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Integrated Modular Propulsion and Regenerative Electro-Energy Storage System (IMPRESS) for Small Satellites

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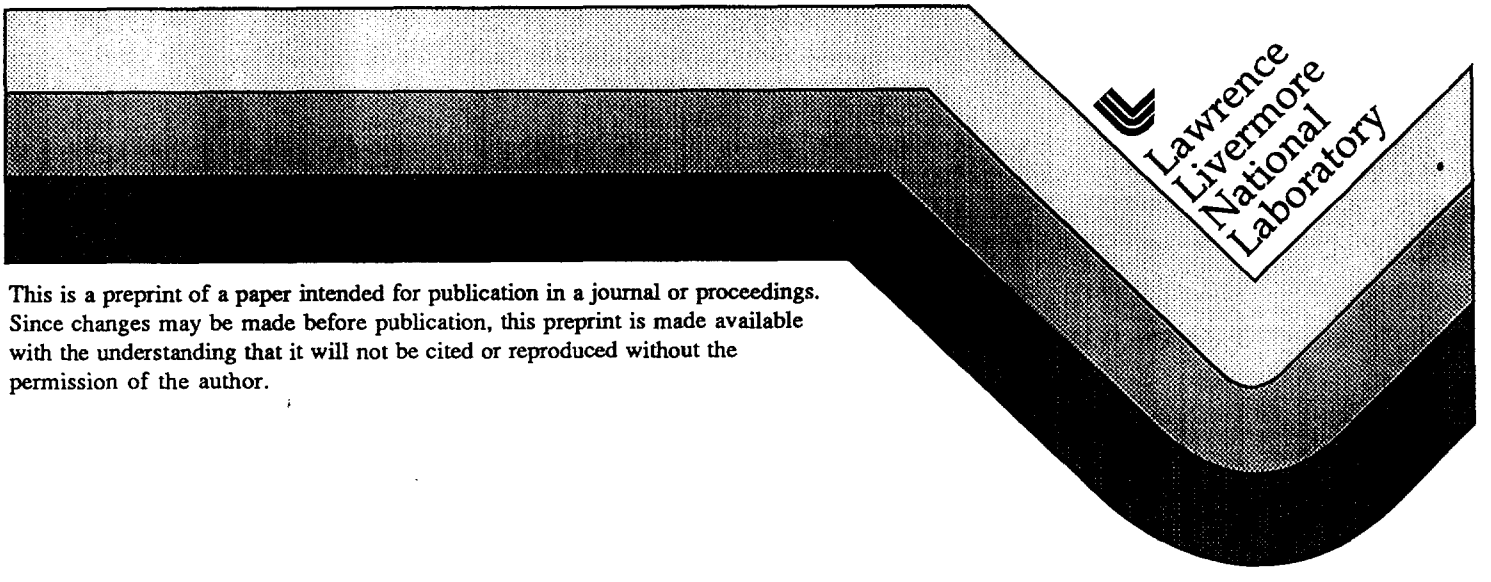

INTEGRATED MODULAR PROPULSION AND REGENERATIVE ELECTRO-ENERGY STORAGE SYSTEM (IMPRESS) FOR SMALL SATELLITES

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Abstract

The IMPRESS is a significant advancement in space system technology as it is able to operate alternately as a fuel cell to produce electrical power from stored hydrogen and oxygen and as a water electrolyzer using electrical power to produce hydrogen and oxygen from stored water. The electrolysis of a controllable fraction of stored water can provide high Isp rocket propellants on demand. The heart of the IMPRESS is the Unitized Regenerative Fuel Cell (URFC), which produces power and electrolytically regenerates its reactants using a single stack of reversible cells. This integrated approach has several significant advantages over separate (battery) power and propulsion systems including:

- Reduced spacecraft wet and dry mass
- Reduced complexity of plumbing and control
- Improved charge/discharge characteristics (>5:1 power peaking capability)
- Utilization of unspent propellant for additional energy storage capacity
- Increased mission flexibility via on-the-fly trade of propulsive ΔV versus stored energy capacity
- Storable, high performance non-toxic propellants
- Scalability of power ratings independent of energy storage capacity
- Outstanding thrust-to-weight ratios

During periods of sunlight, the solar arrays power the URFC to produce hydrogen (H_2) and oxygen (O_2). These gases are stored at pressure and the function of the electrochemical cell stack is "reversed" to produce electrical power during the dark periods of the orbit or mission. During electrolysis, excess H_2 and O_2 are produced, and stored to be used for propulsion through gaseous H_2/gaseous O_2 (gH_2/gO_2) bipropellant ΔV thrusters and cold gas attitude control system (ACS) thrusters.

In summary, the IMPRESS module integrates the functions of the URFC with a fully functional attitude control and ΔV propulsion system to yield breakthrough gains in weight reduction, power density, and mission applicability.

IMPRESS Description

The IMPRESS multifunctional system schematic is depicted in Figure 1. This unique integrated system combines the high specific energy storage of a H_2/O_2 URFC with the high Isp of a gH_2/gO_2 propulsion system, and uses part of the structural mass for storing non-toxic reactants/propellants (gH_2/gO_2). The gH_2/gO_2 are stored primarily as water at launch, which enables low pressure/high safety factor handling at the launch range without incurring the usual mass penalties associated with handling and launching fully pressurized vessels. Maximum system pressure of H_2/O_2 is achieved in space (after deployment), where high safety factors are no longer necessary.

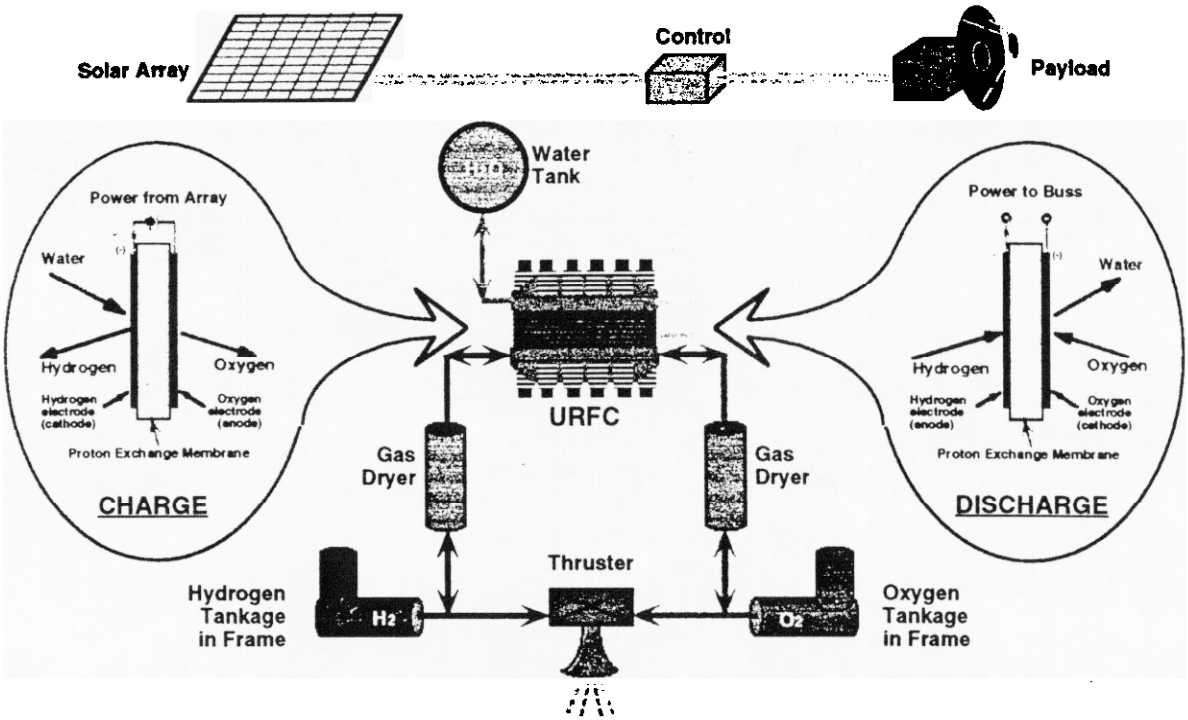

Figure 1 The SPE URFC is the Key Enabling Technology of the IMPRESS

The IMPRESS integrates the enabling URFC technology with other advanced technologies to address the needs of small satellites. The combined functionality of energy, power, propulsion, and structure in a synergistic package translates into a lightweight, modular system that can support a range of mission profiles from low earth orbit (LEO) to interplanetary orbital and extended lander/surface/sampling missions.

The IMPRESS for small spacecraft consists of a solar rechargeable URFC for energy storage and gH_2/gO_2 propulsion. High pressure SPE® cell stack designs have been developed in recent years to address 2,000 psi commercial aircraft crew oxygen generation needs.[8] This design and packaging effort serves as the basis for the URFC for small satellites. An example of a URFC has the following characteristics:

- # of cells - 38
- Active area per cell - 0.43 in^2
- Weight - 0.6 lb_m
- Operating pressure - 2,000 psi
- Power output - 20 watts max. @ 28 Vdc
- Power input - 30 watts max. @ 28 Vdc

The energy density of a URFC prior to integration with the propulsion system can be greater than 1,000 watt-hours per kg. Energy densities of this magnitude are projected by NASA/Lewis for lunar surface applications. Figure 2, based on NASA studies, shows the stand alone URFC to be nearly an order or magnitude lower in mass than projected advanced rechargeable batteries. [17]

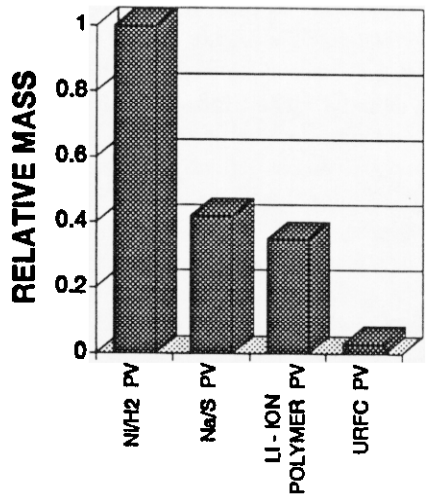

Figure 2 Energy Storage for Lunar Surface Applications

The stand-alone mass advantage of the URFC increases with increasing discharge period duration. This is because, unlike batteries, the energy and power are uncoupled in the URFC. The reactor stack is sized only for power, and the H_2 and O_2 storage are sized for

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energy. As an example, a 20 watt reactor stack will be the same size regardless of whether the discharge time is 1 minute or 1 year. Nonetheless, the URFC has significant mass advantages over state-of-the-art (SOTA) battery systems for many mission scenarios. For example, a martian surface URFC application (with approximate 12 hour charge and discharge times), provides more than a two-fold mass advantage over batteries assuming SOTA photovoltaics.

The URFC allows for integration with the gH_2/gO_2 propulsion subsystem, thereby significantly reducing the overall system mass. The stand alone gH_2/gO_2 propulsion system mass advantage using an SPE reactor stack to generate H_2 and O_2 from stored water is displayed in Figure 3.

When a gH_2/gO_2 "water rocket" system is installed on a vehicle, the increased mass to provide even short discharge times of electrical energy is significantly less than the best rechargeable battery. Figure 4 shows the specific energy for the stand-alone URFC and the IMPRESS module compared to alternate energy (battery) systems for five different mission scenarios. Table I depicts the specific energy estimates for a URFC and a number of conventional and SOTA battery technologies. The specific energy values in Table I[10,13] are uniformly higher than those in Figure 4 because the values in the table do not include the weight of photovoltaic cells.

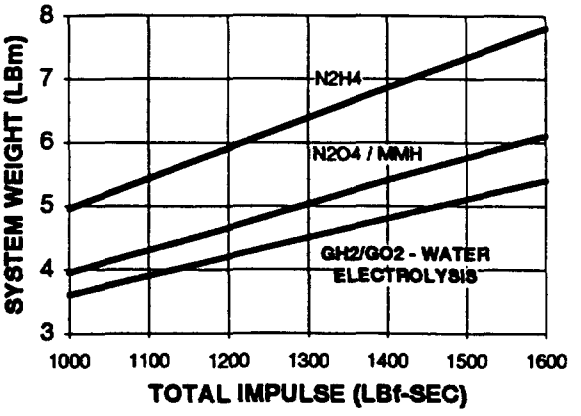

Figure 3 Mass Advantage of gH_2/gO_2 Propulsion

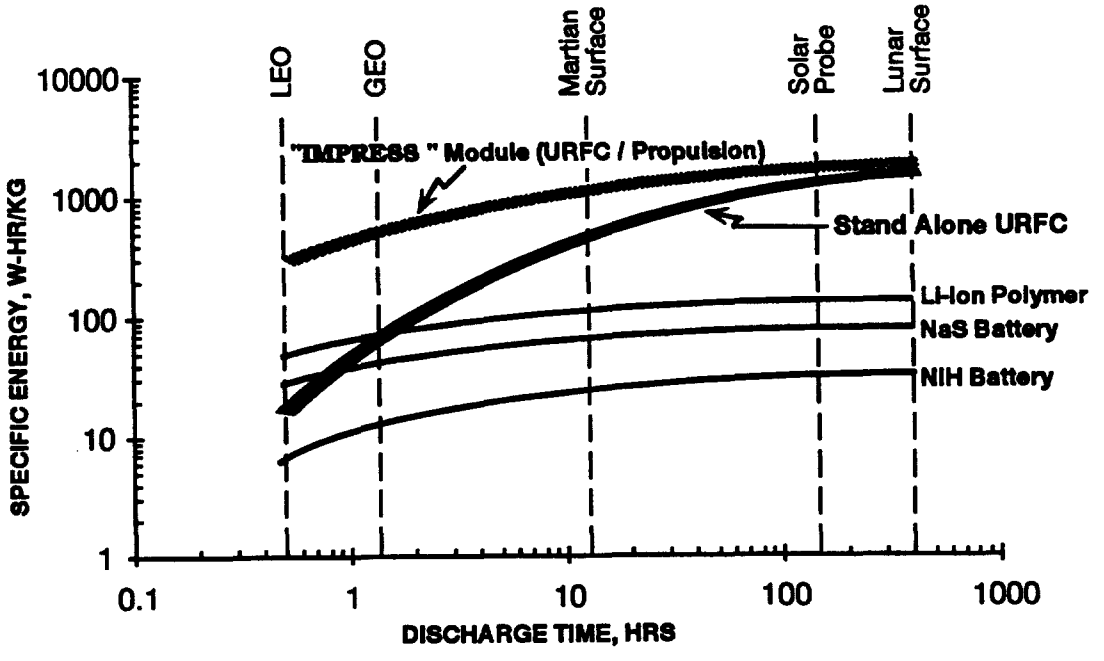

Figure 4 Energy Density Comparisons

Table I Theoretical and Packaged Specific Energy for URFCs and Rechargeable Batteries.[2]

Battery/URFC System	Theoretical Specific Energy (Wh/kg)	Packaged Specific Energy (Wh/kg)	Comments
H_2/O_2 URFC	3660	400-1000	URFCs with lightweight pressure vessels
Li-SPE/MO_x	735	220	Novel packaging for unmanned system
Ag/Zn	450	200	Excess Zn required, low charge rate
Li/$LiCoO_2$	735	150	Poor cycle life, high capacity fade
Li/$AlFeSe_2$	515	150	≥400°C thermal management
Na/S	1180	150	~350°C thermal management
Li/TiS_2	470	130	~50% DOD for high cycle life (900 cycles)
Li/ion	700	100	Marginal improvement for larger cells
Ni/Zn	305	90	Excess Zn required, low specific energy
Ni/MH_x	470	70	MH_x is metal hydride Low specific energy
Ni/H_2	470	60	Low specific energy
Ni/Cd	240	60	Low specific energy
Pb/acid	170	50	Low specific energy

Combining energy, propulsion, and structure in an integrated system provides up to a 15-fold mass savings over SOTA distributed, non-integrated systems for a wide range of missions envisioned for small satellites. By integrating three of the major functional elements of the spacecraft (power, propulsion, and structure), the IMPRESS provides a tangible reduction in system mass from that of a discrete component configuration.

The IMPRESS supports a broad range of the capability requirements identified for the New Millennium Program (NMP) to perform missions identified for small satellites. Missions identified by the Planetary subgroup, such as landers and outer planetary probes, require capabilities where the IMPRESS delivers a 10:1 performance improvement based on energy density alone. In this case, the URFC serves as an innovative energy collection and management device.

The Space Physics subgroup, which identified missions that include solar probes and outer planet orbiters, requires advanced propulsion for timely access to the entire solar system and innovative energy collection technology. Our IMPRESS module is configured to meet these requirements. Finally, the Terrestrial subgroup identified capabilities that require high efficiency energy and power systems. Our IMPRESS peaking capability will be able to power several instruments simultaneously and enable high speed data processing and high-rate communications bursts.

The enabling URFC technology, the miniaturized gH_2/gO_2 propulsion technology, and the advanced lightweight tankage technology are all sufficiently mature as shown in Table II.

Table II
All IMPRESS Technologies Have Demonstrated Performance at NASA's Technology Readiness Level (TRL) 4 or Higher

Element	NASA TRL	Comments
SPE Fuel Cell	Level 9	Gemini & Biosatellite
SPE Electrolyzer	Level 6	Air Force Program
SPE URFC	Level 4	700 Cycles demonstrated in laboratory
gH_2/gO_2 Engines • Valves • Combustion Chamber • Ignition	 Level 8-9 Level 6 Level 4	DOD Programs
Graphite Bladder Tankage	Level 4	Solar Rechargeable Aircraft & DOE & Ford

URFC Reactor Subsystem

Hydrogen/Oxygen SPE Cell Background

SPE fuel cell systems have been flight proven in space programs dating back to the Gemini Program enabling seven successful manned missions. (See Figure 5)

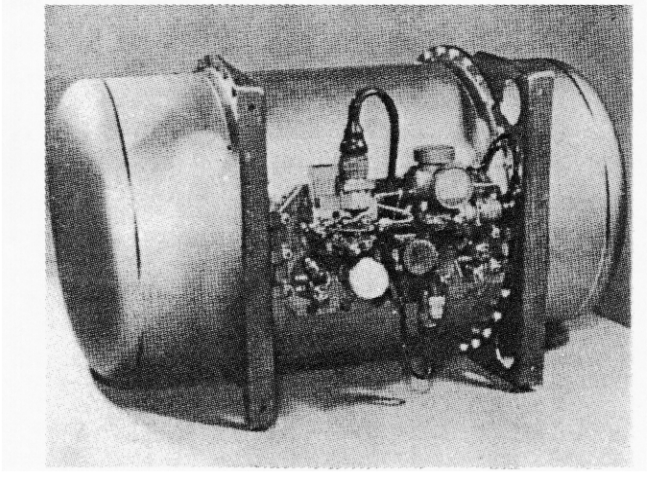

Figure 5 1 KW Fuel Cell for Gemini Spacecraft

SPE water electrolyzers have been developed for use in conjunction with gH_2/gO_2 propulsion systems. A completely static system was developed in the 1970s and early 1980s. A reactor stack was developed with the capability to generate 100 standard liters of propellants per hour. In the early 1990s, NASA recognized the significant advantage of gH_2/gO_2 reboost propulsion for Space Station Freedom. A 3,000 psi SPE propellant (gH_2/gO_2) generator was developed and tested at NASA/JSC. The SPE electrolyzer, as shown in Figure 6, produces up to 3,700 standard liters of propellants per hour. This system has operated for 1,000 hours in the propulsion testbed at NASA/JSC and is currently at the NASA/JPL site for use in the JPL/NASA Lewis regenerative fuel cell testbed.[7] Tests currently underway at NASA/Lewis to evaluate the performance of a static SPE water electrolyzer with a 0.25 lb_f (1.1 N) high temperature rhenium-iridium thruster are providing promising results.

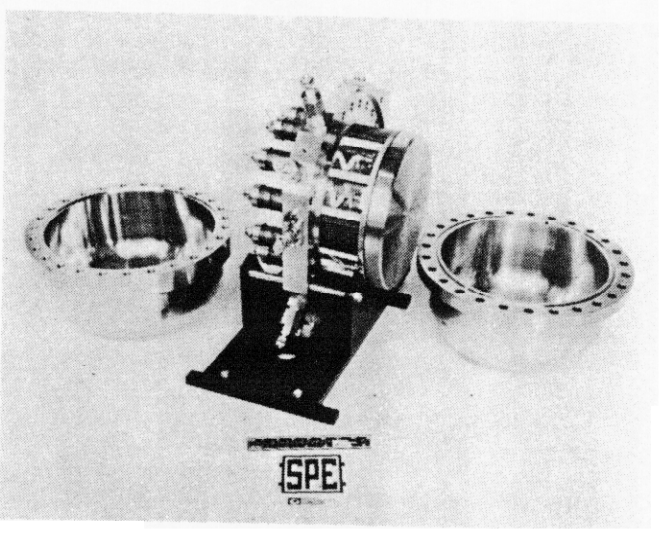

Figure 6 NASA Integrated Propulsion Test Article (Electrolyzer)

URFC Background and Testing

A URFC produces power and electrolytically regenerates its reactants using a single stack of reversible cells[11]. URFCs have been designed for high altitude long endurance (HALE) solar rechargeable aircraft (SRA),[9,10] zero emission vehicles (ZEVs),[15] hybrid energy storage/propulsion systems for long duration satellites,[9] energy storage for remote (off-grid) power sources, and peak shaving for on-grid applications.[6] URFCs have been examined using bifunctional electrodes (oxidation and reduction electrodes reverse roles when switching from charge to discharge, as with a rechargeable battery)[6,9,15,17] and monofunctional electrodes (an electrode always undergoes either oxidation or reduction regardless of whether the system is charging or discharging).[5,16] URFCs have been considered using hydrogen/oxygen, hydrogen/air, or hydrogen/halogen chemistries. Hydrogen/halogen URFCs have achieved higher round-trip efficiency than hydrogen/oxygen, but are significantly heavier.[6]

A single cell cycle life test for a URFC (Figure 7) showed that reversible operation of cell membrane and catalyst is feasible without significant degradation,[2] thus refuting comments to the contrary made at the 1994 Fuel Cell Seminar. This test was performed in the early 1970s at ambient temperature using a membrane that is similar to DuPont's Nafion 120. The catalyst (E-5) is a proprietary Hamilton Standard mixture of Pt, Pt-group metals, and their oxides. This test was a proof-of-principle energy storage system for a long life (7-10 yr) geosynchronous satellite, that was required not to use mechanical pumps (for reliability). The cell used a wicking cloth (typically quartz or Dacron) to feed water to the cell in zero-gravity. Upon disassembly of the cell, the initially hydrophilic wicks had become hydrophobic which degrades wicking and may well account for most of the limited cell degradation (<40 mV) shown in Figure 8. It should be noted that other substitutes for wicks exist for zero-gravity operation, and wicks are clearly not required for terrestrial applications. Since this early data is sparse and masked by the unnecessary wicking cloth, we plan to perform a series of lifetime tests to show that high cycle life URFCs are feasible.[14]

A primary fuel cell (FC) test rig with a single cell (0.05 ft^2 active area) has been modified and operated reversibly as a URFC at LLNL. This URFC uses bifunctional electrodes (oxidation and reduction electrodes reverse roles when switching from charge to discharge, as with a rechargeable battery) and cathode feed electrolysis (water is fed from the hydrogen side of the cell). Cycle life test results are expected in late 1996.

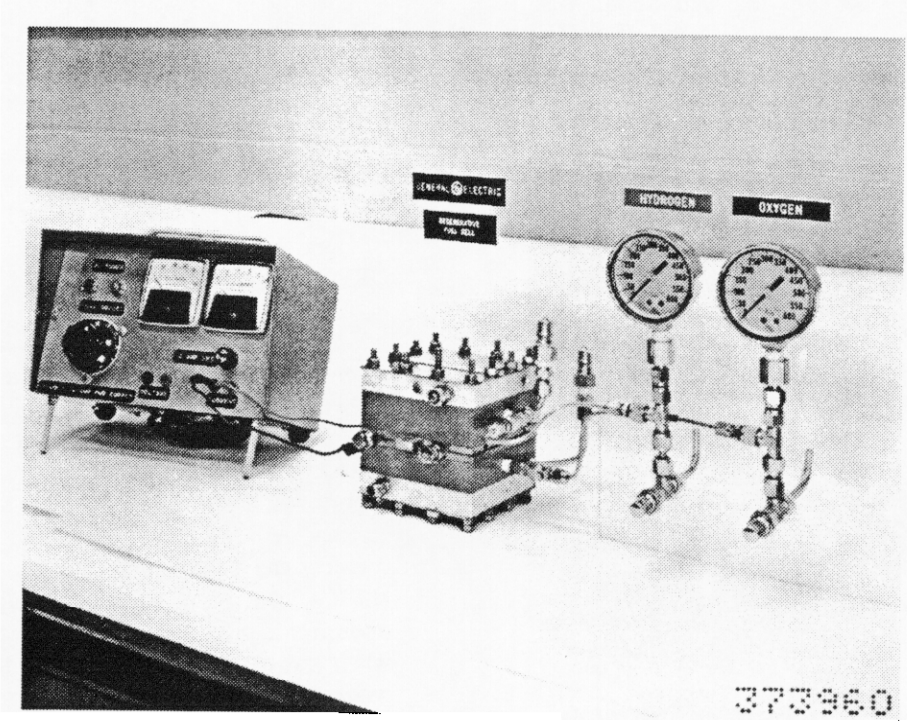

Figure 7 URFC Demonstrated 700 Cycles

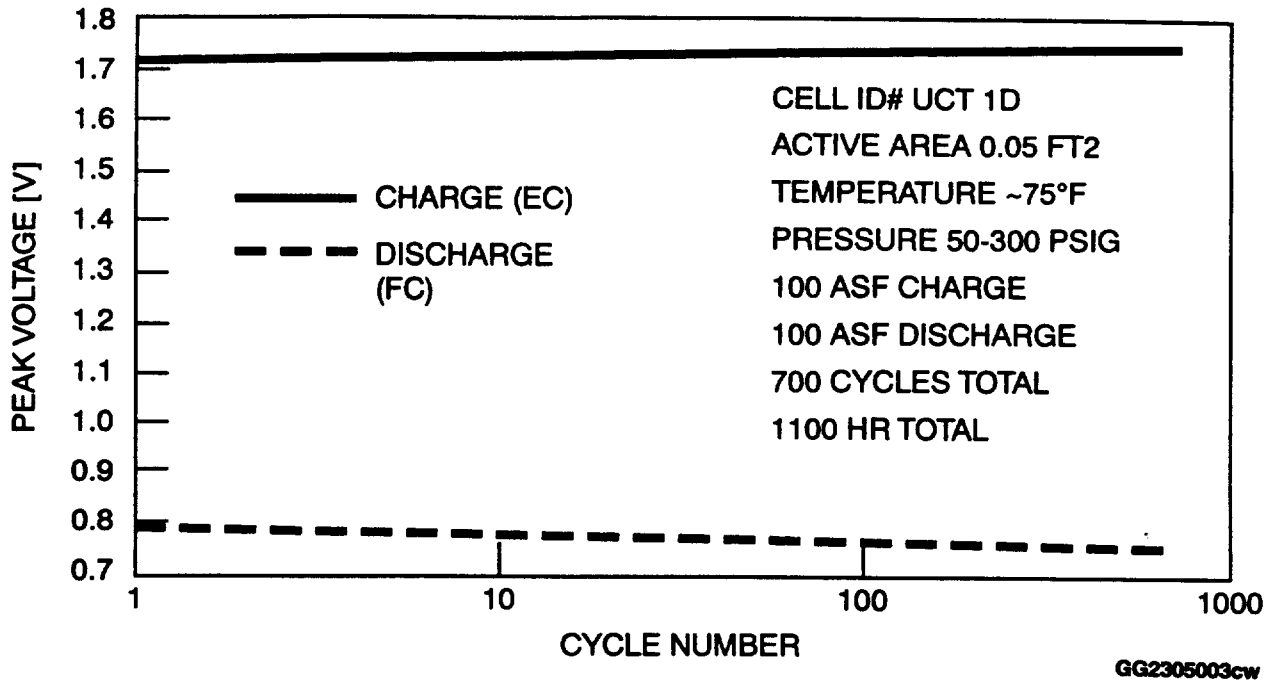

Figure 8 A URFC Cycle Life Test shows less than 40mV degradation over 700 cycles (1100 hr).[2]

SPE URFC Design

The H_2/O_2 SPE URFC design is based on the proton exchange membrane as the sole electrolyte. The sulfonic acid membrane electrolyte is fashioned into electrochemical cells by bonding catalyst electrodes to both faces of the membrane. Using the water cycle, hydrogen and oxygen are produced with the application of DC power, whereas DC power and water are produced by reversing the electrochemical cell. Figure 9 shows the electrochemical reactions of the SPE cell used in the water cycle.

The membrane electrolyte of choice is the perfluorosulfonate acid type. The several advantages of this material include:

- Long useful life (15+ years demonstrated)
- Stable performance (≤ 1 microvolt/cell-hr decay)
- High pressure (6,000 psi demonstrated)
- High differential pressure (3,000 psi demonstrated)

Life requirements for small satellites or planetary missions may be as long as eight-to-ten years. Therefore, an SPE URFC energy storage system must be designed to be maintenance-free and reliable for eight to ten years. The use of pumps or other rotating equipment is therefore a liability that URFC designs can eliminate. The selected SPE URFC uses electrochemically generated pressures to distribute reactant and product fluids to and from storage tanks. Thermal control is accomplished by heat conduction to a cold plate.

The SPE URFC for small satellites employs passive phase separation in the microgravity environment. This major feature of the SPE URFC energy storage system provides:

- A passive means of supplying water vapor to the cell during the charge electrolysis period.
- A passive means of removing the liquid product water from the cell during the fuel cell discharge period.
- A passive means of eliminating gas from the water side of the water vapor barrier membrane.

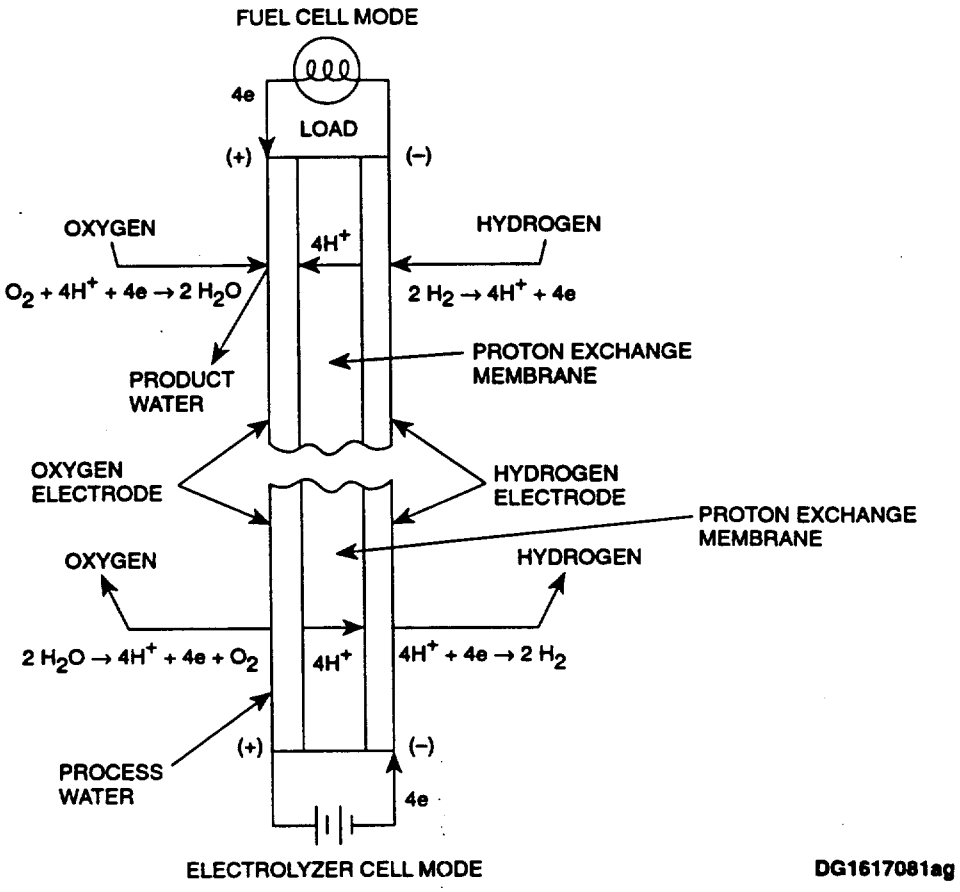

Figure 9 Water Cycle SPE Cell Reactions

The SPE URFC simplified fluid schematic is shown in Figure 10. In the fuel cell mode of operation, unregulated hydrogen and oxygen are delivered to the cell as demanded by consumption. Product water, produced on the oxygen side, contacts the porous hydrophilic membrane separator and is transferred to the water chamber by a forced differential pressure. This differential pressure (approximately 1 psi) is created by the spring in the oxygen/water bellows tank. Any gaseous or dissolved oxygen in the separated product water is removed by hydrophilic membranes as the water flows through the water side of the electrochemical hydrogen pump. Waste heat is removed from the cell by conduction to a cold plate.

In the electrolysis mode, water, free of dissolved gases, enters the water side of the electrochemical hydrogen pump cell membrane and is transported to the operating electrolysis cell by osmosis. Osmotic transport is assisted by the proton pumping (whereby four water molecules are "dragged" through the membrane with each passing proton). A porous hydrophilic membrane (separator) also transports some minor amount of water vapor to the electrolyzer cell. But, this amount is small because of the larger chamber diffusion gap. Water reaching the electrolyzer cell is then reacted to produce hydrogen and oxygen.

Because both hydrogen and oxygen chambers are maintained free of liquid water, instantaneous switching of fuel cell and electrolyzer modes is assured. The following paragraphs describe key features of the SPE URFC in detail.

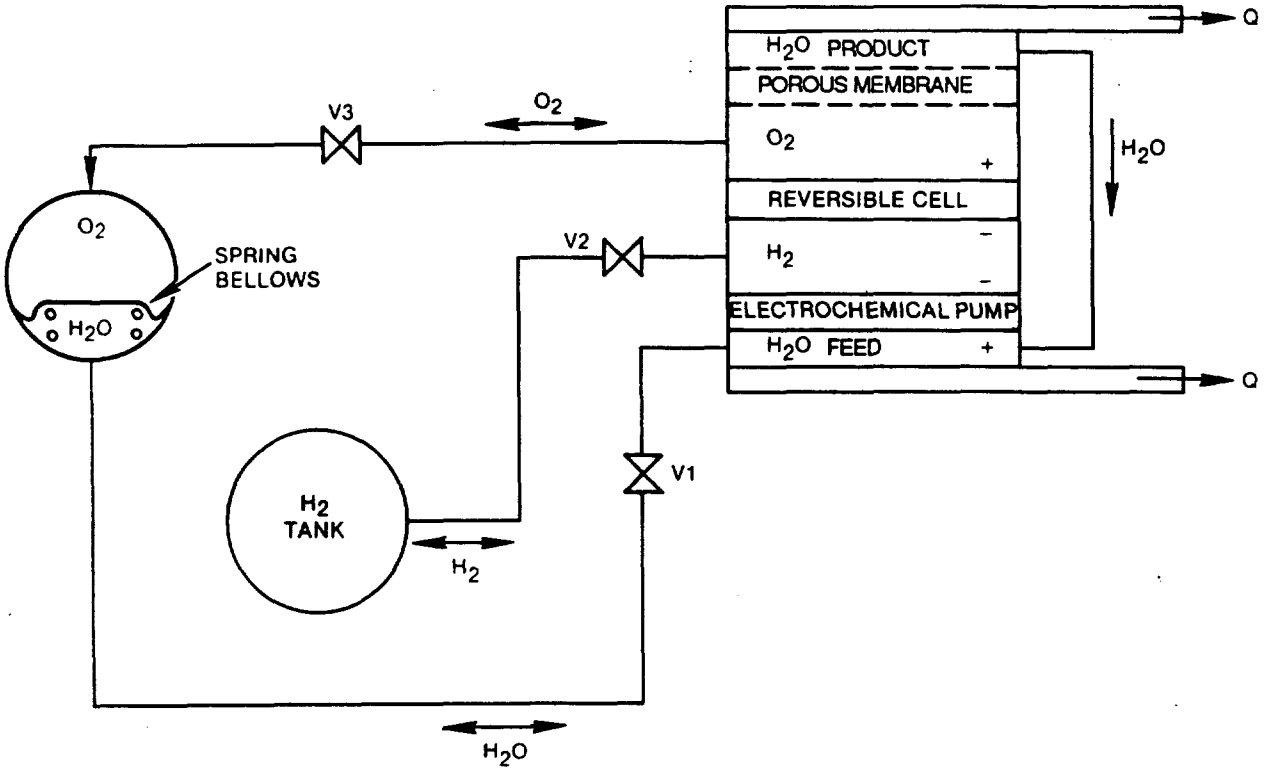

Figure 10 SPE URFC System Fluid Schematic

Reversible SPE Cell Operation - The SPE URFC cell structure consists of a four-chamber arrangement. This arrangement is shown in Figure 11. The product water and process water are statically transported to and from the operating cell by membranes. The reactant storage tanks are sized to store reactant gases at 2,000 psi. Due to the varying pressure, there are slight variations in the performance of the cells during the course of a cycle. The design performance for the SPE URFC at 115 psia is shown on Figure 12.[1]

Passive Fuel Cell Product Water Removal/Separation - Passive liquid/gas phase separation is significant for two aspects of the SPE URFC operation:

- Fuel cell product water removal from the oxygen chamber.
- Removal of dissolved O_2 from the fuel cell product H_2O.

In the fuel cell mode, oxygen and hydrogen react to produce electrical energy, heat and water. The fuel cell product water must be separated from the oxygen gas in a microgravity environment and delivered to a storage location. Wicking systems previously used in NASA's Gemini and Biosatellite SPE fuel cells worked successfully but had limited water transport capability. This was one factor in limiting cell operating current density.

A newly developed approach to zero gravity water/gas separation uses a modified hydrophilic polysulfone membrane device, labeled as porous membrane in Figure 10. Ground testing showed this technique to be very effective in withdrawing the liquid product water from the oxygen chamber. A small differential pressure extracts product water without loss of gO_2. The porous membrane separator has a maximum bubble pressure of approximately 50 psi differential. This separator operates with a differential pressure well below the bubble pressure (oxygen chamber pressure greater than water collection chamber pressure by approximately one psi) which is sufficient to remove many times the water produced. This component has been successfully tested in ground level tests in a worst case negative one-g attitude (i.e., water separated up).

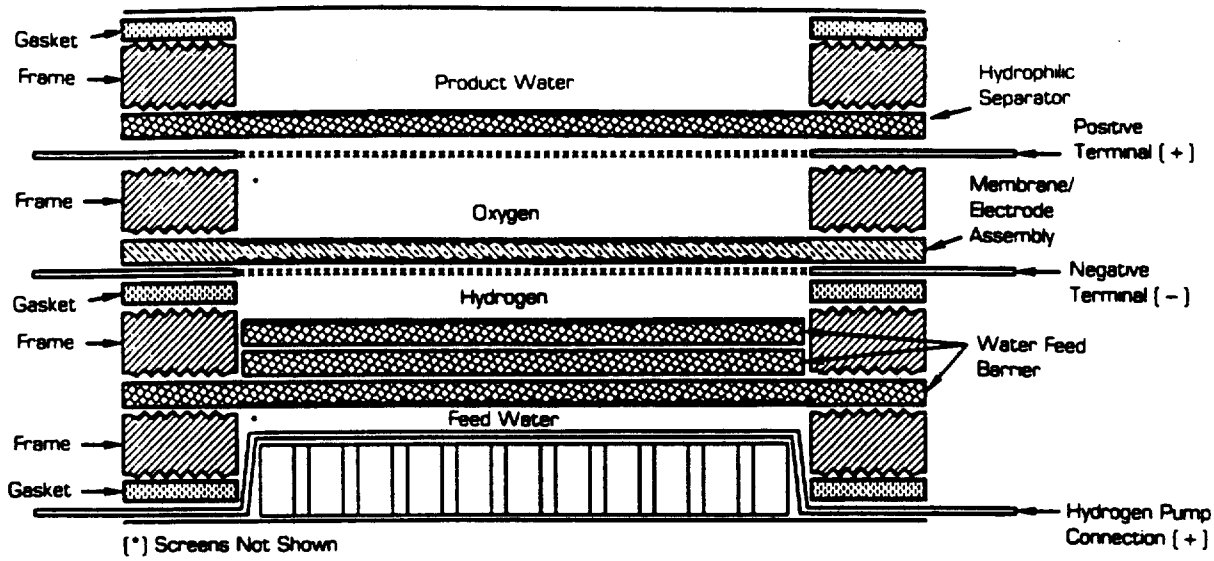

Figure 11 Orbital SPE URFC Cell Structure

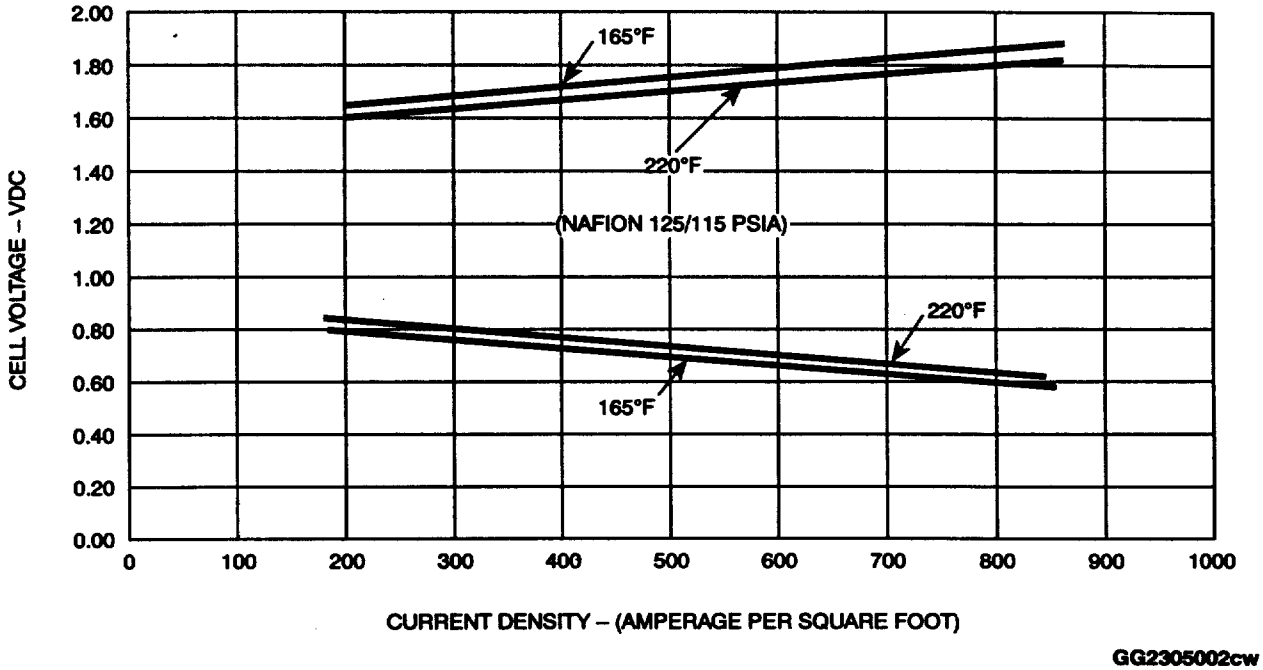

Figure 12 SPE URFC Design Performance

The fuel cell product water is saturated with oxygen as both are in contact within the oxygen cavity. Because the pressure is reduced as the reactants are consumed, dissolved oxygen will come out of solution and form two phases again. To eliminate this oxygen, the two-phase mixture is directed through the water feed cavity prior to being stored in the water storage tank. Final elimination of gaseous and dissolved oxygen is accomplished by consumption with diffusing hydrogen at the hydrogen pump cell positive electrode. This step is important in preventing potential vapor lock in the water storage volume.

Testing has demonstrated that the dissolved oxygen and the "free" oxygen gas are eliminated (by safe controlled reaction with hydrogen) upon passage through the water feed cavity. This passive technique eliminates the need for complex systems involving surface tension tanks or rotating equipment.

Passive Process Water Transport - In the charge (electrolysis) mode the stored water and the fuel cell product water are directed into the water feed chamber of the URFC. The water feed chamber is separated from the hydrogen gas chamber by water permeable membranes which allow osmotic water transport into the hydrogen chamber. A schematic of the basic principles of this vapor feed concept is shown in Figure 13.

Since water is being consumed to produce hydrogen and oxygen gas during recharge, a water gradient is established across the water feed barrier and more water from the storage tank enters the cell. No forced water circulation is required for proper operation.

The passive transport of water to an active electrolysis cell has been ground tested for many thousands of cell hours. The voltage/current stability of the electrolyzer cells during each cycle as well as measured electrochemical gas pump current indicate that passive water transport is performing properly.

Electrochemical Gas Pumping - The osmotic water transport described in Figure 13 is an effective means of providing an adequate supply of water even when the water pressure is lower than that of the generated hydrogen. Within the water compartment, however, there is the possibility of hydrogen gas accumulation. If this condition persisted, water starvation of the cell would result. This gas would accumulate by the slow diffusion of H_2 gas across the water feed barrier membrane into the water compartment if the water chamber was at a lower pressure than the H_2 chamber.

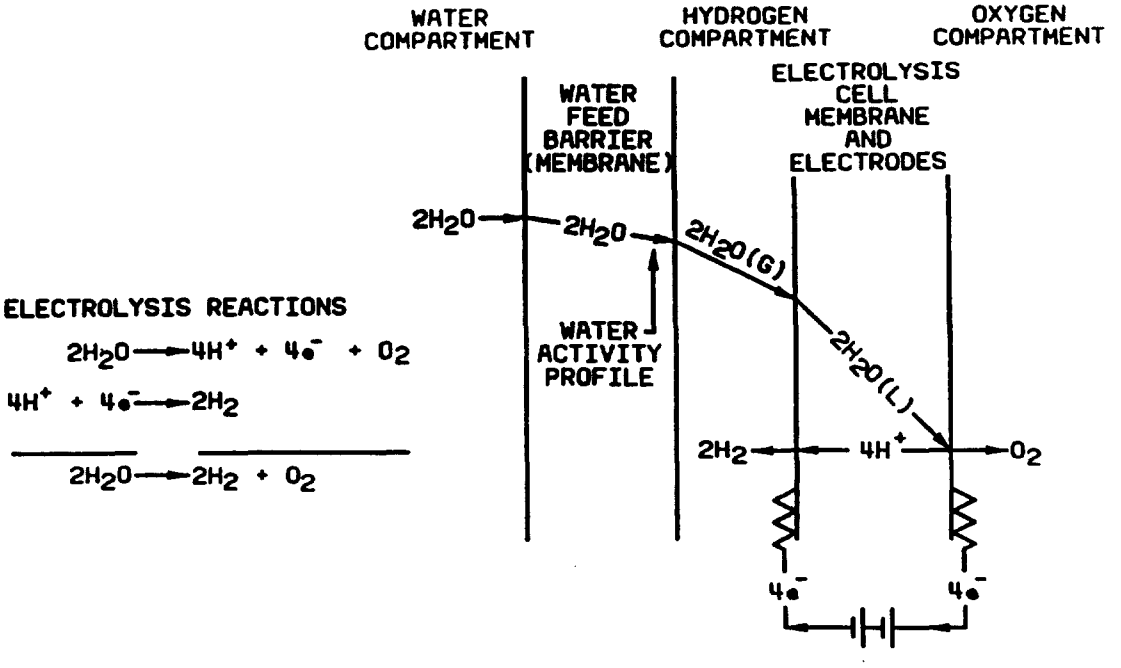

Figure 13 Principles of Water Vapor Feed Electrolysis

The accumulation of diffused H_2 gas is prevented by the incorporation of an electrochemical hydrogen pump. This self-regulated electrochemical hydrogen pump, which draws only a few milliwatts, electrochemically returns any diffused hydrogen back into the hydrogen chamber. Figure 14 displays the arrangement of the electrochemical pump and the operating cell.

Static Heat Removal - Thermal balance of the URFC is maintained by conduction to a satellite structure thermal interface. During the fuel cell mode of operation a significant amount of waste heat is generated as the cell is producing power with a 55-to-60% thermal efficiency. This heat is conducted away from the active area of the cell to a thermal interface. This technique is identical to current technology employed by vapor feed electrolyzer modules. Since the URFC operates continuously (either charging or discharging), a fraction of the waste heat it generates can be used to prevent complications resulting from water freezing.

Propulsion Subsystem

Development Background

Conventional spacecraft propulsion technology is mature, highly refined, and advances occur only in small evolutionary steps. All standard liquid propellants are toxic, so testing is dangerous and costly. The number of facilities in the U.S. where such rocket testing is permitted is decreasing. It is paramount at these facilities to avoid any test failures which might restrict future operations by damaging the facility or releasing toxic propellants. Typically, tests involve hardware that is just slightly improved from an earlier design, and there is a high likelihood of test success. Each test is very carefully planned and conducted, with extensive, highly accurate data collection, which results in a high expense. This advanced level of development testing is not conducive to radical advances.[19]

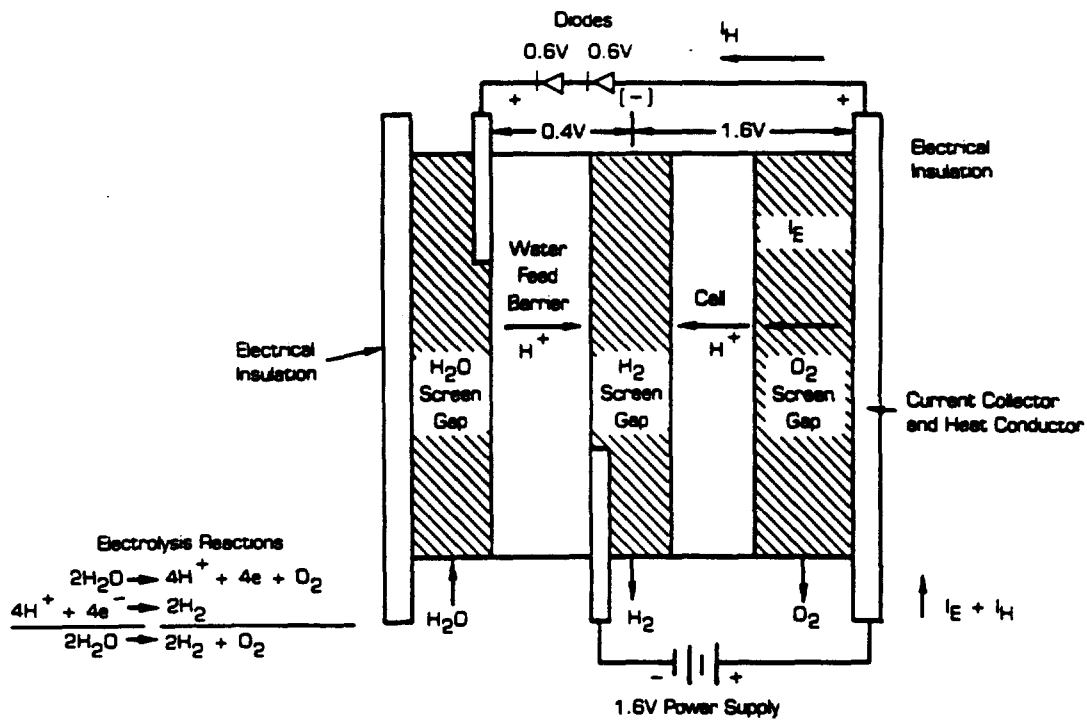

Figure 14 SPE Static Water Vapor Feed Electrolysis Cell Schematic with Hydrogen Pump

In contrast, cost-effective development of revolutionary technology requires a completely different approach to testing. Frequent, low-cost, high-risk tests are required, with significant learning at each step and major design changes from one test to the next. Data collection is inexpensive, because each test need only answer a few simple but critically important questions. The use of non-toxic propellants can enable implementation of this type of testing operation.[19]

Even if rocket technology development with toxic propellants could be made easier and safer, toxicity is a major drawback for field testing or integrated testing for spacecraft. Today's standard for spacecraft propulsion is to design, build, and fly with little or no functional testing at the system level. In an attempt to compensate for the lack of complete system testing, people overemphasize the importance of flight heritage for the individual components. As a result, spacecraft propulsion technology has been advancing only very slowly because there is little room for creativity or revolutionary approaches in system design. Designing a new system is presently a matter of component selection followed by a packaging and plumbing exercise. Given today's environmental laws, safety rules, and liability fears, terrestrial flight testing is extremely difficult or impossible (i.e., expensive and time-consuming) if toxic propellants are involved.[19]

After technology development and qualification testing comes the mission launch itself. Propellant toxicity concerns at launch ranges have a significant impact on spacecraft propulsion design. The standard of all-welded plumbing joints is driven in part by leakage fears at launch ranges. The all-welded approach is expensive, time consuming, and severely restrictive of design changes. It adds an extra design-change step between disassembleable test hardware and flight hardware.[19]

Electrolysis Propulsion System

The use of gH_2/gO_2 as propellants provides the opportunity for revolutionary advances. Propulsion using gH_2/gO_2 coupled with an SPE electrolysis system was demonstrated at low pressure with 0.1 lb_f and 5.0 lb_f thrusters. The reliability and efficiency of the system was successfully demonstrated with an Isp of more than 360 seconds with the 5.0 lb_f engine using a molybdenum combustion chamber and 60% H_2 film cooling. Based on these tests it was determined that an Isp of more than 380 seconds could be attained using system materials with higher temperature capability.

An SPE electrolysis propulsion system for small satellite propulsion is currently being evaluated at NASA LeRC. A laboratory test bed has been built, which is shown in Figure 15. Besides a percolating SPE electrolysis system, it also incorporates a 300 cc hydrogen tank, a 150 cc oxygen tank, and a 0.25 lb_f (1.1 N) high temperature rhenium-iridium thruster. Venturies in the propellant lines, scaled for optimum mass flow rate at 100 psi for the given thruster, control the mass flow rates. Pressure transducers in the propellant tanks, the electrolysis unit, and the combustion chamber record the pressure during the charge and discharge (propulsion) cycles. The system is mounted in a high altitude chamber where ambient pressure can be maintained at 0.2 psi during a test. Because of the low thrust level, thrust could not be recorded in this facility.

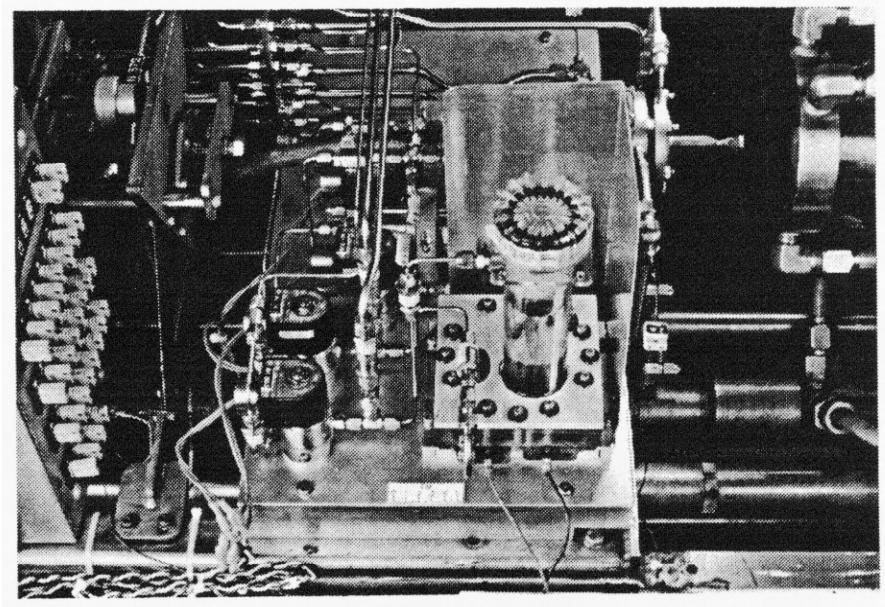

Figure 15 Propulsion Test Bed (Electrolyzer-Rhenium-Iridium Thruster)

The SPE electrolysis unit has been modified to operate up to a maximum pressure of 150 psi. This limits the pressure regime that can be evaluated, but future tests should involve higher pressures. During current tests, the unit is typically operated until the propellant tank pressure reaches this limit. Electrolysis unit input powers for tests performed thus far varied from 1.5 up to 17.5 watts. Temperature measurements at the electrolysis unit base plate show the temperature to be stable at 90°F.

A high temperature rhenium-iridium thruster is used as the propulsion unit. Because of the high temperature and oxidation resistance of these materials it is not necessary to use part of the hydrogen film for wall cooling. Therefore, better mixing and a higher combustion efficiency can be obtained. The ignition source is a modified spark plug. As an alternate, low weight, ignition option, resonance tube ignition with hydrogen is considered.

The propulsion part of the cycle works on the simple blowdown principle. This eliminates the need for regulating valves. The thruster is fired by opening the thruster valves and using spark ignition. The thruster firing is terminated when the combustion chamber pressure reaches a preset lower limit. As a result of the blowdown design, the oxygen to fuel (O/F) ratio varies. For the tests performed thus far, this ratio varied from 7.5 to 9.1. A typical test firing lasts from 2.5 to 4.5 seconds, depending on the lower limit set. More than 25 cycles have been done, with excellent repeatability (within 3%). Characteristic velocities of 5,400 ft/sec were measured, for a combustion efficiency of 85%, which is excellent considering the non-optimized injector on this 0.25 lb_f thrust chamber.

The system is currently in the process of being modified. Standard flow valves are being replaced with miniature valves. The thruster injector adapter is modified and optimized, and resonance ignition with hydrogen is being investigated. After replacing most standard components with miniature components, mass estimates can be made for specific missions.

Possible Mission Scenarios

The IMPRESS module can support a wide range of missions from low earth orbit (LEO) to interplanetary probes. One such mission was investigated for an orbit transfer and plane change mission with a small, 40 lb_m satellite.[3] The hypothetical mission assumed that the satellite was placed into a 550 km, 97.5° circular orbit by a launch vehicle on a piggy-back ride with a larger satellite. It also assumed that the desired final orbit was the Landsat spacecraft 705 km circular, 98.2° sun-synchronous operating orbit.[20] The performance of an electrolysis system was compared with the performance of a SOTA monopropellant system for this mission, which includes the orbit transfer and plane change and subsequent orbit correction duties for three years. The total mission ΔV requirement was 184 m/s for each system. The SOTA monopropellant used a commercial 4.48 N thruster. The electrolysis system used a 0.45 N thruster. It was shown that the electrolysis based propulsion system provided a weight advantage of 1.75 kg (2.75 kg for electrolysis vs. 4.5 kg for monopropellant) over the monopropellant system. Additional weight savings (~1.6 kg) were projected by replacing the baseline battery with a fuel cell integrated into the electrolysis unit.

Reactant Storage Subsystem

Lightweight pressure tanks with SOTA performance factors (burst pressure x internal volume/tank weight = P_bV/W) have been designed and prototyped.[12,13] These tanks provide a lightweight means of storing reactant gases required for fuel cells (FCs) or URFCs. The tanks use lightweight bladder liners that act as inflatable mandrels for composite overwrap and provide the permeation barrier for gas storage. The bladders are fabricated using materials that are compatible with humidified gases which may be created by the electrolysis of water and are compatible with elevated temperatures that occur during fast fills. Details of the bladder liner construction have been discussed elsewhere.[10,12,13]

The development of these lightweight composite storage tanks has been partially performed under a program funded by the DOE, Office of Transportation Technologies, in conjunction with Ford Motor Company.[4] Tanks fabricated using this technology have advanced the SOTA in P_bV/W, and should be capable of achieving the high cycle life capability of thick metal or polymeric liners (see Figure 16). Since the liners are thin and lightweight, the weight and volume penalties associated with packaging tanks into multiple units is reduced. The P_bV/W of a bladder lined tank using lower strength/less expensive carbon fibers (such as T700S or Panex 33) can match the performance factor of similar tanks with thick liners using higher strength/more expensive carbon fiber (such as T1000G). This is important because tank cost is dominated by fiber cost and the fiber cost per tank for T1000G is currently a factor of three-four times that of T700S or Panex 33.

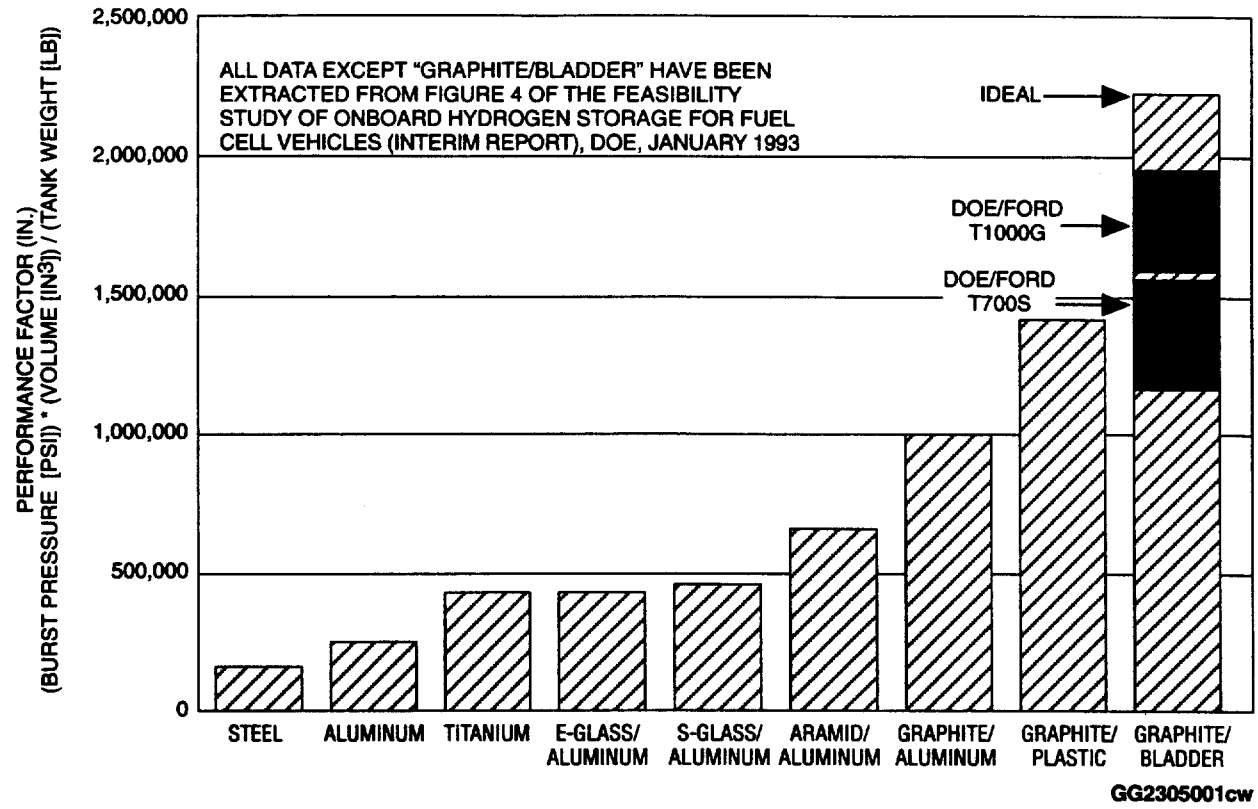

Figure 16 Comparison of High Cycle Life Tank Performance Factors (P_bV/W) for Various Materials

Lightweight pressure vessels were designed, fabricated, and tested. One particular prototype tank designated tank #03, weighed 24.2 lb_m had a measured internal volume of 3180 cubic inches at ambient pressure (estimated volumes were 3280 cubic inches at max operating pressure of 5,000 psi and 3390 cubic inches at burst), and an estimated burst pressure of 11,250 psi. The performance factor for this vessel at burst was estimated to be a record 1.6 million inches (4.0 million cm). Modest design changes to this vessel should result in high cycle life pressure vessels with performance factors of ~ 2.0 million inches.[13] Alternately, tanks with thick liners and T1000G carbon fiber can be replaced with bladder lined tanks that have comparable fiber cost and P_bV/W, but use lower strength/higher modulus carbon fiber (such as M40J) in order to achieve the higher stiffness desired for structural components.

Lightweight tanks have been designed and fabricated to react purely pressure loads or hybridized pressure and structural loads. Use of these hybridized tanks can result in lower system mass for various vehicles, such as high altitude long endurance (HALE) solar rechargeable aircraft (SRA),[10,11] planetary rovers, and spacecraft with gaseous reactants/propellants. We have designed, fabricated, and load tested to failure (in bending) a series of prototype hybridized vessels that can withstand the structural loads expected in a HALE SRA,[10] in addition to storing the reactant gases required by a URFC energy storage system. Additional test results will be available in the next month, and will be presented at the 1996 Fuel Cell Seminar.[14]

For the small satellite this tankage is integrated into the structure to save system weight. This structurally integrated tankage concept is shown in Figure 17.

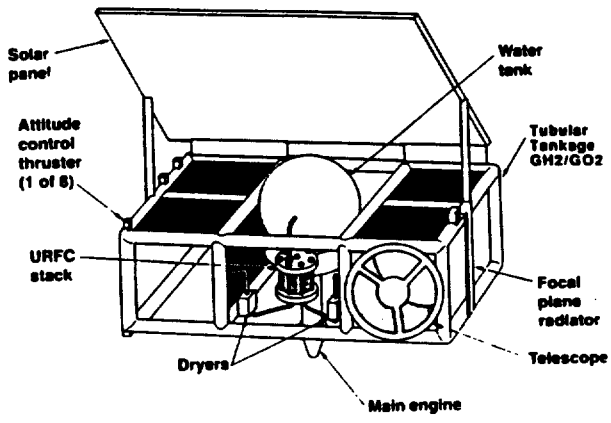

Figure 17 Small Spacecraft with IMPRESS

Summary

The IMPRESS advances the SOTA for small satellites in power, propulsion, and structurally-integrated tankage. Moreover, this system integration and synergism enabled by the SPE URFC, provides a breakthrough in small satellite subsystem performance. The significant gains associated with this compact, integrated design include:

- Reduced spacecraft mass
- Improved mission flexibility
- Non-toxic propellants
- Simplified ground logistics
- Outstanding thrust-to-weight ratios

Performance testbeds and proof-of-concept demonstrations are validating the projected performance gains attributable to the IMPRESS. A flight experiment, employing an IMPRESS module for power, propulsion, and structurally-integrated reactant storage, is suggested as the next logical step in the development of this novel, high-performance satellite subsystem.

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