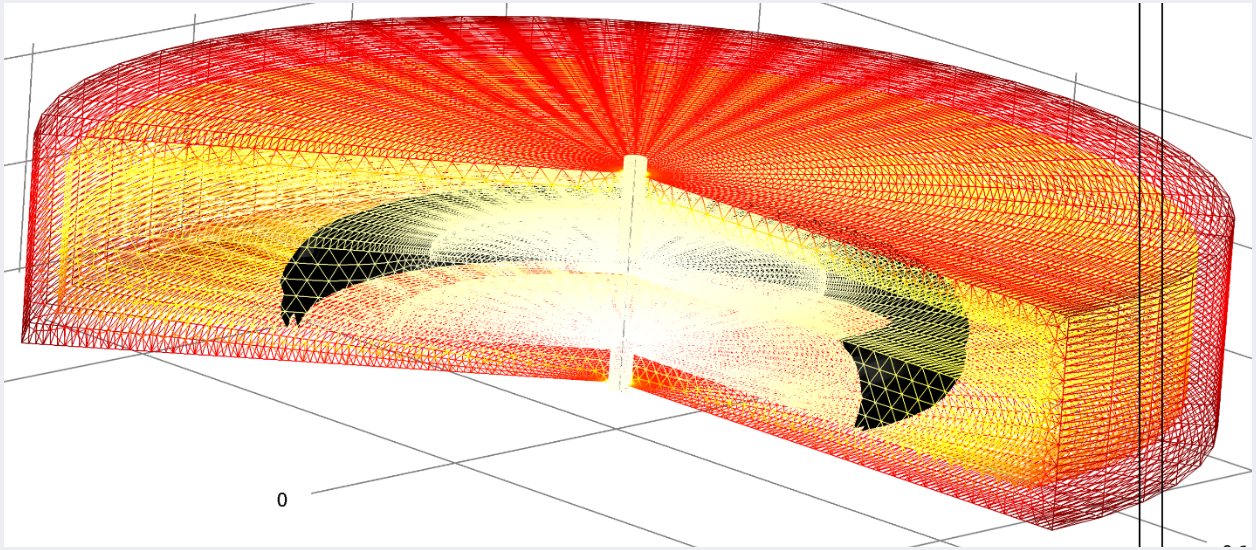
Utilizing Molten Regolith Electrolysis Reactors to Produce Oxygen on the Moon



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[1]MIT Aero Astro; [2]ESC-Team Vencore, NASA KSC; [3]NASA JSC

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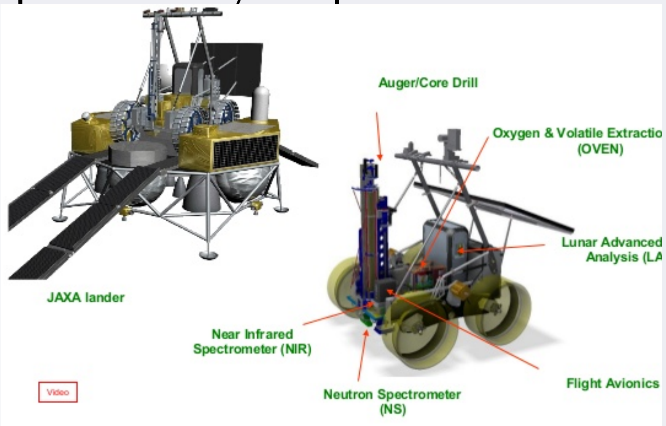
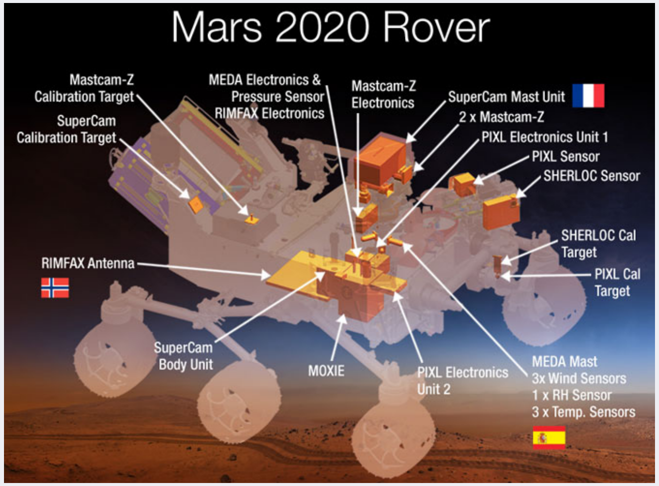
What is ISRU?

- **ISRU = In-Situ Resource Utilization**
  - Leveraging resources in space to fulfill or enhance mission capabilities/requirements





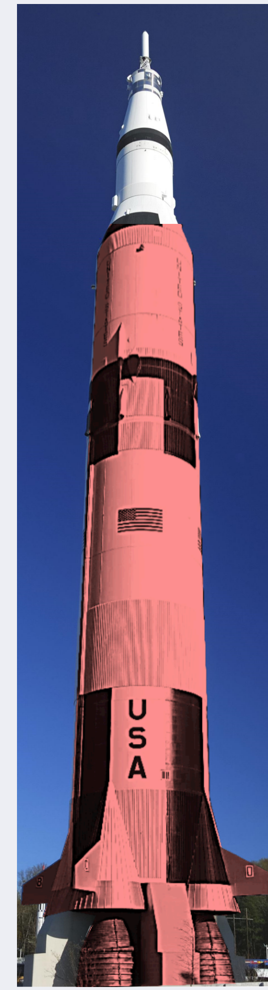
Lunar ISRU Motivation

- **High launch costs prohibitive to space exploration**
  - ≈ \$110,000/kg to lunar surface (CSM 2004)
- **~70% launch vehicle mass = O_2** (Badescu '12)
- **Lunar Resources** (Sanders '12)

≈40 wt% O_2

Table 2. Lunar Regolith and Volatile Constituents (Heiken et al. and T. Colaprete, personal communication, 2010)

Mare regolith		Solar wind volatiles	
Mineral	Concentration	Volatile	Concentration
Pyroxene	50%	Hydrogen	50–150 ppm
$CaO \cdot SiO_2$	36.7%	Helium	3–50 ppm
$MgO \cdot SiO_2$	29.2%	Helium-3	10^{-2} ppm
$FeO \cdot SiO_2$	17.6%	Carbon	100–150 ppm
$Al_2O_3 \cdot SiO_2$	9.6%		
$TiO_2 \cdot SiO_2$	6.9%	Major volatiles from LCROSS	
Anorthite	20%	Carbon monoxide	5.70%
$CaO \cdot Al_2O_3 \cdot SiO_2$	97.7%	Water/ice	5.50%
Olivine	15%	Hydrogen	1.40%
$2MgO \cdot SiO_2$	56.6%	Hydrogen sulfide	0.92%
$2FeO \cdot SiO_2$	42.7%	Mercury	0.48%
Ilmenite	15%	Ammonia	0.33%
$FeO \cdot TiO_2$	98.5%		

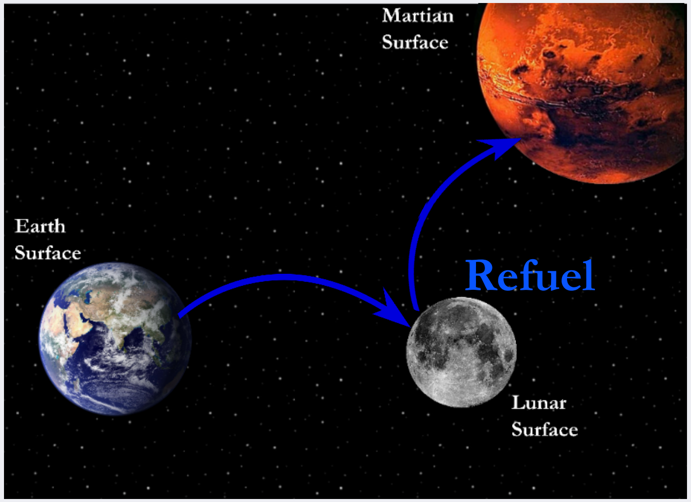


The Value of Lunar ISRU

- **Sherwood (1993)**
  - Producing oxygen on lunar surface ($18,370/kg)
  - Strong dependence on mass of production hardware
    - $12,570/kg - $29,850/kg (ISRU system mass varied by factor of 2)

- **Significantly less than cost to launch from Earth**
  - $110,000/kg

- **Other destinations?**
  - Refueling on the journey to Mars
    - *Ho et al. 2014: ~1-5 (kg/year)/kg*
  - <u>Modeling ISRU system mass is critical to determining feasibility of lunar oxygen production</u>



Oxygen Extraction

- 1988 (Eagle Engineering) + 1992 (Bechtel Group)

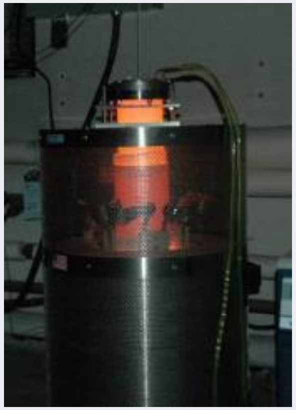
Table 3 Qualitative comparison of lunar oxygen processes

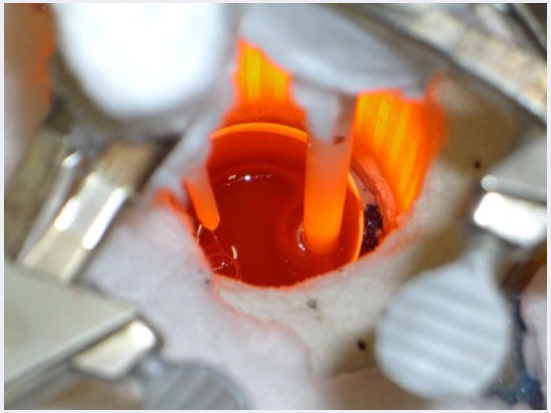
Processes	Technology[a]	No. of steps[b]	Process conditions[c]	Feedstock[d]	Total	Rank
Solid/gas interaction						
Ilmenite reduction with H_2	8	9	7	3	27	4
Ilmenite reduction with C/CO	7	8	7	3	25	7
Ilmenite reduction with CH_4	7	8	7	3	25	8
Glass reduction with H_2	7	9	7	6	29	2
Reduction with H_2S	2	6	6	8	22	12
Extraction with F_2	5	1	2	10	18	16
Carbochlorination	3	3	3	10	19	15
Cl_2 plasma reduction	4	5	5	10	24	9
Silicate/oxide melt						
Molten silicate electrolysis	6	8	5	10	29	3
Fluxed silicate electrolysis	6	6	5	10	27	5
Caustic dis. electrolysis	5	4	3	10	22	13
Carbothermal reduction	6	3	3	10	22	14
Magma partial oxidation	2	2	4	5	13	19
Li or Na reduction of ilmenite	2	3	5	2	12	20
Pyrolysis						
Vapor pyrolysis	6	8	6	10	30	1
Ion plasma pyrolysis	4	8	4	10	26	6
Plasma reduction ilmenite	7	8	6	3	24	10
Aqueous solution						
HF acid dissolution	5	1	2	10	18	17
H_2SO_4 acid dissolution	5	3	3	5	16	18
Coproduct recovery						
H_2-He-water production	7	9	7	1	24	11

[a]Technology readiness: 1 = major technologic development required; 10 = no major unknowns.
[b]No. of steps: 1 = many (>5); 10 = one step.
[c]Process conditions (temperature, energy, plant mass, corrosion): 1 = severe; 10 = low.
[d]Feedstock requirements: 1 = huge quantities; 2 = mare, beneficiated (ilmenite); 5 = mare unbeneficiated; 10 = any feedstock, unbeneficiated.

Molten Regolith Electrolysis (MRE)

- **$M_xO_y \rightarrow xM + y/2\ O_2$**
  - $2FeO \rightarrow 2Fe + O_2$
  - $SiO_2 \rightarrow Si + O_2$
  - $2/3Al_2O_3 \rightarrow 4/3Al + O_2$

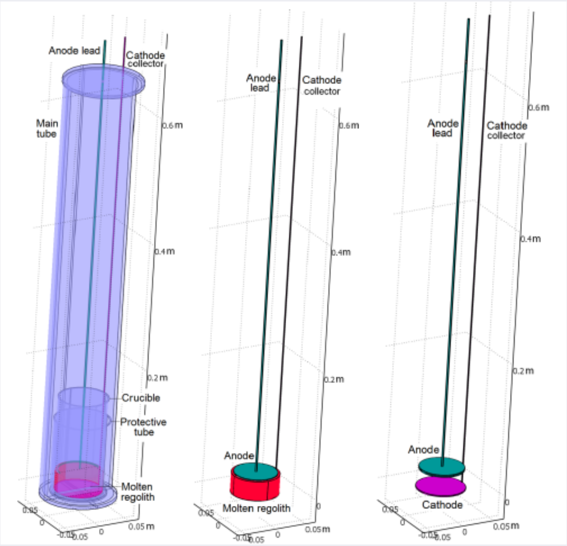


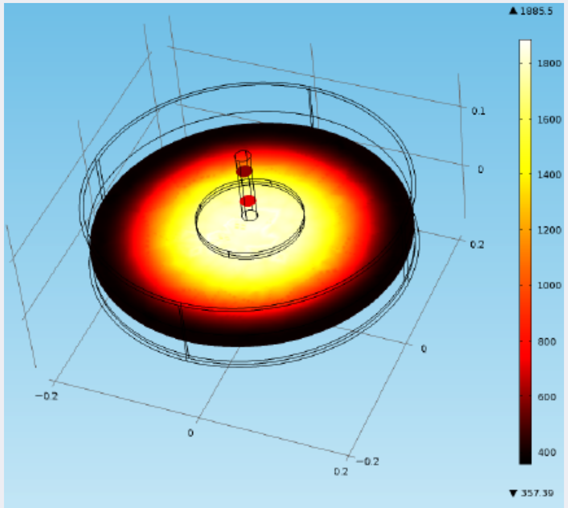


- **Benefits**
  - Higher oxygen yield
    - HRI: 1-5 kg O_2/100 kg regolith (Sanders '12)
    - CTR: 10-20 kg O_2/100 kg regolith (Sanders '12)
    - MRE: 16-44 kg O_2/100 kg regolith (this work)
  - No reagent gas recycling required
  - Fe + Si + glass = Solar Cells! (Ignatiev '98, Curreri '06)
  - Terrestrial green metal production spin-off/in (Allanore '13)
  - 3D printing metal products (Owens '14)

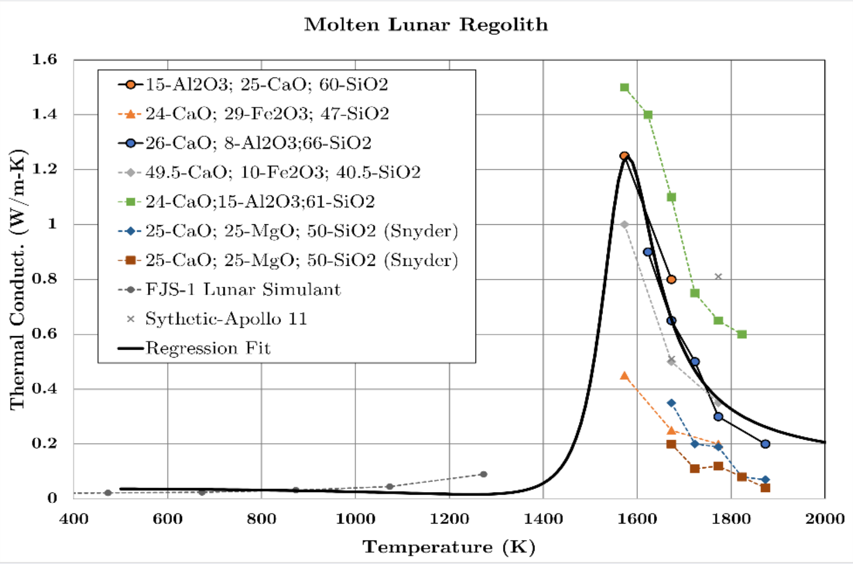
Molten Regolith Electrolysis (MRE)

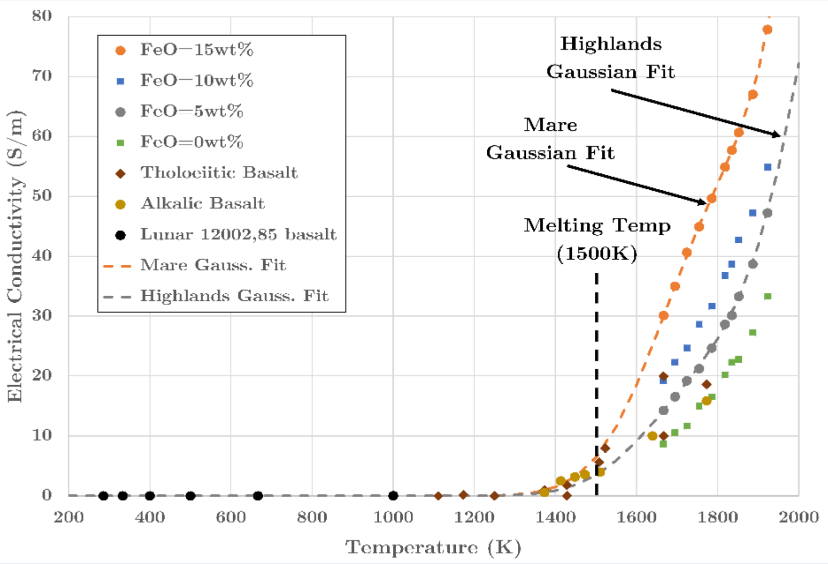
- **Drawbacks**
  - Regolith corrosion
    - Solve by joule-heated, cold-wall (JHCW)
    - Similar to Hall-Heroult cells *(Al production)*
  - JHCW design tradespace uncertain
    - Initial modeling conducted (Dominguez '10, Sibille '12)
    - Parametric design (mass & power) connected to oxygen production level needed
    - Optimal operating conditions and reactor size yet known (Altenberg '90)
    - Process power highly uncertain (Gmitter '10)

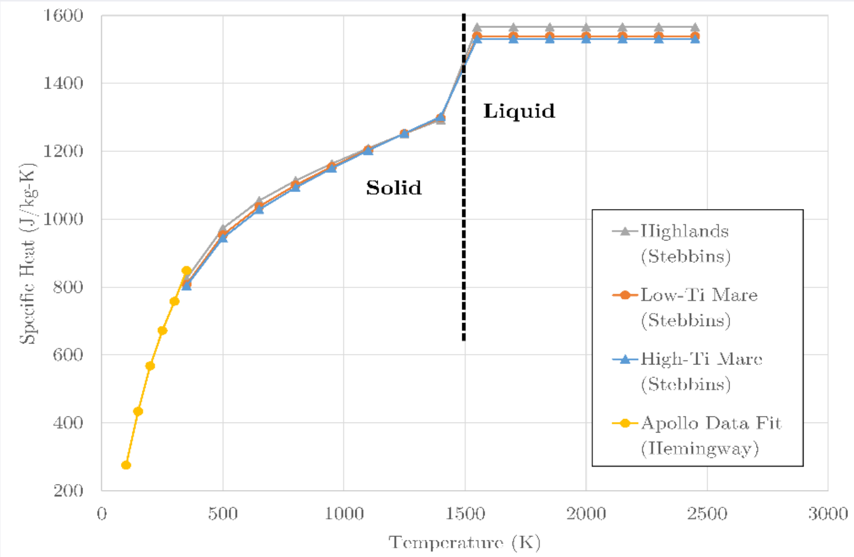


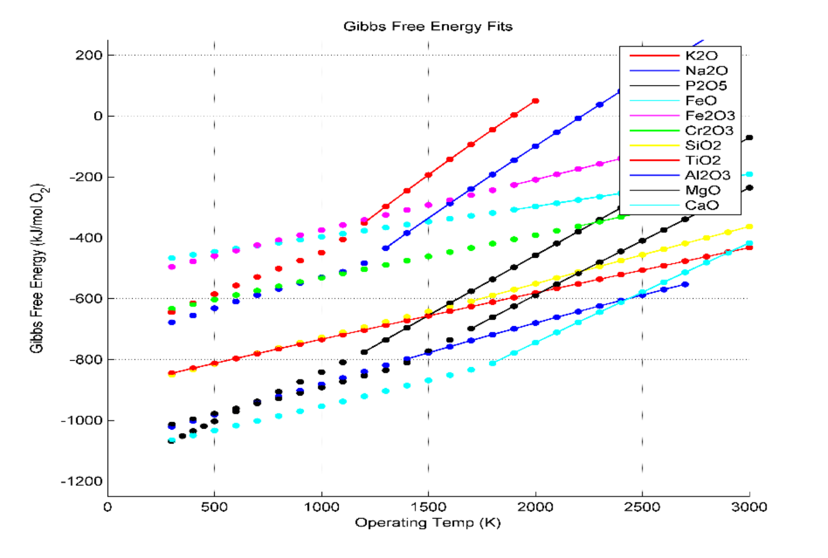


Regolith Database Building

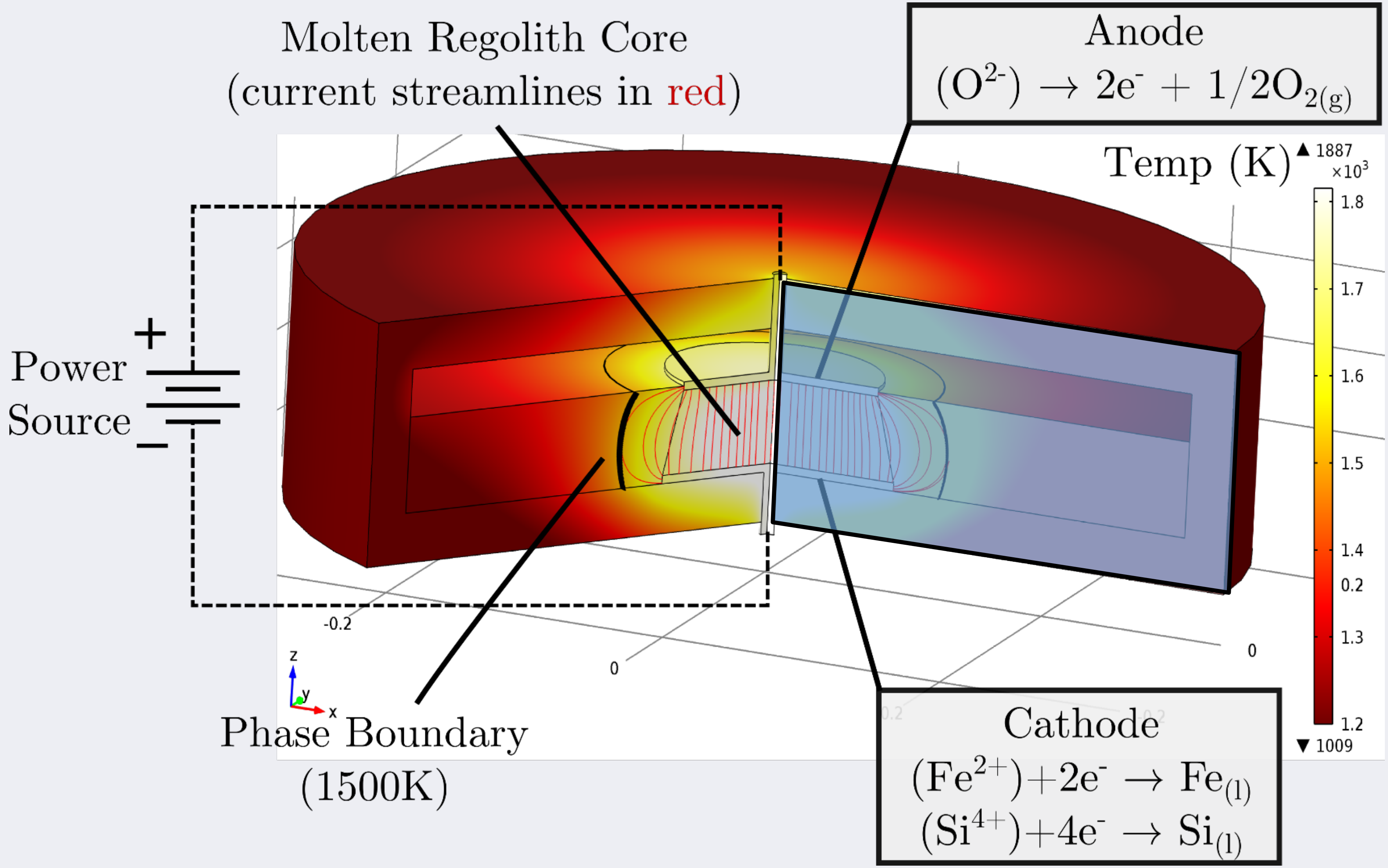




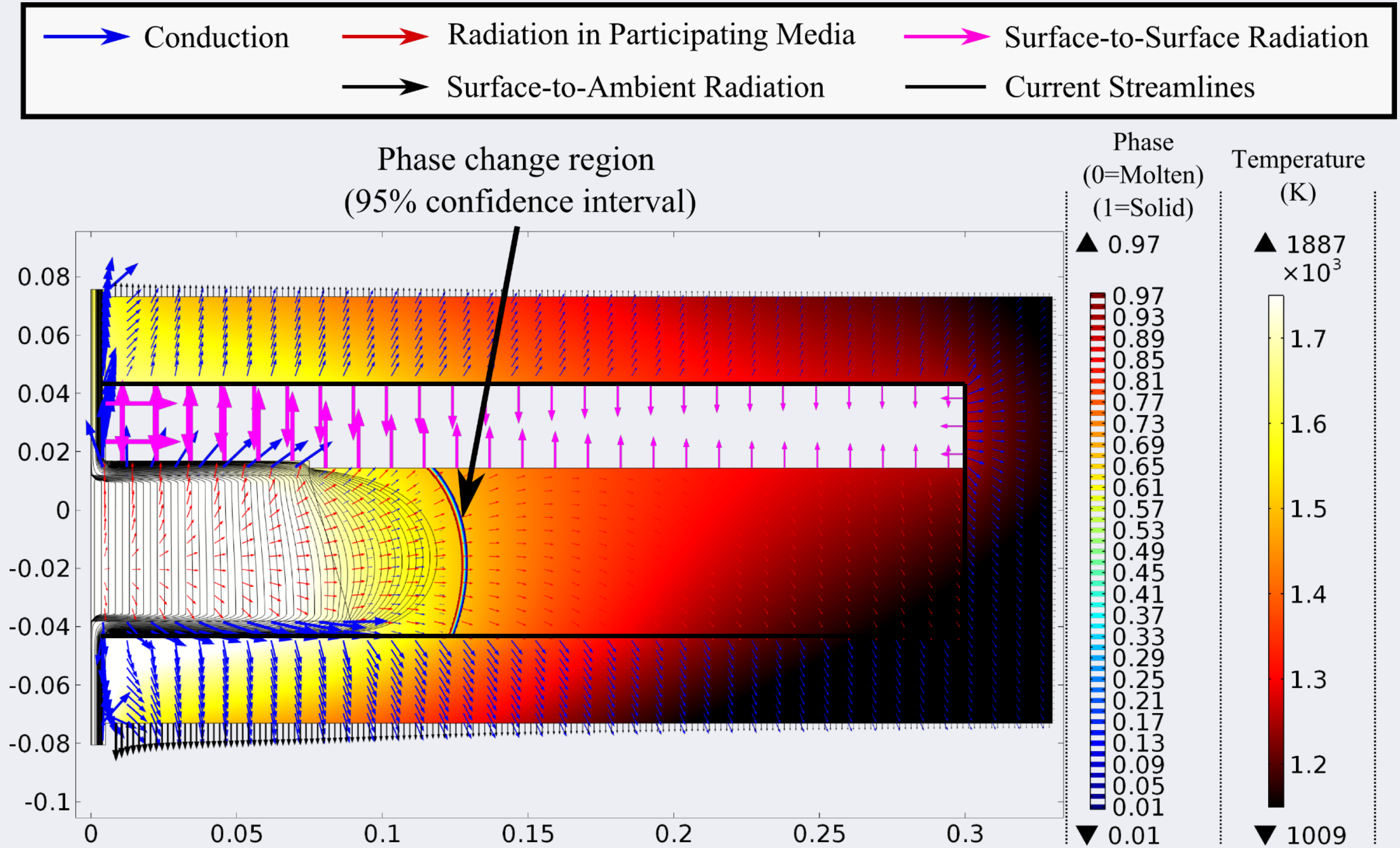




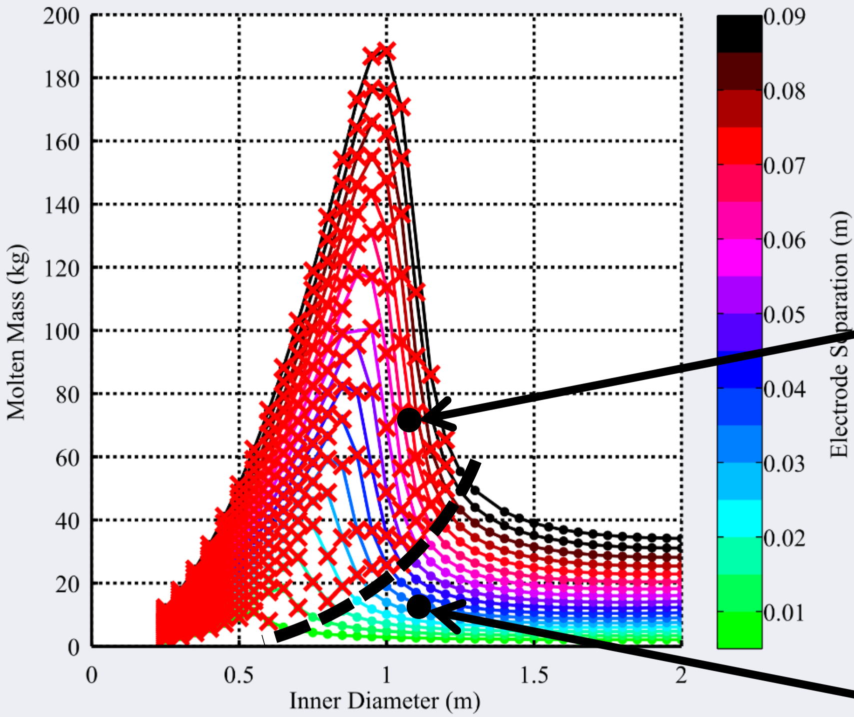
Reactor Model



Multiphysics Simulation

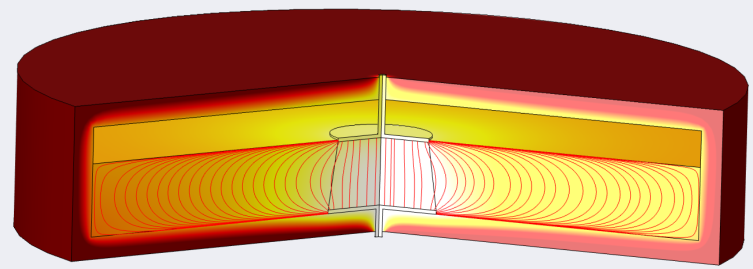


Molten Mass



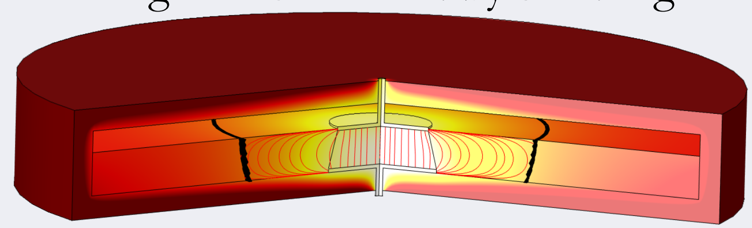
Infeasible Designs:

Molten regolith touches wall



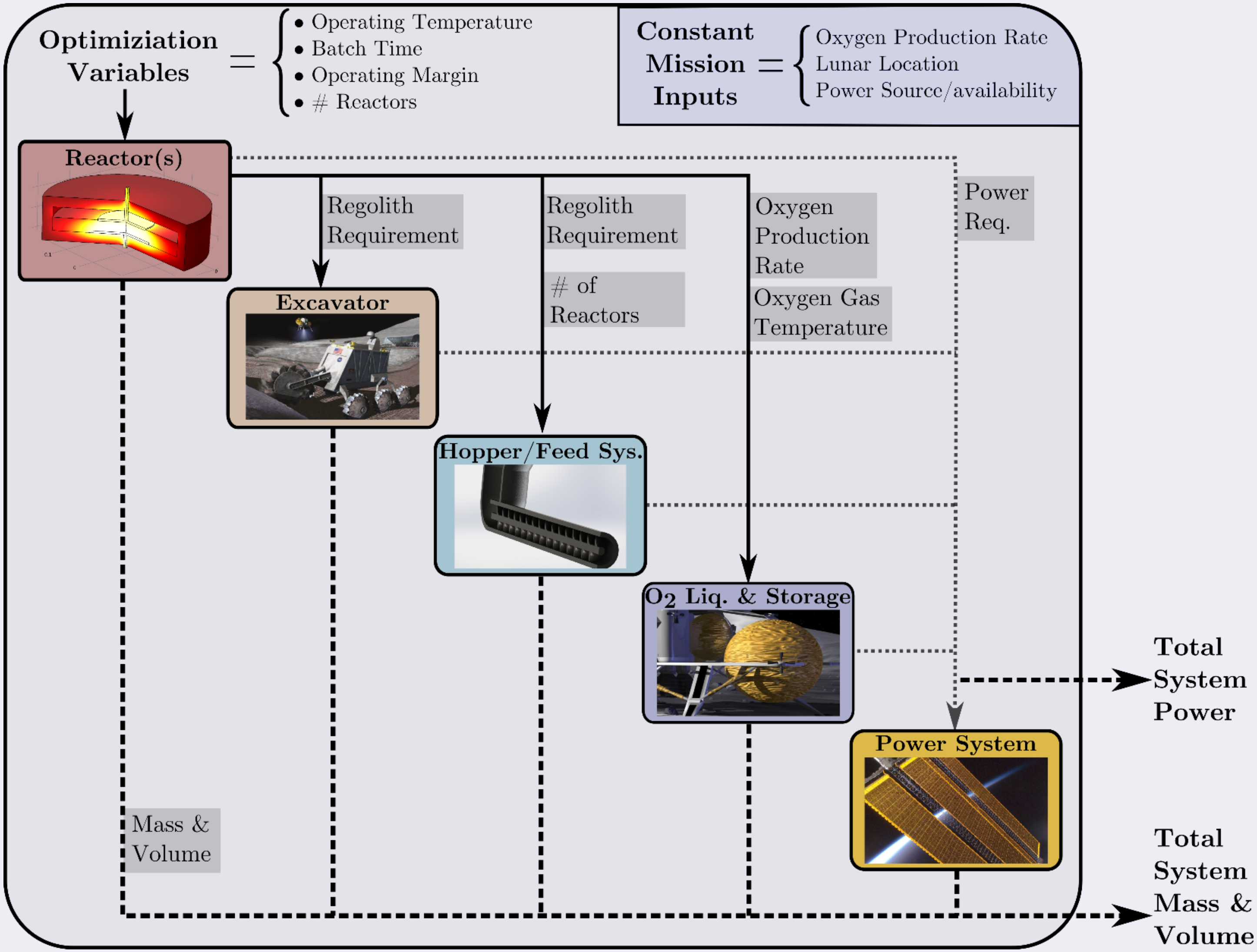
Feasible Designs:

Molten regolith contained by solid regolith



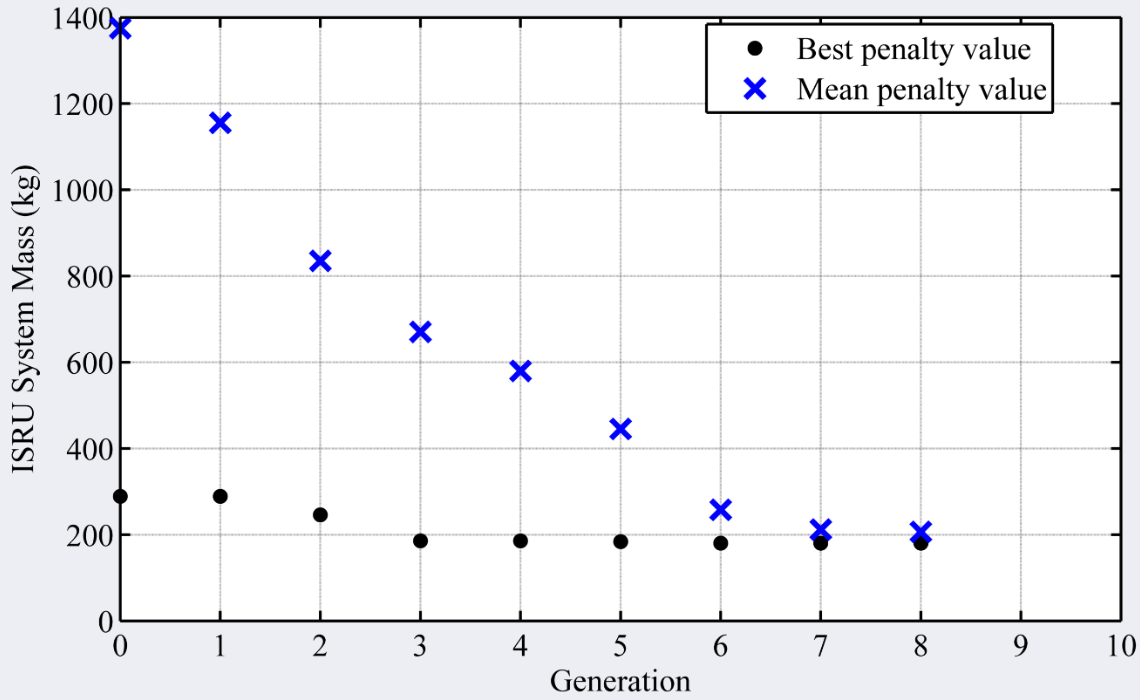
- "Cutoff Lines"
  - Border between feasible and infeasible designs

System Model Layout

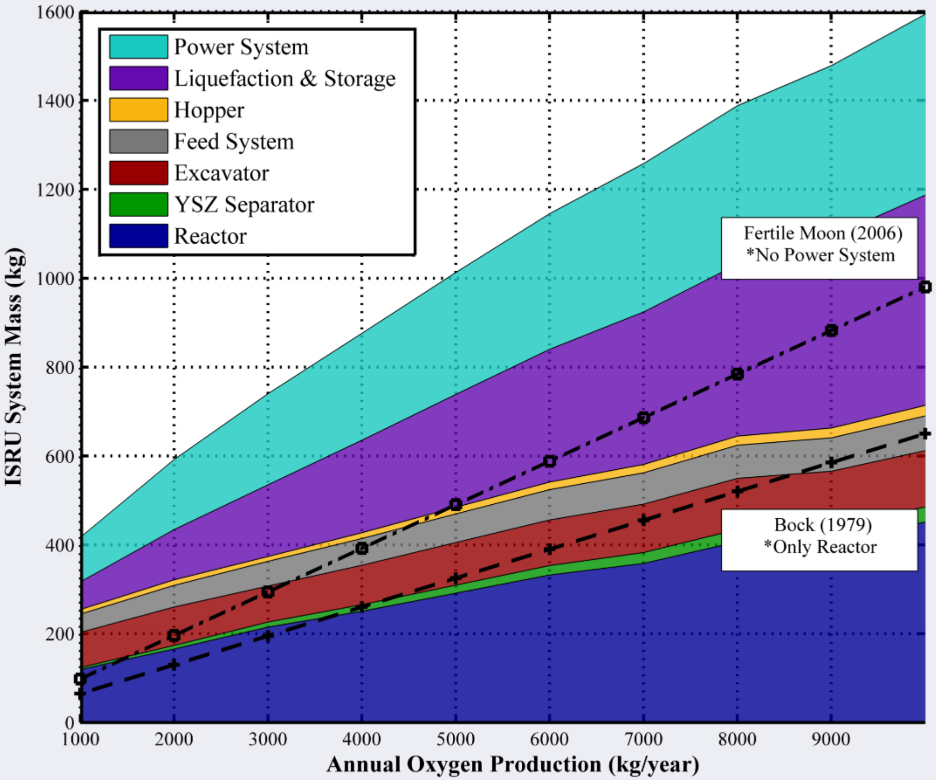


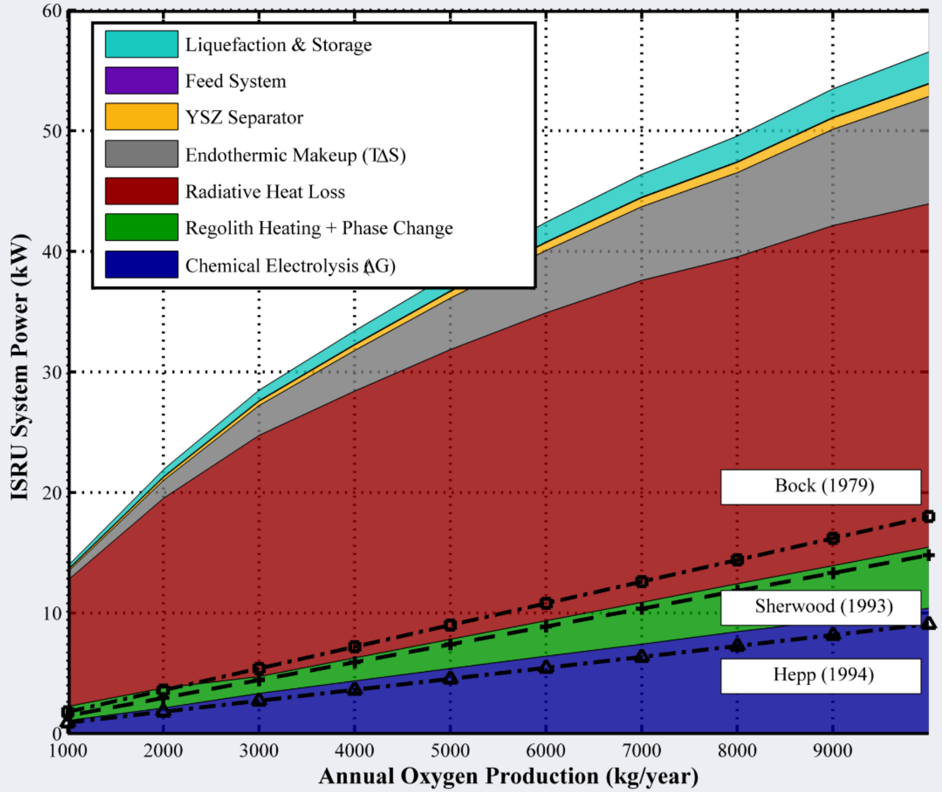
System Optimization

- **GA (Genetic Algorithm)**
  - Locates global minimum region
- **Gradient-based**
  - Hones in on the exact optimal system design



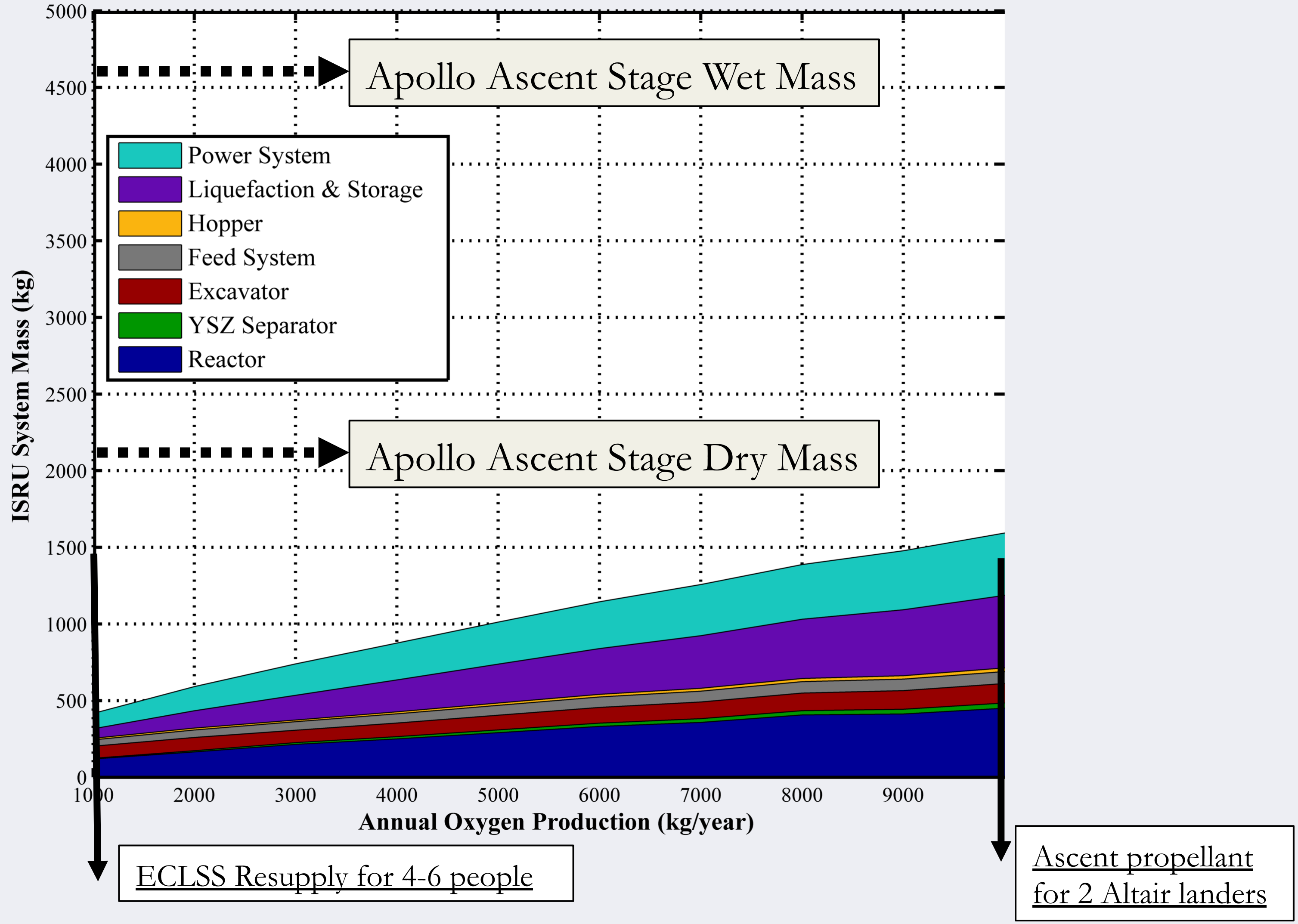
System Mass and Power



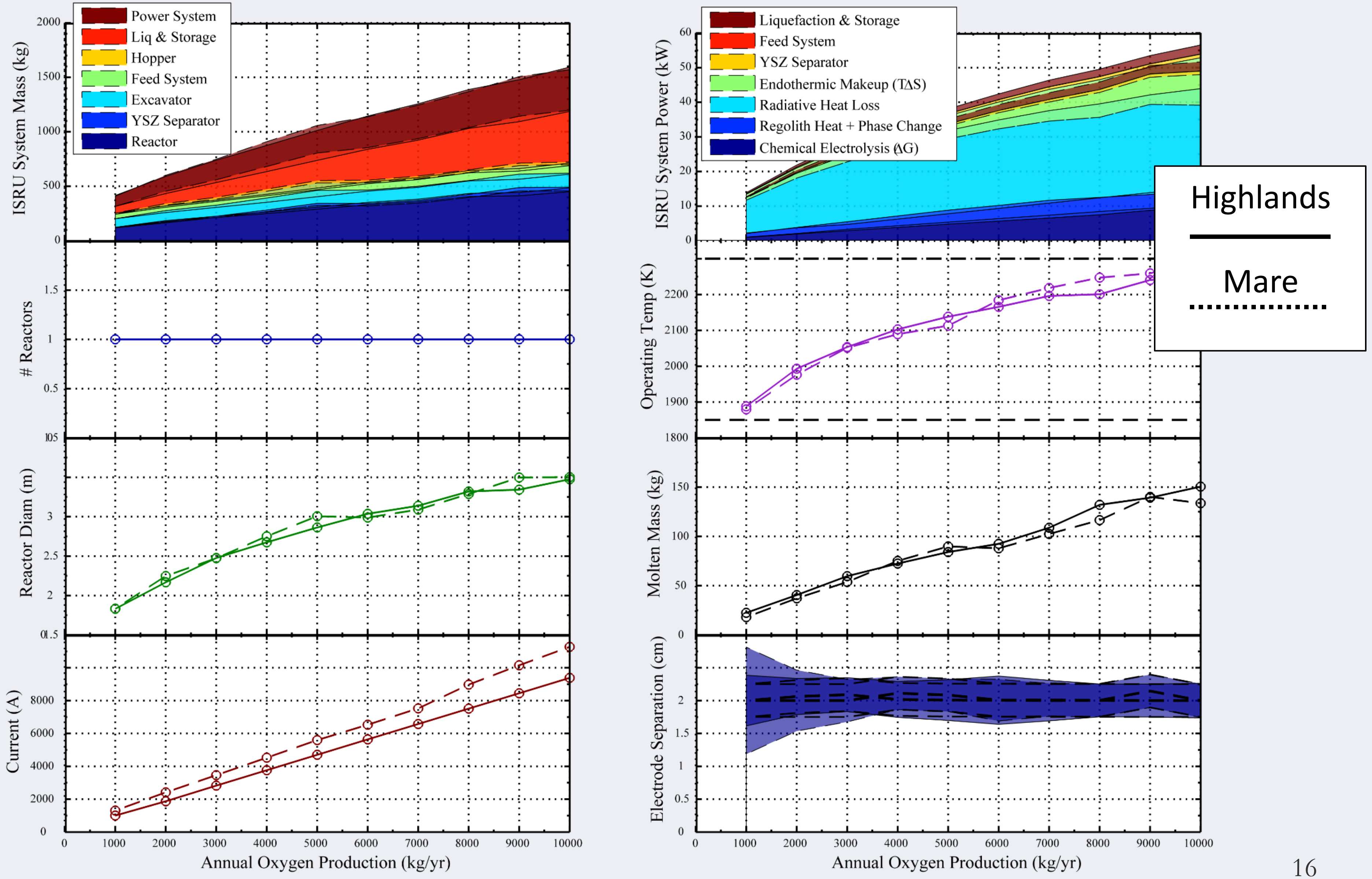


- **Major Mass Drivers**
  - Reactor & Liq/Storage (both 30%)
  - Power System (25%)
- **Major Power Drivers**
  - Electrolysis – ΔG (20%)
  - Radiative Loss (50%)

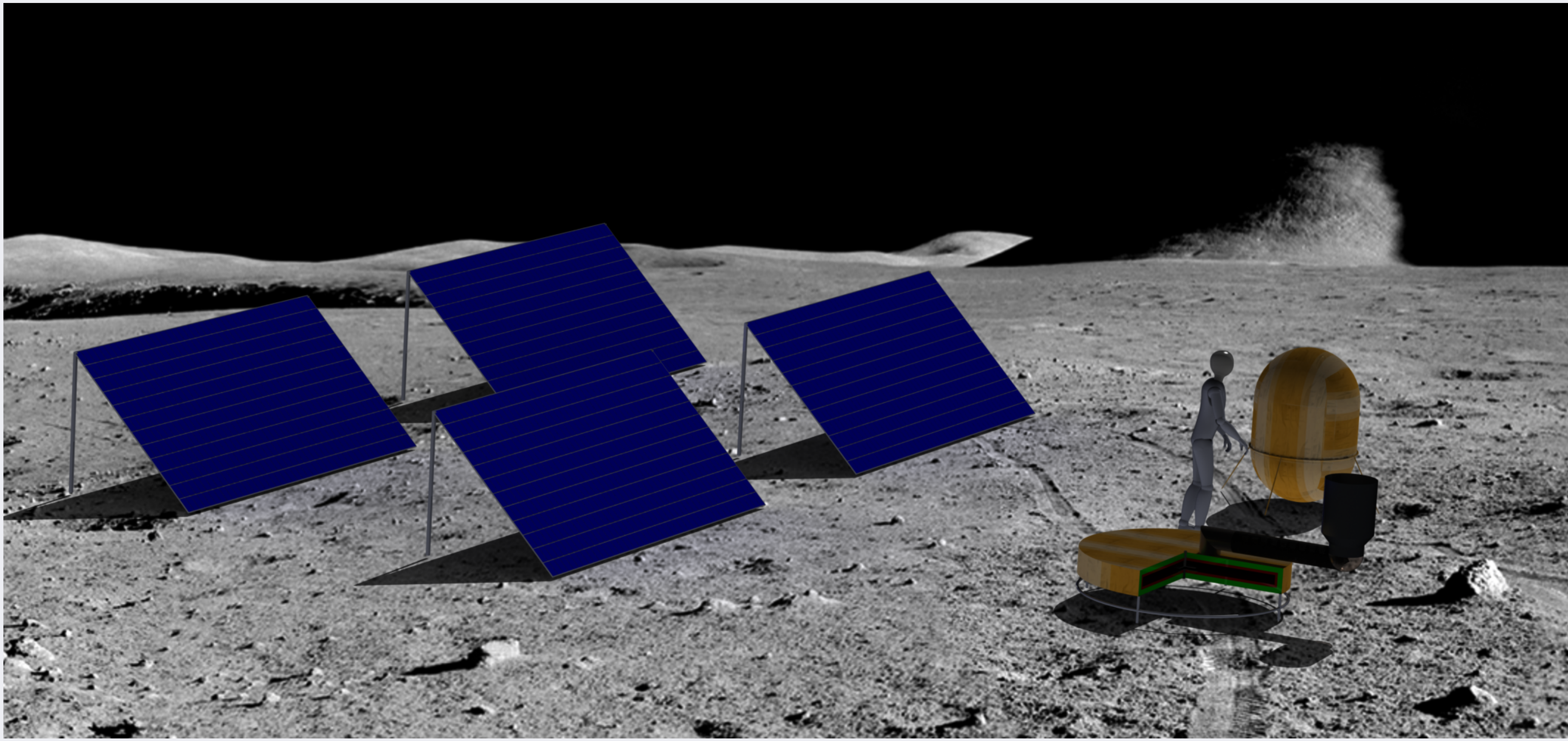
A Little Perspective



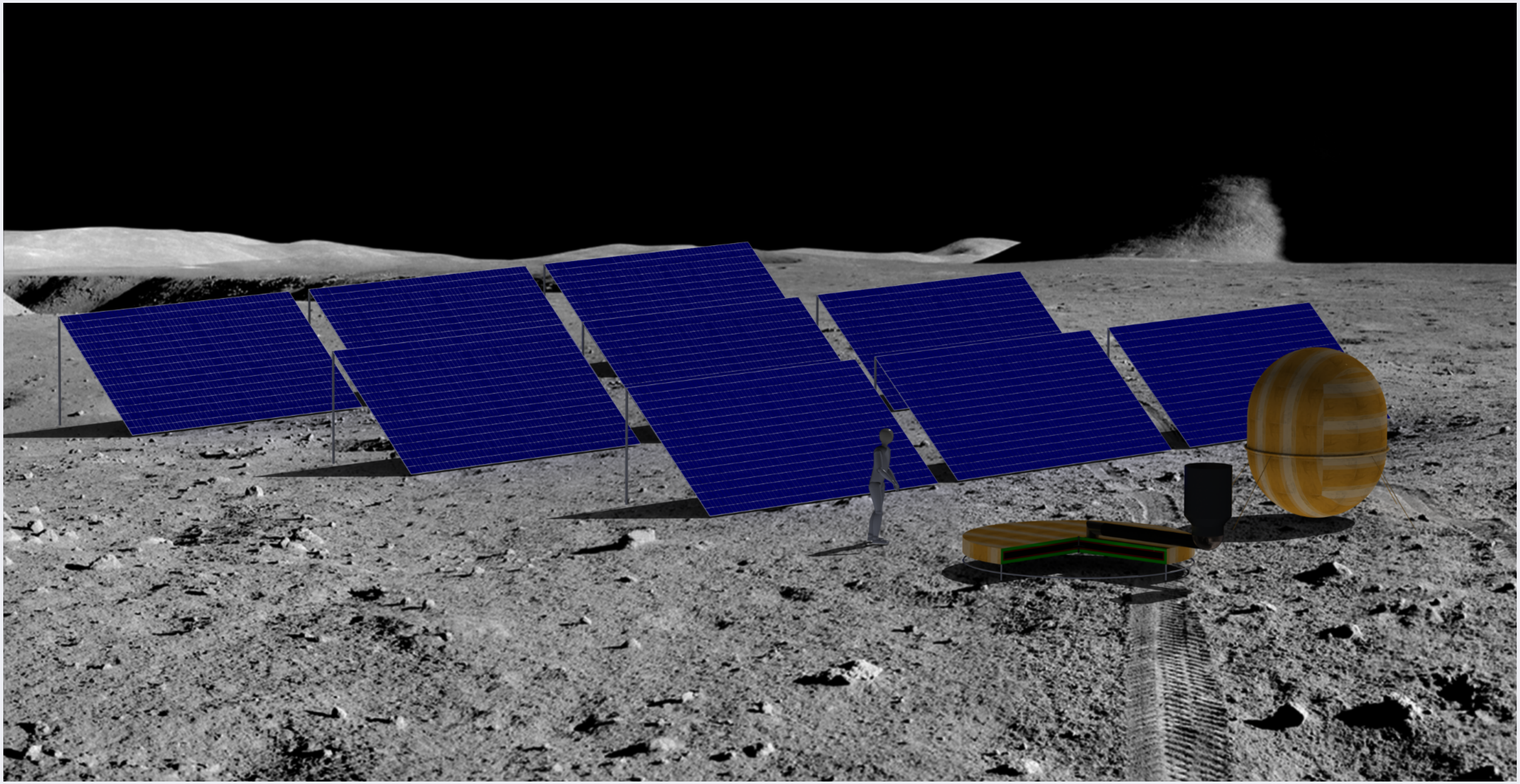
Feedstock Sensivity



1,000 kg/year Oxygen



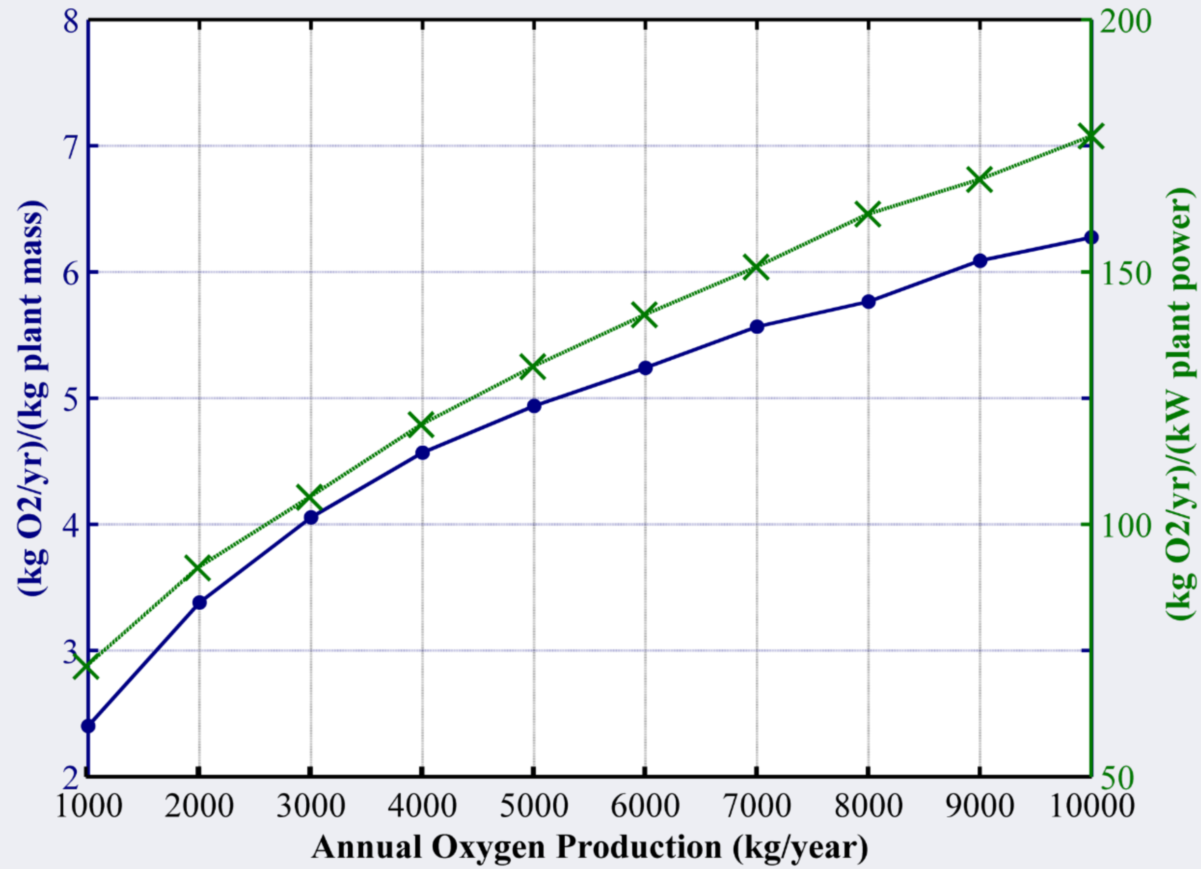
10,000 kg/year Oxygen



System Mass & Power

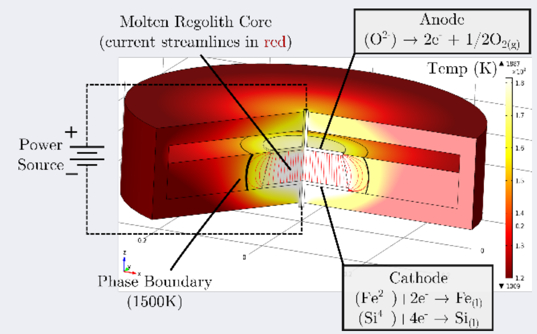
- **6.2 kg O_2/yr per kg system mass**
- **59 days till mass payoff (O$_2$ alone)**
- **Above threshold for Mars applicability** *(~5 (kg/year)/kg system mass[1])*

[1] Ho et al. 2014

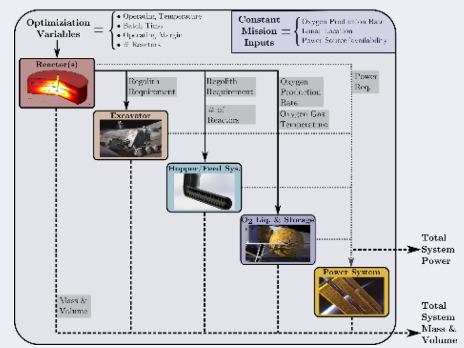


Conclusions

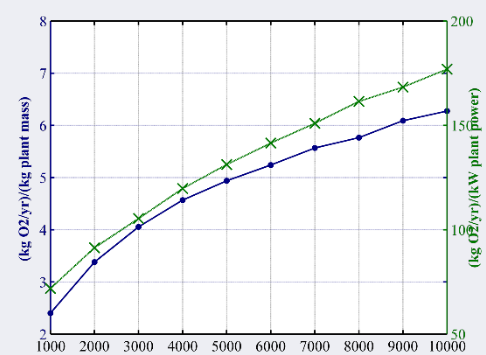
- **Created an MRE reactor model**
  - Multiphysics simulation
  - Reactor mass and power estimates



- **Developed an integrated ISRU system model**
  - Leveraged model to optimize tradespace of ISRU system designs
  - Model compares well with literature



- **Lunar ISRU is relevant for both Moon and Mars exploration**
  - 59 days until mass payback (O_2 alone)
  - ~35 days until mass payback (O_2+Fe+Si)



Acknowledgements

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  - Jerry Sanders (JSC)
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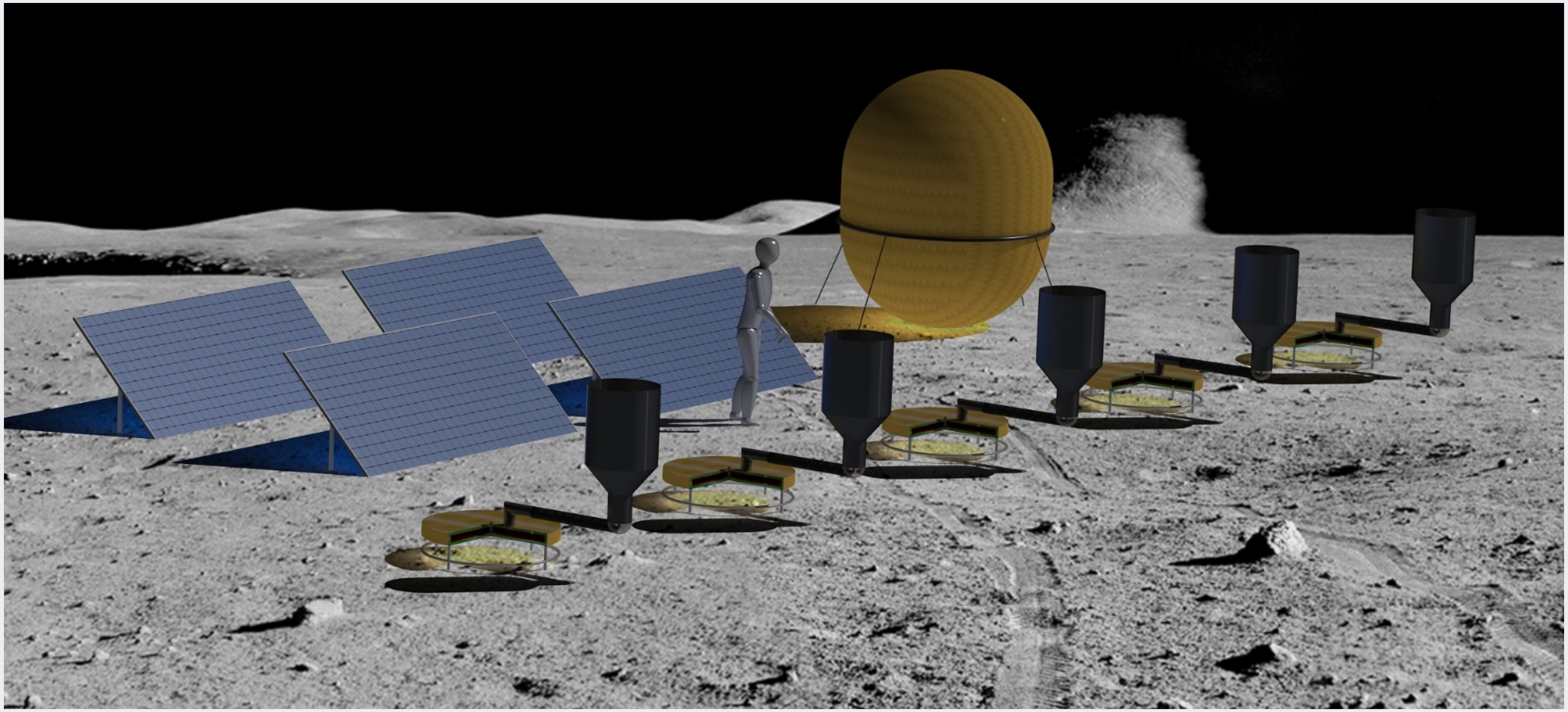

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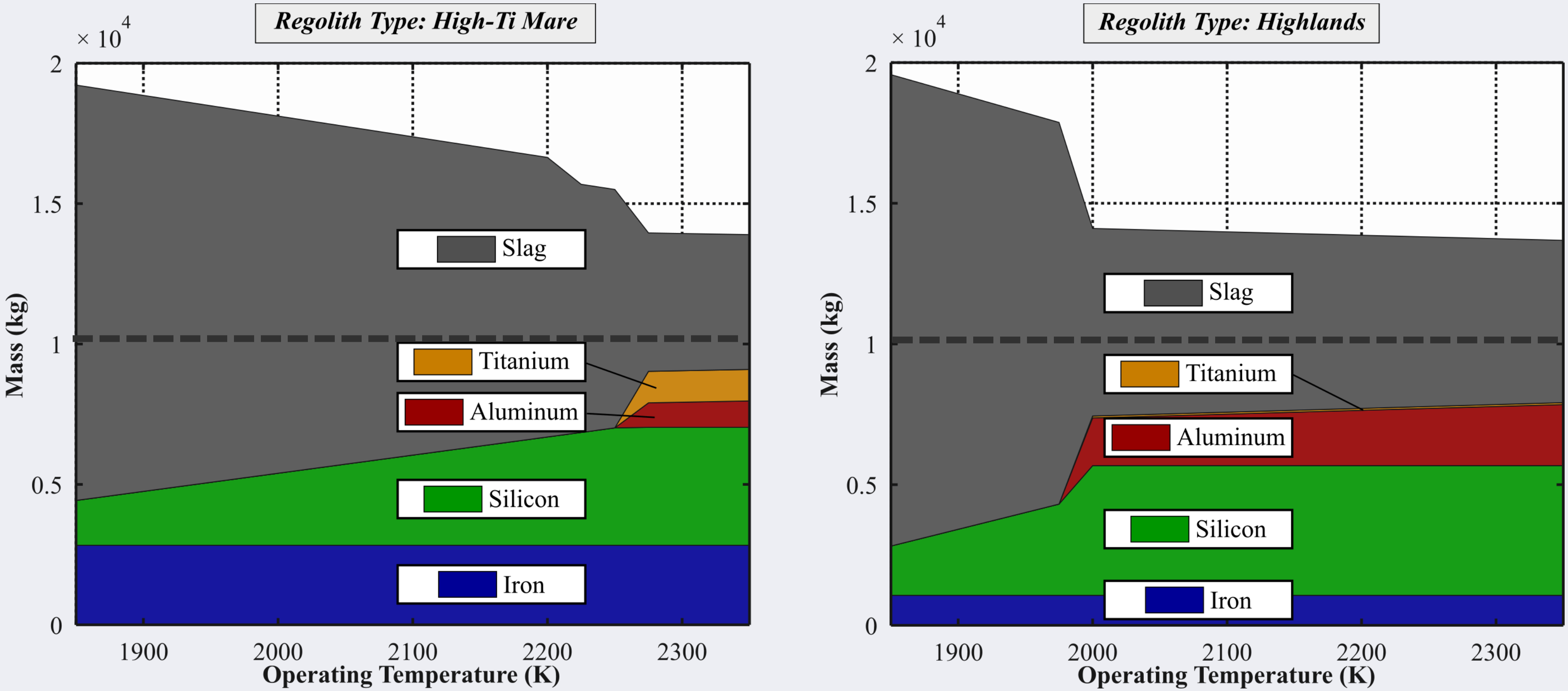
Backup Slides

Metal Production



- Some electrochemical challenges have yet to be solved
- Evolutionary capability
- Higher operating temperatures open up more metal products

Research Overview

- **Primary Objectives**
  - How does the design of an MRE reactor scale?
  - What does an optimal ISRU system with an MRE reactor look like?

- **Methods**
  - Develop parametric MRE reactor sizing model
  - Optimize holistic ISRU system model

- **Results**
  - MRE reactor scaling trends
  - ISRU system optimized mass & power tradespaces

Oxygen Production Methods

H_2 Reduction of Ilmenite (HRI)

- $FeO{\bullet}TiO_2 + H_2 \rightarrow Fe + TiO_2 + H_2O$ *(1000°C)*
  - $2H_2O \rightarrow 2H_2 + \mathbf{O_2}$ (Electrolysis)
- **Modeled By:**
  - Steffen (2007); Hegde (2009, 2010);
  - Linne (2009, 2010) at GRC

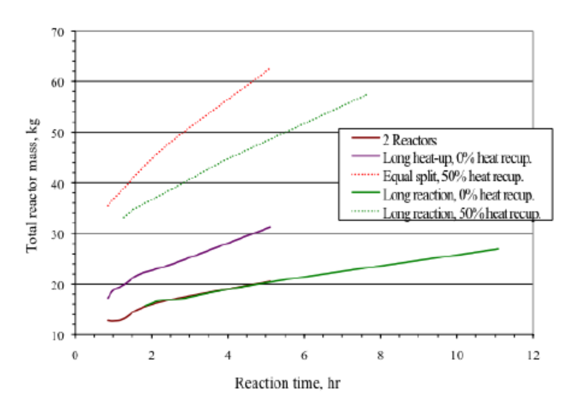
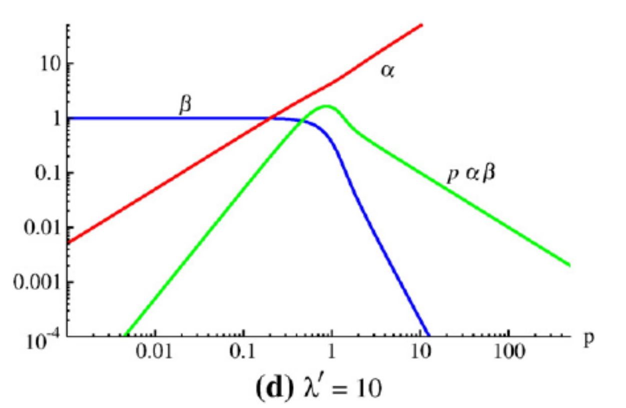


Figure 15. Comparison of reactor system mass for different operational options.

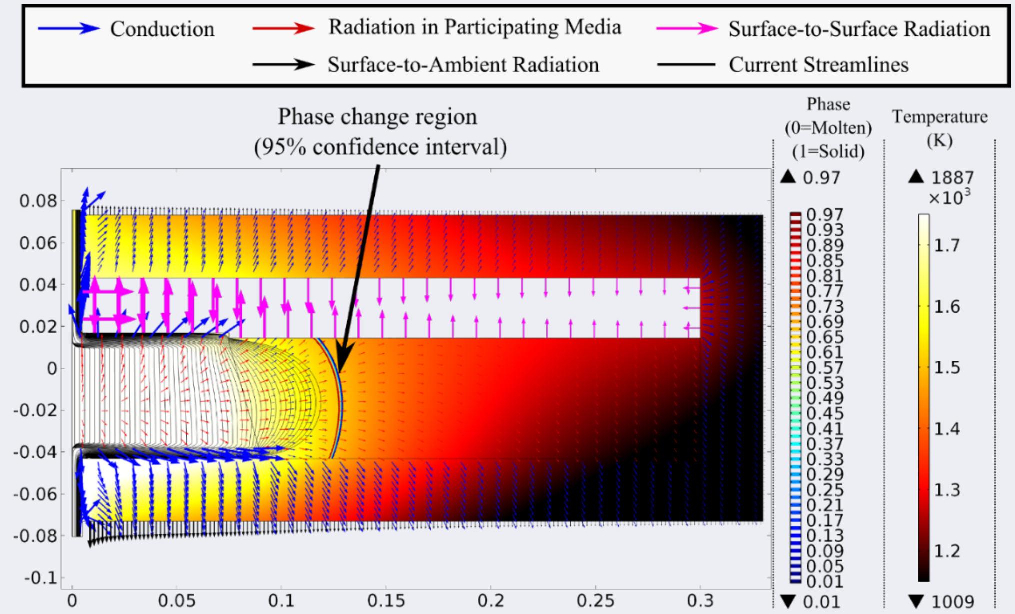
CH_4 Reduction (CTR)

- $(MgO)_2{\bullet}SiO_2 + 2CH_4 \rightarrow 2MgO + 2CO + Si + 4H_2$ *(1625°C)*
  - $2CO + 6H_2 \rightarrow 2CH_4 + 2H_2O$
  - $H_2O \rightarrow 2H_2 + \mathbf{O_2}$ (Electrolysis)
- **Modeled By:**
  - Balasubramaniam (2009, 2010) at GRC



Multiphysics Simulation

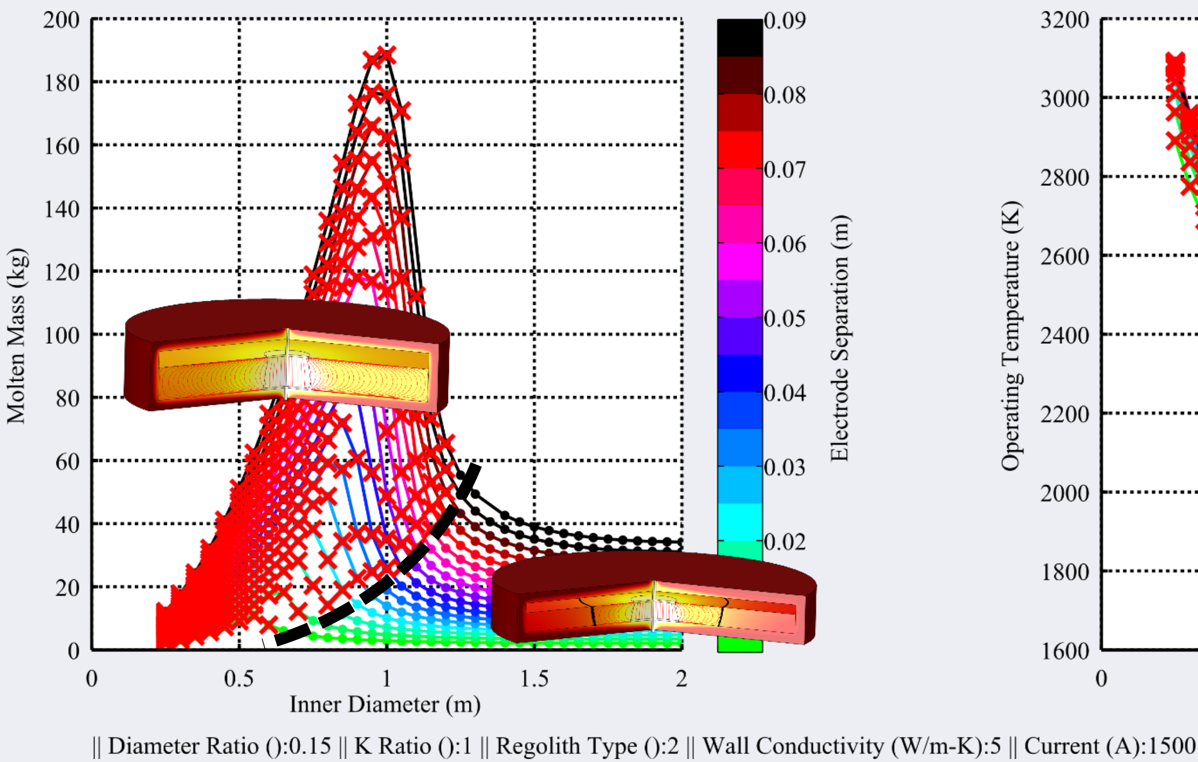
- **Evaluate a wide range of reactor designs**
  - Geometry
  - Current
  - Regolith Type



- **3 Design variables:**
  - Diameter
  - Electrode separation
  - Wall thermal conductivity *(wall thickness)*

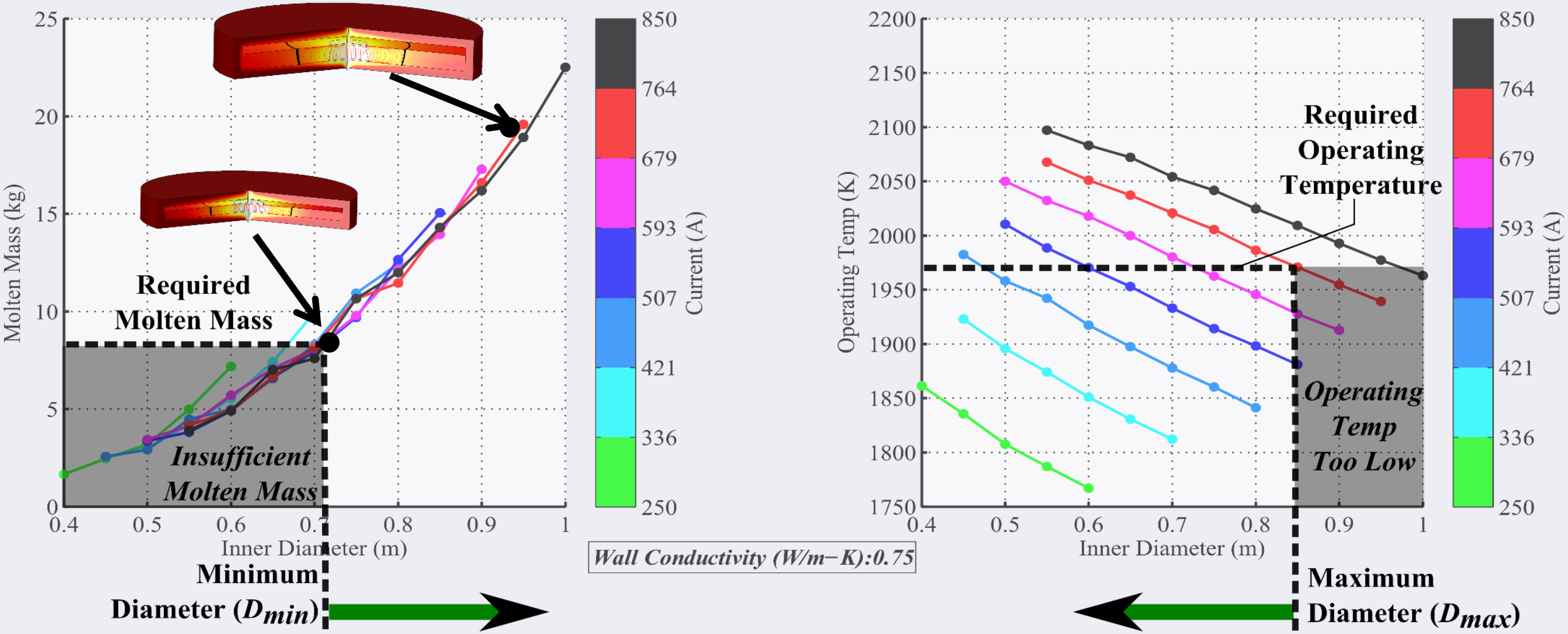
- **4 Performance criteria:**
  - Oxygen production level
    - Molten mass
    - Current
  - Operating temperature
  - Joule-heated cold-wall

Multiphysics Results



- **Design diameter and electrode separation to be near cutoff line**
  - One-to-one mapping between diameter and electrode separation
  - Ensures feasible designs

Novel Design Methodology II



{ Diameters **larger than D_{min}** result in enough molten mass in the reactor } AND { Diameters **smaller than D_{max}** result in high enough operating temperature }

$D_{min} = f(I, \mathbf{MM}, k_{wall})$

$D_{max} = f(I, \mathbf{T_{op}}, k_{wall})$

Design Methodology

- "Design Margin" $\Phi = D_{max}/D_{min} = f(I, T_{op}, k_{wall})/f(I, MM, k_{wall}) = f(k_{wall})$

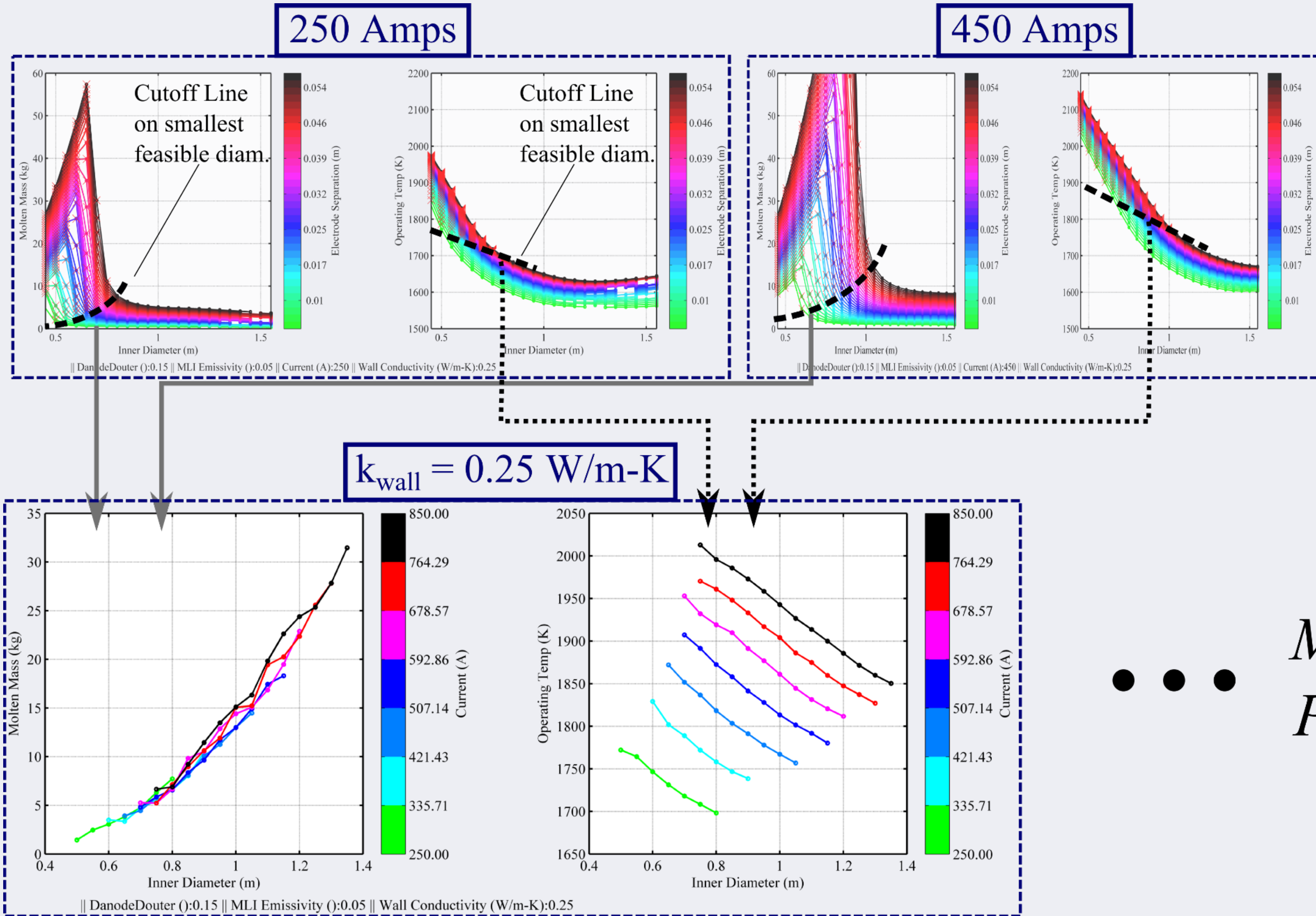
- Chose Φ → Set k_{wall}

- Use k_{wall} → Set (D_{max}) & (D_{min})
  - Choose $D_{min} < D_{design} < D_{max}$

- Use D_{design} → Electrode Separation (Δe)
  - One-to-one mapping to stay on cutoff line

- From D_{design}, Δe, and k_{wall}, can estimate:
  - Heat loss, operating voltage, etc.

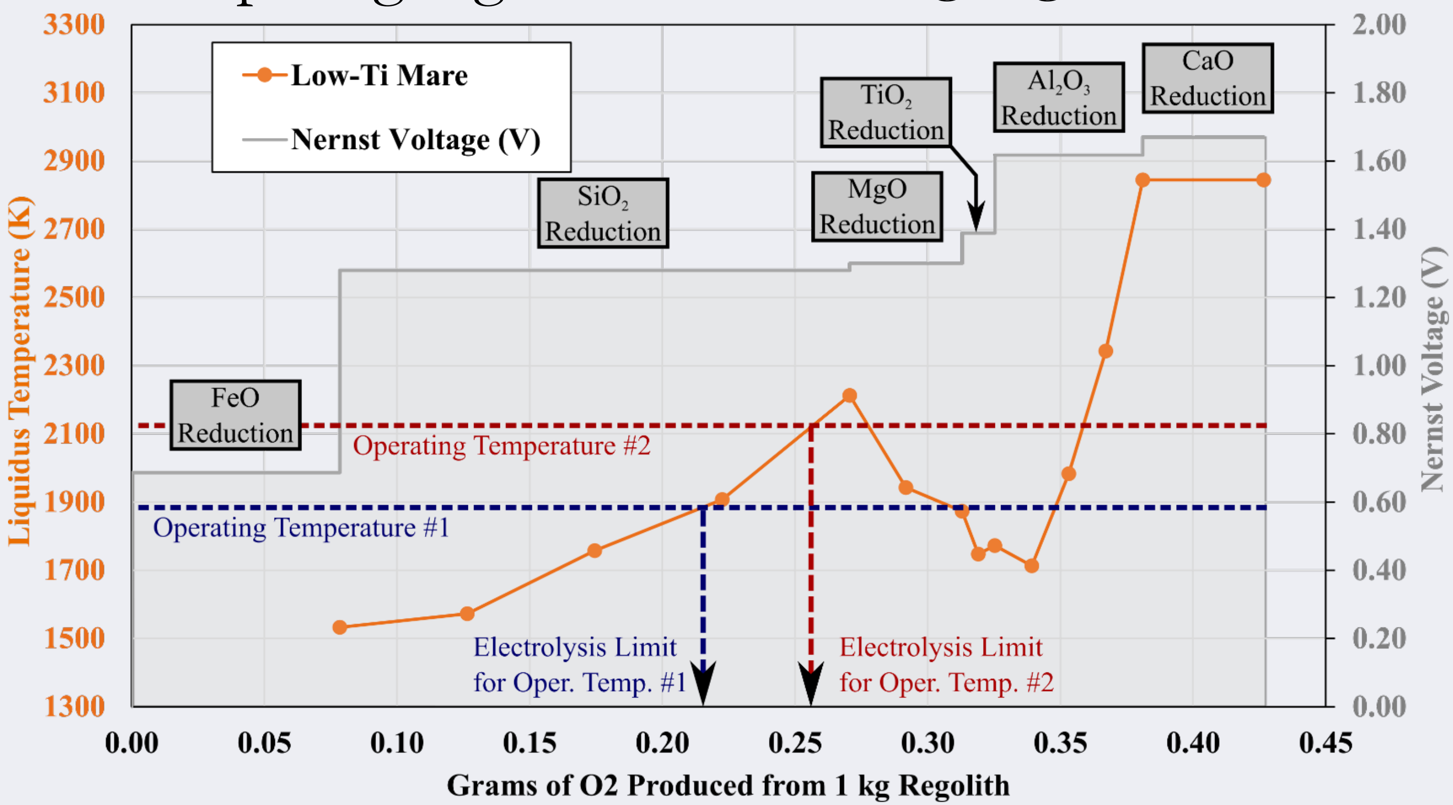
Novel Design Methodology



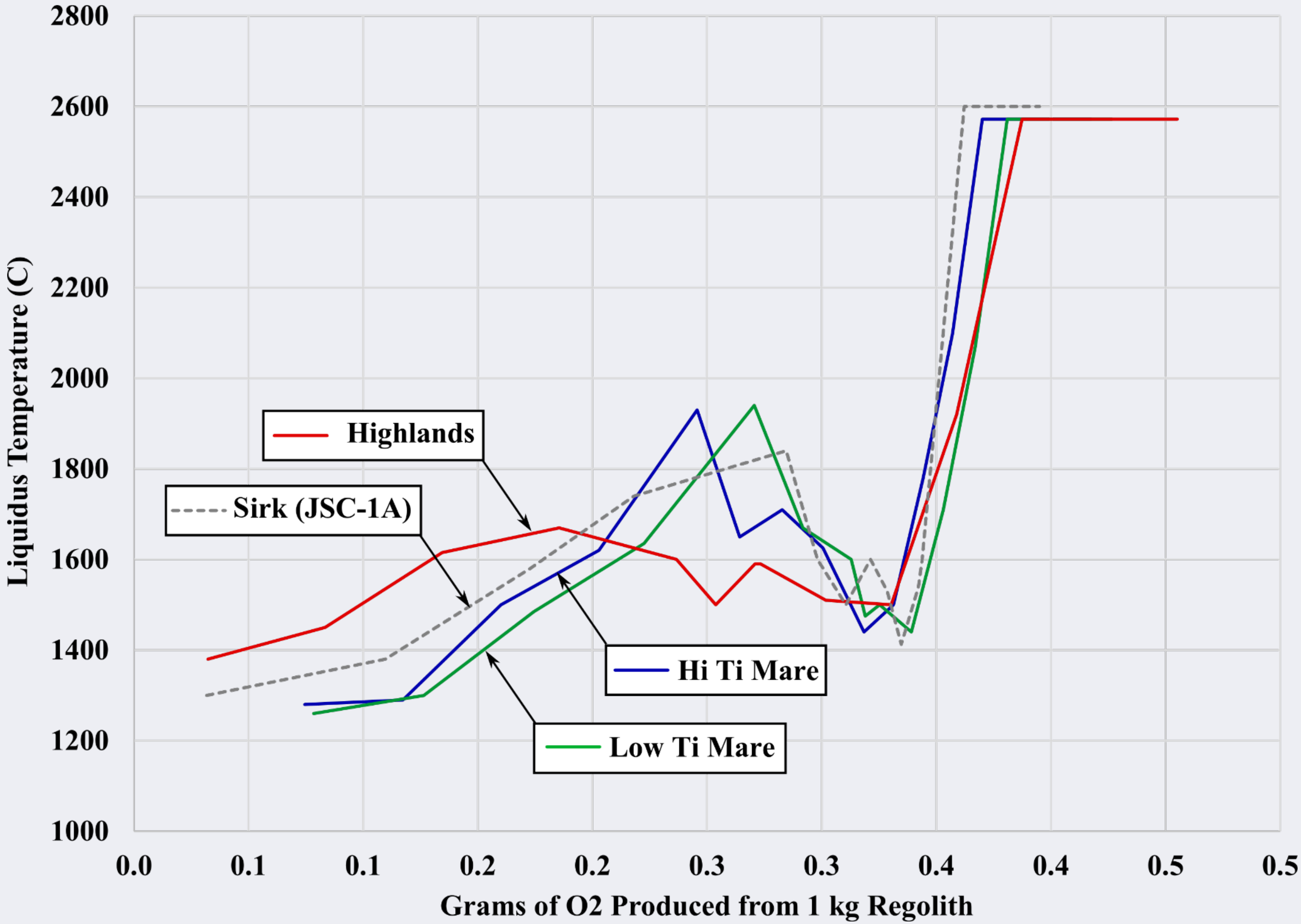
• • • *More Plots*

Operating Temperature

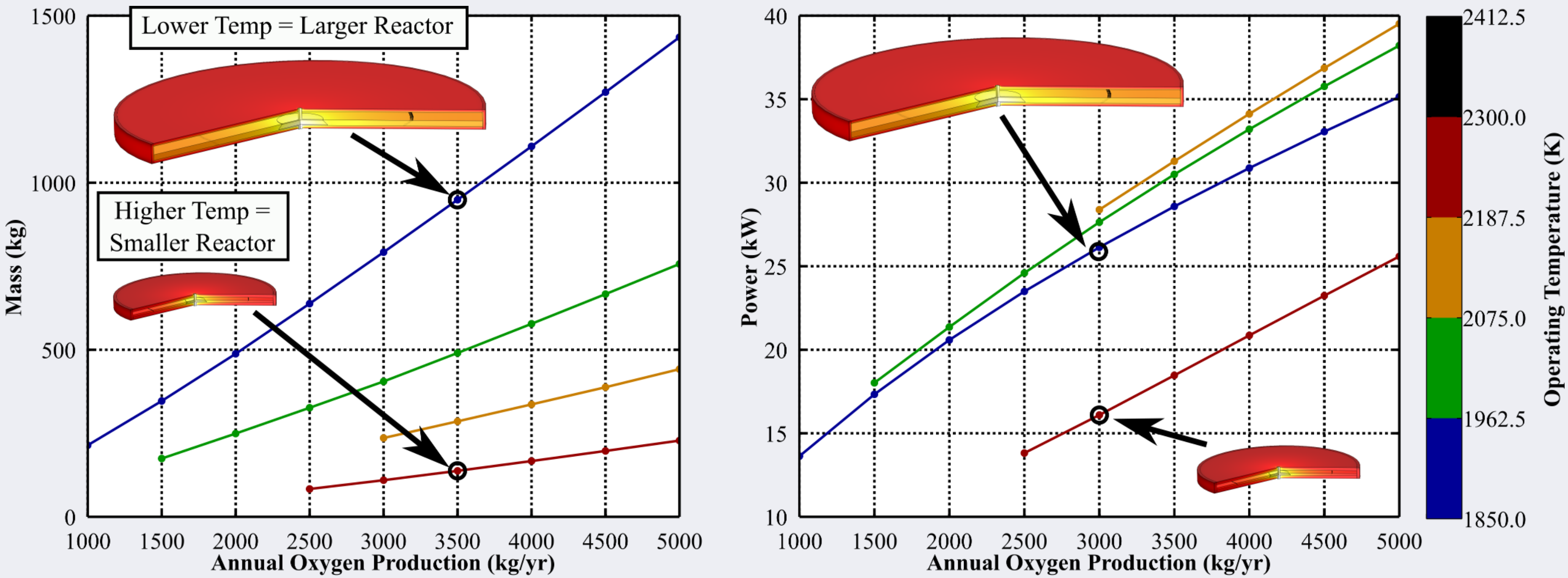
- **Higher Operating Temperature**
  - X Larger reactors
  - X More heat per kg regolith
  - ✓ Slightly lower reaction energy
  - ✓ Less kg regolith



Melting Temp = f(Regolith Type)



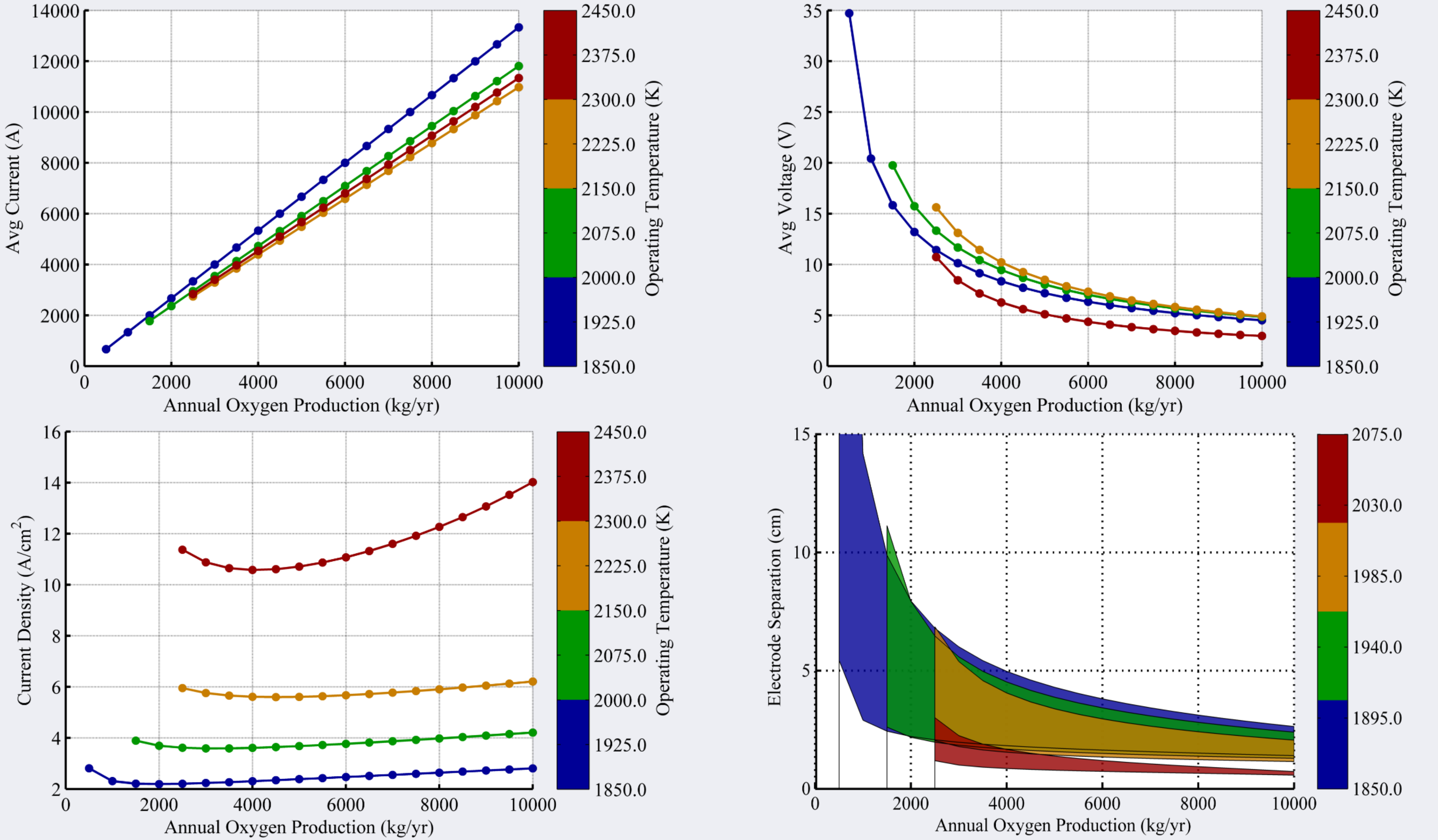
Optimal Operating Temp



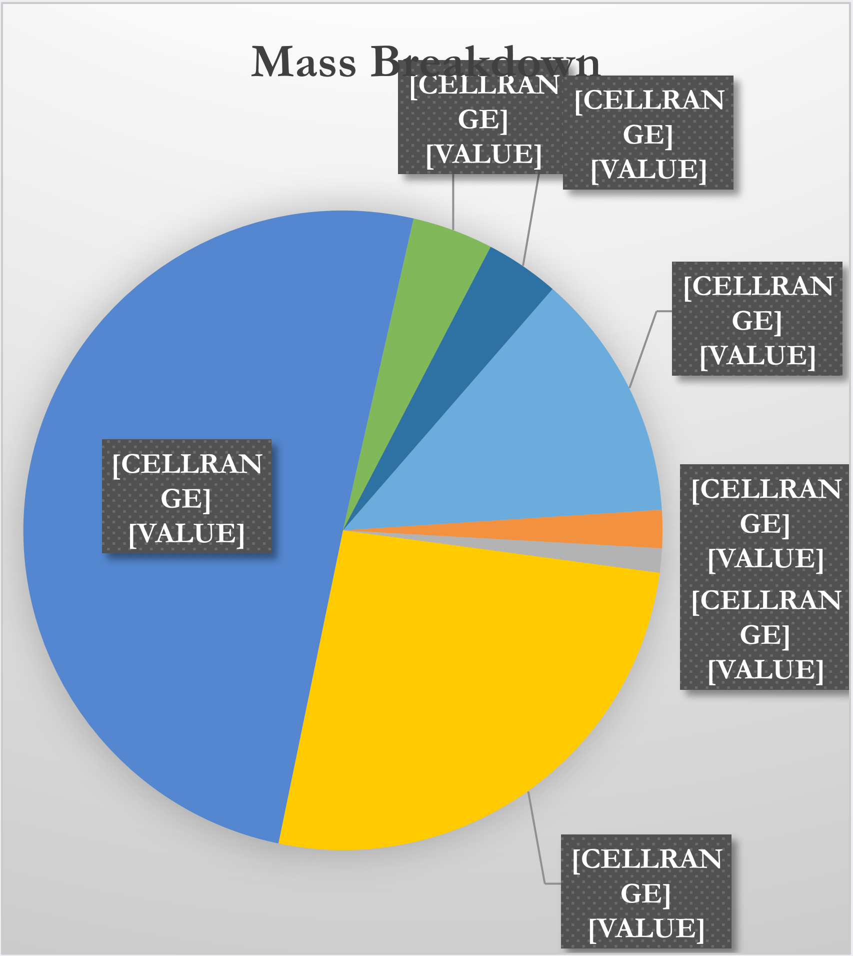
Regolith Type: High-Ti Mare || BatchTime: 8 (hr) || Design Margin: 1.5 || MaxWallTemp: 1400 (K)

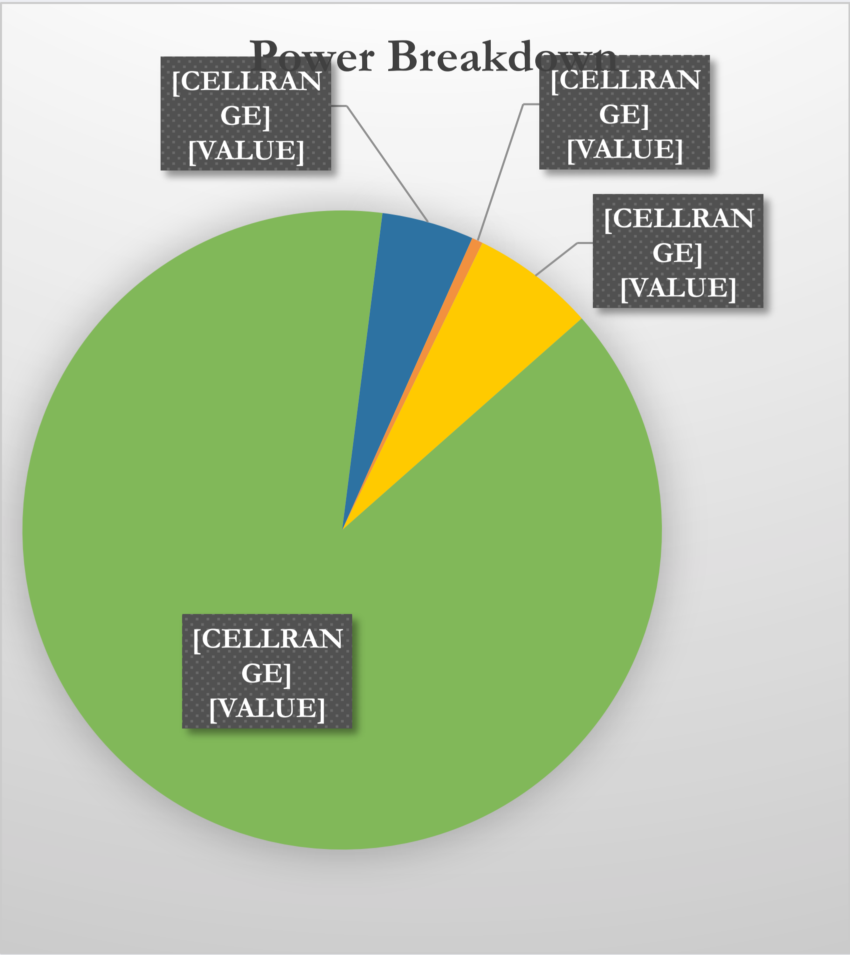
- **Increasing Operating Temperature**
  - Reactor mass ↓
  - Reactor power ↑,↓
  - Min Production Level ≈ →

Reactor Design Characteristics



Point Design (5000 kg/yr)





ISRU System Model Limitations

- **Excavation Module**
  - Never selects more than one excavator
  - Mass growth
  - Power consumption not modeled
  - ~90% of computation time, unnecessary
- **Auger/Fill System**
  - Not parametrically sized w/ regolith flowrate/fill time
  - Pneumatic methods?
- **MRE-specific**
  - Fill mechanism
  - Start-up procedure (PSI Solar Concentrator?)
- **YSZ Filter**
  - Rudimentary, needs better mass/volume estimates