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PACKER ENGINEERING Inc.
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Electrical Energy Storage using only Lunar Materials

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Dave Dietzler (The Moon Society)
Peter J. Schubert, Ph.D., P.E. (Packer Engineering)

Permanently-occupied Lunar Base

- POWER
  - Must persist through lunar night (O354 hours
  - Must be highly-reliable, or redundant
- Base-load options:
  - Nuclear reactor
  - Beamed power from orbiting SPS
- Storage options:
  - Batteries
  - Hydrogen

Brief History of Batteries

- Count Alessandro Giuseppe Antonio Anastasio Volta
  - Invented the "voltaic pile" in 1800.
  - The term "**battery**" was coined by Benjamin Franklin in 1748
    - Described an array of charged glass plates
- Gaston Plante: **rechargeable** battery
  - Same lead-acid battery used in cars today – in 1859

- Thomas Edison: **alkaline** storage battery
  - The top selling battery today! – invented in 1901
- A "**battery**" is a collection of electrochemical "**cells**" wired together to boost power.
  - Cells inside a 9V battery

ISRU Battery Fabrication

- Edison Cell
  - Sold until '72
- Electrodes:
  - Iron anode
  - Nickel cathode
- Electrolyte:
  - Potassium hydroxide in water
- Casing
  - Cast basalt, or polymer-lined container

$$Fe + 2OH^- \Leftrightarrow Fe(OH)_2 + 2e^-$$

$$2NiOOH + 2H_2O + 2e^- \Leftrightarrow 2Ni(OH)_2 + 2OH^-$$

$$2NiOOH + Fe + 2H_2O \Leftrightarrow 2Ni(OH)_2 + Fe(OH)_2$$

Electricity Storage Requirements

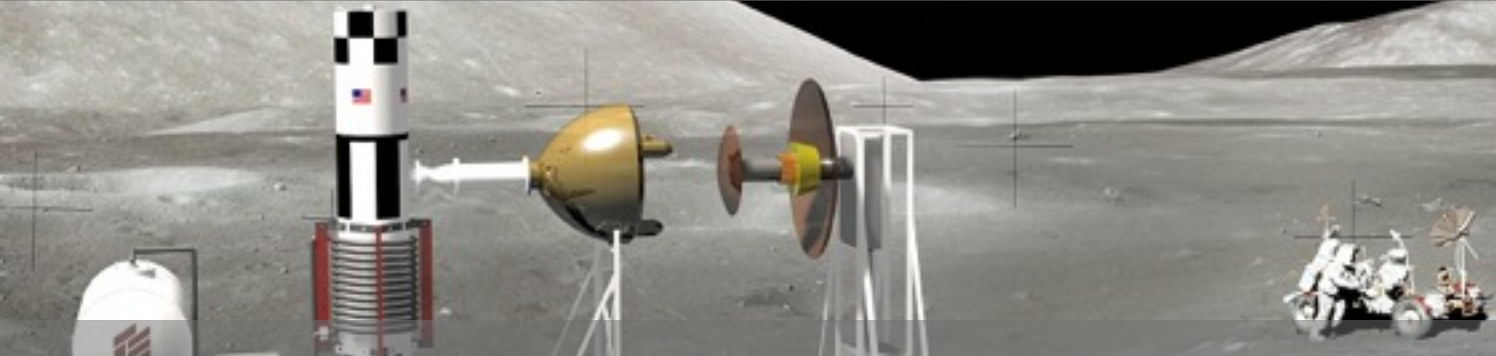
- Consider 2-person base
  - Average 1.2 kW
  - 100 sq. meters
- Equatorial location
- Horticulture:
  - 20 sq. meters per person
  - 100 W per sq. meter
- Inside 23 ºC, outside 0-233 ºC
  - With burial, outside temp is also 23 ºC!

Fe and Ni – Method A

- Magnetically harvest fines
- Crack off silicates
  - Centrifugal grinder
- Mond process selects out Ni
  - At 60 ºC $Ni(s) + 4CO(g) \text{ ® } Ni(CO)_4(g)$
- For further Fe refinement, us Mond process at 180 ºC
- Precipitate metals at different T

Fe and Ni – Method B

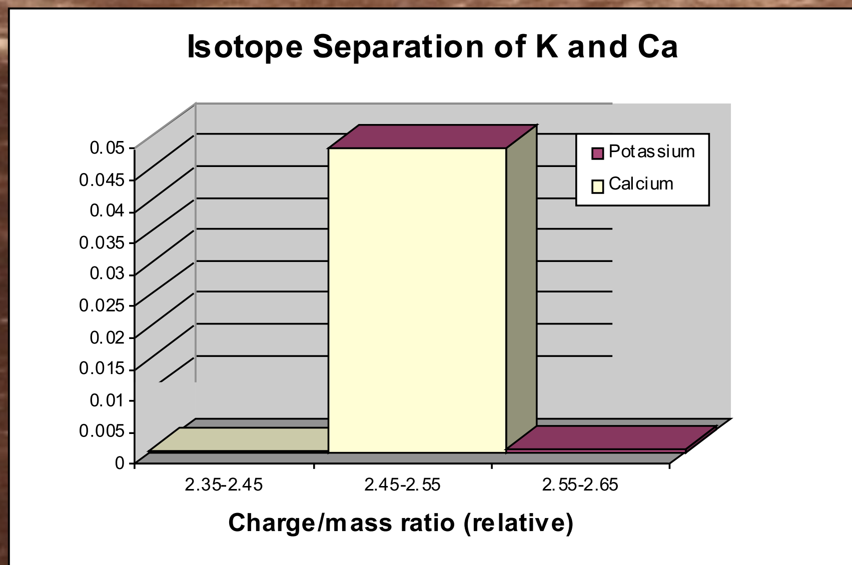
- Separate from plasma by charge-to-mass ratio (3 US Patents granted)



- Same process as for Si, Al extraction
- Refractory slag (dolomite):
  - Can be formed into net shapes
  - Use for casting of electrodes
  - Use to build battery vessels

Potassium Extraction

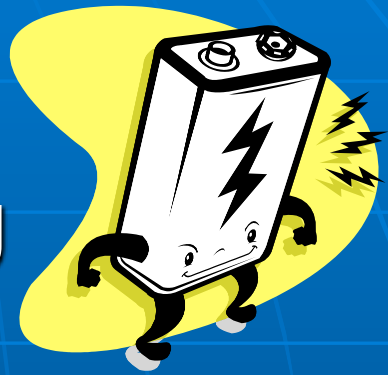
- Vacuum roasting between 900 and 1200 °C releases 30% of K.
- K is in lunar atmosphere, so we know it is volatile
- <u>Alternate</u>:
  - Isotope extraction
  - Separate by solubility
  - KOH: 110 g/100ml
  - CaOH: 0.17 g/100ml



Water and Casing

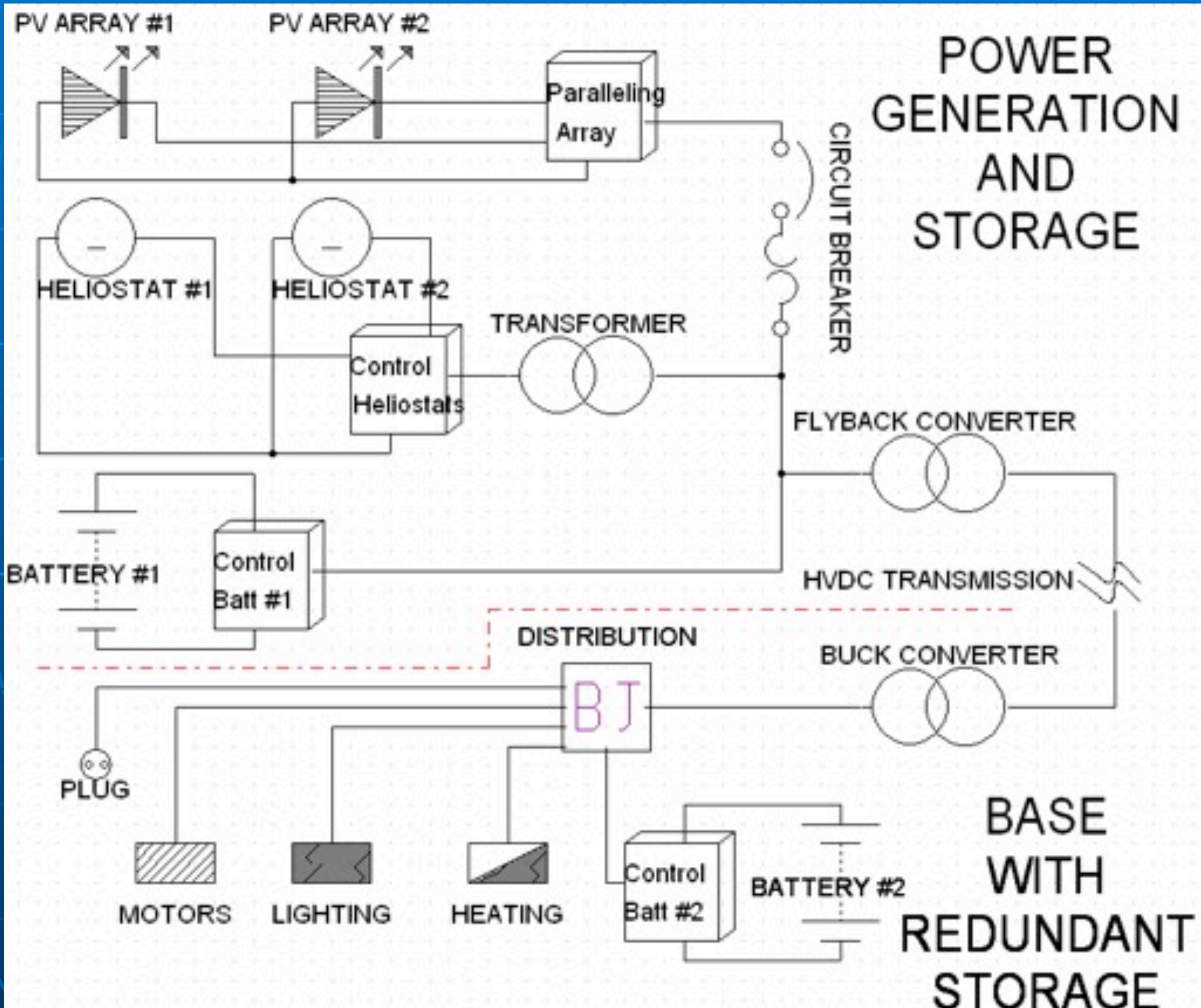
- Water abundant at poles only
  - Subsurface temperatures are low
  - Assume 85% insolation
  - With 2 meter masts, can get to 90%
- Vessels from cast basalt, dolomite, or polymer-lined vessels
  - Need a sealed lid
  - Assume 1 m^3 H_2O each

Battery Specifications



- Specific power = 0.04 kWh/kg
- Leakage rate = 30%/month
- Deep cycling limit = 65%
- Electrolyte specific density = 1.4
- Assuming 24 V = 21 cells/battery
- Electrode mass = 0.5 MT/battery
- Heat loss by radiation = 4.6 W/m^2

Distribution Schematic



Results – 2-man base 85% sun

Energy Storage System		
electrolyte	1400	kg
Electrodes	500	kg
specific power	0.04	kWh/kg
Storage	76	kWh/battery
discharge	1%	per day
T-background	40	K
T-inside	163	K
surface area	6	m2
heat loss	-0.04	kW/m2
nightspan	53.1	hours
radiative loss	-12.71	kWh
self-discharge	-1.68	kWh
deep discharge	0.65	fraction
Net storage	**40.05**	**kWh/battery**
Batteries	**6**	
Redundancy	**12**	

Base Needs		
Baseload	1.2	kW
Energy needed	63.72	kWh
Width	10	m
Breadth	10	m
height	3	m
Floorspace	100	m2
Volume	300	m3
Surface area	320	m2
T-external	40	K
heat loss rate	12.76	kW
heat loss	677.68	kWh
plant needs	100	W/m2
plant floor	50	m2
duty cycle	0.5	half time
Plant power	2.5	kW
Plant energy	132.75	kWh
Total energy	**209.23**	**kWh**

Logistics

- Water harvesting assumed
- Iron extraction:
  - 16 batteries/year by isotope separation
    - *Also get Si, Al, K, plus dolomite slag*
  - 55 batteries/year by magnetic extraction
    - *Requires CO for carbonyls*
- Factory launch masses:
  - 1.3 MT for isotope separator
  - 0.4 MT for magnet harvester

CONCLUSIONS

- Electric energy storage is possible using only lunar materials, plus an earth-launched ISRU factory.

- In one year, we can serve up to 2-3 continuously-occupied, polar-located 2-person lunar bases.