Journal of Power Sources, *36* (1991) 235–250

Space water electrolysis: space station through advanced missions

Ronald J. Davenport*, **Franz H. Schubert** and **David J. Grigger**
Life Systems, Inc., Cleveland, OH 44122 (U.S.A.)

Abstract

Static feed electrolysis technology has long been recognized as being important in meeting the National Aeronautics and Space Administration's requirements for life support within the Space Station 'Freedom' and future, advanced missions. The static feed electrolysis technology makes it possible to very efficiently generate oxygen to sustain the crew, and hydrogen for the efficient and economical operation of other space systems. More recently, additional applications for the static feed electrolysis technology have been evaluated and tested. This paper summarizes the results of those studies. The applications addressed here are those involving energy storage, propulsion, extravehicular activity and other, specialized applications, such as providing support for experimentation and manufacturing. The environmental control and life support system application is included for comparison.

Introduction

This paper summarizes how static feed electrolyzer (SFE) technology can satisfy the need for oxygen (O_2) and hydrogen (H_2) in the Space Station Freedom and future, advanced missions. These applications are identified in Fig. 1. The efficiency with which the SFE technology can be used to generate O_2 and H_2 is one of its major advantages. In fact, the SFE is baselined for the oxygen generation assembly (OGA) within the Space Station Freedom's environmental control and life support system (ECLSS).

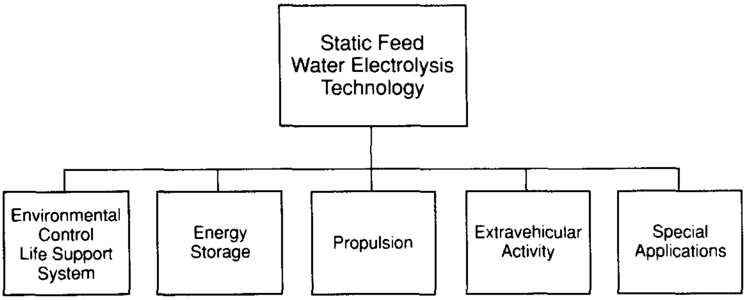

Fig. 1. Major SFE technology development applications.

---

*Author to whom correspondence should be addressed.

0378-7753/91/$3.50

Figure 2 shows the conventional SFE process. An alkaline electrolyte is contained within the matrix and is sandwiched between two porous electrodes. The electrodes and matrix make up a unitized cell core. The electrolyte provides the necessary path for the transport of water and ions between the electrodes, and forms a barrier to the diffusion of O_2 and H_2.

A hydrophobic, microporous membrane permits water vapor to diffuse from the feed water to the cell core. This membrane separates the liquid feed water from the product H_2 and, therefore, avoids direct contact of the electrodes by the feed water. This eliminates the possibility of catalyst poisoning by contaminants in the feed water. The feed water is also circulated through an external heat exchanger to control the temperature of the cell.

Electrical power, when applied to the electrodes, consumes water within the cell core. This increases the difference between the water vapor pressures in the electrolyte in the cell core, and in the liquid in the feed compartment. As a result, water vapor diffuses from the feed water compartment into the cell core. An external water supply tank replenishes water consumed from the feed compartment. The operation and performance of SFE have been previously described in greater detail [1–3].

In a typical SFE subsystem, the electrochemical cells are combined to form an electrolysis module. The cells are arranged electrically in series, but the fluids flow through the cells in parallel. In addition to the module, the other mechanical components within the subsystem consist of the thermal control assembly (TCA), a fluids control assembly (FCA) and a pressure control assembly (PCA).

The TCA supplies a constant flow rate of feed water to the electrochemical module. The temperature of this water is varied to maintain the module at the desired temperature. Temperature control is achieved by proportioning the flow of the feed water between a bypass and a heat exchanger.

The FCA controls and monitors the flow of feed water and purge gas into the SFE subsystem. The PCA maintains the absolute and differential pressures in the subsystem and controls pressurization of the system during startup and shutdown.

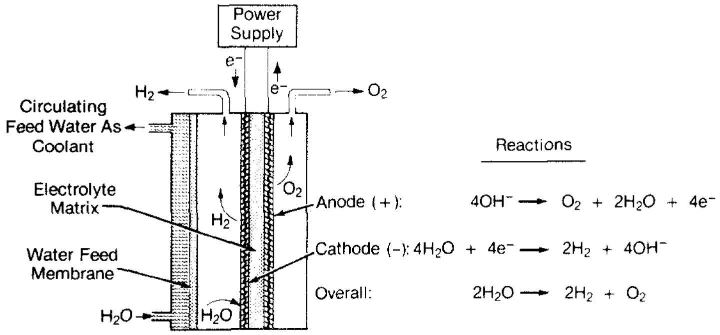

Fig. 2. Conventional static feed electrolysis (SFE) process.

The TCA, FCA and PCA are mechanically integrated assemblies, made up of valves, pumps, pressure regulators and sensors which monitor and control the subsystem. These components were developed and refined by Life Systems as part of SFE subsystem development efforts performed during the last 20 years. The integrated design of these components offers significant savings in volume and weight, compared to the use of discrete components [4]. Equally important, the use of integrated components enhances the maintainability of SFE subsystems [5].

The operation of the SFE subsystem is controlled and monitored by microprocessor-based instrumentation. The instrumentation performs process control, automatic mode transition, fault diagnostics and data acquisition functions.

Applications

This section discusses the application of the SFE technology to the energy storage, ECLSS, propulsion, extravehicular activity (EVA) and other, special applications. Typical O_2 and H_2 production and delivery requirements for some of these applications are listed in Table 1. This Table shows the diversity of the requirements that be accommodated by SFE technology.

This section also addresses future studies that are planned to demonstrate the performance of SFE water electrolyzers under low-*g* conditions.

Energy storage

The energy storage application requires the SFE to provide O_2 and H_2 for use in a regenerative fuel cell subsystem (RFCS) [6]. Electrical power is converted by the SFE into O_2 and H_2, which the fuel cells use later to generate electrical power when there is a power demand.

TABLE 1

Typical application requirements

Application	Gas delivery pressure (kPa) (psia)	O_2 gas production (kg/h) (lb/h)	H_2 gas production (kg/h) (lb/h)
ECLSS[a]	138 (20)	0.17 (0.38)	0.02 (0.04)[b]
Energy storage (regenerative fuel cell)[c]	2172 (315)	18.64 (41.09)	2.35 (5.19)
Propulsion[d]	20685 (3000)	0.81 (1.78)	0.101 (0.22)
EVA O_2 bottle recharge[e]	41370 (6000)	0.11 (0.24)	

[a] Based on four-person crew: metabolic O_2 at 0.83 kg (1.84 lb) O_2/person-day; air lock pressurization at 0.54 kg (1.20 lb) O_2/day; station leakage at 0.24 kg (0.52 lb) O_2/day; O_2 delivery pressure 138 kPa (20 psia); H_2 delivery pressure 172 kPa (25 psia).

[b] Required for CO_2 reduction.

[c] For 75 kW nominal bus power to user.

[d] Nominal rate of 0.91 kg (2.0 lb) water/h.

[e] Nominal rate of 3.0 kg (6.5 lb) water/day.

A process schematic for the SFE in this application is shown in Fig. 3. The O_2 and H_2 product gases are stored in tanks at 2 172 kPa (315 psia), ready to be consumed by the fuel cell. The fuel cell provides feed water to the SFE. An advantage of using SFE in this application is that H_2 from the fuel cell, dissolved in the feed water, is not a problem.

To demonstrate the readiness of SFE technology for this application, endurance tests of SFE single cells and modules were performed [7]. A total test time of 238 616 cell-h were accumulated (Table 2). Part of this testing (160 710 cell-h) was performed in a continuous-operation mode, but an additional 77 906 cell-h were obtained under cyclic operation to simulate the operation of the SFE in orbit. The SFE hardware was operated 54 min with current on, and 36 min with current off.

An integrated breadboard RFCS (Fig. 4) was assembled, using a 2.12 kW Shuttle Orbiter fuel cell power plant (X708) [8]. The SFE contained a 6-cell, 1.0 ft^2 water electrolysis module, which is sized for operation at 3 kW. The SFE in this subsystem was operated for 635 h at Life Systems, including 602 h of cyclic operation. A light cycle time (SFE current on) of 56 min was used, with a dark cycle time (SFE current off) of 36 min. Figure 5 shows the cell voltage performance and the variation of O_2-to-system and H_2-to-system pressure differentials during this cyclic operation.

The projected configuration of an SFE subsystem, sized to produce 3.9 kg (8.5 lb) O_2/h is shown in Fig. 6. The characteristics of this subsystem are summarized in Table 3. Utilization of cells having an active area of 0.09 m^2 (1.0 ft^2) achieves the high production rates required for this application.

Environmental control and life support system (ECLSS)

Extensive development has been performed during the past 20 years to use SFE technology to generate O_2 for life support. The space station ECLSS requires O_2 for the crew, pressurization of the air lock and to replenish external leakage. Hydrogen is required for the efficient operation of other subsystems.

A process schematic of the SFE is shown in Fig. 7. Low pressure water and electricity are used to produce the O_2 and H_2. Feed water is circulated

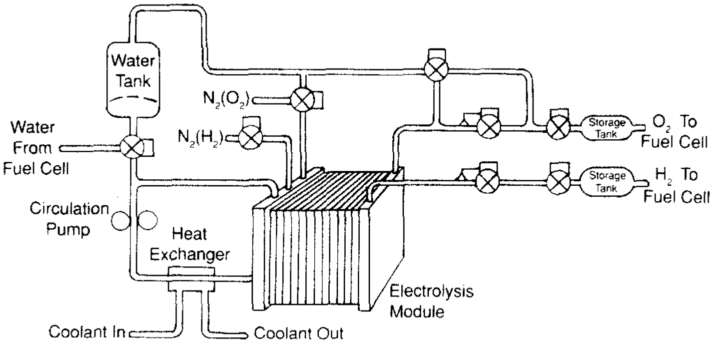

Fig. 3. SFE process schematic for energy storage application.

TABLE 2

Static feed water electrolysis endurance test summary

Cell no.	Electrode type	Total test time (cell-h)	Continuous		Cyclic		Total current 'on' time (cell-h)
			Test time (cell-h)	Current density (mA/cm^2) (ASF)	Test time (cell-h)	Current density (mA/cm^2) (ASF)	
105A	advanced	16856	8578	323.0 (300)			16856
			8278	161.5 (150)			
105B	advanced	45197	6300	161.5 (150)	38897	161.5 (150)	29638
105C	super	46251	11313	323.0 (300)			46251
			34938	161.5 (150)			
105D	super	44269	5260	161.5 (150)	39009	161.5 (150)	28665
127-SWEC	advanced	6900	6900	161.5 (150)			6900
127 Six-cell Module	super unitized core	63936	63936	161.5 (150)			63936
128 Three-cell 0.093 m^2 (1.0 ft^2) module	advanced	2535	2535	21.5–107.6 (20–100)			2535
WS-6 Six-cell 0.093 m^2 (1.0 ft^2) module	advanced	12672	12672				12672
Total		238616	160710		77906		207453

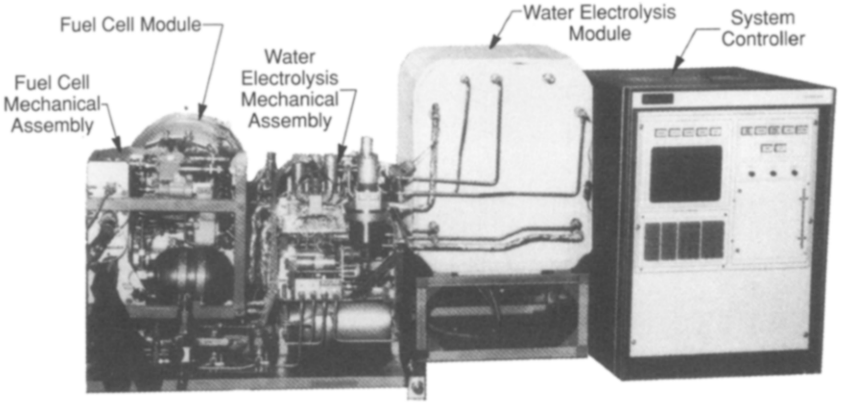

Fig. 4. 3 kW regenerative fuel cell system breadboard.

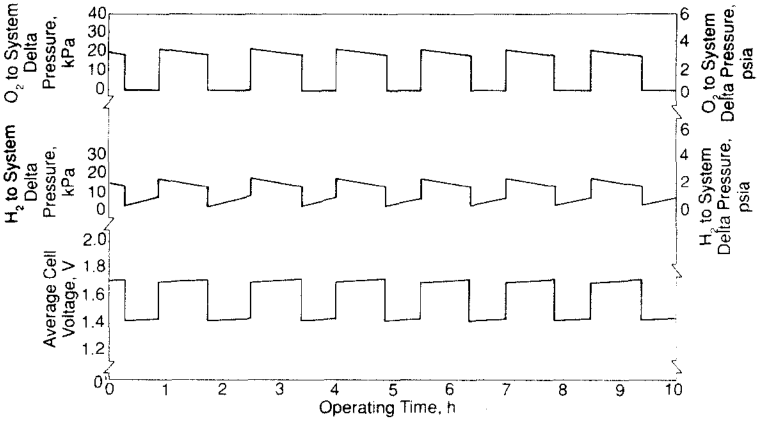

Fig. 5. WES cyclic performance vs. operating time in RFCS normal mode.

through an external heat exchanger in the TCA to control the temperature of the module. During normal operation, coolant is used to remove waste heat produced by the electrolysis reaction, and a small amount of nitrogen (N_2) is used during startup to pressurize the water tank. The dew point of the product gases, after expansion to ambient pressure is within the range of 278–289 K (40–60 °F), so a dryer or condenser/separator is unnecessary for removal of moisture from the product gases.

Technology Demonstration hardware has been produced (Fig. 8) to support the development of the OGA for Space Station Freedom. The Technology Demonstration hardware is being tested at the National Aeronautics and Space Administration (NASA) George C. Marshall Space Flight Center (MSFC) and at Life Systems. One unit is undergoing endurance testing at Life Systems, and on 03/04/91 it surpassed 2500 operating h.

Life Systems also initiated other tests before the Technology Demonstration hardware was available for testing. For example, a module that

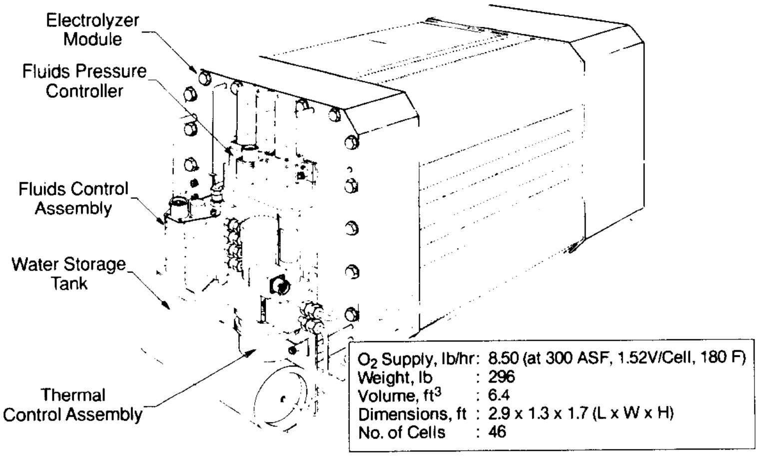

Fig. 6. Conceptual representation of a large production electrolysis subsystem.

TABLE 3

Projected SFE energy storage electrolysis subsystem characteristics for a 91 kW RFCS[a]

Number of cells	107
Oxygen generation, kg/day (lb/day)	112.1 (247)
Current density, mA/cm^2 (ASF)	157 (146)
Cell area, m^2 (ft^2)	0.09 (1.0)
Operating temperature, K (F)	339 (150)
Operating pressure, kPa (psia)	2172 (315)
Subsystem weight, kg (lb)	247 (544)
Subsystem volume[b], m^3 (ft^3)	0.3 (10.6)
Subsystem power[c], kW	22.7

[a] Four units are required, for 75 kW nominal bus power to user.
[b] Includes mechanical and electrical subassemblies (cables excluded).
[c] Nominal level for electrolysis only (excludes ancillary components).

contains cells identical to those to be used in the OGA also has been under endurance test, and more than 10 190 operating hours have been accumulated as of 03/04/91.

Based on this experience and other design data, the OGA is projected to have the characteristics listed in Table 4. The baseline operating level for the OGA is production of O_2 at a four-person rate (plus O_2 to make up for leakage and air lock repressurization) of 4.12 kg/day (9.09 lb/day). By adjusting the current density and operating temperature, the OGA can increase production by 73% to a 45-day emergency level of 7.14 kg/day (15.75 lb/day).

Propulsion

The SFE is currently being evaluated for use in the Space Station Freedom's propulsion system. In this application O_2 and H_2 propellants must be generated at a pressure of 20 680 kPa (3000 psia).

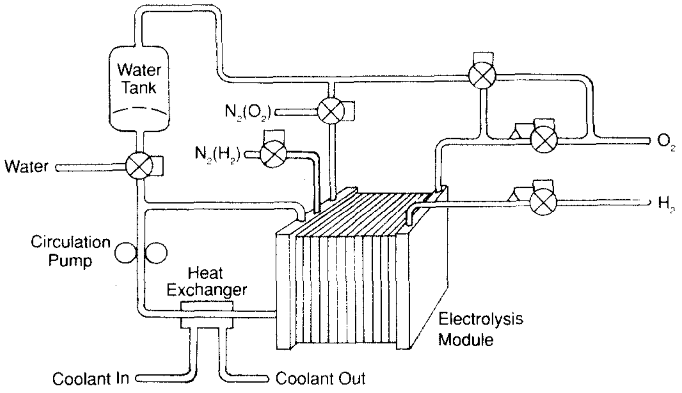

Fig. 7. SFE process schematic for the ECLSS application.

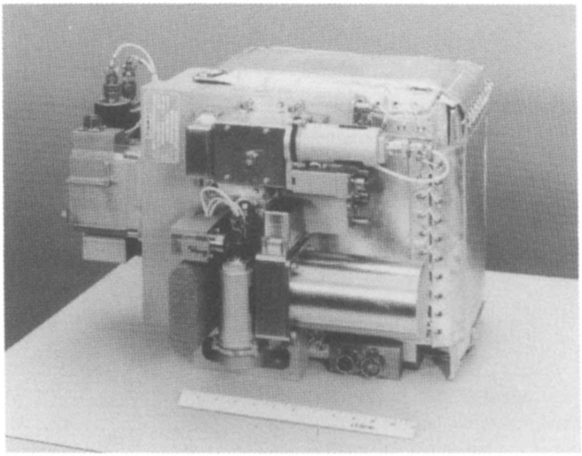

Fig. 8. SFE technology demonstration hardware.

A schematic of the SFE for propulsion is shown in Fig. 9. The module is contained within a pressure containment vessel. Inert fluid within the pressure containment vessel is pressurized with N_2 to the same pressure as the product gases, so the module experiences a minimal internal-to-external pressure differential. A pressure intensifier, external to the pressure containment vessel, pumps low pressure feed water into the water tank to make up for water electrolyzed by the module. The feed water in the pressure vessel is then pressurized by the inert fluid. Because of the low temperatures to be experienced by the propulsion system, the product gases must be dried prior to storage.

The SFE for propulsion is projected to have circular cells with an active area of 0.046 m^2 (0.5 ft^2). The major objective of the current evaluation is to demonstrate the performance of a 15-cell SFE module having cells of

TABLE 4

ECLSS subsystem characteristics

Number of cells	20
Oxygen generation, kg/day (lb/day)	4.12 (9.08)
Current density, mA/cm^2 (ft^2)	124 (115)
Cell area, m^2 (ft^2)	0.023 (0.25)
Operating temperature, K (F)	339 (150)
Operating pressure, kPa (psia)	1241 (180)
Subsystem weight[a], kg (lb)	56.8 (125.0)
Subsystem volume[b], m^3 (ft^3)	0.094 (3.32)
Subsystem power[c], W	876

[a] Design goal. Current weight is 86.6 kg (190.7 lb).

[b] Includes mechanical subassembly (electrical subassembly and cables excluded).

[c] Nominal level electrolysis only (excludes ancillary components).

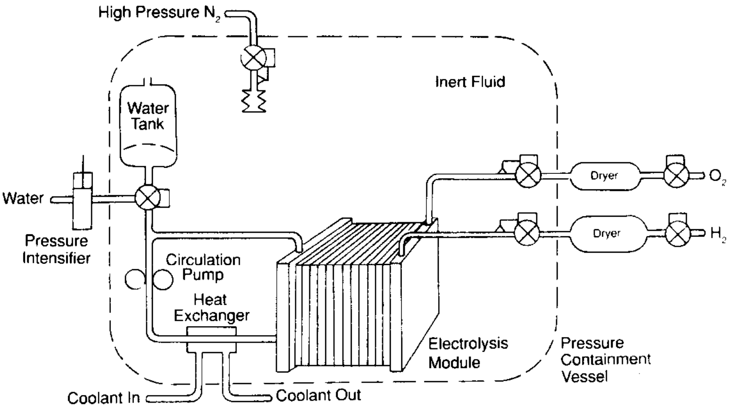

Fig. 9. SFE process schematic for propulsion application.

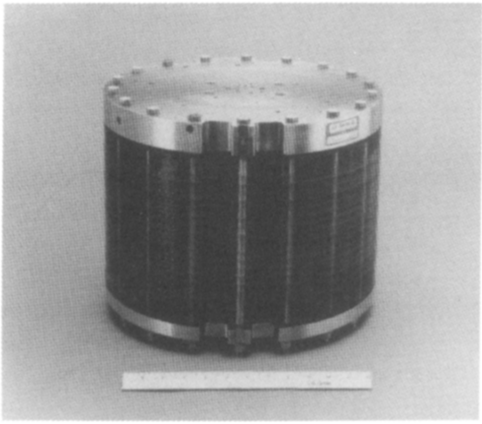

Fig. 10. Preprototype SFE propulsion electrolysis module.

this size (Fig. 10), and operating at 20 680 kPa (3000 psia). The normal operating pressure of previous SFE subsystems is 1241 kPa (180 psia), although one subsystem has operated for nearly 1200 h at 2172 kPa (315 psia) in tests at Life Systems and NASA MSFC. Tests of SFE single cells have been performed at higher pressures. For example, Fig. 11 illustrates the voltage characteristics of one of these cells, operating at ambient temperature and 20 857 kPa (3025 psia). Its performance has been projected to that which would be achieved at a normal operating temperature of 355 K (180° F).

The characteristics projected of a prototype-level SFE for propulsion are listed in Table 5.

Extravehicular activity (EVA)

In the EVA application, production of O_2 at 41 369 kPa (6000 psia) is necessary to recharge the O_2 bottle in the Extravehicular Mobility Unit (EMU).

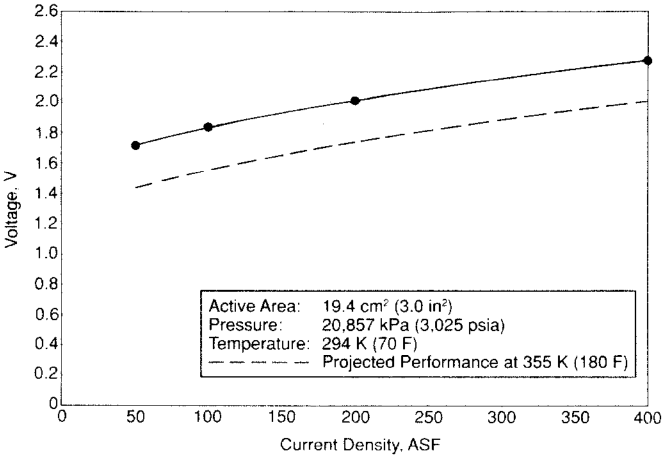

Fig. 11. Performance of 3000 psia circular SFE cell.

TABLE 5

Projected propulsion electrolysis subsystem characteristics

Number of cells	45
Oxygen generation, kg/day (lb/day)	19.4 (42.7)
Current density, mA/cm^2 (ASF)	134 (124)
Cell area, m^2 (ft^2)	0.046 (0.5)
Operating temperature, K (F)	356 (180)
Operating pressure, kPa (psia)	20685 (3000)
Subsystem weight[a, b], kg (lb)	487 (1072)
Subsystem volume[a, b], m^3 (ft^3)	0.26 (9.1)
Subsystem power[c], kW	4.28

[a] Design goal.
[b] Includes mechanical and electrical subassemblies (gas dryers and cables excluded).
[c] Nominal level for electrolysis only (excludes ancillary components).

To achieve this, Life Systems has modified the original SFE concept to incorporate a solid metal cathode (SMC) (Fig. 12). The SMC serves as a solid separator between the O_2 and H_2 compartments, and is capable of safely withstanding very large pressure differentials, with 41 369 kPa (6000 psia) actually demonstrated.

The SMC is constructed of a proprietary alloy which only allows transmission of H_2. As a result, the SMC electrolyzer has the unique ability to simultaneously generate O_2 at 41 369 kPa (6000 psia) and generate ultra-high purity H_2 at low pressure. These characteristics make the SMC SFE ideally suited for use in the EVA application.

Feasibility tests were conducted in a high-pressure electrolysis cell test vessel shown in Fig. 13. These tests indicated that it is possible to simultaneously generate O_2 at 41 369 kPa (6000 psia) and H_2 at ambient pressure with a current efficiency at 93.7%. Life Systems used a proprietary electrode

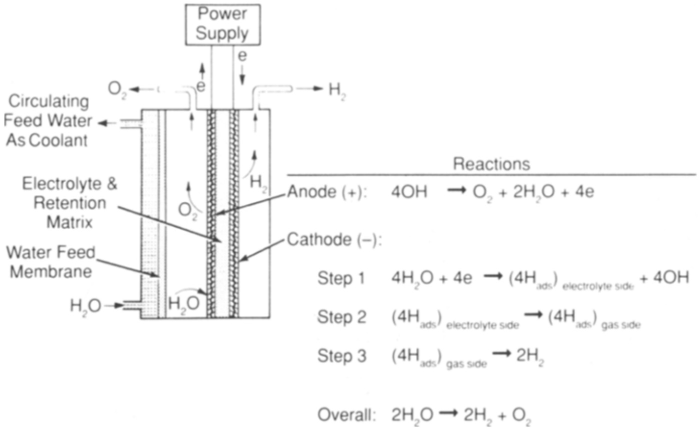

Fig. 12. Modified static feed electrolysis with a solid metal cathode.

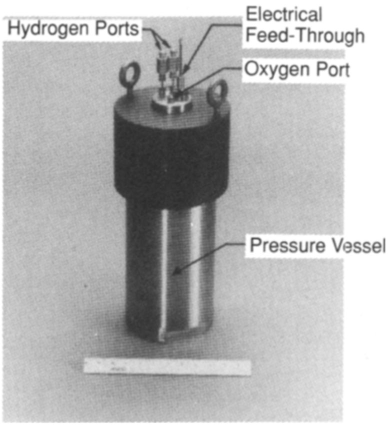

Fig. 13. High-pressure solid metal cathode electrolysis test vessel.

catalyst, which produces a nominal cell voltage of 1.865 V at 358 K (184 °F) at a current density of 47.8 mA/cm^2 (44.4 ASF) (Fig. 14). Subsequent testing at NASA Lyndon B. Johnson Space Center (JSC) has confirmed these results.

A schematic of the SFE for the EVA application is shown in Fig. 15. The schematic is nearly identical to that for the propulsion application, with the exception that the H_2 gas dryer is not required because the H_2 product contains no water. Projected characteristics of the SMC SFE for EVA are listed in Table 6.

The SMC SFE also might be the technology of the future for the energy storage, propulsion and life support applications. It is potentially highly reliable and tolerant of hardware failures downstream of the SFE, since it can withstand the loss of pressure in either the O_2 of H_2 streams without being damaged by the resulting pressure differential, up to at least

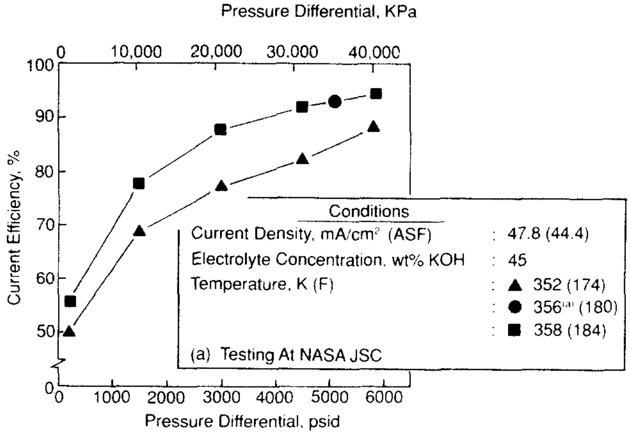

Fig. 14. Current efficiency vs. pressure differential for a high-pressure SMC cell.

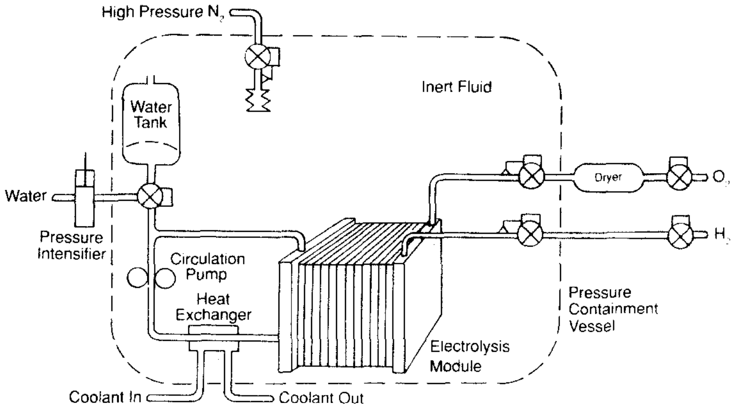

Fig. 15. SFE process schematic for EVA application.

TABLE 6

Projected SMC electrolysis subsystem characteristics for the EVA application

Number of cells	7
Oxygen generation, kg/day (lb/day)	2.6 (5.8)
Current density, mA/cm^2 (ASF)	53.8 (50)
Cell area (cathode), m^2 (ft^2)	0.058 (0.63)
Operating temperature, K (F)	383 (230)
Operating pressure, kPa (psia)	41370 (6000)
Subsystem weight, kg (lb)	272 (600)
Subsystem volume, m^3 (ft^3)	0.078 (2.74)
Subsystem power, W	537

41 369 kPa (6000 psia). More effort is required to assess the SMC SFE for these applications.

Special applications

Future space habitats, such as the Lunar Base, will have all the applications and requirements discussed above. In addition, scientific and manufacturing requirements for O_2 and H_2 that will arise aboard Space Station Freedom are likely to be expanded and diversified within these habitats. The development of new emergency systems (e.g., O_2 for emergency atmosphere repressurization) will probably introduce additional requirements.

These requirements will doubtless necessitate both small-scale and large-scale hardware. The SFE has already demonstrated its ability to efficiently accommodate both needs. For example, evaluations of SFE technology for large-scale H_2 generation applications addressed the capability of the SFE to electrolyze impure water without costly purification equipment and expendables. In those evaluations [9] SFE modules electrolyzed Cleveland, OH, tap water for 1750 h without any pretreatment and no adverse effects. Simulated sea water was also electrolyzed for 1100 h, and real sea water was electrolyzed for 1550 h without adverse effects on the module.

The above discussion has shown that the SFE can be used to generate O_2 and H_2 at a variety of pressures and production rates. Therefore, nearly all experimentation and manufacturing needs can be satisfied by SFE technology. In addition, a special capability exists within the SMC SFE for the generation of ultra-high purity, dry H_2 and O_2 at very high pressures. Special needs can be satisfied with this technology.

Electrolysis performance improvement concepts studies (EPICS)

An effort is being planned for the testing of three integrated SFE units aboard the Shuttle Orbiter. The objectives of the electrolysis performance improvement concepts studies (EPICS) is to investigate the ways that a low-*g* environment may improve SFE performance by increasing the uniformity of thermal gradients and mass transport within the cells.

Each integrated electrolysis unit in the EPICS consists of an electrolysis cell, a thermal control plate, and accumulators for H_2 and O_2 (Fig. 16). Each

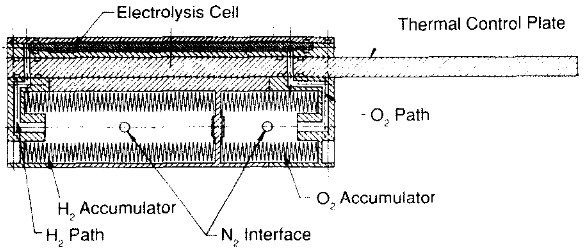

Fig. 16. Cross section of integrated electrolysis unit.

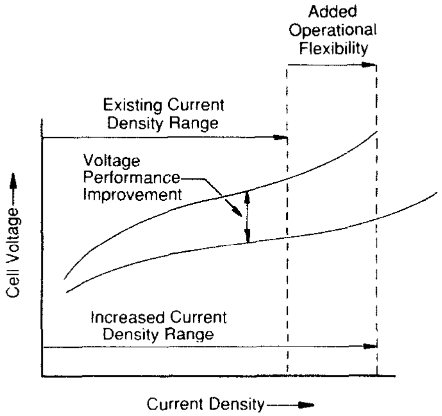

Fig. 17. Projected SFE performance improvements in 0-*g* environment.

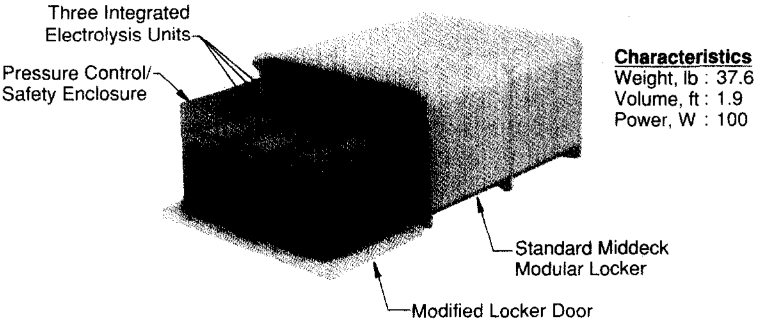

Fig. 18. EPICS experiment packaging concept.

unit will contain electrodes with a different catalyst microstructure. By comparing the performance of each unit, it is expected that knowledge will be gained on how to optimize the electrodes for a low-*g* environment, to result in decreased cell voltage and increased operational current densities (Fig. 17).

Figure 18 shows the EPICS packaging concept, consisting of the three integrated electrolysis units contained in a pressure control enclosure with external control/monitor instrumentation.

Concluding remarks

Static feed water electrolysis technology has been demonstrated to satisfy the O_2 and H_2 generation requirements of energy storage, life support, propulsion, EVA and other applications. Prototype and preprototype SFE subsystems have shown that SFE technology efficiently satisfies both small- and large-scale requirements. In addition to low power consumption, compact dimensions and low weight, these subsystems have demonstrated the ability to operate using impure water sources. Without the need for special water purification equipment, gas/liquid separators and other components, the SFE subsystems have the benefits of simplicity and reliability. Additional efficiency improvements are envisioned as a result of the planned low-*g* Electrolysis Performance Improvement Concepts Studies. Finally, applications requiring ultra-high pressure O_2 and/or ultra-high purity H_2 at low pressure, such as the extravehicular activity application, can be satisfied by the Solid Metal Cathode static feed electrolyzer. An evaluation of the Solid Metal Cathode for energy storage, propulsion and life support applications is also recommended to evaluate how its ability to withstand large O_2-to-H_2 pressure differentials could improve the reliability of those systems.

Acknowledgements

The authors wish to acknowledge NASA Lewis Research Center, NASA MSFC, NASA JSC, Boeing, the Department of Energy and Life Systems, Inc, in the development of SFE subsystems. In addition, the authors wish to acknowledge the assistance of Dr B.-J. Chang and Andrew J. Kovach in the preparation of this paper.

References

1 F. H. Schubert, R. A. Wynveen and F. C. Jensen, Development of an advanced static feed water electrolysis module, *Intersociety Conf. Environmental Systems, San Francisco, CA, July 21–24, 1975*, Paper No. 75-ENAs-30.

2 F. H. Schubert, M. K. Lee, R. J. Davenport and P. D. Quattrone, Water electrolysis systems: H_2 and O_2 generation, *Intersociety Conf. Environmental Systems, San Diego, CA, July 10–13, 1978*, Paper No. 78-ENAs-03.

3 J. T. Larkins and A. J. Kovach, Static feed water electrolysis system for space station O_2 and H_2 generation, *Intersociety Conf. Environmental Systems, San Francisco, CA, July 16–17, 1985*, Paper No. 851339.

4 P. D. Quattrone, F. H. Schubert and D. B. Heppner, Air revitalization system integration, *Intersociety Conf. Environmental Systems, San Diego, CA, July 16–19, 1984*, Paper No 840959.

5 F. A. Fortunato, A. J. Kovach and L. E. Wolfe, Static feed water electrolysis system for space station oxygen and hydrogen generation, *Intersociety Conf. Environmental Systems, San Francisco, CA, July 11–13, 1988*, Paper No. 880994.

6 B. J. Chang, F. H. Schubert, A. J. Kovach and R. A. Wynveen, Engineering model system study for a regenerative fuel cell, *Study Rep., Contract NAS 3-21287, NASA CR-174801, TR-376-30*, Life Systems, Inc., Cleveland, OH, Sept. 1984.

7 A. J. Kovach, F. H. Schubert and B. J. Chang, Endurance test and evaluation of alkaline water electrolysis cells, *Final Rep.*, *Contract NAS3-21287*, *TR-614-3*, Life Systems, Inc., Cleveland, OH, Apr. 1987.
8 B. J. Chang, A. J. Kovach, F. H. Schubert and J. T. Larkins, Water electrolysis subsystem for a regenerative fuel cell system breadboard for orbital energy storage, *Final Rep.*, *Contract NAS9-16659*, *TR-529-4*, Life Systems, Inc., Cleveland, OH, Mar. 1986.
9 Life Systems, Inc., Development of static feed water electrolysis for large scale hydrogen production, *Final Rep.*, *Contract 522723-S*, *BNL 51578*, *TR-470-4*, Life Systems, Inc., Cleveland, OH, July 1982.