The Development of Fuel Cell Technology for NASA's Human Spaceflight Program

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My task this morning is to review the history and current direction of fuel cell technology development for NASA's human spaceflight program and to compare it to the directions being taken in that field for "The Hydrogen Economy." The concept of "The Hydrogen Economy" involves many applications for fuel cells, but for today's discussion, I'll focus on automobiles.

Automotive Power Systems:

• Development, Production & Operation Cost ($/kW)

• Specific Power/Energy (kW/kg, kW/l, kWh/kg, kWh/l)

• Emissions (NO_x, CO_x, noise)

Constraint: Public Safety

I'll begin with a review of the fundamentals of power systems engineering. For any application, systems engineering is about tradeoffs between various attributes bounded by absolute constraints. What varies among applications is the priority of those attributes and the nature of the constraints. For an automobile propulsion systems, the three most important attributes are:

•Cost. For any application requiring mass production, such as that of cars, priority is placed on recurring manufacturing and maintenance costs.

•Specific power and energy. It is useful to 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 is the ability to decrease or eliminate harmful emissions that makes fuel cell technology so important in development of the "Hydrogen Economy." Also, a fuel cell plant is much quieter than a diesel generator set, yielding an obvious benefit to the military's "silent watch" concept.

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, such as most of us in this room.

Spacecraft Power Systems:

• Specific Energy (kWh/kg)

• Specific Energy (kWh/kg)

• Specific Energy (kWh/kg)

• Development Cost

Constraint: Full Mission Reliability

The priority attributes in spacecraft applications are rather different from those of cars and, in fact, parallel with those of real estate. What are the three most important things in real estate: Location, Location, and Location.

Likewise, the three most important things is spacecraft power systems are: Specific energy, specific energy, and specific energy.

Spacecraft must carry a full mission load of both fuel and oxidant. With launch costs hovering at $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 already been developed commercially to the extent it exists. The last thing we want to do in a flight project is invent something, but, if it's worth a couple of hundred kilograms, we will invest a lot to do just that. Note that recurring production cost is not a significant consideration. The Space Shuttle Orbiter is fuel cell powered. In the thirty year history of the space shuttle program, NASA has only procured just over 100 fuel cell stacks.

   The absolute constraint is not so much public safety but mission reliability, almost always judged by having verifiable redundancy, and sufficient durability, which, with the advent of the long missions planned for Exploration Initiative, is becoming a much more challenging issue. In general, redundancy trumps weight in importance. NASA's general rule is to have two fault tolerance to catastrophic failure. This implies a requirement for AT LEAST THREE INDEPENDENT POWER STRINGS except when this doesn't end up decreasing reliability. Redundancy management is thus crucial and complicated. This why the Space Shuttle Orbiter, on which launch mass is extremely valuable, carries three independent fuel cell power plants feeding three cross-strapped power buses, when, in a pinch, it could limp home on one. As reliable as the Shuttle's fuel cells have been, this configuration is not over conservative. Among the 116 Shuttle missions to date, only four have had to be terminated prematurely. Of those two have been terminated due to a real or perceived failure in a fuel cell power plant.

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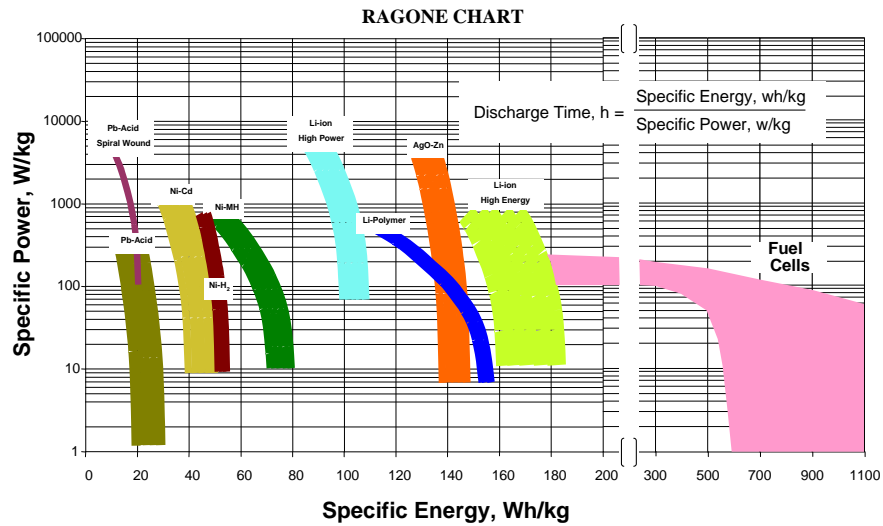Power Generation Specific Energy Trade Space
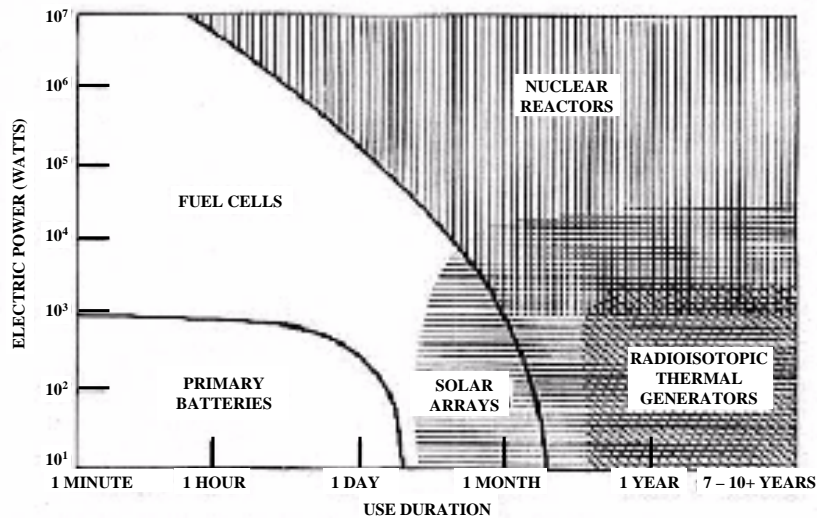
A common tool in spacecraft power system engineering is illustrated here. This plots the locus of maximum specific energy solutions for a given power demand and mission duration.

It looks old because it is. It's taken from an 1960's NASA report. 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.

RAGONE CHART

Specific Power, W/kg (y-axis): 100000, 10000, 1000, 100, 10, 1

$$\text{Discharge Time, h} = \frac{\text{Specific Energy, wh/kg}}{\text{Specific Power, w/kg}}$$

Chart labels: Pb-Acid Spiral Wound, Ni-Cd, Ni-MH, Pb-Acid, Ni-H$_2$, Li-ion High Power, Li-Polymer, AgO-Zn, Li-ion High Energy, Fuel Cells

Specific Energy, Wh/kg (x-axis): 0, 20, 40, 60, 80, 100, 120, 140, 160, 180, 200, 300, 500, 700, 900, 1100

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24 May 2007

Lower level trades are commonly conducted with charts such as this, illustrating the capabilities of various battery chemistries and fuel cells in both energy storage and power output. 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 the previous chart indicates another primary source (such as solar), as secondary energy storage.

Human Space Flight Energy Storage Roadmap
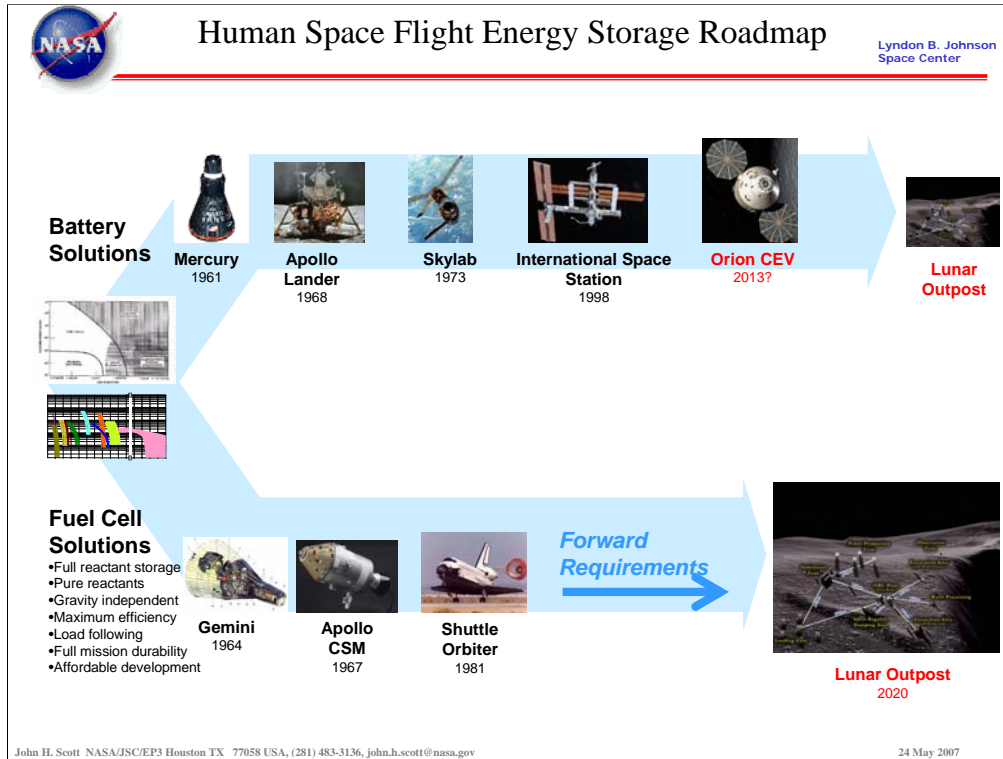
Charts such as the two just displayed have been the basis for the selection of spacecraft power systems since the beginning of human spaceflight. For the relatively short missions of the Mercury and Apollo LEM vehicles, batteries proved to be the lowest mass solution, and, though their very long missions drove the selection of photovoltaics as the primary power source, eclipse energy storage for the Skylab and International Space Station was best provided by secondary batteries. This same scenario appears likely for NASA's new Orion crew exploration vehicle. While that design is still in the early stages, the best system currently appears to be high-efficiency photovoltaic arrays with eclipse energy storage by Lithium Ion batteries. Similar solutions may be repeated in some elements of NASA's future lunar outpost architecture.

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 have remained remarkably consistent since the beginnings of the human spaceflight program. Vehicles are expected to carry a full mission load of very pure hydrogen and oxygen, and, in order to maximize total system specific energy, fuel cell plants are required to be as efficient (and, thus, have a high a cell voltage) as possible, even at the price of sacrificing specific power. 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 durably support very rapid load swings, up and down from 15 to 100 % power in less than a quarter of a second. Finally, in order to minimize our investment in technology, all of our fuel cell development efforts started from commercial state-of-the-art, though, early on, this meant using technology that was very much still in the lab.

Human Space Flight Fuel Cell Roadmap

Lyndon B. Johnson Space Center
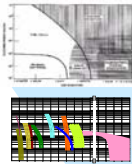
Fuel Cell Solutions
•Full reactant storage
•Pure reactants
•Gravity independent
•Maximum efficiency
•Load following
•Full mission durability
•Affordable development

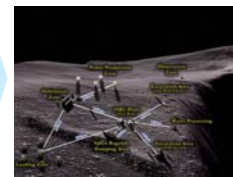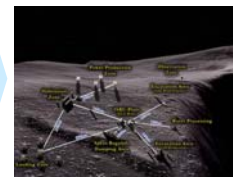**Gemini** 1964

Apollo CSM 1967

Shuttle Orbiter 1981

Forward Requirements

Lunar Outpost 2020

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Human Space Flight Fuel Cell Roadmap

The first NASA fuel cell was developed for the Gemini missions. At the time, General Electric had recently invented proton exchange membrane fuel cells using sulfonated polystyrene membranes, and they were contracted to design and provide the Gemini flight units. This was a very challenging development effort. Even a very heavy layer of unsupported platinum catalyst resulted in only modest cell voltage, due to the relatively high ohmic resistance of even the thinnest membrane then available. Development schedule delays forced the use of batteries on the first four (shorter) Gemini missions. The fuel cell design that finally did fly was rated for only 200 hours, but this operating life was long enough for the Gemini missions, and, given the Gemini power load of under 650W, still provided better specific energy than the batteries then available. Also, extreme measures in weight control led NASA to fly with only two power strings on these missions fed by only one pair of reactant tanks.

Human Space Flight Fuel Cell Roadmap

Apollo Fuel Cell
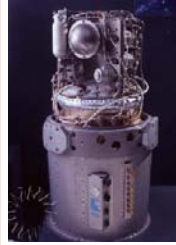
- Mobile alkaline electrolyte
- Catalyst: Ni
- 894 mV @ 167 mA/cm^2 (1.5 kW)
- 400 hr operating life
- 204 ^{o}C operating temp
- Flight set of 3
- 13.5 W/kg
- 1.2 kWh/kg with 3 reactant sets

Fuel Cell Solutions
- Full reactant storage
- Pure reactants
- Gravity independent
- Maximum efficiency
- Load following
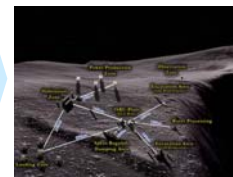- Full mission durability
- Affordable development

Gemini 1964

Apollo CSM 1967

Shuttle Orbiter 1981

*Forward Requirements*

Lunar Outpost 2020

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Coming out of the Gemini experience, NASA chose as its fuel cell subcontractor the firm now part of UTC Power in Connecticut, who in turn based their design on the alkaline chemistry that had been developed to practice by 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 C. With this operating temperature, a less active nickel catalyst was able to be substituted for platinum. In order to keep the potassium hydroxide solution from boiling at that temperature, the concentration was set at 75%, which would have been solid at lower temperatures. 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 voltage yielded a much improved specific energy.

Human Space Flight Fuel Cell Roadmap
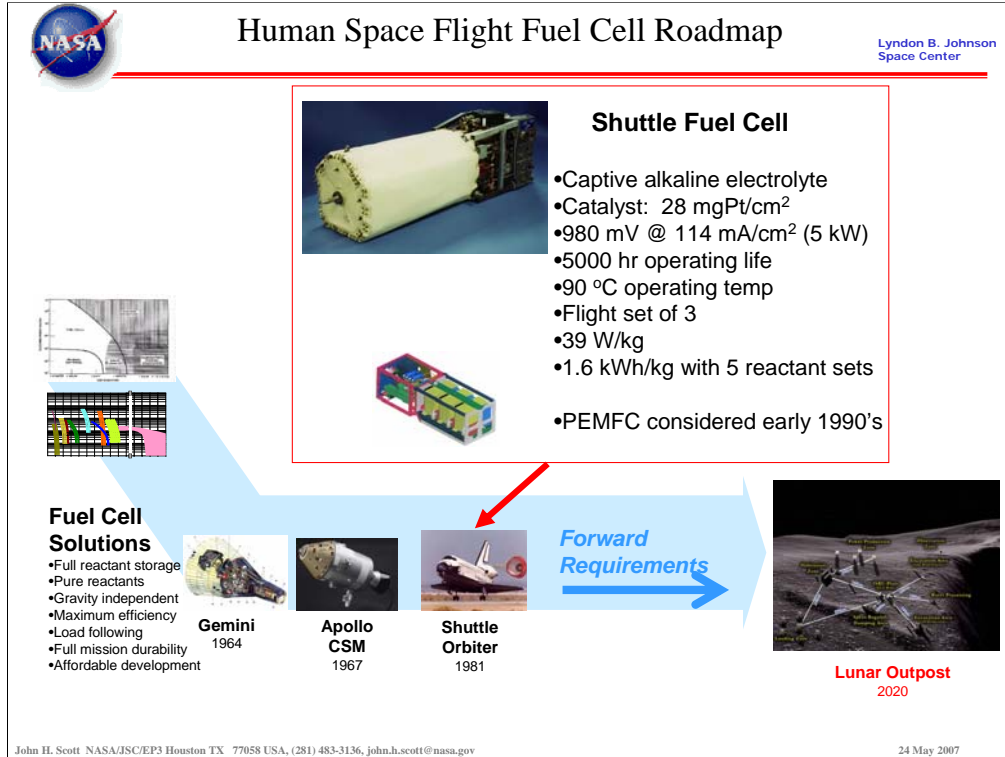
The Space Shuttle's plant represents a vast improvement over the Apollo unit in every figure of merit important to a spacecraft application. The polarization curve is much flatter, and higher cell voltage and much lower mass yields massively improved specific power, and specific energy is also improved significantly. The lower operating temperature enables much faster load following response.

The Shuttle plants were originally rated for a 2500 hour operating life. 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 seals on the electrode perimeter. In the early 90's this issue led NASA to consider replacing the Shuttle plant with one based on the proton exchange membrane technology which by then had been greatly improved via commercial investment. This technology promised not only longer operating life but also much better specific power at the price of somewhat lower cell voltage and 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 certification was completed just a few years ago, but the upcoming retirement of the Space Shuttle has led NASA to refrain from fielding the longer life stacks in the fleet.

Human Space Flight Fuel Cell Roadmap
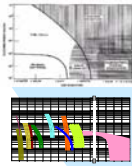
NASA

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Space Center

Fuel Cell Solutions
•Full reactant storage
•Pure reactants
•Gravity independent
•Maximum efficiency
•Load following
•Full mission durability
•Affordable development

Gemini 1964

Apollo CSM 1967

Sh
Or

Forward Requirements:

•Vacuum environment

•130 W/kg

•H_2/O_2 reactants

•Primary η_{th} >67 %

•Regen round trip η_{th} > 55%

•6:1 load swing in 200 ms

•10,000 hrs operating

Lunar Outpost 2020

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The studies of PEM technology in the 90's did, however, lead NASA to develop a set of generic requirements for future spacecraft fuel cells. As these include a 10,000 hour (plus) operating life and rapid start-up and load following response, alkaline and solid oxide chemistries have basically been eliminated from near-term consideration for NASA's spacecraft fuel cell technology investments. The focus is on PEM technology, with no expense to be spared to obtain the highest possible efficiency and specific energy. PEM technology is also seen to offer factor of three improvement in specific power over the Shuttle alkaline plant.

Human Space Flight Fuel Cell Roadmap
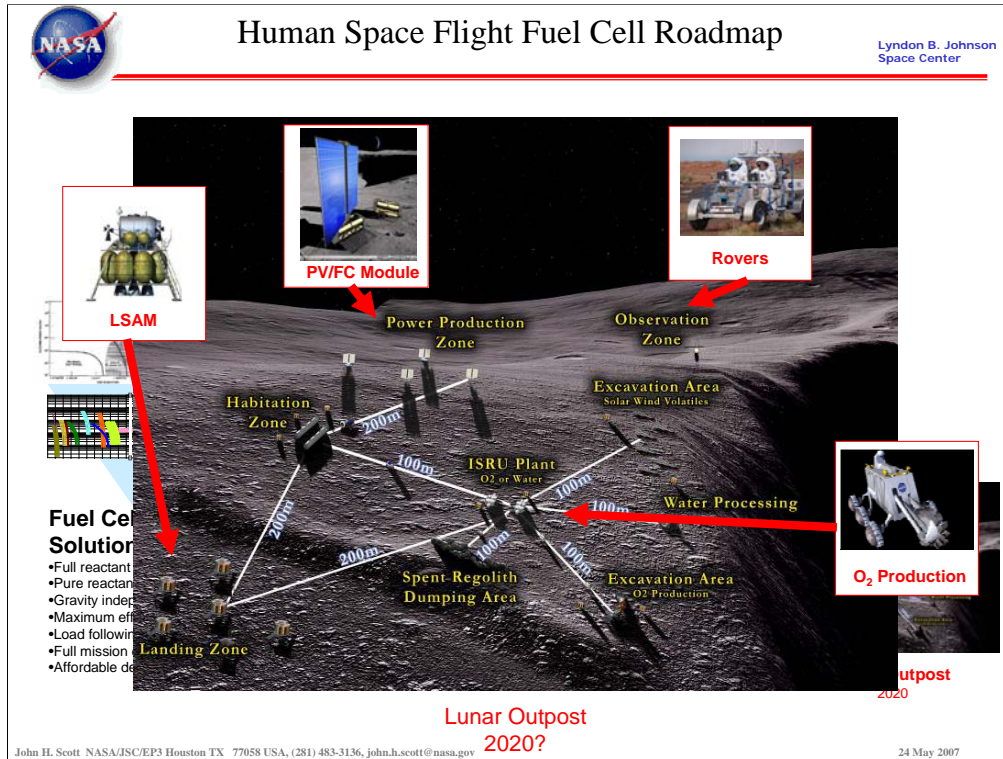
PEM fuel cells and electrolyzers will likely find many applications in NASA's future lunar outpost, now projected to begin assembly in 2020. Along with the lunar lander and various pressurized and unpressurized surface rovers, a key application may be in base power. Current architectural concepts have 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 at least 20 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 base architecture may also include the production of oxygen from the lunar soil for use in life support, rocket propellant, and power reactant. This concept is known within our community as In-situ resource utilization or 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 requires considerably less energy than accelerating the 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 to the Moon to visit and going to the Moon to stay.
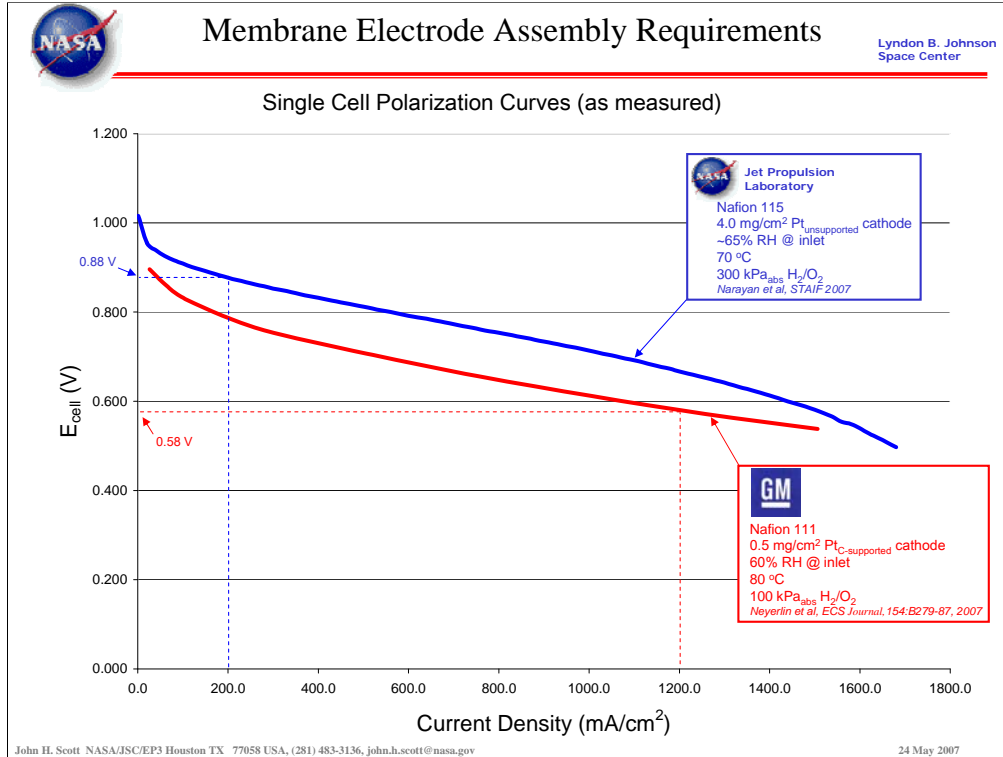
Human Space Flight Fuel Cell Roadmap
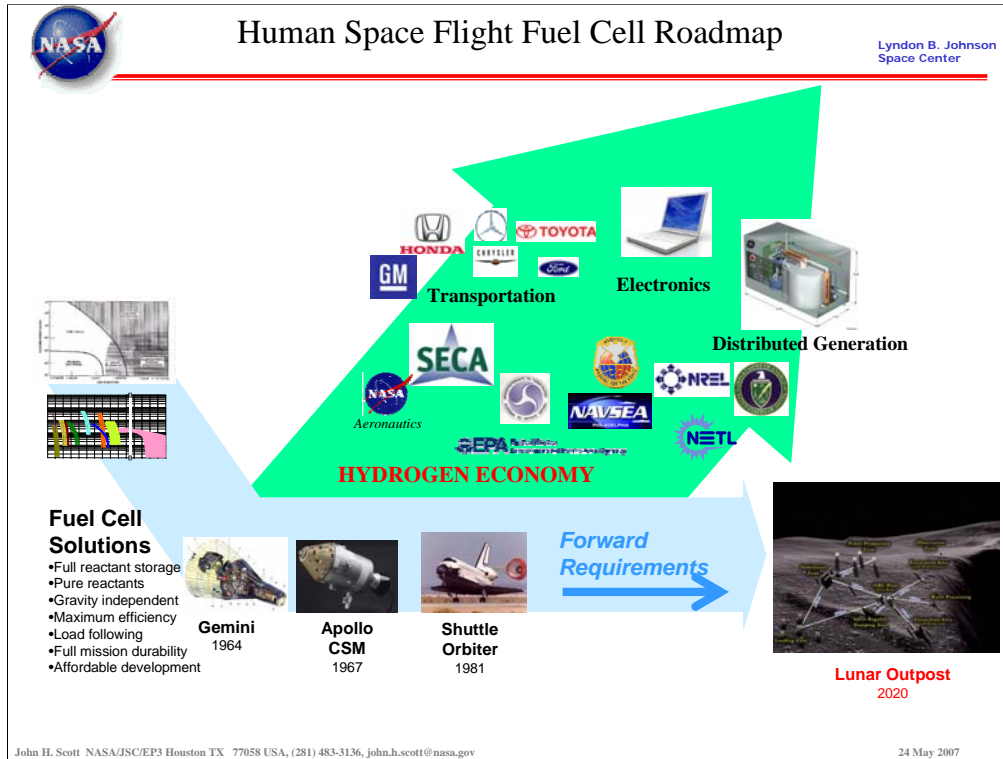
In sum, we at NASA have continued to support the development of fuel cell technology over many decades, following a defined roadmap that consistently focuses on the requirements most important to our application. As a means of minimizing the investment required, NASA has of course tried to use fuel cell technology already developed for commercial applications. However, as the human space flight program offered the first truly economic advantageous application of fuel cells, NASA found little commercial work upon which to build until the mid-1990's. Then it all changed. Interest in "Green Power" and "The Hydrogen Economy" has led to an enormous increase in investment in fuel cell development, 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, one might presume that we at NASA could, certainly after ten years of this massive development program, find the power plants we need off the shelf. This is completely untrue. The differences in requirements between the human spaceflight program and almost all commercial applications drive fundamental design differences down to even the level of the catalyst lay-up in MEAs. While these differences exist to varying degrees with all commercial applications, I'll simplify the discussion by illustrating this point with a comparison between fuel cell power plant designs for spacecraft and those for automobiles.

Elements of A Fuel Cell Power System
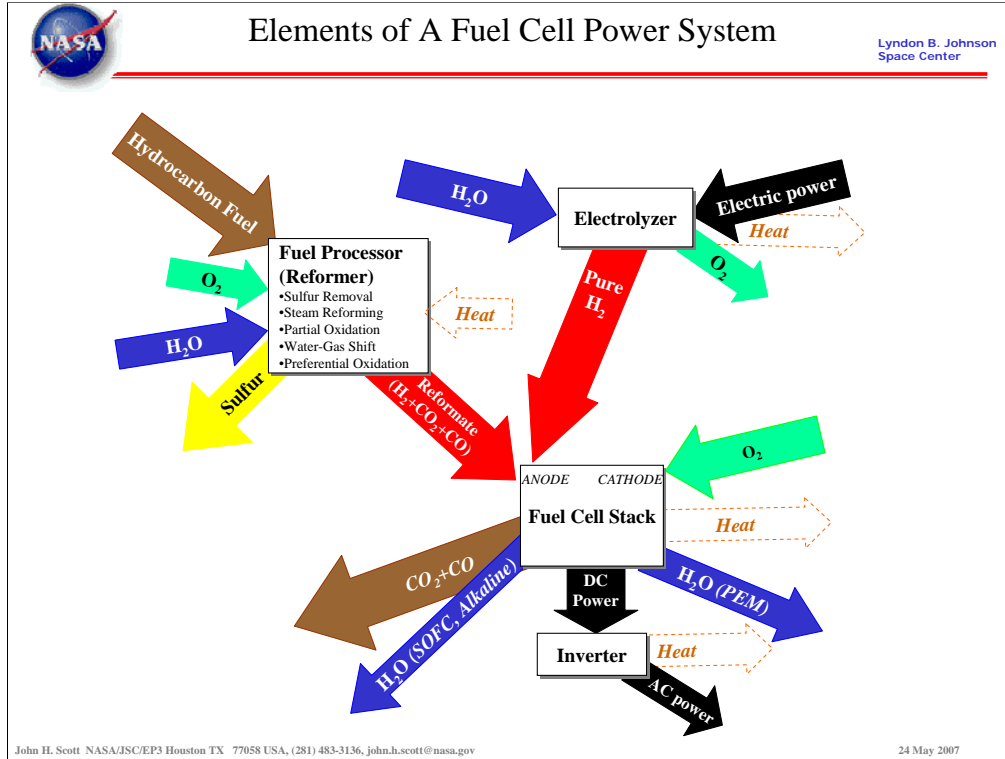
Spacecraft developers have special interests in all elements of a fuel cell power system, just as do auto designers, but the priorities vary widely.

Elements of A Fuel Cell Power System
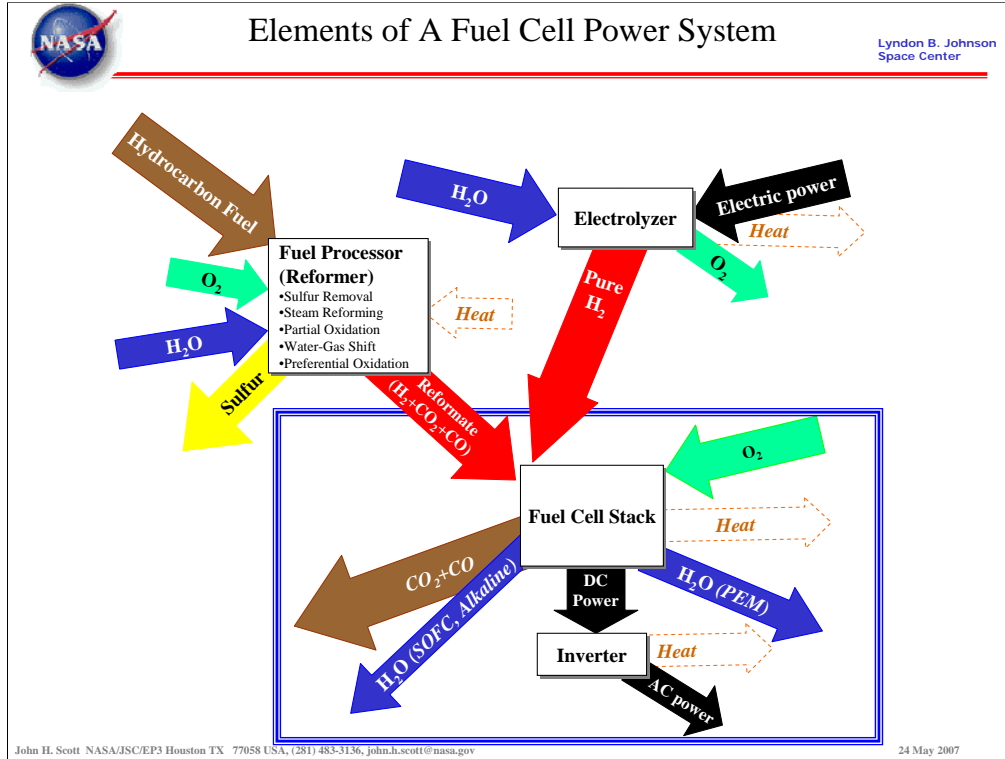
Of course, the development priority for both auto and spacecraft system developers is the fuel cell plant itself, from the MEAs to the balance of plant for reactant management.

Membrane Electrode Assembly Requirements

NASA

Lyndon B. Johnson
Space Center

Single Cell Polarization Curves (as measured)

Jet Propulsion
Laboratory
Nafion 115
4.0 mg/cm^2 Pt$_{unsupported}$ cathode
~65% RH @ inlet
70 ºC
300 kPa$_{abs}$ H$_2$/O$_2$
Narayan et al, STAIF 2007

0.88 V

0.58 V

GM
Nafion 111
0.5 mg/cm^2 Pt$_{C-supported}$ cathode
60% RH @ inlet
80 ºC
100 kPa$_{abs}$ H$_2$/O$_2$
Neyerlin et al, ECS Journal, 154:B279-87, 2007

Y-axis: E$_{cell}$ (V) — 0.000 to 1.200
X-axis: Current Density (mA/cm^2) — 0.0 to 1800.0

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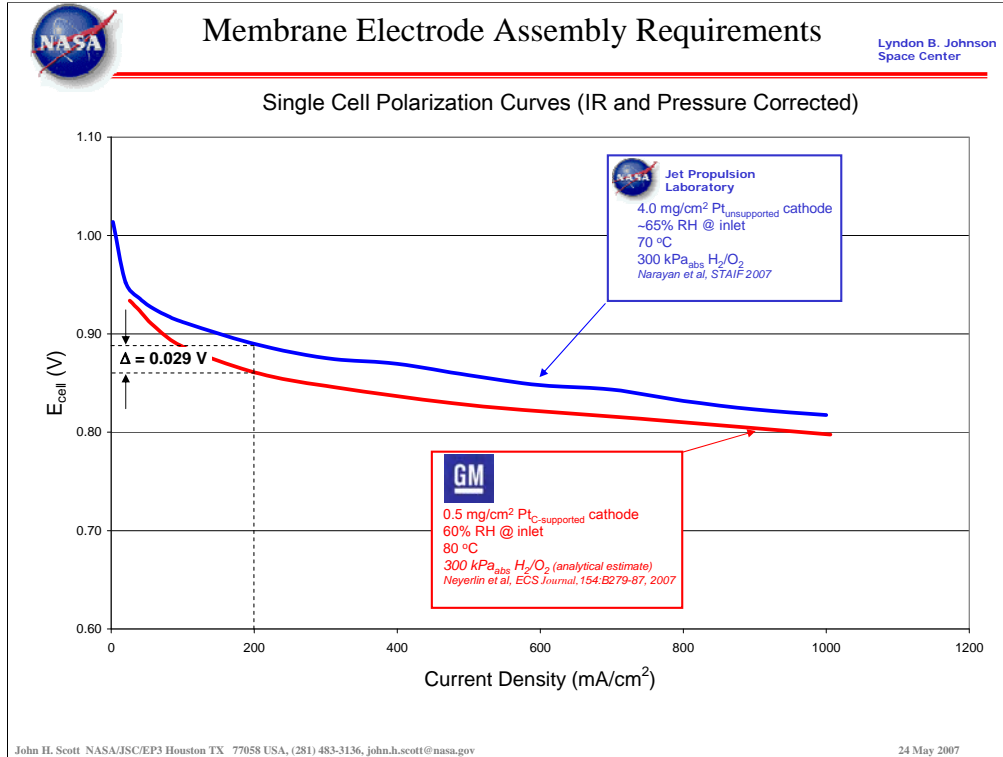
The differences between spacecraft and automotive MEA designs are significantly driven by the location on the polarization curve at which they will be operated and by their operating life and humidification requirements. The major resulting MEA design difference to notice is in catalyst loading and support. Presented here for comparison are single cell polarization curves for a spacecraft MEA developed under NASA sponsorship and for an automotive MEA developed in the labs of General Motors. The curves presented were taken at conditions representative of how they would be run in their respective applications. Temperature and humidification are thus similar, but pressure is quite different. Note, however, that, while an automotive cell would be run on air, pure oxygen data is shown here to normalize the comparison.

The spacecraft MEA is catalyzed with fine platinum power pressed into the membrane ionomer. As this arrangement yields much lower activity per unit mass of precious metal than the carbon supported catalysts of the automotive cell, the spacecraft cell requires an order of magnitude more platinum per unit area to maximize cathode activity.

Automotive stacks will be operated at a much higher current density than those of spacecraft. This is a result of a priority placed on specific power by an automotive application verses the penultimate priority placed on specific energy by a spacecraft application. Differences in operating pressure notwithstanding, if run at the 200 mA/cm2 spacecraft current density shown, the an automotive power plant producing a given power would require a stack weighing six times what it would weigh if run at the 1200 mA automotive current density. Conversely, 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 (even with the oxidant carried as pure oxygen). Thus, for 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. Humidification requirements play into this as well. It is important to note that, as spacecraft systems recirculate both reactants as a matter of course, product water is managed with heaters 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 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 powerplant, 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%. Note that this same specific energy/specific power/complexity tradeoff often leads to spacecraft stacks being operated at higher pressure than automotive stacks (as is done in the example shown here). We'll discuss this trade further later on.

It is these differing requirements on operating voltage, oxidant purity, and humidification that drive the selection of a catalyst layer design. Electrochemists understand that platinum dissolution and sintering is notably accelerated at the higher spacecraft cell potentials. Platinum dissolution is also enhanced at the higher humidification provided for spacecraft applications. The spacecraft's higher cell potentials, along with the required use of pure oxygen, also accelerates corrosion of the carbon supports which enable high activity with even the small amount of precious metal used in an automotive cell. 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 cell voltage, 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. In contrast, metal powder catalysts are stiffer and protect the membrane with larger contact surfaces. Spacecraft fuel cell designers therefore continue in the direction unsupported metal powder for catalysts. Note that alloy catalysts, such as platinum cobalt, are understood by researchers to offer notably higher activity for a given mass of pure platinum, making them very attractive for further lowering production cost in automotive applications, but the carbon-supported version appears susceptible to even more rapid activity degradation at higher cell voltages.

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Membrane Electrode Assembly Requirements

Single Cell Polarization Curves (IR and Pressure Corrected)

Another significant driver for the design solutions chosen for spacecraft and automotive MEAs is the emphasis in the automotive application on minimizing recurring costs. This is what motivates using as little platinum as possible and the resulting development of the carbon-supported catalysts that enable more highly efficient distribution of platinum, at the price of the durability limitations I just discussed. On the other hand, anticipated production quantities of spacecraft fuel cells are very very low. Thus, a spacecraft designer will choose to use as much platinum as will do any good at all for maximizing specific energy.

It is instructive therefore to examine with a rough analysis the relative cost and value of platinum in the two applications to point. Presented here are data from the previous NASA and GM curves focused in at the 200 mA/cm2 and 800 mV range and normalized for ohmic losses and pressure. We thus see the cell voltage difference due purely to catalysis kinetics in the current and voltage ranges of interest. As one can see, the application of an order of magnitude heavier platinum loading in the NASA case yields, at the spacecraft current density design point, a cell voltage improvement of only 29 millivolts. If assembled into a set of Shuttle class power plants producing 15 kW (a typical shuttle power demand)at 200 mA/cm2, this small improvement in cell voltage comes at the price of $9,800 in additional cathode platinum alone (at roughly current prices). This would amount to $59,000 additional cathode platinum cost in an 90 kW automotive power plant. I know little of the auto business, but I imagine that a fuel cell built at this recurring cost would not be commercially competitive. Now, lest this appear to be a case of government "gold plating", one should consider that this small increase in cell voltage and efficiency DECREASES reactant consumption by 190 g/hr. The savings there are not even measurable in a terrestrial 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 of on orbit operation.

This discussion illustrates why on-going NASA-sponsored research is pointed toward applying even heavier platinum loading (doubling to ~8 mg/cm2 at the cathode) in an attempt to make durable MEAs that provide better than 900 mV at the spacecraft standard current density, while automotive researchers seek to provide just the cell polarization performance illustrated here with even less platinum and no active humidification.
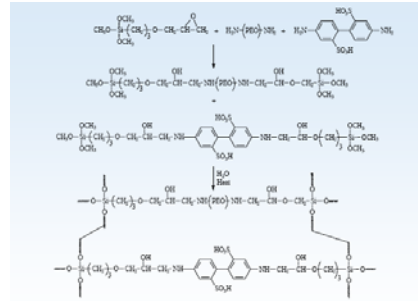
Membrane Electrode Assembly Requirements

e.g. Nafion — DUPONT
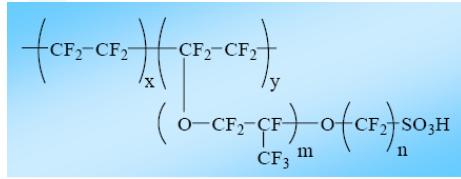
Perfluorosulphonic acid (PFSA) based membranes
- High Humdification
- $T_{opp} < 80\ ^oC$

Hydrocarbon based membranes
- Low Humidification
- More tolerant of CO
- $T_{opp} \geq 120\ ^oC$
- No fluoride corrosion

e.g. ORMOSil — NASA Glenn Research Center

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

In the automotive industry, however, a great deal of effort in being put into development of hydrocarbon-based membranes. Remarkably, automotive requirements on membranes are much more severe than those of spacecraft. The ohmic losses at the high current density are much more significant, driving designers to thinner membranes that still must meet their durability requirements. Also, automotive fuel cell designers wish to run at temperatures upwards of 120 C (which would enable use of current automotive heat rejection systems) without any external humidification and to be able to start up at temperatures well below freezing. Current membranes like Nafion 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 certain range) and have available any desired humidity and a much colder heat sink. As spacecraft fuel cell performance would also be enhanced by the higher cell voltages that could be enabled by higher temperature membranes, NASA may likely make use of these hydrocarbon membranes but is only minimally participating in their development, though I've used a NASA-developed membrane as an example.

In sum, then, while spacecraft applications will likely make use of commercial membranes as they are developed, the differences in catalyst layer requirements are so significant that NASA Human Spaceflight has to sponsor development of its own MEAs.
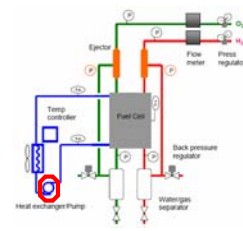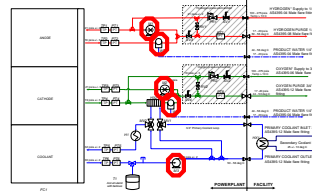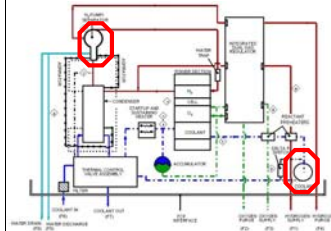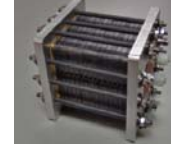
In the fuel cell balance of plant, spacecraft and automotive engineers share the same goals of minimum weight, simplicity and high reliability. The only difference is how far each is able to go. With automobiles, the primary tradeoff in this field is between the added power drain and complexity of a compressor and the efficiency of high pressure oxidant. A spacecraft would always feed reactants from high pressure storage, so the question is how simple the plant can be and still manage water in the stack.

For the Shuttle's Alkaline power plants, reactants are fed dry from high pressure cryogenic storage to the stack at a regulated pressure (around 60 psia). 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 contained aqueous electrolyte. The condensed product water is stored for life support use. Excess heat is removed by a pumped coolant stream.

The balance of plant for PEM power plants built to date under NASA sponsorship is rather more complex than that of the shuttle alkaline. Dry reactants are again fed to the stack at a pressure regulated down to, here, 20 psia (thus helping to enable a lighter stack than with the Shuttle). In the plant we most recently tested, both reactants are recirculated with centrifugal pumps, and, as the various diffusion processes in PEM stacks can yield liquid water on the anode as well at the cathode, both reactant streams feature rotating machinery for water separation. Product water is managed thermally to keep both reactant streams highly humidified (around 70% relative) at the stack inlet. As the oxygen steam exits the stack at well above 100% relative humidity, 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.

As a result, current NASA 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 (the latter being shown here). Another concept, which we call "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.

Elements of A Fuel Cell Power System
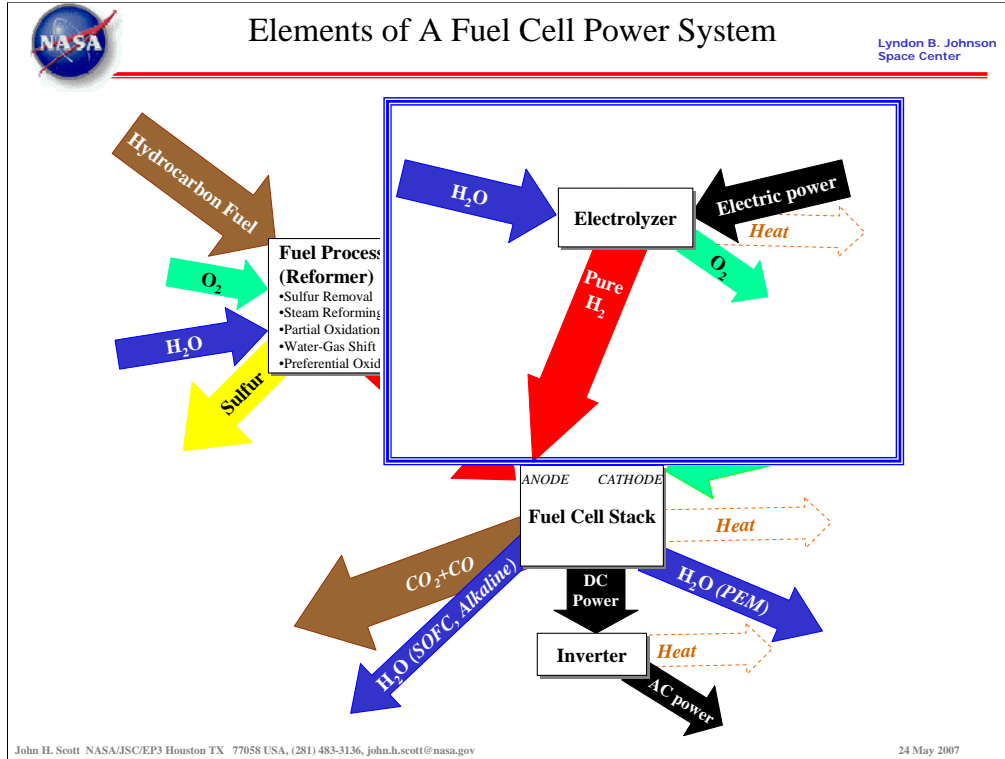
The role of an electrolyzer is quite different between spacecraft and automotive systems. For cars, electrolyzers are the core of the stationary plant that produces hydrogen for vehicular use. In a spacecraft, they are either half of a regenerative fuel cell storage system or the last step in a lunar oxygen production plant.
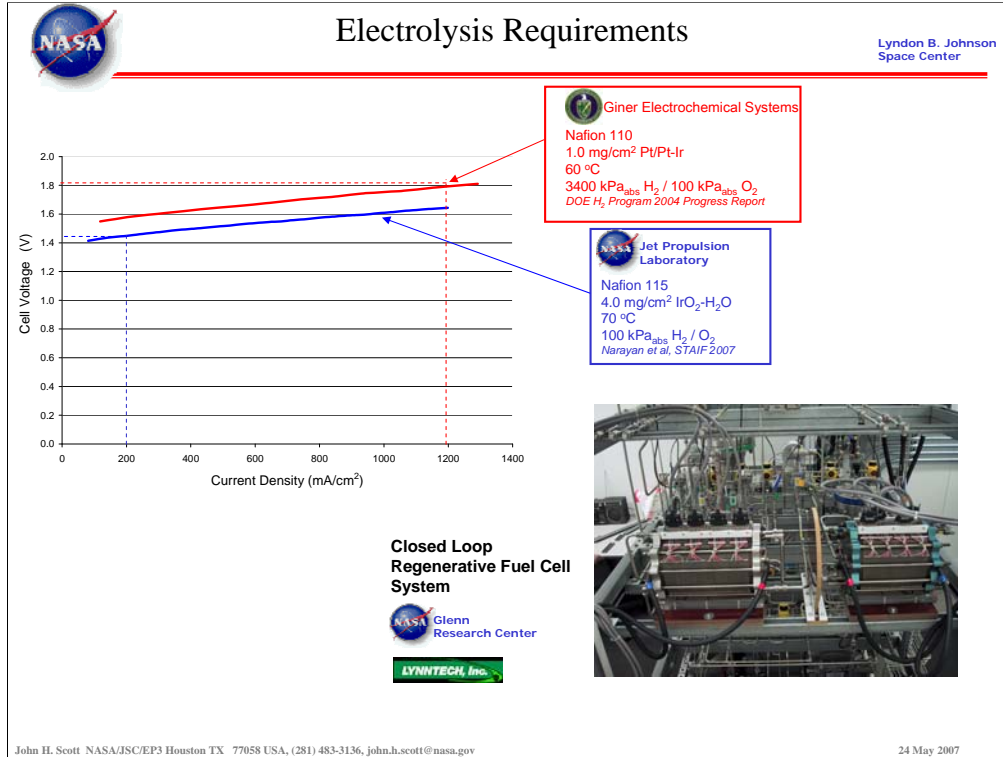
At the MEA level, the similarities and differences between spacecraft and automotive designs are essentially the same as with fuel cells. Spacecraft system designers wish the highest possible specific energy and thus the highest efficiency and lowest cell voltage. To achieve this, the electrolysis mode 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 assembled stack and balance of plant level, major difference between spacecraft and commercial electrolysis applications is the requirement, in the energy storage case, to store 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 completely 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 of type of system will become the storage core of the photovoltaic modules at the lunar base will depend, of course, on 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 PEM versions of 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.

Elements of A Fuel Cell Power System
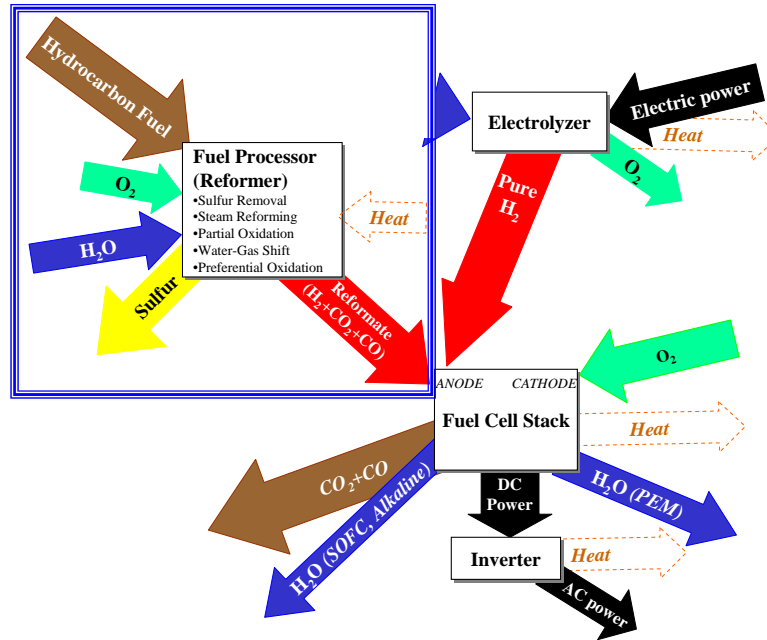
Finally, while hydrocarbon fuel processing is perhaps the most challenging issue for automotive fuel cell systems and the recipient of a large percentage of the development funding, spacecraft designers see it as becoming an issue farther down the road in the Exploration Program.

Fuel Processing Requirements

Primary H_2O/CO_2 Processing Options Under Consideration
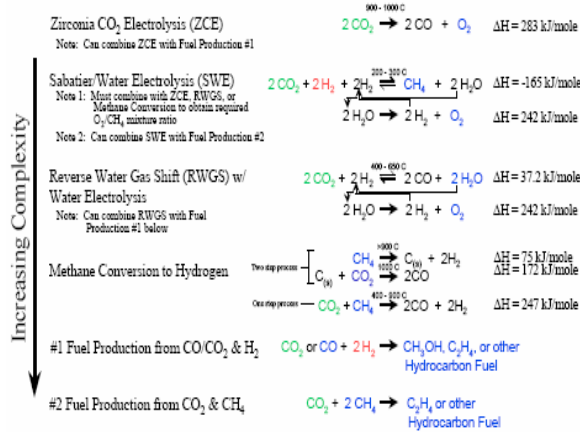
Breadboard Sabatier Reactor
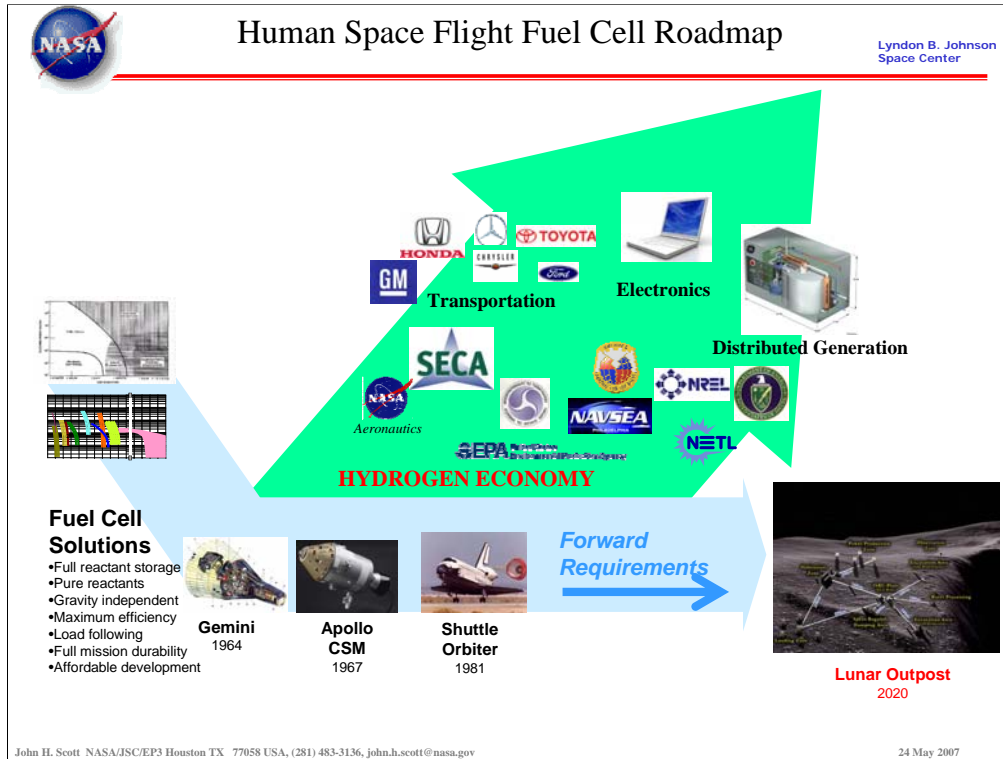
In the nearest term, the development of the future lunar outpost's process plants for cracking oxygen from regolith will likely benefit from application of commercial desulfurization technology, as the moon's soil contains enough sulfur to quickly degrade such a plant's electrolyzer. Also, it is theorized that the hydrogen which the Clementine mission detected near the lunar poles may be in the form not only of water ice but 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 develop 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 CO2 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.

Human Space Flight Fuel Cell Roadmap

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In supporting our Exploration initiative, we at NASA would of course like to see technology useful to our mission 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 national defense. It is always preferable to have the inventing one needs done with someone else's money. However, as I've discussed in the last few minutes the fuel cell development needs of NASA's Exploration Program and those of the "Hydrogen Economy" have surprisingly little in common. What's more, the sheer magnitude of development investment and market potential associated with "green energy" applications makes the leaders in this field reluctant to bother with NASA's small development contracts. A future as a NASA subsystem contractor, producing a custom system with little potential for other customers and maintaining a sustaining engineering workforce for many years, doesn't fit with their business models.

I would of course be pleased if someone hear at this conference were to point out where I'm wrong in all this. Anyone needing a technology development path pursued would wish to have more resources directed to it. However, human exploration of the solar system and the "Hydrogen Economy" are both truly long term problems. Our role as engineers is not to convince our agencies, shareholders, or taxpayers to put more of our scarce resources toward solving these problems. Some investment must be made in such things, but we're all going to eat lunch in a couple of hours. The job of our profession is to explain to those who allocate those resources what can be done for how much…and to be right about it. We are then to get it done, on time and on budget. This is true whether our mission is to explore other worlds or take better care of this one. Regardless of the size of our budgets, none of this happens without our best efforts. In the end, it's up to us. This is why we all got into engineering in the first place. It is an intimidating and exciting challenge. Thank you for your kind attention.

Acknowledgements