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**SPE® WATER ELECTROLYZERS IN SUPPORT OF THE LUNAR OUTPOST**

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**Abstract**

During the 1970s, the SPE water electrolyzer, which uses ion exchange membranes as its sole electrolyte, was developed for nuclear submarine metabolic oxygen production. These developments included SPE water electrolyzer operation at up to 3,000 psia and at current densities in excess of 1,000 amps per square foot. The SPE water electrolyzer system is now fully qualified for both the U.S. and U.K. Navies with tens of thousands of system hours accumulated at sea.

During the 1980s, the basic SPE water electrolyzer cell structure developed for the Navies was incorporated into several demonstrations for NASA's Space Station Program. Among these were:

- The SPE regenerative fuel cell for electrical energy storage
- The SPE water electrolyzer for metabolic oxygen production
- The high pressure SPE water electrolyzer for reboost propulsion reactant production

In the 1990s, one emphasis will be the development of SPE water electrolyzers for the Lunar Outpost. Currently defined potential Lunar Outpost applications for the SPE water electrolyzer include:

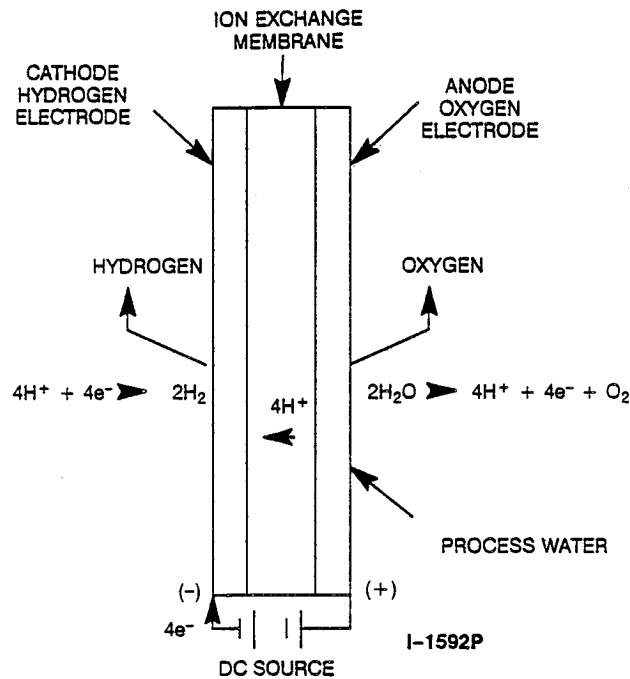
- SPE water electrolyzers for metabolic oxygen and potable water production from reclaimed water
  - SPE water electrolyzers operating at high pressure as part of stationary and mobile surface energy storage systems

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## SPE WATER ELECTROLYSIS TECHNOLOGY OVERVIEW

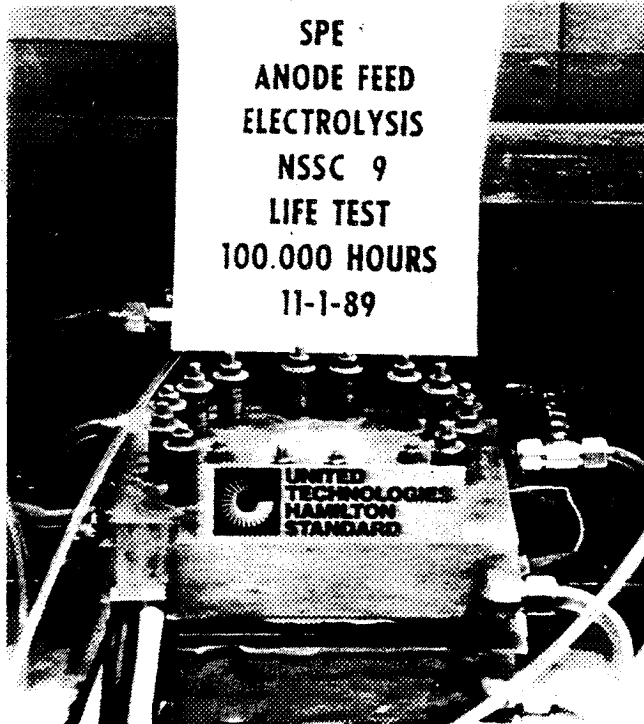
The heart of the SPE water electrolyzer is the electrolysis cell which consists of an ion exchange membrane with Teflon bonded, finely divided metal electrodes. Figure 1 shows this arrangement along with the water electrolysis reactions. Since the fixed acid ion exchange membrane has neither a traditional bubble point nor free electrolyte, operating pressures and hydrogen-oxygen differentials are limited only by the surrounding structures. This affords a significant safety factor in maintaining positive separation of the hydrogen and oxygen products.



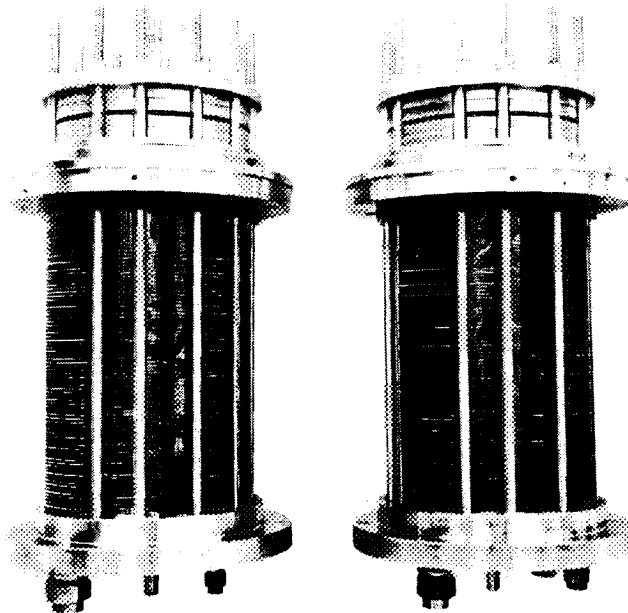
**FIGURE 1. SPE WATER ELECTROLYZER REACTIONS**

The introduction of the perfluorocarbon cation exchange membrane in the late 1960's enabled the development of the SPE electrolyzer. In prior years, water electrolyzers made with existing ion exchange membranes had useful lifetimes of only a few hundred hours. With the use of perfluorocarbon ion exchange membranes, the SPE water electrolyzer cell life has been demonstrated to be in excess of 13 years and projected to over 30 years depending on operating conditions. Figure 2 displays the longest lifetime SPE water electrolyzer cell at its 100,000 hour milestone in 1989. This cell and two others have now accumulated in excess of 110,000 operational hours without disassembly or modification. These three cells continue to accumulate additional operational hours.

In most practical applications, a number of cells are stacked in a filter press arrangement with as many as 100 or more cells electrically connected in series while the fluids are passed through the cells in parallel. Figure 3 displays a pair of SPE water electrolyzers, each with 81 cells, in a filter press arrangement. Without any free electrolyte, the parallel fluid flows can be conducted without fear of shunt currents inducing stray water electrolysis and its potentially deleterious result of product gas mixing. The purity of the product gases from SPE water electrolyzers is typically greater than 99.99%.



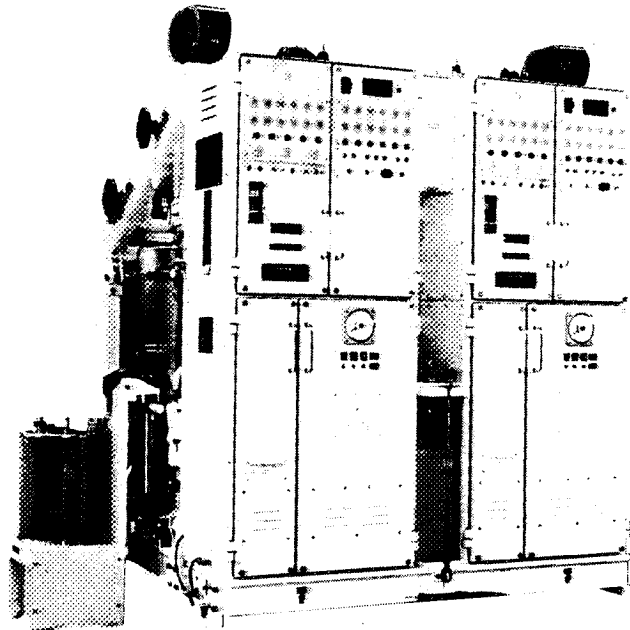
**FIGURE 2. SPE ELECTROLYZER LIFE TEST**



**FIGURE 3. SPE WATER ELECTROLYZER MODULES**

## NUCLEAR SUBMARINE OXYGEN GENERATORS

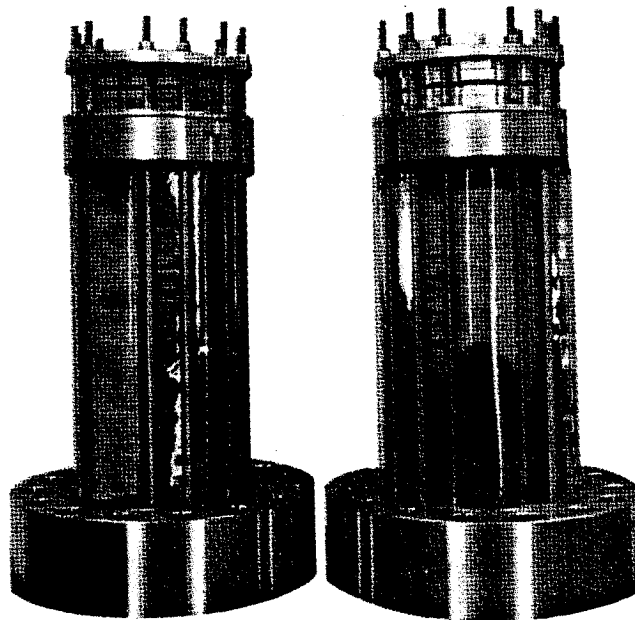
Both the U.S. Navy and U.K. Royal Navy have sponsored the development of SPE water electrolyzers for oxygen generation in nuclear submarines. In the case of the U.K. Royal Navy, the SPE water electrolyzer system is fully qualified with more than 35 systems delivered to date. The SPE water electrolyzer module equipment is supplied by Hamilton Standard and the supporting system equipment supplied by CJB Developments of Portsmouth, England. The modules previously shown in Figure 3 are the type used in the U.K. Royal Navy system and the overall oxygen generation system itself is depicted in Figure 4. The operational experience of the SPE water electrolyzer has been exceptional with over 69,500 operational system hours without a single malfunction. The longest operational service for any single 150 psia SPE electrolyzer module is 13,900 hours as of December 31, 1991.



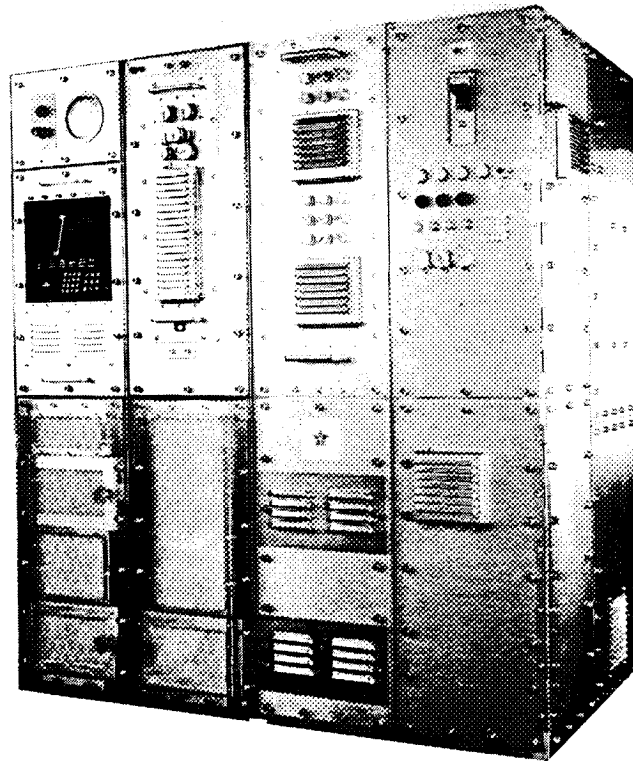
**FIGURE 4. A DUPLEX LOW PRESSURE ELECTROLYZER (LPS)**

The U.S. Navy SPE water electrolyzer system, which operates at pressures up to 3000 psia, has passed all qualification testing, including shock, vibration and sea trials. The U.S. Navy SPE water electrolyzer modules and overall oxygen generation plant are shown in Figures 5 and 6 respectively.

During the course of developing the two Naval oxygen generation systems and the subsequent operation in the U.K. Royal Navy, over 10 million cell hours have been accumulated on the basic 0.23 ft<sup>2</sup> cell design. This high level of maturity is further described in Table 1.



**FIGURE 5. 225 SCFH U.S. NAVY SPE OXYGEN GENERATOR MODULES**



**FIGURE 6. HIGH PRESSURE OXYGEN GENERATING PLANT (OGP) FOR NAVAL USE**

**TABLE 1**  
**DEMONSTRATED MATURITY-NUCLEAR SUBMARINE SPE WATER ELECTROLYZERS**  
**AS OF DECEMBER 31, 1991**

Type of Service/ Product Description Navy Electrolyzers	Electrolysis Rate lbs/hr H <sub>2</sub> O	Cell Area ft <sup>2</sup>	Operating Pressure PSI	Number of Stacks	Number of Cells Per Stack	Total Number of Cells	System Hours	Stack Hours	Cell Hours
U.S. Navy:									
3000 psi System Qualification Unit (OGP #2)	21	0.23	300 to 3000	2	100	200	8,325	8,325	832,500
3000 psi System Preprototype (OGP #1)	21	0.23	300 to 3000	2	100/83	183	10,000	13,000	1,181,000
Development System (Breadboard)	21	0.23	300 to 3000	2	100	200	14,000	28,000	2,800,000
Development Stack OGP Program	1	0.23	300 to 3000	1	5	5	1,900	1,900	9,500
Development Stack OGP Program	2	0.23	300 to 3000	1	10	10	1,500	1,500	15,000
Development Stack OGP Program	4	0.23	300 to 3000	1	20	20	2,500	2,500	50,000
Development Stack OGP Program	7.4	0.23	300 to 3000	1	35	35	3,900	3,900	138,500
Development Stack NSSC 4	0.2	0.23	ambient	1	1	1	115,900	115,900	115,900
Development Stack NSSC 7	0.2	0.23	ambient	1	1	1	111,900	111,900	111,900
Development Stack NSSC 9	0.2	0.23	ambient	1	1	1	116,900	116,900	116,900
United Kingdom Navy									
Development Stack S/N #1	12.5	0.23	150	1	58	58	3,000	3,000	174,000
Development Stack S/N #2	15	0.23	150	1	70	70	8,000	8,000	420,000
Production Stacks:									
Various Production	15 to 17	0.23	150	38	70 or 81	2,850	69,500	69,500	5,212,500
Longest Life UK Stack	15 to 17	0.23	150	1	81	81	13,900	13,900	1,125,900
<b>TOTAL</b>				<b>53</b>		<b>3,474</b>	<b>482,725</b>	<b>479,725</b>	<b>10,975,100</b>

With over 10 million cell hours of successful operation, the SPE 0.23 ft<sup>2</sup> cell design is well established.

## SPACE STATION DEMONSTRATORS

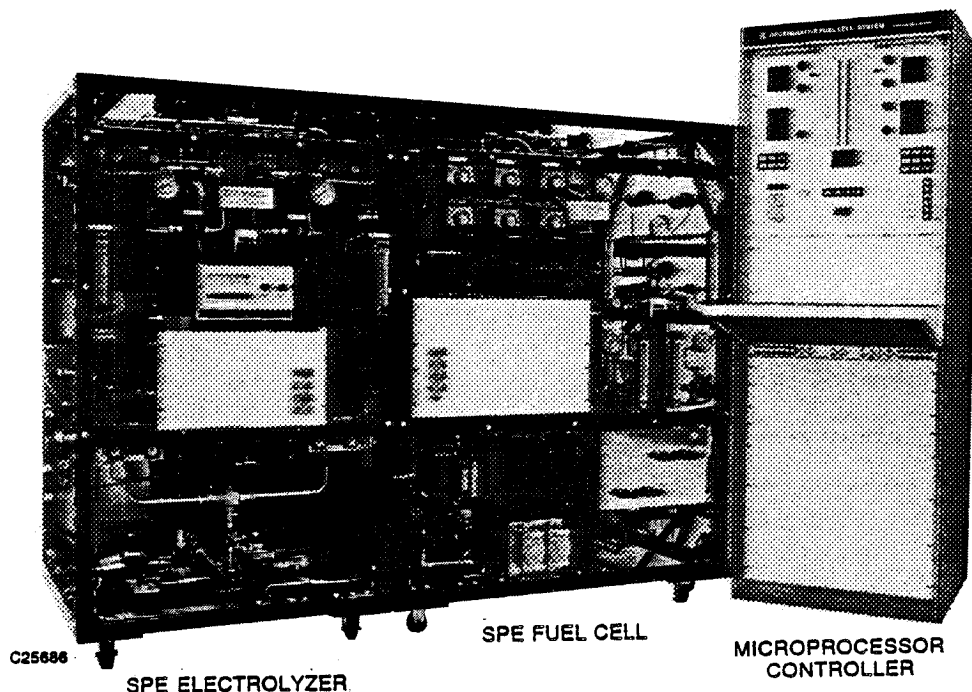
During the decade of the eighties, a series of demonstrators were fashioned, delivered and tested at NASA. Each of these demonstrators made use of the identical 0.23 ft<sup>2</sup> SPE water electrolyzer design with its naval maturity.

### **SPE Regenerative Fuel Cell**

The SPE regenerative fuel cell for electrical energy storage was the first of the demonstrators to be delivered to NASA in support of Space Station Freedom. Figure 7 shows the three subsystems making up the demonstrator as follows:

- SPE fuel cell subsystem
- SPE water electrolyzer subsystem
- Microprocessor controller

The SPE fuel cell module consists of eight cells, each of an active area of 1.1 ft<sup>2</sup>. The SPE water electrolyzer module contains 22 cells, each of the 0.23 ft<sup>2</sup> design.



**FIGURE 7. SPE REGENERATIVE FUEL CELL DEMONSTRATOR**

The SPE regenerative fuel cell demonstrator, with its 1 to 2 kW rating, underwent parametric testing at the factory prior to its delivery to NASA/JSC. NASA/JSC conducted extensive testing of the system accumulating 1,630 simulated low earth orbit charge/discharge cycles [1]. Including the pre-delivery factory cycles, over 2,000 cycles were accumulated on the combined SPE water electrolyzer and SPE fuel cell.



Other demonstrated features included:

- Closed system fluid cycle balance
- Direct solar array/electrolyzer voltage/current control compatibility (i.e., no power conditioning required)
- An electric energy storage efficiency of 48% recorded with the SPE water electrolyzer at ambient temperature.

At the successful conclusion of the SPE regenerative fuel cell demonstration, the SPE fuel cell was replaced with a Space Shuttle alkaline development fuel cell subsystem. This hybrid of alkaline fuel cell and acid SPE water electrolyzer was operated by NASA through an additional 100 low earth orbit charge/discharge cycles [2]. Both subsystems displayed stable performance throughout the 100 cycles and proved the compatibility of the hybrid approach.

Following the 100 cycle hybrid testing, the SPE water electrolyzer module was retrofitted with two high performance cells using a membrane manufactured by Dow Chemical. After the factory modifications, the SPE water electrolyzer module with 20 standard 0.23 ft<sup>2</sup> cells and the two high performance 0.23 ft<sup>2</sup> cells underwent parametric testing at NASA/JSC [3]. The testing at various temperatures and pressures showed a significant performance improvement with the Dow membrane cells, especially at the higher current densities. The curves in Figure 8 are typical of the improvement.

The most recent activity with the SPE water electrolyzer subsystem was to upgrade the electronic controls. Checkout of the subsystem with the new controls was shown to be nominal. Following the checkout, the SPE water electrolyzer subsystem was loaned to the University of Arizona. At the university the subsystem is currently being used as a demonstrator for valuable gas production from extraterrestrial resources.

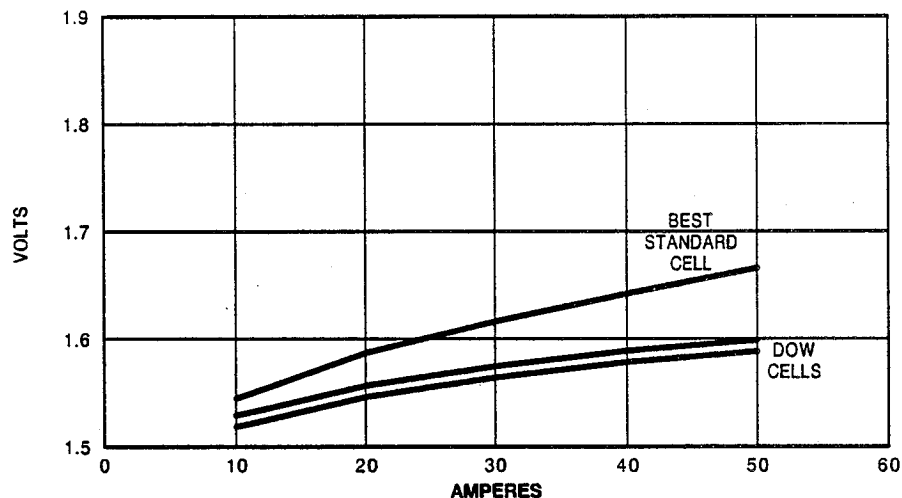
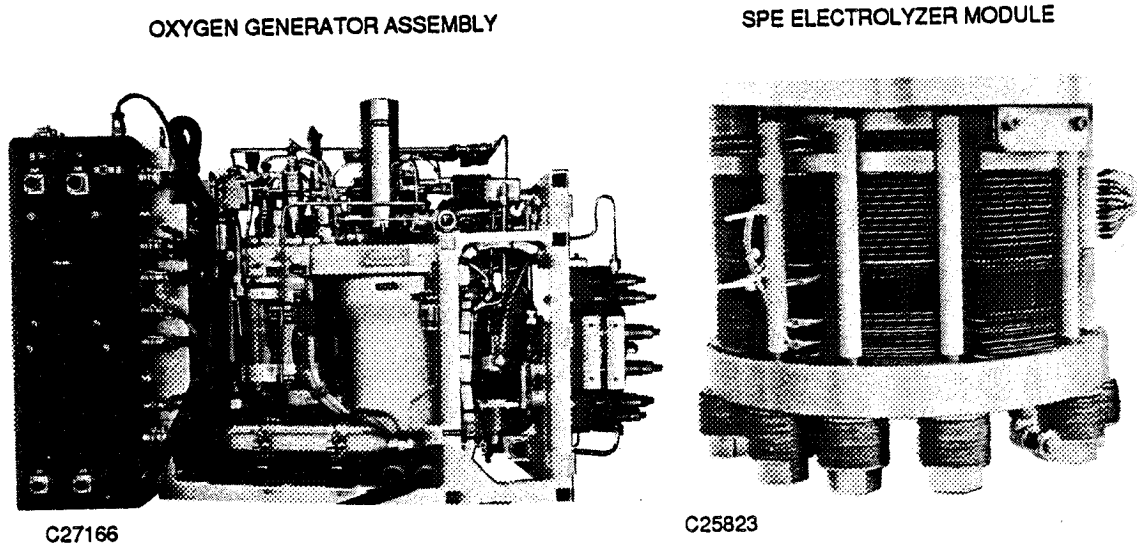


FIGURE 8. COMPARISON OF CELLS AT 150 PSI AND 105°F

## SPE Metabolic Oxygen Generator

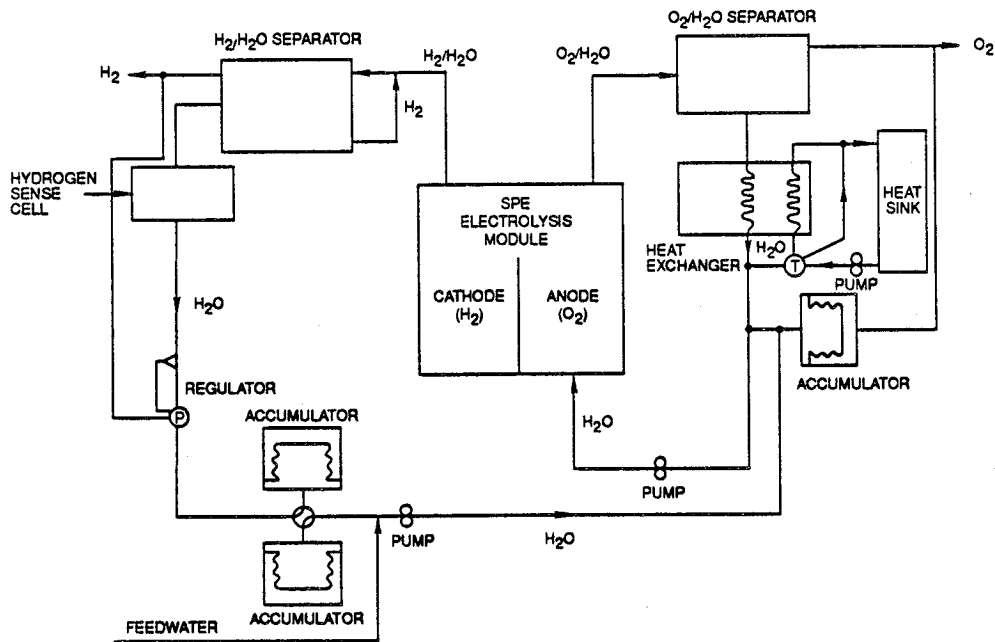
Under contract to the Boeing Aerospace and Electronics Company, an oxygen generator assembly technology demonstrator was constructed and is being evaluated. The heart of the oxygen generator is a 12 cell SPE water electrolyzer module of the identical 0.23 ft<sup>2</sup> SPE cell configuration used on the Navy programs. Figure 9 displays the oxygen generator assembly technology demonstrator with its SPE electrolyzer module. The operating pressure, temperature and current density of the technology demonstrator are well within the technology maturity established by the Navy experiences. Where this technology demonstrator differs from the Navy data base is in the need to operate in a microgravity environment and to use processed hygiene water as the feedstock.



**FIGURE 9. OXYGEN GENERATOR ASSEMBLY TECHNOLOGY DEMONSTRATOR**

In the normal operation of the SPE water electrolyzer, liquid water is circulated through the oxygen anode. This loop requires a phase separator as an oxygen/water mix is discharged from the module. Also, as hydrogen protons pass through the cell membranes, water is carried to the hydrogen cathode and thus a phase separator for hydrogen/water is required.

In the microgravity situation, the functions of gravity type pressure vessel phase separators must be accomplished by other means in order to make use of the high performance SPE water electrolyzer. Prior designs have performed the microgravity function of the one gravity pressure vessel phase separator with a combination of bellows accumulators and motor driven centrifugal devices. Although this arrangement has been used successfully, the drawbacks include lower reliability and higher power consumption. The approach taken in the Boeing Technology Demonstrator utilizes two membrane static phase separators to replace the pressure vessel phase separators. This arrangement is displayed in Figure 10.



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**FIGURE 10. SIMPLIFIED MICROGRAVITY FLUID SCHEMATIC  
(SPE ELECTROLYZER SYSTEM)**

Three basic types of membranes are used in the construction of the membrane phase separators:

- **Hydrophillic Membrane** - This membrane easily passes liquid water with a small differential pressure but blocks the passage of gas up to the bubble point of the membrane.
- **Hydrophobic Membrane** - This membrane easily passes gas with a small differential pressure but blocks the passage of liquid water up to the water intrusion pressure of the membrane.
- **Ion Exchange Membrane** - an ion exchange membrane with attached electrodes is a very efficient hydrogen separator/compressor for removing dissolved hydrogen from water. With an applied voltage of between 0.5 and 1.0 volt, hydrogen is rapidly transferred through the membrane at a rate proportional to the electrical current draw.

The Technology Demonstrator was activated at NASA/MSFC in November 1990 and, in operating for 529 hours, exceeded the test objective of 450 hours. The water electrolysis was conducted at an eight-man rate, with both deionized water and shower water processed through an ultrafiltration/reverse osmosis subsystem. Throughout the operation of the Technology Demonstrator, the microgravity phase separators worked in a very satisfactory manner. After a year of storage, the technology demonstrator was reactivated for checkout purposes. All system components, including the electrolysis module and phase separators, performed at the prestorage level.

### SPE Propellant Generator

Under contract to NASA/JSC, a 3,000 psi hydrogen-oxygen generator based on the Naval 0.23 ft<sup>2</sup> SPE water electrolyzer cell configuration was designed and delivered. The purpose was to demonstrate the feasibility of producing 3,000 psi hydrogen and oxygen on orbit for periodic rocket motor firing to maintain Space Station Freedom orbital altitude.

In high pressure SPE electrolyzers, a pressure vessel is used to enclose the module. Filling this pressure vessel with high pressure nitrogen precludes the necessity of designing cell seals to withstand the high pressure differential.

To reduce the mass and decrease the volume, as compared to the U.S. Navy design, several configuration changes were made to the supporting pressure vessel and fluid manifold. The resultant SPE propellant generator demonstrator is significantly smaller and lighter.

In the SPE propellant generator demonstrator, the pressure vessel is two torispherical domes opposed on either side of a central fluid plate. This configuration is shown in Figure 11. The domed design allows for a wall thickness of as low as one quarter of an inch when using Inconel or other high strength materials.

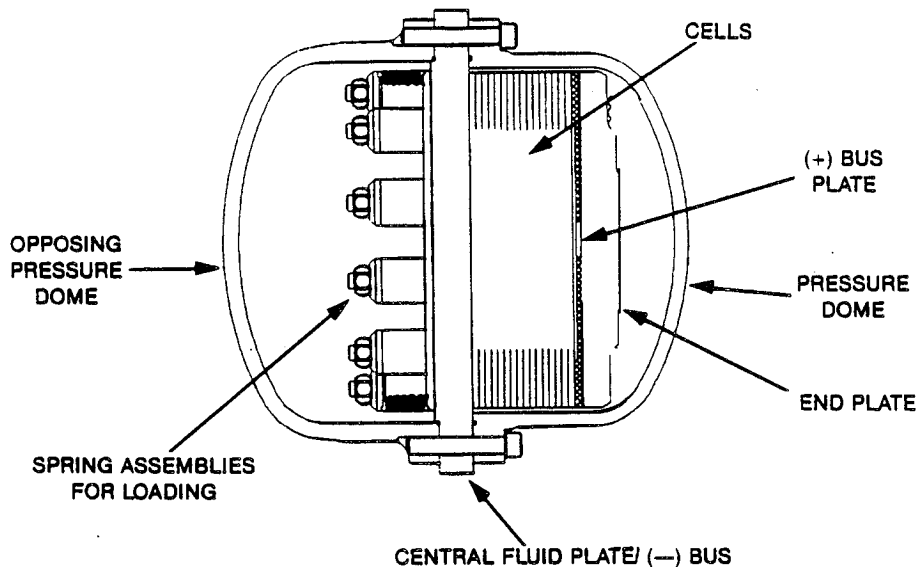


FIGURE 11. CROSS-SECTION, SPE PROPELLANT GENERATOR DEMONSTRATOR

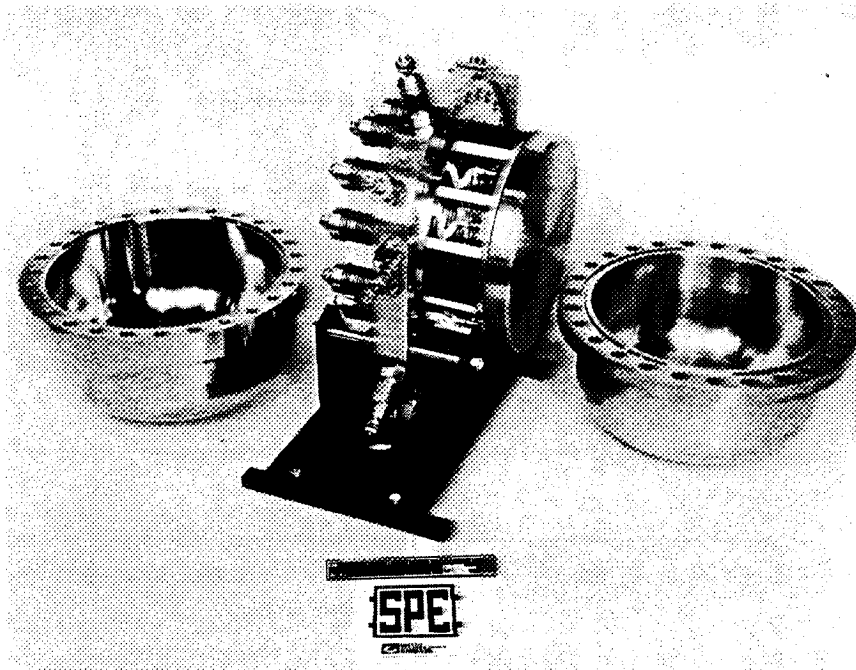
The fluid plate manifold is pressure balanced between the two pneumatic domes, eliminating the need for a thick plate to resist the pneumatic load, as is used in the U.S. Navy hardware. The demonstrator fluid manifold is only one inch thick. In the demonstrator, the cell stack is located on one side of the fluid plate within the volume of one dome.

Compression springs are located in the volume of the opposing dome. Volume is available for incorporation of gas/water phase separators and/or other system ancillaries, allowing for additional savings in system weight and volume. In addition, the cell stack incorporated edge electrical connections to a low profile positive terminal plate instead of using a plate and post assembly for additional mass and volume savings.

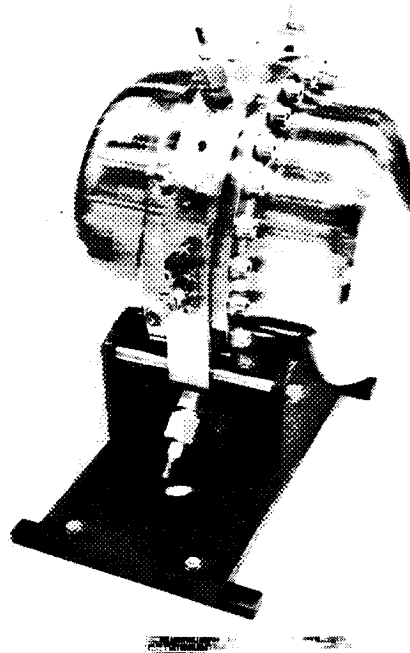
The SPE propellant generator demonstrator is shown in Figures 12 and 13. The dimensions of the demonstrator are 13 inches across the domes and 13 inches in diameter at the dome flanges. The total weight of the cell stack for space station propulsion is 193 lbs or 20% of the naval version. The volume is reduced 70% from the naval stack.

The demonstrator is designed to produce 2 pph normal rate/4 pph emergency rate of propellant (i.e., oxygen and hydrogen) gas at 3000 psia, 120°F at an efficiency of greater than 70%. Performance is shown in Figure 14 for conditions of 3,100 psia and 120°F. This performance was established at the factory prior to delivery to NASA/JSC in 1990.

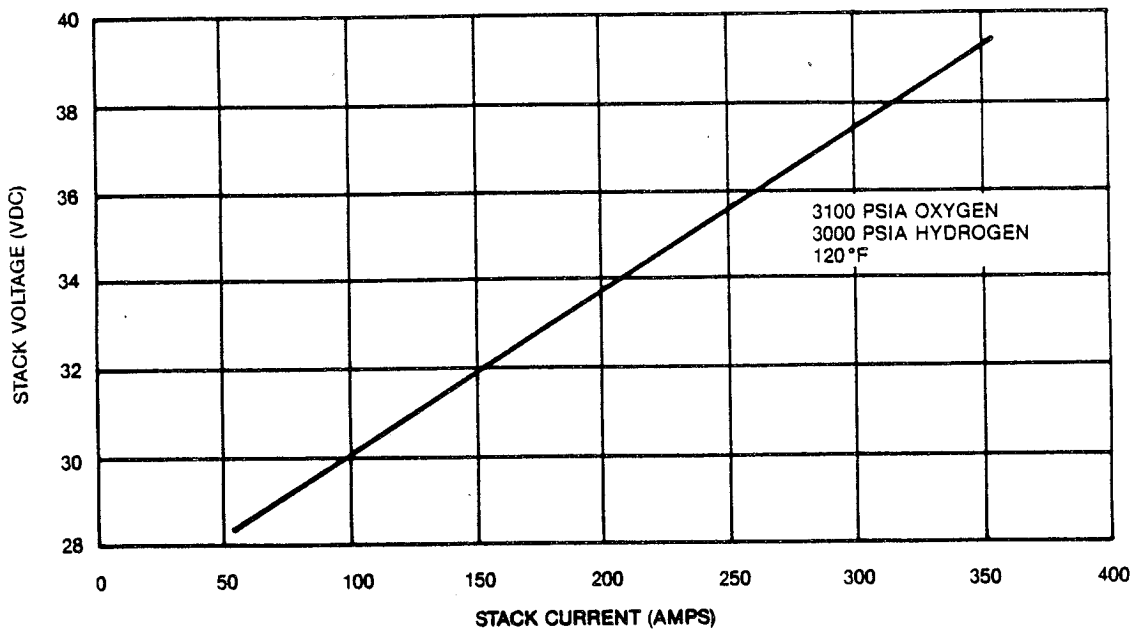
This demonstrator has been set up and operated intermittently at NASA/JSC over the last two years having accumulated over 850 hours of operation at 3000 psia. NASA personnel have expressed a high degree of satisfaction with the demonstrator performance.



**FIGURE 12. SPE PROPELLANT GENERATOR, DOMES REMOVED**



**FIGURE 13. ASSEMBLED SPE PROPELLANT GENERATOR**



**FIGURE 14. SPE PROPELLANT GENERATOR PERFORMANCE (STACK VOLTS VS. AMPS)**



## Energy Storage

Recent stationary power system studies have shown that, short of nuclear power, solar energy combined with an oxygen-hydrogen regenerative fuel cell is a mission enabling and preferred technology for Lunar and Mars bases [4]. Figure 16 displays the relative mass of three leading candidates for electrical energy storage as presented by NASA Lewis Research Center. The long occult periods for the lunar outpost, 14 days, make the separation of power and energy in the oxygen-hydrogen regenerative fuel cell decisive. In Figure 17, showing an overall power plant schematic, energy storage mass is related to the tankage and stored fluids whereas the power rating mass is related to the modules and thermal management. The electrolysis and fuel cell modules can be of either the alkaline or acid type; however, the acid SPE water electrolyzer, of the Naval 0.23 ft<sup>2</sup> configuration in particular, has demonstrated the life, stability, reliability required of a lunar outpost energy storage system.

The schematic for 3000 psi SPE water electrolysis is much the same as the low pressure schematic except that the electrolyzer module is enclosed in the nitrogen filled pressure vessel. Figure 18 displays the overall SPE water electrolyzer efficiency at various temperatures. The 1000 amps per square foot (ASF) current density, which is below the Naval design point of 1300 ASF, will provide an efficiency in excess of 70% at the 20,000 hour end-of-mission point.

A fuel cell operating at 70% overall fuel cell efficiency will require approximately 21.6 pounds per hour of hydrogen-oxygen reactants in a 1 to 8 weight ratio to produce 25 kW direct current. If one assumes an equal charge discharge time for the lunar outpost application, the electrolyzer will have to convert a maximum of 21.6 pound per hour of water into hydrogen and oxygen. The mass of the SPE water electrolyzer subsystem with 138 cells would be about 200 kg using the proven cell structure with DuPont's Nafion® 120 ion exchange membrane. Figure 19 shows that a decreased mass can be obtained by the use of higher performance membranes and/or advanced cell structures. However, the low mass is gained at the expense of design maturity.

A single SPE water electrolyzer subsystem would probably not be considered because of reliability aspects. Over a five-year period, the loss of a pump or gas regulator is predicted. These difficulties can be overcome by redundancy within the subsystem at a small weight penalty. Reliability is further enhanced by having multiple SPE water electrolyzer subsystems. Preliminary estimates show that three subsystems, each with selected component redundancies, would be highly reliable for a multiple year mission.

A second lunar outpost energy storage application for the SPE water electrolyzer involves mobile power. A payload unloader, a mining excavator/loader and a regolith hauler have all been identified as potential applications for the oxygen-hydrogen regenerative fuel cell (see Figure 20). Two basic charging approaches have the water electrolyzer subsystems located either at a central fixed refueling station, or on-board the individual vehicles.



TECHNOLOGY IMPACTS  
25kW SURFACE POWER SYSTEM

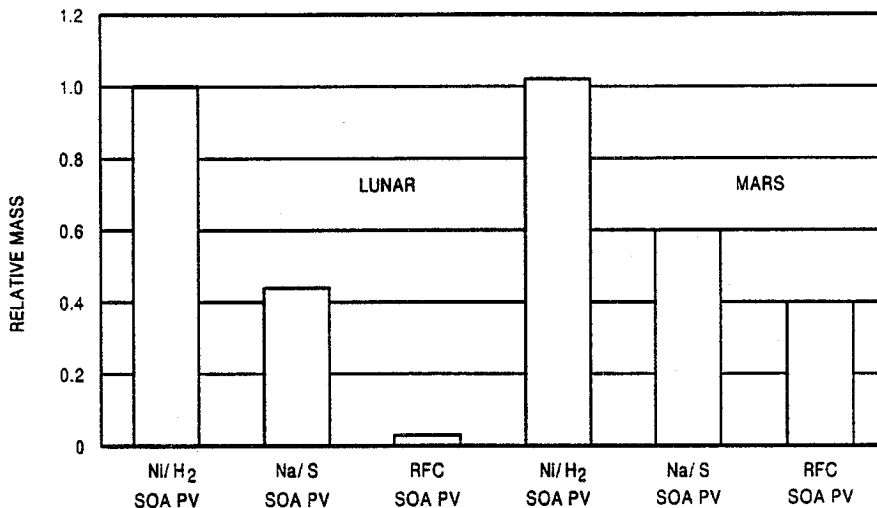


FIGURE 16. RELATIVE MASS OF ENERGY STORAGE TECHNOLOGIES

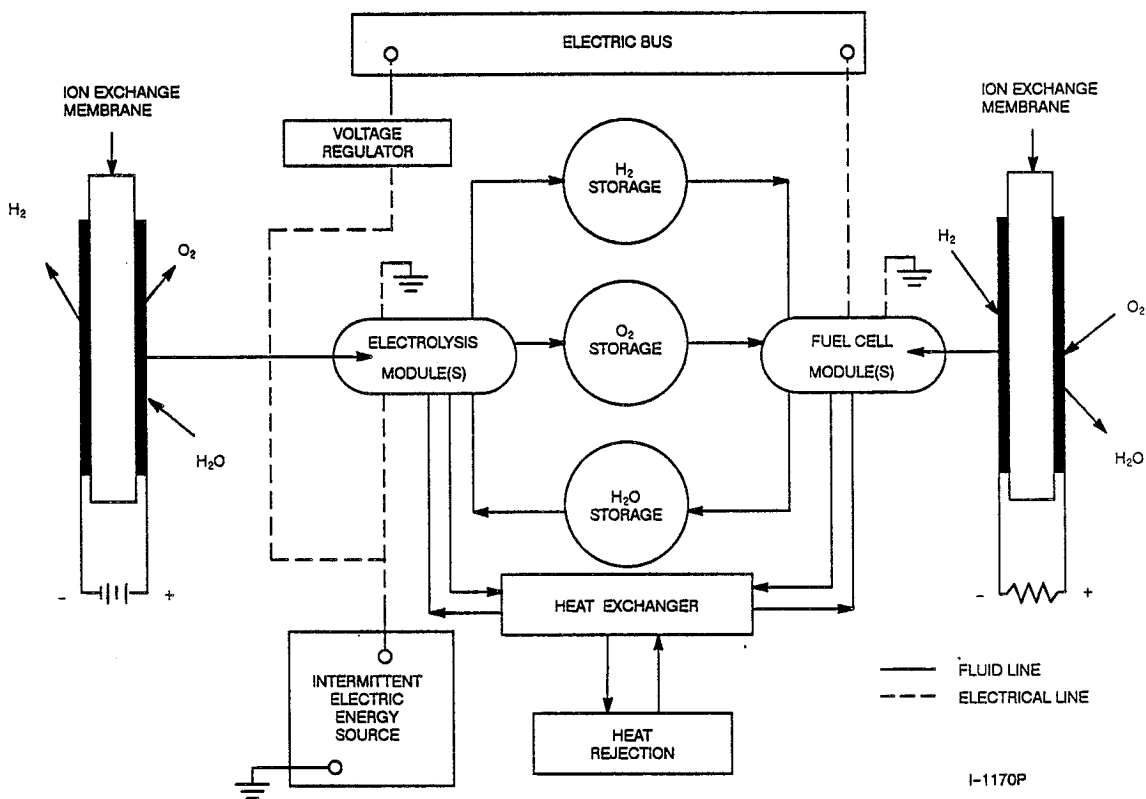
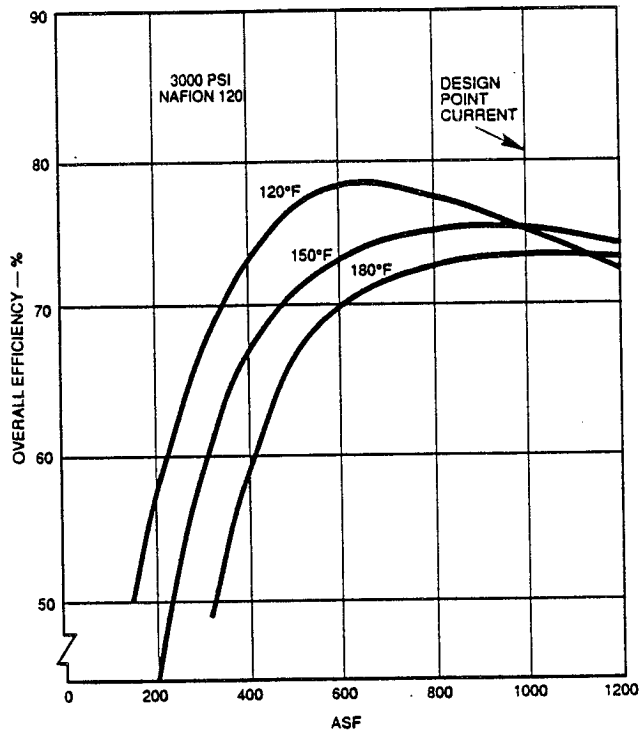


FIGURE 17. POWER PLANT FUEL SCHEMATIC INCLUDING HYDROGEN/OXYGEN  
REGENERATIVE FUEL CELL ENERGY STORAGE SYSTEM



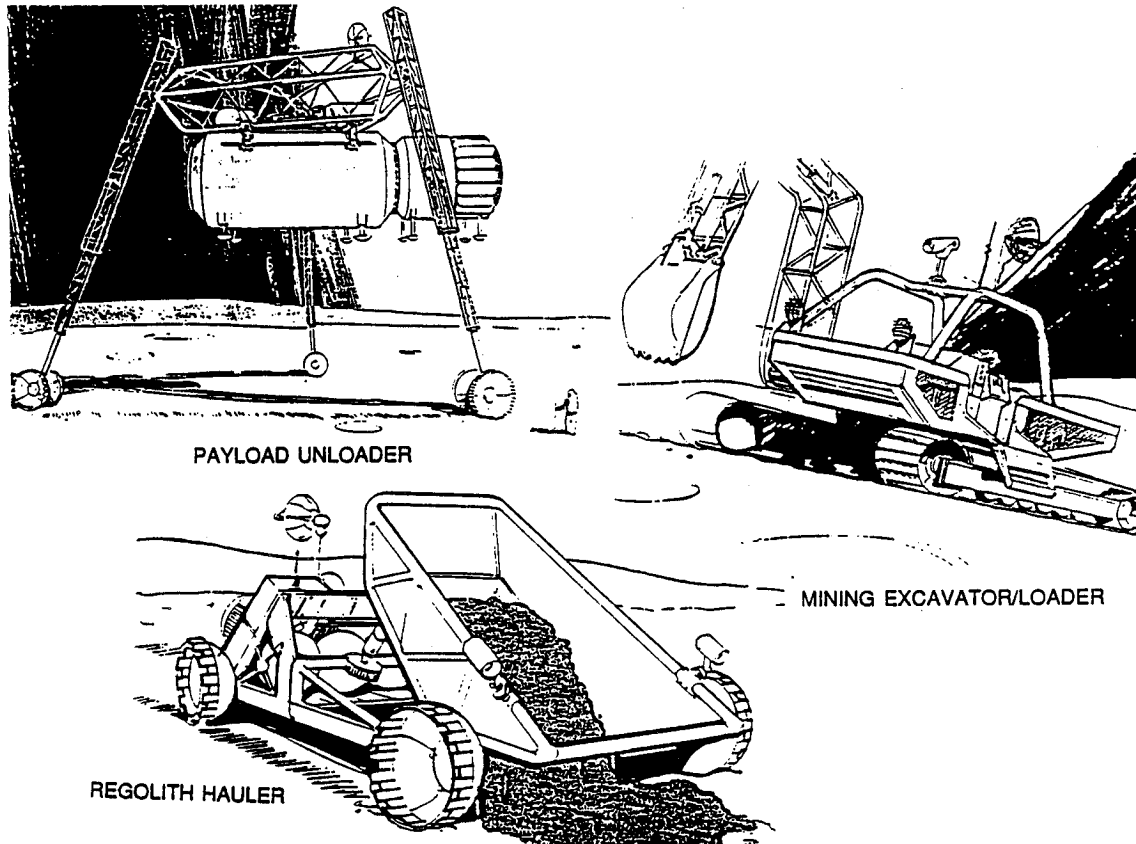
**FIGURE 18. OVERALL SPE WATER ELECTROLYZER EFFICIENCY AT 3000 PSI**

ELECTROLYZER SUBSYSTEM DESCRIPTION	NAFION 120 MEMBRANE		NAFION 125/117 MEMBRANE		ADVANCED MEMBRANE	
	LBS	KG	LBS	KG	LBS	KG
"STATE OF THE ART" WITH STATIC SEPARATORS	439	200	363	165	324	147
ADVANCED DESIGN WITH STATIC SEPARATORS	347	158	316	144	301	137

- BASED ON:
- 21.6 HR IF WATER ELECTROLYZED
  - 70% THERMAL EFFICIENCY FOR 20,000 HRS
  - 3,000 PSIA GAS GENERATION PRESSURE
  - THERMAL VACUUM COMPATIBLE
  - EQUAL CHARGE/DISCHARGE TIMES

- NOTES:
- ONLY NAFION 120 HAS THE PEDIGREE
  - ADVANCED DESIGN NEEDS DEVELOPMENT VERIFICATION

**FIGURE 19. SPE WATER ELECTROLYZER SUBSYSTEM MASS SUMMARY FOR 25 KW SYSTEM**



**FIGURE 20. POTENTIAL ENERGY STORAGE APPLICATIONS FOR SPE WATER ELECTROLYZERS**

The central fixed refueling station approach would have a large electrolyzer subsystem continuously electrolyzing water during the lunar day. Each vehicle would be refueled by connecting up to the fixed hydrogen and oxygen storage and performing a pressure transfer of the gases. Simultaneously, the product water from the prior mission would be pumped from the vehicle back to the central station to be re-electrolyzed.

With an electrolyzer on board each vehicle, the refueling is accomplished by connecting the vehicle to the electrical grid and reforming hydrogen and oxygen from the on-board product water. The majority of this recharging would also be performed during the lunar day when the direct solar photovoltaic energy is available.

Each of the two approaches have significant advantages over the other. However, two advantages, one for each approach, appear to be overriding:

- Major refueling station advantage - this approach allows a rapid recharge of each vehicle.
- Major on-board electrolyzer advantage - this approach has a closed fluid system with only an electrical hook-up required.

The SPE water electrolyzer could be easily sized for either approach. However, from a system viewpoint, the automatic making and breaking of fluid connections in a dusty environment is judged to be very troublesome. For this reason, many analysts believe that the on-board electrolyzer is the right choice.

### **Indigenous Gas Production**

Many approaches have been suggested for the recovery of valuable gases from indigenous lunar materials. These gases include oxygen, hydrogen, carbon dioxide and nitrogen. The source of the oxygen would be the chemical compounds within the lunar soils and rocks whereas hydrogen, carbon dioxide, and nitrogen would be solar wind-implanted in the lunar soil.

In several of the chemical processes proposed to garner oxygen from the lunar soil an intermediate product is water. This water is split into hydrogen and oxygen; the product oxygen gas is delivered to storage; and the hydrogen gas is returned for reuse in the chemical process. The SPE water electrolyzer would be a viable candidate for many of these processes.

The principles of the SPE electrolyzer can have additional, not so obvious, application in the recovery of valuable gases. For example, a process could produce a mixture of hydrogen, carbon dioxide and nitrogen by operating on the solar wind-implanted species. An SPE hybrid cell, part water electrolyzer and part fuel cell, could operate on the mixture to electrochemically produce purified hydrogen. The principles behind the SPE hydrogen separator hybrid cell is displayed on Figure 21.

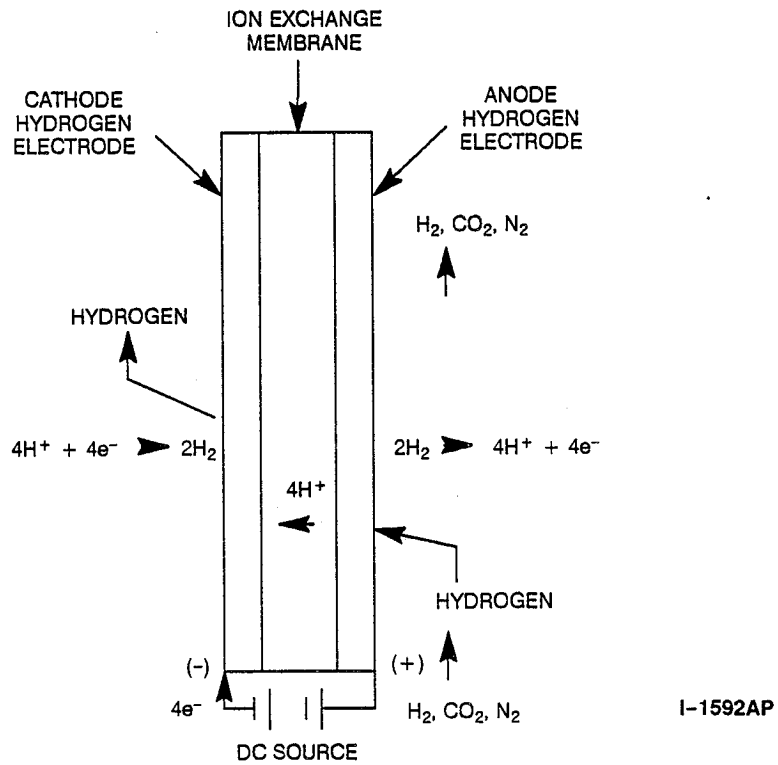
The electrochemical separation of hydrogen from other gases has been demonstrated using a feed stock of hydrogen and nitrogen. In addition to separating the hydrogen from a mixture, the same SPE hybrid cell can electrochemically compress the separated hydrogen. In a similar manner, oxygen gas can be separated electrochemically from a mixture and be compressed by means of an SPE hybrid cell. The SPE oxygen separator/compressor principles are shown on Figure 22.

### **SUMMARY**

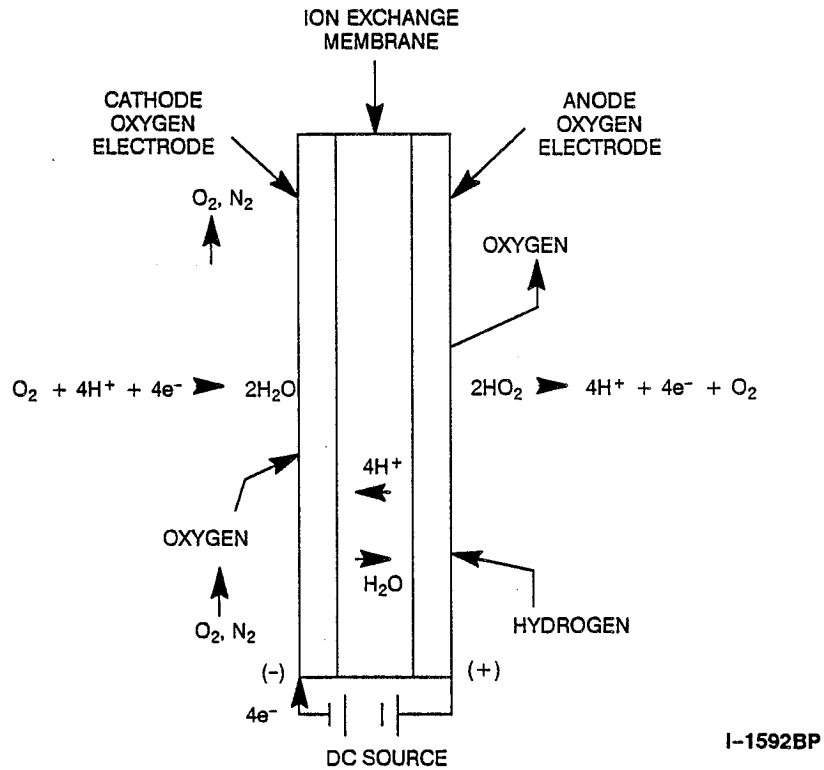
Although the Lunar Outpost is still in the early planning stage, several unique and potentially enabling uses of the SPE water electrolyzer have been identified. The maturity of the SPE water electrolyzer cells gained from the Naval applications should give mission planners the confidence to take advantage of the leveraging effects of the SPE cell technology. Although the inherent capabilities of this technology have been proven, significant development effort remains to package these cells for the Lunar Outpost applications.

### **REFERENCES**

- [1]: NASA/JSC Internal Note Document No. JSC-22044, dated 04/28/86
- [2]: NASA/JSC Internal Note Document No. JSC-22632, dated 09/30/87
- [3]: NASA/JSC Internal Note Document No. JSC-24411, dated 07/25/90
- [4]: NASA Conference Publication 3016; September 12-13, 1988, p. 206



**FIGURE 21. PRINCIPLES OF THE SPE HYDROGEN SEPARATOR/COMPRESSOR**



**FIGURE 22. PRINCIPLES OF THE SPE OXYGEN SEPARATOR/COMPRESSOR**

