Fuel Cell Development for NASA's Human Exploration Program

Benchmarking with "The Hydrogen Economy"

John H. Scott [1]
Energy Systems Division
Lyndon B. Johnson Space Center/EP3
National Aeronautics and Space Administration
Houston, TX 77058
e-mail: john.h.scott@nasa.gov

Abstract— *The theoretically high efficiency and low temperature operation of hydrogen-oxygen fuel cells has motivated them to be the subject of much study since their invention in the 19th Century, but their relatively high life cycle costs kept them as a "solution in search of a problem" for many years. The first problem for which fuel cells presented a truly cost effective solution was that of providing a power source for NASA's human spaceflight vehicles in the 1960's. NASA thus invested, and continues to invest, in the development of fuel cell power plants for this application. This development program continues to place its highest priorities on requirements for minimum system mass and maximum durability and reliability. These priorities drive fuel cell power plant design decisions at all levels, even that of catalyst support. However, since the mid-1990's, prospective environmental regulations have driven increased governmental and industrial interest in "green power" and the "Hydrogen Economy." This has in turn stimulated greatly increased investment in fuel cell development for a variety of commercial applications. This investment is bringing about notable advances in fuel cell technology, but, as these development efforts place their highest priority on requirements for minimum life cycle cost and field safety, these advances are yielding design solutions quite different at almost every level from those needed for spacecraft applications. This environment thus presents both opportunities and challenges for NASA's Human Exploration Program*

Index Terms— **Energy Conversion, Energy Storage, Batteries, Fuel Cells**

I. Introduction

THIS paper reviews the history and current direction of fuel cell technology development for NASA's Human Exploration Program and compares these to the directions being taken for "The Hydrogen Economy." The concept of "The Hydrogen Economy" involves myriad applications for fuel cells, but, for purposes of this benchmarking study, the application for comparison is that to automobiles.

II. Power Systems Engineering

For any application, systems engineering is about tradeoffs among prioritized attributes bounded by constraints. What varies among applications are the priorities in the tradeoffs the nature of the constraints. For automobile propulsion systems, the three highest priority attributes in trades are:

•Total Life cycle Cost. For any application requiring mass production a high priority is placed on recurring manufacturing cost.

•Gravimetric and volumetric specific power and energy (kW/kg, kWh/kg, kW/l, kWh/l). Note that for a car the relatively low 300-mile range expected for one tank of fuel and the availability of oxidant from the atmosphere makes the weight and volume of the power plant more significant than that of the fuel storage.

•Emissions (pollutants, greenhouse gases, noise). It's the ability to decrease or eliminate harmful emissions that makes fuel cell technology a core tool in the development of the "Hydrogen Economy."

All of these attributes must be optimized within a hard constraint of safe operability in the field. For cars, this includes enabling safe transfer of fuel by fatigued, untrained personnel.

The priorities for spacecraft applications are rather different from those of automobiles. In fact, they are parallel with those of real estate. An oft-repeated aphorism is that the three most important things in real estate are: Location, Location, and Location. Likewise, the three most important things in spacecraft power systems are: Specific energy (kWh/kg, kWh/l), specific energy, and specific energy. Fuel-cell powered spacecraft must carry a full mission load of both fuel and oxidant. With the marginal cost of accelerating mass to low earth orbital velocity remaining beyond $20,000/kg, specific energy thus overwhelms almost all other considerations. A fourth consideration might be development cost. When searching for technology to maximize specific energy, spacecraft designers will always favor technology that has already been developed in the private sector to the extent that it exists. The least desirable constraint in a flight project with a real schedule and budget is a need to invent something, but, if it is worth a couple of hundred kilograms, spacecraft project managers will invest a lot to do just that. Note that production cost is not a significant consideration. Spacecraft programs never build very many units. Case in point: In the more than thirty year history of the Space Shuttle program, NASA has only procured just over 100 stacks for the fuel-cell powered Shuttle Orbiters. The absolute constraint is not so much public safety as mission reliability, almost always judged by having verifiable redundancy. Redundancy trumps even weight in importance. NASA human spaceflight paradigm requires two fault tolerance to catastrophic failure. For power systems this implies a requirement for at least three independent power strings, except when this does not decrease reliability. Redundancy management is thus crucial and complicated. This why the Shuttle Orbiter, on which launch mass is extremely valuable, carries three independent fuel cell power plants feeding three cross-strapped power buses, when, in an extreme contingency, it could limp home on one. As reliable as the Shuttle's fuel cells have been, this design is not

[1]Submitted to ASME for publication in the Journal of Fuel Cell Science and Technology. Manuscript received on July 15, 2007. Preparation of this publication was supported by the National Aeronautics and Space Administration.

John H. Scott is with the National Aeronautics and Space Administration, Lyndon B. Johnson Space Center, Houston, TX 77058 USA (ph: 281-483-3136; fax: 281-483-3096; e-mail: john.h.scott@nasa.gov).

overly conservative. Among the 116 Shuttle missions safely completed as of this writing, only four have had to be terminated prematurely. Of those, two have been terminated due to a real or suspected failure in a fuel cell power plant.

A common tool in spacecraft power system engineering is illustrated Fig. 1. This plots the locus of maximum specific energy solutions for a given power demand and mission duration. The chart looks old because it is. It's taken from a NASA report of the 1960's. The lines have not and will not move very much. What has changed over the decades is the development cost required to take any of these technologies from commercial state-of-the-art to spaceflight-ready. Lower level trades are commonly conducted with charts such the classic Ragone plot, which compares the specific energy and specific power capabilities of various battery chemistries and fuel cells. Such charts are used to determine the best specific energy solution between batteries and fuel cells whether they are to be used as the mission's primary energy source or, when Fig.1 might indicate another primary source (such as solar), as secondary energy storage.

III. NASA Spacecraft Fuel Cell Roadmap

As can be seen in Fig. 2, charts such as Fig. 1 have been the basis for the selection of spacecraft power systems since the beginning of human spaceflight. For the relatively short missions of the Mercury and Apollo LEM vehicles, batteries proved to be the lowest mass solution for primary power. Batteries also proved optimal as secondary eclipse energy storage for the solar-powered Skylab and International Space Station. This same scenario appears likely for NASA's new Orion crew exploration vehicle. While that design is still in the early stages as of this writing, the best system currently appears to be high-efficiency photovoltaic arrays and eclipse energy storage with lithium-ion batteries. Similar solutions may be repeated in some elements of the architecture of NASA's future lunar outpost, as of this writing projected to begin assembly in 2020 [1].

For crewed vehicles in which mission duration and power demand have pointed to fuel cells as the lowest mass solution, the basic requirements on the fuel cell itself have remained remarkably consistent since the beginnings of human spaceflight. Vehicles are designed to carry a full mission load of very pure hydrogen and oxygen, and, in order to maximize total system specific energy, fuel cell power plants are required to be as efficient as possible. The fuel cell plant is also expected to be able to operate in an acceleration environment from 0 to 4 g's along any axis and to be able to support very rapid load swings, up and down from 15 to 100 % rated power in less than a quarter of a second. Even with all this, in order to minimize investment in new technology, all of NASA's fuel cell development efforts have started from commercial state-of-the-art. Early on, though, this meant starting with technology that was very much still in the lab. Fig. 3 details crewed spacecraft fuel cell design solutions to date.

NASA's first fuel cell was developed for the Gemini missions. At the time, General Electric had recently developed proton exchange membrane fuel cells using sulfonated polystyrene membranes, so that firm was contracted to provide the Gemini flight units. Due to the relatively high ohmic resistance of even the thinnest membrane then available, even a very heavy layer of unsupported platinum catalyst resulted in only modest cell voltage at a very low current density. This turned out a very challenging development effort, and development delays forced the use of batteries on the first four, relatively short Gemini missions. The fuel cell design that finally did fly was rated for only around 200 hours, which was just long enough, but it still provided better specific energy than the batteries then available, even with relatively low the 650 W Gemini power load. Also, extreme launch mass limitations led NASA to fly with only two power strings on these missions fed by only one pair of reactant tanks.

After the Gemini experience, NASA chose as its fuel cell subcontractor the firm that, as of this writing, is part of UTC Power in Connecticut, who in turn based their design on the alkaline chemistry that had been developed to practice by Francis Bacon at Cambridge University around 1950. In order to save weight, NASA's Apollo plant ran at much lower pressure than the Bacon design, and, in order to pump the cell voltage back up to Bacon's level, ran at 204 ^{o}C. With this operating temperature, a less active nickel catalyst could be substituted for platinum. In order to keep the electrolyte solution from boiling at that temperature and to minimize ohmic losses, the potassium hydroxide concentration was set at 75% [2]. All this yielded much better cell voltage than the Gemini PEM plant, and, though the Apollo unit represented a step back in specific power, the higher cell voltage yielded a much improved specific energy.

The Space Shuttle's fuel cell plant represents a vast improvement over the Apollo unit in every figure of merit important to a spacecraft application. The polarization curve is much flatter, and higher cell voltage and much lower dry mass yield massively improved specific power. Specific energy is also improved significantly. The Shuttle plants were originally rated for a 2500 hour operating life, limited by the ability of the cells to respond to large load swings after many operating hours. However, the need for multiple mission use drove NASA to consider ways to improve upon this. A fundamental limit on the life of alkaline fuel cells stems from the propensity of the strong potassium hydroxide electrolyte solution to eventually eat its way through the electrode frames. In the early 90's this issue led NASA to consider replacing the Shuttle plant with one based on proton exchange membrane (PEM) chemistry, which by then had been greatly improved via private sector and U.S. Department of Energy investment. This technology promised not only longer operating life but also much improved specific power at the price of somewhat lower specific energy. Nevertheless, relatively minor modifications to the Shuttle's existing alkaline plant were found to enable double the operating life (to 5000 hours) at much less investment than that of developing a new PEM plant. This new Shuttle certification was completed in 2003, but the projected retirement of the Space Shuttle in 2010 has led NASA to refrain from fielding the longer life stacks in the fleet.

The studies of PEM technology in the 90's did, however, help NASA to develop a set of generic requirements for future spacecraft fuel cells. As these include a 10,000 hour (plus) operating life, rapid start-up and load following response, and capability for less than perfectly pure reactants, alkaline and solid oxide chemistries have basically been eliminated from near-term consideration for NASA's spacecraft technology investments. The Human Exploration Program's focus is on PEM technology, with no expense to be spared to obtain the highest possible efficiency and specific energy. PEM technology is also projected to offer a factor of three improvement in specific power over the Shuttle's alkaline plant. Note that this prospective fuel cell, like all of the previous spacecraft fuel cells, is to be operated at low current density in the high voltage regime of the polarization curve. This has significant implications for technology development, which will be discussed in the next section.

PEM fuel cells and electrolyzers will likely find many applications in NASA's future lunar outpost, now projected to begin assembly in 2020. Along with the lunar lander and various pressurized and unpressurized surface rovers, a key application may be in base power. Current architectural concepts have the outpost located on a crater rim at one of the lunar poles, thus enabling continuous sunlight for the greatest part of any year. A field of photovoltaic arrays looks to be the best power solution for this location, but, as there are periods of up to 6 days of continuous eclipse at even the best such sites, there is a requirement for a large amount of energy storage. PEM regenerative fuel cell systems look to be the best solution for this.

The outpost architecture may also include the production of oxygen from the lunar soil for use as life support, rocket propellant, and power reactant. This concept is known within the spaceflight community as in-situ resource utilization (ISRU). The lunar soil, or, more properly, regolith, is made up of silicon oxide and various metal oxides combined in an assortment of minerals. NASA is studying commercial metal refining processes (such as hydrogen reduction) for use in cracking the oxygen from these minerals. While these processes are considered very energy intensive in commercial applications, producing oxygen on the moon in this way should require considerably less energy than accelerating the bulk oxygen from the Earth's surface. The final step in cracking oxygen by these methods generally involves water or steam electrolysis at a steady rate, so solid oxide chemistry may find application here. The economic yield from successful development of such technology may make the difference between going back to the Moon to visit and going back to the Moon to stay.

IV. Benchmarking with "The Hydrogen Economy"

NASA has continued to support the development of fuel cell technology over many decades, following a defined roadmap that consistently focuses on the requirements most important to spacecraft application. As a means of minimizing the investment required, NASA has of course tried to use technology already developed for commercial applications. However, as the human space flight program offered the first truly economically advantageous application of fuel cells, NASA found little commercial work upon which to build until the mid-1990's. Then the environment changed. Interest in "Green Power" and "The Hydrogen Economy" has led to an enormous increase in investment in fuel cell development by the private sector and by various domestic and foreign government agencies, at a level dwarfing that of NASA by a good two orders of magnitude. As much of this commercial investment is focused on the PEM chemistry to which NASA is also primarily looking for the future, it might be presumed that the Human Exploration Program could, certainly after ten years of this massive program, find the power plants needed "off the shelf." This is an incorrect assumption. The differences in requirements between human spaceflight applications and almost all commercial applications, particularly automobiles, drive fundamental design differences down even to the level of the catalyst lay-up in membrane electrode assemblies (MEAs).

Spacecraft designers have interests in all elements of a fuel cell power system, just as do automobile designers, but the emphasis varies. Benchmarking results follow for several significant fuel cell system components: fuel cell MEAs, fuel cell balance of plant, electrolyzers, and hydrocarbon fuel processors.

A. The Fuel Cell MEA

Presented in Fig. 4 for comparison are single cell polarization curves for a spacecraft MEA developed under NASA sponsorship [3] and for an automotive MEA developed in the laboratories of General Motors [4]. The curves presented were taken at conditions nearly representative of how they would be run in their respective applications. Temperature and humidification are thus similar. Note, however, is that, while an automotive cell would be run on air, pure oxygen data for that cell is shown here to normalize the comparison. It is first noted that the voltage performance across the current density range is not very different. What is notably different between these two examples is the operating pressure (which will be discussed in a subsequent section) and the platinum catalyst loading chosen for the cathode. In this example, the spacecraft cell has 4 mg/cm^2 of unsupported platinum metal powder on the cathode, while the automotive cell has 0.5 mg/cm^2 of the carbon supported platinum catalyst that has been developed to minimize the cost of platinum for mass production fuel cell applications. The reasons a spacecraft fuel cell designer would choose to apply an order of magnitude more precious metal at the cathode and to not take advantage of the tremendous investment that has been applied to development of carbon supported catalysts have to do with differences between the spacecraft and automobile applications in the priorities placed on specific energy and on recurring manufacturing cost.

To understand the differences in operating conditions, one must first consider that, as illustrated on Fig. 4, automotive fuel cells are operated at a much higher current density (~1000 mA/cm^2) than spacecraft fuel cells (~200 mA/cm^2). This is a result of the priority placed on specific power in an automotive application verses that placed on specific energy in a spacecraft application. Differences in operating pressure notwithstanding, if run at the spacecraft current density, an automotive plant producing a given power would require a stack weighing six times what it would weigh if run at the typical automotive current density. Also, the higher operating voltage in the spacecraft cell translates into higher efficiency, which is critically important when the power system must carry with it a full mission load of both reactants. Thus, in a spacecraft application, the mass of the stored reactants required for a given mission would be fifty percent greater if the fuel cells were run at the automotive cell voltage rather than at the spacecraft cell voltage. This higher efficiency also reduces the load on and, therefore, the mass of a spacecraft's heat rejection system.

Humidification also plays into these differences in operating conditions. One must note that, as spacecraft systems will recirculate both reactants as a matter of course, product water can be managed so as to maintain the full humidification that minimizes membrane ohmic resistance even when utterly dry gas is being provided. On the other hand, while pure hydrogen automotive systems often do recirculate the fuel, the oxidant is drawn from the atmosphere and product water is expelled along with it. As air humidifiers significantly impact the reliability and weight of an automotive power plant, automotive fuel cell developers are working toward MEAs that can provide the efficiency associated with the curve shown at a relative humidity down to 25%. One should note that this same specific energy verses specific power verses complexity tradeoff often leads to spacecraft stacks being operated at higher pressure than automotive stacks (as is done in the example shown here). This trade will be discussed in the section dealing with fuel cell balance of plant.

Requirements for durability under the differing operating conditions discussed above drive the selection of different catalyst layers for spacecraft and automobiles. The first reason for this difference is that, in carbon supported catalysts, platinum dissolution and sintering is notably accelerated at the higher spacecraft cell potentials. Second, platinum dissolution is also enhanced at the higher humidification provided for spacecraft applications. Third, the spacecraft's higher cell potential, along with the required use of pure oxygen, act to accelerate corrosion of the carbon supports [5]. Thus, the conditions under which a spacecraft fuel cell must operate significantly impact the ability of the carbon supported catalysts to meet even the 5000 hour automobile durability requirements, much less the 10,000+ hours required in spacecraft. Metal powder catalyst layers require much more platinum for the same cathode activity, but are less susceptible to these side reactions. Additionally, carbon supported catalysts do not protect the membrane from local pinching by the sharp points of the gas diffusion layer's carbon mesh, allowing the creation of pinholes as the membrane swells and shrinks under humidity cycling. Metal powder catalysts are stiffer and protect the membrane with larger contact surfaces. Spacecraft fuel cell developers therefore continue in the direction of unsupported metal powder for catalyst.

Along with operating conditions, another significant driver for the design solutions chosen for spacecraft and automotive MEA catalysts is the differing priorities placed on specific energy and recurring costs. For automotive plants this is what motivates using as little platinum as possible, and in turn motivates development of the carbon-supported catalysts that provide more efficient distribution of platinum at the price of the durability limitations discussed above. Conversely, anticipated production quantities of spacecraft fuel cells are very low, in the dozens of units. Thus, a spacecraft designer will choose to use as much platinum as will do any good at all for maximizing efficiency and specific energy.

It is instructive therefore to examine with a rough analysis the relative cost and value of platinum in the two examples presented. Fig. 5 plots polarization curves from the spacecraft and automotive cells of Fig. 4, focused in at the spacecraft operating point and normalized for ohmic losses (i.e., iR-free) [3] [4] and for operating pressure [6]. We thus see the cell voltage difference due purely to cathode catalysis kinetics. It can be seen that the application of an order of magnitude heavier platinum loading in the spacecraft case yields, at the spacecraft current density design point, a cell voltage improvement of only 29 millivolts. If assembled into a set of Space Shuttle class power plants producing 15 kW (a typical Shuttle power demand) at that current density, this small improvement in cell voltage comes at the price of $9,800 in additional cathode platinum alone (at prices roughly current as of this writing). This would amount to $59,000 additional cathode platinum cost in a 90 kW automotive power plant. An automotive fuel cell built at this cost would, of course, not be commercially competitive. Lest this appear to be a case of government "gold plating", one should consider that this small increase in cell voltage and efficiency, at 15 kW, decreases reactant consumption by 190 g/hr. These savings are not even measurable in an automotive application, but, noting that the accepted marginal cost of accelerating a gram of anything to low Earth orbit remains at around $20, arithmetic left to the student reveals that all this additional platinum pays for itself in the first two and a half hours on-orbit. The payback is somewhat faster if one also accounts for the reduction in radiator mass resulting from use of even this slightly more efficient power plant.

This illustrates why on-going NASA-sponsored research is pointed toward applying even heavier platinum loading (up to ~8 mg/cm^2 at the cathode) in an attempt to make durable MEAs that provide better than 900 mV at the spacecraft standard current density [3], while automotive researchers seek to provide just the cell polarization performance illustrated in Fig. 4 with even less platinum (down to 0.2 mg/cm^2) and no active humidification [4].

As for the membranes themselves, foreseeable spacecraft requirements are being met reasonably well with the current class of perfluorosulphonic acid membranes. Spacecraft designers will select thicker membranes than will automotive designers, thereby gaining stack durability. The resulting increase in ohmic resistance is counteracted by operating at low current density and by using full humidification in the reactant streams.

In the automotive industry, however, a great deal of effort is being put into the development of hydrocarbon-based membranes [5] [7]. Remarkably, automotive requirements on membranes are much more severe than those of spacecraft. The ohmic losses at the high automotive current density are much more significant, driving designers to thinner membranes that must still be sufficiently durable. Also, automotive fuel cell designers wish to run their power plants at temperatures above 120 ^{o}C (which would enable use of current automotive heat rejection systems) and without any external humidification. Further, the plants must be able to start up at temperatures well below freezing. Current membranes, such as Nafion, can quickly lose both their proton conductivity and their durability under these conditions, hence the interest in other chemistries. In contrast, spacecraft applications feature much tighter control of environmental temperature (driven by the need to maintain other spacecraft components within a benign range) and have available any desired humidity and a much colder heat sink. As the higher cell voltages that could be enabled by higher temperature membranes would also enhance spacecraft fuel cell performance, NASA may likely make use of these hydrocarbon membranes but is only minimally participating in their development.

In sum, while spacecraft applications will likely make use of automotive membranes as they are developed, the differences in catalyst layer requirements are so significant that the NASA Human Spaceflight Program will likely have to continue independent development of unique MEAs.

B. *The Fuel Cell Balance of Plant*

In the fuel cell balance of plant, spacecraft and automotive engineers share the same goals of minimum weight, simplicity and high reliability. With automobiles, the primary tradeoff in this field is between the added power drain and complexity of an air intake compressor and the efficiency benefits of high pressure oxidant. With a spacecraft reactants would always be fed from high pressure storage, so the question is how simple the plant can be and still manage water and heat in the stack. A brief review of NASA's solutions in this area is in order.

For the Shuttle's alkaline power plants, reactants are fed dry from high pressure cryogenic storage to the plant at a regulated pressure (around 400 kPa$_{abs}$). As water is produced at the anode in this chemistry, pure oxygen is deadheaded to the cathode, and hydrogen is recirculated by a low pressure centrifugal pump and water separator. The fuel is humidified by product water evaporating from the stack, and the rate at which this water is condensed out is regulated by a thermal control system so as to maintain proper concentration of the cell's electrolyte. The condensed product water is stored for life support use. A pumped coolant stream removes excess heat. Two pieces of rotating machinery are thus required in this balance of plant.

The balance of plant for PEM power plants built to date under NASA sponsorship is rather more complex than that of the Shuttle. Dry reactants are again fed to the plant at a pressure regulated down to, here, 140 kPa$_{abs}$ (thus helping to enable a lighter stack than with the Shuttle). In the plant NASA most recently tested, both reactants are recirculated with centrifugal pumps, and, as the various diffusion processes in PEM cells can yield liquid water at both electrodes, both reactant streams feature rotating machinery for water separation. Product water is managed thermally to keep both reactant streams highly humidified (~70% RH) at the stack inlet. As product water in the stack is managed with flow entrainment and the oxygen steam exits the stack at well above 100% RH, a high cathode stoichiometric ratio (10-20) is used to inhibit flooding. Note that, not only does such a balance of plant involve five pieces of rotating machinery to the Shuttle's two, two of the PEM's pieces must spin in a stream of pure oxygen. NASA safety assessments label this as a catastrophic hazard, which does not exist in alkaline power plants. Also, the exposure of so many components to warm, humidified oxygen creates corrosion issues.

As a result, current spacecraft development efforts are focused on developing high reliability power plants that require no rotating machinery at all in the reactant streams. One concept under test, known as "flow through", involves both reactants being recirculated with ejectors and water removal being accomplished by either a flow driven centrifuge or a bubble pressure-driven sieve of alternating hydrophobic/hydrophilic foams. Another concept, named "non-flow through", involves deadheading both reactants and using a foam wicking structure between MEAs to remove product water. Developing a system that can provide the proper reactant flows, humidity control, cooling, and bubble pressure over the full load following range of a spacecraft plant is proving to be a challenge.

C. The Electrolyzer

The role of an electrolyzer is quite different between spacecraft and automotive systems. For an automobile system, an electrolyzer can be the core of the stationary plant that produces hydrogen for vehicular use. In a spacecraft, they are either half of a regenerative fuel cell storage system or the last step in an oxygen production plant.

At the MEA level, the differences between spacecraft and automotive designs are essentially the same as with fuel cells. Spacecraft system designers wish the highest possible specific energy and thus the lowest overvoltage. To achieve this, the electrolysis mode of a spacecraft regenerative fuel cell system will be run at low current density, and the MEAs will be built with heavier loadings of the more active and expensive electrolysis catalysts, such as iridium oxide.

At the level of the assembled stack and balance of plant, a major difference between spacecraft and commercial electrolysis applications is the requirement, in the energy storage case, to generate both hydrogen and oxygen at high pressure, rather than venting the oxygen as would an electrolyzer at an automotive hydrogen fueling station. This drives very different membrane support structures in the stacks and, thus, the many electrolyzer products being developed for "The Hydrogen Economy" are unsuitable for spacecraft applications. NASA has thus recently had custom-built and tested the first full multi-kilowatt class closed hydrogen oxygen regenerative fuel cell plant. This is a discrete system. NASA is also sponsoring the development of a prototype unitized system. Which type of regenerative system will in any given application will depend upon the relative importance in this application between maximum stored specific energy and maximum specific power.

Equally significant electrolyzer plant-level differences exist between automotive applications and those of lunar oxygen production. While both run at steady currents with fewer load swings and start-ups than with a mobile fuel cell, in case of the lunar plant, it is the oxygen that must be evolved at high pressure for storage, with the hydrogen being recirculated back into the process at relatively benign pressures. NASA is also having to sponsor custom designs for these units. While the efficiency and integration advantages of solid oxide electrolysis may prove worthwhile in these applications, NASA has not yet begun significant development in that area.

D. The Hydrocarbon Fuel Processor

While hydrocarbon fuel processing is perhaps the most challenging issue for automotive fuel cell systems and the focus of a large percentage of the development funding in that industry, spacecraft designers see it as becoming an issue farther down the road in the Human Spaceflight Program. Nearest on the horizon, the development of the future lunar outpost's process plants for cracking oxygen from regolith will likely benefit from application of commercial desulfurization technology, as the lunar regolith contains enough sulfur to quickly degrade such a plant's electrolyzer. Also, it is theorized that the hydrogen, which the Clementine mission detected near the lunar poles, may be in the form not only of water ice but also of hydrocarbons such as methane. If this turns out to be the case, then these hydrocarbons may not only be used directly as propulsion reactants but be processed into hydrogen for use in fuel cells. Also, some years ago, NASA invested some development funding in Sabatier reactors with an eye toward processing the carbon dioxide in the Martian atmosphere with any water which might be found there into methane for propulsion use. In a Martian outpost in the hopefully not too distant future, this methane could also be reformed back into carbon dioxide and hydrogen. Thus, reforming processes are of interest to NASA in the longer term. Just like with fuel cells and electrolyzers, the priorities of NASA will be skewed heavily toward minimum mass and maximum efficiency and away from any concerns for low recurring cost.

V. Conclusion

In carrying forward the Human Spaceflight Program, NASA project managers would of course prefer that technology useful to NASA's mission be developed in the private sector, just as the private sector has benefited over the years from technology developed in support of the space program and of national defense. It is always preferable to have the inventing one needs done with someone else's money. However, as discussed in the preceding text, the development needs of NASA's Human Spaceflight Program and those of "The Hydrogen Economy" have surprisingly little in common. The space program's interest in fuel cells has nothing to do with "alternative energy." Spacecraft designers in fact do not have any alternative but to choose the highest specific energy and highest reliability source of the energy needed for a vehicle's mission. Of even more significance, the sheer magnitude of development investment and market potential associated with "green energy" applications makes the leaders in the fuel cell industry reluctant to bother with NASA's small development contracts. A future as a NASA subsystem contractor, producing a unique system with little potential for other customers and maintaining a sustaining engineering workforce for many years, does not fit well with the business model of a corporation that is traded on the NASDAQ and that is seeking to launch a product into a potential market of hundreds of thousands of units.

NASA's Human Spaceflight Program will of course continue to benchmark developments in "The Hydrogen Economy" and to share its own results. Human exploration of the solar system and realization of "The Hydrogen Economy" are truly long term programs, and NASA/DOE/industry partnerships are key to the sustainability of both efforts. Whether the mission is to explore other worlds or to take better care of the one that humans inhabit now, it is cooperative engineering that will speed progress.

ACKNOWLEDGMENT

The author wishes to thank the ASME for the invitation to create this publication. The author also wishes to recognize the invaluable technical contributions to this study of Messrs. Koroosh Araghi, Art Vasquez, and Ken Poast of NASA's Lyndon B. Johnson Space Center, Mr. Mark Hoberecht of NASA's John H. Glenn Research Center, Dr. Sri Narayan of NASA's Jet Propulsion Laboratory, Mr. Patrick Davis of the U. S. Department of Energy, Dr. Rodney Borup of Los Alamos National Laboratory, Dr. John Kopasz of Argonne National Laboratory, Mr. Robert Byron of United Technologies Corporation Power, and Dr. Mark Mathias of the Fuel Cell Activities Division of General Motors Corporation.

REFERENCES

[1] LaVoie, A. R., Kerslake, T. W., Freeh, J. E., Fincannon, H. J., 2007, "Candidate Power/Energy Architectures from NASA's Lunar Architecture Team (LAT-1) Study Panel," 5th International Energy Conversion Engineering Conference, June 25-27, St. Louis.

[2] Warshay, M., Prokopius, P. R., "The Fuel Cell in Space: Yesterday, Today, and Tomorrow," 1989, NASA TM-102366.

[3] Narayan, S. R., Valdez, T., and Sirdosy, S., 2007, "High Performance Membrane Electrode Assemblies for Primary and Regenerative Fuel Cells," Space Technology Applications International Forum (STAIF) 2007, February 12-16, Albuquerque.

[4] Neyerlin, K. C., Gu, W., Jorne, J., Clark, A., and Gasteiger, H. A., 2007, "Cathode Catalyst Utilization for the ORR in a PEMFC," J. Electrochem. Soc., **154** (2), pp. B279-B287.

[5] Mathias, M. F., Makharia, R., Gasteiger, H. A., Conley, J. J., Fuller, T. J., Gittleman, C. J., Kocha, S. S., Miller, D. P., Mittelsteadt, C. K., Xie, T., Yan, S. G., Yu, P. T., 2005, "Two Fuel Cell Cars in Every Garage?" *Interface*, **14** (3), pp. 27-35

[6] Larminie, J., Dicks, A., 2003, *Fuel Cell Systems Explained*, John Wiley & Sons Ltd., Chichester, pp. 102-106.

[7] Dunwoody, D., Leddy, J., 2005, "Proton Exchange Membranes: The View Forward and Back," *Interface*, **14** (3), pp. 37-39.

Fig. 1. Spacecraft Energy Source Capabilities. This plots the locus of maximum specific energy solutions as a function of power demand and mission duration..

Fig. 2. NASA Spacecraft Power Source Roadmap. NASA has consistently pursued, and continues to pursue, high specific energy solutions for the human spaceflight program.

Fig. 3. Normalized performance data on historical human spaceflight fuel cells with prospective goals for future power plants [2] [3].

Fig. 4. Representative Fuel Cell Polarization Performance. Single cell data for (a) a spacecraft fuel cell built of Nafion 115 with 4.0 mg/cm^2 of unsupported Pt on the cathode and operated with pure H_2/O_2 at ~65% inlet relative humidity, 70 ^oC, and 300 kPa_{abs} [3]; and (b) an automotive fuel cell built of Nafion 111 with 0.5 mg/cm^2 of carbon support Pt on the cathode and operated with pure H_2/O_2 at 60% inlet relative humidity, 80 ^oC, and 100 kPa_{abs} [4].

Fig. 5. Normalized Fuel Cell Catalyst Performance. Single cell data, iR-free, for (a) a spacecraft fuel cell built of Nafion 115 with 4.0 mg/cm^2 of unsupported Pt on the cathode and operated with pure H_2/O_2 at ~65% inlet relative humidity, 70 ^oC, and 300 kPa_{abs} [3]; and (b) an automotive fuel cell built of Nafion 111 with 0.5 mg/cm^2 of carbon support Pt on the cathode and operated with pure H_2/O_2 at 60% inlet relative humidity, 80 ^oC, and (by analysis [6]) 300 kPa_{abs} [4].