# SPE® water electrolyzers in support of Mission from Planet Earth*

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## Abstract

Although the Mission from Planet Earth 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 Mission from Planet Earth applications.

## Introduction

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 3000 psia and at current densities in excess of 1000 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 demonstrators 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 propellant production

In the 1990s, the emphasis will be the development of SPE water electrolyzers for Mission from Planet Earth. Currently defined potential applications for the SPE water electrolyzer include:

- SPE water electrolyzers operating at high pressure as part of a regenerative fuel cell extraterrestrial surface energy storage system
- SPE water electrolyzers for propellant production from extraterrestrial indigenous materials

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0378-7753/91/$3.50 

- SPE water electrolyzers for metabolic oxygen and potable water production from reclaimed water

## 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.

The introduction of the perfluorocarbon cation exchange membrane in the late 1960s 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 12 years and projected to over 30 years depending on operating conditions. Figure 2 shows the longest lifetime SPE water electrolyzer cell at its 100 000 h milestone in 1989. This cell and two

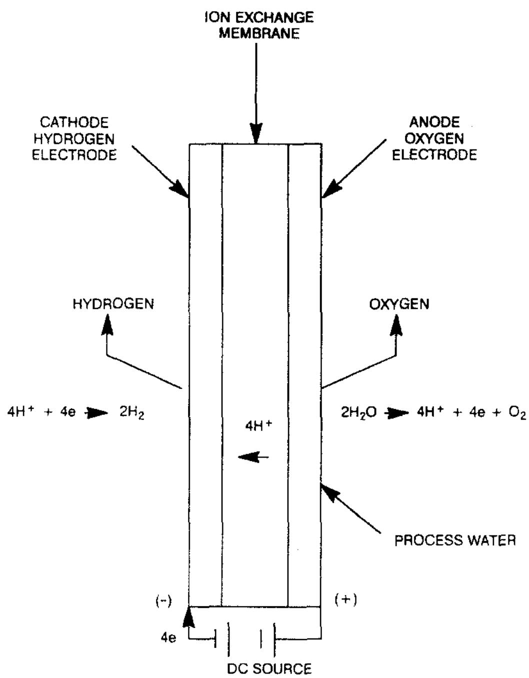



Fig. 1. SPE water electrolyzer reactions.

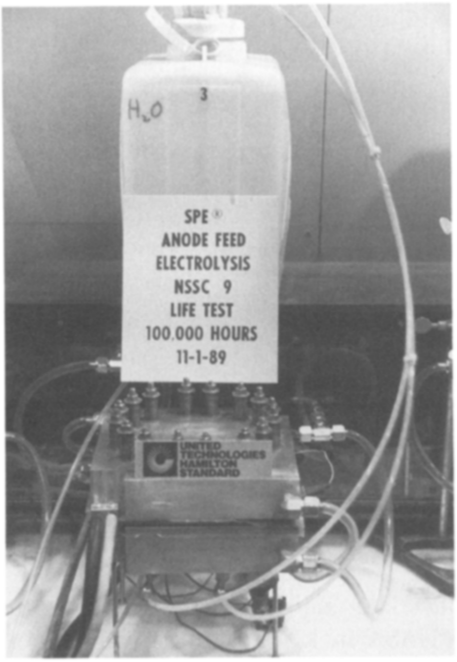



Fig. 2. SPE electrolyzer life test.

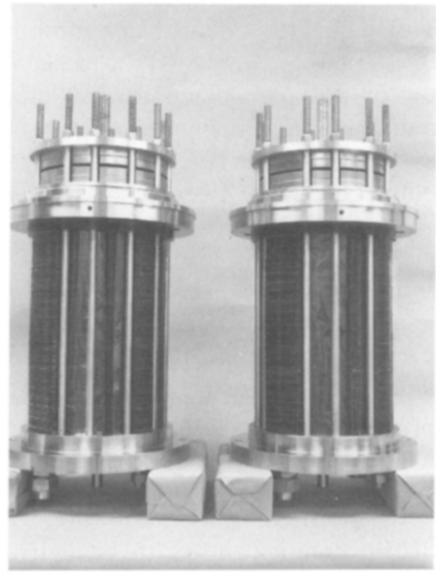


Fig. 3. SPE water electrolyzer modules.

others have now accumulated in excess of 100 000 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 a many as 100 or more cells electrically connected in series while the fluids are passed through the cells in parallel. Figure 3 shows 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%.

## Nuclear submarine oxygen generators

Both the U.S. Navy and the 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 30 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, U.K. The modules shown in Fig. 3 are the type used in the

U.K. Royal Navy system. The operational experience of the SPE water electrolyzer has been exceptional with over 41 000 operational system hours without a single malfunction. The longest operational service for any single 150 psia SPE electrolyzer module is 8539 h as of Dec. 31, 1990.

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. During the course of developing the two Naval oxygen generation systems and the subsequent operation in the U.K. Royal Navy, over 8 million cell hours have been accumulated on the basic 0.23 $ft^2$ cell design.

## 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 $ft^2$ 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.

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

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 1630 simulated low earth orbit charge/discharge cycles [1]. Including the pre-delivery factory cycles, over 2000 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. The most recent activity with the SPE water electrolyzer subsystem was to replace two random cells of the 22 cell SPE water electrolyzer module with high performance cells using a membrane manufactured by Dow Chemical. Following the factory modifications, the SPE water electrolyzer module with 20 standard 0.23 $ft^2$ cells and the two high performance 0.23 $ft^2$ cells underwent parametric testing at NASA/JCS [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 Fig. 4 are typical of the improvement.

*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 $ft^2$ SPE cell configuration used on the Navy programs. Figure 5 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 Navy experience. 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.

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

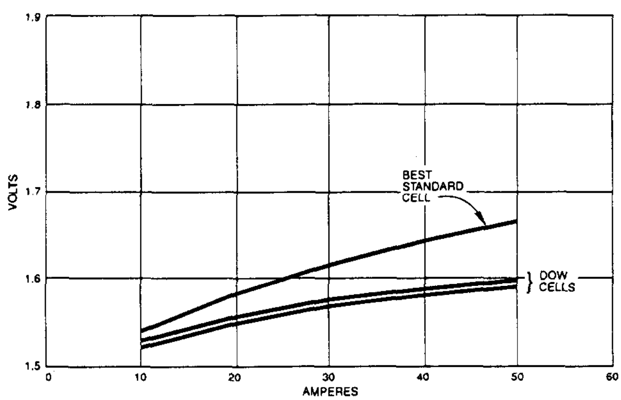
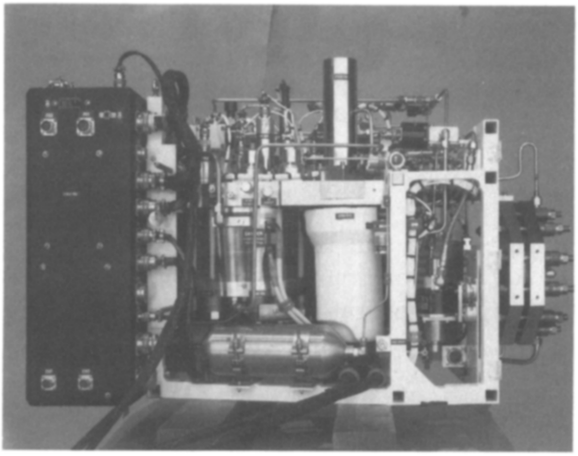
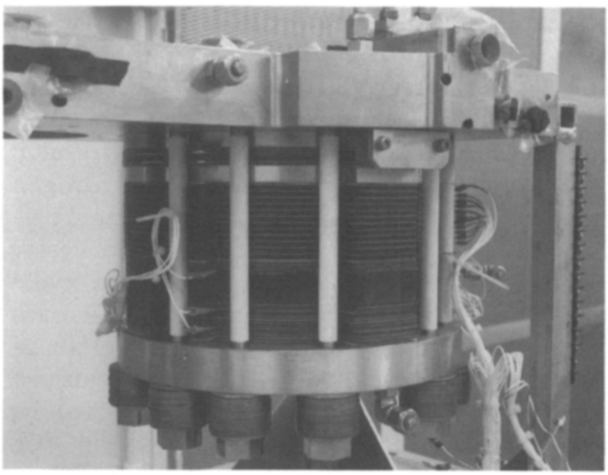


Fig. 4. Comparison of cells at 150 psi and 105 °F.



(a)



(b)

Fig. 5. Oxygen generator assembly technology demonstrator for the Space Station. (a) Oxygen generator assembly; (b) SPE electrolyzer module.

static phase separators to replace the pressure vessel phase separators. This arrangement is shown in Fig. 6. Three basic types of membranes* are used in the construction of the membrane phase separators.

- Hydrophilic 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. The chosen material for the Boeing technology demonstrator is Supor®, having a bubble pressure of approximately 25 psi differential.

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*Supor® is a registered trademark of Gelman Sciences, Inc. Gore-Tex® is a registered trademark of W.L. Gore & Associates, Inc. Nafion® is a registered trademark of E.I. DuPont DeNemours & Co.

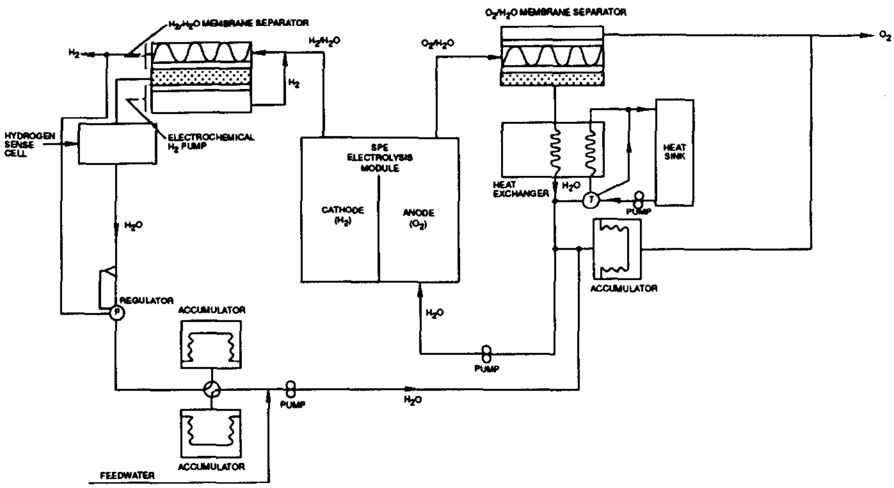


Fig. 6. Simplified microgravity fluid schematic (SPE electrolyzer system).

- 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. The chosen material for the Boeing technology demonstrator is Gore-Tex®, having a water intrusion pressure of approximately 75 psi differential.
- Ion exchange membrane. Nafion® membrane with attached electrodes is a very efficient hydrogen compressor. With an applied voltage of between 0.5 and 1.0 V, 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 h, exceeded the test objective of 450 h. 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. The electrical performance of the technology demonstrator is shown in Fig. 7. Continuing tests and evaluations are in process to improve the SPE cell voltage performance on processed hygiene water.

*SPE propellant generator*

Under contract to NASA/JSC, a 3000 psi hydrogen–oxygen generator based on the Naval 0.23 $ft^2$ SPE water electrolyzer cell configuration was designed and delivered. The purpose was to demonstrate the feasibility of producing 3000 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

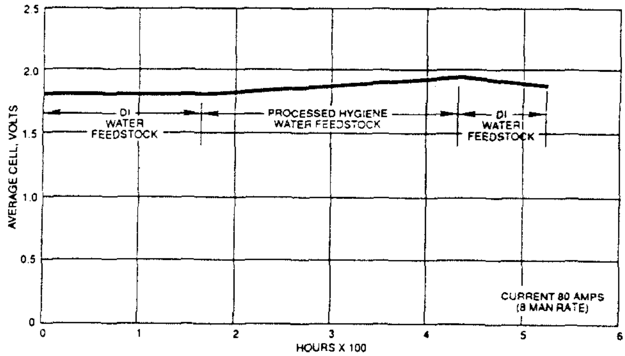


Fig. 7. SPE electrolyzer technology demonstrator performance.

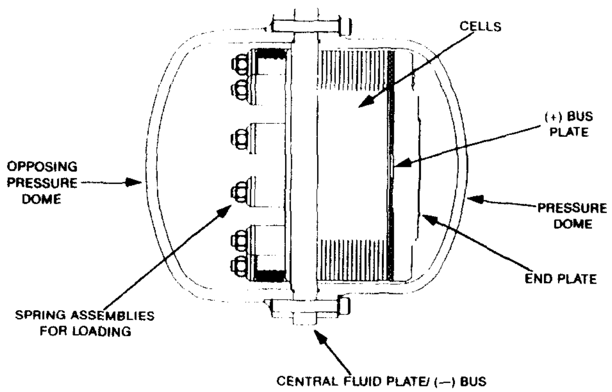


Fig. 8. Cross section, SPE propellant generator demonstrator.

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 Fig. 8. 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.

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 dimensions of the SPE propellant generator demonstrator are 13 in. across the domes and 13 in. 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 pounds per hour normal rate/4 pounds per hour 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 Fig. 9 for conditions of 3100 psia, 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 few months. NSA personnel have expressed a high degree of satisfaction with the current performance.

## For the Mission from Planet Earth applications

The technology maturity gained from the 8 million cell hours of operation of the 0.23 $ft^2$ hardware, combined with the experience obtained from the Space Station Freedom demonstrators has placed the SPE water electrolyzer in position to support Mission from Planet Earth. Three potential applications for the SPE water electrolyzer are described in the following sections:

*Extraterrestrial surface energy storage*

Recent studies have shown that, short of nuclear power, solar energy combined with an oxygen–hydrogen regenerative fuel cell is a mission enabling

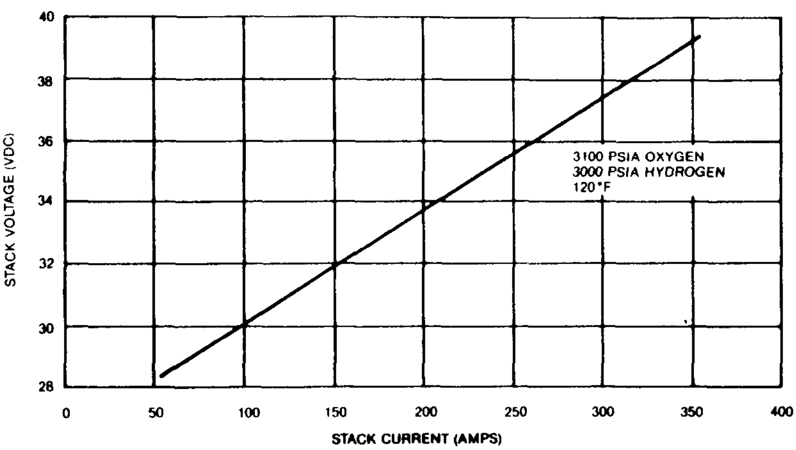


Fig. 9. SPE propellant generator performance (stack V vs. A).

and preferred technology for Lunar and Mars bases [4]. Figure 10 shows the relative mass of three leading candidates for electrical energy storage as presented by NASA Lewis Research Center. The long occult periods, 14 days and 12 h, respectively, make the separation of power and energy in the oxygen–hydrogen regenerative fuel cell decisive. In Fig. 11, 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,

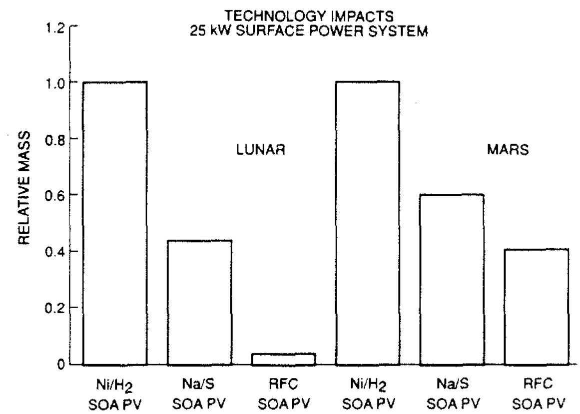


Fig. 10. Relative mass of energy storage technologies.

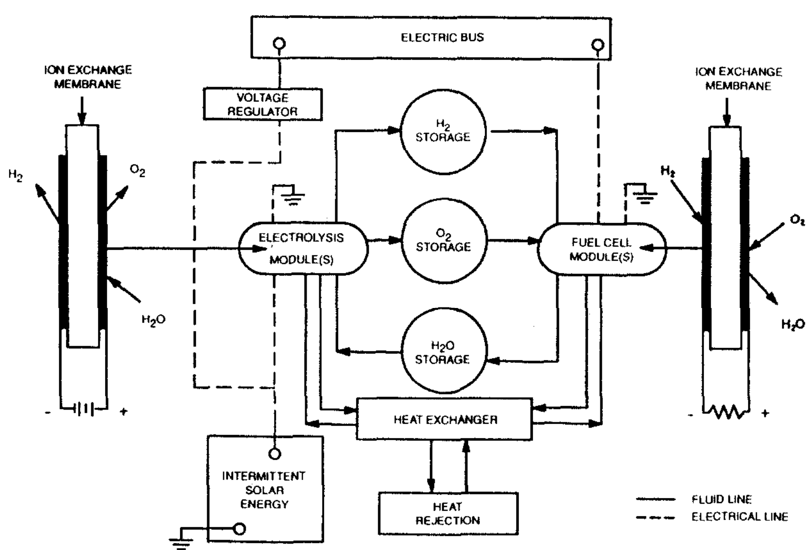


Fig. 11. Power plant schematic including hydrogen/oxygen regenerative fuel cell energy storage system.

of the Naval 0.23 ft$^2$ configuration in particular, has demonstrated the life, stability, reliability and high pressure capability required of an extraterrestrial surface 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 12 shows 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 equal charge and discharge times for either the Lunar or Mars application, the electrolyzer will have to convert a maximum of 21.6 pounds 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 13 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.

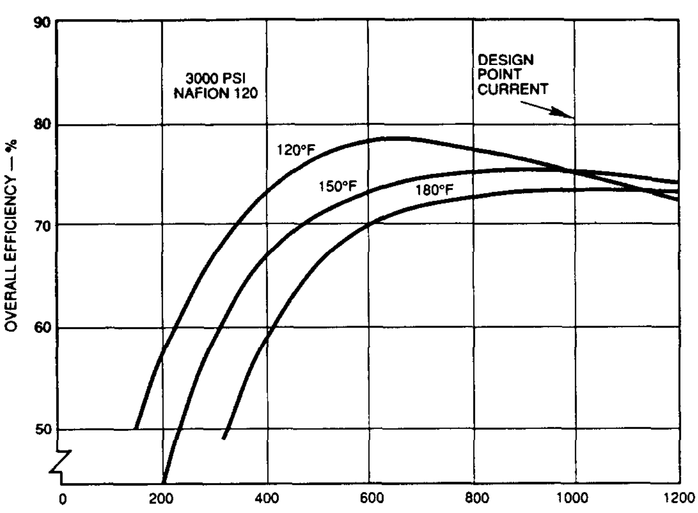


Fig. 12. Overall SPE water electrolyzer efficiency at 3000 psi.

| 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 of water electrolyzed
- 70% thermal efficiency for 20,000 hours
- 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

Fig. 13. SPE water electrolyzer subsystem mass summary for 25 kW system.

Preliminary estimates show that 3 subsystems, each with selected component redundancies, would be highly reliable for a multiple year mission.

*Propellant production*

In any round trip to Mars, the propellant for the return trip is a most significant mass factor when the propellant is brought from Earth. For manned missions to Mars, multiple launches with Earth orbital vehicle assembly will be required in mission architectures which bring the return propellant to Mars from Earth. By contrast, the use of *in situ* propellant production can greatly reduce mission mass and, together with a heavy lift launch vehicle, can eliminate the need for on-orbit assembly.

A system which combines an SPE water electrolyzer with Sabatier and carbon formation reactors can produce methane and oxygen from carbon dioxide in the Martian atmosphere and hydrogen delivered from Earth [5]. This arrangement can increase the Earth return propulsive reactant mass leverage by up to 18 fold. Each of the required subsystems has demonstrated individually with high confidence that they can be combined to produce the desired results.

A top level schematic with subsystem reactions is shown in Fig. 14. In this mission architecture, liquid hydrogen is transported from the Earth directly to the Martian surface. This hydrogen is reacted with atmospheric carbon dioxide to produce methane and water in the exothermic Sabatier reactor. The water is delivered to the SPE water electrolyzer and the methane is liquified and stored. Hydrogen and oxygen are produced within the SPE water electrolyzer with the oxygen being liquified and stored and the hydrogen returned to the Sabatier for the formation of more methane and water. With these two subsystems alone, a 12 to 1 propellant mass leverage is obtained.

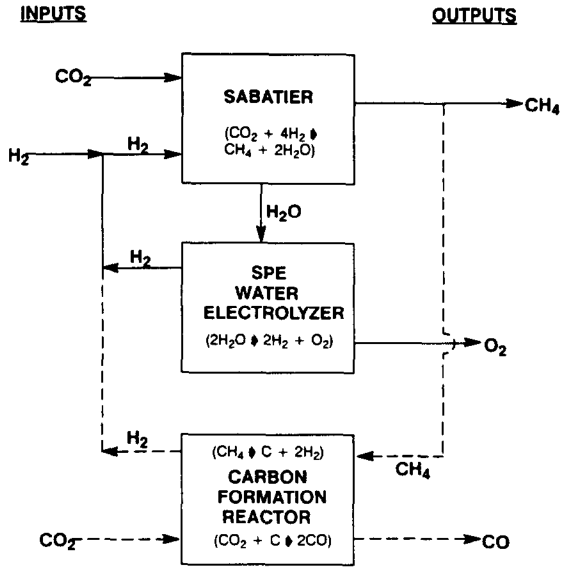


Fig. 14. Top level schematic of Martian fuel and oxygen generator.

The combined Sabatier and SPE water electrolyzer produce the oxygen and methane at a 2 to 1 mass ratio. Burning this mixture provides a specific impulse of about 340 S at a nozzle expansion ratio of 100. However, an optimum oxygen to methane combustion mixture ratio is about 3.5 to 1. This mixture would provide a specific impulse of 353 S. To obtain the 3.5 to 1 ratio, which increases the propellant to hydrogen mass leveraging to 18 to 1, additional oxygen must be obtained. The carbon formation reactor provides this opportunity.

Referring back to Fig. 14, a portion of the methane produced in the Sabatier is borrowed and delivered to the carbon formation reactor. In the reactor, the methane is endothermically converted to solid carbon and hydrogen. The hydrogen is returned to the Sabatier/SPE water electrolyzer combination to replace the borrowed methane and produce the additional oxygen. By continuing this process, any desired level of excess oxygen can be produced. However, the 36 extra tonnes of excess oxygen needed for a manned mission would require a huge carbon formation reactor to hold all the solid carbon produced. This difficulty is overcome by having two carbon formation reactors which alternately cycle between carbon formation and an endothermic regeneration reaction with carbon dioxide.

Preliminary mass estimates for the required subsystems have been made for a Mars Sample Return Mission and a Mars Manned Mission. Table 1 provides these estimates. Since the subsystems, once on the Martian surface, will have to produce propellants for up to one year, a degree of redundancy is required. The mass estimates assume two complete units each with 100% mission capacity for the system used in the Mars Sample Return Mission

TABLE 1

Mass estimates for $CH_4/O_2$ plant

| Reactor | Mars sample return | Manned Mars |
|---|---|---|
| Sabatier (kg) | 36 | 164 |
| Electrolysis (kg) | 90 | 477 |
| Carbon reactor (kg) | 105 | 450 |
| Total (kg) | 231 | 1091 |
| Propellant generation requirement (kg/day) | 3.6 | 360 |
| Capability (kg/day) | 7.2 | 540 |

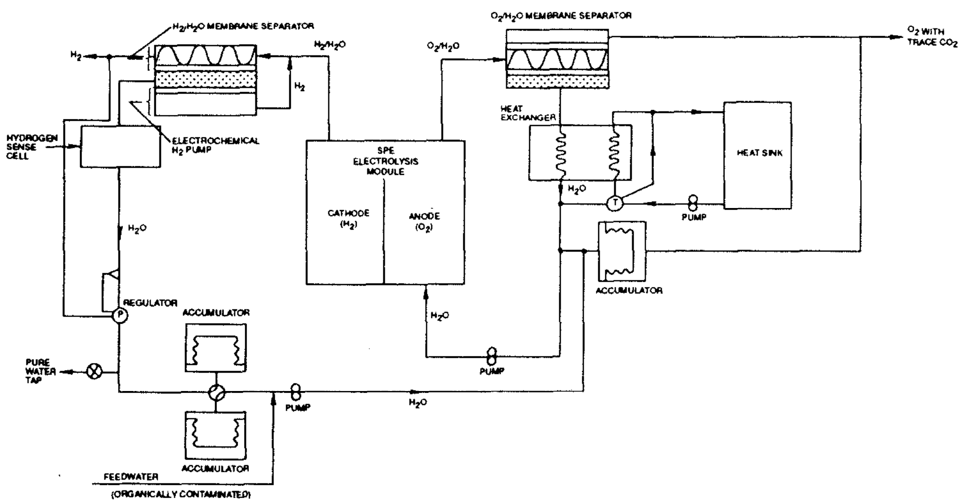


Fig. 15. Metabolic oxygen/potable water generator.

and three units each with 50% capacity for the system employed on the manned Mars mission.

*Metabolic oxygen and potable water production*

The production of metabolic oxygen for space applications has been under investigation for a number of years. Recently, water feedstock with various organic contaminants has been tested with the SPE water electrolyzer to assess the impact on the voltage stability. In these tests, the contaminated water feedstock has been introduced into the oxygen anode chamber in the same fashion as the Naval SPE water electrolyzers. As discussed earlier, continuing tests and evaluations are in process to improve the SPE cell voltage performance on water feedstock with organic contaminants.

Test conducted on the quality of the water at various points in the system indicated that organic species were being oxidized within the oxygen chamber and that the proton pumped water was free of any detectable organics. These observations have led to the speculation that the SPE water electrolyzer can be configured to produce potable water as well as metabolic oxygen. Figure 15 shows the metabolic oxygen generator schematic as modified to show delivery of potable water. The rate of protonically pumped water is such that up to eight pounds of potable water can be delivered for each pound of oxygen produced. For manned Lunar and Mars bases and the Lunar and Mars manned transportation vehicles a combined oxygen generator and potable water processor could have significant mass advantages.

## References

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