2O can be used "as is" for life support back-up, as a minimum

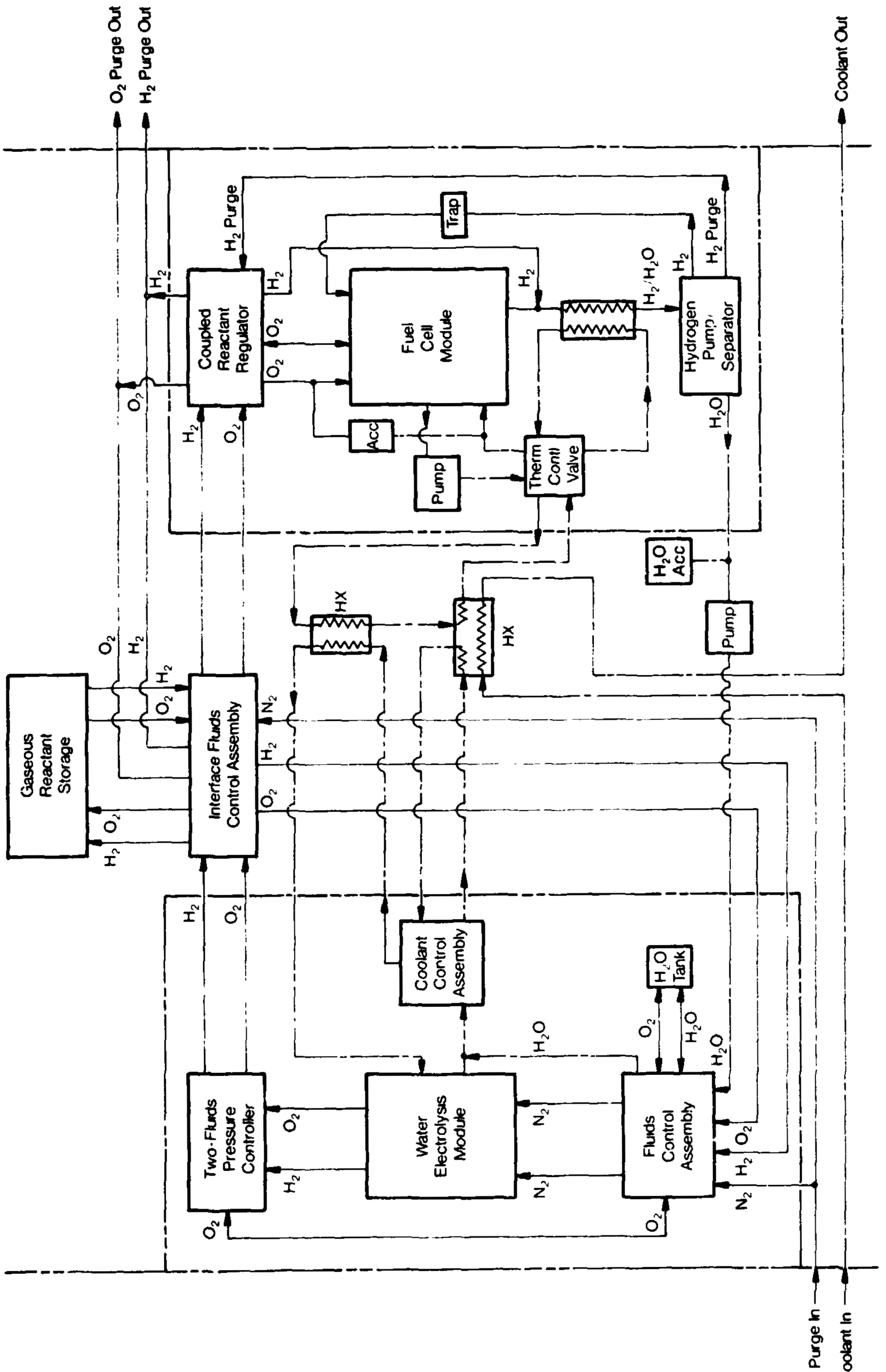


FIGURE 6 RFCS SCHEMATIC

TABLE 3 EMS DESIGN GUIDELINES

Fuel Cell	
Power Out, kW	10
Voltage, VDC	120^{+10}_{-20}
Dark Period Operation, min	35.7
Continuous Operation, h	2.0
Parasitic Power, % of Net Power	1.26
Electrolyzer	
Light Period Operation, min	58.8
Parasitic Power, % of Net Power	0.67
Power Conditioner	
Efficiency, %	95
Specific Weight, lb/kW	5.0
Tankage	
Minimum Reactant Storage Pressure, psia	70
Maximum Reactant Storage Pressure, psia	300
Tank Material	Inconel B
Safety Factor	1.5
Ultimate Strength, psi	125,000
Material Density, lb/in^3	0.3
Space Radiator	
Emissivity	0.92
Thermal View Factor, Light Period	0.5
Thermal View Factor, Dark Period	1.0
Sink Temperature, F	-127
Radiator Specific Weight, lb/ft^2	1.42
Solar Array	
Specific Weight, lb/kW	43.40
Propellant, lb/ft^2-yr	0.268
Weight-to-Orbit Time, yrs	5.0

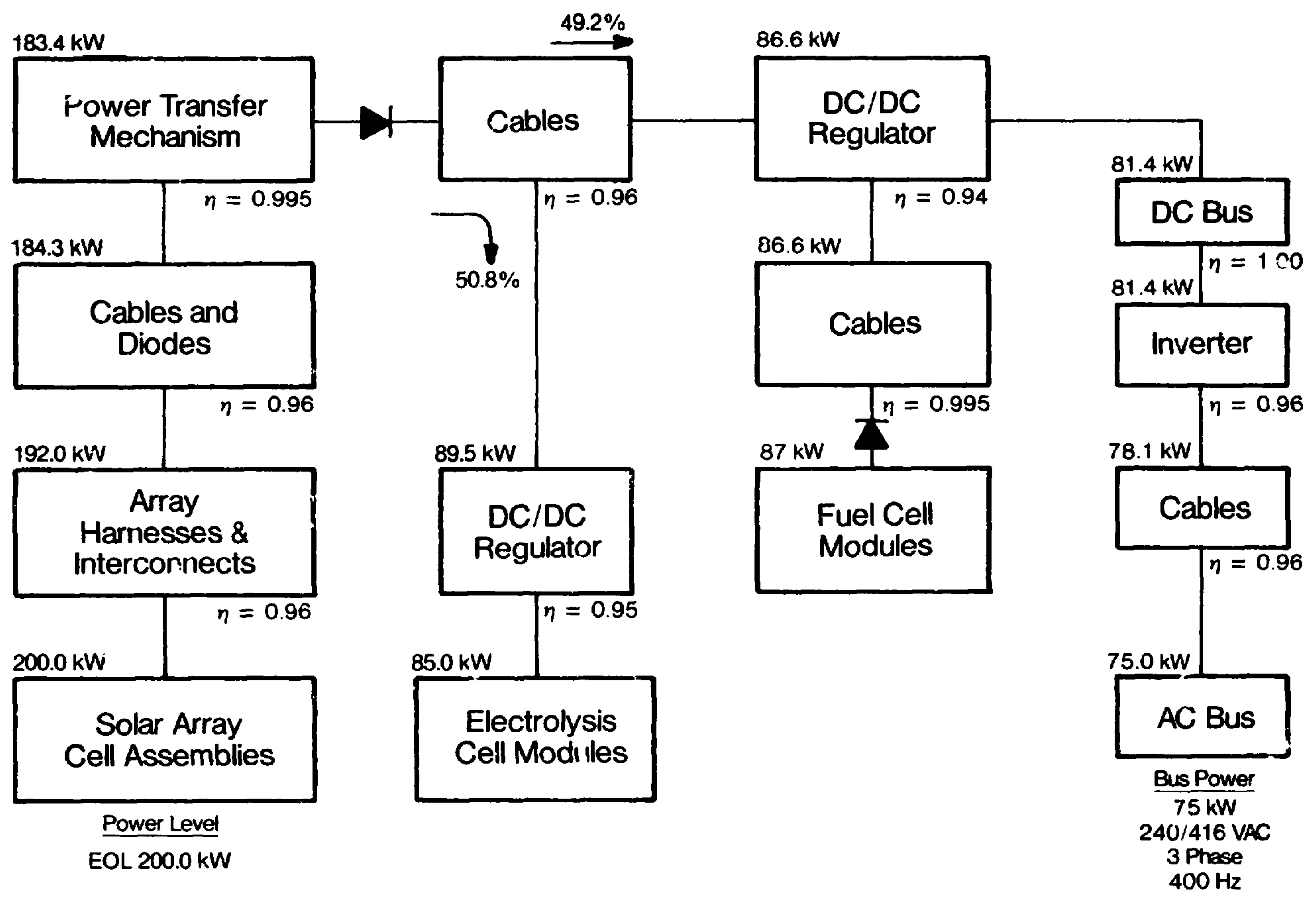


FIGURE 7 SOLAR ARRAY/RFCS POWER FLOW DIAGRAM

Where

P_{SA} = Power of Solar Array (End of Life (EOL)), kW

P_{BUS} = Bus Power to Space Station User, kW

η_{CAB} = Efficiency of Cables

η_{INV} = Efficiency of Inverter

η_{BUS} = Efficiency of Bus

$\eta_{REG/F}$ = Efficiency of DC/DC Regulator For Fuel Cell Power Out

η_{PT} = Efficiency of Power Transfer Mechanism

$\eta_{D/CAD}$ = Efficiency of Diodes and Cables

η_{HARN} = Efficiency of Array Harnesses and Interconnects

t_D = Time on Dark Side (Discharge), minutes

t_C = Time on Light Side (Charge), minutes

$\eta_{CAB/F}$ = Efficiency of Cables to Fuel Cell

$\eta_{REG/E}$ = Efficiency of DC/DC Regulator for Electrolyzer Power In

E_E = Single Electrolyzer Cell Voltage, VDC

E_F = Single Fuel Cell Voltage, VDC

Using Equation 1 and the efficiency data, the power levels at different elements of the EPS were calculated under the following conditions: an IOC Space Station power of 75 kW, an electrolyzer cell voltage of 1.48 VDC, and a fuel cell voltage of 0.92 VDC. The results are presented in Figure 7. The cell voltages used in the calculation were determined based on the cell performance characteristics discussed in the following sections and the projected RFCS operating conditions. It can be seen that 50.8% of the solar array output power goes to recharging the RFCS. This percentage can be lowered if a more efficient method of operating the station is used, such as cycling the high loads off during the occult portion of the orbit.

The power and area requirements for solar arrays of different degrees of degradation allowance are shown as a function of the energy storage efficiency in Figures 8 and 9, respectively. High energy storage efficiency and low degradation performance all result in smaller size solar arrays.

To meet the 75 kW IOC requirements, different RFCS configurations, i.e., modular units, can be used. Table 4 presents the number of the fuel cell, electrolyzer and reactant storage units for different RFCS modular (building block) sizes. The RFCS module weight and number of cells per module as a function of the

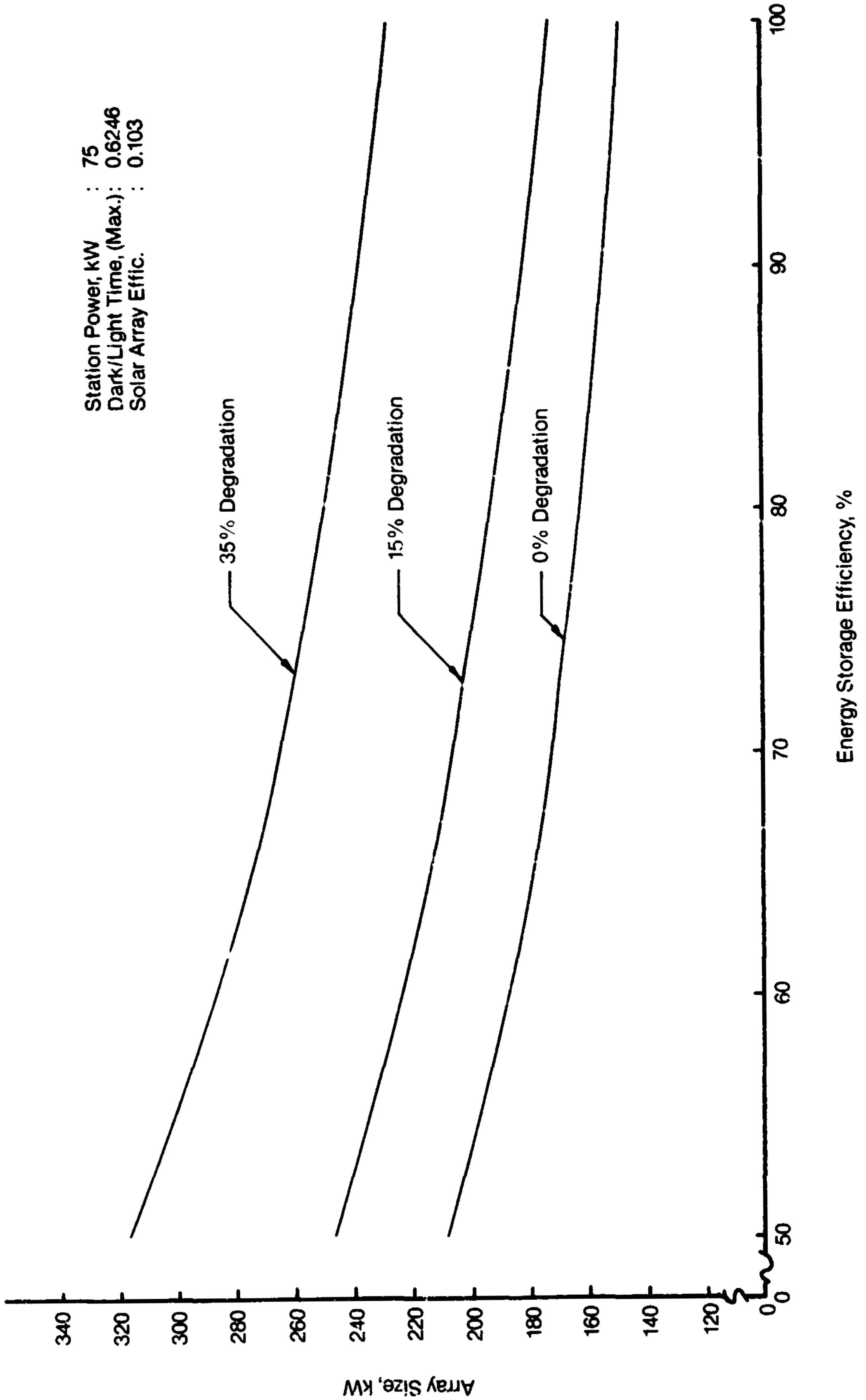


FIGURE 8 SOLAR ARRAY POWER VERSUS ENERGY STORAGE EFFICIENCY

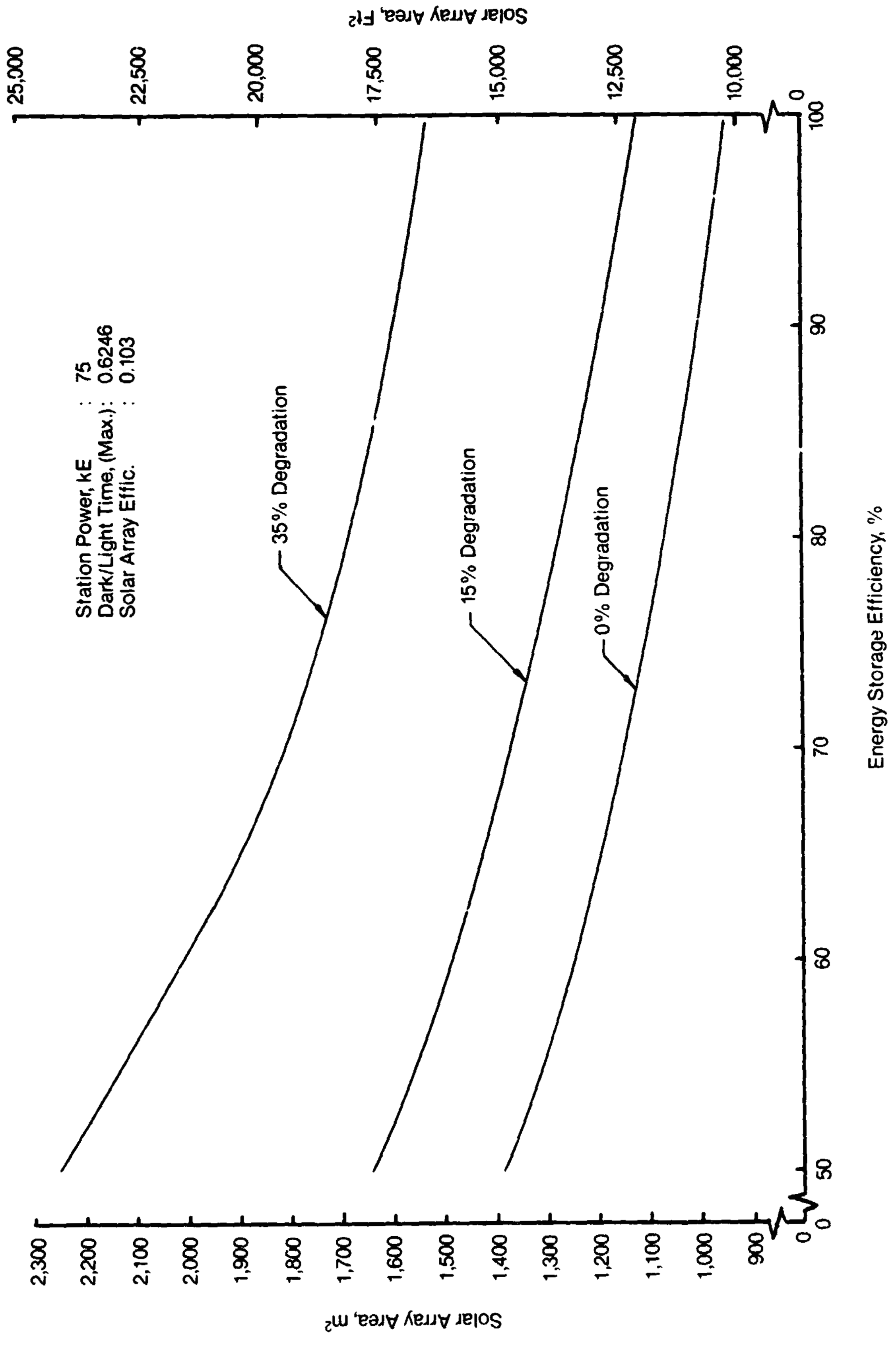


FIGURE 9 SOLAR ARRAY AREA VERSUS ENERGY STORAGE EFFICIENCY

TABLE 4 IOC RFCS CONFIGURATION

	Basic Building Block Size		
	10 kW	20 kW	30 kW
	No. Units - Power Level	No. Units - Power Level	No. Units - Power Level
Fuel Cell (87.0 kW)	9-10 kW	5-20 kW	3-30 kW
Electrolyzer (85.0 kW)	9-9.8 kW	5-19.6 kW	3-29.4 kW
Reactant Storage			
Without 2 Hour Emergency	9-6 kW-hr	5-12 kW-hr	3-18 kW-hr
With 2 Hour Emergency	30-6 kW-hr	15-12 kW-hr	10-18 kW-hr

module size are shown in Figure 10. Table 5 presents the number of the RFCS units for both 75 kW IOC and 150 kW Growth Capability (GC) requirements. The recommended minimum number of spare units, excess power available, total RFCS weight and volume are also tabulated in Table 5. The optimum RFCS modular unit size for the EPS of the Space Station may be determined based on the information presented here and other factors such as number of components, tolerance to failures, maintainability and needs for new component development. For purposes of defining an EMS of the RFCS, a 10 kW capacity unit was a requirement.

Fuel Cell Characteristics

The fuel cell voltage versus current density is shown for the effect of temperature, pressure and electrolyte concentration in Figures 11, 12 and 13, respectively. The data shown are for the "long life configuration" fuel cell hardware tested for the NASA Lewis Research Center for over 14,000 hours. This fuel cell has life capability different from that of the Shuttle Orbiter fuel cell power plant because it operates at a lower current density and temperature. Actual cyclic life test data are shown in Figure 14. The weight and volume for a FCS are presented in Figures 15 and 16, respectively. The FCS envisioned for the EMS has a similar configuration as the Shuttle Orbiter fuel cell power plant with similar ancillary components and an individual cell area of 0.508 ft^2. Repackaging for maintenance, a "high" output voltage cell stack configuration and different cell frame material, separators and electrode reservoir plates are projected to be implemented/available for the actual EMS hardware.

The information on the FCS characteristics was provided by United Technologies. The curve-fitting polynomial equation in Figure 11 was determined by regression analysis at Life Systems and was used for the EMS optimization.

Electrolyzer Characteristics

Cell Construction

The electrolyzer subsystem in the RFCS is based on the alkaline electrolyte-based static feed water electrolysis concept developed by Life Systems. The electrolysis cell assembly consists of a unitized cell core, a unitized feed matrix and a cell frame. Depending on the design of the unitized feed matrix and the cell frame, the cell assembly forms either four compartments or three compartments, both of which are illustrated in Figure 17.

The three-compartment cell design eliminates a separate coolant compartment and the electrolyte from the water feed compartment. As a result, it is lighter, more simplified and free from the problem of hydrogen accumulation in the feed compartment due to evolution of the dissolved hydrogen from the FCS product water. During prolonged shutdown (i.e., greater than seven hours), water in the water feed compartment is isolated and emptied. The three-compartment cell configuration is projected for the EMS design.

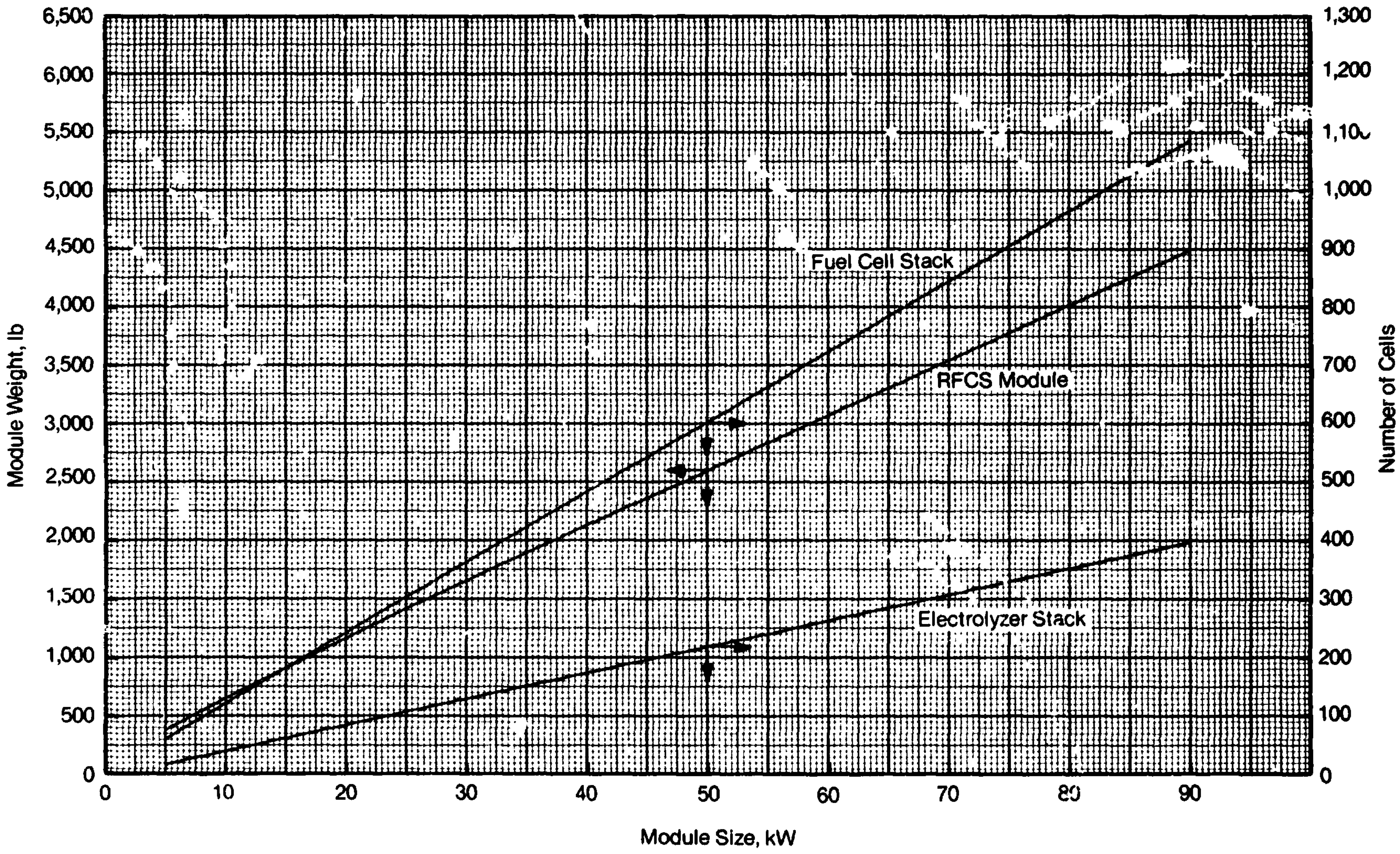


FIGURE 10 RFCS MODULE WEIGHT AND NUMBER OF CELLS VERSUS MODULE SIZE

TABLE 5 RFCS MODULARIZATION APPROACHES FOR THE SPACE STATION

Modular Size, kW	Modular Wt, lb	Modular Volume, ft^3 (d)	IOC (75 kW)(a) No. Units(e)	IOC (75 kW)(a) Excess, kW	GC (150 kW)(b) No. Units(e)	GC (150 kW)(b) Excess	Recommended Min. No. Spare Units(c) IOC	Recommended Min. No. Spare Units(c) GC	Total RF[illegible] Weight, [illegible] IOC	Total RF[illegible] Weight, [illegible] GC	Total RFCS Volume, ft^3 (d) IOC	Total RFCS Volume, ft^3 (d) GC
90	4,511	178.8	1	3	2	6	2	1	13,533	13,533	536.4	536.4
45	2,333	91.4	2	3	4	6	1	1	6,999	11,665	274.2	457.0
30	1,607	62.4	3	3	6	6	1	1	6,428	11,249	249.6	436.8
25	1,364	52.9	4	13	7	1	1	1	6,820	10,912	264.5	423.2
18	1,025	39.3	5	3	10	6	1	1	6,150	11,275	235.8	432.3
15	881	33.6	6	3	12	6	1	1	6,167	11,453	235.2	436.8
10	636	23.9	9	3	18	6	1	1	6,360	12,084	239.0	454.1
5	396	14.3	18	3	36	6	1	1	7,542	14,652	271.7	529.1

(a) Requires 87 kW at fuel cell output bus.
(b) Requires 174 kW at fuel cell output bus.
(c) Minimum numbe- of spares always greater than one and, after two faiiures, must still have 50% of baseline power.
(d) Summation of component values.
(e) Unspared.

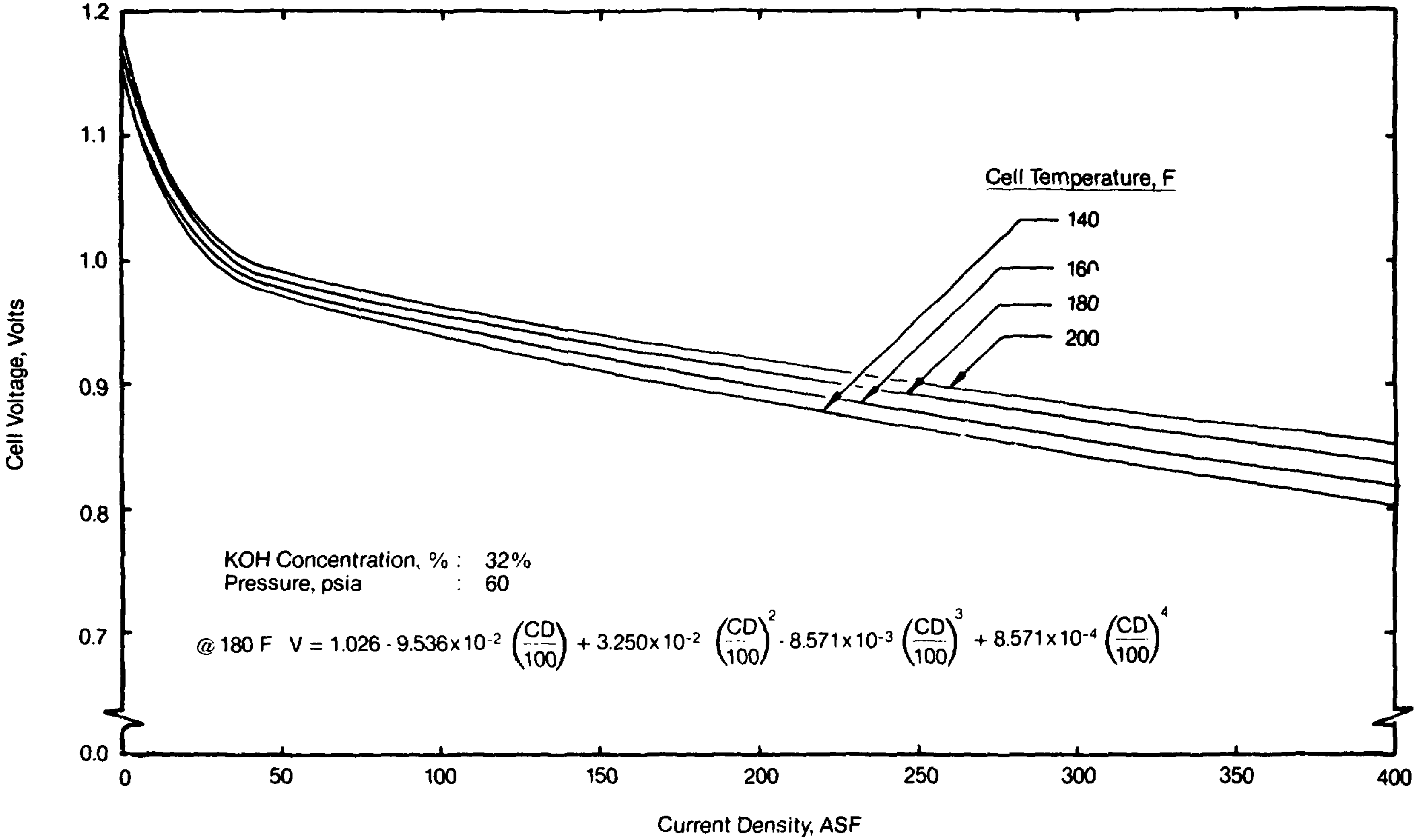


FIGURE 11 ALKALINE FUEL CELL PERFORMANCE AS A FUNCTION OF TEMPERATURE (LONG LIFE CONFIGURATION)

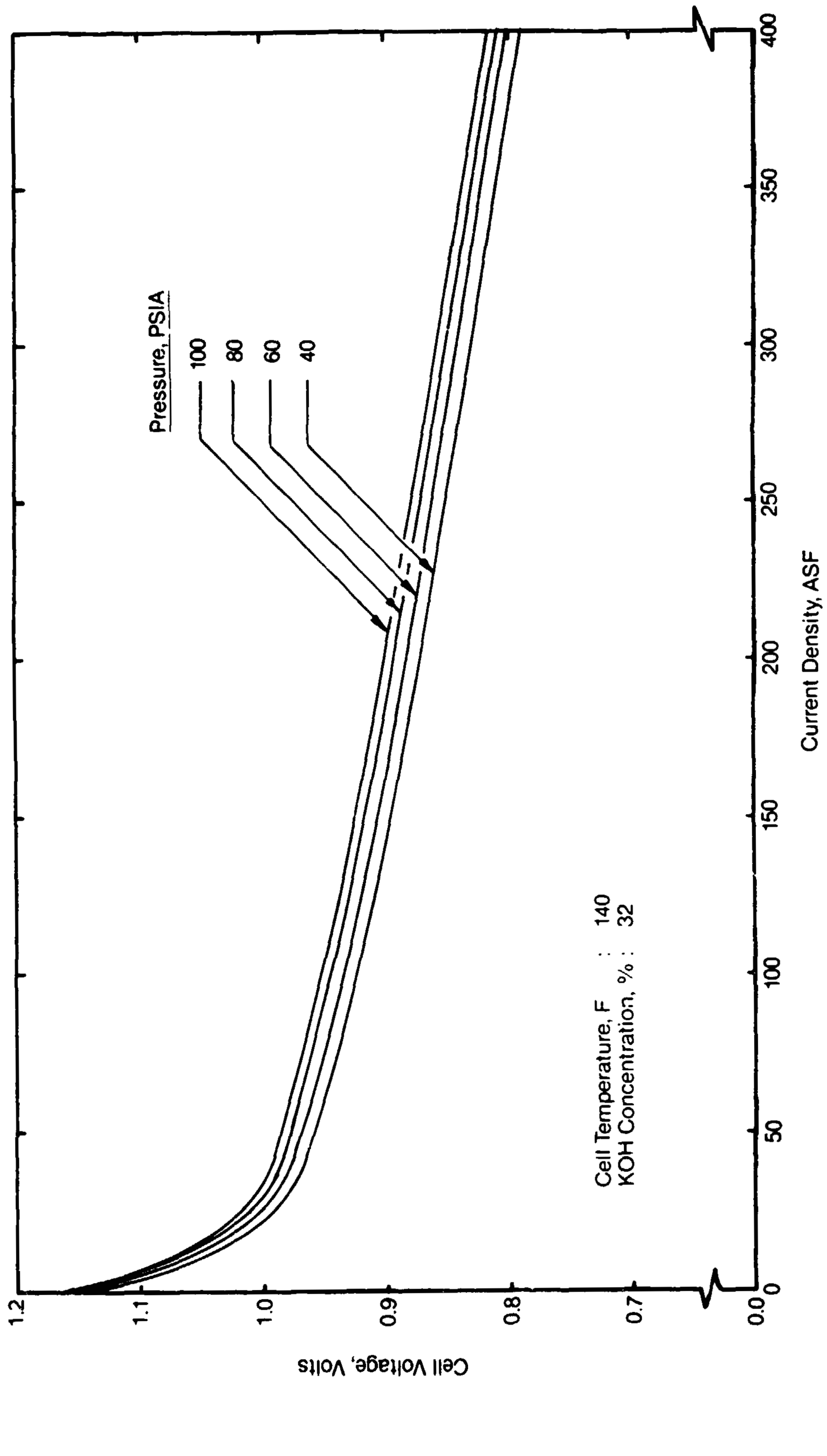


FIGURE 12 ALKALINE FUEL CELL PERFORMANCE AS A FUNCTION OF PRESSURE
(LONG LIFE CONFIGURATION)

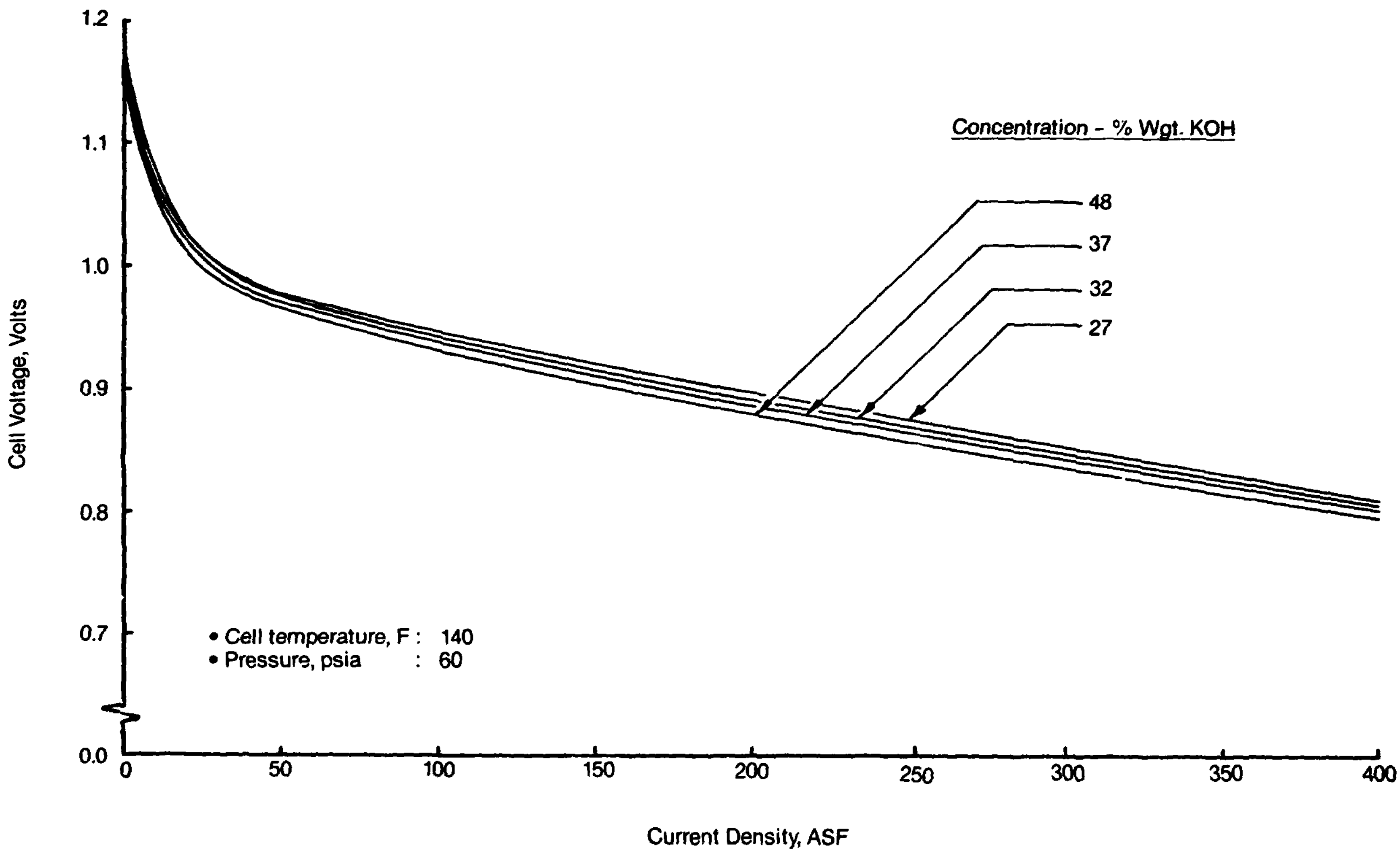


FIGURE 13 ALKALINE FUEL CELL PERFORMANCE AS A FUNCTION OF ELECTROLYTE CONCENTRATION (LONG LIFE CONFIGURATION)

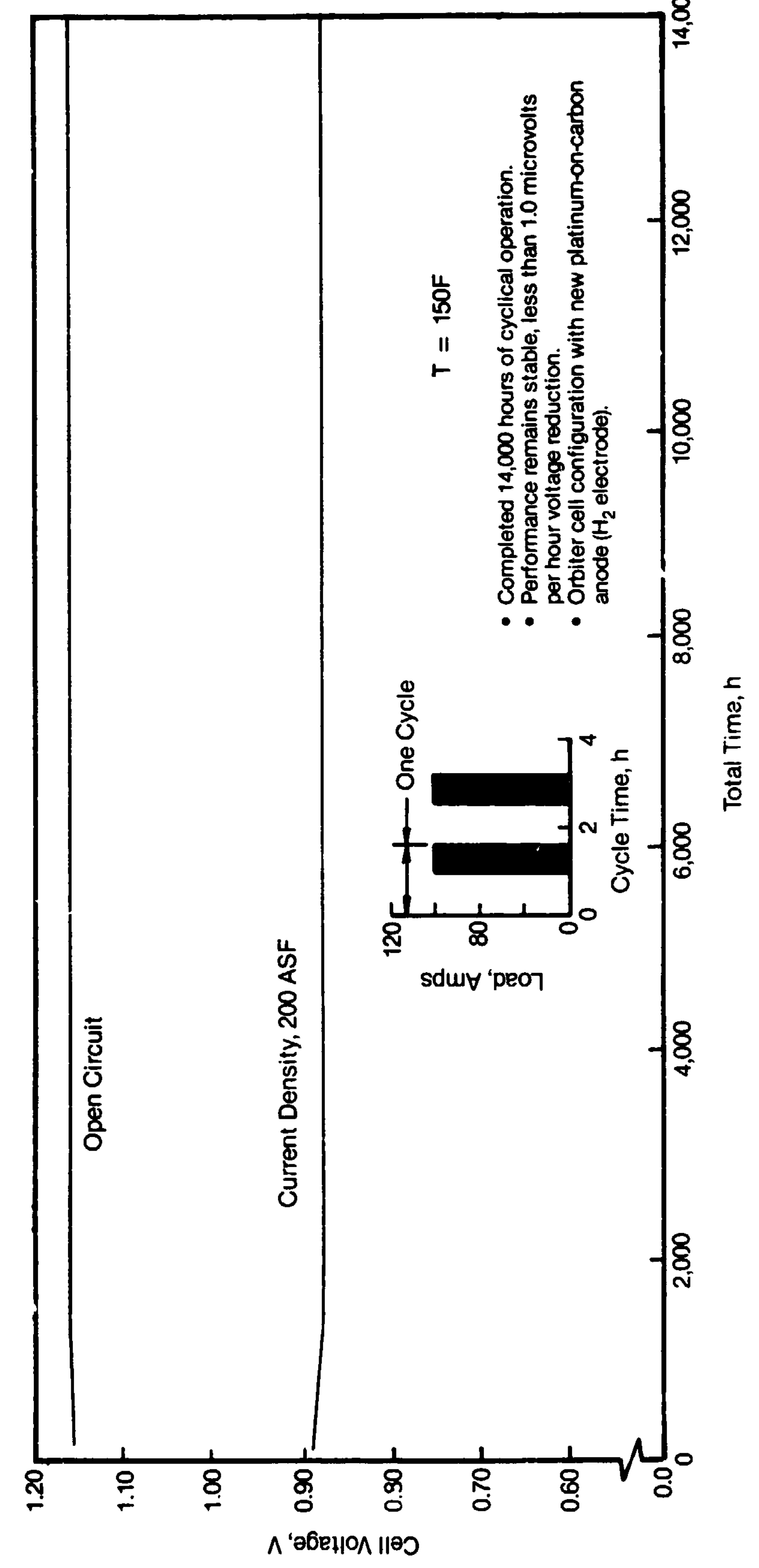


FIGURE 14 FUEL CELL LONG-TERM ENDURANCE TEST (SIX CELL STACK)

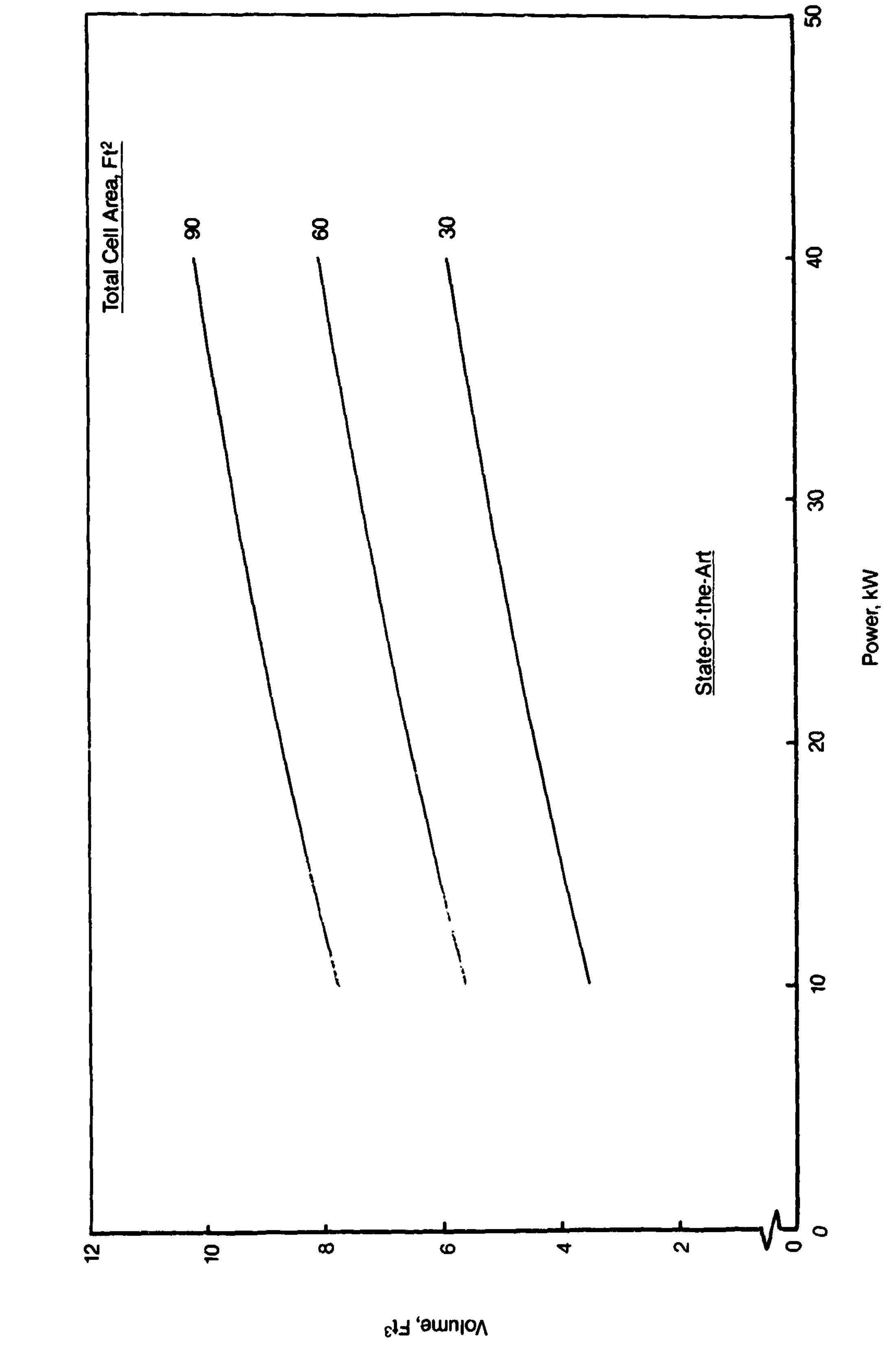


FIGURE 15 FUEL CELL SUBSYSTEM WEIGHT

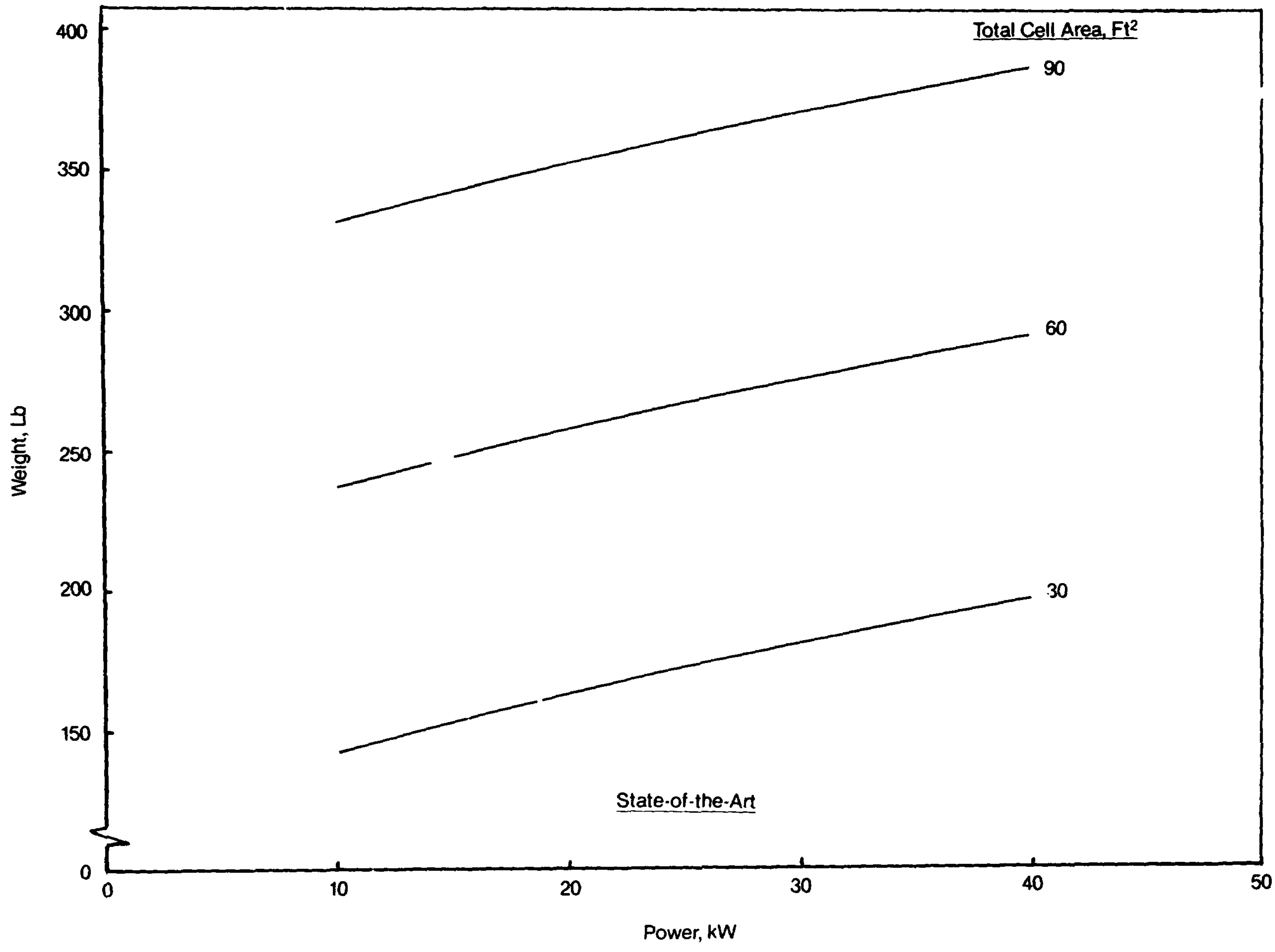


FIGURE 16 FUEL CELL SUBSYSTEM VOLUME

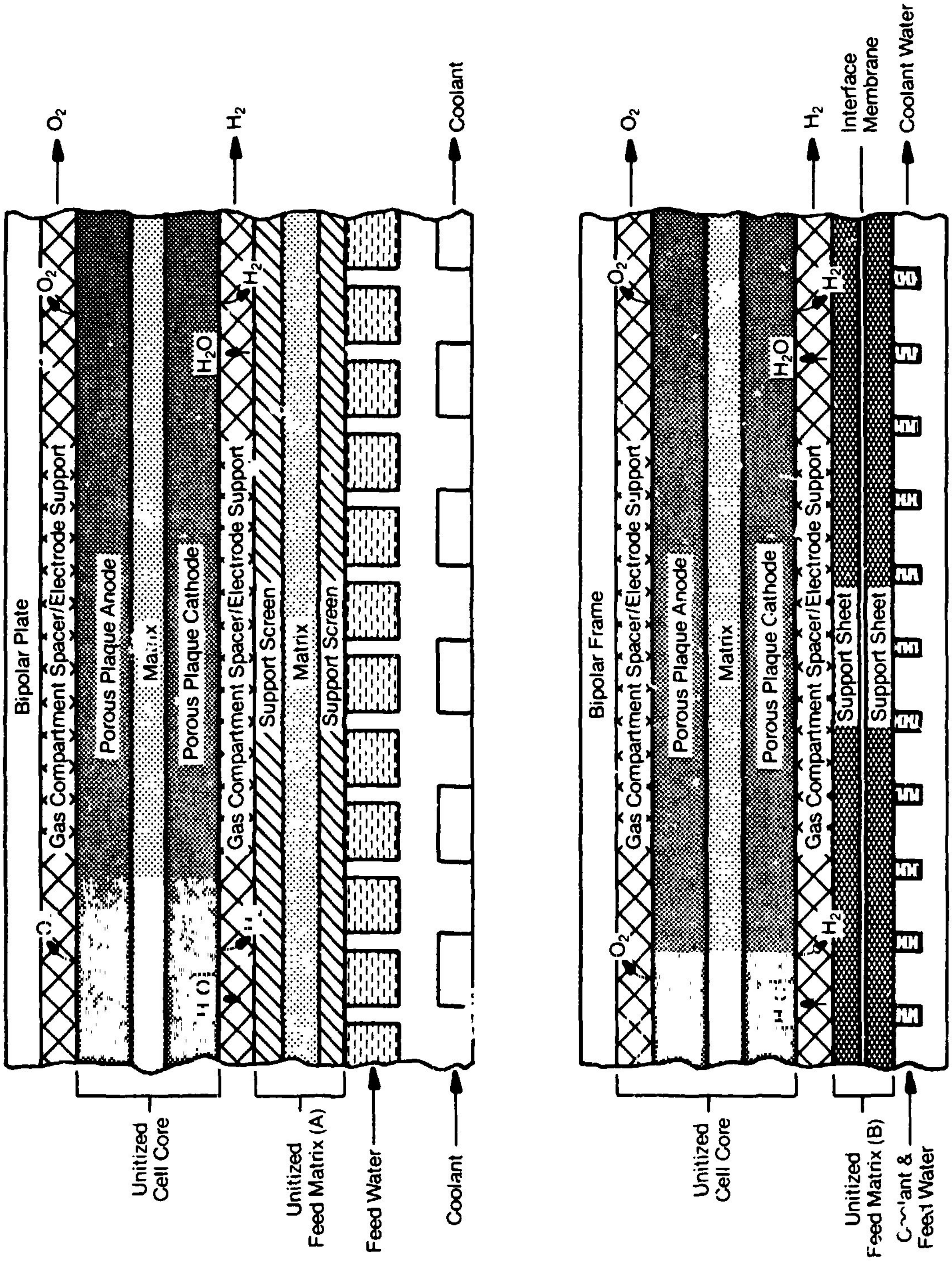


FIGURE 17 STATIC FEED ELECTROLYSIS CELL ASSEMBLY

Cell Performance

The voltage versus the current density is the key parametric performance relationship for the water electrolysis cells. This relationship is shown in Figure 18 for Life Systems' alkaline electrolysis cells. The performance is plotted for four temperatures (140, 160, 180, and 200F). Pressure effects on electrolysis performance are minimal and can be neglected over the pressure range of 120 to 550 psig. The alkaline electrolysis performance as a function of time is shown in Figure 19.

Based on the cell performance of both the fuel cell and the electrolyzer, the RFCS electrochemical efficiency can be plotted as in Figure 20. It should be noted that the electrochemical efficiency does not take the system parasitic power into consideration. Since the RFCS parasitic power demands are low, the electrical-to-electrical system efficiency is approximately 98% of the electrochemical efficiency shown in Figure 20.

Cell Size Optimization

Large cell sizes tend to decrease the total cell weight but at the same time they increase the end plate weight. Therefore, there exists an optimum cell size that results in minimum electrolysis module weight for a given set of operating conditions. The key operating parameters are the water consumption rate, the current density and the pressure. A computer program using the Rosen algorithm[a] was written to determine the optimum cell sizes for different operating conditions. Results for a Static Feed Electrolyzer (SFE) module suitable for the 10 kW EMS are plotted in Figure 21. The acceptable range of optimum cell size is determined based on the cell size that gives the minimum module weight and the larger cell size that gives a module weight 5% higher than the minimum weight. The larger cell size is preferred because of the improved electrolyzer reliability due to reduced number of cells. A 1.0 ft^2 cell is within the acceptable range of optimum cell size for the 10 kW EMS application and was selected. This cell size is identical to the hardware currently being developed under the NASA LeRC sponsored technology program (NAS3-21287). Actual 1.0 ft^2 cell hardware and a six cell module with lightweight honeycomb end plates are shown in Figures 22 and 23, respectively.

The effect of the water consumption rate, the current density and the pressure on the optimum electrolysis cell size is shown in Figures 24, 25 and 26, respectively. The trend of the optimum cell size may be summarized as follows: as either the water consumption rate increases, the current density decreases, or the pressure decreases, the optimum cell size increases.

Electrolyzer Design

As an aid to the electrolysis module design, the effect of the electrolysis current density and source voltage on the number of cells was defined and is shown in Figure 27 for a 10 kW RFCS. The impact of the electrolysis current density and cell area on the load current is shown in Figure 28 for the same size RFCS. Similar graphs for the 20 kW and 30 kW RFCS had been prepared and were presented in the final presentation, but are not included in this report.

(a) Reference 6, page 81.

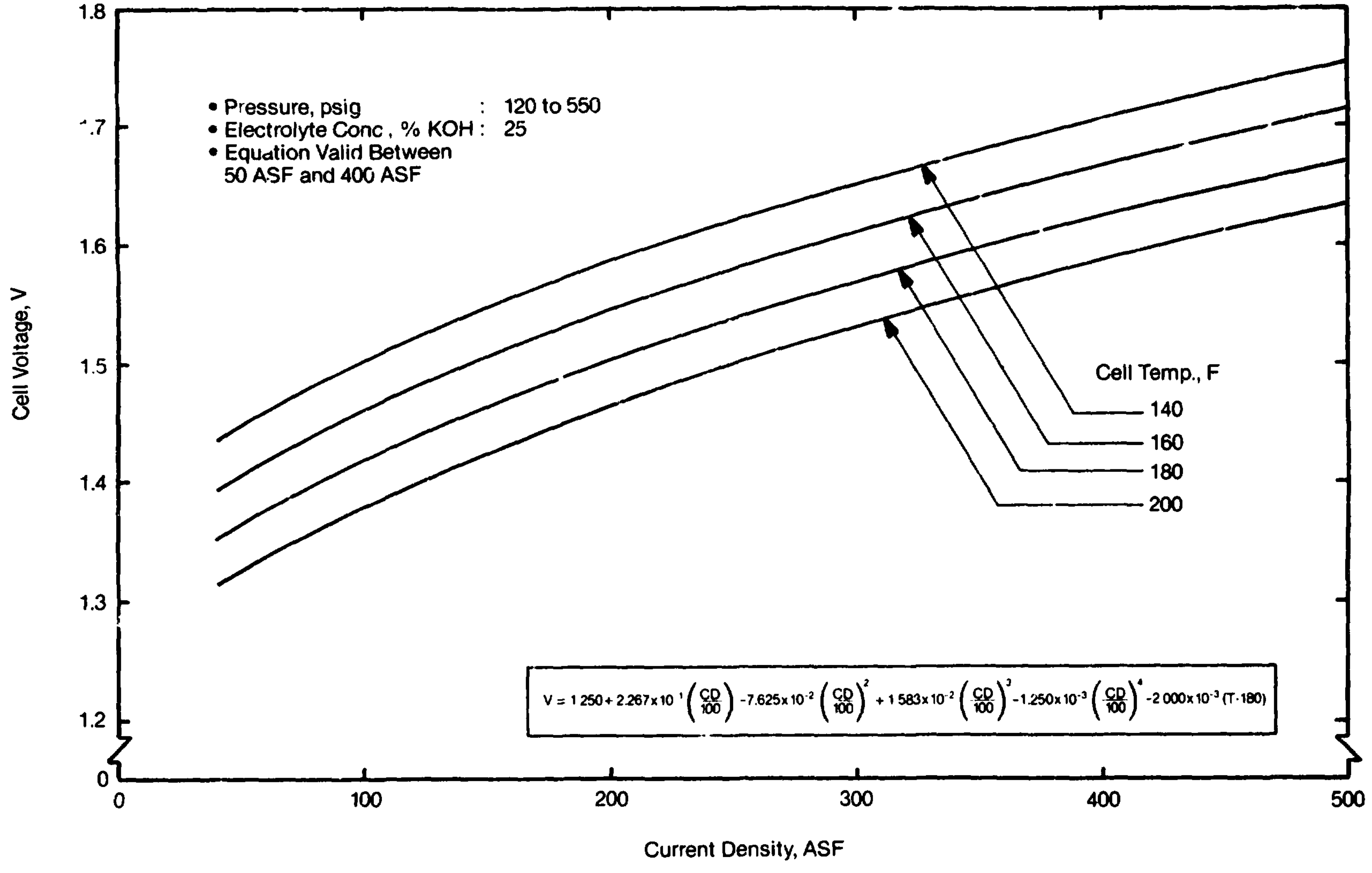


FIGURE 18 ALKALINE ELECTROLYSIS PERFORMANCE AS A FUNCTION OF TEMPERATURE

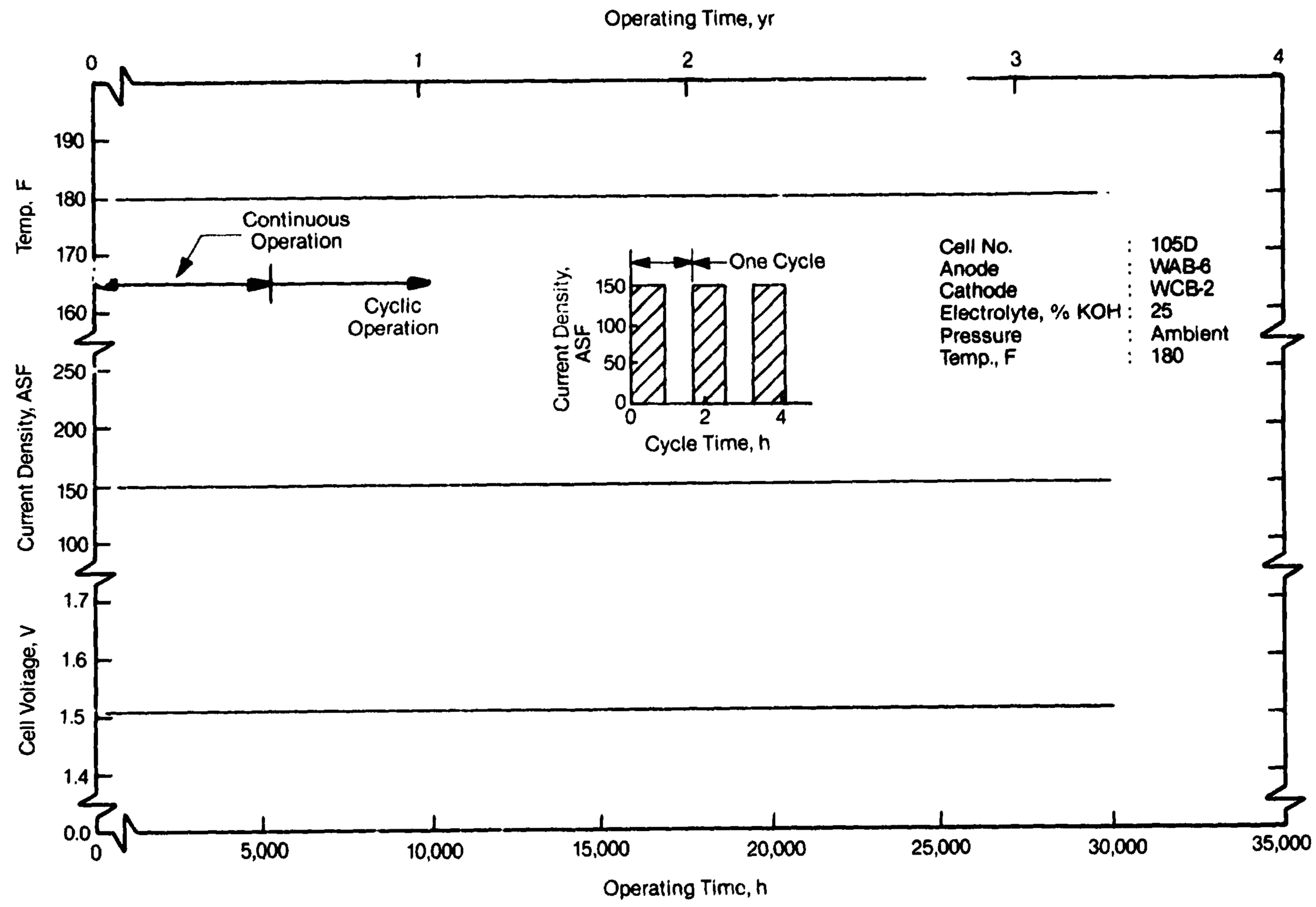


FIGURE 19 ALKALINE ELECTROLYSIS PERFORMANCE VERSUS OPERATING TIME ($0.1\ FT^2$ SINGLE CELL WITH SUPER ELECTRODE)

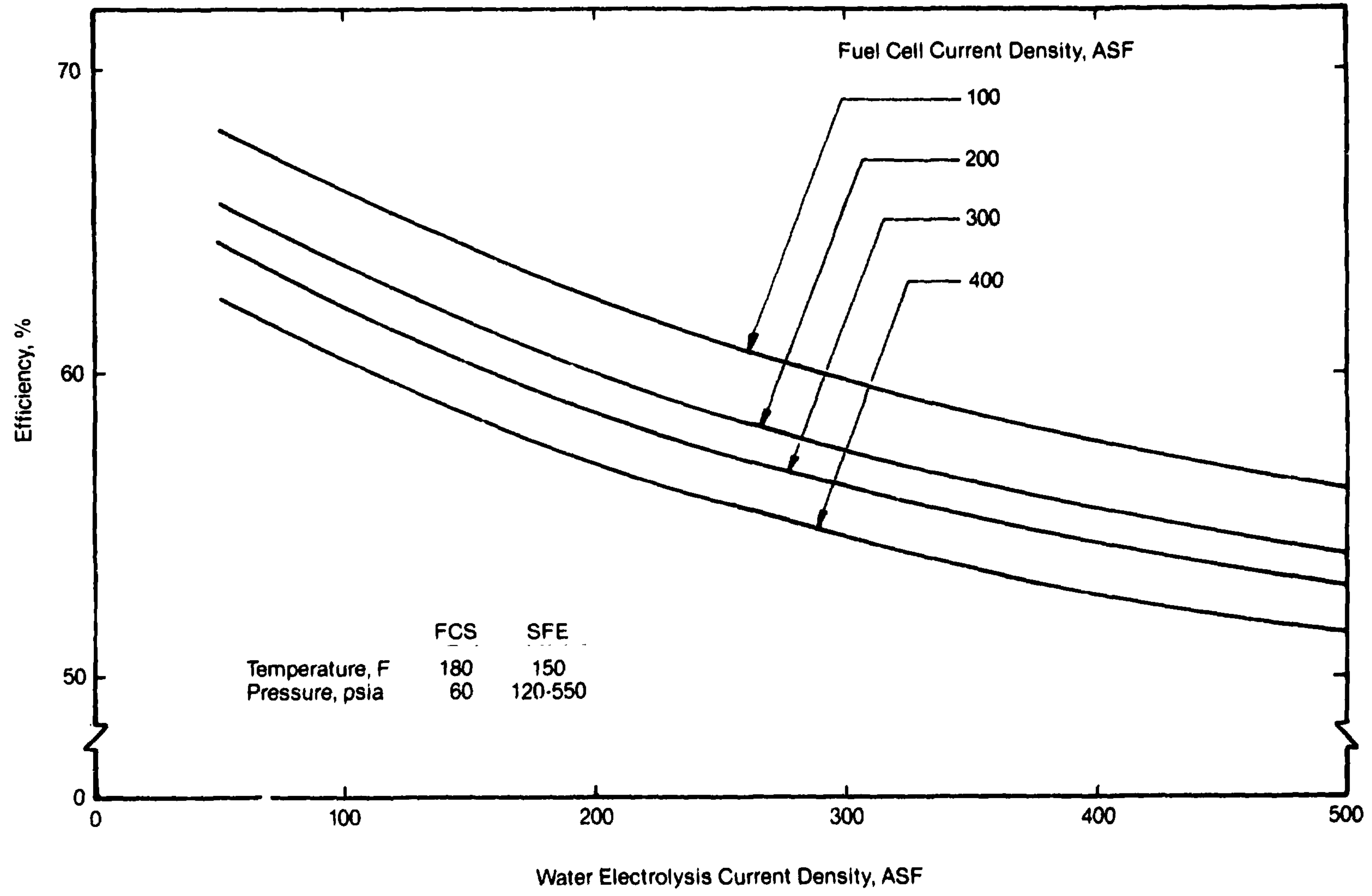


FIGURE 20 RFCS ELECTROCHEMICAL EFFICIENCY

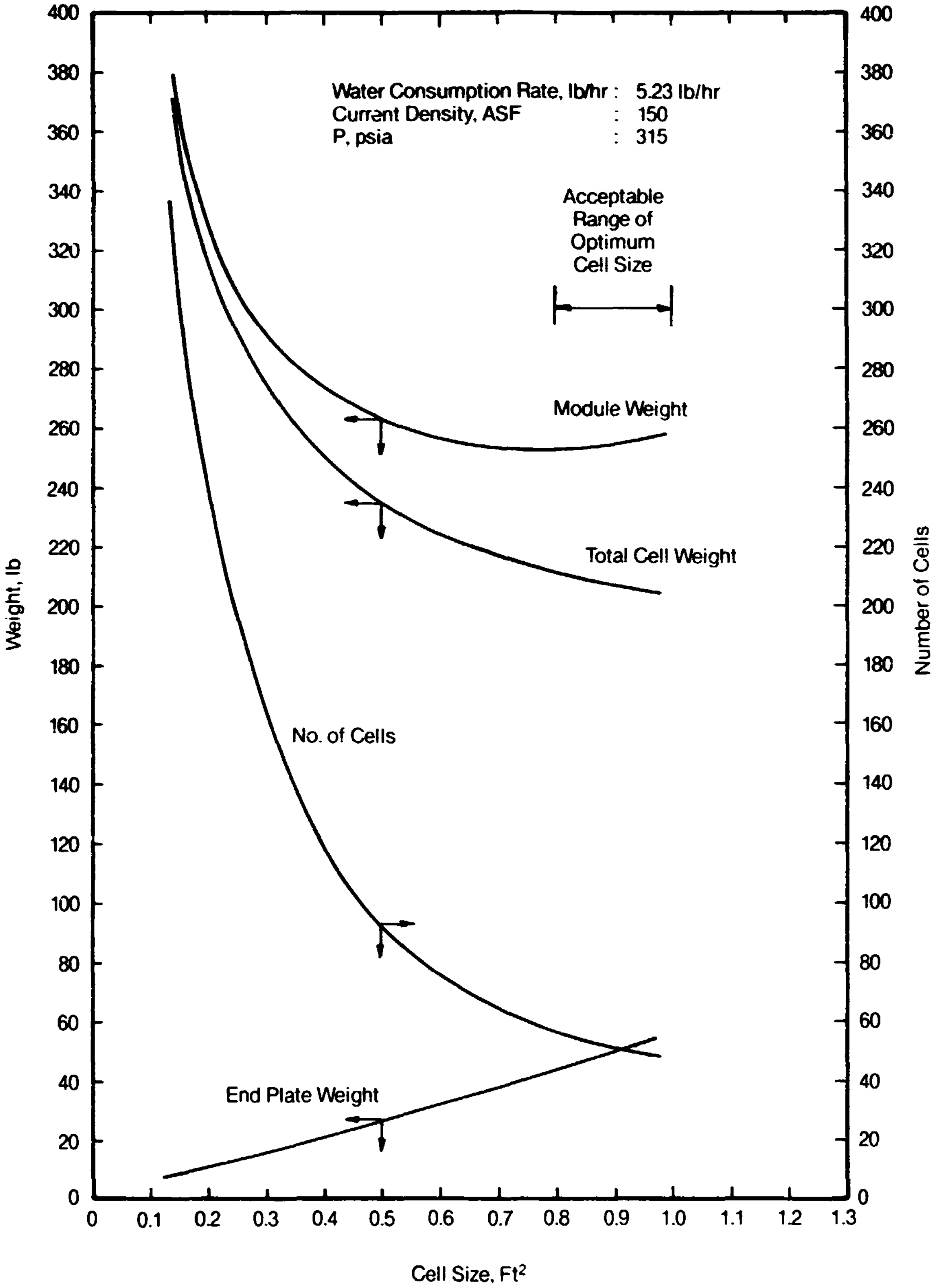


FIGURE 21 ELECTROLYSIS CELL STACK/PARTS WEIGHTS VERSUS CELL SIZE (5.23 LB REACTANT/HR, 150 ASF AND 315 PSIA)

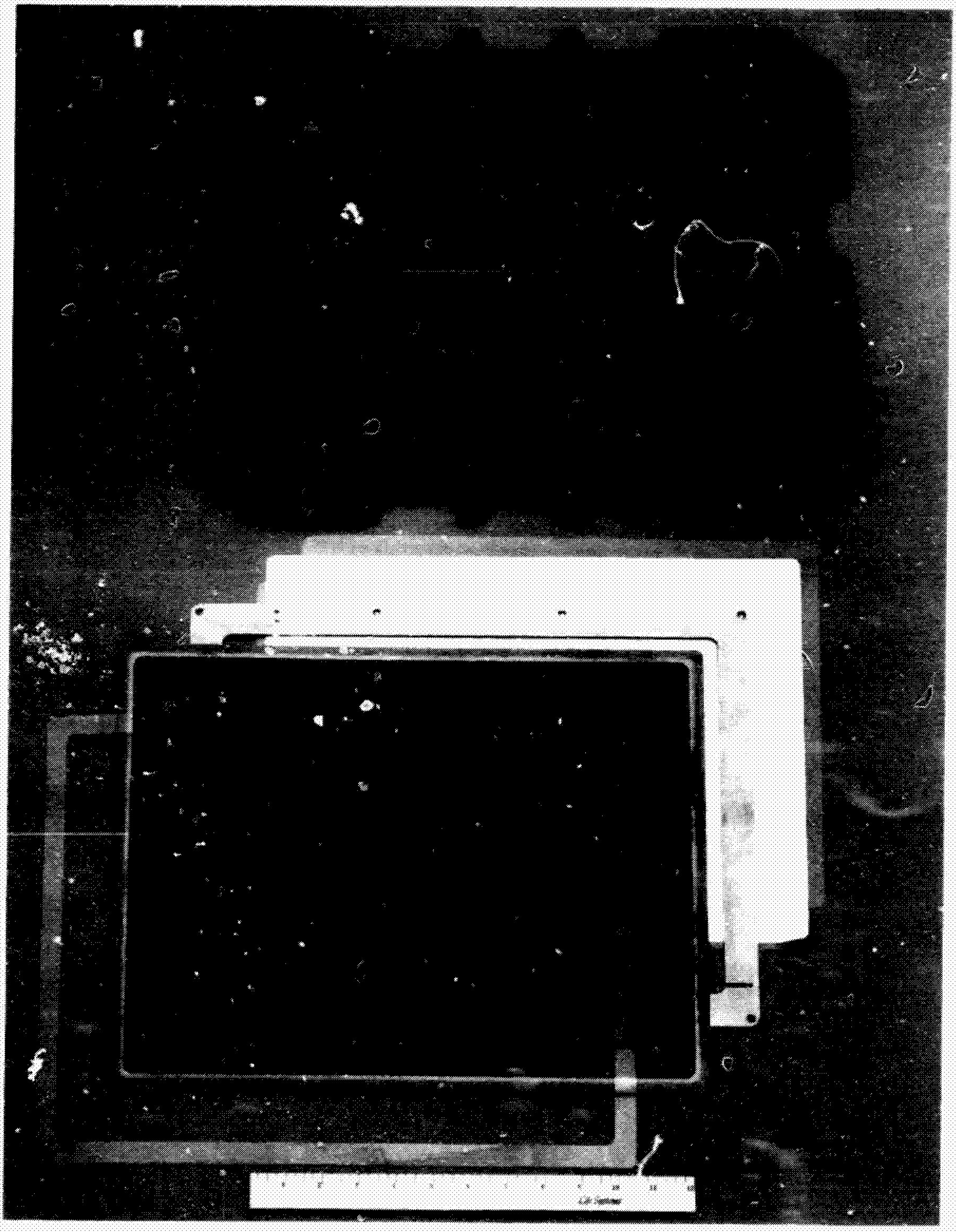


FIGURE 22 ONE FT^2 WATER ELECTROLYSIS SUBSYSTEM CELL HARDWARE

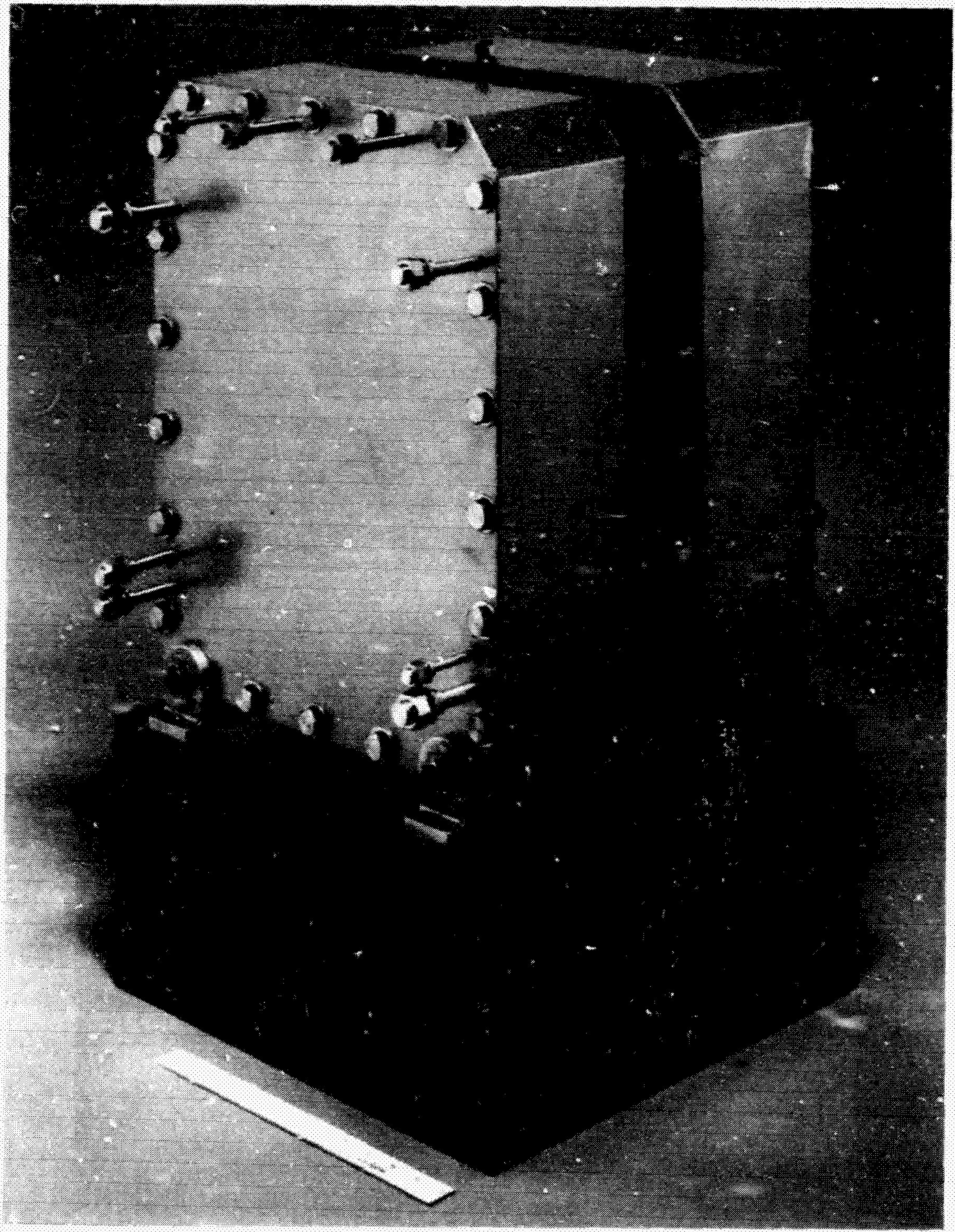


FIGURE 23 SIX-CELL, 1.0 FT^2 WATER ELECTROLYSIS MODULE WITH LIGHTWEIGHT HONEYCOMB END PLATES

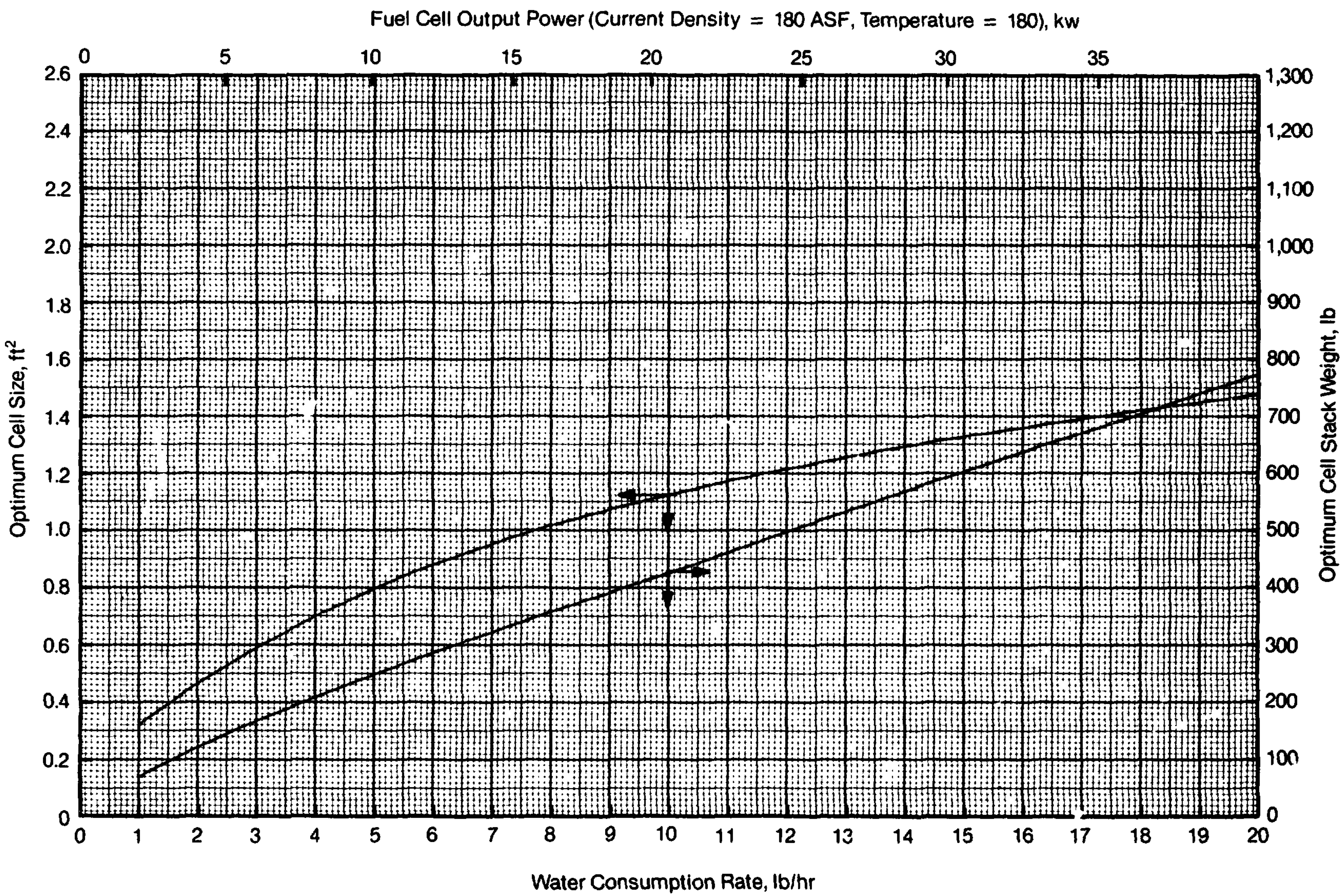


FIGURE 24 OPTIMUM SFE CELL SIZE AND CELL STACK WEIGHT VERSUS WATER CONSUMPTION RATE

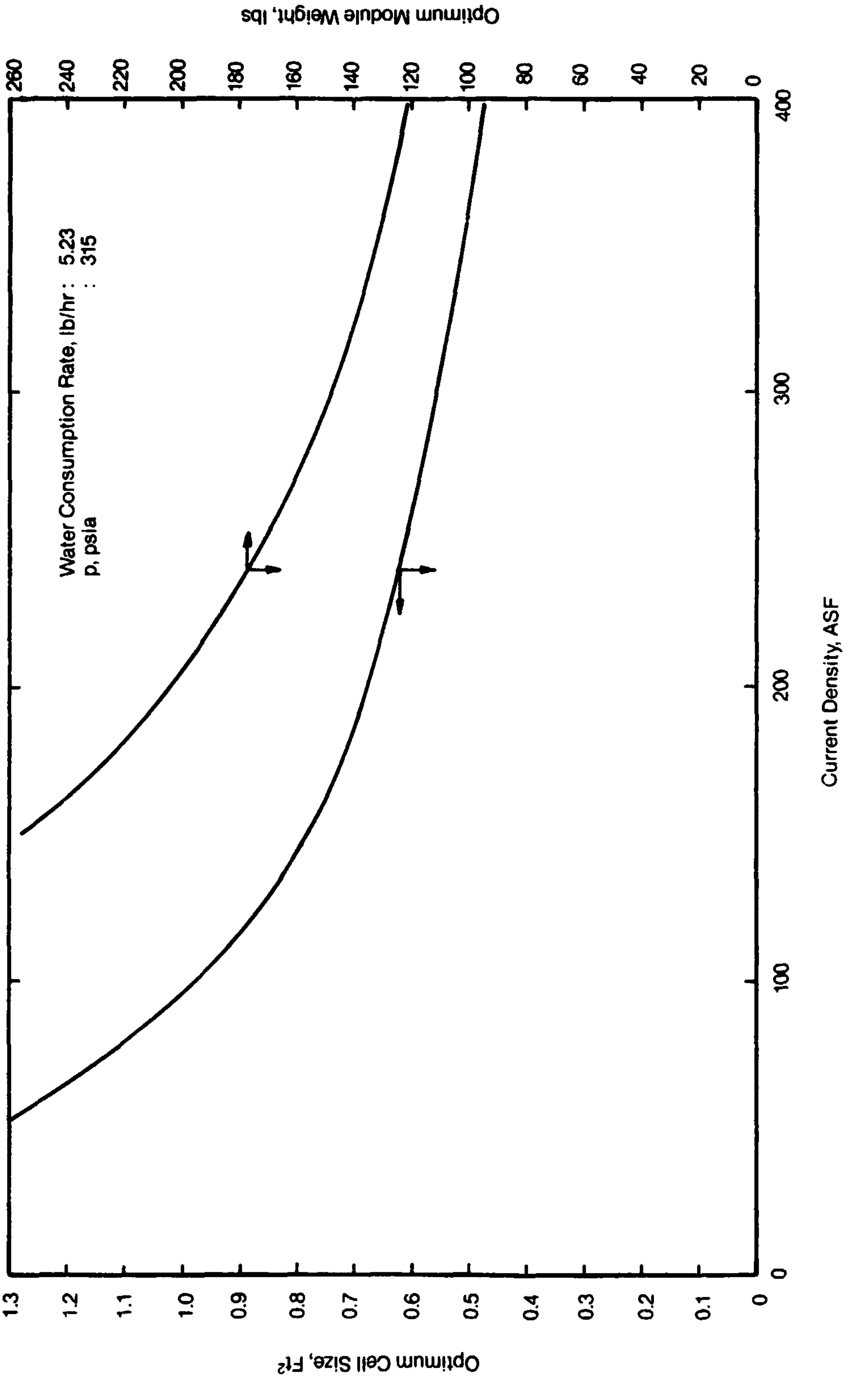


FIGURE 25 OPTIMUM SFE CELL SIZE AND MODULE WEIGHT VERSUS CURRENT DENSITY

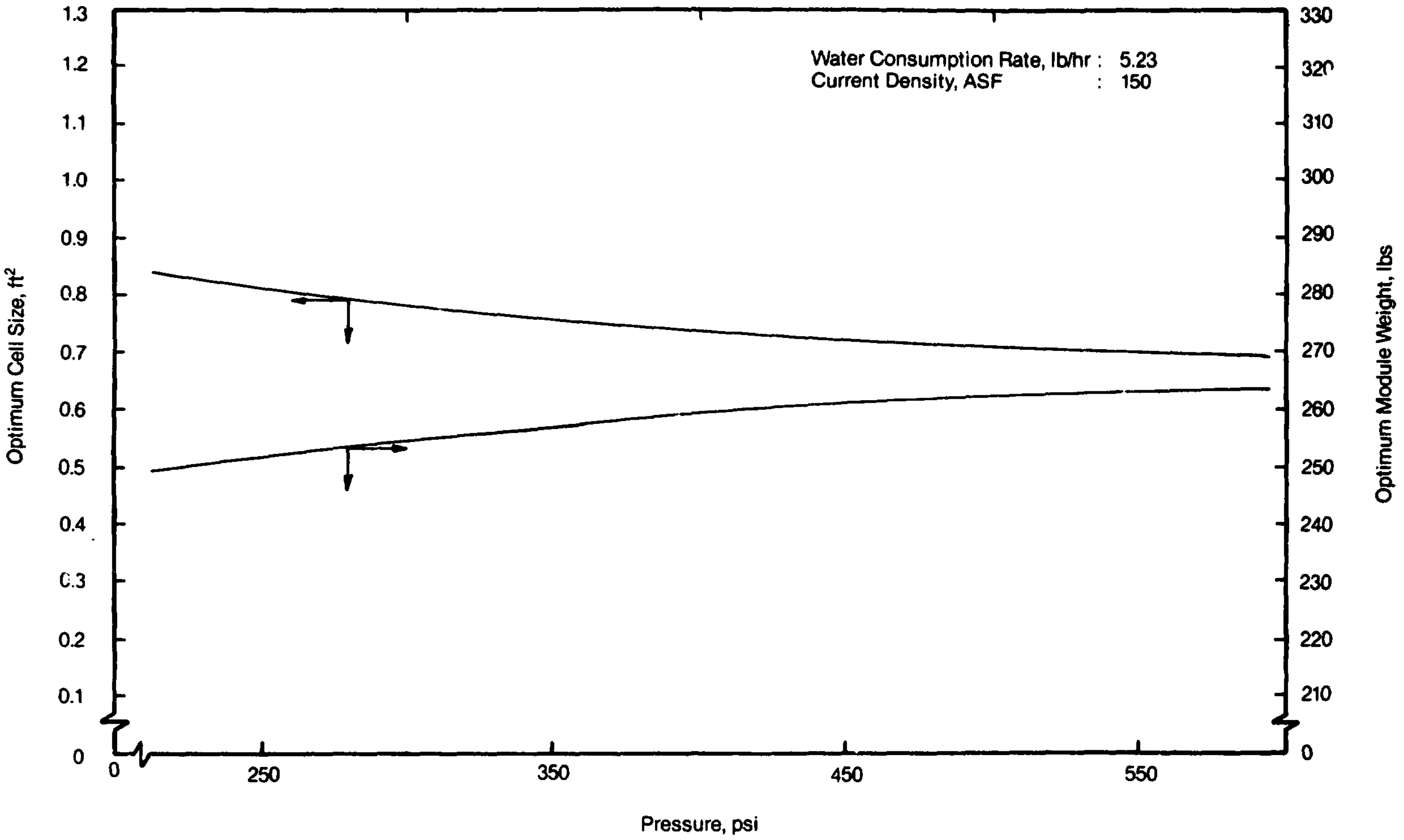


FIGURE 26 OPTIMUM SFE CELL SIZE AND MODULE WEIGHT VERSUS PRESSURE

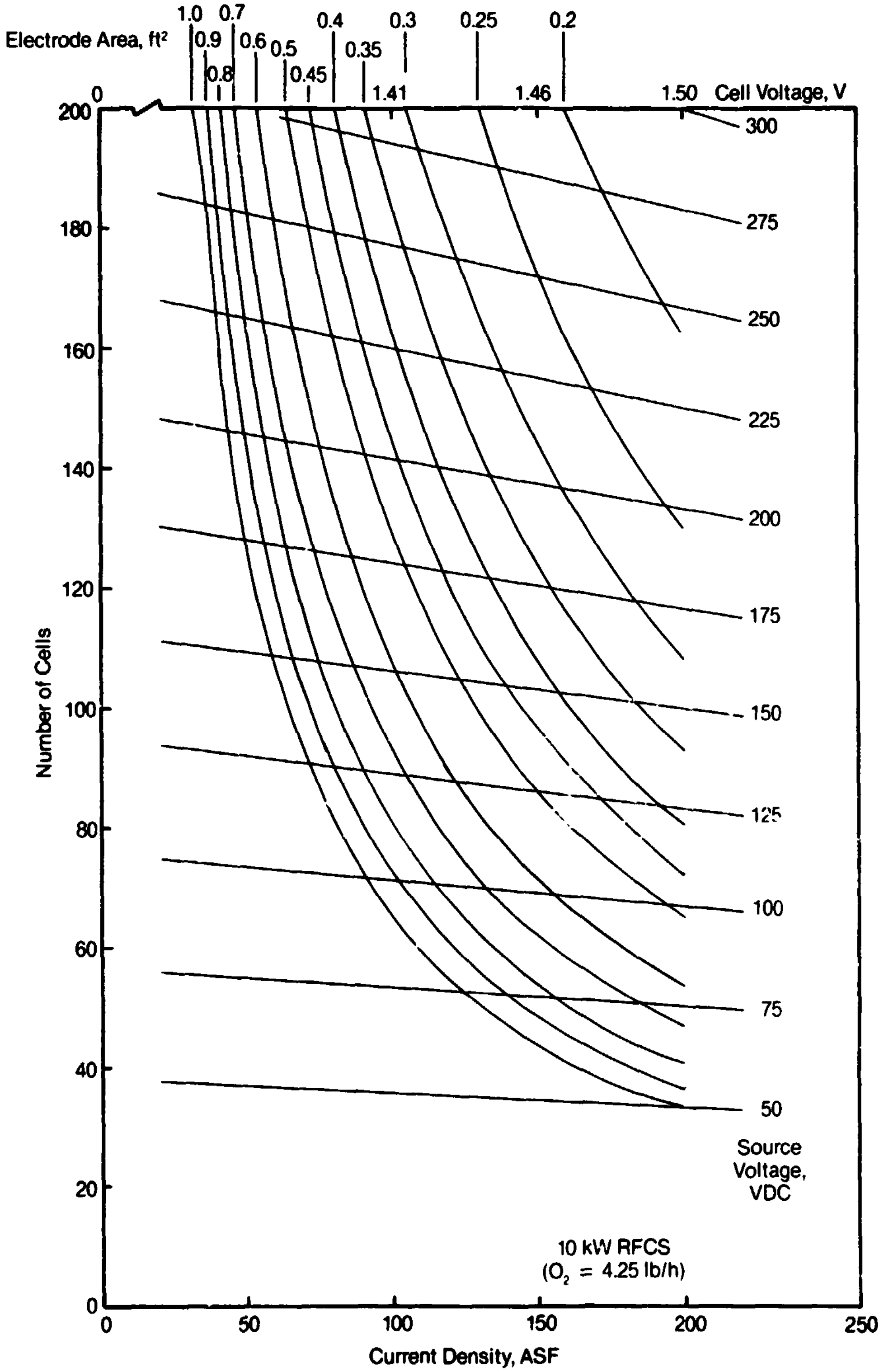


FIGURE 27 EFFECT OF SFE CURRENT DENSITY AND SOURCE VOLTAGE ON NUMBER OF CELLS (10 kW RFCS)

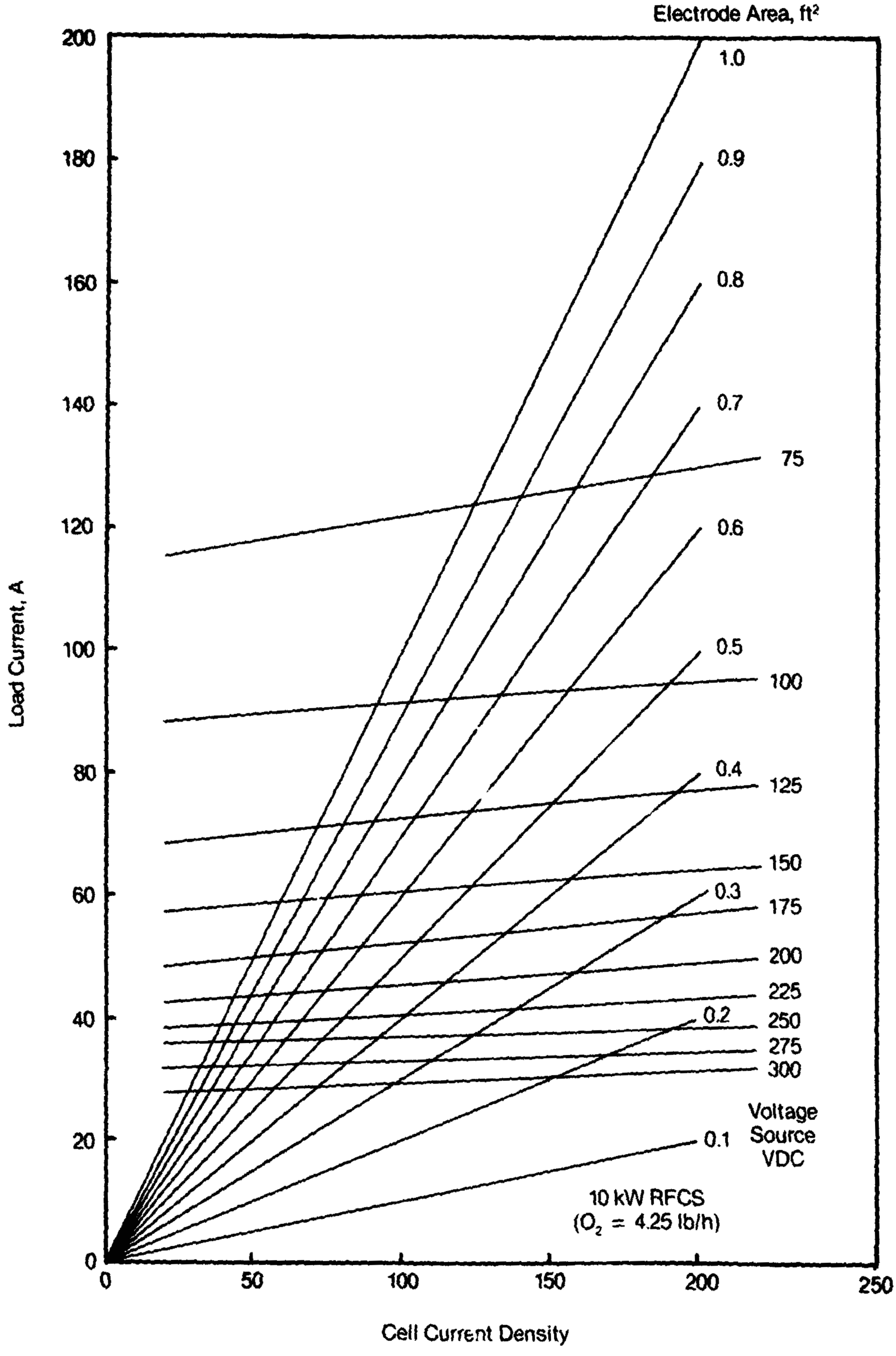


FIGURE 28 EFFECT OF SFE CURRENT DENSITY AND CELL AREA ON LOAD CURRENT (10 kW RFCS)

The weight and volume of the WES which includes the module and the ancillary components are shown in Figures 29 and 30, respectively, as a function of the RFCS power and the total cell area. The ancillary components proposed for the electrolyzer in the EMS include the following integrated mechanical components: Fluids Control Assembly (FCA) (shown in Figure 31), Two-Fluids Pressure Controller (2-FPC) for the three-compartment cell and Coolant Control Assembly (CCA) Unit 2. Figure 32 presents the capacity of these integrated mechanical components plus the existing Three-Fluids Pressure Controller (3-FPC) (see Figure 33) and CCA Unit 1 (see Figure 34). It is clear that all of these components can handle flow rates corresponding to at least 10 kW power level with the ones proposed for the EMS having capacities up to the 30 kW level.

10 kW EMS Prototype

Detailed Mechanical Schematic

A more detailed EMS prototype schematic is shown in Figure 35. The components to be developed include Interface Fluids Control Assembly, heat exchanger assembly, 2-FPC, upgraded FCA and upgraded coupled reactant regulator which has a maximum pressure drop of 10 psi as opposed to 40 psi in the current version.

EMS Optimization

The RFCS can be designed to be the most efficient, the most reliable, the lowest weight or the lowest cost. The preferred operating conditions for these different design criteria are shown in Table 6. It should be pointed out that the lowest weight design referred to in Table 6 considers only the RFCS weight. An optimum RFCS design should take into consideration the weights of solar arrays, radiator and station keeping propellant for the specified years to orbit operation. This study includes the latter.

A computer program using the Rosenbrock search method was written that minimizes the RFCS weight for any given years-to-orbit operation by optimizing the electrolyzer current density, fuel cell current density and electrolyzer operating pressure. The results for the 10 kW EMS indicate that the optimum electrolyzer current density, fuel cell current density and electrolyzer operating pressure are 157 ASF, 167 ASF and 247 psia, respectively. The five-year to orbit weight is 2,790 lb and the electrical to electrical efficiency is 61.1% under these optimum conditions.

Another computer program was used to determine the effect of the water electrolysis current density on the system design for fixed fuel cell current density and electrolyzer operating pressure. Figure 36 presents the 10 kW RFCS five-year-to-orbit component weights as a function of the electrolyzer current density. The system weight and efficiency versus the water electrolysis current density are plotted in Figure 37 for the same RFCS design. The electrolyzer operating pressure of 315 psia used in these calculations is close to the optimum value of 247 psia determined previously. The weight increase due to this increase in operating pressure is very small (2 lb) because the RFCS system weight is a weak function of the electrolyzer operating pressure. The volume of the gaseous reactant storage tanks, however, is

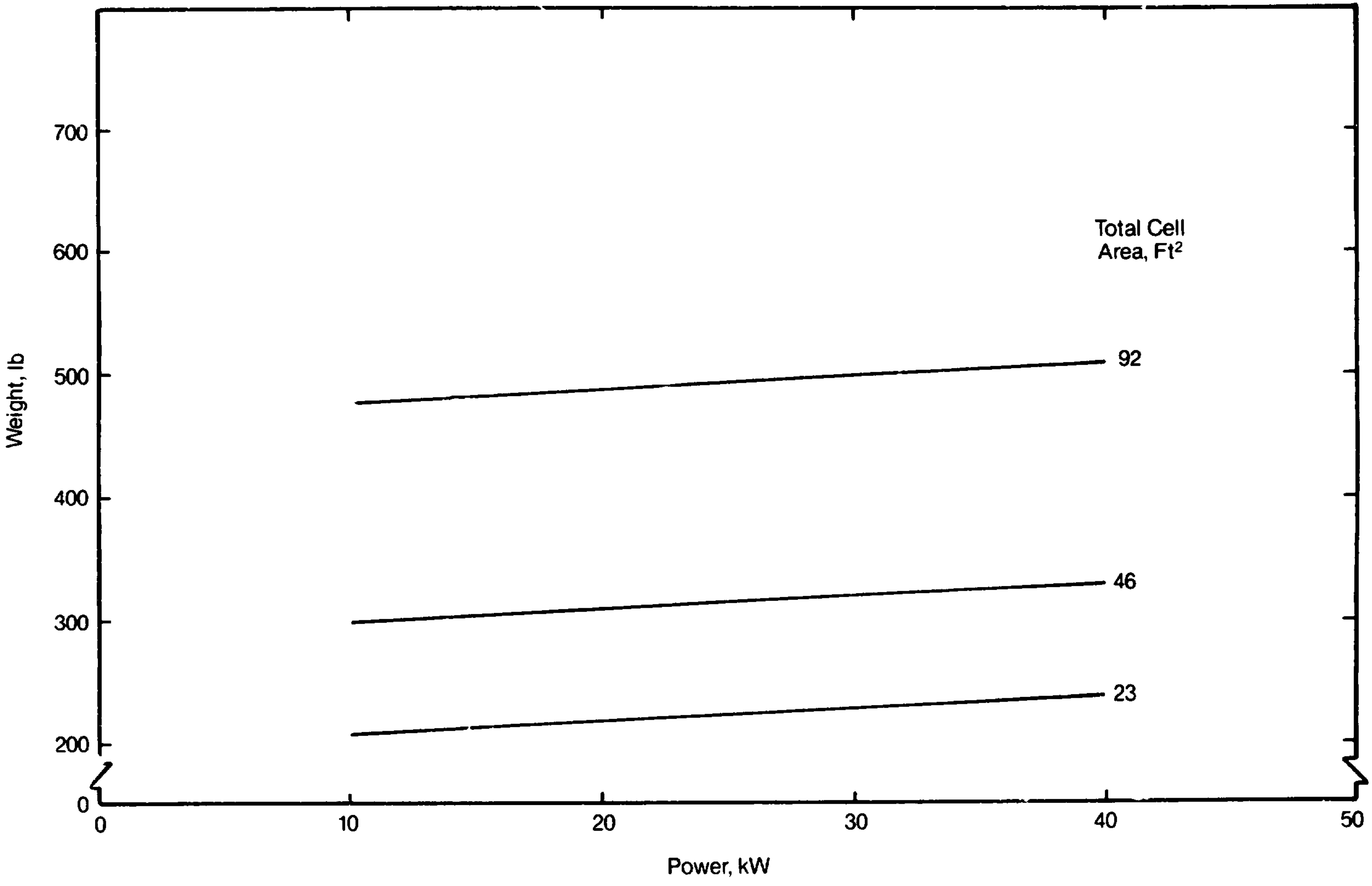


FIGURE 29 WES WEIGHT VERSUS POWER AS A FUNCTION OF TOTAL CELL AREA

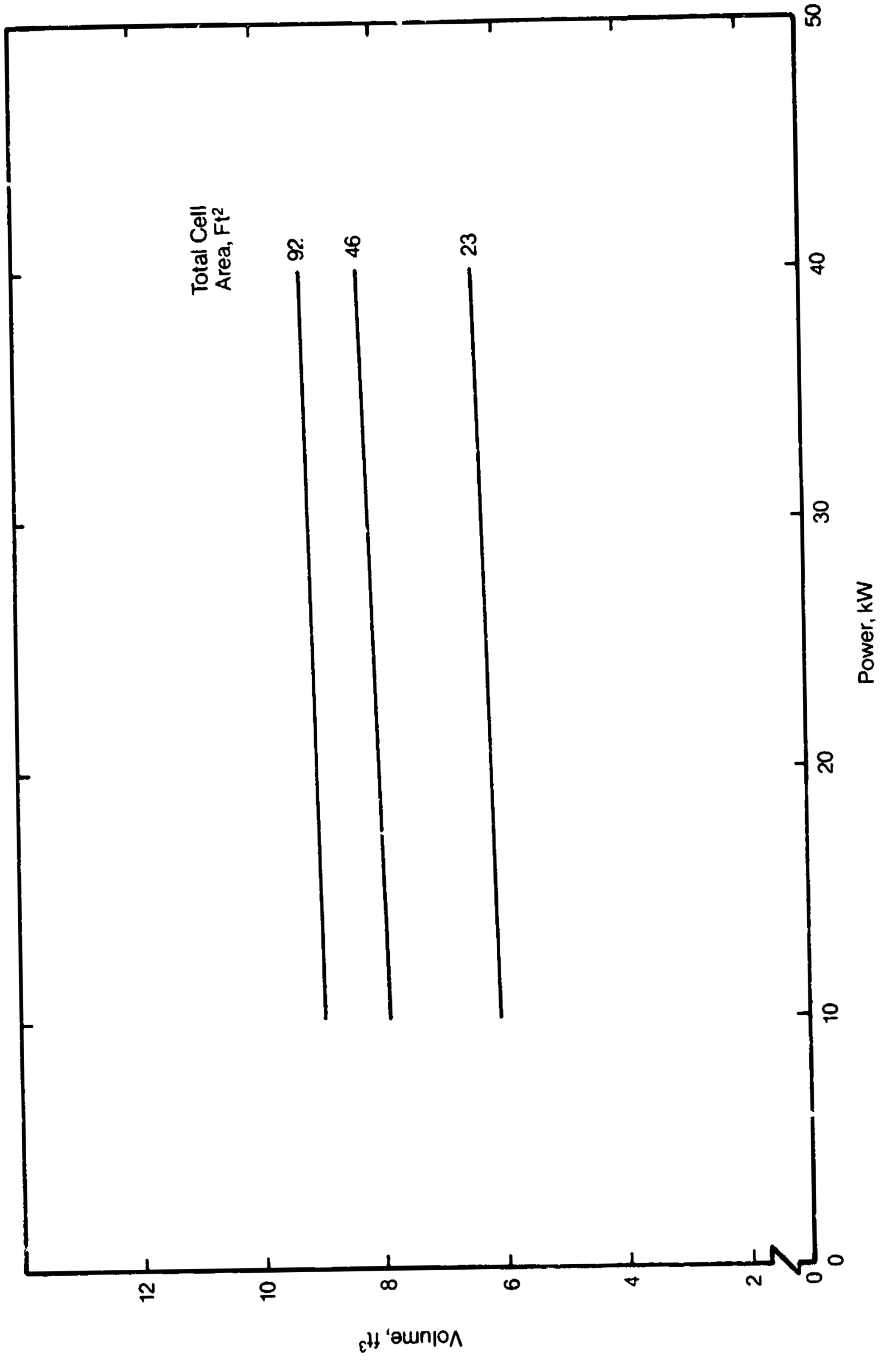


FIGURE 30 WES VOLUME VERSUS POWER AS A FUNCTION OF TOTAL CELL AREA

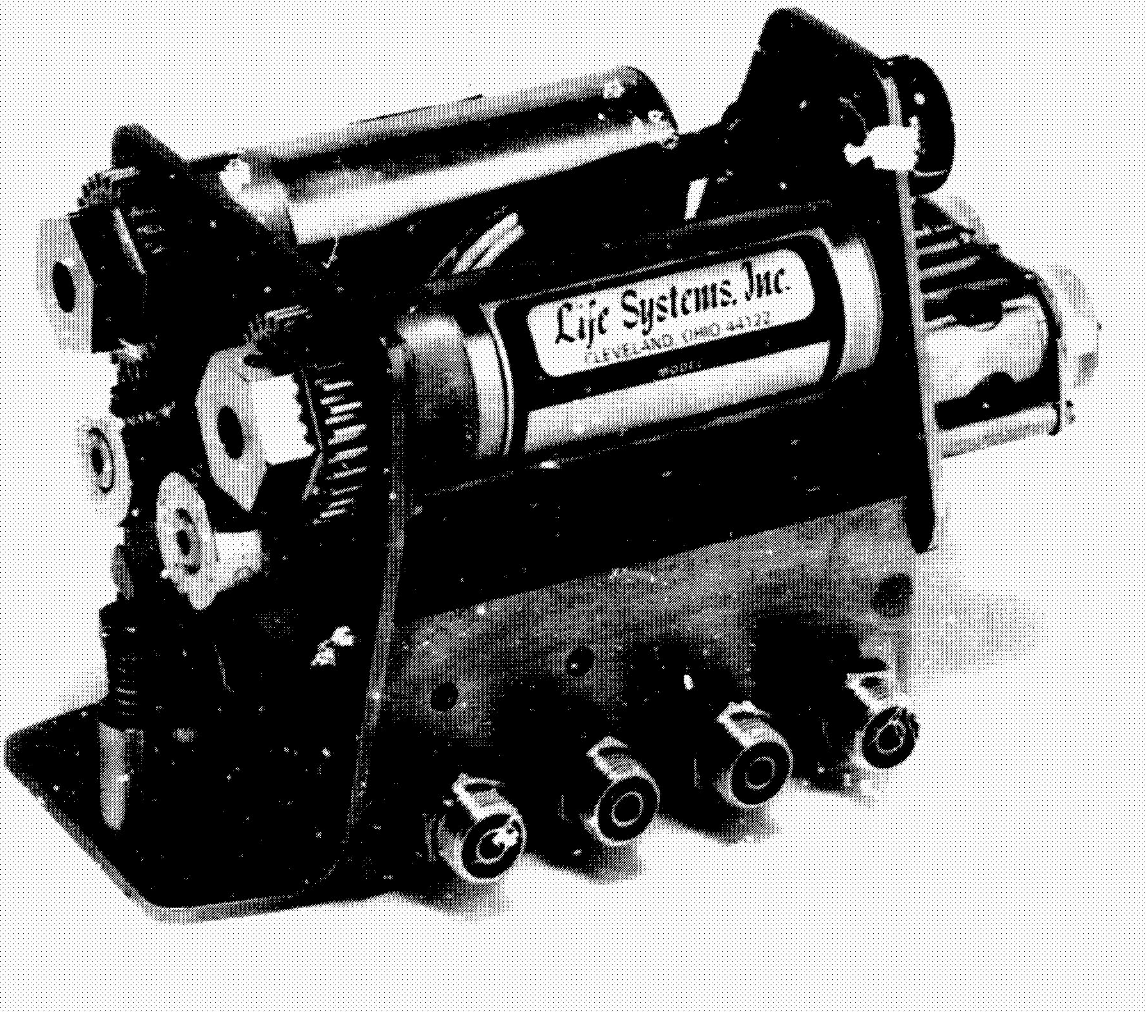


FIGURE 31 WATER ELECTROLYSIS SUBSYSTEM FLUIDS CONTROL ASSEMBLY

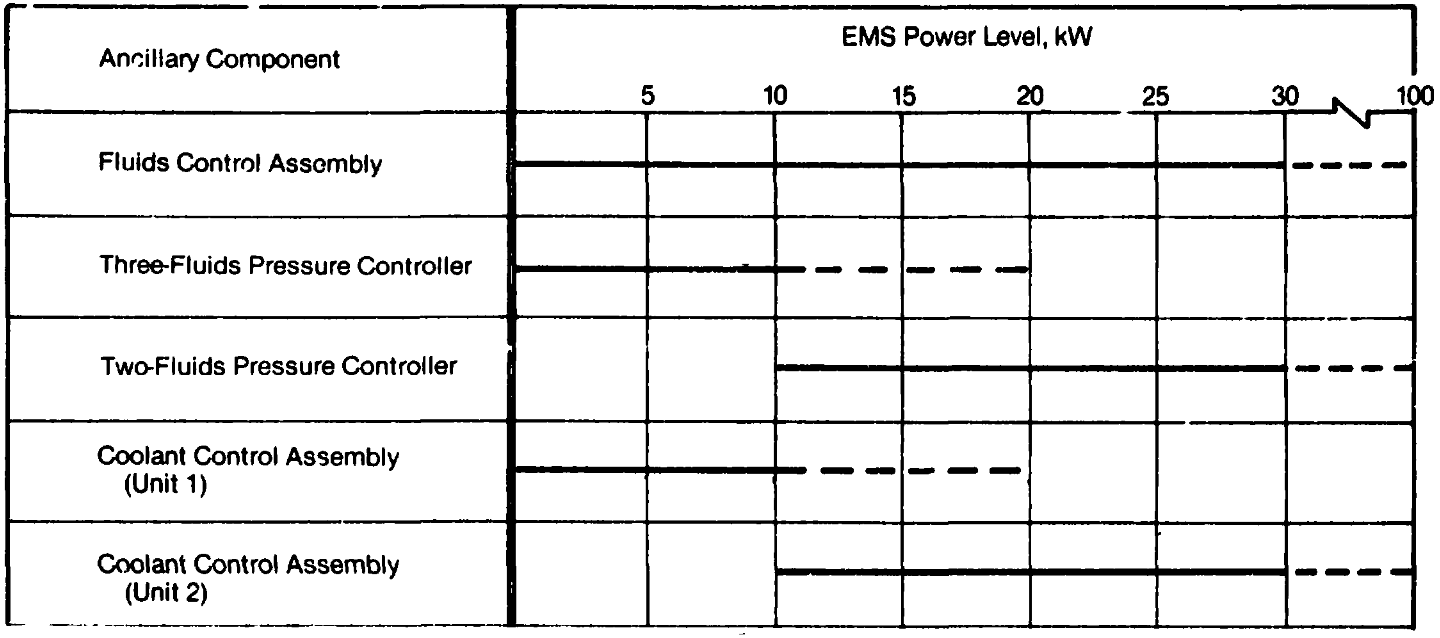


FIGURE 32 CAPACITY OF WES INTEGRATED MECHANICAL COMPONENTS

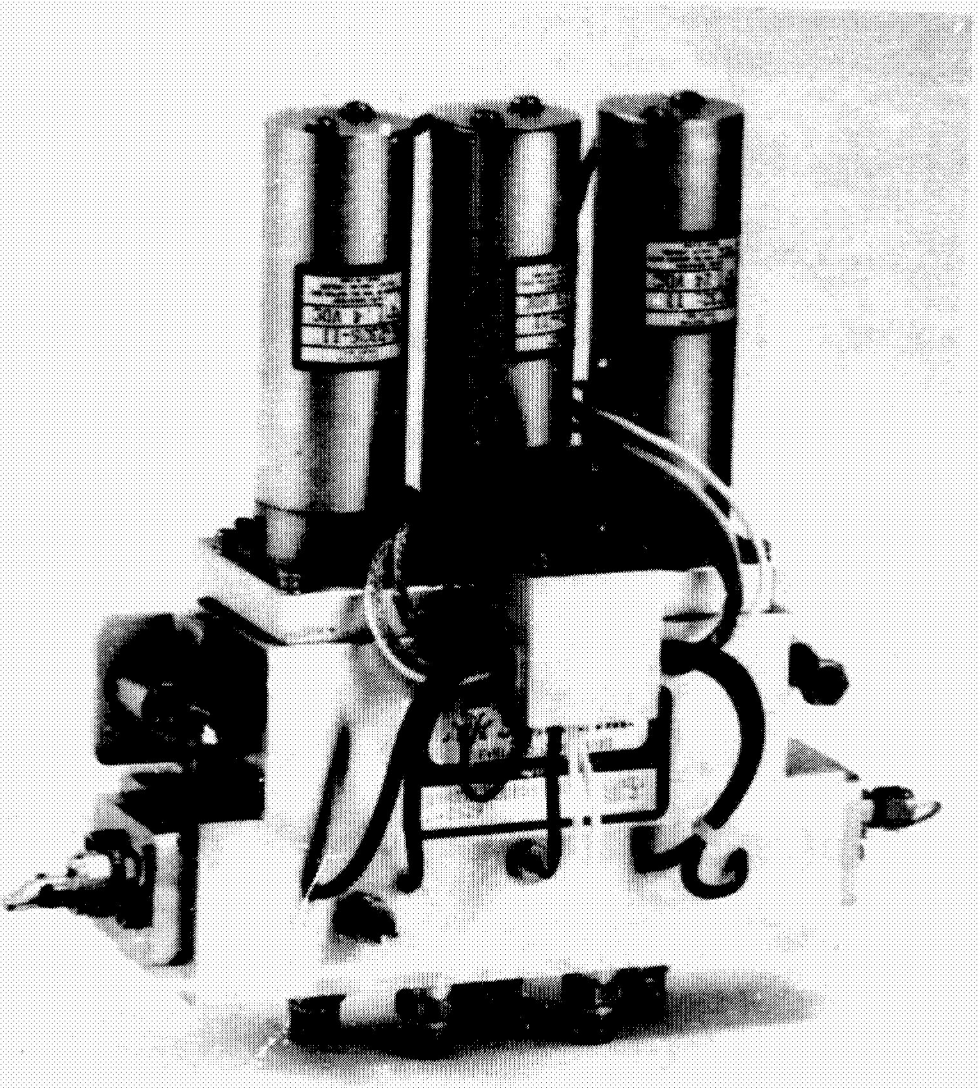


FIGURE 33 WATER ELECTROLYSIS SUBSYSTE 3-FLUIDS PRESSURE CONTROLLER

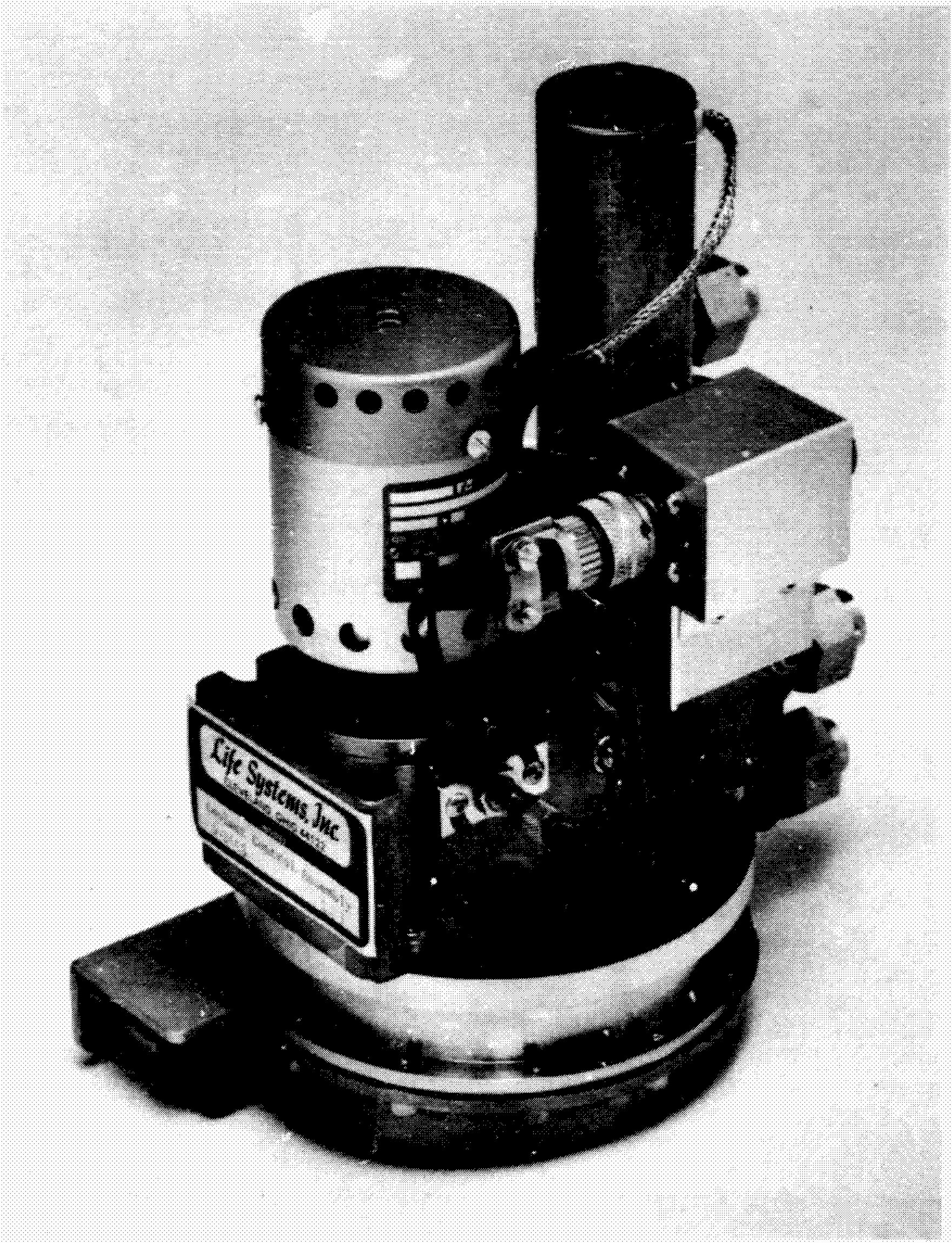


FIGURE 34 WATER ELECTROLYSIS SUBSYSTEM COOLANT CONTROL ASSEMBLY

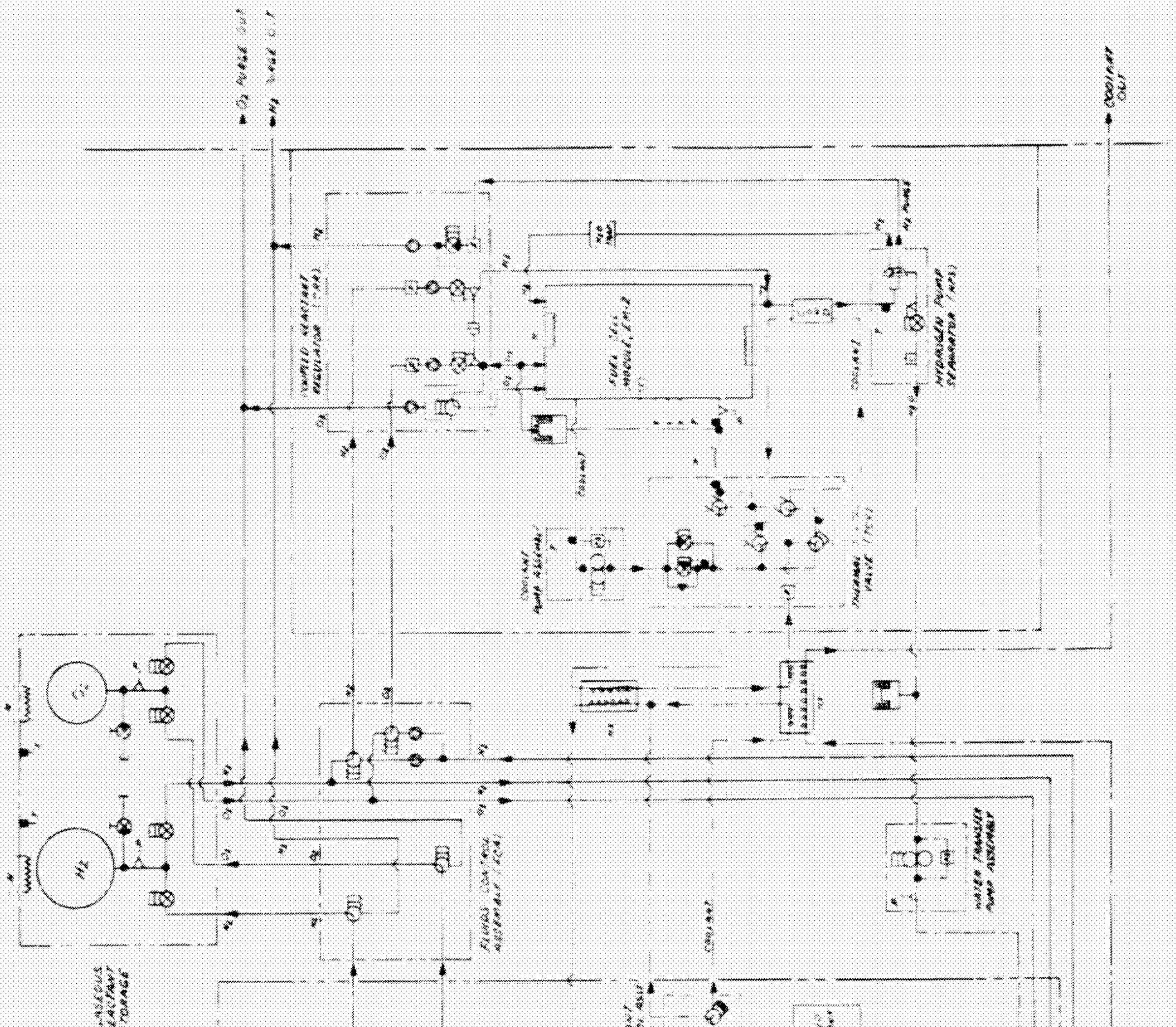


FIGURE 35 RFCS SCHEMATIC (EMS PROTOTYPE)

TABLE 6 PREFERRED OPERATING CONDITIONS FOR DIFFERENT RFCS DESIGN CRITERIA

	Operating Condition		
Design Criteria	Temperature	Pressure	Current Density
Most Efficient	Highest	Lower	Lowest
Most Reliable	Lower	Lower	Lower
Lowest Weight	Highest	Lowest	Highest
Lowest Cost[a]	Lower[b]	Lower	Higher

(a) After development successfully completed.
(b) Increased life means lower operating cost.

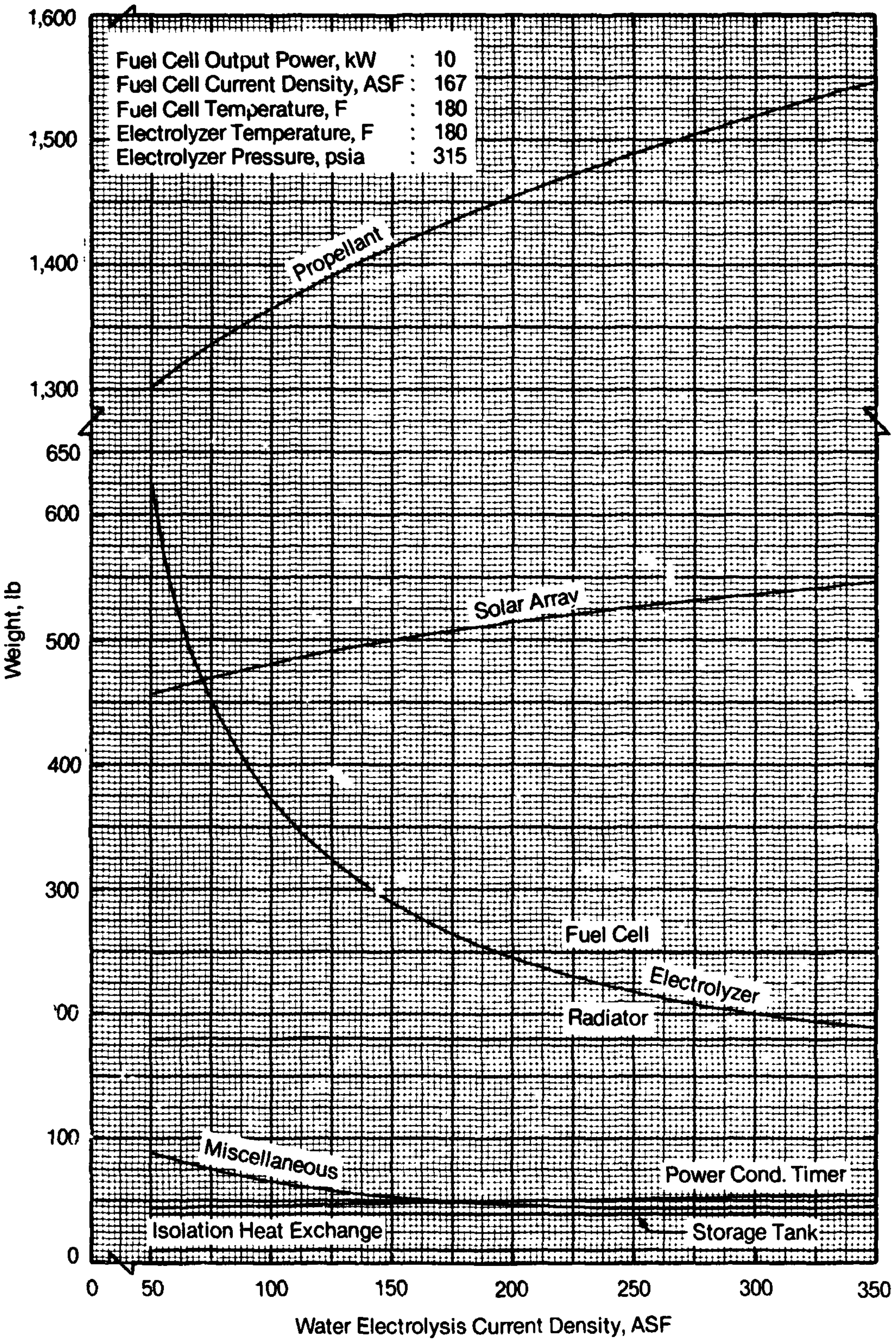


FIGURE 36 RFCS FIVE-YEAR-TO-ORBIT WEIGHT AND RFCS EFFICIENCY VERSUS WATER ELECTROLYSIS CURRENT DENSITY

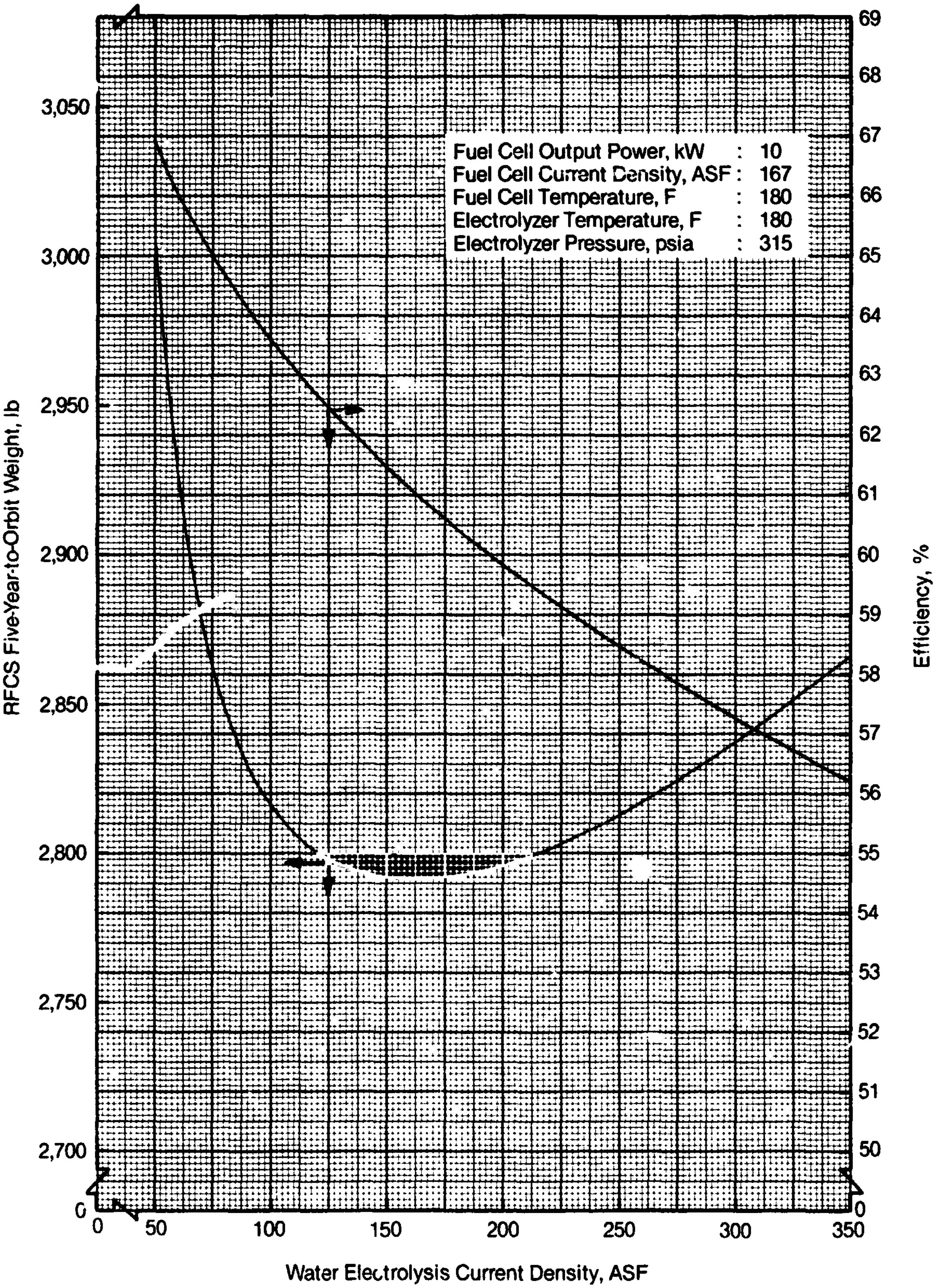


FIGURE 37 RFCS FIVE-YEAR-TO-ORBIT WEIGHT AND RFCS EFFICIENCY VERSUS WATER ELECTROLYSIS CURRENT DENSITY

reduced by 4.8 ft^3 using the higher operating pressure. It should be pointed out that light weight materials may be used for fabricating the storage tanks to reduce the RFCS system weight.

Physical Characteristics

The projected fuel cell current density, electrolyzer current density and electrolyzer operating pressure are 180 ASF, 150 ASF and 315 psia, respectively. These conditions do not deviate much from the optimum conditions and result in a five-year to orbit weight of 2,840 lb and an efficiency of 60%.

Because even the optimum conditions are subject to change in the final analysis for the space station, the projected operating conditions were used in sizing the 10 kW EMS. The 10 kW EMS prototype characteristics were determined as shown in Table 7. This EMS contains a 45-cell SFE and a 120-cell FCS. The total weight of the EMS is 636 lb. The operational limits of the EMS are shown in Table 8.

The isometric drawing of the electrolyzer and the 10 kW EMS without the gaseous storage tanks are shown in Figures 38 and 39, respectively. The capability to package the EMS electrolyzer as shown in Figure 38 is apparent when viewing a 2 kW capacity WES currently under test at Life Systems and shown in Figure 40. The gaseous reactant storage tanks are not shown in the isometric drawing because they are state-of-the-art hardware and are also envisioned to be packaged separately.

Mass and Energy Balance

A mass and energy balance was performed for the 10 kW EMS. Figure 41 shows the locations where the mass and energy data were calculated. The data for both dark and light orbit operations were compiled in Table 9.

EMS Control/Monitor Instrumentation

A major, but often overlooked component of a RFCS is its controller. Operation of the RFCS aboard the Space Station must be autonomous and totally automatic. The essential functions of the RFCS Control/Monitor Instrumentation (C/M I) are therefore the controlling and monitoring of the processes for fail-operational, fail-safe operation. A possible C/M I interface with the Power Management Subsystem within the EPS is shown in Figure 42. A Power Management Subsystem architecture and its possible interfaces are shown in Figure 43. The automation concept envisioned for the Space Station is illustrated in Figure 44. Controllers in different tiers perform different level controlling and monitoring functions.

A Life Systems' 200 Series controller is proposed for the EMS C/M I. It performs RFCS system control, indicates status, gives status message code and communicates with external devices through communication link. Because of its advanced design, the 200 series controller does not have operator/system visual interface, dedicated key board, actuator overrides, automatic protection overrides and manual controls of actuators. Figure 45 shows the Life Systems'

TABLE 7 10 kW EMS PROTOTYPE CHARACTERISTICS

	Electrolyzer	Fuel Cell	Interface Hardware/Reactant Storage Assembly	Total Modular RFCS
Power (Nominal), kW				
Output	-	10.0	-	10.0
Input				
Stack	9.89	-	-	9.89
Parasitic	0.07	0.13	0.08	0.28
Voltages (Nominal), VDC				
Output	-	110	-	110
Input	66	-	-	66
Cell Voltage, VDC	1.48	0.92	-	-
No. of Modules	1	1	-	-
No. of Cells (Total)	45	120	-	-
Current Density, ASF	150	180	-	-
Cell Area, ft^2	1.0	0.51	-	-
Heat Generation Rate, kW				
Light Side	0	0.3	0.1	0.4
Dark Side	0	6.1	0.1	6.2
Pressure, psia	315	60	300	-
Temperature, F	180	180	160	-
Weight, lb	292	239	105	636
Dimensions (HxWxL), ft	1.7x1.3x2.9	1.4x1.5x4.2	0.5x0.6x1.2	1.9x3.5x4.2[(a)]
Volume, ft^3				
Without Tanks	6.4	8.8	0	15.2[(b)]
With Tanks	6.4	8.8	12.5[(c)]	27.7
Solar Array Penalty				
Area, ft^2	1,089	-	-	1,089
Weight, lb	514	-	-	514
Radiator Penalty				
Area, ft^2	(d)	130	(d)	130
Weight, lb	(d)	185	(d)	185

continued-

(a) Maximum envelope dimensions.
(b) Summation of Electrolyzer and Fuel Cell volumes.
(c) Based on two H_2 tanks, one O_2 tank and one water tank.
(d) Fuel Cell requirement governs.

Table 7 - continued

	Electrolyzer	Fuel Cell	Interface Hardware/Reactant Storage Assembly	Total Modular RFCS
Power Conditioning Penalty, lb	49	-	1	50
Propellant Penalty (5-yr to Orbit), lb	-	-	-	1,457
Equivalent 5-yr to Orbit Wt., lb	-	-	-	2,840
Equivalent Energy Storage Density, W-hr/lb				
Without 2-hr Cont. Operation	-	-	-	2.10
With 2-hr Cont. Operation	-	-	-	6.82
Energy Storage Density, W-hr/lb				
RFCS Without 2-hr Cont. Operation	-	-	-	9.36
RFCS With 2-hr Cont. Operation	-	-	-	27.43
Specific Weight, lb/kW				
RFCS Without 2-hr Cont. Operation	-	-	-	63.6
RFCS With 2-hr Cont. Operation	-	-	-	72.9

TABLE 8 EMS OPERATIONAL LIMITS

	Fuel Cell	Electrolyzer	Reactant Storage	Controller
Temperature, F				
Design	180	180	160	70
Minimum	40	40	40	60
Maximum	250	200	200	130
Reactant Pressure, psia				
Design	60	315	300	N/A
Maximum	100	500	500	N/A
Pressure Differential, psid				
O_2/H_2 Design	4 ($O_2>H_2$)	2 ($O_2>H_2$)	N/A	N/A
O_2/H_2 Maximum	10 ($O_2>H_2$)	10 ($O_2>H_2$)	N/A	N/A
Inside/Outside	60	315	300	N/A
Ambient Pressure, psia				
Design	0	0	0	15
Minimum	0	0	0	10
Maximum	20	20	3[(a)]	20
Electrolyte Concentration, %				
Minmum - Local	25	20	N/A	N/A
- Average	27	28	N/A	N/A
Maximum - Local	48	45	N/A	N/A
- Average	45	40	N/A	N/A

(a) Multi-layer insulation loses effectiveness.

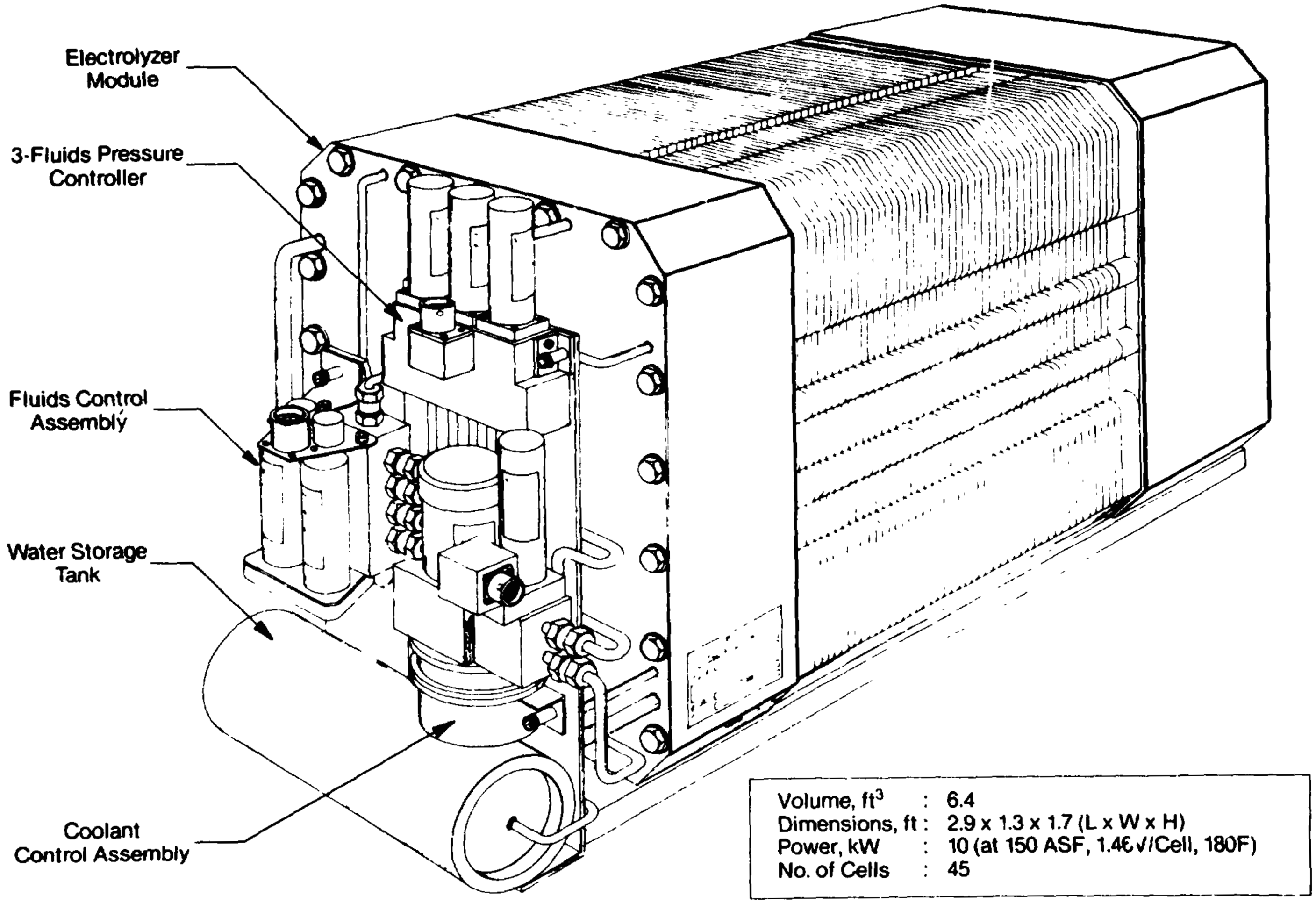
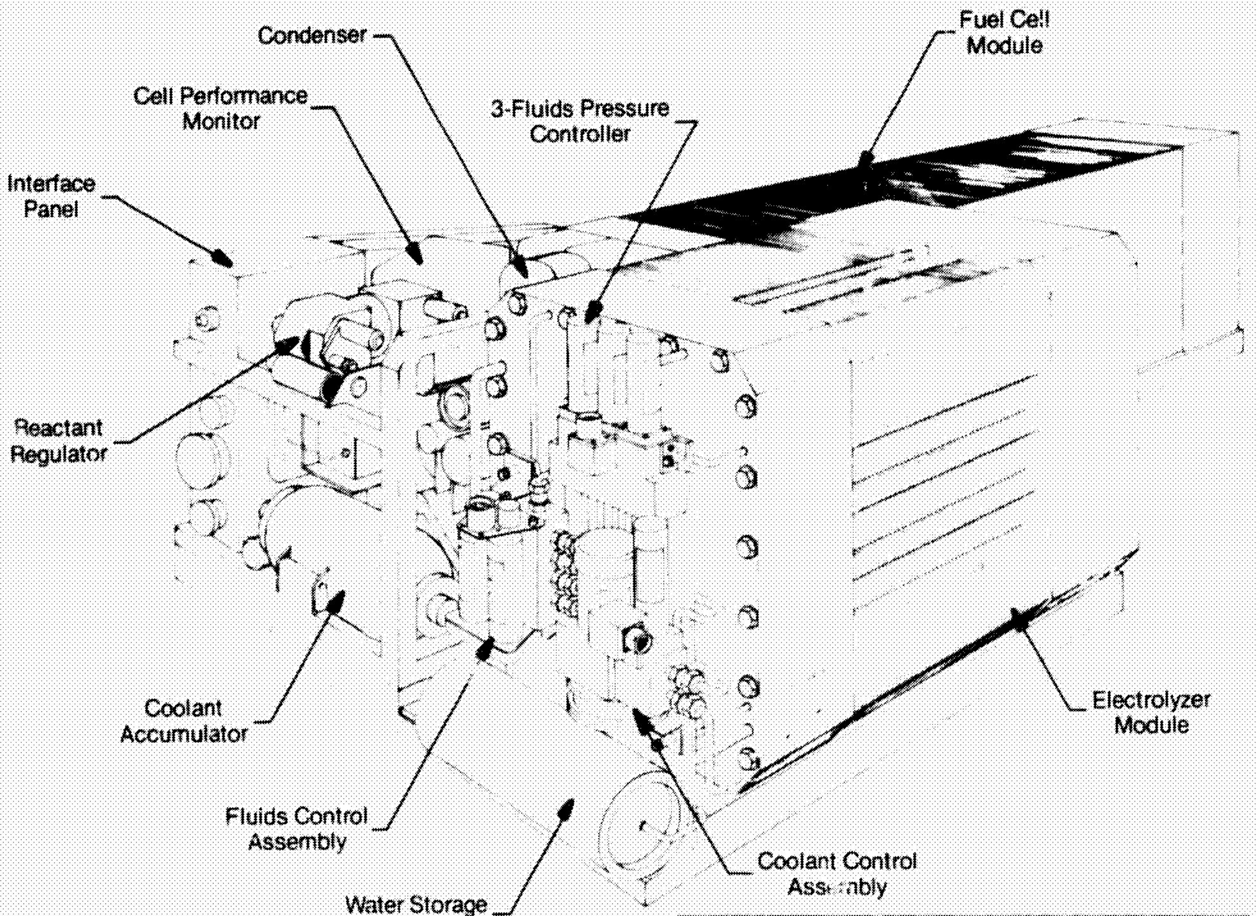


FIGURE 38 ISOMETRIC OF STATIC FEED ELECTROLYZER FOR 10 kW EMS



Volume, ft^3	: 18.4
Dimensions, ft	: 4.2 x 2.8 x 1.9 (L x W x H)
Power, kW	: 10
No. of Cells	: FCS (120) SFE (45)

a. Gas and water storage tanks not shown or included in characteristics.

FIGURE 39 10 kW EMS ISOMETRIC

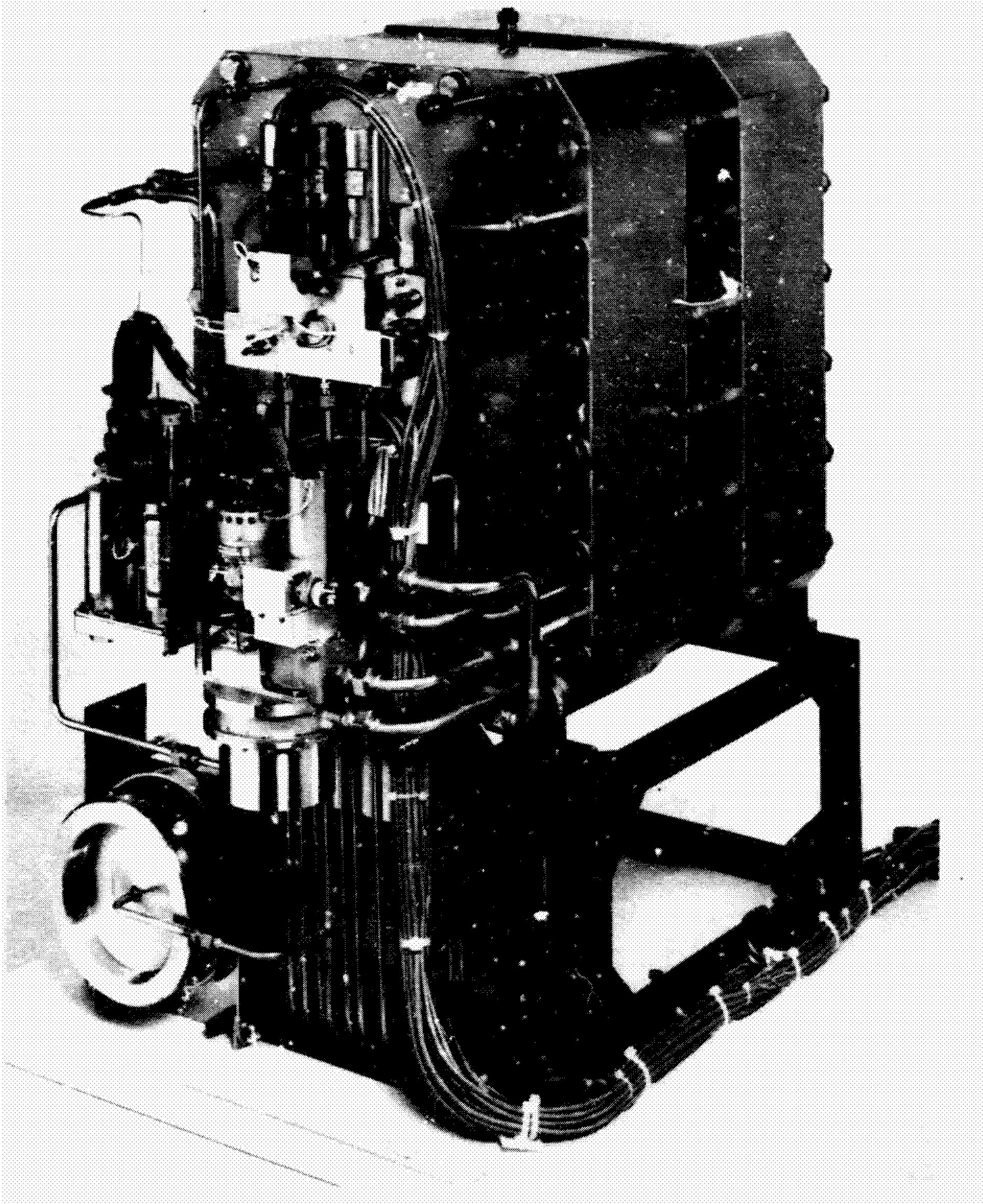


FIGURE 40 TWO kW CAPACITY 1.0 FT^2 SIX-CELL WATER ELECTROLYSIS SUBSYSTEM

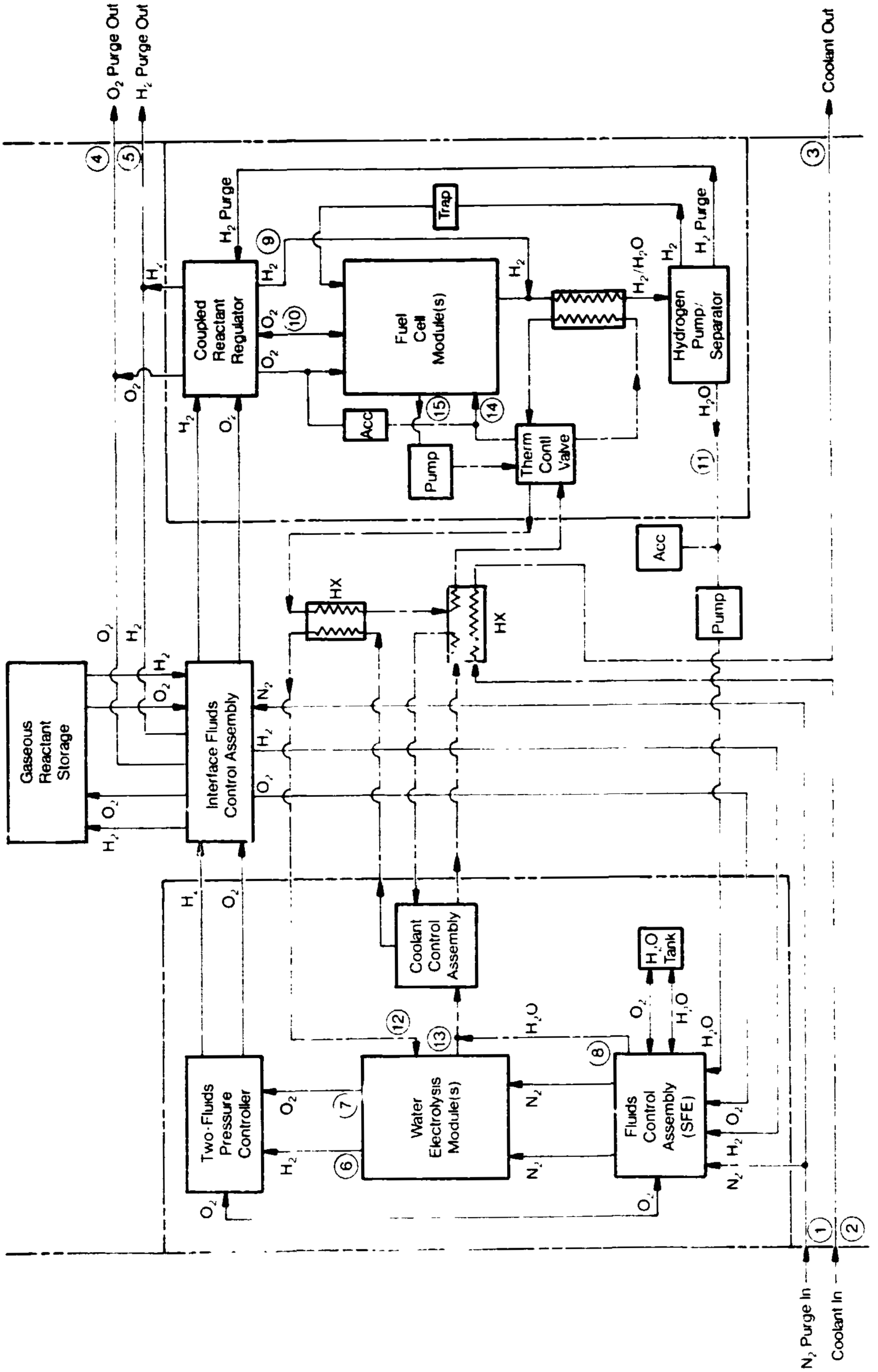


FIGURE 41 10 kW EMS MASS AND ENERGY BALANCE

TABLE 9 10 KW EMS MASS AND ENERGY BALANCE LIGHT PERIOD

Light Period

Location	Temperature, F	Press., psia	H_2 Mass Flow, lb/hr	O_2 Mass Flow, lb/hr	H_2O Mass Flow, lb/hr	Coolant Mass Flow, lb/hr	N_2 Mass Flow, lb/hr	H_2 Partial Press., psia	O_2 Partial Press., psia	H_2O Partial Press., psia	Dew Point, F
1	70	325	-	-	-	-	VAR	-	-	-	-30
2	40	18.7	-	-	-	3,221[(a)]	-	-	-	-	-
3	40.4	16,7	-	-	-	3,221[(a)]	-	-	-	-	-
4	70	14.7	-	VAR	-	-	VAR	-	VAR	VAR	VAR
5	70	14.7	VAR	-	-	-	VAR	VAR	-	VAR	VAR
6	180	313	0.55	-	0.082	-	-	307.8	-	5.2	164
7	180	315	-	4.36	0.041	-	-	-	309.8	5.2	164
8	70	315	-	-	4.91	-	-	315	-	-	-
9	150	59	0	-	0	-	-	58.0	-	0.98	101
10	150	63	-	0	0	-	-	-	62.5	1.04	103
11	90	45	-	-	0	-	-	45	-	-	-
12	148	316	-	-	250	-	-	-	-	-	-
13	148	315	-	-	250	-	-	-	-	-	-
14	152.3	63	-	-	-	1,200[(b)]	-	-	-	-	-
15	152	61	-	-	-	1,200[(b)]	-	-	-	-	-

(a) 50% ethylene glycol solution.
(b) FC 40.

Table 9 - continued

Dark Period

Location	Temperature, F	Press., psia	H_2 Mass Flow, lb/hr	O_2 Mass Flow, lb/hr	H_2O Mass Flow, lb/hr	Coolant Mass Flow, lb/hr	N_2 Mass Flow, lb/hr	H_2 Partial Press., psia	O_2 Partial Press., psia	H_2O Partial Press., psia	Dew Point, F
1	70	325	-	-	-	-	VAR	-	-	-	-30
2	40	18.7	-	-	-	3,221[a]	-	-	-	-	-
3	48.8	16,7	-	-	-	3,221[a]	-	-	-	-	-
4	70	14.7	-	VAR	-	-	VAR	-	VAR	VAR	VAR
5	70	14.7	VAR	-	-	-	VAR	VAR	-	VAR	VAR
6	170	313	0	-	0	-	-	307.8	-	5.2	164
7	170	315	-	0	0	-	-	-	309.8	5.2	164
8	70	315	-	-	0	-	-	0	-	-	-
9	180	59	0.90	-	0.137	-	-	58.0	-	0.98	101
10	180	63	-	7.18	0.068	-	-	-	62.5	1.04	103
11	90	75	-	-	8.08	-	-	45	-	-	-
12	142.3	316	-	-	250	-	-	-	-	-	-
13	142	315	-	-	250	-	-	-	-	-	-
14	155.7	63	-	-	-	1,200[b]	-	-	-	-	-
15	178	61	-	-	-	1,200[b]	-	-	-	-	-

(a) 50% ethylene glycol solution.
(b) FC 40.

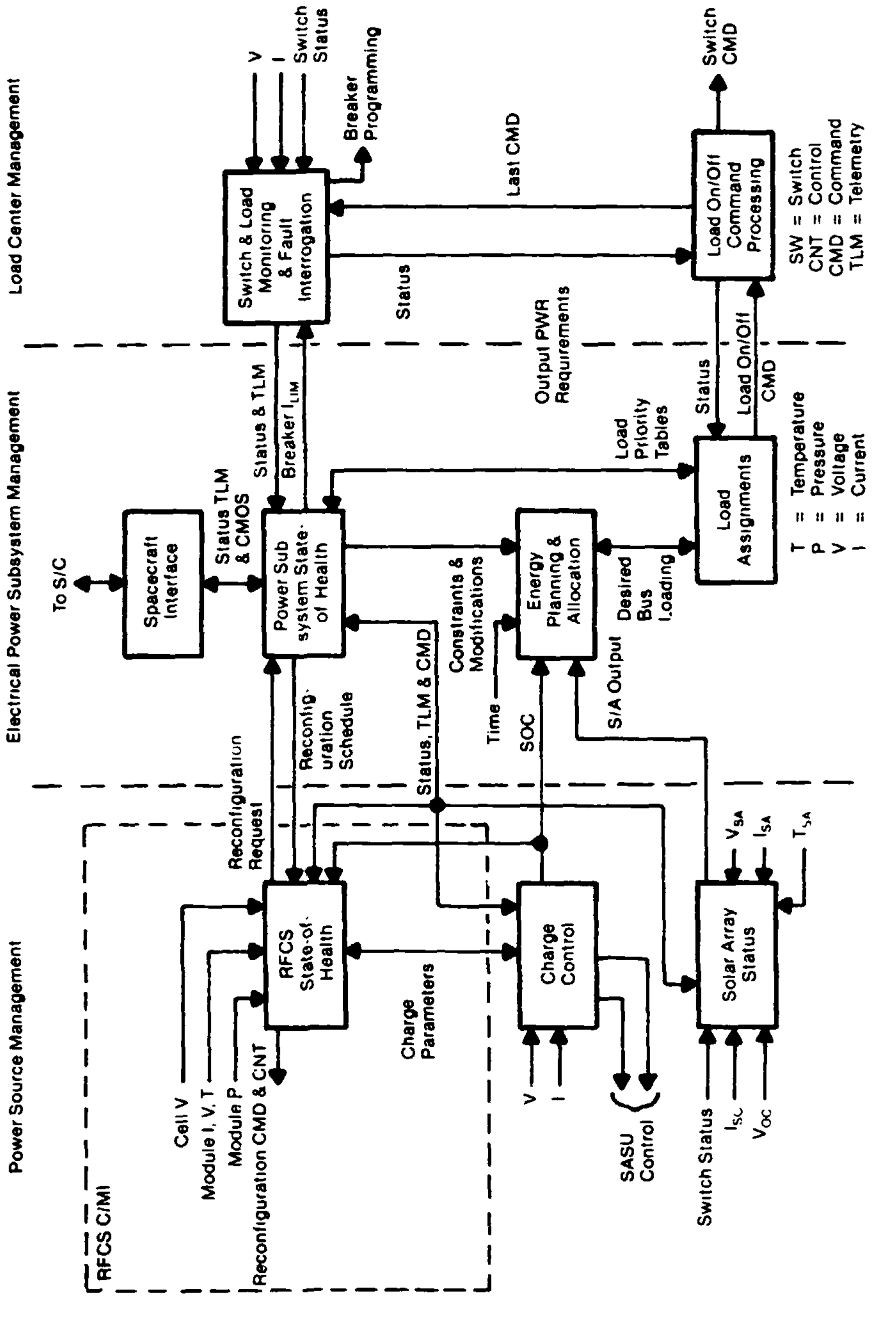


FIGURE 42 POWER MANAGEMENT SUBSYSTEM FUNCTIONS

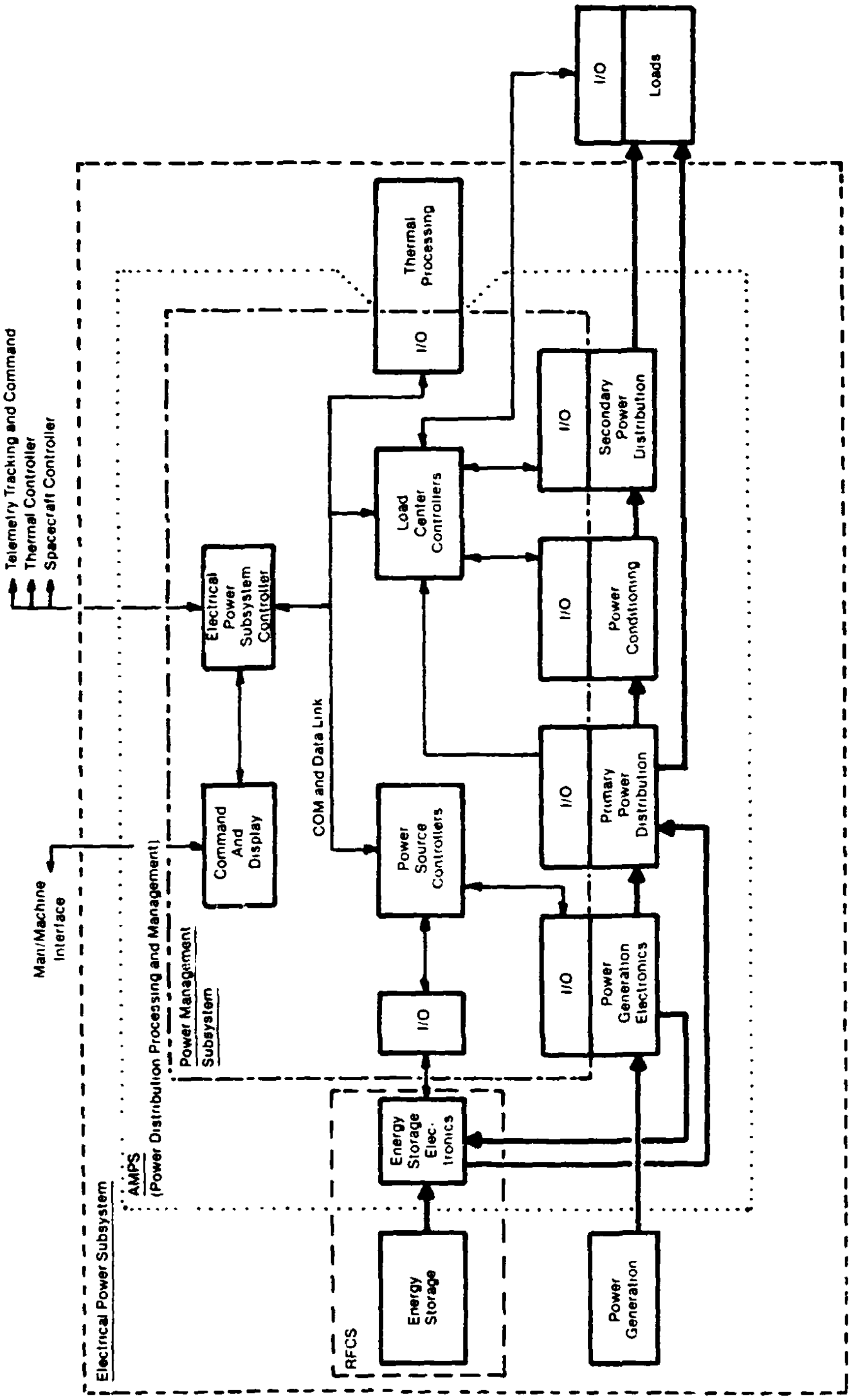


FIGURE 43 POWER MANAGEMENT SUBSYSTEM ARCHITECTURE AND INTERFACES

RECOMMENDATION MADE:

3-Level Interconnected Hierarchy, With A Linear Bus Topology At All Levels Repeated In Each Station Module

BLOCK REPRESENTATIONS:

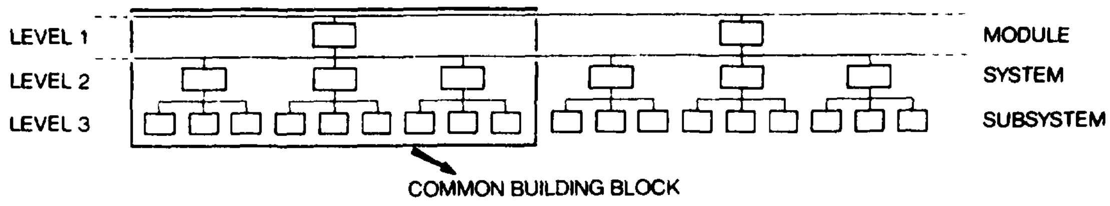


ILLUSTRATION:

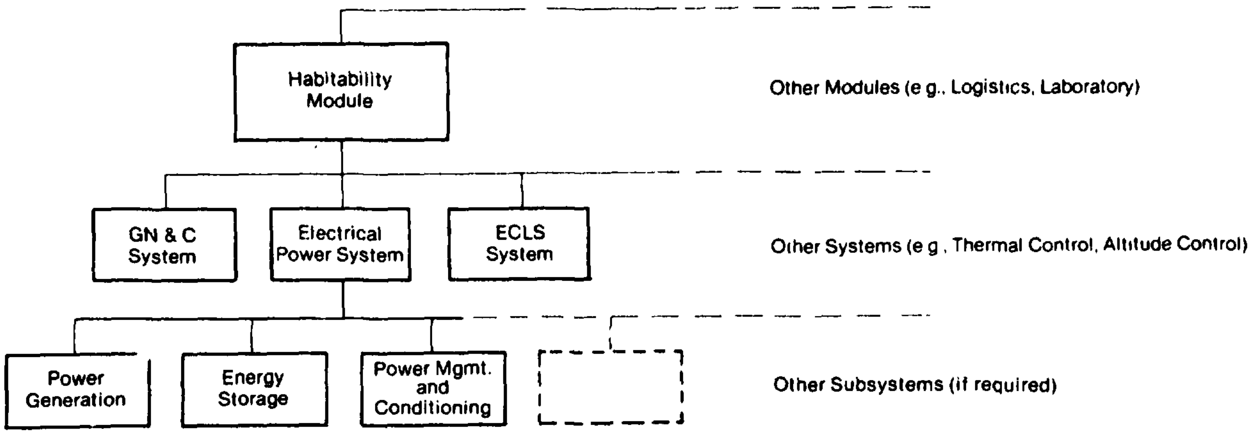


FIGURE 44 SPACE STATION AUTOMATION CONCEPT

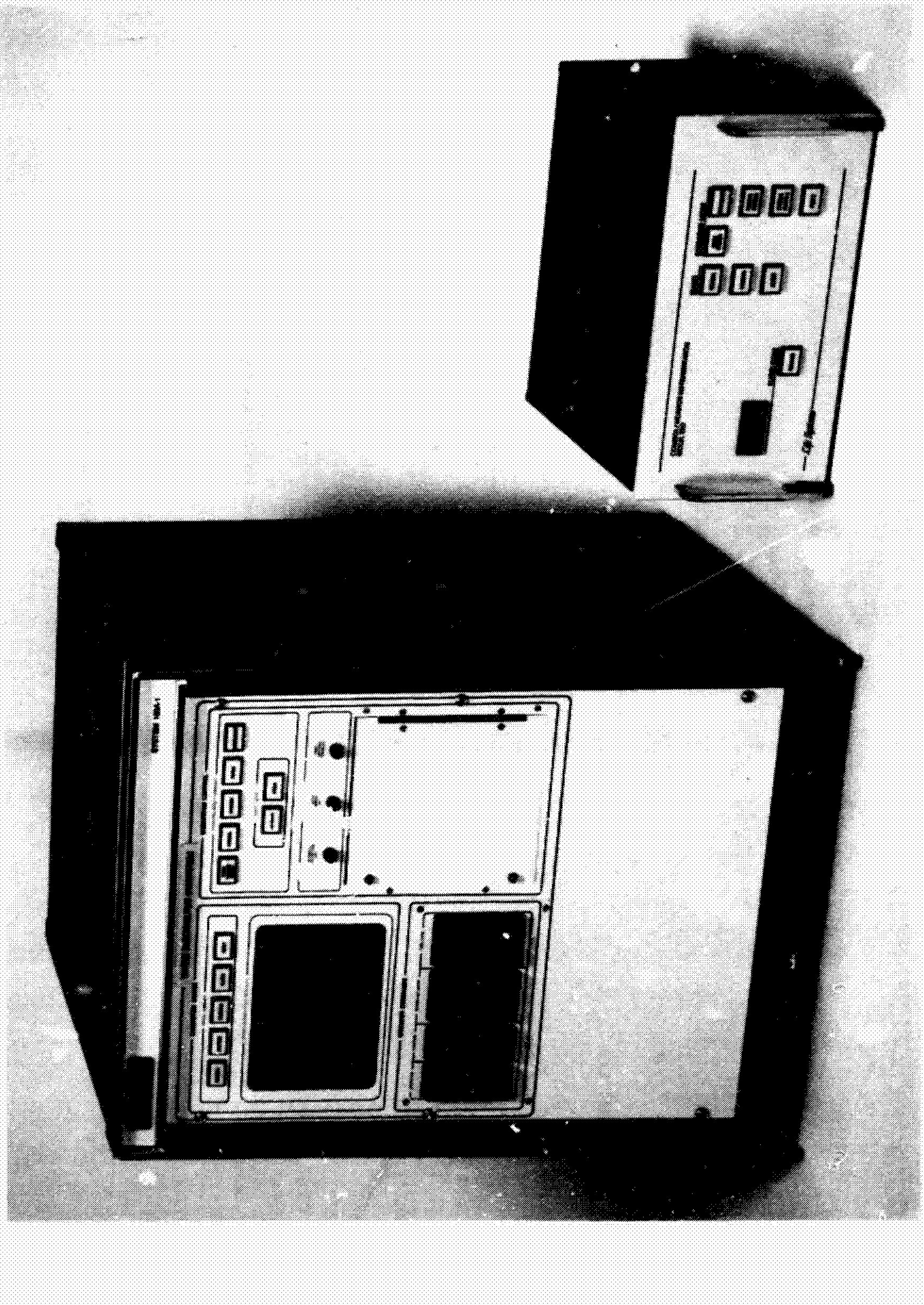


FIGURE 45 LIFE SYSTEMS' 100 AND 200 SERIES CONTROL AND MONITORING INSTRUMENTATION

100 and 200 Series C/M Is. The 100 Series is currently being used with a 2 kW RFCS breadboard (see Figure 46) and an application sized (1.0 ft^2 cells) WES for RFCS end use (see Figure 47).

A more advanced concept of the C/M I would be the generic controller. The tentative architecture for such generic controller (300 series) is shown in Figure 48. The Life Systems' 300 Series controllers have three packaging options. Option A has microcomputer, power conversion, sensor signal conditioning (S/C) and actuator S/C all in one enclosure. Option B has the sensor S/C local to the sensors. Option C has both sensor S/C and actuator S/C packaged separately. Option C is the most desirable design for the space station application.

Life Systems is also developing an advanced signal conditioning concept. These generic signal conditioning cards will be available to the 300 series controllers for the Space Station to reduce the power required and the signal noise level.

RFCS Integration with Other Systems

The RFCS uses in its operation water, O_2 and H_2 which are common fluids in Environmental Control Life Support System (ECLSS) and Reaction Control System (RCS), if H_2/O_2 propellant engine is used in the latter system. The way by which these systems can be tied together is to use a "split" or "open loop" regenerative fuel cell. The basic concept of the open loop regenerative fuel cell is shown in Figure 49. The major advantages of integrating these systems are: (1) major hardware items except for the Static Feed Electrolyzer (SFE) have already been flight qualified; (2) the SFE development is underway; and (3) the fuel cell generated water is qualified as potable. The disadvantages include: (1) the dissolved H_2 needs to be removed from the fuel cell product water for crew consumption (but a flight qualified unit exists); and (2) the H_2 so removed represents a permanent loss.

The water production rates of the RFCS at different output power levels are determined in order to quantify the need of RFCS for crew water consumption. The results are plotted in Figure 50. A 12 kW "split loop" regenerative fuel cell is sufficient to meet the water demand of four persons. The O_2 produced in this 12-kW unit is also sufficient for crew metabolic requirements. Consequently, the majority of the RFCS capacity can still be operated in the closed-loop fashion.

Remaining RFCS Technical Problems and Solutions

Based on the analyses performed as part of this study and on Life Systems' experience from the development of the RFCS breadboard, potential technical problems and recommended solutions to these problems are summarized in Table 10. Some of the technical problems and solutions are currently being tested/resolved with the RFCS breadboard.

RFCS Pacing Technologies

A list of RFCS pacing technologies and their impacts on the RFCS design was prepared as shown in Table 11.

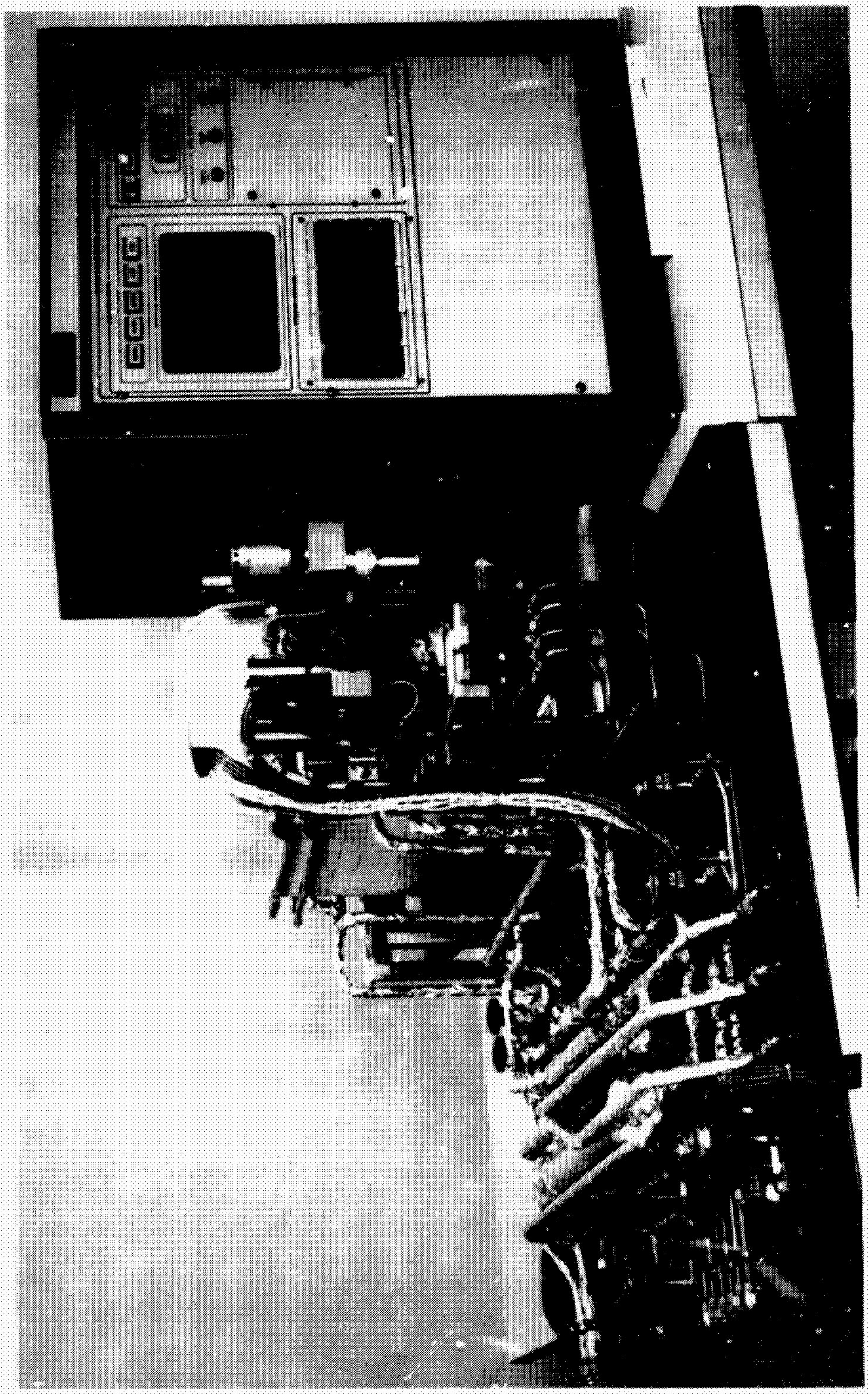


FIGURE 46 TWO kW REGENERATIVE FUEL CELL SYSTEM BREADBOARD WITH 100 SERIES CONTROLLER

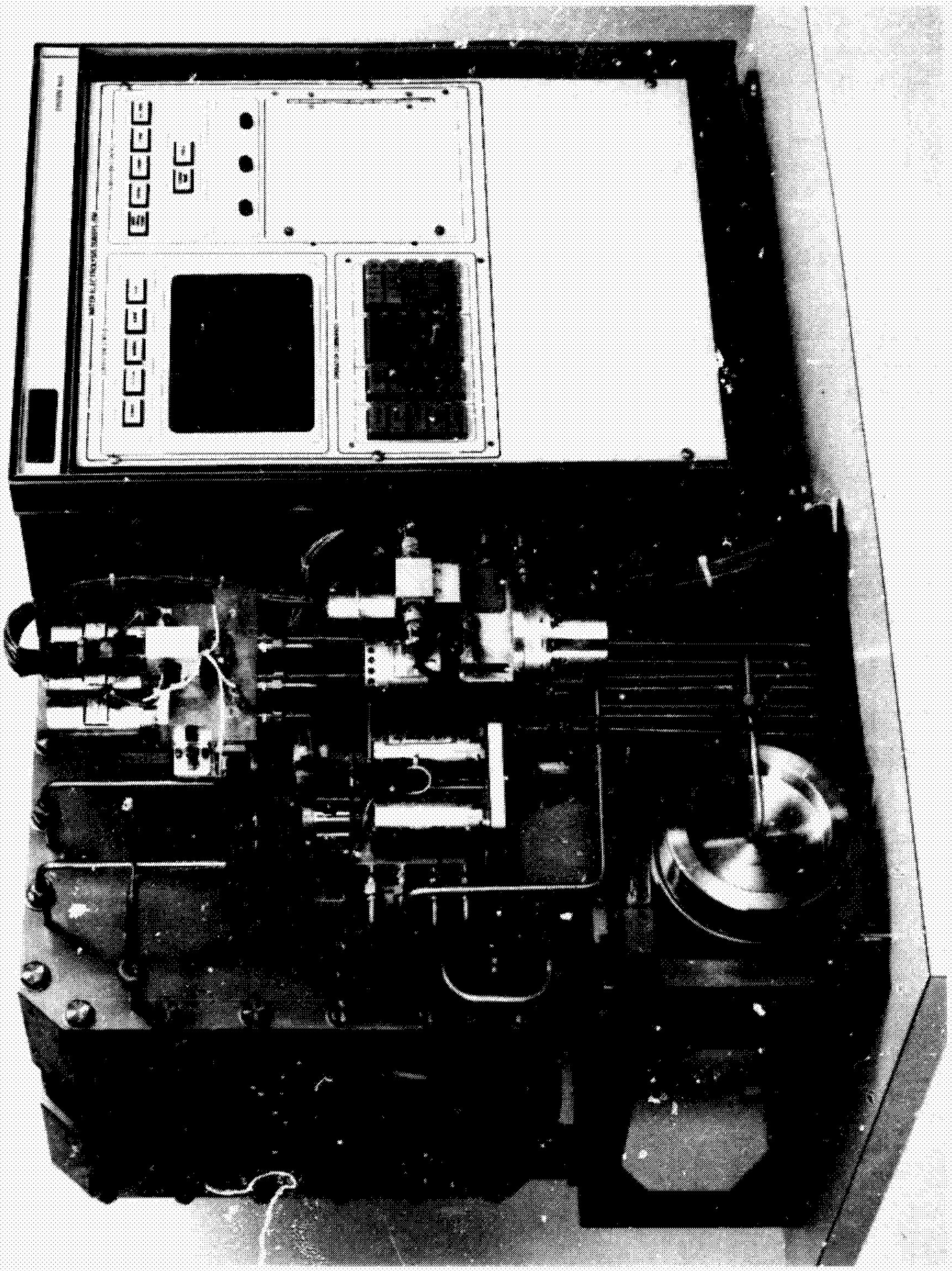


FIGURE 47 SIX-CELL 1.0 FT^2 WATER ELECTROLYSIS SUBSYSTEM WITH 100 SERIES CONTROLLER

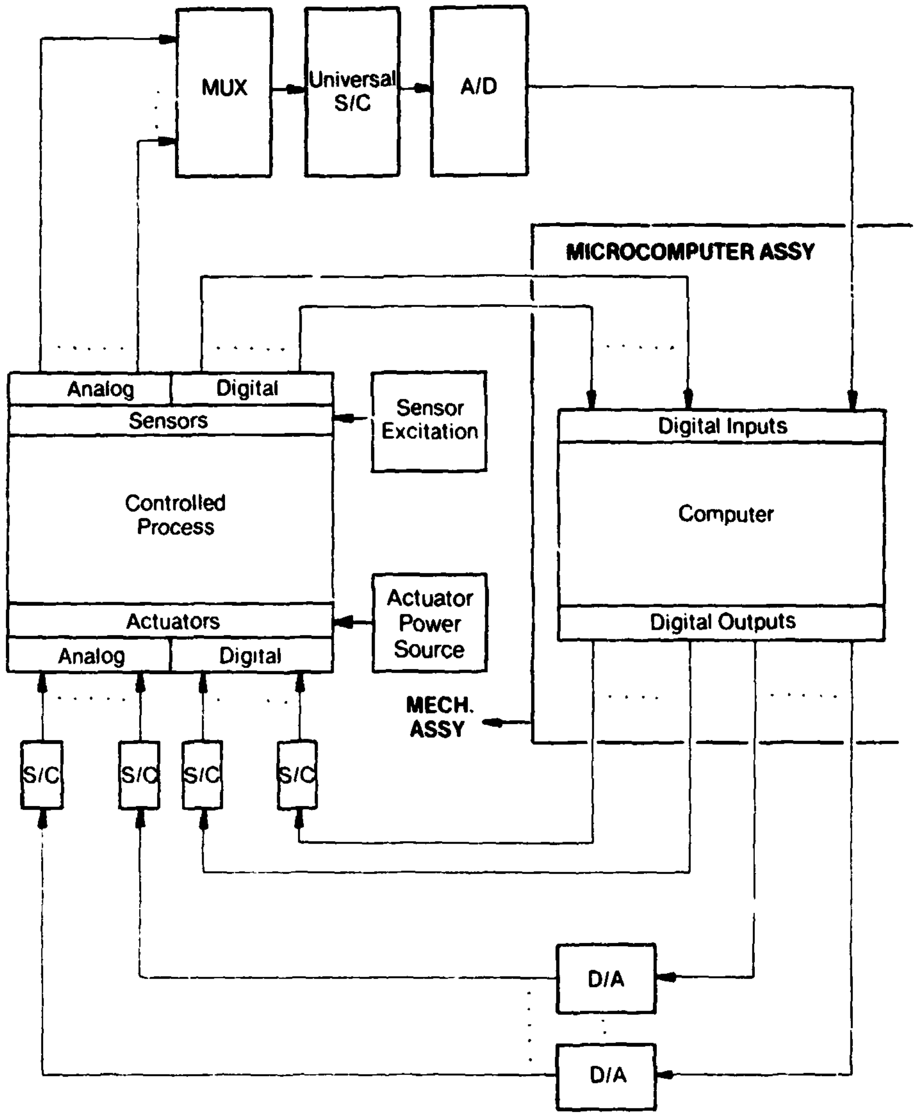


FIGURE 48 TENTATIVE ARCHITECTURE FOR GENERIC CONTROLLER

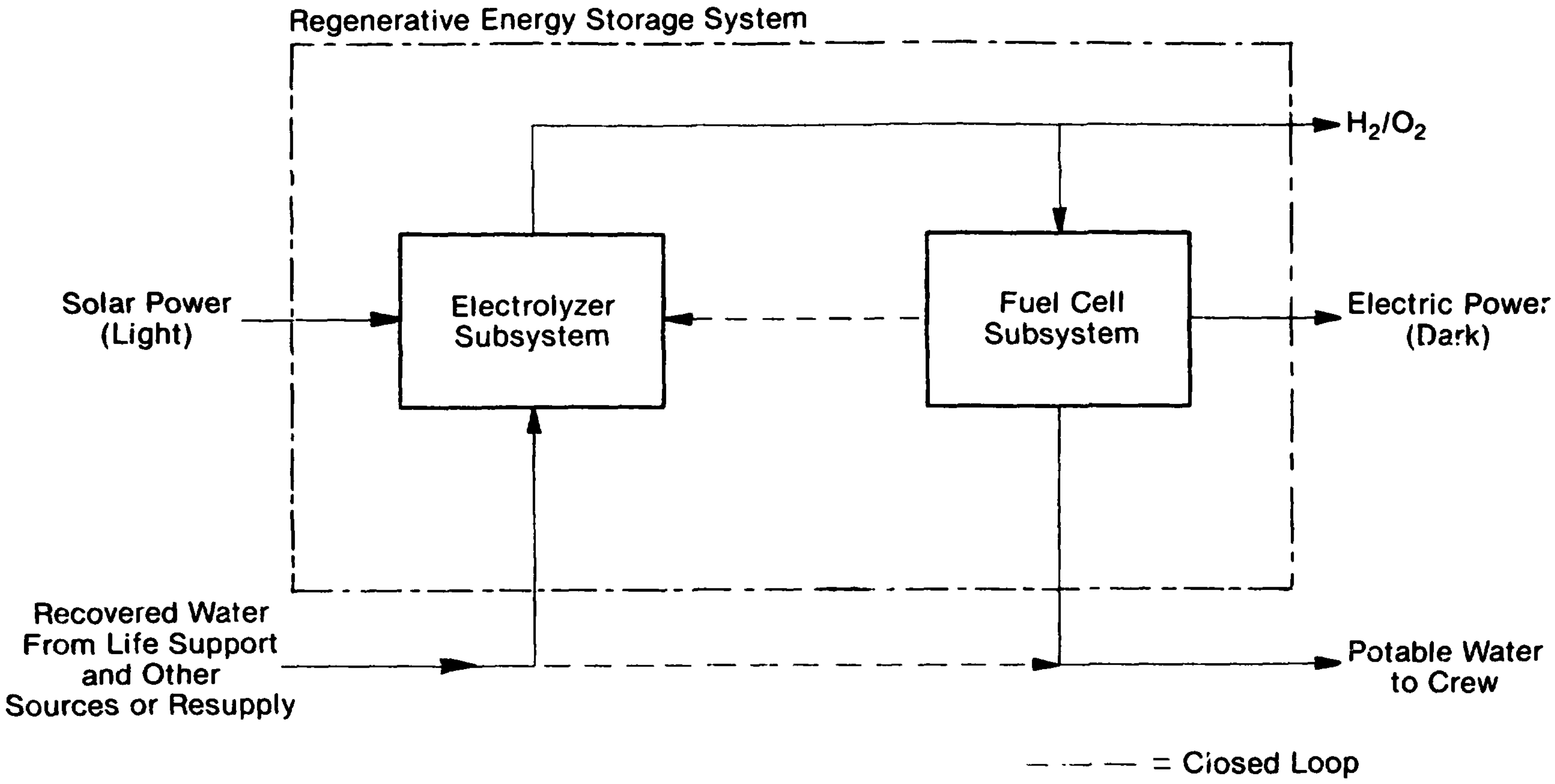
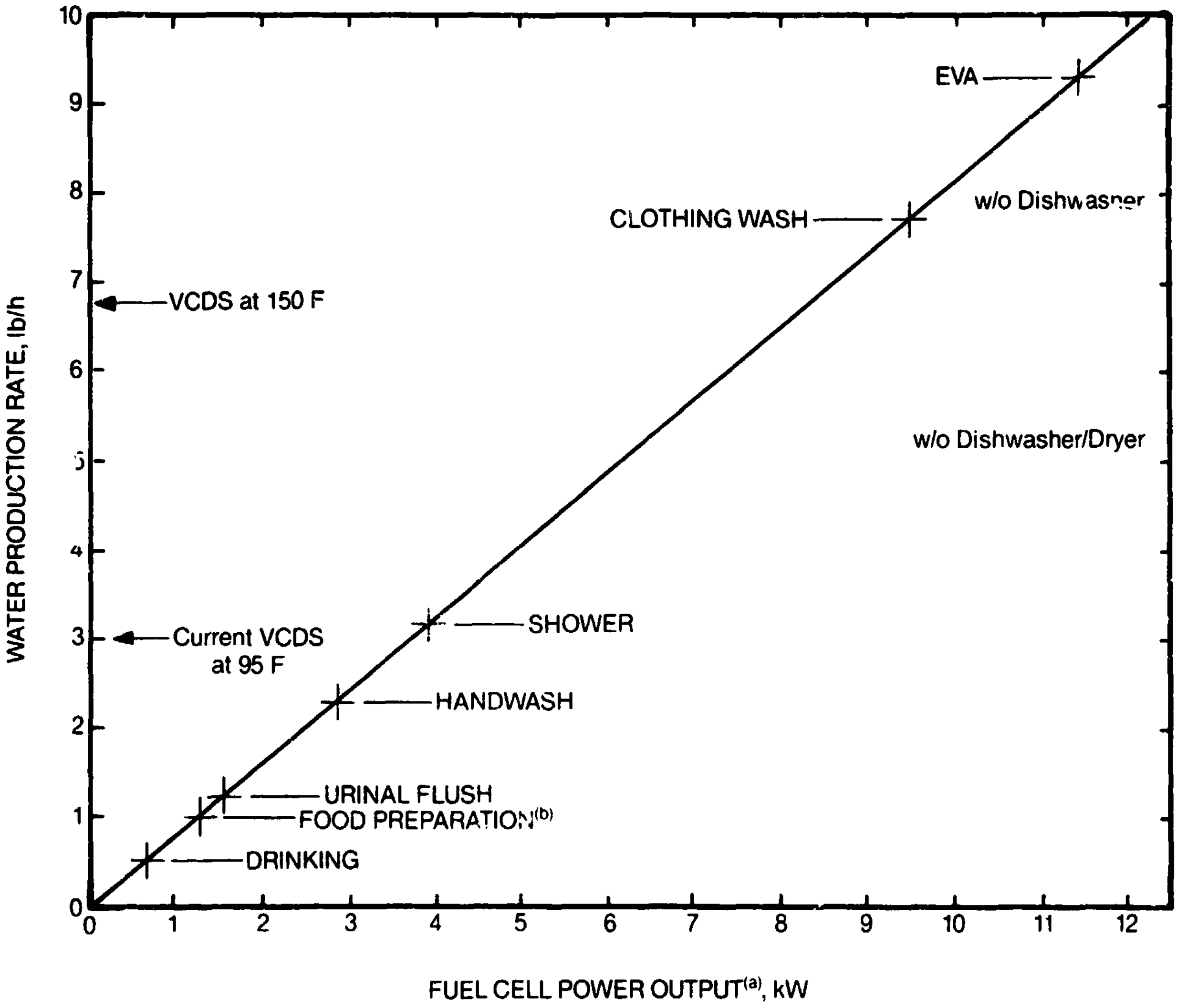


FIGURE 49 OPEN LOOP REGENERATIVE FUEL CELL



(a) Based on Shuttle Orbiter Ec . it Fuel Cell Hardware operating at 0.91 V/cell, 200 ASF and 180F
(b) Cited use rates are cumulative . d include all lower use rates

FIGURE 50 WATER PRODUCTION AND USE RATE FOR FOUR PERSONS VERSUS FUEL CELL POWER OUTPUT

TABLE 10 RFCS TECHNICAL PROBLEMS AND SOLUTIONS

Problem	Solutions
H_2 in fuel cell water	Use developed H_2/H_2O separator (some H_2 lost), use three-compartment SFE (simplest solution) or employ a "ruggedized" four-compartment SFE (minimum impact to baseline)
Moisture in reactant gases	Keep all plumbing and gaseous storage tanks above reactant dew point
Temperature loss during idle	Operate FCS & WES at approximately same temperature (or FCS higher than WES) and use shared heat exchanger to transfer heat between FCS and WES
WES pressure loss on idle	Use WES trickle current to keep pressure; add shutoff valve downstream from 2-FPC
FCS pressure loss on idle	Maintain reactant pressure upstream of coupled regulator
Lower fuel cell water pressure	Add water transfer pump
High SFE efficiency	Use FCS waste heat to raise SFE temperature
SFE maturity<fuel cell	Increase WES development on multiple fronts

TABLE 11 RFCS PACING TECHNOLOGIES AND IMPACTS

Pacing Technology	Impacts
3-Compartment SFE[a]	• Lowers module weight • Resolves dissolved H_2 in fuel cell Water • Eliminates sensitivity to loss of water feed • Fewer cell components
Scale-Up in No. of Cells/Module	• Required for full size module (e.g., 45 cells/10 kW module)
Development of Integrated Components 1. Interface Fluids Control Assembly 2. Heat Exchanger Assembly 3. 2-Fluids Pressure Controller[b] 4. Upgraded Fluids Control Assembly	• Increases reliability • Simplifies maintenance and training • Saves weight, volume and power • Lower qualification costs
Development of Integrated Mechanical Components as Orbital Replaceable Units	• Decreases impact of failure • Simplifies assembly and repair • Enables in-flight maintenance

(a) Not critical for EMS, does enhance performance and simplify RFCS. Alternatively could employ a "ruggedized" four-compartment WES.
(b) If a three-compartment SFE is selected.

RFCS Developments and Demonstrations

The recommended advanced developments for RFCS are set forth in Table 12. The demonstrations needed to ensure successful development and timely availability of a flight version RFCS include the demonstration of a full scale static feed electrolyzer and the demonstration of LEO RFCS cycle capability and endurance testing. The current and future RFCS hardware candidates for these developments and demonstrations are listed in Table 13.

CONCLUSIONS

The following conclusions were drawn based on the study completed:

1. The 1.0 ft^2 SFE cell is within the optimum cell size range for the 10 kW EMS.

2. The propellant weight has the major impact upon the RFCS five-year to orbit weight.

3. The RFCS can achieve high energy storage efficiencies and still maintains its lightweight advantage.

4. The optimization technique developed in this study can be used in the final sizing of the RFCS for the Space Station.

5. The 10 kW EMS is to contain 45 static feed electrolysis cells and 120 fuel cell cells and to have a weight of 636 lb.

6. Remaining technical problems in the development of the RFCS exist, but so do the solutions to these problems.

7. The open loop RFCS can be integrated with the ECLSS and the Reaction Control System (RCS). The ECLSS requirements on the open loop RFCS are small compared with the total RFCS capacity for the EPS.

8. Increased development activities in the RFCS, particularly the SFE, are necessary to ensure the RFCS readiness for the Space Station.

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2. Wynveen, R. A. and Schubert, F., "Regenerative Fuel Cell Subsystem Design Handbook," Contract NAS9-12509, ER-151-3; Life Systems, Inc., Cleveland, OH; December, 1972.

3. Wynveen, R. A. and Schubert, F. H., "A Regenerative Fuel Ce[illegible] System for Modular Space Station Integrated Electrical Power," Paper No. 739055, 8th Intersociety Energy Conversion Engineering Conference; Philadelphia, PA; August, 1973.

TABLE 12 RECOMMENDED RFCS ADVANCED DEVELOPMENTS

Subsystem/Component	Developments
Fuel Cell Subsystem (Alkaline)	Add Advanced Fuel Cell Stack to Shuttle Powerplant Test Under LEO Cyclic Conditions Convert to Maintainable Design Combine Thermal Control Valve with Coolant Pump/Pressure Relief Connect Coupled Reactant Regulator with Passive Liquid Coolant Thermal Control
Water Electrolysis Subsystem (Alkaline)	A Key Technology is the Development of a Unitized Feed Matrix Continue RFCS Breadboard Testing Continue Existing Endurance Testing • Single Cells • Module (4,300 hr)[a] • 3-FPC (14,670 hr)[a] • CCA (11,330 hr)[a] • FCA (2,400 hr)[a] • Metal Bellows Water Tank Develop 3-Compartment Cell Module • Circulate Feed Water as Coolant • Lower Weight • Convert CCA to be 3-Compartment Compatible and Add Long Life Motor • Convert FCA to be 3-Compartment Compatible - Pressure Referenced Tank - Modified 3-FPC - O_2/H_2 Purge Philosophy Convert 3-FPC to be 3-Compartment Compatible - Eliminate One Regulator (3- to 2-FPC)
Reactant Storage Subsystem and Interface Hardware	Identify Flight Qualifiable Tanks - Incorporate Active Thermal Control Develop Integrated Interface Fluids Control Assembly Develop Shared Heat Exchanger Develop Heat Storage Device Using Phase Change Material

continued-

(a) Current, i.e., September, 1984, level.

Table 12 - continued

Subsystem/Component	Developments
RFCS Controller	Convert Life Systems' 100 Series to 200 (or 300 Series)[a] Add Independent Controller Develop RFCS Process Simulator to enable testing controller(s) and verify software under "what if" conditions Develop[b] • Balance of Fault Isolation Techniques • Fault Correction Techniques - Automatic - Correction Instructions • Fault Tolerance Techniques

(a) 300 Series uses generic sensor signal conditioning.
(b) Assumes all fault detection techniques and some (most) of the Fault Isolation techniques developed.

TABLE 13 CURRENT ANT POTENTIAL RFCS HARDWARE CANDIDATES

	WES			FCS			RFCS	
Unit	No. Cells	Cell Area, Ft^2	Current Density, ASF	No. Cells	Cell Area, Ft^2	Current Density, ASF	Type	Capacity, kW
1	30	0.1	350	64[a]	0.5	625	Breadboard	2
2	6	1.0	350	64[a]	0.5	125	Breadboard	4
2A	32	1.0	150	64[a]	0.5	250	Breadboard	7
3	C[b]	0.1	D[c]	-	-	-	Flight Experiment (SFE Only)	<!
4	45	1.0	150	120[d]	0.5	180[d]	EMS Prototype	10
5	F[c]	G[e]	H[e]	120[d]	0.5	180[d]	Flight Experiment	10
6	I[f]	J[f]	K[f]	L[f]	0.5	200	Developmental	M[f]
7	1	J	K	L	0.5	200	Qualification Unit	M
8	1	J	K	L	0.5	200	Qualified Unit(s)	M

(a) 625 ASF (2 kW) to 400 ASF (12 kW).
(b) C = $\geq$3 Cells.
(c) D = $\geq$75 to $\geq$ 200 ASF, projected to be 150 ASF.
(d) Determined by bus voltage specified at 110V for EMS Prototype.
(e) May be of EMS size or flight qualifiable size, i.e., area $\leq$1.0 ft^2.
(f) The actual values for flight hardware, e.g., I, J, K, L and M to be determined by Phase B Space Station Study Results.

4. Boeing Aerospace Co., "Analysis of Regenerative Fuel Cells," Final Report, Contract NAS9-16151; Seattle, WA; November, 1982.

5. Schubert, F. H.; Reid, M. A. and Martin, R. E., "Alkaline Regenerative Fuel Cell Systems for Energy Storage," 16 Intersociety Energy Conversion Engineering Conference, Atlanta, GA; August, 1981.

6. Rosen, J. B., "The Gradient Projection Method for Nonlinear Programming, Part I, Linear Constraints," J. Society Industrial Applied Math., 8, 181-217; 1960.