TFAWS Interdisciplinary Paper Session

Thermal Management Challenges and Technology Options for Lunar Regenerative Fuel Cells

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Presented By
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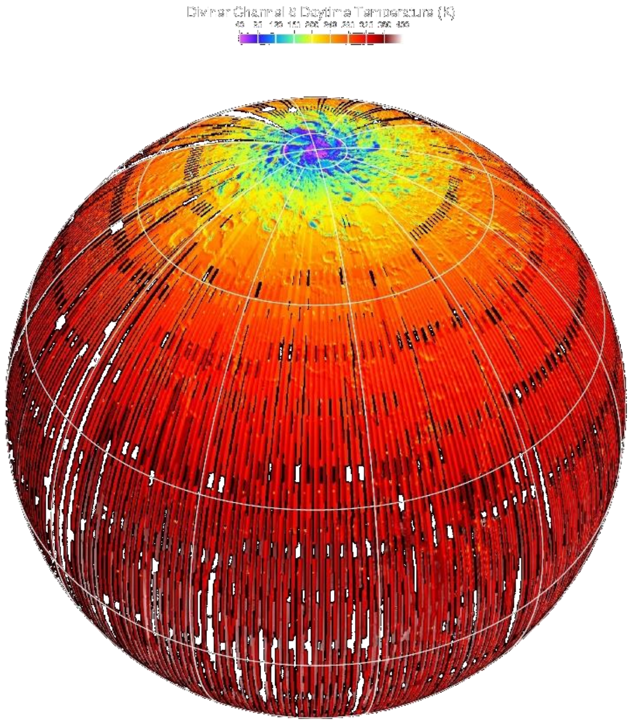
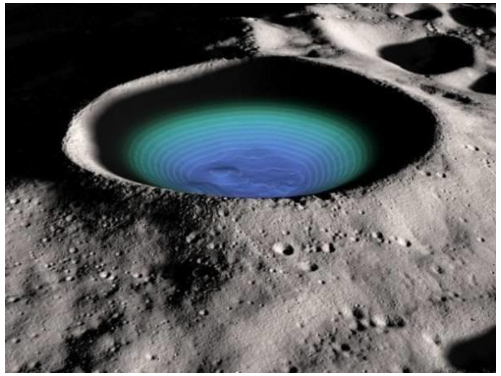
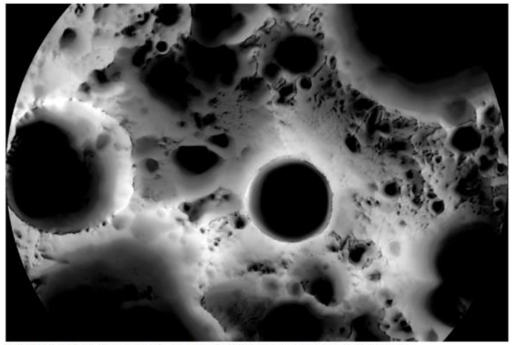
Outline

- Lunar Surface Energy Storage Need
- Why RFCs?
- What Are RFCs?
- RFC Thermal Management System Example
- High Flux Thermal Switch Requirements
- High Flux Candidate Technology Review
- Summary

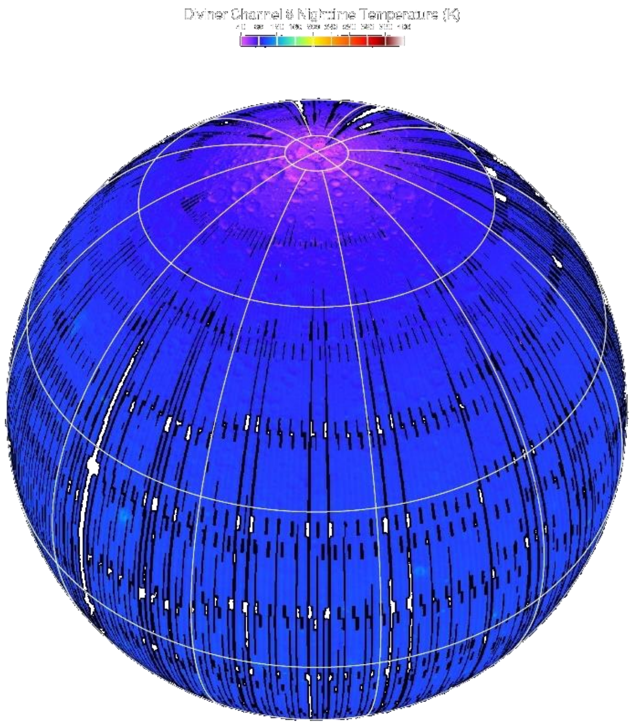
The Lunar Environment







LUNAR RECONNAISSANCE ORBITER: Permanently Shadowed Regions on the Moon



Temperature maps of Lunar surface during day (left) and night (right) as measured by Lunar Reconnaissance Orbiter Diviner. Impact craters (middle). [Ref 1]

- 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 near 35 Kelvin (-397 ^{o}F or -238 ^{o}C) within the permanently shadowed large polar impact craters
- Lunar day/night cycle lasts between 27.32 and 29.53 Earth days (655.7 to 708.7 hours)
- Regulating hardware temperatures in this varying environment requires both **power** and **energy**

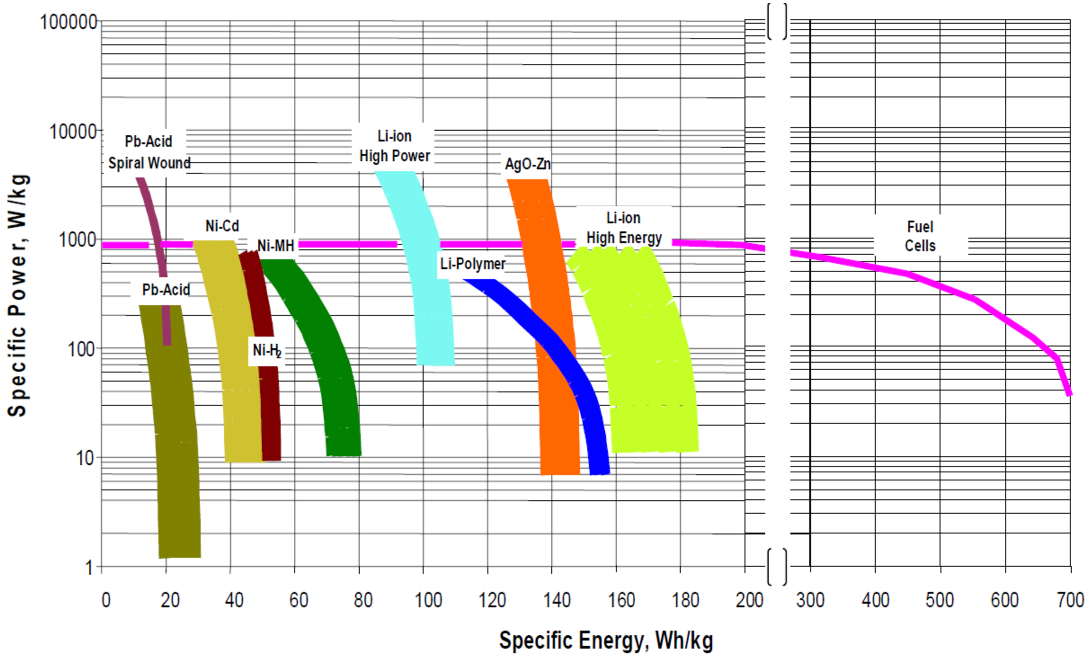
Regenerative Fuel Cells are an integral part of a Lunar Surface Power Architecture

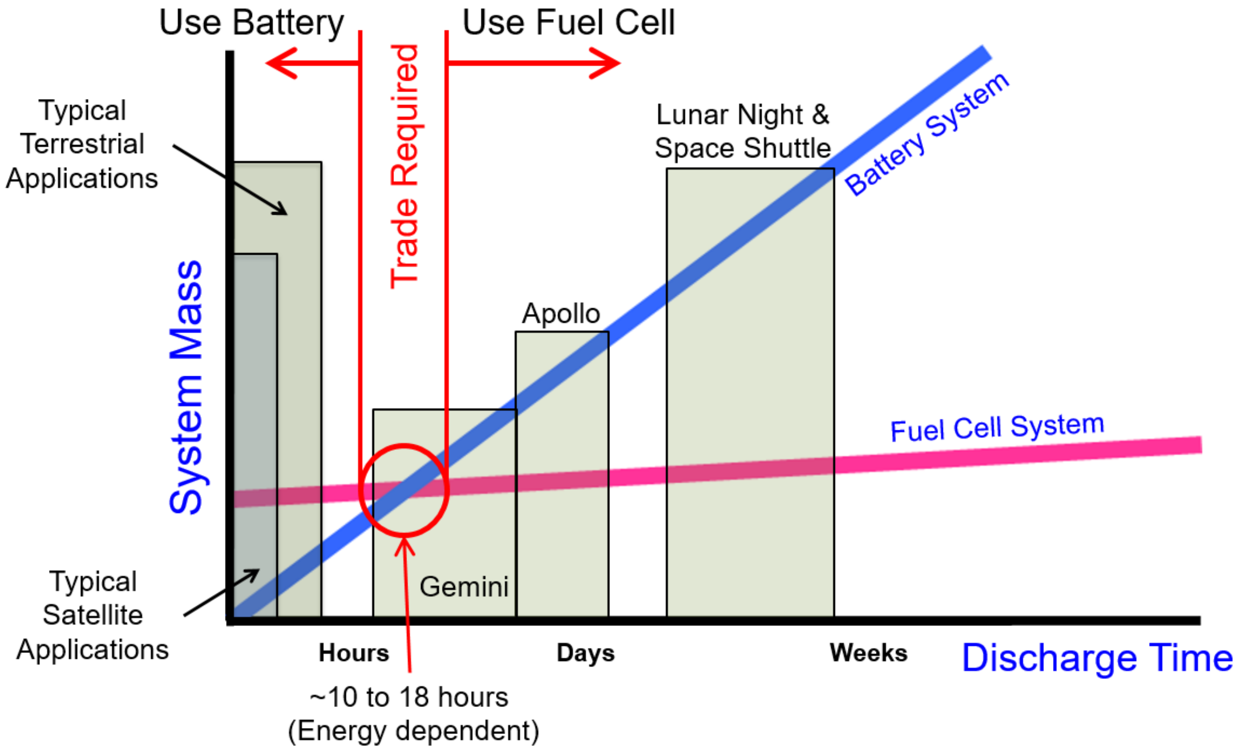
Regenerative Fuel Cells (RFCs) for Lunar Exploration

- RFCs can provide energy storage to provide power in locations near humans where nuclear power may not be an option
- RFCs can provide continuous power for longer-term operations (such as the lunar night)
- RFCs enable mission operations in harsh environments such as permanently shadowed craters

Why RFCs

- Technologies are *Complementary* not *Competitive*
  - No power or energy storage technology meets all requirements for all applications
  - Each technology has a place within the overall exploration space
  - Energy Storage Metric = Specific Energy (W·hr/kg)
    - Packaged Li-ion Battery Systems ~ 160 W·hr/kg
    - Regenerative Fuel Cell Systems <100 to >600 W·hr/kg based on location and energy requirements





Energy Options for Space Applications

Battery = TRL 9
Primary Fuel Cell = TRL 5
Regenerative Fuel Cell = TRL 3

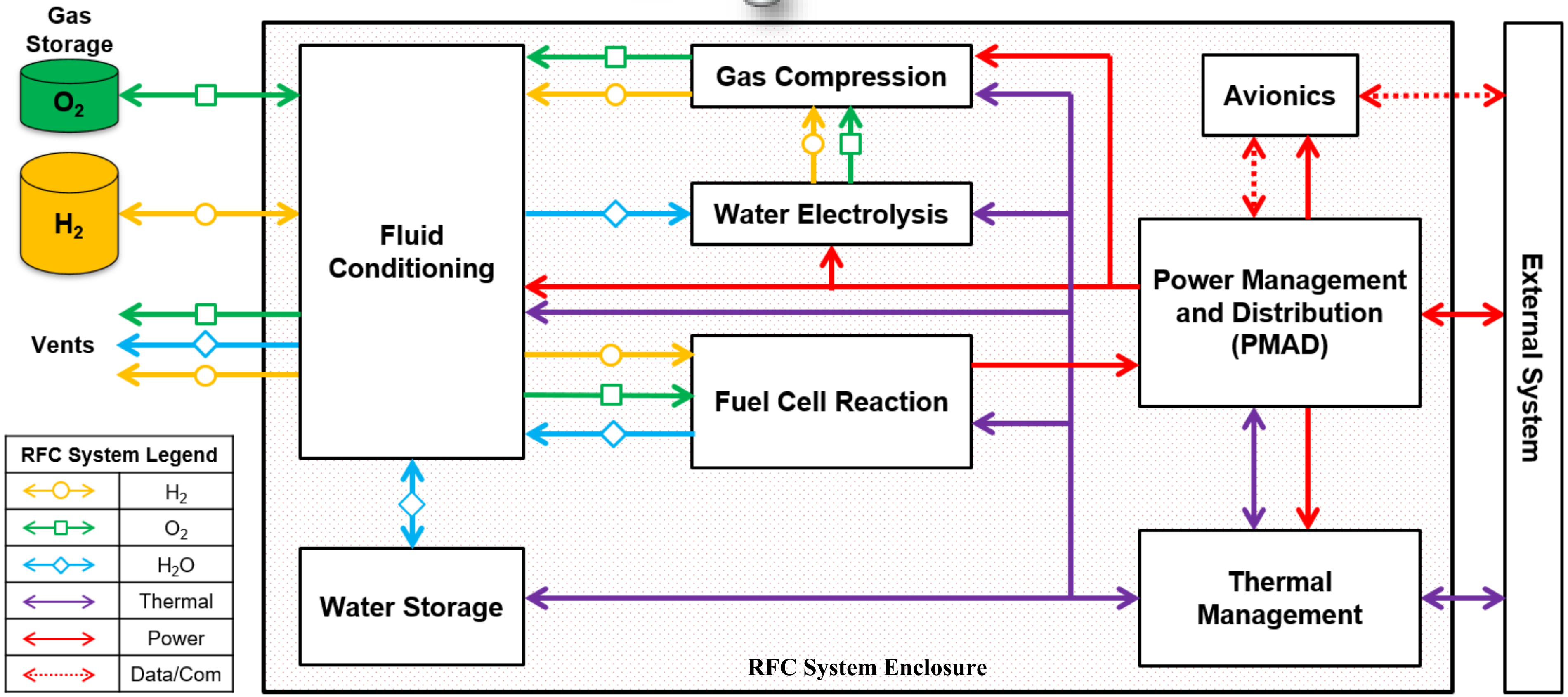
What is a Regenerative Fuel Cell?

What:

A ***system*** that utilizes fluids (e.g. H_2 and O_2 gases) to store energy

Why:

Higher specific energy (W·hr/kg) for ***high energy*** applications than a fully packaged battery system



RFC Project: Technology Challenges by Element

O_2 Gas Storage

- ○ Water-accelerated *corrosion*
- • Cleanliness
- • Pressure Cycles
- • Thermal Cycles

H_2 Gas Storage

- ○ Water-accelerated *embrittlement*
- • Cleanliness
- • Pressure Cycles
- • Thermal Cycles

Legend

➢ Tech Dev Required

○ Tech Dev Recommended

• Engineering Required

*** = Required development depends on electrolyte: PEM vs Alkaline vs Solid Oxide

Fluid Processing and Control Module

- ➢ DI Water Lift Pumps
- ➢ Electrolysis-compatible Biocides***
- ➢ Sensor Calibration Stability
- ➢ Water Polishers / De-ionizers
- ➢ Water Quality
- ○ Catalytic Recombiner
- ○ Phase Separators
- ○ Regenerative Gas Dryers
- • Cleanliness
- • Corrosion
- • Material Compatibility
- • Operations / Procedures
- • Pressure Cycles
- • Thermal Cycles

Water Storage

- ➢ Water Quality
- ○ Contaminant Mitigation
- ○ Dormancy / Shelf Life
- • Cleanliness
- • Corrosion
- • Fluid Volume Management
- • Material Compatibility
- • Pressure Cycles

Water Electrolysis & Gas Compression

- ➢ Efficient / Reliable Reactant Compression
- ➢ Electrolyte Mechanical Properties***
- ➢ Safety Sensor (H_2–in–O_2, High Pressure)
- ➢ Stack Integration (Life, Performance, Reliability)***
- ○ Bipolar Plate / Interconnect Performance***
- ○ Catalyst Performance***
- ○ Electrode Performance***
- ○ Electrolyte Ionic Conductivity***
- ○ Safety Sensor (O_2–in–H_2, High Pressure)
- ○ Water Quality***
- • Cleanliness
- • Corrosion
- • Material Compatibility
- • Pressure Cycles

Fuel Cell Reaction

- ➢ Electrolyte Mechanical Properties***
- ➢ Electrolyte Performance Stability***
- ➢ Stack Integration (Life, Performance, Reliability)***
- ○ Bipolar Plate / Interconnect Performance***
- ○ Catalyst Performance***
- ○ Degassing Product Water***
- ○ Electrode Performance***
- ○ Electrolyte Ionic Conductivity***
- ○ Gas Diffusion Layer Performance***
- ○ Internal Water Management
- • Cleanliness
- • Corrosion
- • Material Compatibility

Avionics

- ➢ Radiation-tolerant Avionics
- • Software

Power Management and Distribution

- ➢ Radiation-tolerant Power Electronics
- ○ Power Standards (Quality, Interfaces)

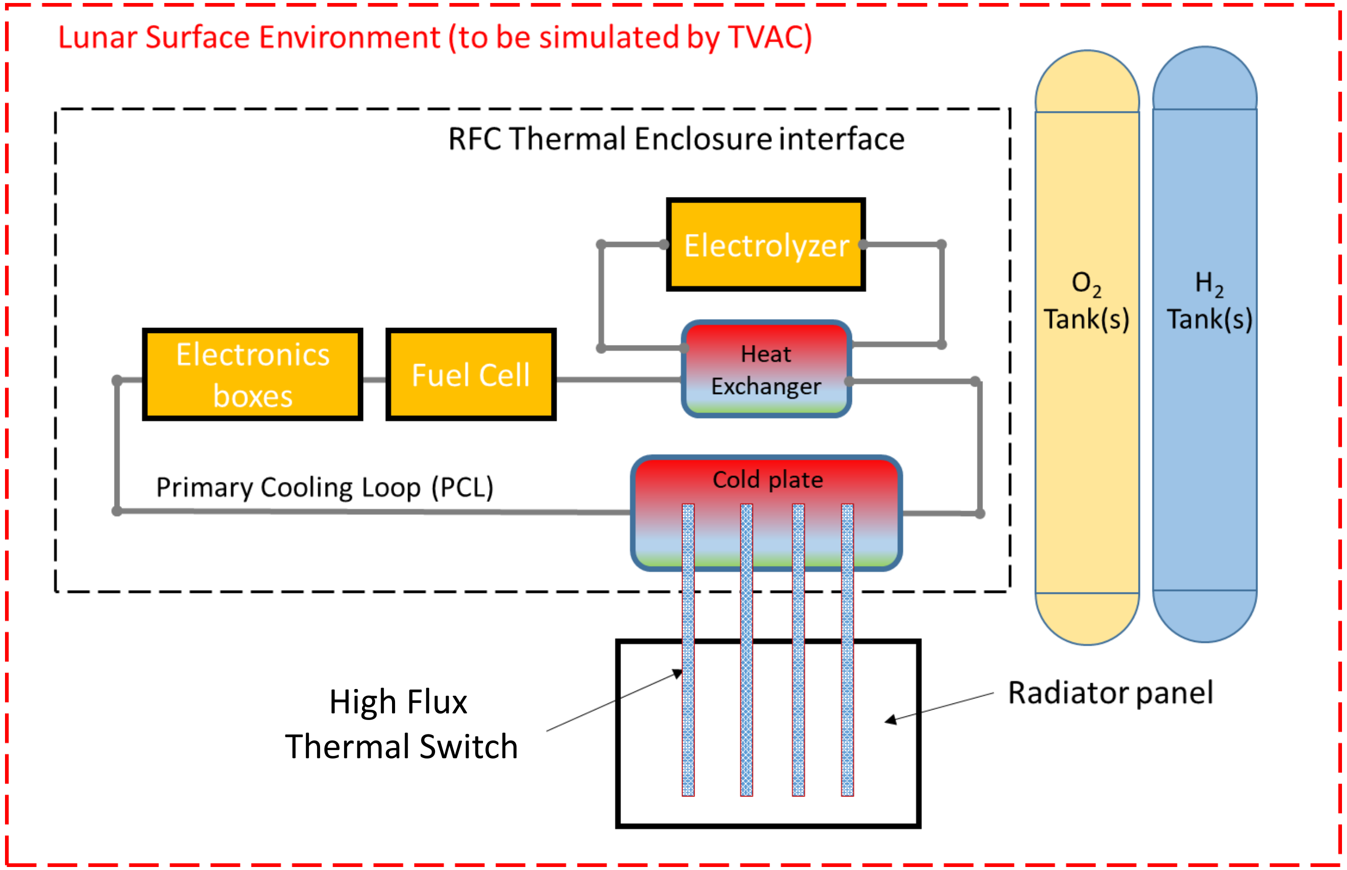
Thermal Management

- ➢ High Flux Thermal Switch (kW-scale)
- ○ Radiator / Heat Sink
- • Multi-range thermal systems
- • Long-life coolant pumps

External System

RFC Thermal Management System Example

- Heat load sources
  - Fuel Cell (FC), Electrolyzer (EZ) Stacks
  - Balance of Plant Components (PMAD/Avionics, valves, pumps, etc)
  - External loads (heat transfer to/from surface environment) via radiation and conduction
- Passive Components
  - Radiator panel
  - MLI
  - Thermal Coupling
- Active Components
  - Pumped cooling loop (x2)
  - Heaters
  - Heat Exchangers



The Primary Cooling Loop (PCL) rejects heat from electronics and FC stacks directly, heat from EZ stack indirectly via a heat exchanger with a secondary recirculation loop. This heat is rejected via a high flux thermal switch to a radiator panel [Ref 2].

High Flux Thermal Switch

- Challenge
  - High internal and external heat load occurs during lunar day
    - Need to reject max heat load when surface environment is also hottest
  - Moderate heat loads during lunar night
    - Need to conserve heat generated internally to keep temperatures within operating ranges while surface temperatures are extremely low
- The radiator and the associated coupling technology must be able to adjust to these contrasting heat rejection needs, and ideally, be able to effectively disconnect during the lunar night to minimize heat loss

Lunar Day			Lunar Night		
Steady State Heat Generation Nominal (W)	Steady State Heat Generation Maximum (W)	Transient Heat Generation Maximum (W)	Steady State Heat Generation Nominal (W)	Steady State Heat Generation Maximum (W)	Transient Heat Generation Maximum (W)
287	**420**	**508**	**286**	**605**	**685**

Representative thermal loads for 100W net-power output scale RFC. Does not include heater power to maintain reactant storage tanks during night.

Thermal Switch Requirements

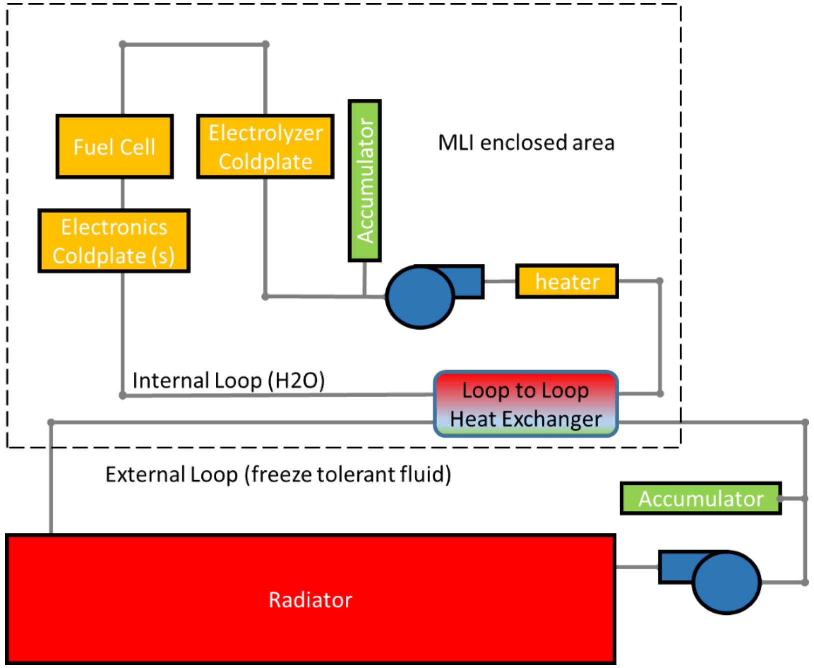
- The method used to thermally connect the PCL to the radiator is a critical consideration and must:
  - Maintain the PCL within a narrow temperature range
  - Accommodate thermal rejection power from a variable PCL temperature and to a variable environmental sink temperature
  - Maintain a minimum fluid temperature during the long lunar night
  - Minimize parasitic losses from the fluid system to the environment during the lunar night
  - Avoid interference with the geometry, orientation, and placement of the radiator
  - Function in a vacuum environment of <1 mPa (10–5 torr)
  - Be freeze-tolerant or nonfreezing to a minimum of 120 freeze and thaw cycles
  - Desirable to use non-toxic fluids

Trade Study

- Technology Options Assessed
  - External pumped loop (EPL) system using regenerative heat exchanger and single-phase freeze-tolerant thermal fluid
  - Freeze-tolerant external pumped loop (FT-EPL) system using two-phase thermal fluid (freeze-tolerant radiator)
  - Passive thermal louvers (PTLs)
  - Conventional heat pipes (CHPs)
  - Variable conductance heat pipes (VCHPs)
  - Paraffin actuated switch
- Performance Metrics
  - Turn down ratio $=\frac{Q_{switch-closed}}{Q_{switch-open}}$
  - Complexity (number of components, moving parts)
  - Technology Readiness Level (TRL)
  - Mass, volume
  - Reliability

EPL System with Regen Heat Exchanger and Single-Phase Freeze-Tolerant Fluid

- Choice of thermal fluid highly dependent on the mission thermal environment
- A radiator bypass line in the loop plus a thermostatic valve (not shown) controls the thermal fluid return temperature to the RFC internal loop heat exchanger
- Pros:
  - Mature and flight demonstrated technology
- Cons:
  - Parasitic loads of pump impact RFC round trip efficiency
  - Freezing concern when bypassing radiator during lunar night
  - Complexity (number of components, moving parts)



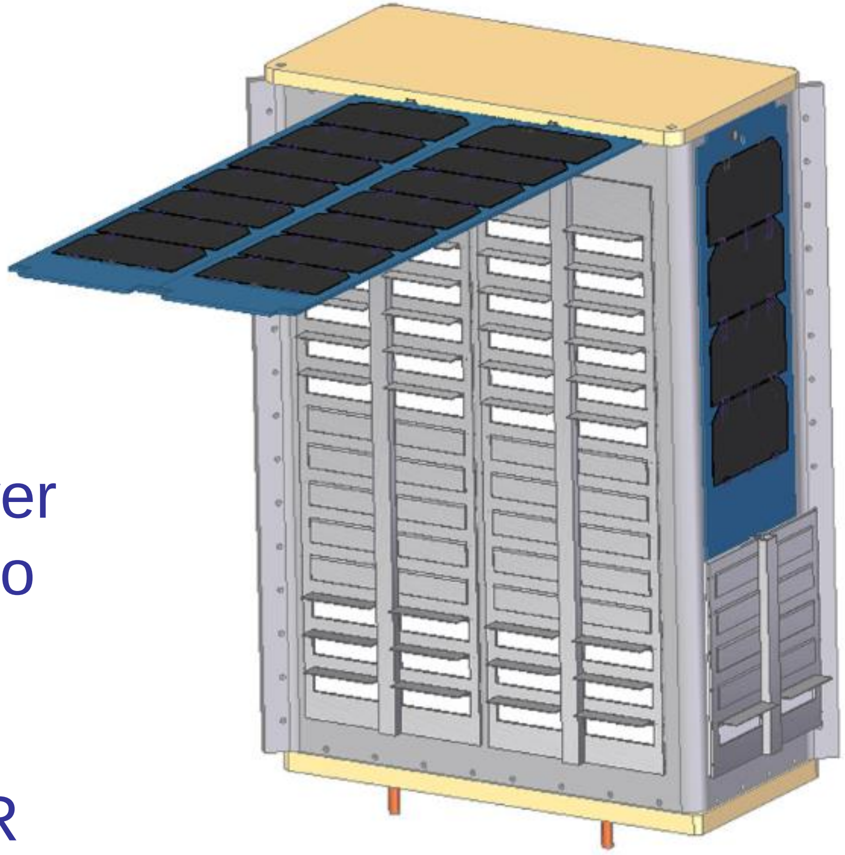
High level process flow diagram showing EPL coupled with RFC thermal management system [Ref 2].

Freeze-Tolerant External Pumped Loop

- Utilizes 2 phase working fluid (WF) that allows gas to flow through radiator under low heat load conditions
- 2 NASA funded SBIRs evaluated this technology
- Design Concept 1
  - Parallel tube configuration with both phases operating under high heat loads
  - Liquid freezes and gas circulates through radiator under low heat loads
- Design Concept 2
  - Freeze-tolerant condensers in parallel tubes fed vapor from a membrane evaporator (coupled to the primary cooling loop)
  - Condensers self-regulate the thermal conductivity by condensing the WF (e.g., H_2O)
    - Potential to achieve turndown ratios >10

Passive Thermal Louvers

- Increases or decreases view factor from radiator panel to surroundings by mechanical louver
- Bimetallic springs that are thermally connected to the radiator actuate pivoting blades or vane louver at predetermined set points
- Commercial Off-The Shelf (COTS) options for louvers are primarily for a lower heat rejection power than what is required for RFC (hundreds of Watts to kW depending on RFC scale)
- Turn down ratios of approximately 6 (effective emissivity of 0.14 to 0.74 for ε* = 0.85 radiator in IR spectrum)



NASA-Developed Passive Thermal Louver for CUBESATs [Ref 3]

Variable Conductance Heat Pipes (VCHPs)

- Uses evaporator, an adiabatic section, and a wick to return the condensate back to the evaporator
- VCHP adds a non- condensable gas (NCG) to the two-phase WF and a NCG reservoir
  - Usually located at condenser end with parasitic heater
  - Applications where this parasitic heater is not available or desirable (RFC), NCG reservoir can be located next to evaporator section
  - NCG quantity in the reservoir is proportional to the evaporator WF vapor pressure
- At full design thermal power most NCG is driven into the gas reservoir allowing the entire condenser region to be active
- At lower thermal power, the evaporator WF vapor pressure drops allowing the WF and NCG boundary to move into the condenser region
  - Reduces the active heat transfer area until a new equilibrium is achieved

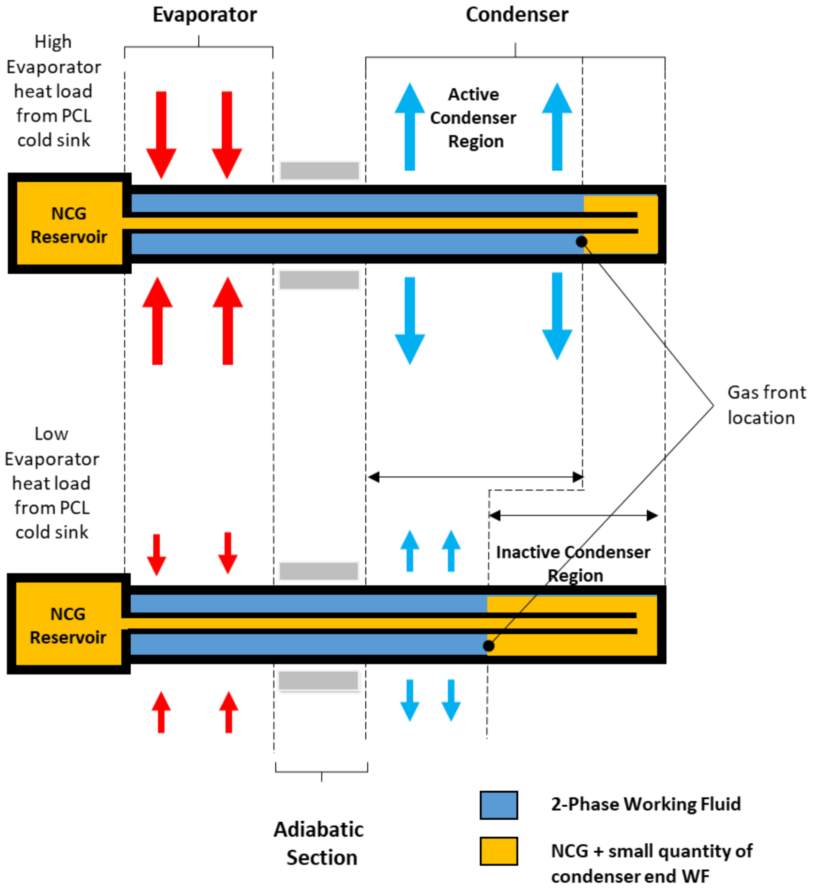
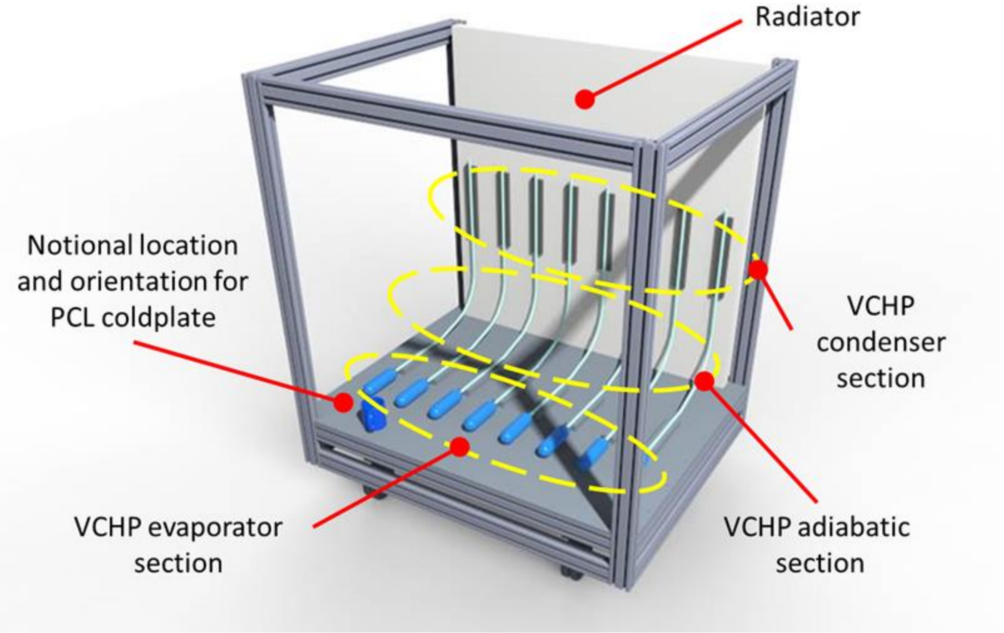


Illustration of working principle of VCHP [Ref 2].

VCHP Operation Continued

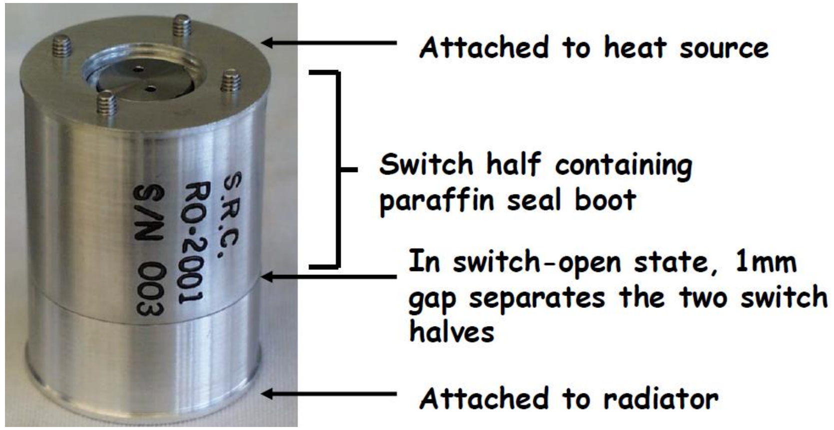
- The WF and VCHP charge pressure combination is chosen to minimize evaporator WF saturation temperature change versus pressure
  - This maintains a small evaporator temperature band
- If the power level is low enough, there will be no convective heat transfer in the VCHP as the NCG will occupy the entire condenser section
  - Small amount of heat transfer via gas and thin-walled tubing conduction
  - Orders of magnitude less than the WF two-phase heat transfer
  - Allows the VCHP to function as a “thermal switch”



VCHP Design Concept for RFC

Paraffin Based Thermal Switch

- Incorporated at the interface between internal and external thermal loops
- Paraffin-based actuator contracts and expands with temperature such that thermal contact varies between a heat source and heat sink at a set temperature
- COTS cylinders 2.5-cm diameter by 3.8 cm-long reject ~6W each (1.2 W/cm^2)
- COTS thin plate thermal switches integrate 2.5 x 2.5 -cm squares each capable of rejecting 12W (1.9 W/cm^2)
- Wide temperature regime from –130 to 100 °C and offer set points from –10 to 50 °C
- High turndown ratios of thermal conductivity around 78:1



Attached to heat source

Switch half containing paraffin seal boot

In switch-open state, 1mm gap separates the two switch halves

Attached to radiator

NASA – JPL Developed Heat Switch [Ref 4]

Conclusion

- RFCs offer potential for high specific energy power solutions for future lunar missions
- Thermal management of RFC in lunar environment is critical challenge due to need to reject thermal energy during lunar day and conserve thermal energy during lunar night
- Different technology options exist to serve as a high heat flux thermal switch between the RFC primary cooling loop and heat rejection interface (radiator)
  - Each technology has advantages and disadvantages as pertains to TRL, complexity, mass, parasitic power required, and cost
  - Different options could be used in combination to obtain the required turndown ratio
  - Advances in these technologies can help enable future lunar missions by addressing one of the primary challenges of sustained operations – *the long, cold lunar night*

References

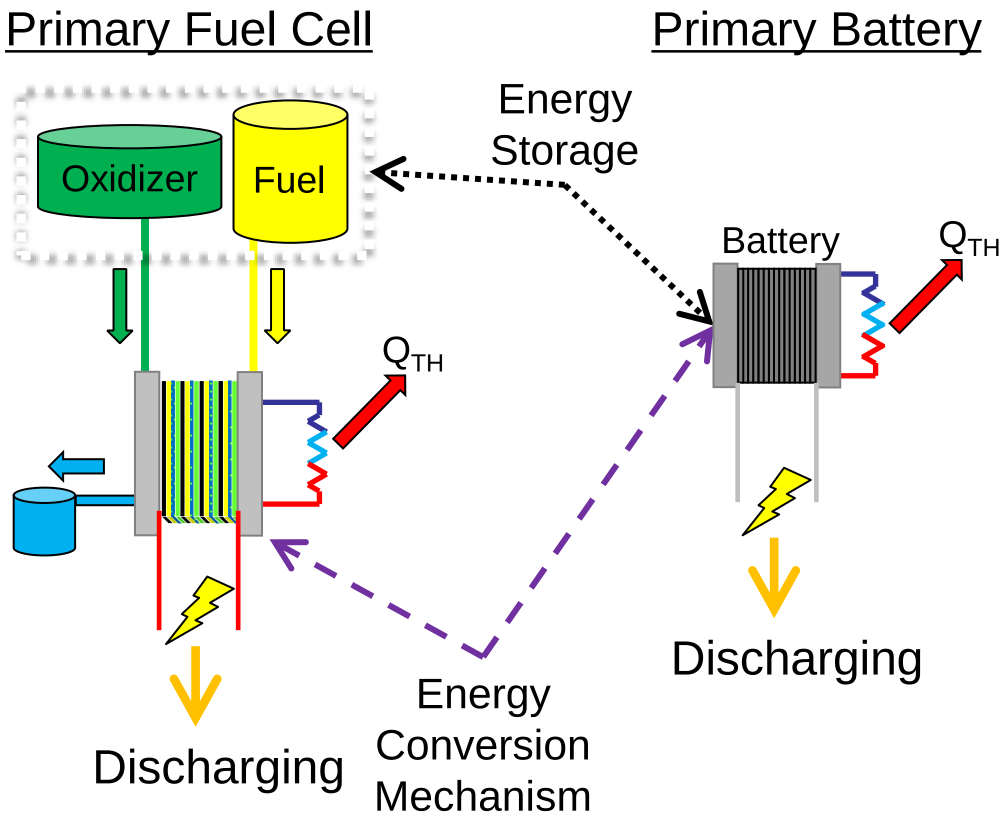
1. Williams, Jean-Pierre. “LRO Diviner Lunar Radiometer Global Data Products.” UCLA. <https://astropedia.astrogeology.usgs.gov/download/Docs/PlanetaryDataWorkshop/Presentations2017/Monday/Humphreys/Williams-Data_Users_Workshop-Flagstaff-2017.pdf>.
2. Smith, Phillip J. et al. “Aerospace Regenerative Fuel Cell Fluidic Component Design Challenges.” NASA TM-20210024659. July 2021.
3. “CubeSat Form Factor Thermal Control Louvers”. NASA Technology Transfer Program. <https://technology.nasa.gov/patent/GSC-TOPS-40>.
4. Sunada, E. et al. “Paraffin Actuated Heat Switch for Mars Surface Applications”. Space Technology Applications International Forum 2002.

BACKUP

Advantages	Disadvantages	Relative maturity
External pumped loop (EPL)		
Simple; flight demonstrated	External loop may contain hazardous fluids. It requires an extra heat exchanger and second loop with associated controls, pumps, and support hardware that increases complexity, parasitic electrical power, and possibility of mechanical failure.	High technology readiness level (TRL)
Freeze-tolerant external pumped loop (FT-EPL)		
Simpler and lighter than external loop pumped system; high thermal turndown ratio; lower parasitic power requirements than external loop pumped system; can use H_2O working fluid (WF)	Adds complexity in terms of additional components to system.	Low TRL
Passive thermal louver (PTL)		
Simple design; high solar irradiance capability; spaceflight heritage; fully passive thermal control; fairly wide range of operational temperature band and set points	Limited turndown ratio (~5.3) Does not allow for both maximum heat transfer and prevention of loop freezing without adding parasitic heating. Limitations of mounting locations. COTs sizes are small, requiring multiple louver systems or a custom designed system. Limited to single source vendor.	High TRL
Conventional heat pipe (CHP)		
Lightweight; passive, no parasitic pumping load loss; flight demonstrated	Limited ability to regulate the PCL temperature within a narrow range. Limited ability to limit heat transfer below a desired temperature.	High TRL
Variable conductance heat pipe (VCHP)		
Lightweight; passive, no parasitic pumping load loss; maintains near constant PCL temperature; can effectively shut off at a desired temperature; parasitic heating requirements are very small	There are specialized design considerations. Careful coordination with VCHP supplier is required to insure adequate performance.	Moderate TRL
Thermal Switches		
Lightweight; passive; modular, easy to package	Small scale relative to RFC thermal loads. Cost is a factor.	Moderate TRL

Primary Fuel Cells vs. Primary Battery

Electrical Power to enable and augment exploration activities



Primary Metric = Specific Power (W / kg)

Batteries store energy intimately with the energy conversion mechanism

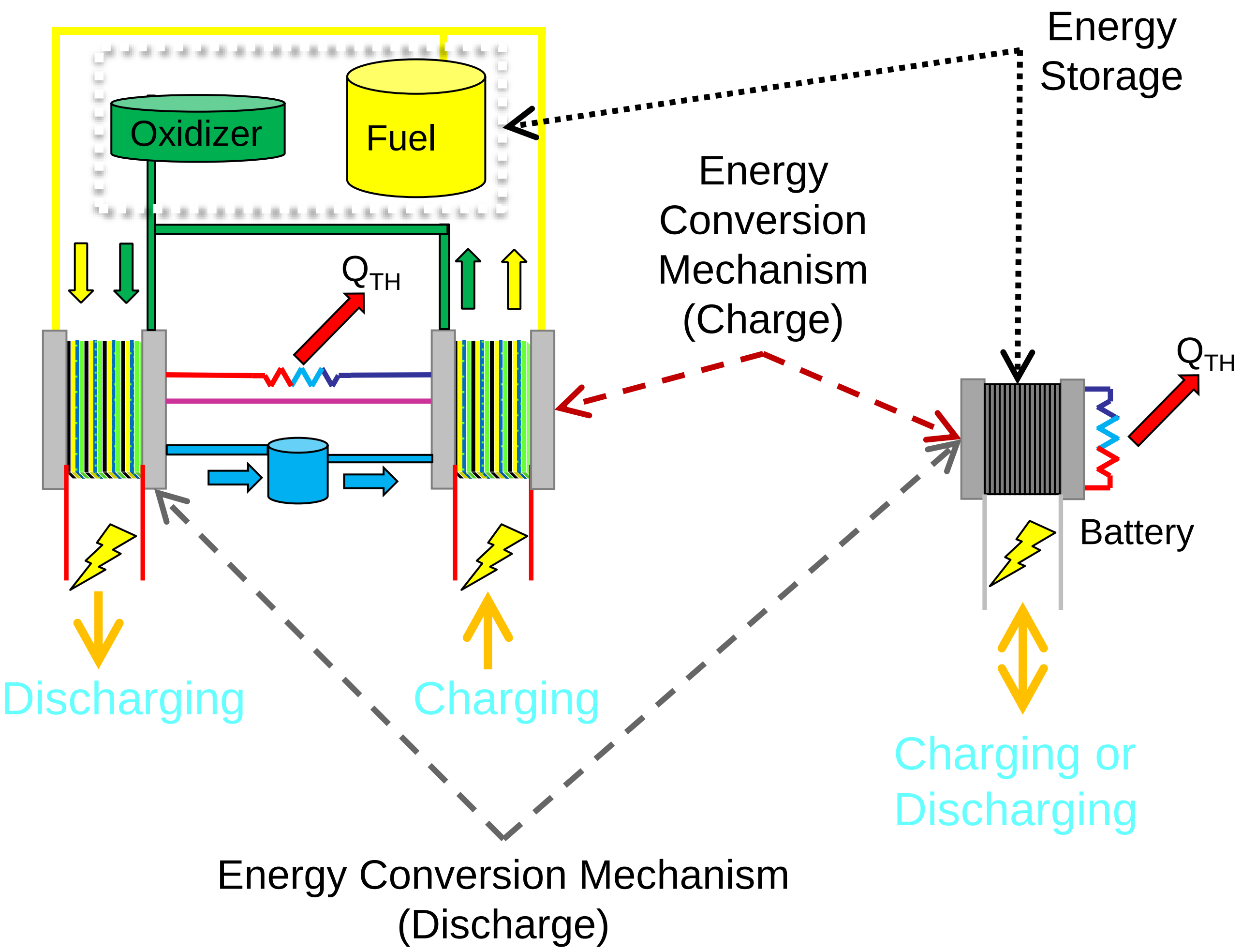
Primary fuel cells store energy remotely from the energy conversion mechanism

- Different Hazards and Mitigations
  - Batteries sensitive to Thermal Runaway
  - Fuel Cells sensitive to Material Compatibility and Process Fluid management issues
- Different Voltage to State-of-Charge (SoC) relationships
  - Battery voltage dependent on quantity of stored energy
  - Fuel Cell voltage independent of quantity of stored energy
- Different Scalability
  - Battery system specific energy determined by chemistry and packaging
  - Fuel Cell system specific energy determined by quantity of reactants and packaging

Regenerative Fuel Cell vs. Rechargeable Battery

Energy Storage enabling and augmenting exploration activities

Regenerative Fuel Cell



Primary Metric = Specific Energy (W·hr / kg)

Rechargeable batteries store energy intimately with the energy conversion mechanism

Regenerative fuel cells (RFCs) store energy remotely from the energy conversion mechanisms

- Different Hazards and Mitigations
  - Batteries sensitive to Thermal Runaway
  - RFC have very complicated supporting systems
- Different Voltage to State-of-Charge (SoC) relationships
  - Rechargeable battery voltage dependent on quantity of stored energy
  - RFC discharge voltage independent of quantity of stored energy
- Different Recharge/Discharge capabilities
  - Battery rates determined by chemistry and SoC
  - Fuel Cell and electrolyzer independently “tunable” for mission location

Electrochemical System Definitions: Primary Fuel Cell

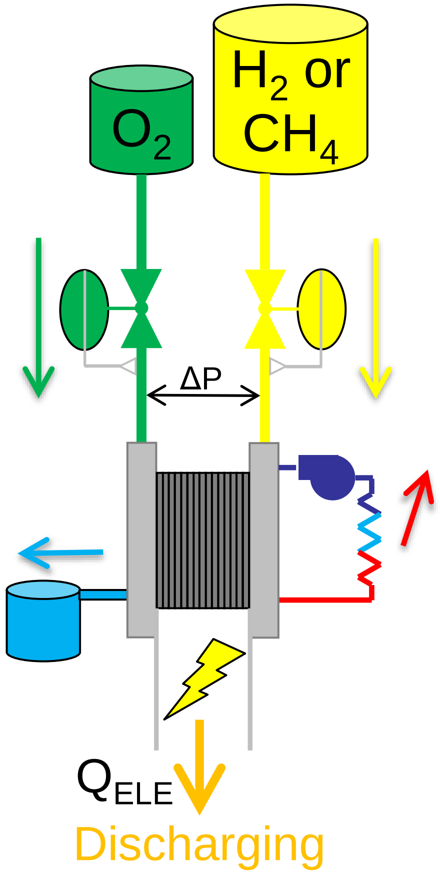
Discharging Only

<u>Proton Exchange Membrane (PEM) Fuel Cell</u>

- Converts gaseous hydrogen and oxygen reactants into electrical power, heat, and water
- Operational duration limited by supplied reactants
- RFC Fuel Cell Operating Conditions:
  - Operation temperature range: 60 – 80 ° C
  - Operational pressure range: 38 – 45 psia

Example Aerospace System

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



Reactant storage determines Specific Energy and Total Energy Capacity

Stack design and operation determines Specific Power

Electrochemical System Definitions: Electrolyzer

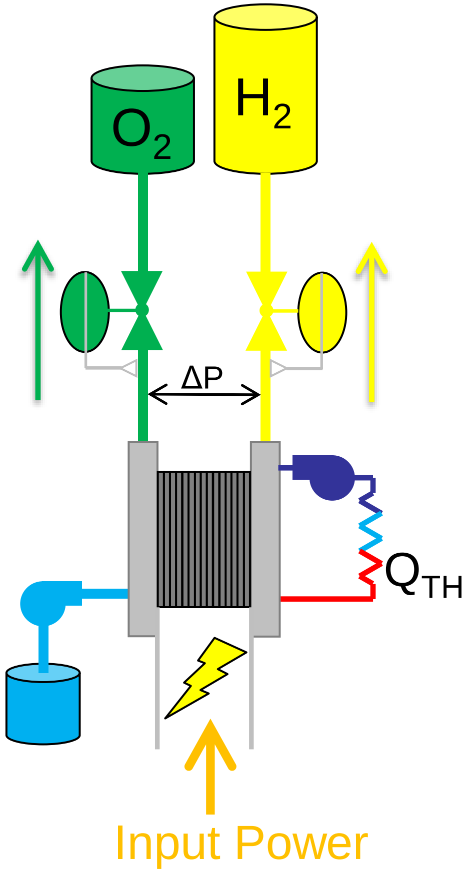
Chemical Conversion

$2\ H_2O$ ⚡ $2\ H_2 + O_2$

PEM Electrolyzer

- Converts liquid water into hydrogen and oxygen gas when supplied electrical power
- RFC Electrolyzer Operating Conditions:
  - Temperature range: 60 – 80° C
  - Pressure range: 15 – 2500 psia

Example Aerospace System



Water From
- Lunar Ice (ISRU)
- Fuel Cell Product Water
- Biological Functions