SOLID OXIDE FUEL CELLS FOR ENERGY STORAGE ON VENUS LANDER

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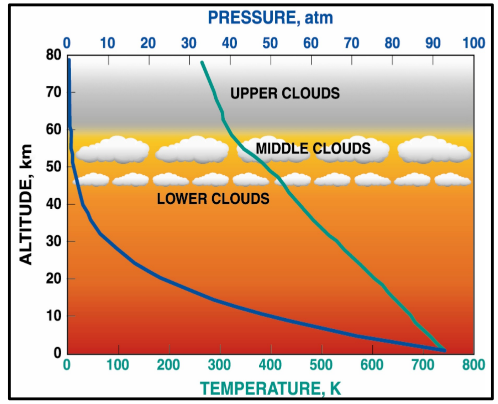
Motivation

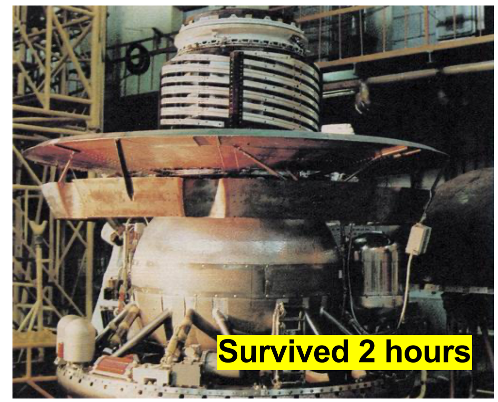
Power Technologies for Venus Surface

- Challenges: High Temperature (465°C) and high CO_2 pressure (90 atm) and corrosive environment (H_2SO_4/ sulfur compounds)
- Reduced solar flux below the clouds and low efficiency of PV (~2-4 W/m² at the surface).
- Radioisotope Thermoelectric Generator (RTG) is not compatible (90 atm; 465°C heat sink)
- We (JPL) have been developing high temperature lithium primary batteries and have demonstrated 30 days of operation at 475°C.
- Desired lifetime of future Venus landers is a minimum of 60 days to capture day/night transition on Venus

Venus Hostile Environment

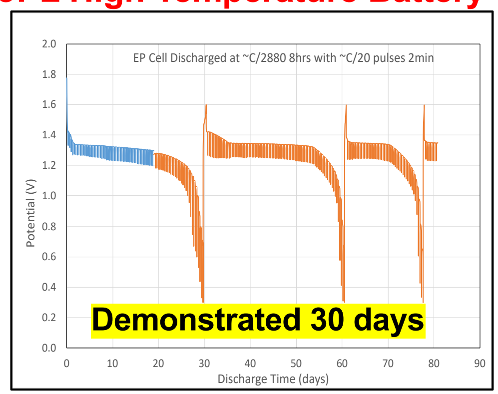


Russian Vega Lander



Venus Lander concept GRC

JPL High Temperature Battery



Explore: High temperature (Solid Oxide) Fuel Cells operation at 500-800°C

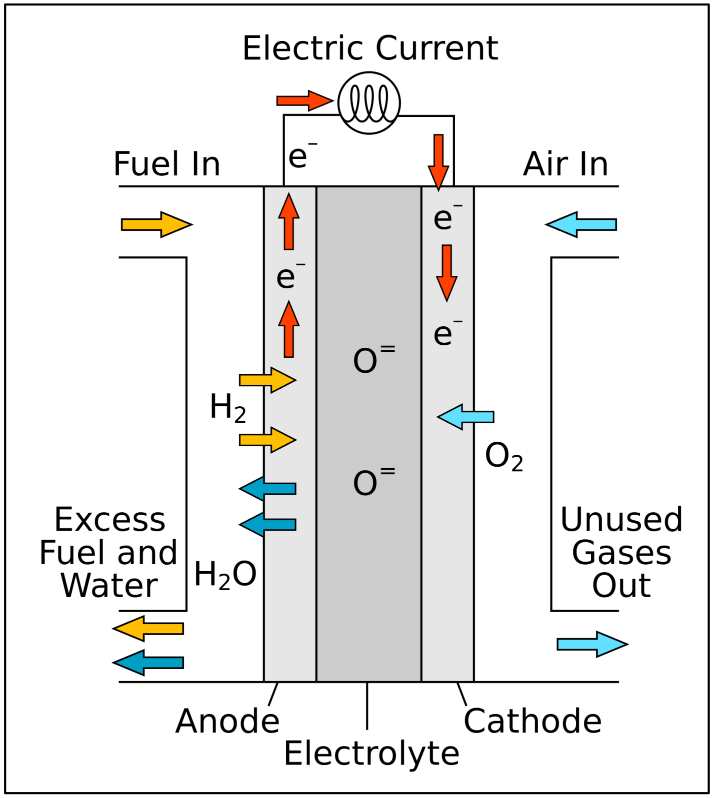
High Temperature Fuel Cells

Hydrogen and oxygen fuel cells

- Conventional solid oxide fuel cell operating at 750-800°C
- Intermediate temperature solid oxide fuel cell (500°C)
- Intermediate temperature solid acid fuel cell (500°C)

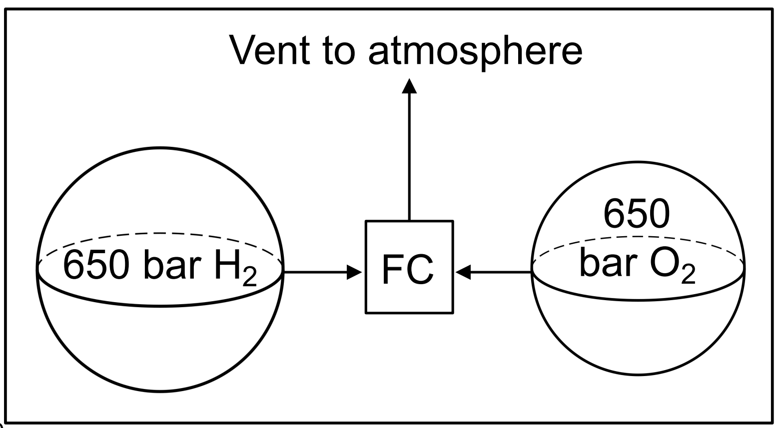
Energy requirements for NASA-GRC Lander, LISSE (Long-life In-situ Solar Exploration)

- Pulse power: 10 W for 2 min every 8 h
- Pulse energy: 60 Wh
- Baseload power: 0.01 W
- Duration: 1440 hr
- Baseload energy: 14.4 Wh
- **Total energy: 74.4 Wh**
- Surface Temp: 465 °C
- Surface Pressure: 92 atm

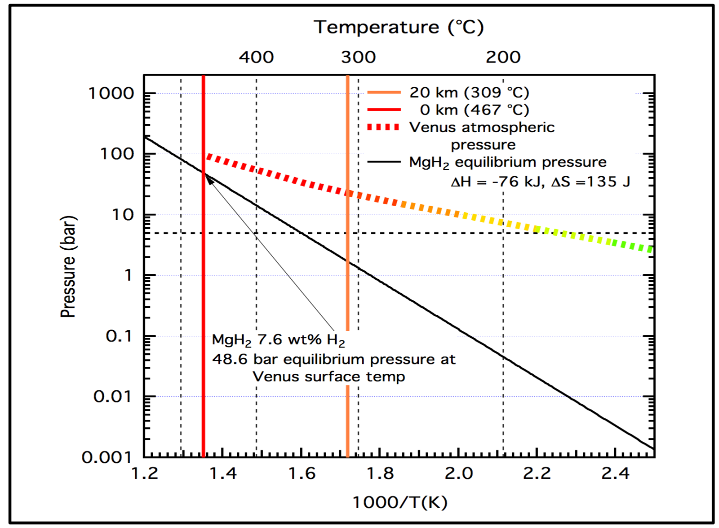


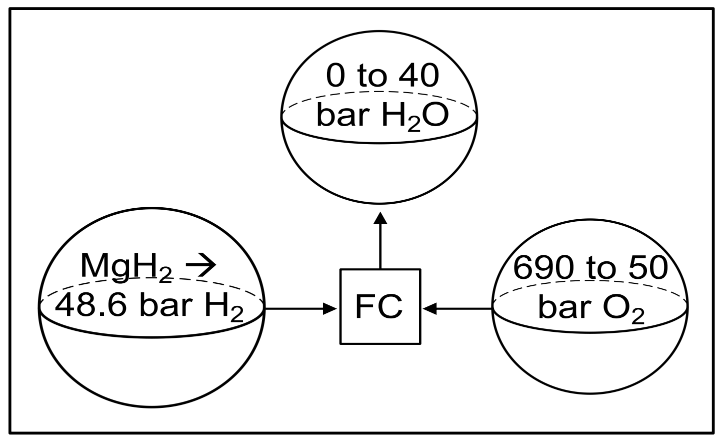
Methods: Basis for Analysis

- Cells requiring warming assumed to have aerogel insulation
  - Heating estimated using simple heat flux calculation
  - Does not take into account interfaces
- H_2 and O_2 stored in hollow spheres
  - Nickel containing alloys not preferred due to concerns over corrosion in Venus atmosphere
  - Assume ideal gas law (PV=nRT)
  - Assume cell vents to atmosphere



van't Hoff Plot for H_2 Storage in Metal hydrides





Sphere sizing

- Use following equation:
  - P = pressure rating (psig)
  - Ro = outer radius (in)
  - Ri = inner radius (in)
  - S = allowable stress (psi)
  - FS = factor of safety

$$P = \frac{(Ro^2 - Ri^2)\times S}{Ri^2 \times FS}$$

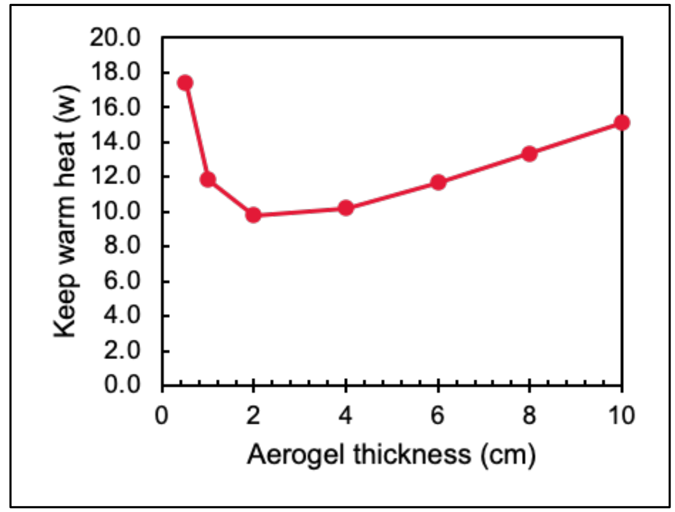
- Pick 650 bar storage pressure (558 bar delta)
- Allowable stress assume to be 60,000 psi based on superalloy tensile strength at elevated temperature
- Adjust Ro and Ri to achieve hollow sphere with enough internal volume for gas storage and pressure rating >560 bar (8100 psig)

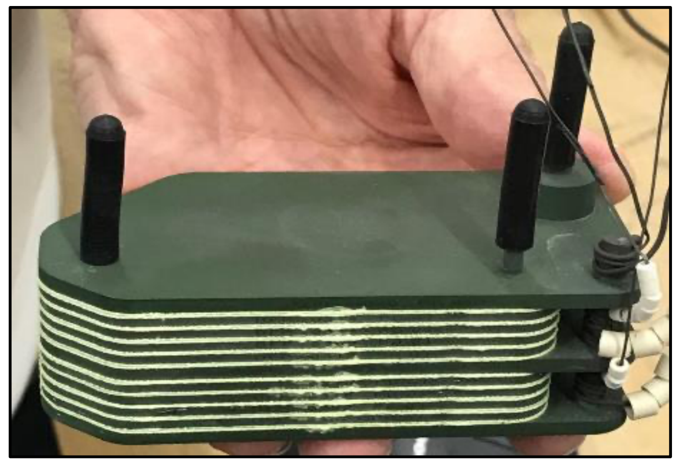
Fuel cell sizing

- Start with pulse power: 10 W
- Find max power density for given fuel cell system
- Divide pulse power by power density to determine fuel cell area
- Require 25 V stack during pulse
- Find voltage at max power
- Divide 25 V by voltage at max power to determine number of cells
- Assume cells are 1 mm thick
- Add 1 cm around perimeter and top and bottom of cell
- Assume density of 8 g/mL

Option 1: SOFC (Conventional)

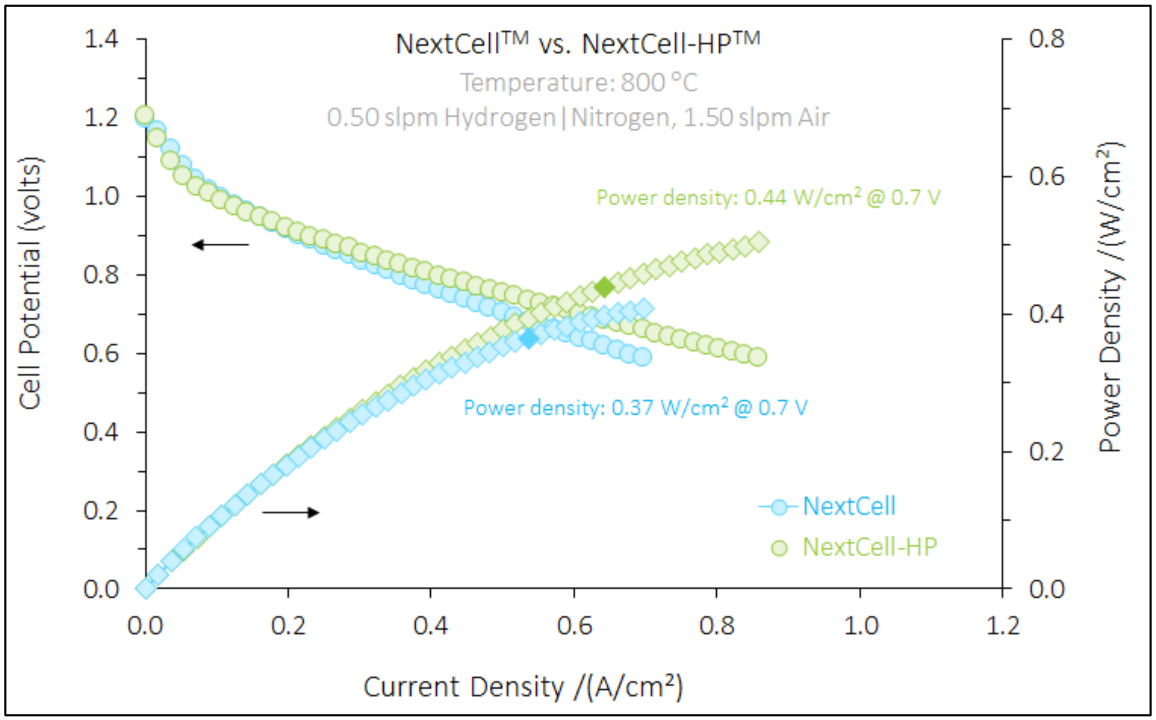
- Cell must be kept at 800 °C for 1440 hr
- ΔT = 335 K
- Assume roughly MOXIE-size stack (5x5x5 cm)
- Assume Aerogel insulation
  - 0.023 W/(m*K)
  - Sphere of insulation around stack
- Thicker insulation reduces heat flux (W/m^2), but increases surface area (m^2)
- More advanced thermal engineering likely required to properly model
- Assume ~10 W sufficient to keep cell warm





Option 1: SOFC

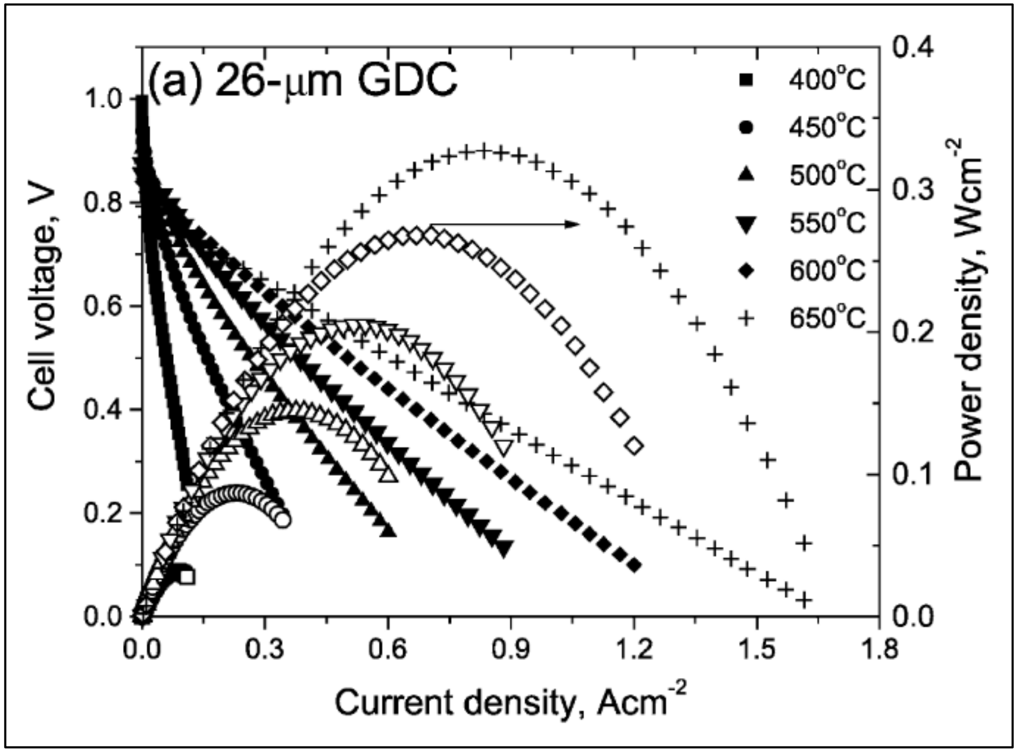
Data from Nexceris: https://fuelcellmaterials.com/nextcell-versus-nextcell-hp-comparing-performance-data/



Baseload energy (Wh):	14.4
Pulse energy (Wh):	60.0
Mission energy (Wh):	74.4
Keep warm energy (Wh):	8,640
H_2 mass (g):	263.0
H_2 vol (L):	12.4
H2 container mass (g):	33,479
O2 container mass (g):	17,391
SOFC size (cm^2):	22.7
SOFC mass (g):	117.0
Total mass (g):	52,302.4
Specific energy (Wh/kg):	**1.4**

Option 2: IT-SOFC

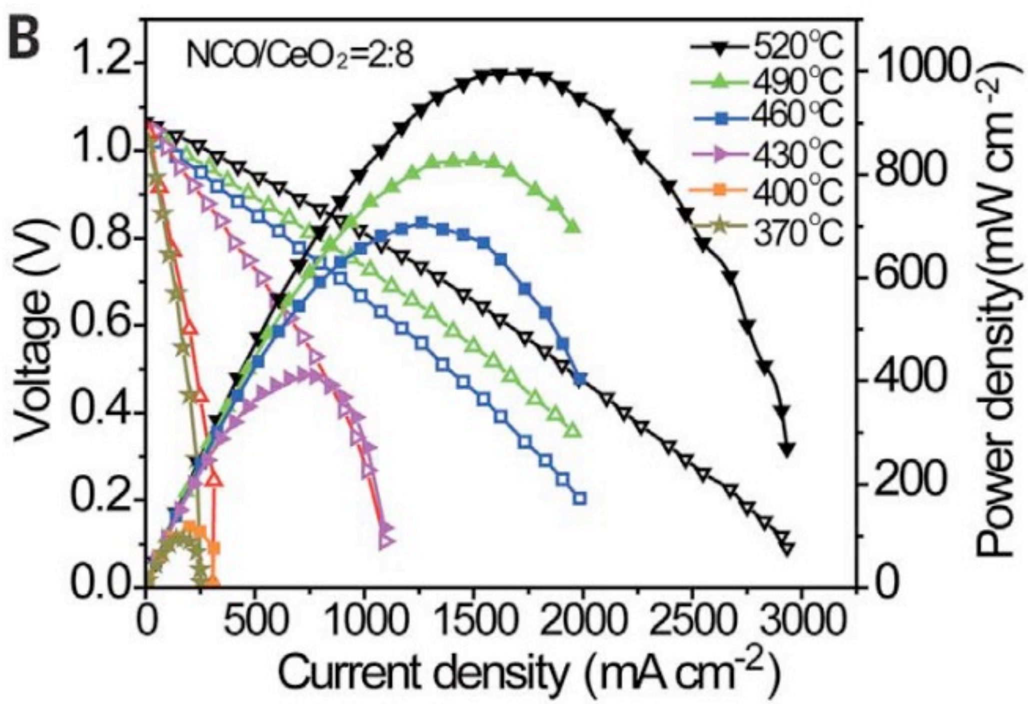
Data from: Xia, C.; Liu, M. Low-Temperature SOFCs; based on $Gd_{0.1}Ce_{0.9}O_{1.95}$; fabricated by dry pressing. *Solid State Ionics* 2001, 144 (3–4), 249–255.



Baseload energy (Wh):	14.4
Pulse energy (Wh):	60.0
Mission energy (Wh):	74.4
Keep warm energy (Wh):	0
H_2 mass (g):	4.96
H_2 vol (L):	0.23
H2 container mass (g):	648
O2 container mass (g):	357
SOFC size (cm^2):	100
SOFC mass (g):	191
Total mass (g):	1,221.5
Specific energy (Wh/kg):	**60.9**

Option 3: IT-Proton FC

Data from: Wu, Y.; Zhu, B.; Huang, M.; Liu, L.; Shi, Q.; Akbar, M.; Chen, C.; Wei, J.; Li, J. F.; Zheng, L. R.; Kim, J. S.; Song, H. B. “Proton transport enabled by a field-induced metallic state in a semiconductor heterostructure. ***Science*** (80-.). 2020, 369 (6500), 184–188. https://doi.org/10.1126/science.aaz9139.



Baseload energy (Wh):	14.4
Pulse energy (Wh):	60.0
Mission energy (Wh):	74.4
Keep warm energy (Wh):	0
H_2 mass (g):	3.30
H_2 vol (L):	0.16
H2 container mass (g):	435
O2 container mass (g):	221
SOFC size (cm^2):	14.3
SOFC mass (g):	109
Total mass (g):	782
Specific energy (Wh/kg):	**95.1**

Fuel Cell Comparison and Conclusions

	Nexceris SOFC	IT-SOFC from Xia et al.	IT-Proton FC from Wu et al.
Electrical energy (Wh):	74.4	74.4	74.4
Keep warm energy (Wh):	8,640	0	0
H2 mass (g):	263	4.96	3.3
H2 vol (L):	12.4	0.23	0.16
H2 container mass (g):	33,479	648	435
O2 container mass (g):	17,391	357	221
SOFC active area (cm^2):	22.7	100	14.3
SOFC mass (g):	117	191	109
Total mass (g):	52,302.4	1,221.5	782
Specific energy (Wh/kg):	**1.4**	**60.9**	**95.1**

- Heating SOFC is not practical due to high energy costs. Based on this, the conventional SOFC is not a feasible option for the Venus lander application.
- IT-SOFC or other fuel cell (proton) technology capable of operating at ~475 °C can provide 60-95 Wh/kg (more than needed for the LISSE mission), and can operate for several months.
- Size of FC does not have strong impact on system mass, hence the fuel cell can be scaled for higher power levels with out impacting specific energy.

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