

TECHNOLOGY STATUS -

FUEL CELLS AND ELECTROLYSIS CELLS

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SUMMARY

Electrochemical technology as it applies to fuel cells and electrolysis cells has been active for sixteen years. This activity has provided the basis for electrical power systems for three successful space flight programs plus a fourth program which is in the final stages of vehicle development testing. The technology has matured from less than 100 hours test operational capability in the beginning to systems operational capability of several thousand hours. Future applications for this technology include large orbital energy conversion and storage facilities in the multi-hundred kilowatt range.

INTRODUCTION

Since the selection of H_2/O_2 fuel cells as the primary electrical power systems for the Gemini and Apollo programs in March 1962, phenomenal strides have been made in the technology. For example, a comparison of the Apollo fuel cell with the Shuttle fuel cell at baselining shows the Shuttle unit at equivalent weight produces eight times as much power for six times as long and is at least an order of magnitude easier to start and stop. Since Shuttle baselining in 1973, additional capability has been achieved in this technology.

There is little doubt that, except for the space program, fuel cells would still be more or less a laboratory curiosity, an oddity seemingly holding the potential of alleviating many energy conversion limitations. The urgency of the space program and particularly the limited lift capability of rockets being dealt with at the time, provided the impetus required to launch the vigorous technology and development programs that brought the concept into fruition. Except for fuel cell electrical power, the Gemini flights using batteries would have been limited to about four days. The Apollo mission as performed would not have been possible on a battery system, even with the 3.4 M kg (7.5 M lbs) thrust of the Saturn V launch vehicles.

This paper will present the status of the baselined Shuttle fuel cell as well as the acid membrane fuel cell and space-oriented water electrolysis technologies. The more recent advances in the alkaline fuel cell technology area are the subject of a companion paper. A preliminary plan for the focusing of these technologies towards regenerative energy storage applications in the multi-hundred kilowatt range will also be discussed.

BACKGROUND

Figure 1 graphically illustrates the Agency background in fuel cell development and applications.

In 1962, contracts were awarded for development of fuel cell electrical power systems for both the Gemini and Apollo programs. At the time of baselining these fuel cells, very limited test operating experience existed.

Gemini

Figure 2 is a picture of the Gemini fuel cell.

One of the fundamental objectives of the Gemini program was to gain long-duration experience in space as a precursor to the Apollo mission. To perform missions beyond approximately four days required a more energy-dense electrical power system than the conventional battery system. Thus the driver that would bring fuel cells into practical reality appeared. The ion-exchange membrane concept indicated the lowest potential weight of all concepts considered, and it operated at relatively low temperature [237-310°K (75-100°F)] and pressure [138 kPa (20 psia)], conditions quite compatible with the low-Earth-orbit environment. This program spanned four years with the flight program completed in February 1966.

Development of the Gemini fuel cell (fig. 2) was highly constrained by the rigorous mission schedule. The technology was in its embryonic stages and the time for the technical thoroughness required for methodical development was an unavailable commodity. Because of this, compromises relative to specification performance were dictated. While all of the electrical requirements of all flights were met, a higher degree of energy austerity was exercised than planned. But the most significant compromise was the non-usability of the fuel cell product water. This was due to a membrane degradation phenomenon which contributed impurities to the product water rendering it unacceptable under the rigid dietary limitations of the astronauts. This degradation was the principal performance and life-limiting issue of this fuel cell and was not understood until after the Gemini program.

Apollo

In its initial conception the Apollo Command/Service vehicle was to land on the surface of the moon. This required the power system to reject heat to a 394°K (250°F) environment which dictates an operating temperature exceeding 394°K. This requirement was a significant issue in selection of the Bacon fuel cell, which as modified operated at approximately 505°K (450°F) and 414 kPa (60 psia).

Basic development of the Apollo fuel cell (fig. 1) occurred between 1962 and 1966. It was incrementally "qualified" in 1966 for Earth-orbital manned operations, called "Block I" configuration, to 400 hours, becoming the first

subsystem to be qualified for Apollo. It was subsequently qualified after additional component development for the lunar missions, called the "Block II" configuration, also to 400 hours. A "delta qual" program was conducted on the Block II configuration to 1000 hours in 1969, toward support of extended duration missions then in the planning stage using Apollo vehicles.

The fuel cell contract was completed in December 1969 with the delivery of the last of approximately 100 units to the prime contractor. At the completion of the Skylab program in 1974, Skylab IV was utilizing fuel cells with approximately five years of shelf life.

There were no major failures of fuel cells on the Apollo flights. A malfunction in the hydrogen pump electrical circuit on one module of Apollo 10 led to isolation of that fuel cell, resulting in a subsequent thermal oscillation in one of the other two modules because of the increased electrical load. These were the most severe fuel cell anomalies experienced in the entire flight program.

The success of the Gemini and Apollo programs, coupled with the technological base developed in support of those programs, has firmly established the fuel cell energy conversion concept as a viable special duty power system.

CAPILLARY MATRIX TECHNOLOGY

Because of developmental problems encountered in the early stages of both Gemini and Apollo fuel cell programs and the uncertainty of meeting program schedules with qualified hardware, backup technology development was initiated in 1964, which was identified as a "Multi-Mission Fuel Cell Development Program." In addition to the backup applications, there were other applications envisioned requiring advanced technology such as Earth-orbital long-duration space stations and extended missions up to 90 days using Apollo vehicles. The alkaline capillary matrix concept, which was first conceived and demonstrated by Mond and Langer (ref. 1) in the late 1800's, was selected for this development. Principal features leading to this selection were relatively mild temperature [355°K (180°F)], flexible operating pressure, liquid electrolyte over a broad temperature range which simplified activation, superior efficiency (over acidic), and most important, electrolyte retention by an inert capillary matrix of asbestos.

Due to the adequate and timely resolution of the problems encountered in the Gemini and Apollo programs, this technology never achieved the status or configuration of a viable alternate. It did, however, achieve baseline status in 1968/69 for both the A.F. Manned Orbital Laboratory and the "wet workshop" concept of the AAP (Apollo Applications Program). The A.F. program was canceled in May 1969. The AAP configuration was then changed to the "dry workshop" concept, which eliminated the requirement for a 2500-hour fuel cell and resulted in the cancellation of the fuel cell development program in June 1969. Figure 4 shows a final version of this effort. After cancellation, the level of effort was then cut back to technology advancement status.

The Shuttle program was taking form in the late '60's and it soon became evident that a fuel cell with even greater capability than the AAP fuel cell was needed. Thus in July 1970, as a result of a competitive solicitation, two contracts were awarded for development of the technology necessary to meet the somewhat indefinite requirements of the Shuttle: the acidic SPE (solid polymer electrolyte) fuel cell and the alkaline capillary matrix fuel cell. The approach was simply to initiate a technology race under an environment not constrained by programmatic issues, and the superior technology at the time of baselining would be selected. The programs were conducted in parallel toward similar specifications and equally funded at approximately \$500K each per year for 3-1/2 years. Both technologies demonstrated 2500 hours of uninterrupted operation as a technology readiness performance test and were thus essentially declared technological equals by the prime Shuttle contractor. In August 1973, the capillary matrix fuel cell was baselined for the Shuttle.

Shuttle Fuel Cell

Figure 5 represents the baselined version and characteristics of the Shuttle fuel cell module. Figure 6 represents the cross section and gives the characteristics of the cell.

The configuration at baselining consisted of the following:

- o 3, 32-cell stacks in electrical parallel
- o Pt/Pd catalyzed electrodes
- o 0.5 mm (.020") reconstituted asbestos matrix
- o 32% (nominal) KOH electrolyte
- o Au-plated Mg separator plates
- o Fiberglass epoxy frame material

The operating conditions of the baselined configuration were

- o 355°K (180°F) nominal
- o 4 atmospheres pressure
- o 44-311 mA/cm² (40-300 ASF)
- o 27.5-32.5 volts
- o 7 kW nominal power rating

Several contributions to this configuration were derived from the capillary matrix technology programs. Among the most important are

a. Reconstituted asbestos matrix electrolyte holder. The physical properties of the commercial grade matrix material were found to be of such irregular proportions that positive and uniform separation of electrodes was unreliable and that capillarity was low (low electrolyte retention ability) due to irregularly distributed, coarse fibers. Reprocessing of the commercial asbestos greatly improved these properties.

b. Matrix thickness. Earlier technology effort established a solid data base for matrix thickness of 0.75 mm (0.030"). The capillary matrix fuel cell technology contractor attempted to use 0.25 mm (0.010") thickness in order to maximize performance. When difficulties were encountered with this thickness, a compromise was made between the previous data base and the 0.25 mm (0.010") thick matrix and 0.50 mm (0.020") thickness was adopted.

c. Separator plate composition, surface finish and protective plating. Magnesium plate stock of high-purity alloy was a prerequisite to achieve the quality finish that was necessary to accept the protective gold plating with minimal imperfections.

d. Reactant flow distribution and pressure control. Reactant labyrinth flow and porting design improvements were developed to assure uniform flow across the cell and also cell to cell from the manifold.

A comparison of the Shuttle fuel cell, which was baselined in 1973, with the Apollo fuel cell, which was baselined in 1962, shows that for essentially equivalent weight, the Shuttle fuel cell produces 8 times as much power (nominally) for 6 times as long and requires only 15 minutes to start up versus 24 hours for Apollo, and shutdown is instantaneous, versus 17 hours for Apollo.

Subsequent to baselining and as a result of electrode catalyst technology effort sponsored by LeRC (Lewis Research Center), the cathode electrode catalyst was changed from a Pt/Pd mix to one of Au/Pt alloy. This change resulted in approximately 50% increase in power capability and led to a reduction of one stack per module, which yielded a 15% [55 kg (120 lbs) total] weight reduction for the power system in the spacecraft.

SOLID POLYMER ELECTROLYTE TECHNOLOGY

Figure 7 illustrates the current version and characteristics of the SPE fuel cell stack. Figure 8 illustrates a cross section of the current cell configuration and its characteristics. Figure 9 illustrates the advanced cell configuration juxtaposed for comparison with the current cell configuration.

Shortly after the completion of the Gemini fuel cell program, the principal life-limiting degradation phenomenon of the ion-exchange membrane was identified. The membrane was synthesized from a ring-structured monomer (styrene) which was attacked chemically during operation by outgassing species of the canister foam filler material. The propagation of ruptured

and cleaved rings slowly deteriorated the membrane until reactant gas cross-over occurred, resulting in localized catalytic H_2 and O_2 ignition, causing failure of the fuel cell. In addition, the deteriorated membrane species contaminated the product water rendering it unusable. These phenomena led to the search for and development of chemically stable, ionically conductive, polymeric materials suitable for electrolytic membrane fabrication. A sulfonated fluorocarbon with a chemical structure and stability similar to duPont Teflon eventually emerged as an acceptable material. In 1969, the Biosatellite was flown with a primate aboard which consumed the product water produced by a fuel cell utilizing this new material for over 30 days.

During the pre-Shuttle technology program of the early '70's, a series of failures occurred which threatened the objective of a long-life (2500-5000 hr), reliable SPE fuel cell. The operating conditions required [$355^\circ K$, 414 kPa, 108-430 mA/cm² ($180^\circ F$, 60 psia, 100-400 ASF)] imposed stresses on the membrane which resulted in failures seemingly similar to the Gemini failures. Through an Agency-wide "Task Force" type effort, the nature of the failures was sorted out and found to be initiated by excessive drying of the membrane by incoming reactants followed by an oxidative attack in the dehydrated zone by an intermediate, short-lived specie of reaction. Understanding the cause (but not the exact mechanism) of the failures led to a chemical treatment of the membrane to buffer the chemical attack and a design feature to eliminate the dehydrating phenomenon. This was a signal success which was verified by a 2500-hour test. This test time demonstrated a factor of 4 improvement from previously achievable results at similar stress levels.

With this milestone of achievement secured, the major limitation in operational life of the SPE fuel cell was resolved. While the membrane is not totally inert, the degradation product, F^- , (in the form of HF) is identifiable in the product water and a measure of its concentration provides a barometer for predicting useful life. Testing of latest configuration cells is producing product water with 50 to 150 PPB (parts per billion) F^- . The longest test run of any fuel cell of record anywhere is continuing beyond 48,000 hours with essentially invariant performance and producing water with 1000-2000 PPB F^- . It seems reasonable to infer, then, that the latest cells producing 50-150 PPB F^- will run 10 to 20 times as long as the cells producing 1000-2000 PPB F^- based upon membrane degradation alone. Using the 48,000-hour test as a base, the technology is now indicating a potential of operating with an indefinite life capability.

Figure 10 illustrates the performance trend of the SPE fuel cell associated with the various applicable programs from the Gemini program to the present technology program.

CONTINUING TECHNOLOGY

Since the 1973 competition for the Shuttle fuel cell program the capillary matrix technology has been advanced under the sponsorship of LeRC, and JSC has sponsored the continued advancements in the SPE technology. These continuing efforts have been justified on several accounts. Among these are

satisfying the ever-increasing power demands of the Shuttle; increasing hardware life capability; and maintaining technological growth capability toward meeting the requirements of the more ambitious space missions in planning such as space construction and manufacturing operations, support of solar power satellite buildup, etc.

ELECTROLYSIS TECHNOLOGY

Figure 11 illustrates the cross section and associated reactions of an electrolysis cell along with a similar illustration of a fuel cell cross section for comparison. Also given are principal elements of the technology status. The SPE is arbitrarily used for this illustration; the alkaline cell would be similar. It is readily apparent that the fuel cell and electrolysis cell technologies are fundamentally one and the same.

Electrolysis technology supported by the Agency and managed by the Crew Systems Division of JSC has been focused on the application of the SPE fuel cell technology toward the on-board generation of H₂ and O₂ from supplied and reclaimed water for life support functions. This effort was initiated under contract in 1970 for a six-man, closed-cycle system. Following that effort a contract was awarded for the fabrication of a closed-cycle, 9 kg/day (20 lb/day) O₂ generating system called, "Space Station Prototype." This effort was completed with delivery of the system in September 1973.

In addition to the Agency support of electrolysis technology, the A.F. has supported development of high-pressure technology to produce propellants for attitude and station-keeping control in synchronous orbit. The Navy has also sponsored development of high-pressure systems toward the life-support requirements of a 140-man crew on nuclear submarines. And finally, the A.F. and Navy have jointly sponsored development of oxygen concentrator systems (a hybrid fuel cell/electrolysis cell) for use on high-flying aircraft.

Cell sizes deriving from the JSC programs range from 7.6 cm (3 in.) diameter to 16.25 cm (6.4 in.) diameter. Other government applications have utilized cells of 21.8 cm (8.6 in.) diameter and commercial applications for bulk hydrogen generation are presently working toward an initial scaled up size of 0.23 m² (2.5 ft²).

Operating conditions for electrolysis cells can be quite variable over a range of temperature from 305°-428°K (90°-300°F), up to 21 MPa (3000 psia), and current density to approximately 1870 mA/cm² (2000 ASF). Operating voltages vary according to conditions. An illustration of cell voltage variation versus current is given in figure 12 for both electrolysis cells and fuel cells.

Electrical power systems trade and design studies have long recognized the potential of this technology in a regenerative configuration with fuel cells and photovoltaic cells as an energy conversion and storage system toward support of the longer duration, high-power missions. Electrolysis technology developers have also recognized this potential, but the driving motivation to

stimulate development has not been present. With the space program outlook for the '80's and '90's and in light of the trade studies already conducted, the motivation is now available to justify initiation of the long-range technology development activity which is required to bring the concept into reality.

The principal electrolysis cell technologies currently available are direct derivatives of the fuel cell technologies which have been developed under NASA sponsorship. The acidic SPE electrolysis concept derives from the Gemini/Shuttle technology development and presently exhibits superior performance efficiency. The alkaline capillary matrix electrolysis concept derives directly from the capillary matrix fuel cell technology which was begun in the mid '60's. As a fuel cell, this concept exhibits superior efficiency to the SPE fuel cell. Thus a regenerative energy conversion and storage system with maximized performance efficiency based upon present capability and ignoring interaction phenomena of dissimilar species (acidic/alkaline) would be composed of acidic SPE electrolysis cells and alkaline capillary matrix fuel cells (fig. 13 and fig. 14). However, continued research in the catalyst, electrode, and electrolyte area could profoundly influence optimization configurations and thus it is premature to make such commitments until the superior technologies emerge through further development.

REGENERATIVE ENERGY STORAGE TRADE STUDIES

Since the early '60's several definition studies for conceptual designs of long-duration space vehicles accommodating up to 150 men have been conducted. These studies have included several power systems using either solar or nuclear energy. Indepth studies were conducted from 1969 to 1972 by Rockwell/Space Division under contract to JSC (ref. 2) and MDAC (McDonnell Douglas Astronautics Company) under contract to MSFC (Marshall Space Flight Center) (ref. 3). Both contractors baselined a photovoltaic/NiCd regenerative power system in the Phase B system definition reports. Then, under an add-on task to the Rockwell/Space Division contract, an RFC (regenerative fuel cell) trade was conducted in light of the SA/NiCd system previously baselined. Results of both trades are given in reference 2. Results of that trade are summarized in figure 15. The RFC system was baselined on the basis of that trade study which was oriented toward a 10-year life including maintenance and replacement, as required.

Following these results, two contracts were awarded to conduct indepth RFC system analyses and component designs, results of which were published as design data handbooks (ref. 4 and ref. 5). These studies honed the initial trades to identify the marginal technology areas, sensitivities, maintenance considerations, etc.

The latest power system trade study for orbiting vehicles was conducted by MDAC in 1977 (ref. 6). The results of this study are summarized in figure 16. The study included NiCd batteries, NiH₂ batteries, energy wheels, and RFC's for energy storage. The RFC system shows a weight savings of 65% compared with the NiCd system.

As a result of these study activities, a large reference base has been established for the concept of the regenerative fuel cell system as a viable energy conversion and storage concept for long-duration orbital operations.

Future mission plans for long-duration orbital operations consistently identify the viability of a fuel cell/electrolysis/photovoltaic system. The fuel cell is already firmly established as the primary power system for the Shuttle and is not likely to be superseded for this generation of logistics vehicle. Solar array augmentation for extending the Earth orbital stay time of the Shuttle is under consideration. Any logical extension of the Shuttle capabilities beyond this level will require a dedicated space power system with heavy dependence on the photovoltaic systems. The RFC fits well with the low Earth orbital requirements for energy storage.

While the RFC technology is justified solely on supplemental power system energy storage applications, it also offers many future options such as certain life support functions and propellant processing. The only resupply requirement for the logistics vehicle is water.

ENERGY CONVERSION/STORAGE TECHNOLOGY PLAN

Future missions of the variety discussed in the previous section could occur in the mid-to-late '80's. Therefore, in keeping with the practice begun and the success realized with the fuel cell technology programs preceding the Shuttle, a preliminary technology plan has been prepared that is designed to bring the technology of regenerative electrochemical cells to a state of readiness for application to those programs.

The initial task of the plan provides for a state-of-the-art assessment during the first year to be conducted by the Agency and by contract. This effort will be a thorough analysis of all aspects of the technology in order to firmly establish a set of guidelines and goals, and to define priorities required to improve the technology to the capability required over the following six years. The technology will be oriented toward establishment of a regenerative orbiting power platform of up to 500 kW_e rating. Using this as a tentative goal, a preliminary set of requirements will be derived in order to permit the technology programs to be conducted on representatively sized cells, stacks, modules, etc., and to determine flow rates, thermal loads, stress levels, and other factors which are required to conduct a well-ordered technology effort. These specifications will be updated as necessary based upon inputs from other programs dealing with requirements and sensitivities analyses of ongoing orbital operations planning.

The major thrust of the technology program will be focused on the electrochemical aspects; i.e., the electrolyte, electrode and catalyst environment because that is where the reactions occur and that is where any improvements in efficiency and life will be achieved. The merits of dual-mode cells will be evaluated during the first three years of the program. Even if final system designs should favor dedicated modules there appear to be advantages to cell commonality from a cost, manufacturing, and inventory standpoint.

A continuing cell and stack task is identified to evaluate and prove out all effort deriving from the electrochemical tasks. At this level, engineering activity becomes visible as related to the cell and stack sizing and design requirements.

At the module level, components become a factor in technology improvement, especially in the area of maintainability.

Early in the technology program an interim breadboard test will be conducted using 5-7 kW_e modules of both fuel cell and electrolysis cells, operating in both the dedicated and reversible modes. Finally, a field technology readiness demonstration test will be conducted on engineering model modules of representative sizes in 1985.

CONCLUDING REMARKS

Over the last 16 years approximately \$170 M has been expended through NASA to develop a strong capability in fuel cell electrochemical technology which is also intimately related to electrolysis technology. This expenditure has provided for the technology advancements as well as development and hardware costs for three flight programs with a fourth program in active development. In the beginning it was difficult to achieve 100 hours of test operation. Routine test durations of 5000 hours have been achieved on test hardware, and isolated one-of-a-kind tests have approached 50,000 hours of test operation. Specific weight [kg/kW (lbs/kW)] has been reduced by an order of magnitude, and a factor-of-two further reduction appears to be feasible. These advancements are graphically illustrated in figure 17 for both the alkaline and SPE technologies. Further weight reduction to less than 5 kg/kW (10 lbs/kW) and life exceeding 100,000 hours appear now to be feasible.

A direct outgrowth of the development of fuel cells for space is the development toward terrestrial applications. The space program proved the utility of the concept and laid the foundation; this is the foundation upon which future utilization of fuel cells will be built.

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5. Lockheed Missiles and Space Division, "Design Data Handbook for Regenerative Fuel Cell Study," LMSC-D159786, NASA Contract NAS9-12508, Nov. 1972.
6. McDonnell Douglas Astronautics Company, "Space Station Systems Analysis Study," Part 3: Documentation, Vol. 7: SCB Alternate EPS Evaluation," MDC G6954, NASA Contract NAS9-14958, Sept. 1977.

Figure 1. Fuel Cell Programs

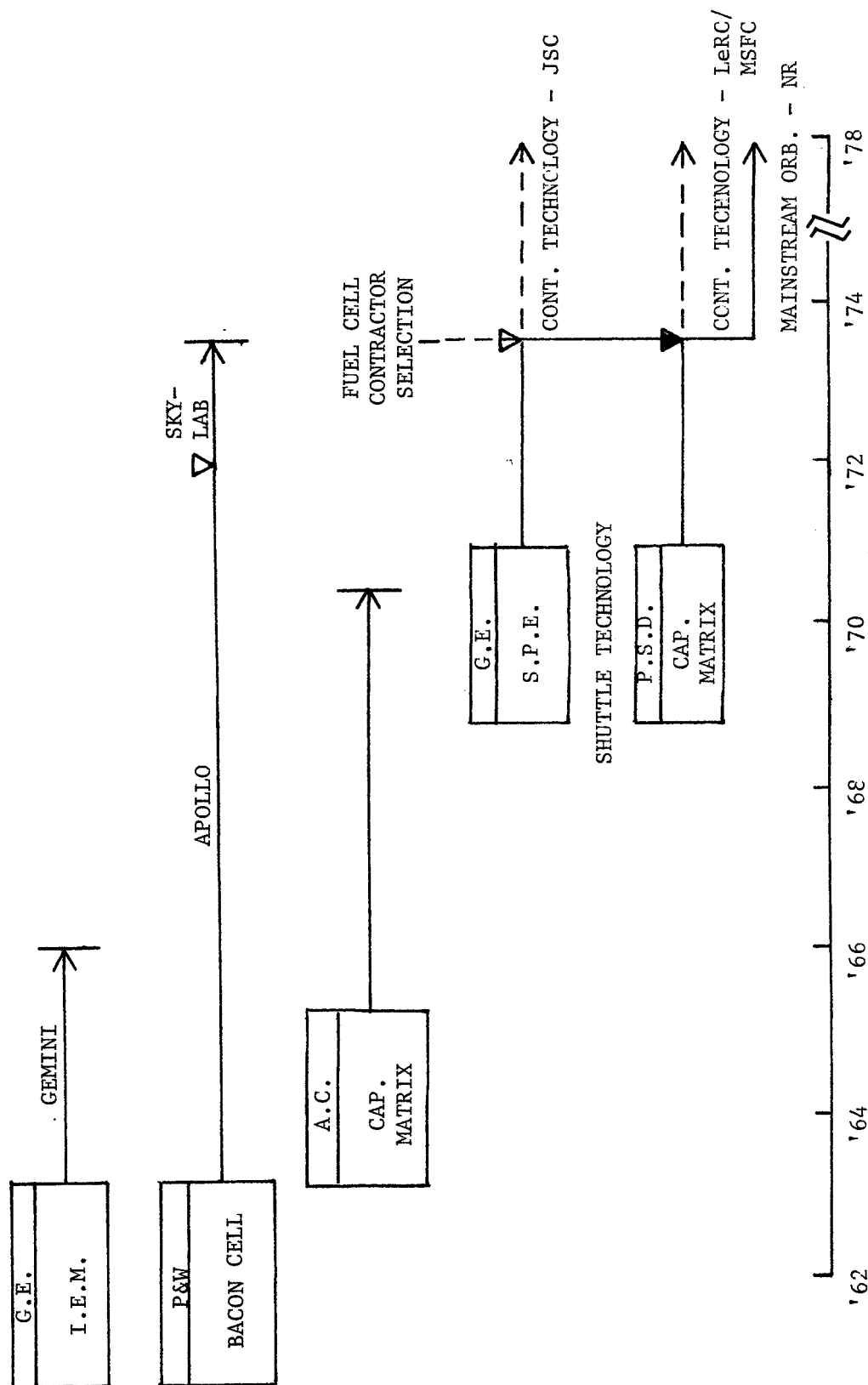
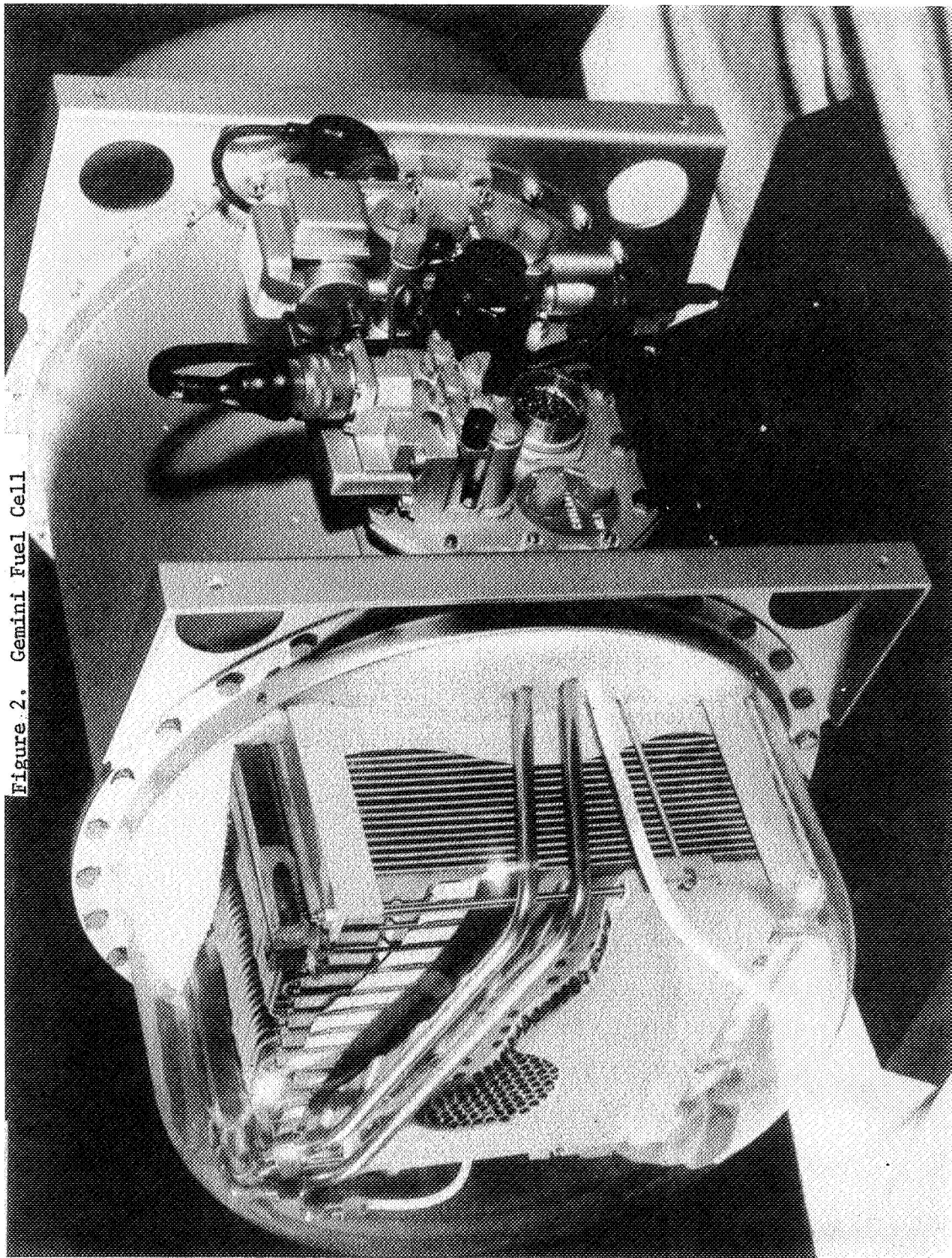


Figure 2. Gemini Fuel Cell



C & SM FUEL CELL MODULE

Figure 3. Apollo Fuel Cell

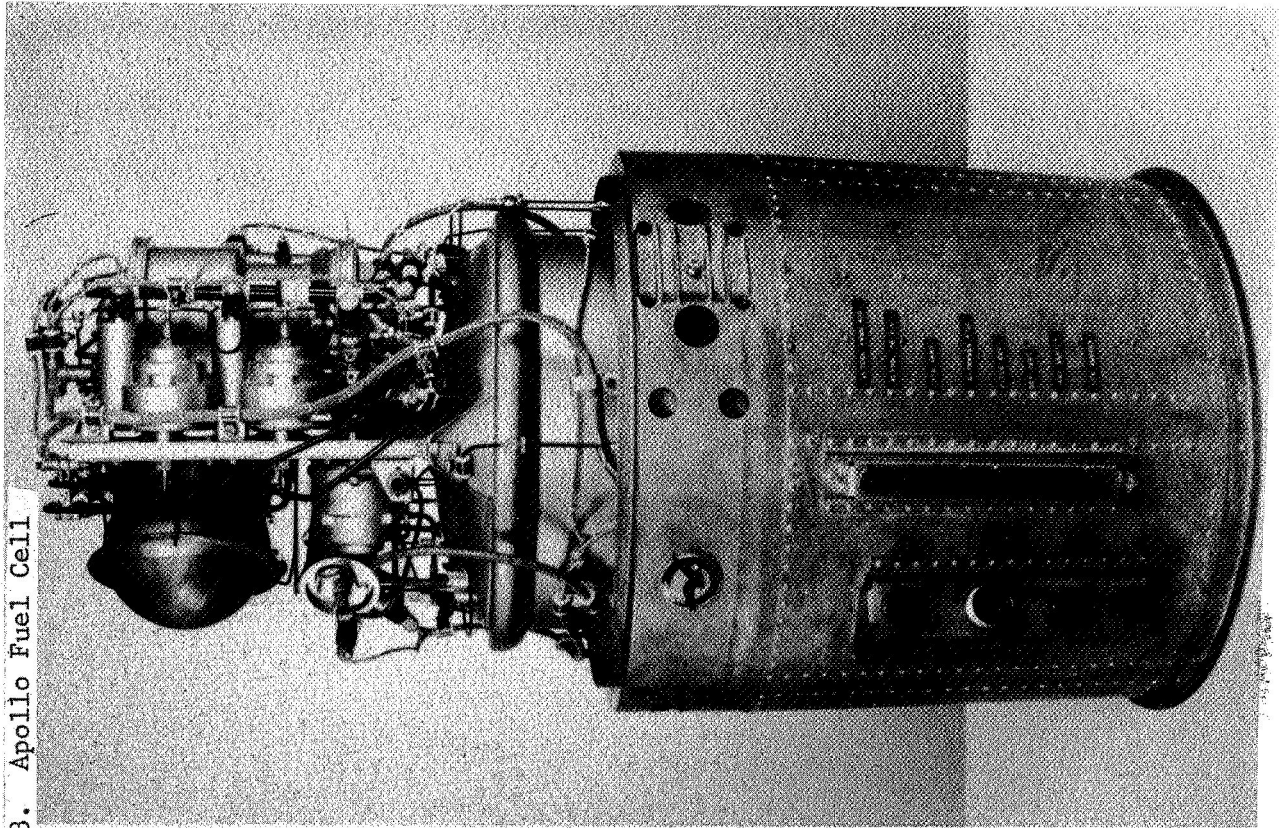


Figure 4. AAP Fuel Cell

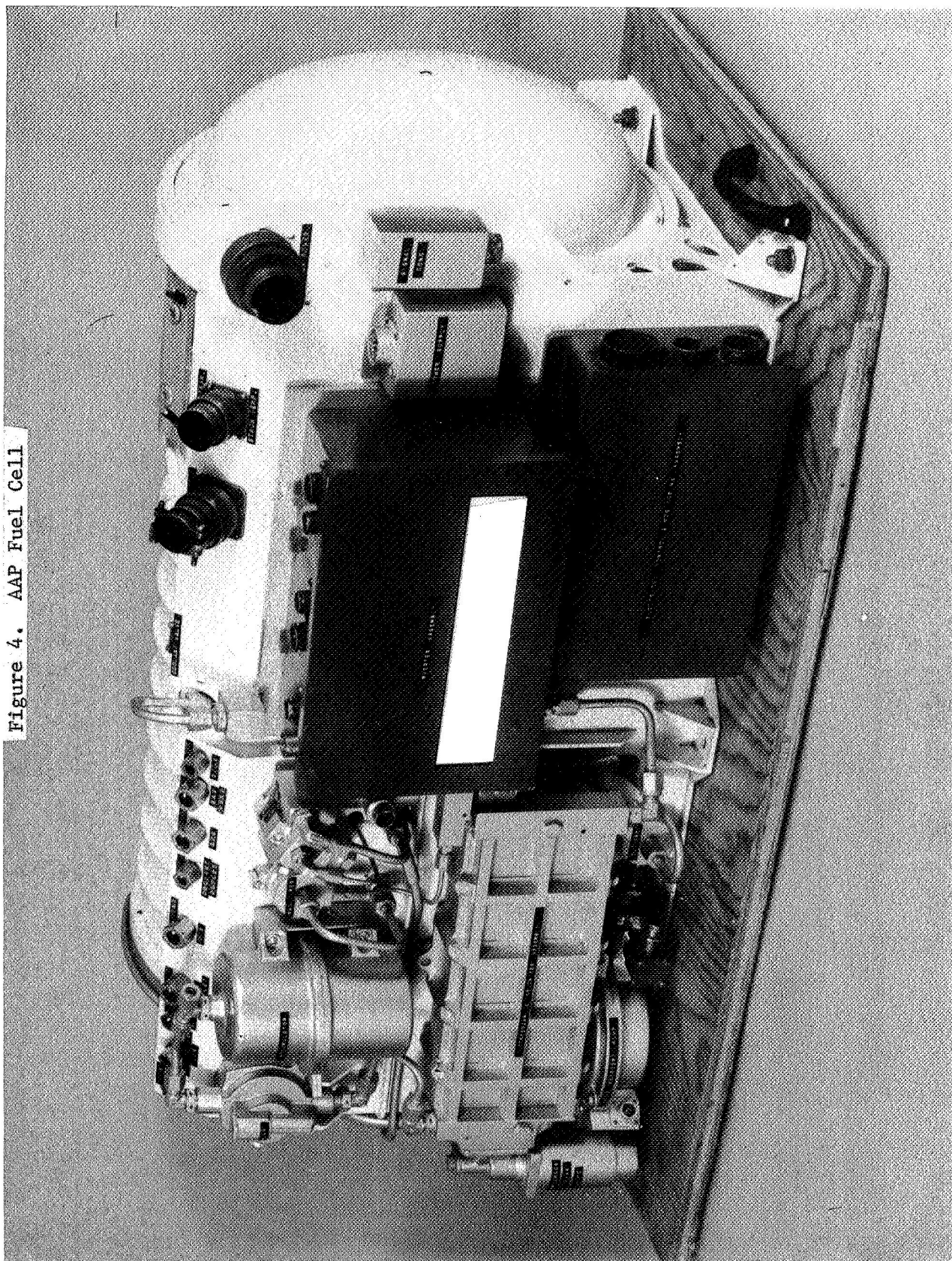
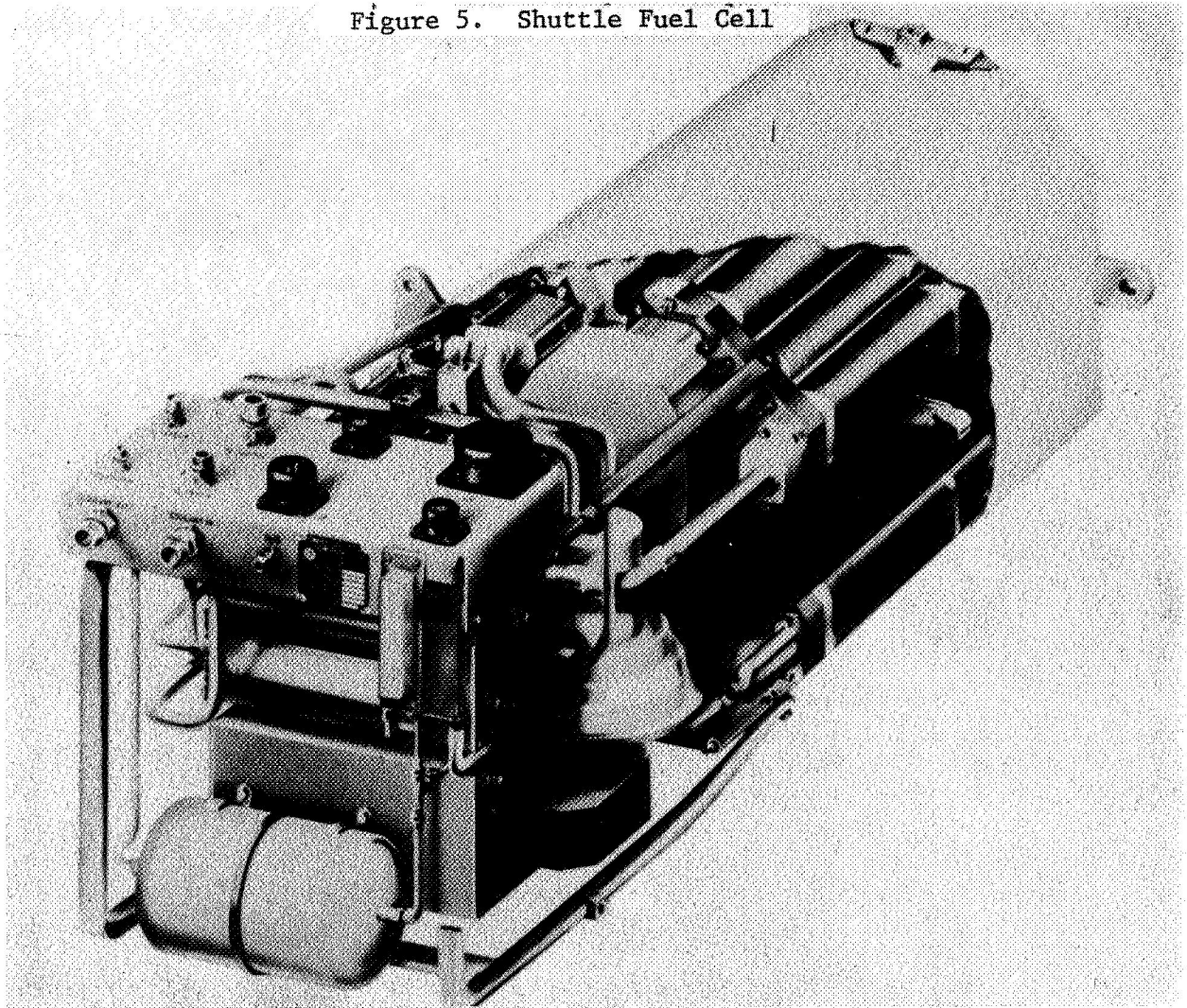


Figure 5. Shuttle Fuel Cell



SPECIFICATIONS

POWER : 2 kW, min. (32.5v)
4.5 kW, avg. (2500 hrs)
7.0 kW, nom.
10 kW, 1 hr. emerg.
12 kW, 15 min.

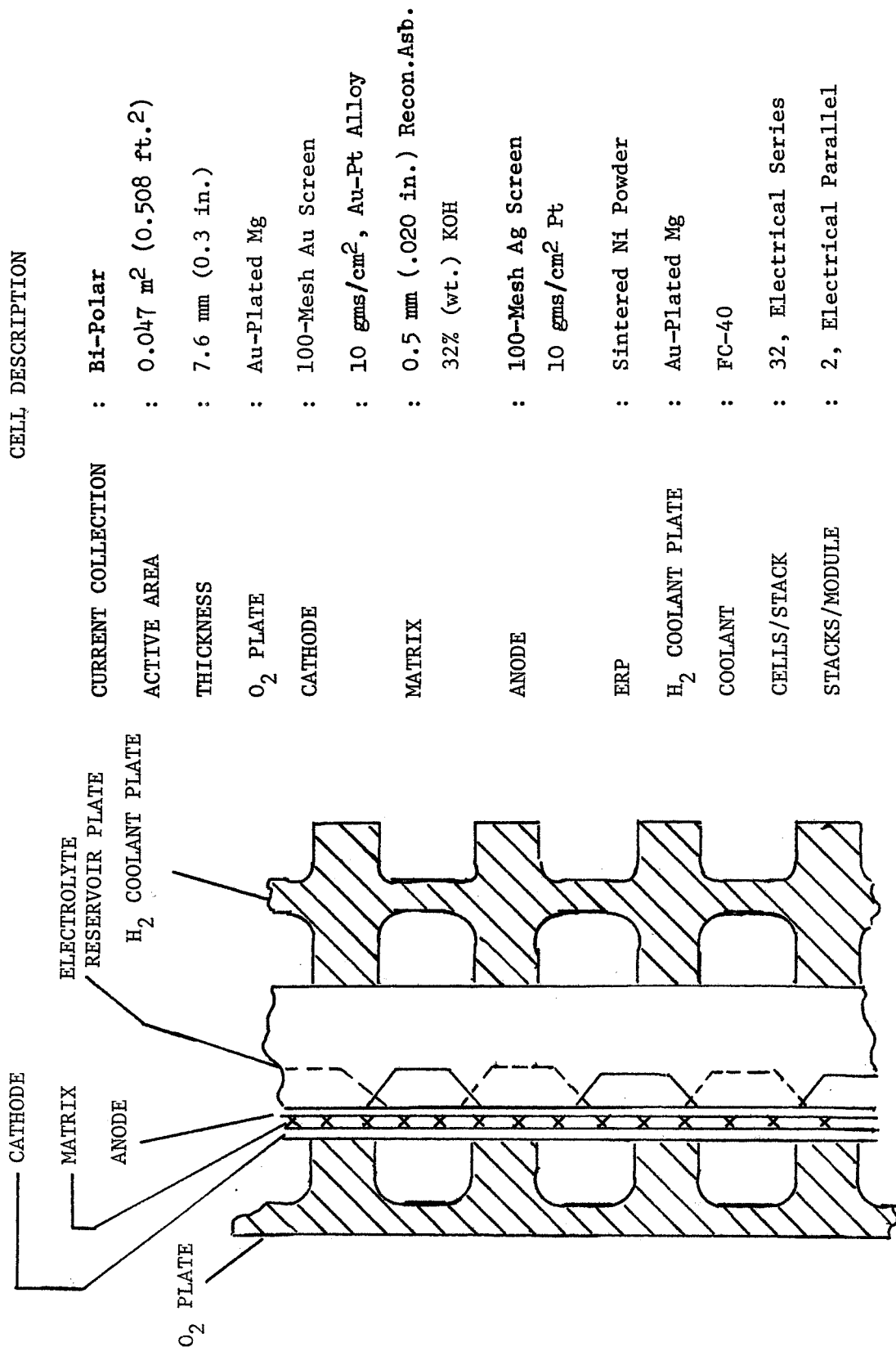
VOLTAGE: 27.5v - 32.5v

OP. TEMP. : 355-383°K (180-230°F)

OP. PRESS. : 414 kPa (60 psia)

LIFE : 2500 hr. @ avg. pwr.
5000 hr. w/maint.

WEIGHT : 91 kg (200 lb.)

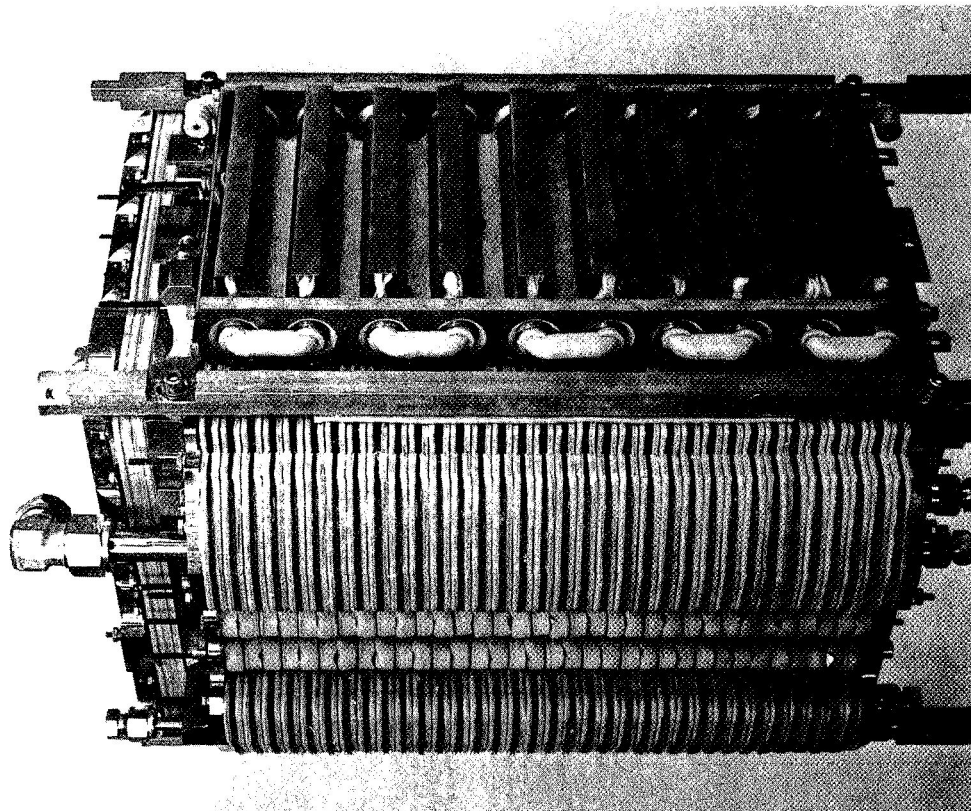


Cell Cross Section

Figure 6. Shuttle Fuel Cells

Figure 7. SPE Fuel Cell

TECHNOLOGY STATUS	
POWER	: Design Option (36 cells, 14 kW)
VOLTAGE	: ('73) 0.75-0.9v; 200-50 mA/cm ² (ASF) ('75) 0.70-0.9v; 500-100 mA/cm ² (ASF) ('77) 0.75-0.95v; 1000-100 mA/cm ² (ASF)
CELL AREA	: 0.035 m ² (0.375 ft ²) (Back-to-back) 0.065 m ² (0.7 ft ²) (Bi-Polar) 0.102 m ² (1.1 ft ²) (Bi-Polar; Optimum)
PERFORMANCE	: Invariant (<1 μ v/cell-hr)
OP. TEMP.	: 355-428°K (180-300°F)
OP. PRESS	: 414-793 kPa (60-115 psia)
LIFE	: ('73) >5000 Hours (module) ('78) >48,000 Hours (short stack)
WEIGHT	: ('73) 9 kg/kW (20 lbs/kW)



SPE REACTOR STACK

Figure 8. SPE Technology

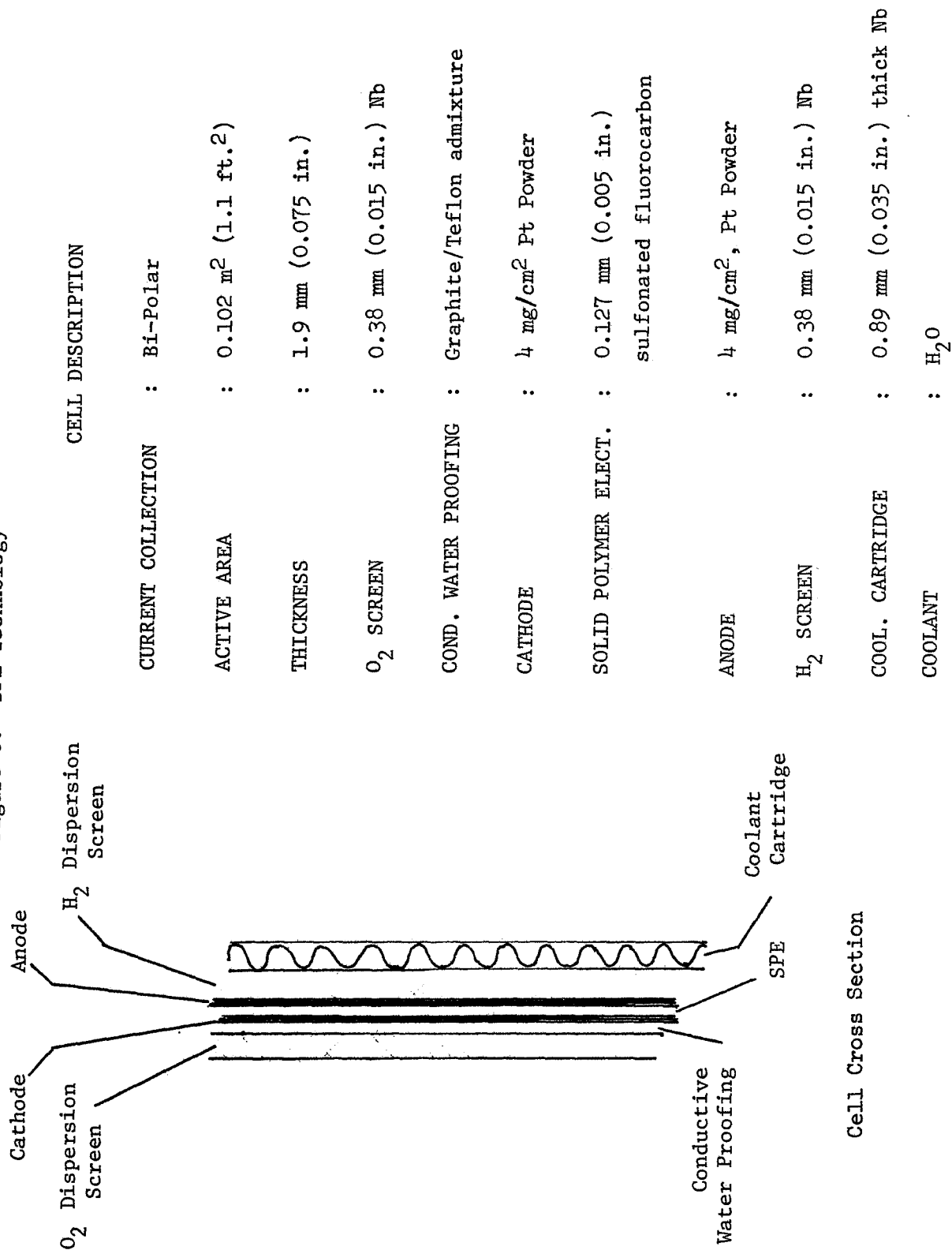


Figure 9. General Electric
SPE Fuel Design

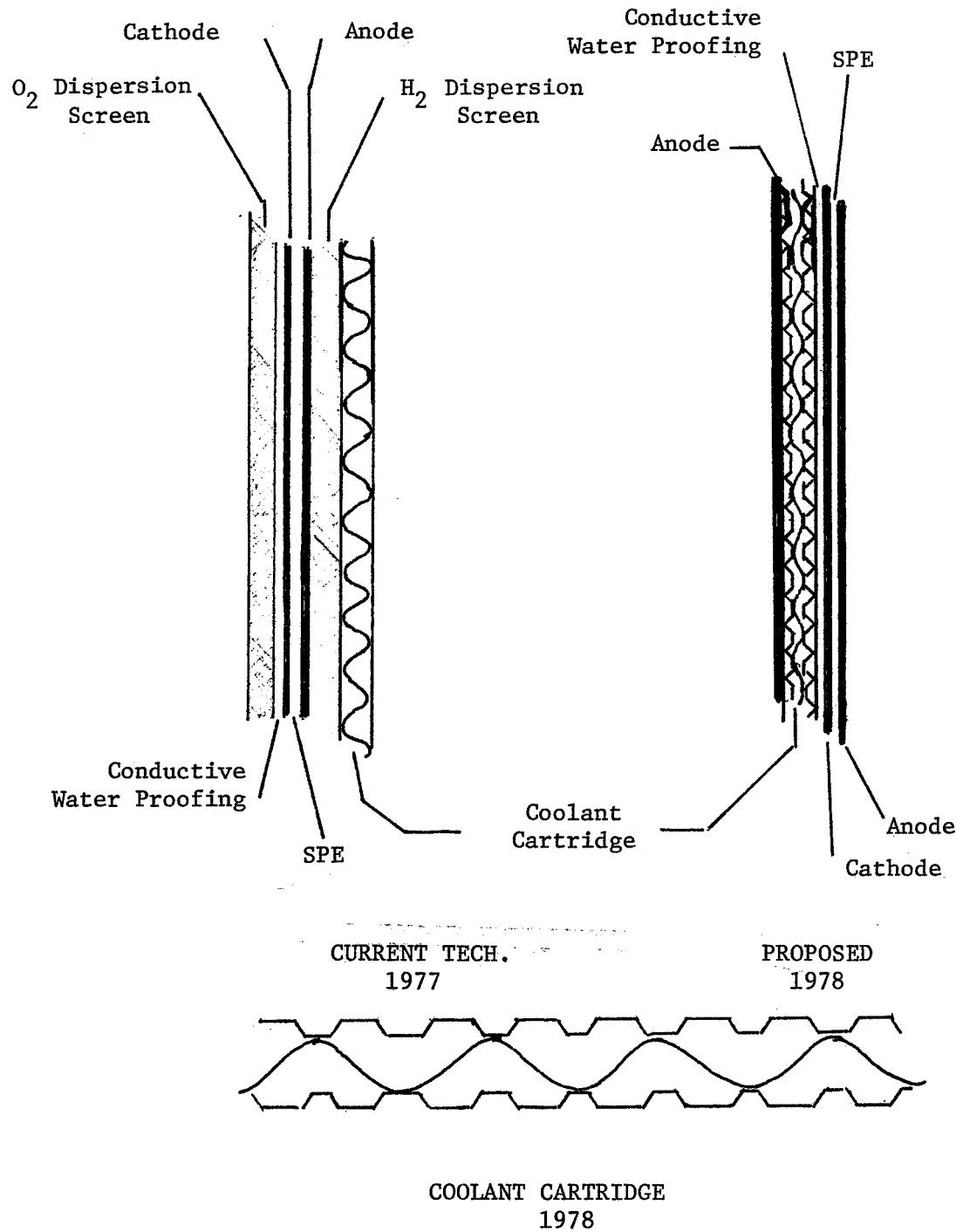


Figure 10. SPE Fuel Cell Performance

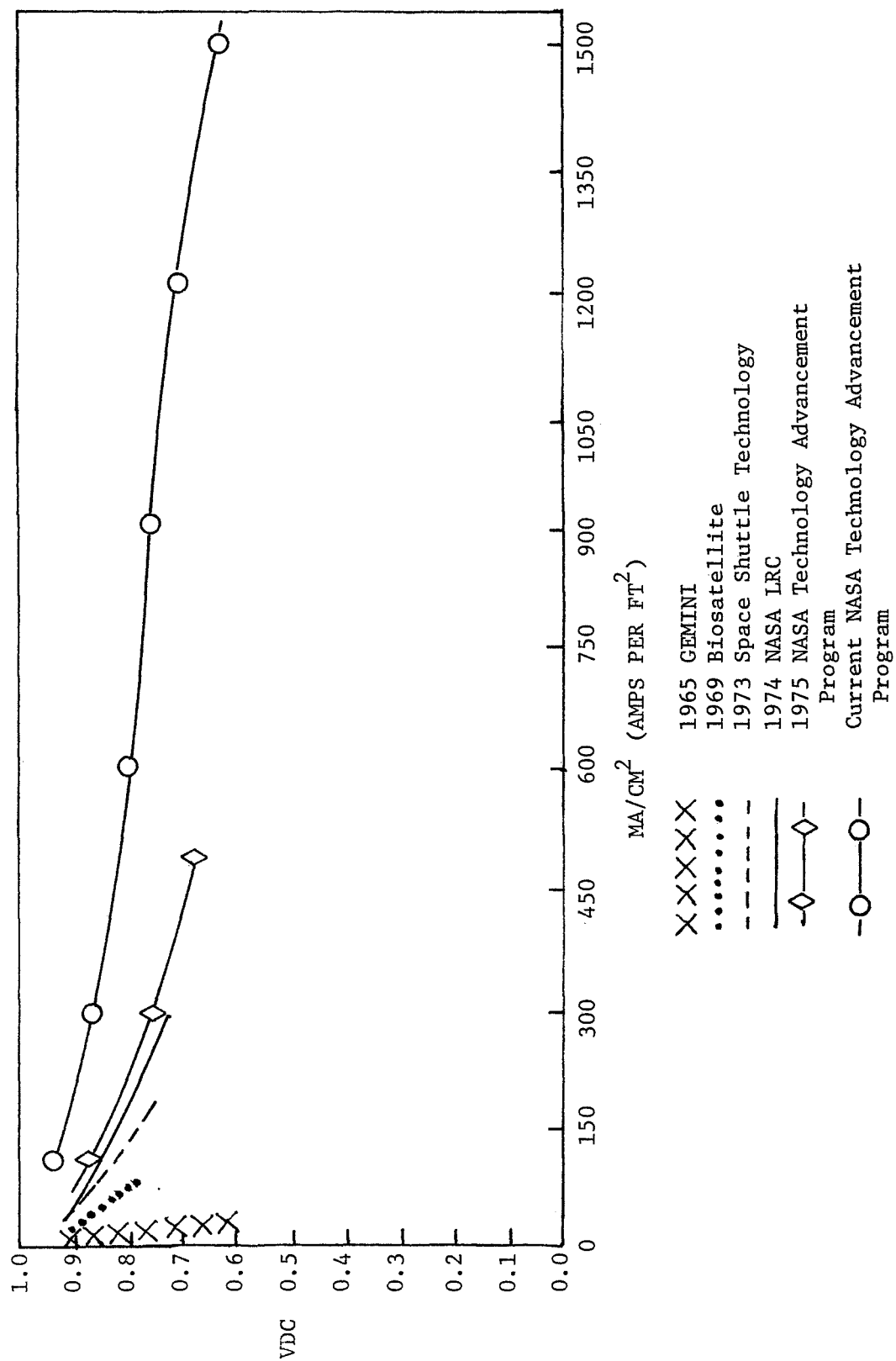


Figure 11. Electrolysis Cell

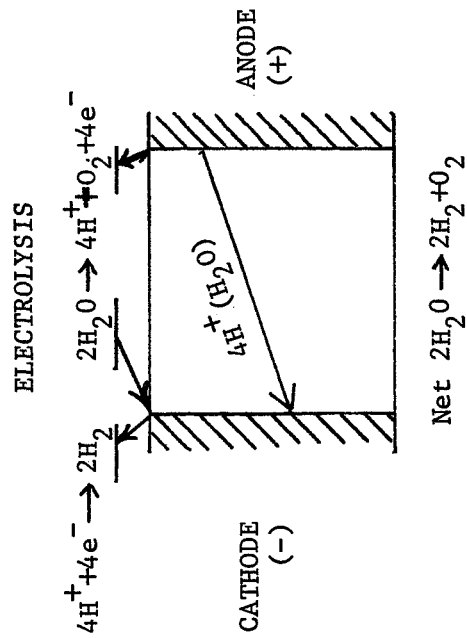
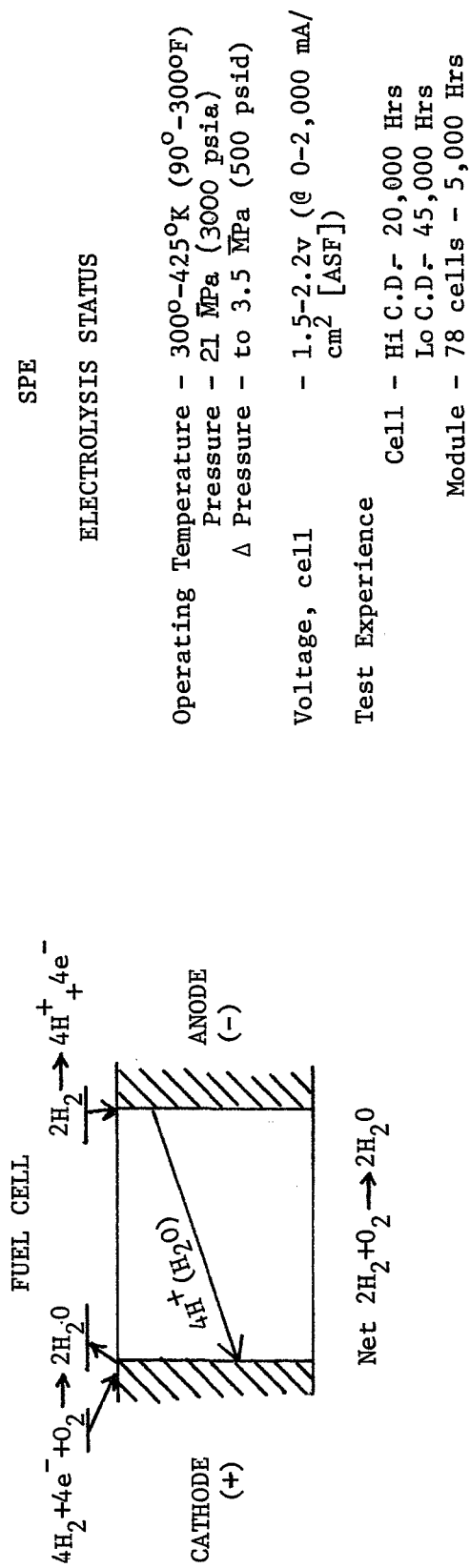


Figure 12. Voltage - Current Trend for H_2/O_2 Electrochemical Cells

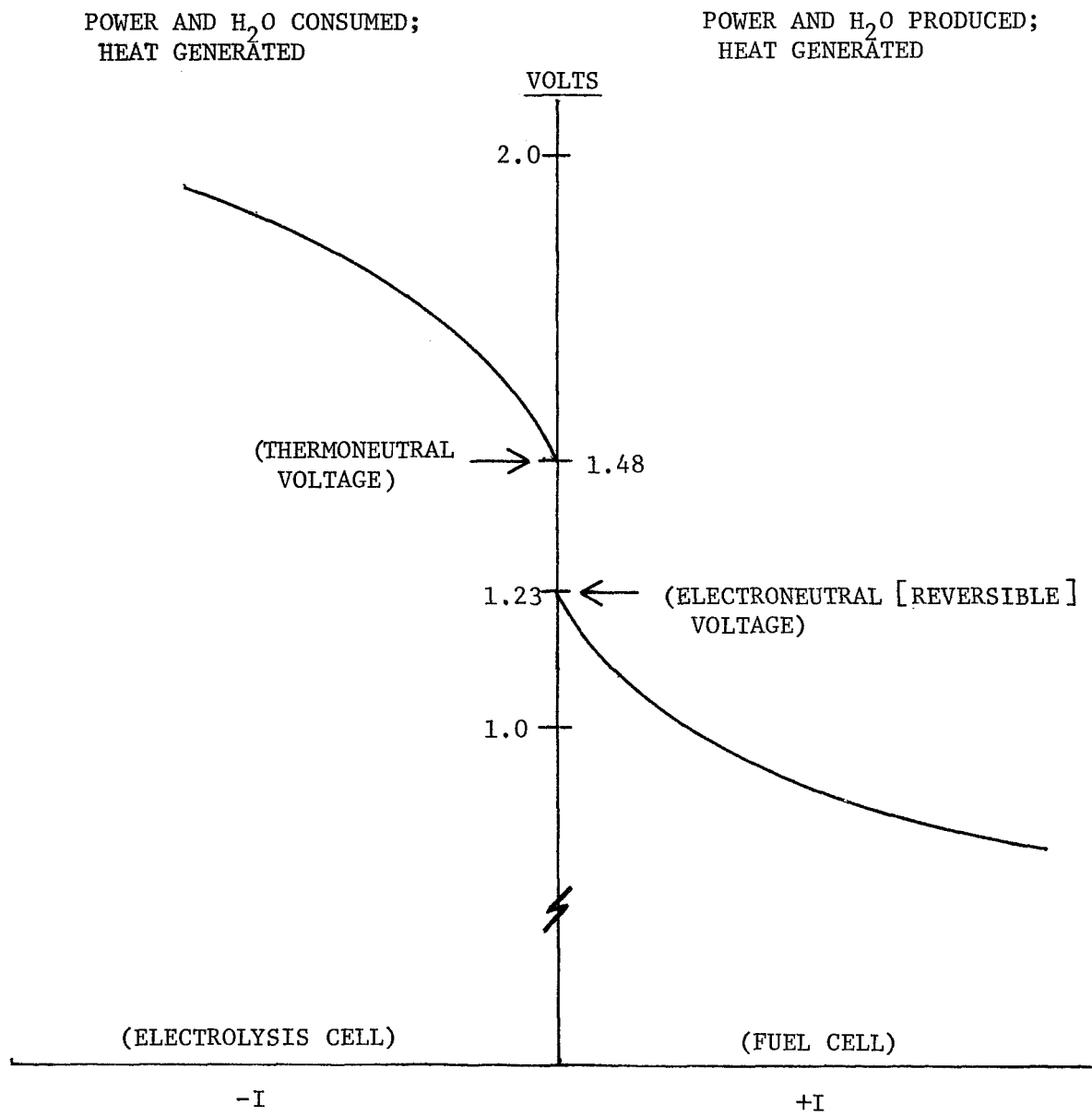


Figure 13. Water Electrolysis Performance

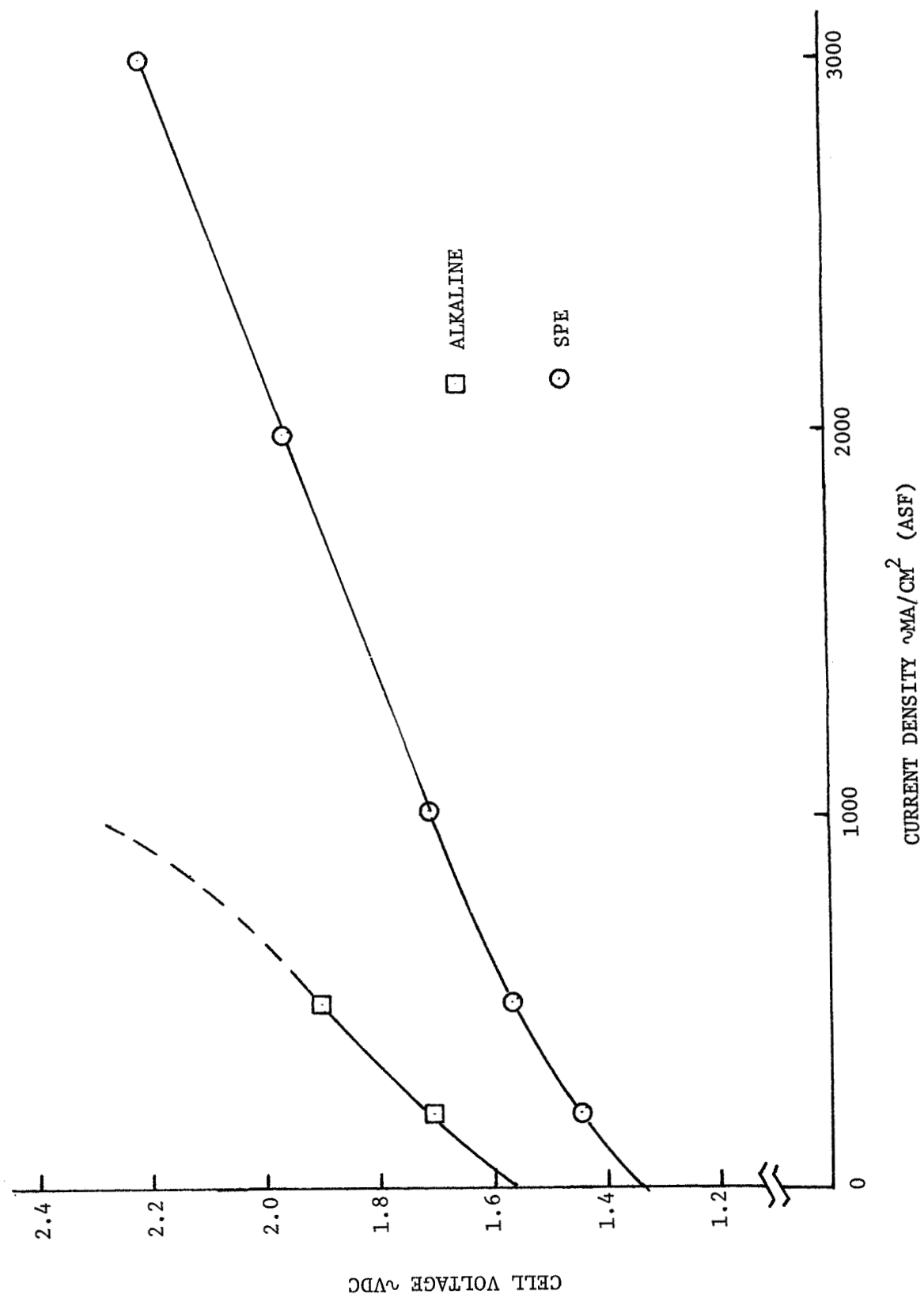


Figure 14. H₂-O₂ Fuel Cell Performance

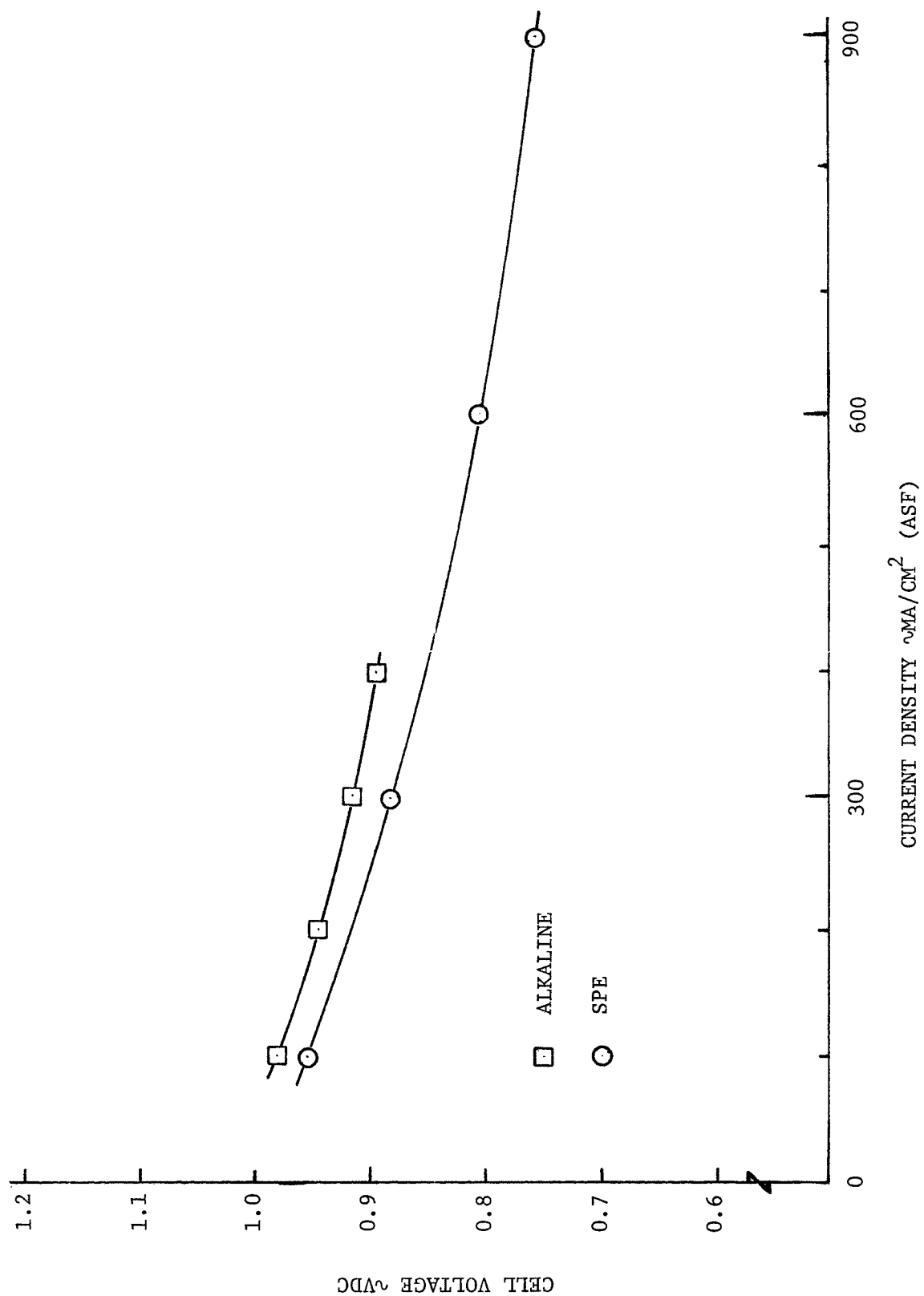


Figure 15. Fuel Cell, Electrolysis Regenerative Energy
Storage Comparisons to Battery Energy Storage

Evaluation Criteria	Fuel Cells, Electrolysis Regener, Energy Storage	Battery Energy Storage
Thermal Control	Single Temperature Development (4.8 M less development cost)	Two loop development Dual temperature ranges
Charge-Discharge Efficiency	0.525	0.625 (higher efficiency)
Solar Array Area Requirement	22 m ² (240 ft ²) less [700 m ² (7540 ft ²) SA] (based on 24-hour cycle)	723 m ² (7780 ft ²) solar array (based on per orbit cycling)
Secondary Power Requirement (emergency, buildup)	Utilize energy storage F C's	Adds F C's to energy storage assembly (battery capacity inadequate)
ISS Interface	Four equivalent subassemblies	32 equivalent sub- assemblies (more complex)
Launch Weight	1280 kg (2817 lbs)	4169 kg (9172 lbs) (heavy!)
Cost, \$		
Development	14.7 M (assumes shared development)	13.7 M (includes secondary power)
Hardware	5.3	7.5 (includes secondary power)
Operations	7.9	10.0 (includes launch)
Overall (IOC + 5-Yr Ops)	27.7	32.2 [\$114/kg](\$250/lb)
Sensitivities:	• Fuel cell lifetimes • Amount of shared development of electrolysis & fuel cells • 24-hr cycling	• Voltage degradation • Charge scheme-- available energy & charge time constraints

Figure 16. Fuel Cell/Electrolysis Cell Energy Storage*
MDAC Summary

	NiCd	RFC
SOLAR ARRAY AREA, m ² (ft ²)	2,407 (25,910)	2,587 (27,847)
STORAGE EFFICIENCY, %	62.0	54.1
DEPTH OF DISCHARGE, %	14.5	33.0
ENERGY DENSITY, Wh/kg (Wh/lb)	3.93/27.08 ⁽¹⁾ (8.66/59.6)	25.0/75.1 ⁽¹⁾ (55/165.2)
PEAK LOAD CAPABILITY	~ 10X	~ 4X
LAUNCH WEIGHT, kg (lbs)	34,763 (76479)	16,083 (35,383)
RESUPPLY WEIGHT, kg (lbs) (10 yrs)	21,000 (46,200)	2,994 (6,587)
TOTAL 10 YR WEIGHT	55,763 (122,679)	19,077 (41,970)

*100 kW_e Average at inverter output; baseline power platform

(1) usable/absolute

Figure 17. H₂-O₂ Fuel Cells Specific Weight and Operating Life versus Calendar Time

