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


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# 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)

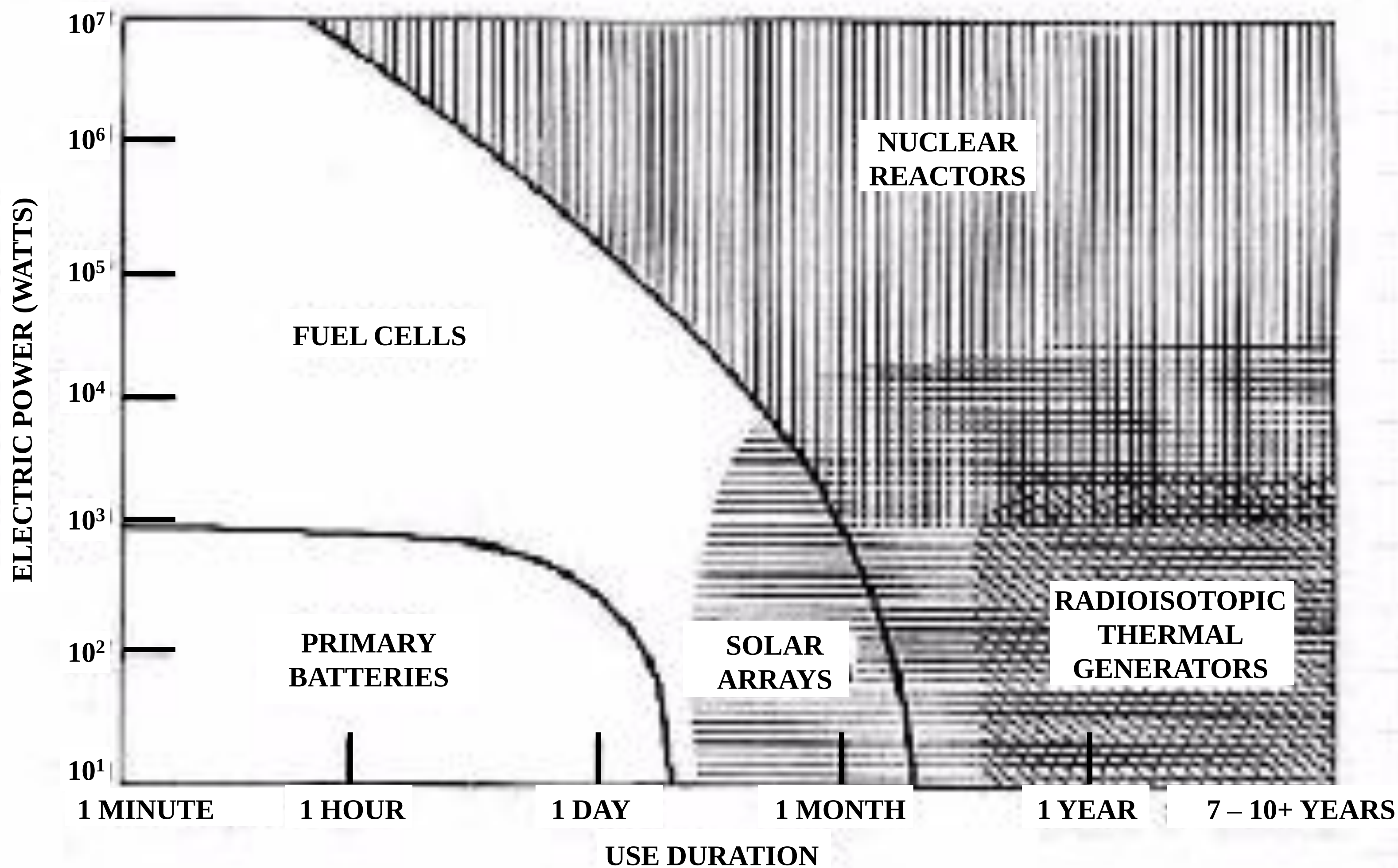
**Constraint: Public Safety**

# Spacecraft Power Systems:

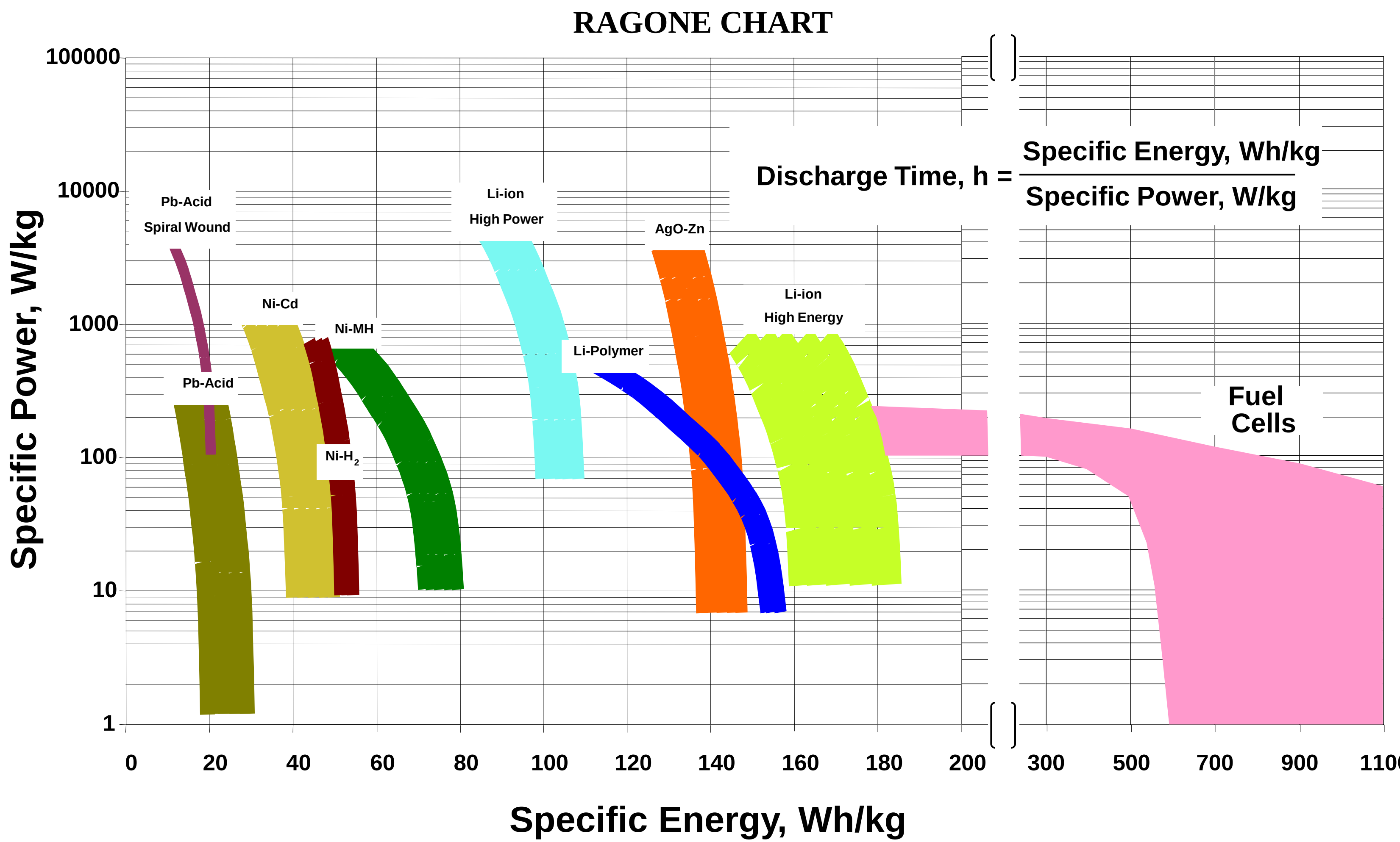
- Specific Energy (kWh/kg)
- Specific Energy (kWh/kg)
- Specific Energy (kWh/kg)
- Development Cost

**Constraint: Full Mission Reliability**

# Power Generation Specific Energy Trade Space



# Energy Storage Specific Energy Trade Space



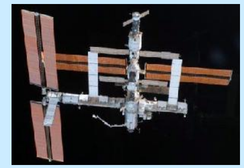
# Human Space Flight Energy Storage Roadmap

**Battery Solutions**

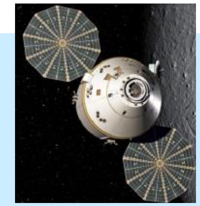
**Mercury**
1961

**Apollo LEM**
1968

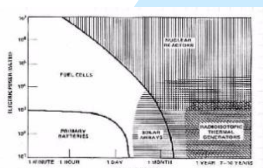
**Skylab**
1973

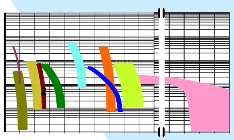


**International Space Station**
1998



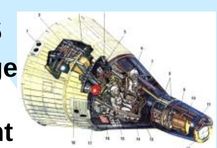
**Orion MPCV**
2016





**Fuel Cell Solutions**

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



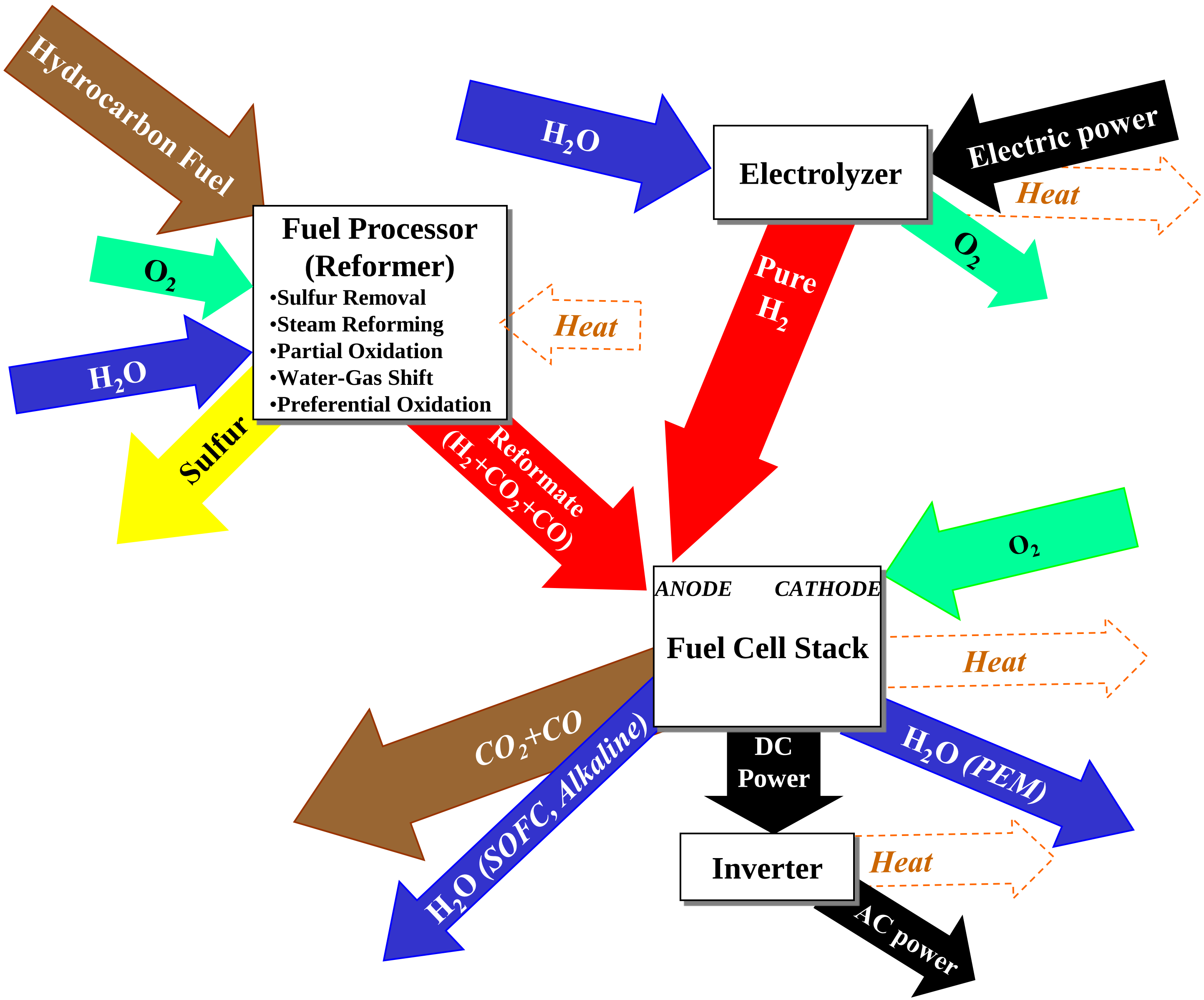
**Gemini**
1964

**Apollo CSM**
1967

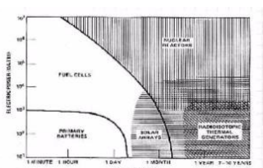
**Shuttle Orbiter**
1981

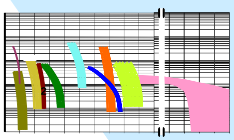
***Forward Requirements***

# Elements of A Fuel Cell Power System



# Human Space Flight Fuel Cell Roadmap





## Fuel Cell Solutions

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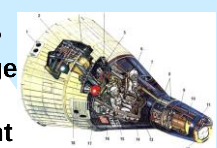

**Gemini**
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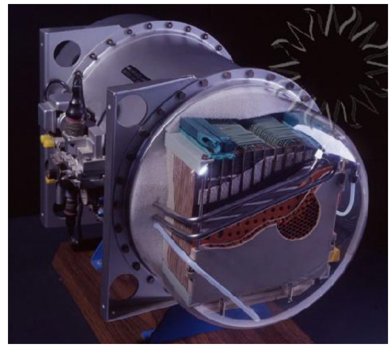
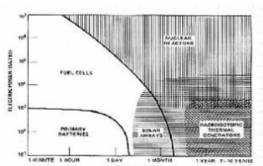
***Forward Requirements***

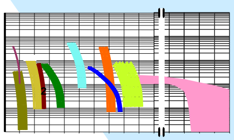
# Human Space Flight Fuel Cell Roadmap

## Gemini Fuel Cell



- Proton exchange membrane (sulfonated polystyrene)
- Catalyst: 28 mgPt/cm$^2$
- 820 mV @ 40 mA/cm$^2$ (1.0 kW)
- 200 hr operating life
- 21 $^{o}$C operating temp
- Flight set of 2
- 30 W/kg
- 0.4 kWh/kg with 1 reactant set





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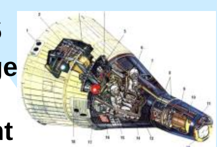

Gemini
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Apollo CSM
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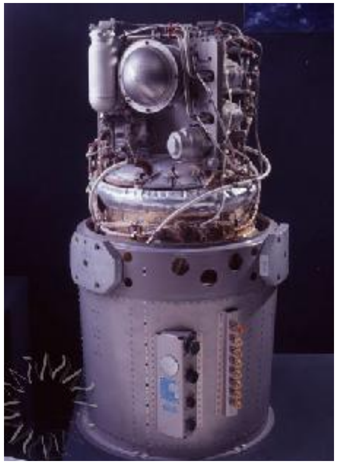
Shuttle Orbiter
1981

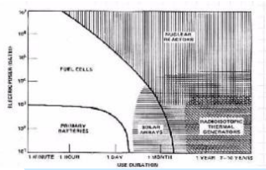
*Forward Requirements*

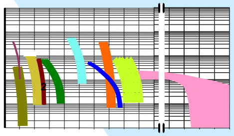
# Human Space Flight Fuel Cell Roadmap

## Apollo Fuel Cell



- Mobile alkaline electrolyte
- Catalyst:  Ni
- 894 mV @ 118 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
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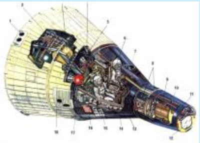
- Affordable development



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Shuttle Orbiter
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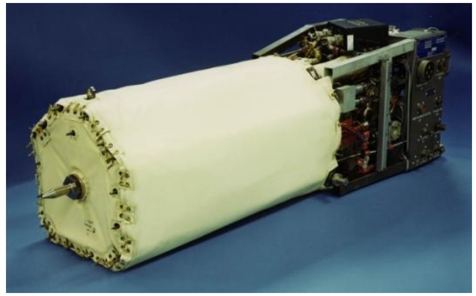
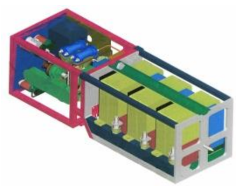
*Forward Requirements*

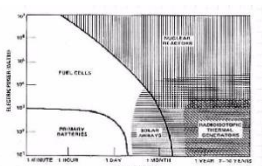


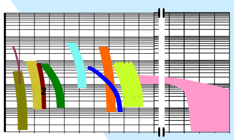
## Shuttle Fuel Cell

- Captive alkaline electrolyte
- Catalyst: 28 $mgPt/cm^2$
- 980 mV @ 114 $mA/cm^2$ (5 kW)
- 5000 hr operating life
- 90 °C operating temp
- Flight set of 3
- 39 W/kg
- 1.6 kWh/kg with 5 reactant sets



- PEMFC considered early 1990's





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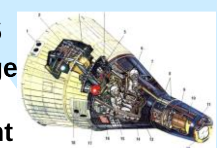

Gemini
1964

Apollo
CSM
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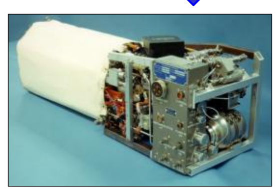
*Forward Requirements*

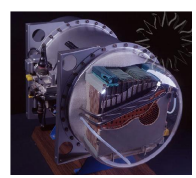
# Chemistries of Interest for Spacecraft Application

| Chemistry | Alkaline Fuel Cell (AFC) | Proton Exchange Membrane Fuel Cell (PEMFC) | Solid Oxide Fuel Cell (SOFC) |
|---|---|---|---|
| Fuel Capability | Pure $H_2$ | $H_2$ from "clean" reformate | CO and $H_2$ from "dirty" reformate |
| Operating Temp. | ~90 °C | ~80 °C | ~800 °C |
| Bootstrap Start? | Yes | Yes | No |
| Operating Life Limiter | Corrosion | Humidity Control | Thermal Cycles |

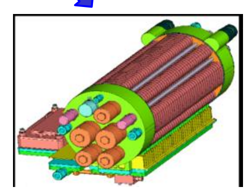
Apollo



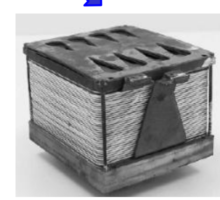
Shuttle



Gemini



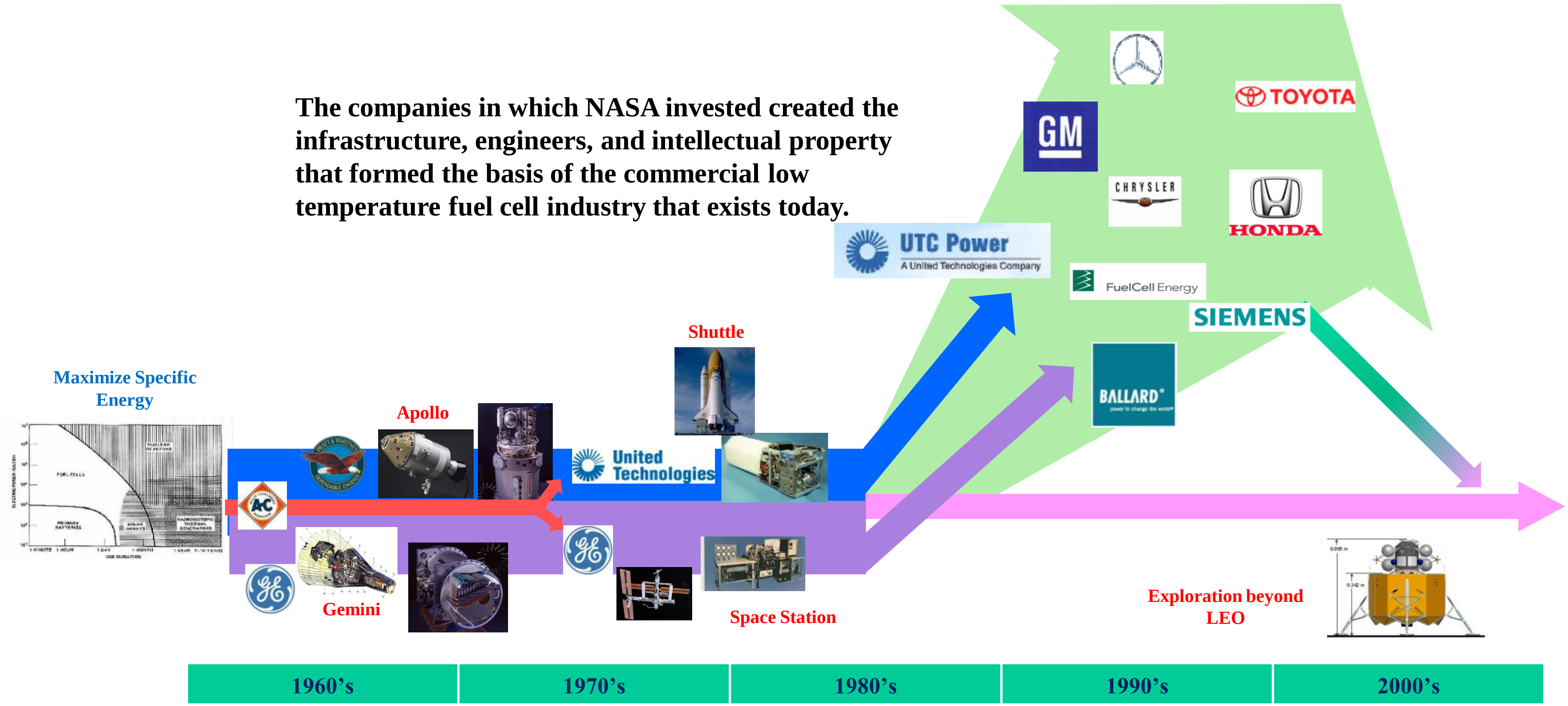
OCT



*Under study for LOX/$CH_4$ spacecraft*

# Modern Fuel Cell Technology is a Spinoff of NASA's Human Spaceflight Program

**The companies in which NASA invested created the infrastructure, engineers, and intellectual property that formed the basis of the commercial low temperature fuel cell industry that exists today.**




**Investment from NASA's Human Spaceflight Program in the 1960's – 1980's brought fuel cells from the laboratory to their first practical application**

**NASA continues to drive innovations in spacecraft low temperature fuel cell technology development while leveraging commercial advances.**

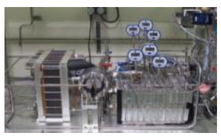
# PEM Fuel Cell Development

## SLI/NGLT/OSP/ETDP/OCT PEMFC Technology Programs

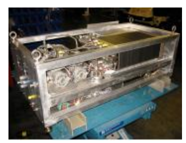
**PEMFC Forward Goals:**
- 10,000 hrs Operating Life *(Shuttle AFC 5,000 hrs)*
- Highest Reliability
- 920 mV @ 100 mA/cm$^2$ *(Shuttle AFC 980 mV)*
- 136 W/kg *(Shuttle AFC 39 W/kg)*

Ballard FC Stack Operates >11,000 hrs.

Passive Short Stack Testing



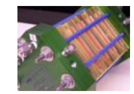
Testing of Teledyne Breadboard



Testing of Teledyne Eng. Model

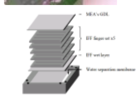
"Non-Flow-Through" SBIR Efforts

Primary



Infinity Fuel Cell

Back-up



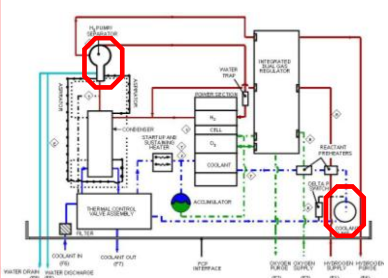
ElectroChem Inc.

Back-up

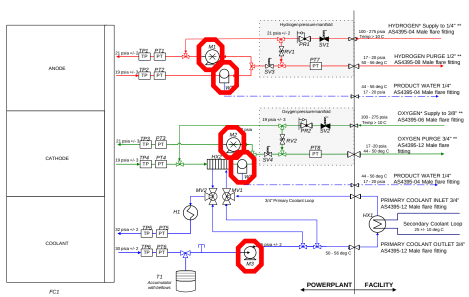

GES

1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011

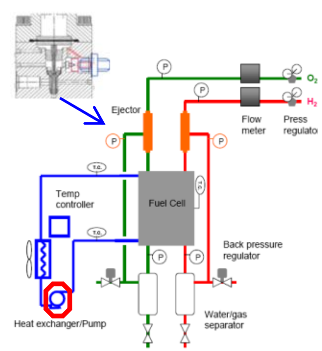
### "Balance of Plant" (BOP) Evolution



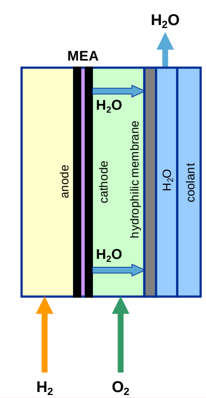
Shuttle AFC

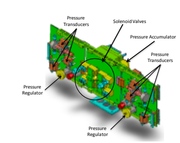



Teledyne PEMFC Breadboard & Engineering Model




Ejector-Based "Passive" or "Flow-Through" Balance-of-Plant (BOP)

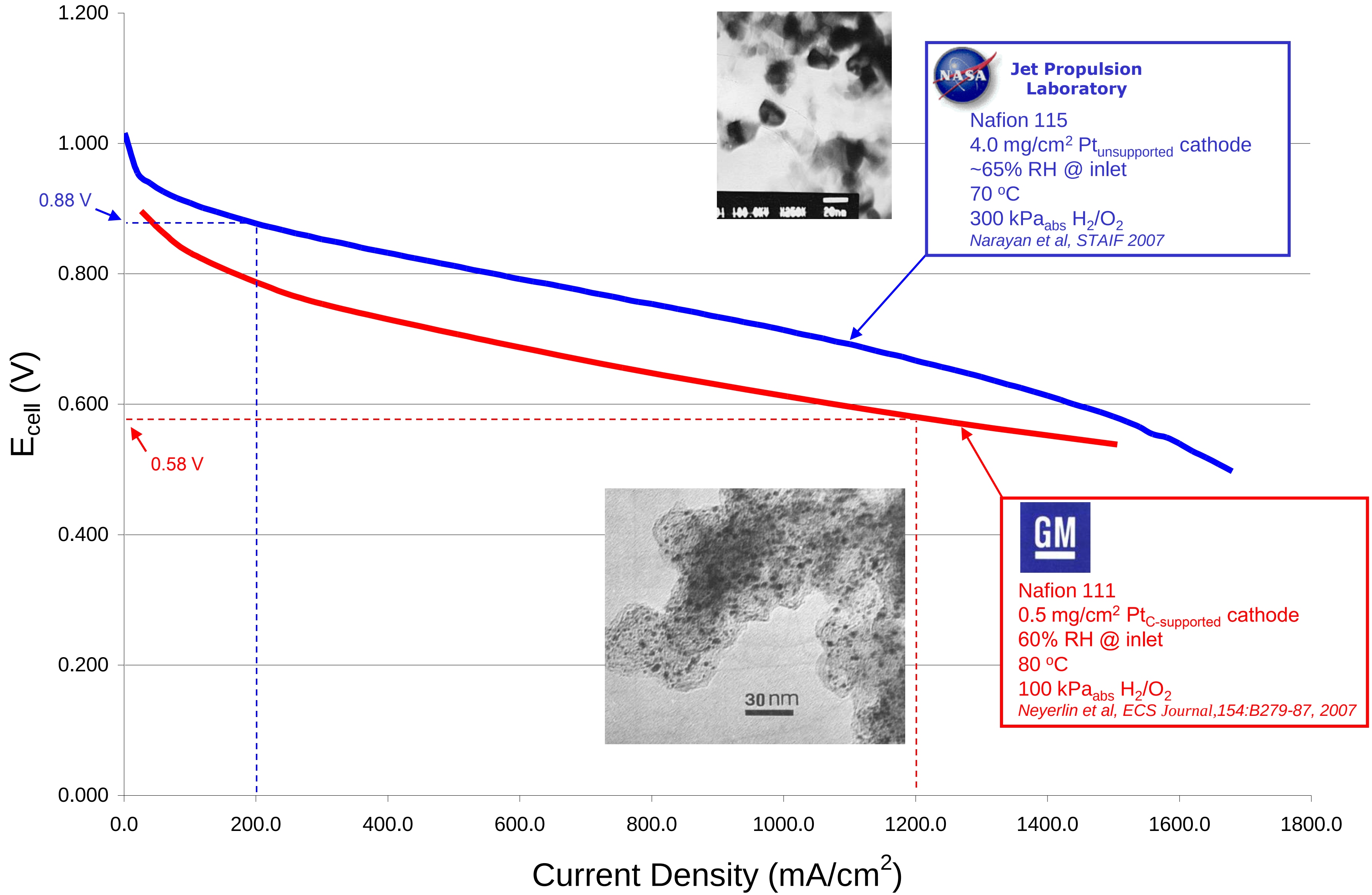


"Non-flow-through" Concept

# PEM Fuel Cell Development

## Single Cell Polarization Curves (as measured)

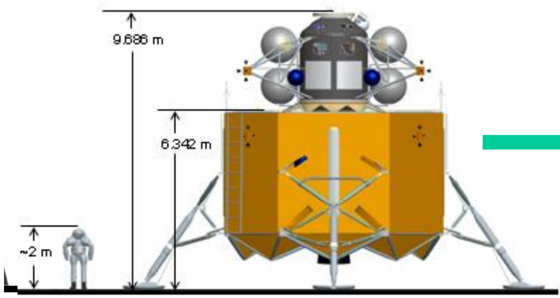


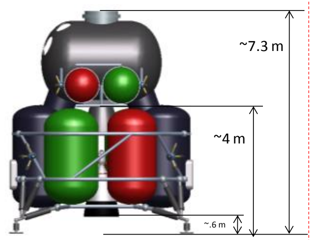
# Solid Oxide Fuel Cell (SOFC) Development

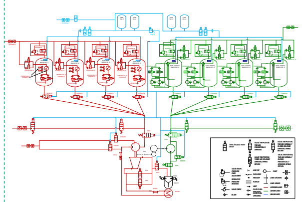
When combined with $O_2/CH_4$ propulsion, Solid Oxide Fuel Cell technology enables a smaller, simpler spacecraft

## *Notional Lander Concepts*

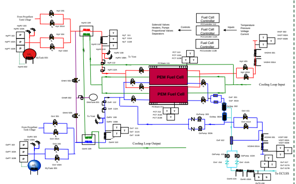
**$H_2/O_2$** **$CH_4/O_2$**



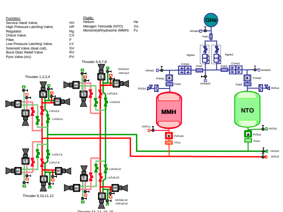



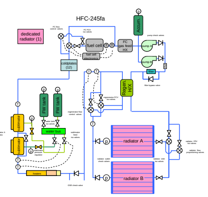
**Descent Main Propulsion**



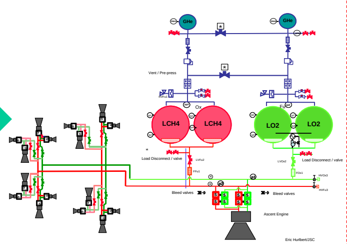
**PEMFC Power**




**RCS Propulsion**

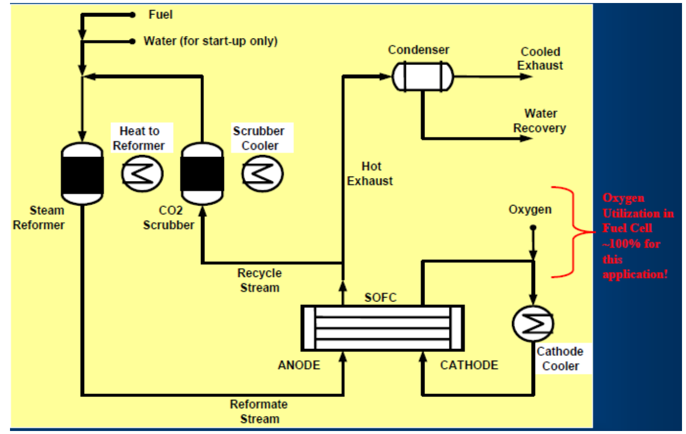


**Active Heat Rejection**




**Integrated Propulsion and SOFC Power**

**ONR/NUWC – DOE/NETL UUV Concept**
- Logistics grade S-8/JP-8 fuel
- Logistics grade liquid $O_2$ oxidant
- Steam reforming
- Complete $CO_2$ capture
- Active cathode cooling via $O_2$ stream




**NASA spacecraft SOFC concept**
- Partial Oxidation reforming
- Deadheaded $O_2$ on cathode
- Cooling via passive conduction to radiator