National Aeronautics and Space Administration

Regenerative Fuel Cell Systems for Lunar Surface Applications

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Presentation Overview

Lunar Environment

What are Regenerative Fuel Cells (RFCs)

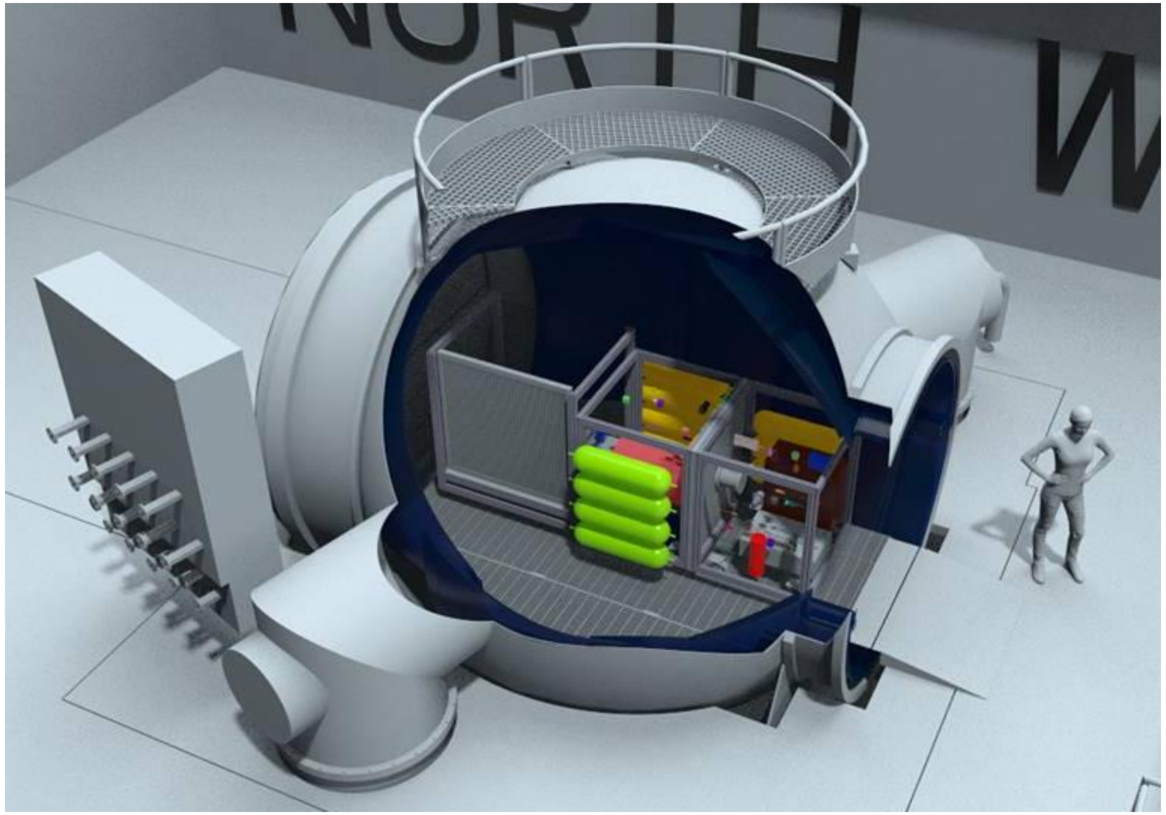
System Integration and Requirements

Fluidic Balance of Plant (FBoP) Component Requirements

FBoP Component Development

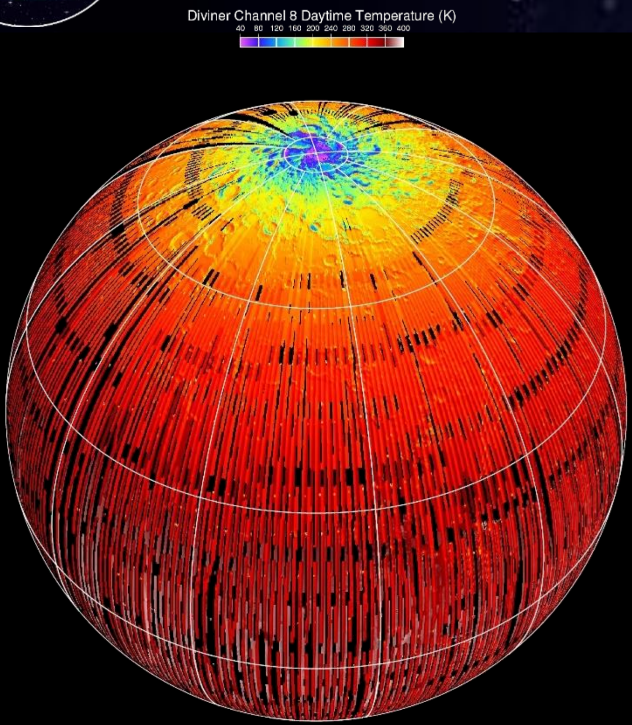
- **Gas Drying**
- **Catalytic Recombiner**
- **High Pressure Lift Pump**

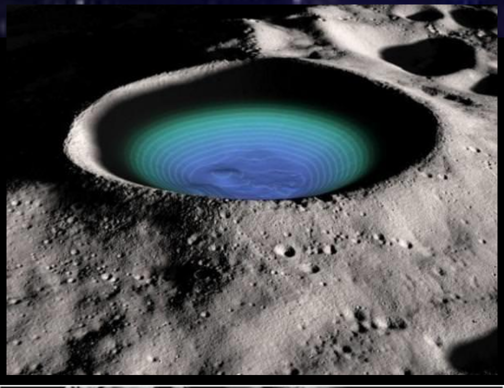
Conclusion

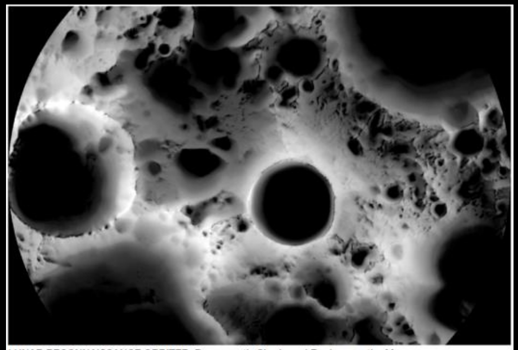


Integrated RFC Test Article in JSC Energy Systems Test Area (ESTA) Thermal Vacuum Chamber

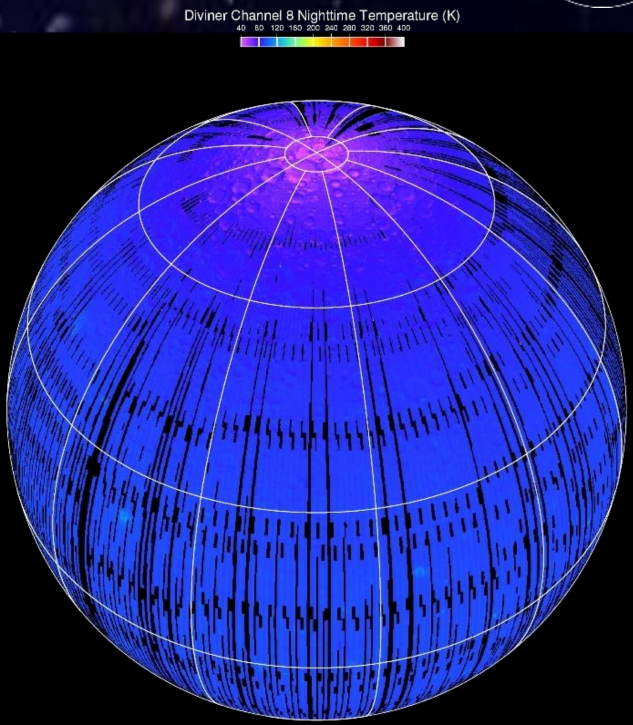
The Lunar Environment







LUNAR RECONNAISSANCE ORBITER: Permanently Shadowed Regions on the Moon

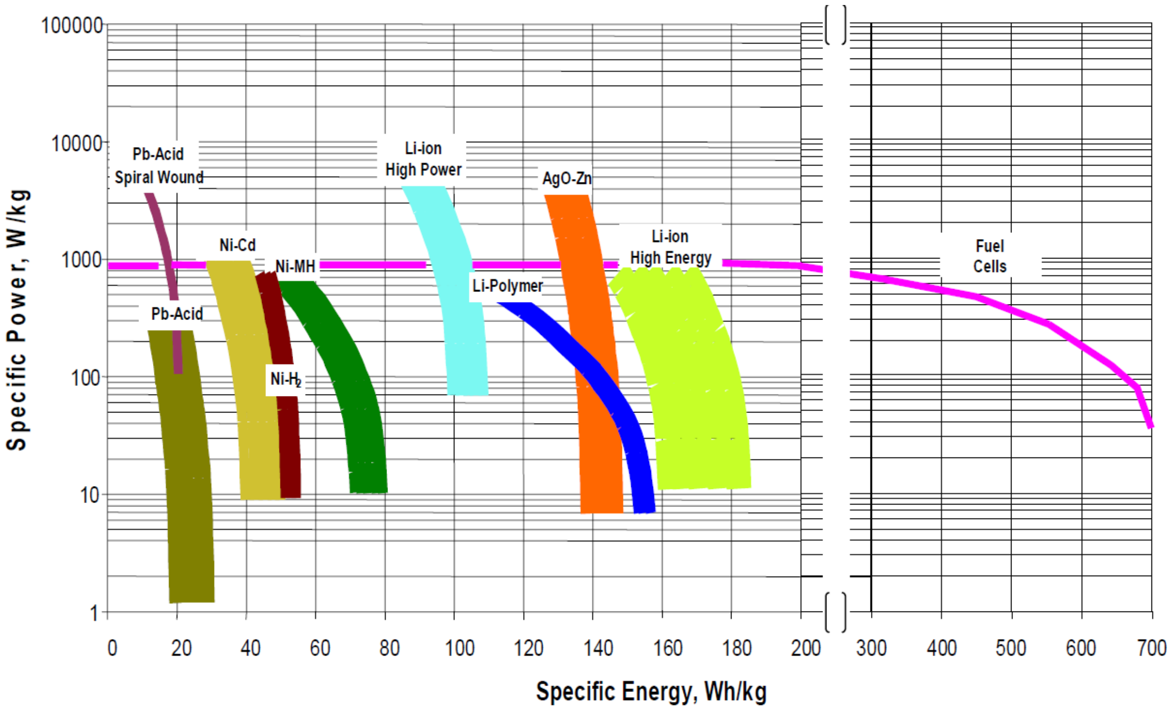


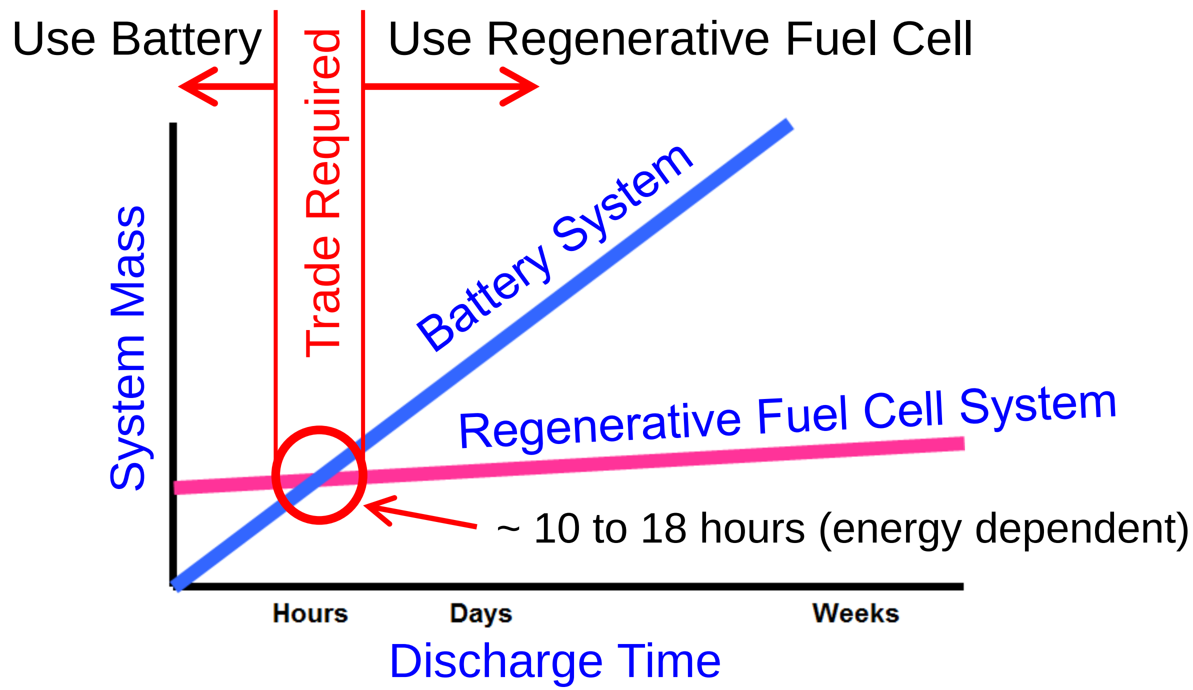
- The average temperature on the Moon (at the equator and mid latitudes) varies from 90 Kelvin (-298 ^{o}F or -183 ^{o}C), at night, to 379 Kelvin (224 ^{o}F or 106 ^{o}C) during the day.
- Extremely cold temperatures within the permanently shadowed regions of large polar impact craters in the south polar region during the daytime is at 35 Kelvin (-397 ^{o}F or -238 ^{o}C)
- Lunar day/night cycle lasts between 27.32 and 29.53 Earth days (655.7 to 708.7 hours)
- Regulating hardware in this environment requires both **power** and **energy**

Energy Storage Options for the Lunar Surface

Battery vs Regenerative Fuel cell

RFC has higher specific energy (W-hr/kg) for high energy applications where fully packaged battery systems become too massive



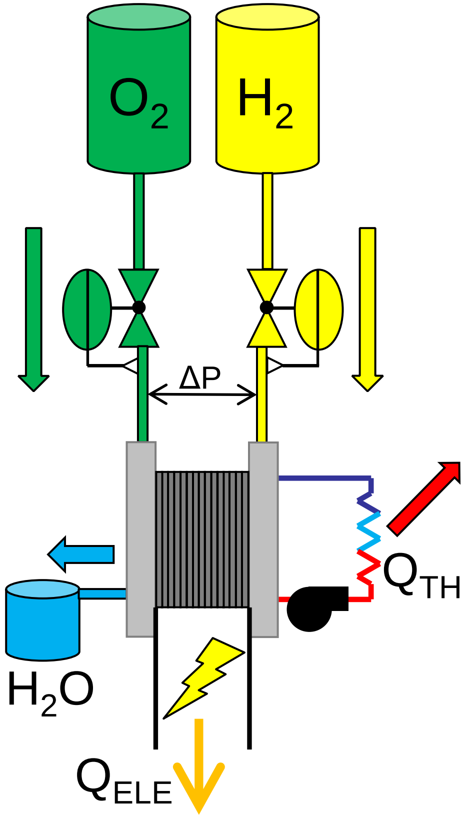


What is a Regenerative Fuel Cell

Primary Fuel Cell

Discharge Power Only

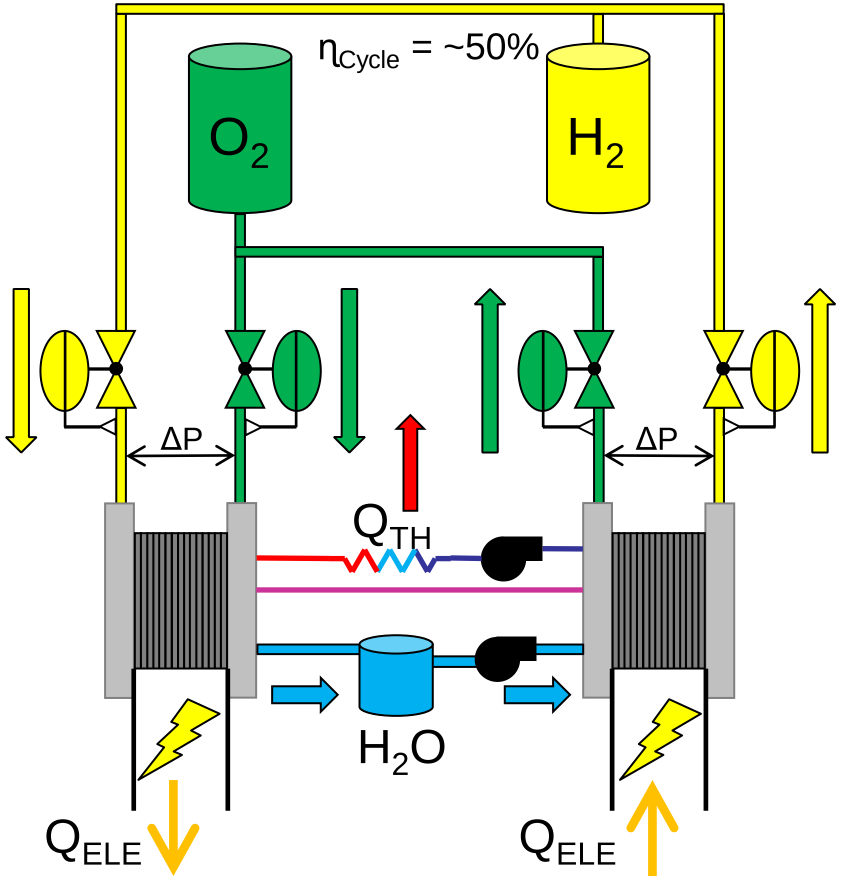
$2H_2 + O_2 \rightarrow 2H_2O + 4e^- + Heat$



Discharging

Regenerative Fuel Cell

Charge + Store + Discharge



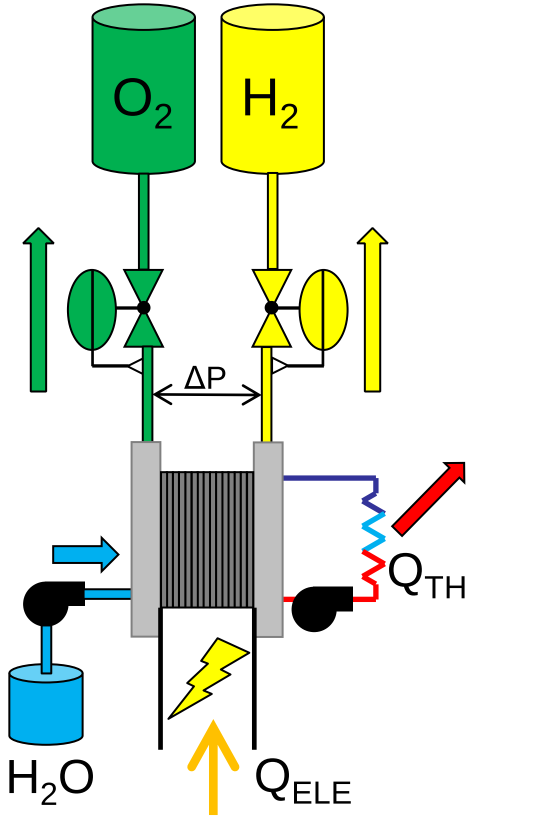
Discharging

Charging

Electrolysis

Chemical Conversion

$2H_2O + 4e^- \rightarrow 2H_2 + O_2 + Heat$



Charging

Regenerative Fuel Cell = Fuel Cell + Interconnecting Fluidic System + Electrolysis

RFC System Integration

RFCs require integration of discrete components with various subsystems including:

PEM Fuel Cell Stack

PEM Electrolyzer Stack

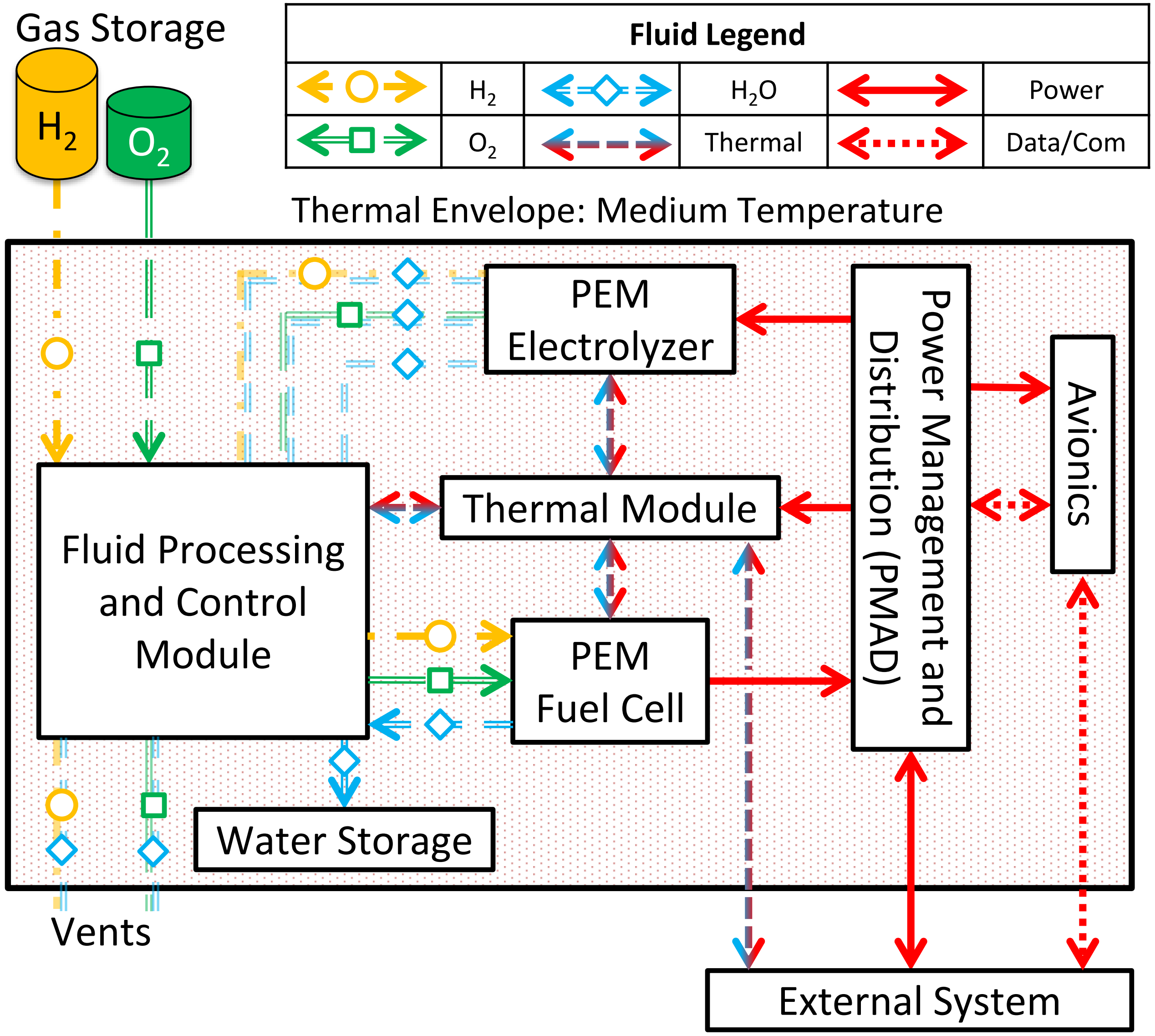
Power Management and Distribution (PMAD)

Avionics

Thermal

Fluidic Balance of Plant

- Balance of Plant is different for space vs terrestrial
- Different wetted material requirements (air vs pure O_2)
- Rated for operation in high vacuum environment
- Multiple thermal zones
- Low mass and low power components



Fluidic Balance of Plant Components

RFC project objectives to minimize mass, volume, and parasitic power loads to increase RFC round-trip efficiency

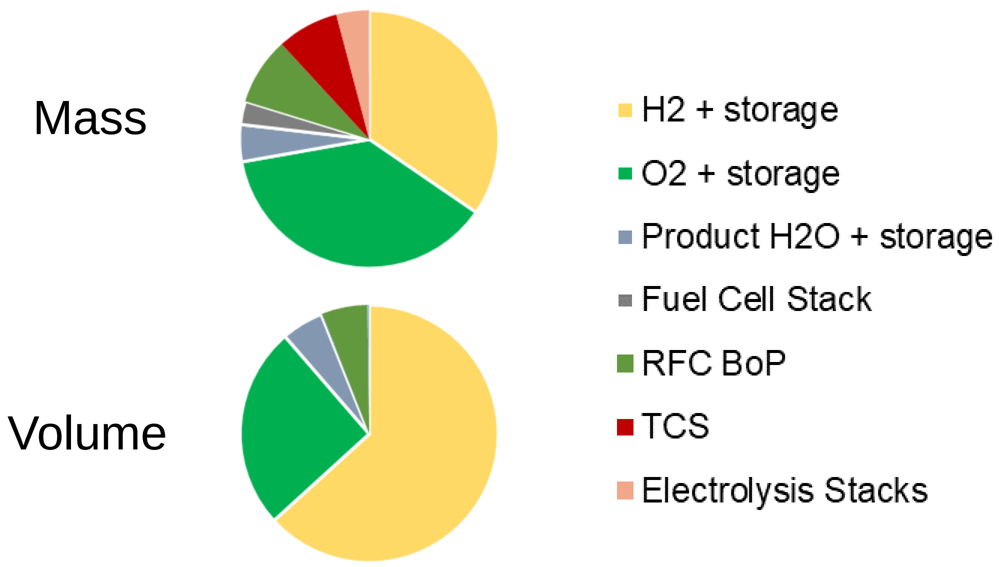
A number of components that meet specifications are not available commercially off-the-shelf (COTS)

Project budget and schedule may not support all preferred component customization

Component level testing is required to characterize performance and inform integrated RFC system design decisions

- Low TRL for many components because they are not designed for and have never been evaluated in a vacuum
- Materials compatibility with fluids
- Long term reliability

Mass and Volume Ratios at the lunar Equator



1500 psia reactant storage, 10 kW class mass and volume ratios

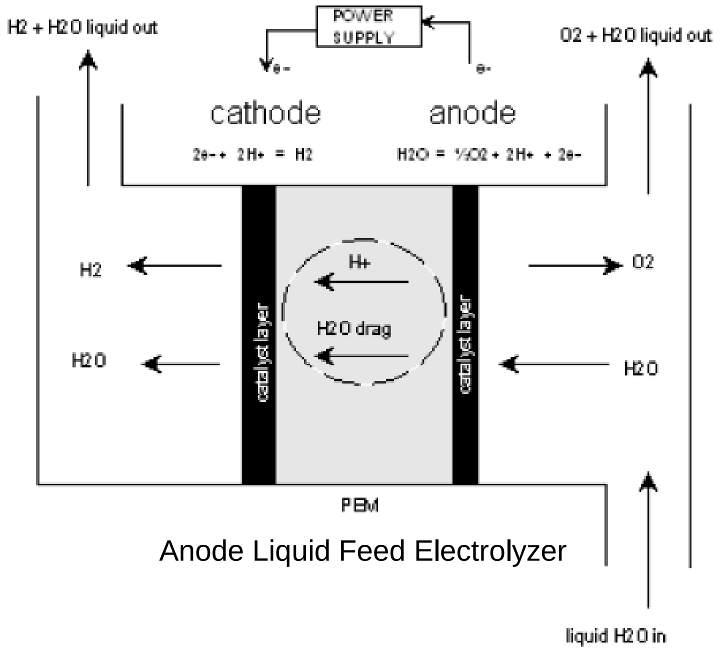
Gas Drying

Electrolyzer produces wet hydrogen and oxygen gas

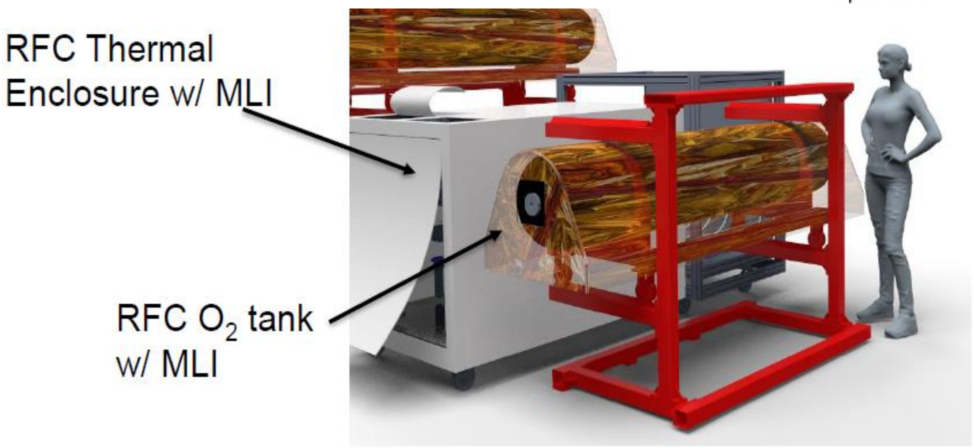
- Water that reaches gas storage tanks may be irrecoverable and would account for new loss of RFC energy storage capability

Gas storage tanks are located outside the thermal envelope

- If RFC heaters are not required to keep storage tanks above the freezing point of water, efficiency improves by over 19% and system mass decreases by 16 %
- Successful water management/gas drying is crucial to RFC performance



Anode Liquid Feed Electrolyzer



RFC with thermal enclosure and gas storage tanks

Gas Drying

Traditional regenerative drying systems vent the captured water to the environment, which, for closed loop systems on the lunar surface in the vacuum of space, would deplete the available stock of water for the electrolyzer

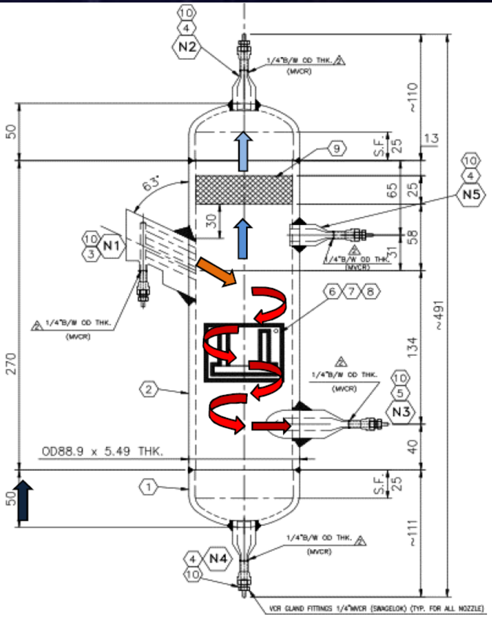
Water planned to remove from electrolyzer outputs in 2 stages

Oxygen

- Stage 1: Phase separator (gravity/centrifugal force driven) removes liquid water from gas stream
- Stage 2: Adsorption dryer with molecular sieve removes water vapor before gas enters storage tanks

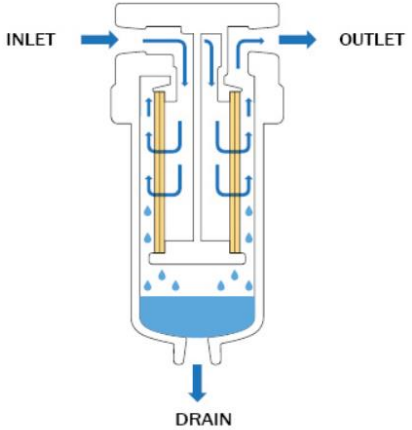
Hydrogen

- Stage 1: Coalescing filter collects any liquid water from gas stream
- Stage 2: Adsorption dryer with silica gel removes water vapor before gas enters storage tank



Vapor Liquid Phase Separator


Molecular Sieve



Coalescing Filter


Silica Gel

Catalytic Recombiner

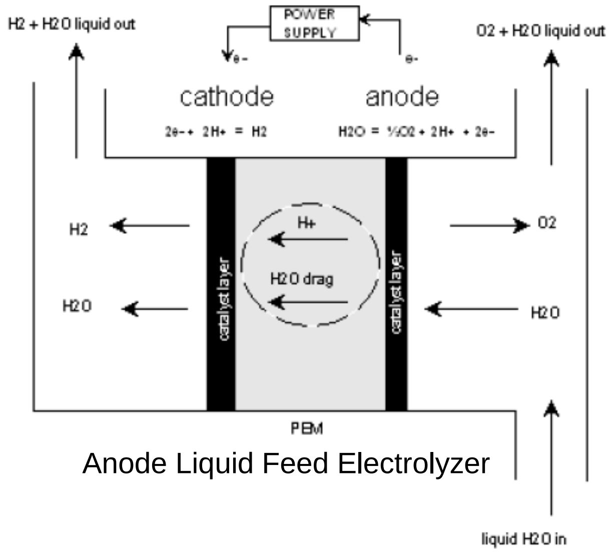
H_2 and O_2 gases permeate electrolyzer MEA at high pressures

- Results in H_2 in O_2 stream and O_2 in H_2 stream
- Maintained << 2 % under normal operation with appropriate design
- Not an issue for terrestrial or open-loop systems

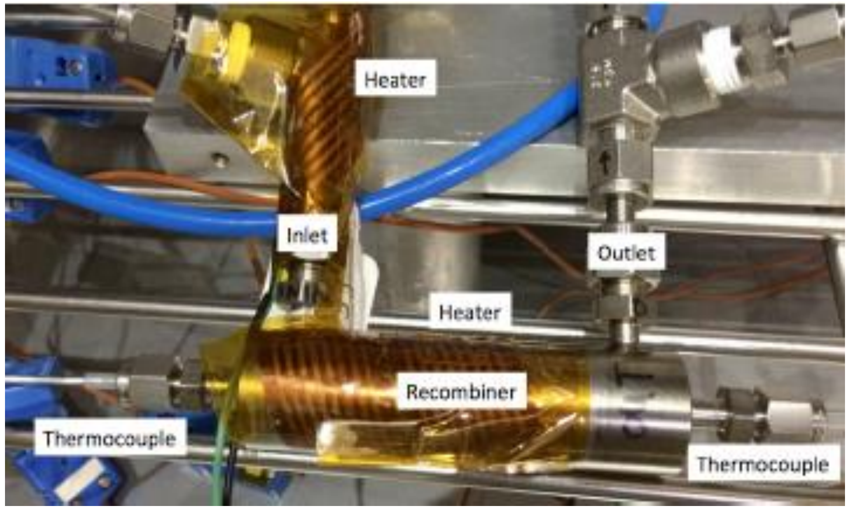
Need to react H_2 and O_2 to form water before flammable/explosive concentrations are reached

Catalyst requirements

- Doesn't absorb water and is self drying
- At least 99.9 % conversion
- Operate at 2500 psia and a temperature range from 4 – 85 ^{o}C



Anode Liquid Feed Electrolyzer



Recombiner for International Space Station Oxygen Generation Assembly

Image from Takada; Ghariani; Van Keuren. 45th International Conference on Environmental Systems, 2015

Catalytic Recombiner

Procured catalyst that is a mixture of activated Pt and Pd

- Cylindrical pieces about 3/8” tall and 3/8” diameter

Sizing

- Catalyst vessel diameter needs to be at least 6x the diameter of catalyst particle to prevent tunneling
- Length based on residence time
- Overall safety factor of 4x

Testing

- 125 psig and ambient temperature
- Procured pre-mixed supply gases with concentrations of:
  - 0.01 – 1.5 mol % H_2 in O_2
  - 0.01 – 1.5 mol% O_2 in H_2
- Using flammable gas sensor to evaluate effectiveness

Knitted Wire Catalyst

High Pressure Water Pump

Required to supply the electrolyzer stack at the pressure level for satisfactory reactant gas storage

Requirements

- Operate in hard vacuum environment and ambient temperature between 4 – 85 ^{o}C
- Motor operating on 24 – 48 VDC
- Pumped fluid is DI water (no lubricants or stabilizers)
- Duty cycle of 15 days powered on, 15 days powered off, for at least 12 cycles
- High reliability with minimal routine maintenance
- Low mass, less than 5 kg desired
- Variable flowrate from 1 mL/minute to 1000 mL/minute
- Capable of generating outlet pressures of at least 2500 psig
- VCR fluidic interface

No pump meets all desired specifications

Candidate pumps were purchased and will be evaluated for performance and life with high purity DI water

Conclusion

Currently working through subsystem and component testing

- Gas drying
- Catalytic recombiner
- High pressure water pump

Planned future work

- System assembly and integration
- Simulated lunar environment testing
- Life cycle testing
- Flight qualification

Acknowledgements

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RFC Project Management
Project Manager: Matt Deminico (GRC)
Product Lead Engineer: Ian Jakupca (GRC)

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PM Integration Support: Chad Gray (GRC)
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Thank you for participating