

Degradation of yttria-stabilized zirconia in molten regolith electrolysis applications

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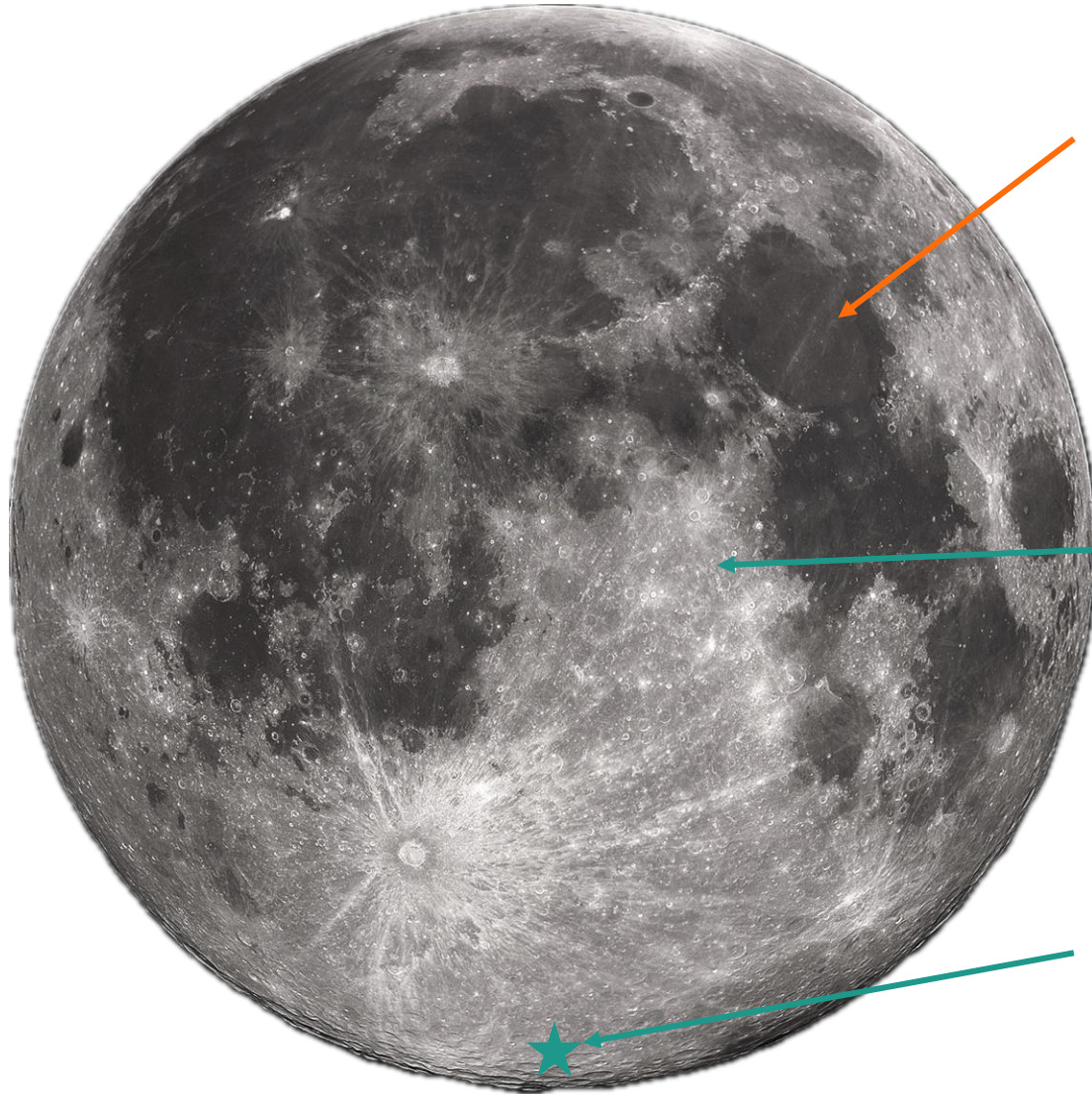
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NASA Marshall Space Flight Center

Lunar surface



Dark regions:
Lunar maria

Bright regions:
Lunar highlands

Artemis 3:
Late 2027



Lunar regolith:
Surface layer of granular
oxide minerals and glasses

Image from Wikipedia

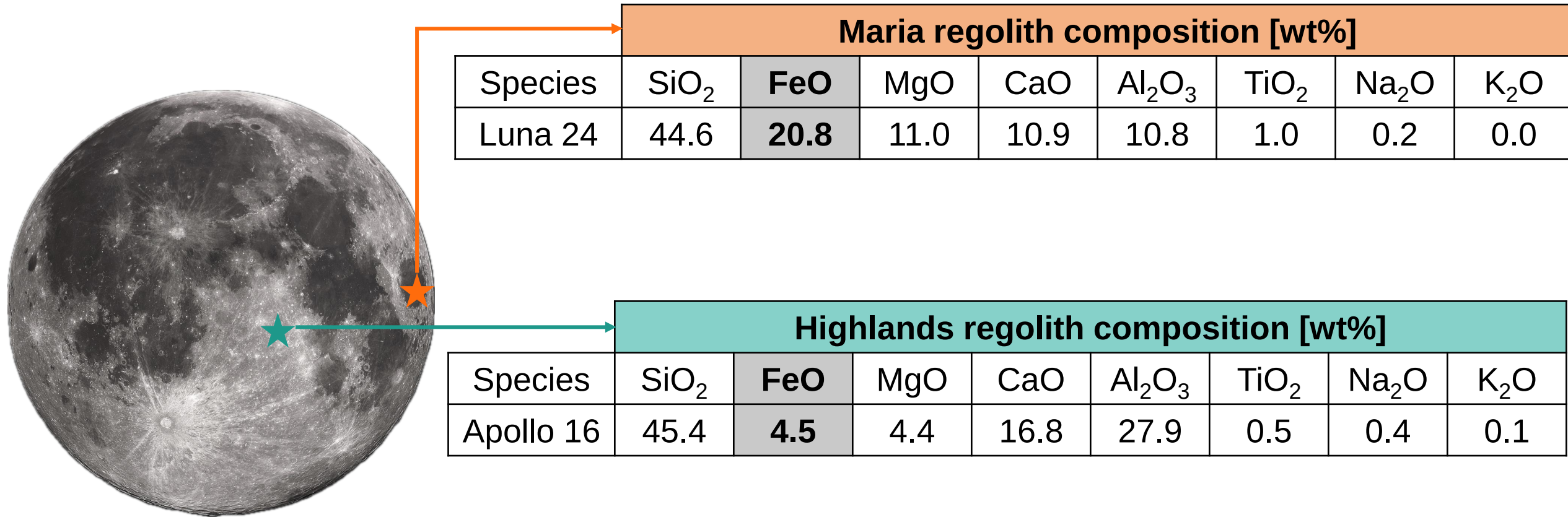
Starship HLS – Artemis 3

- Starship (Human Landing System variant) can deliver 100 mt of payload to lunar surface
- If lunar-derived O_2 can be used to refuel on the lunar surface:
 - Payload can increase to ~550 mt
 - Cost (\$/mt) can be cut by ~80%

Producing O_2 from lunar resources significantly reduces the cost of a sustained human presence on the lunar surface

Adapted from Abdin, A. et al. 72nd IAC (2021).

Lunar regolith composition

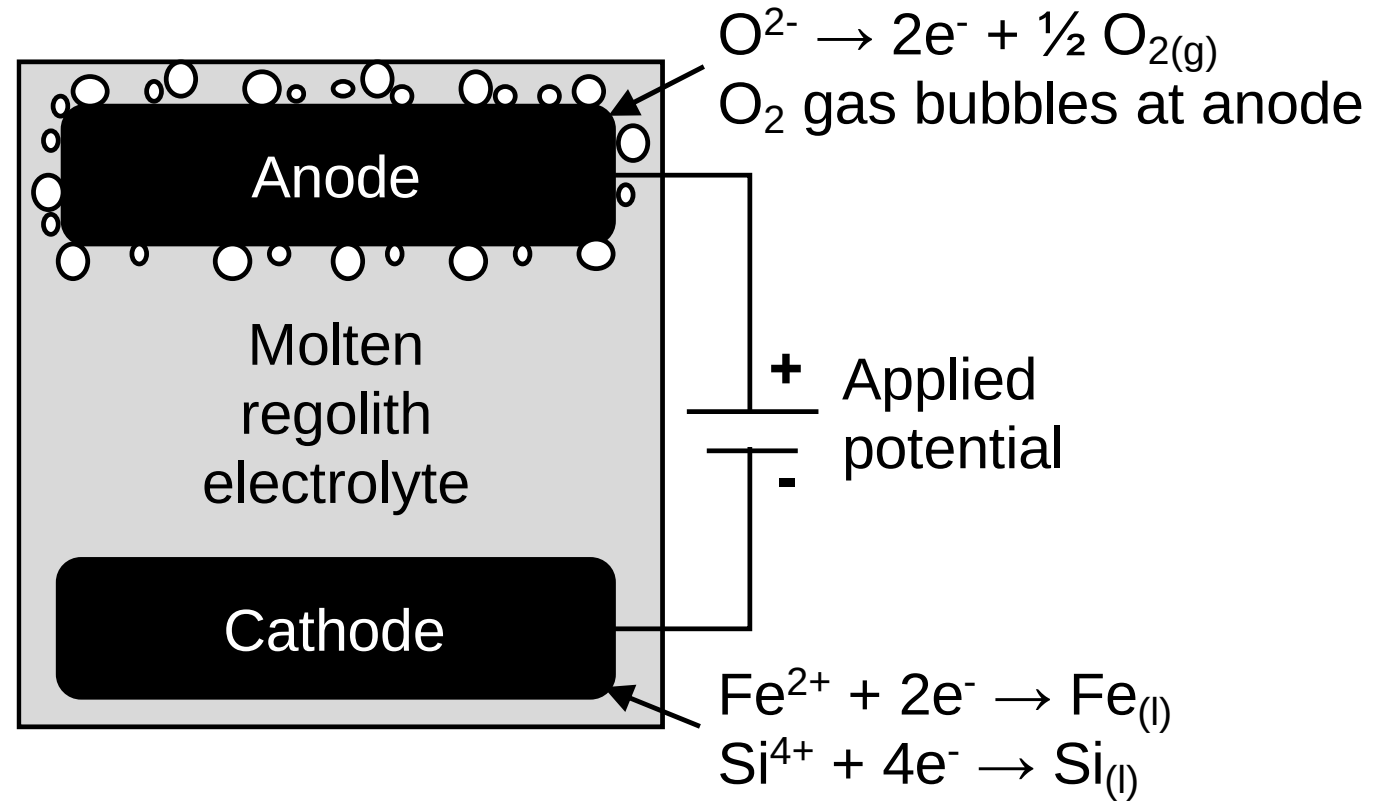


Lunar regolith is ~40 wt% oxygen → ideal feedstock for oxygen production

Humbert, M.S. et al. *Planet Space Sci.* **219** (2022).

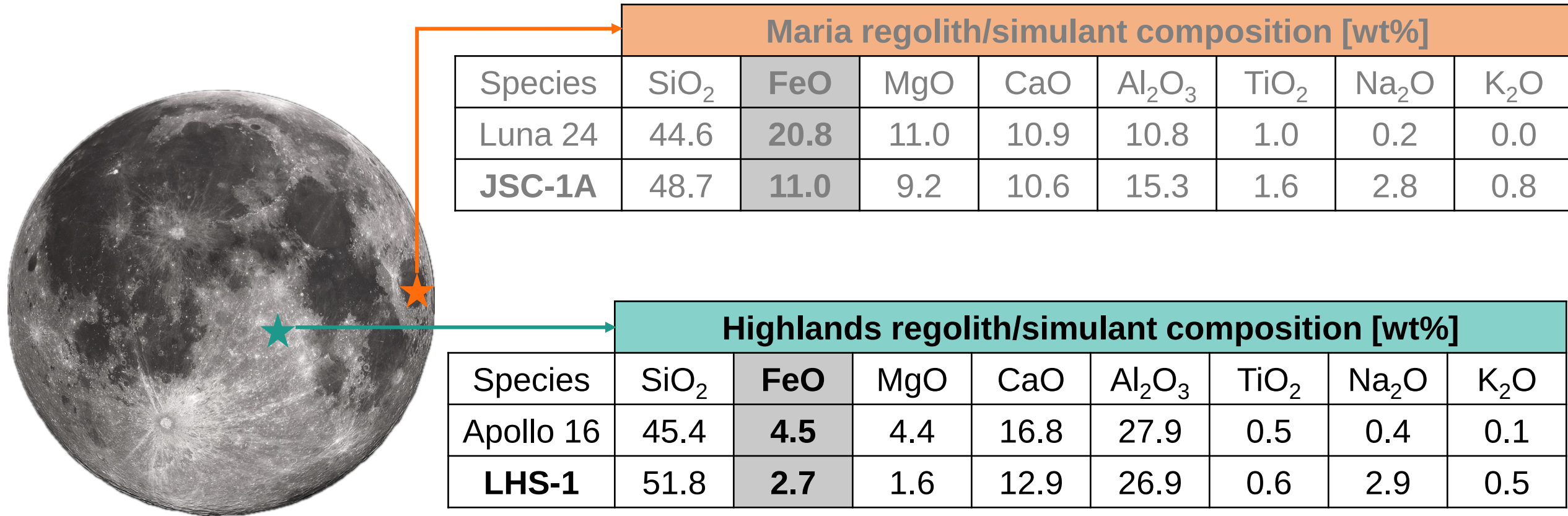
Molten regolith electrolysis (MRE)

- Directly electrolyzes molten regolith to generate O_2 and Fe-Si alloys
- High oxygen extraction efficiency (up to 100%)
- Requires high operating temperatures (1600°C)
- Materials challenges:
 - **Containment**
 - **Anode**



Yttria-stabilized zirconia (YSZ) is a promising option based on testing

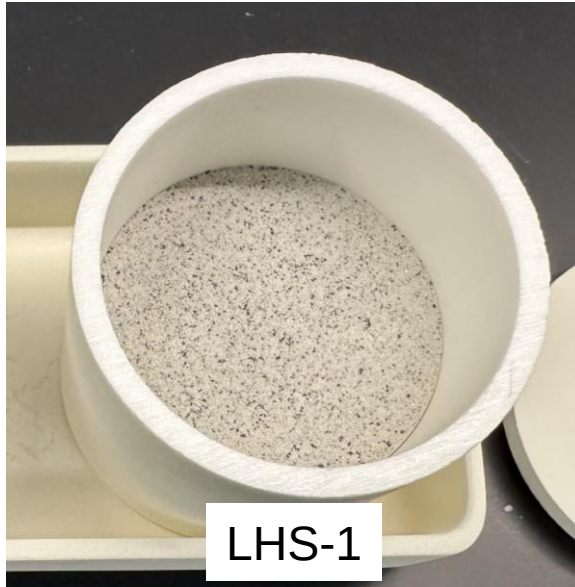
Lunar regolith simulants



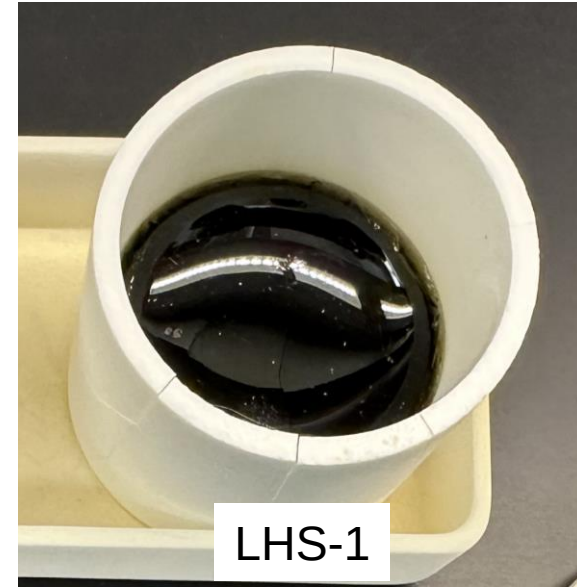
Two simulants evaluated → **LHS-1 for highlands** and JSC-1A for maria

Humbert, M.S. et al. *Planet Space Sci.* **219** (2022).

Crucible experiment



1600°C
3 hours

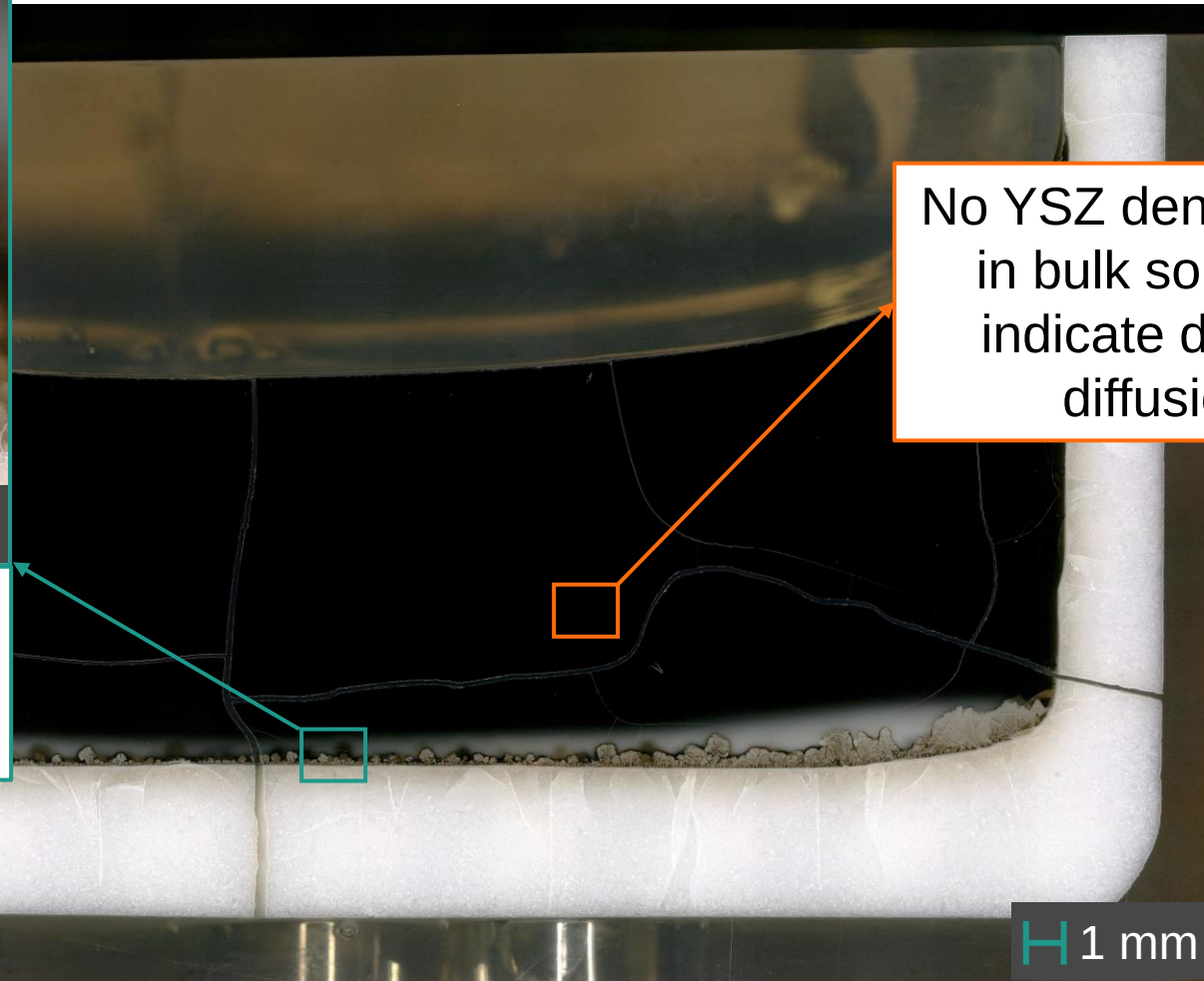


- 8 mol% YSZ crucibles used for containment/reactivity testing
 - LHS-1 (highlands) tested
 - Crucible size: 40 mm height, 40 mm ID
 - Crucible loading: ~30 g of LHS-1

Crucible experiment – LHS-1



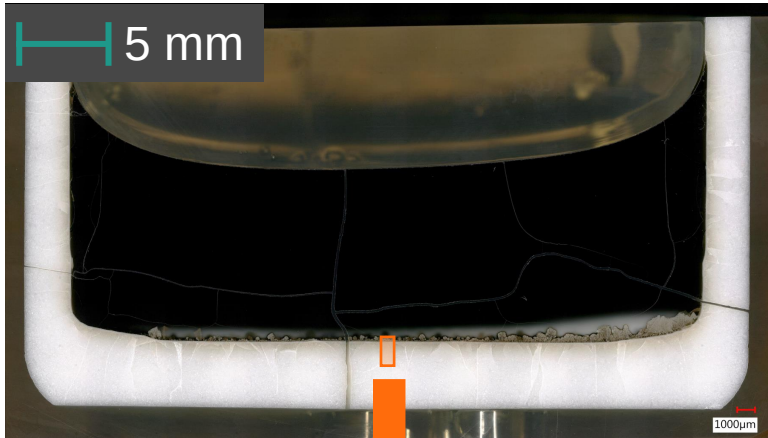
YSZ dendrites suggest dissolution-reprecipitation occurring near YSZ/LHS-1 interface



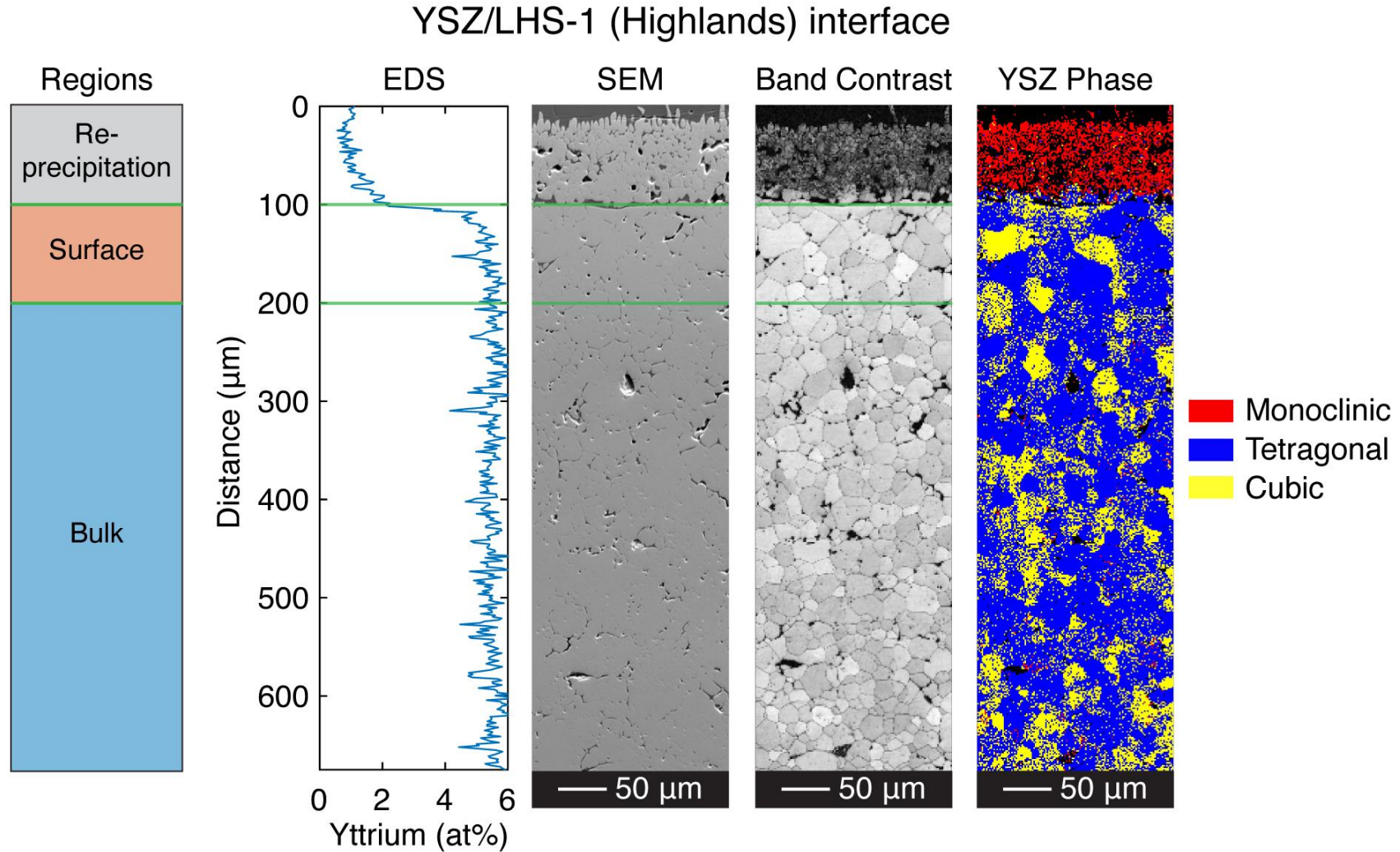
No YSZ dendrites observed in bulk solidified LHS-1 indicate degradation is diffusion-limited

Yu, K. et al. *J Am Ceram Soc.* **107** (2024).

Microstructural characterization

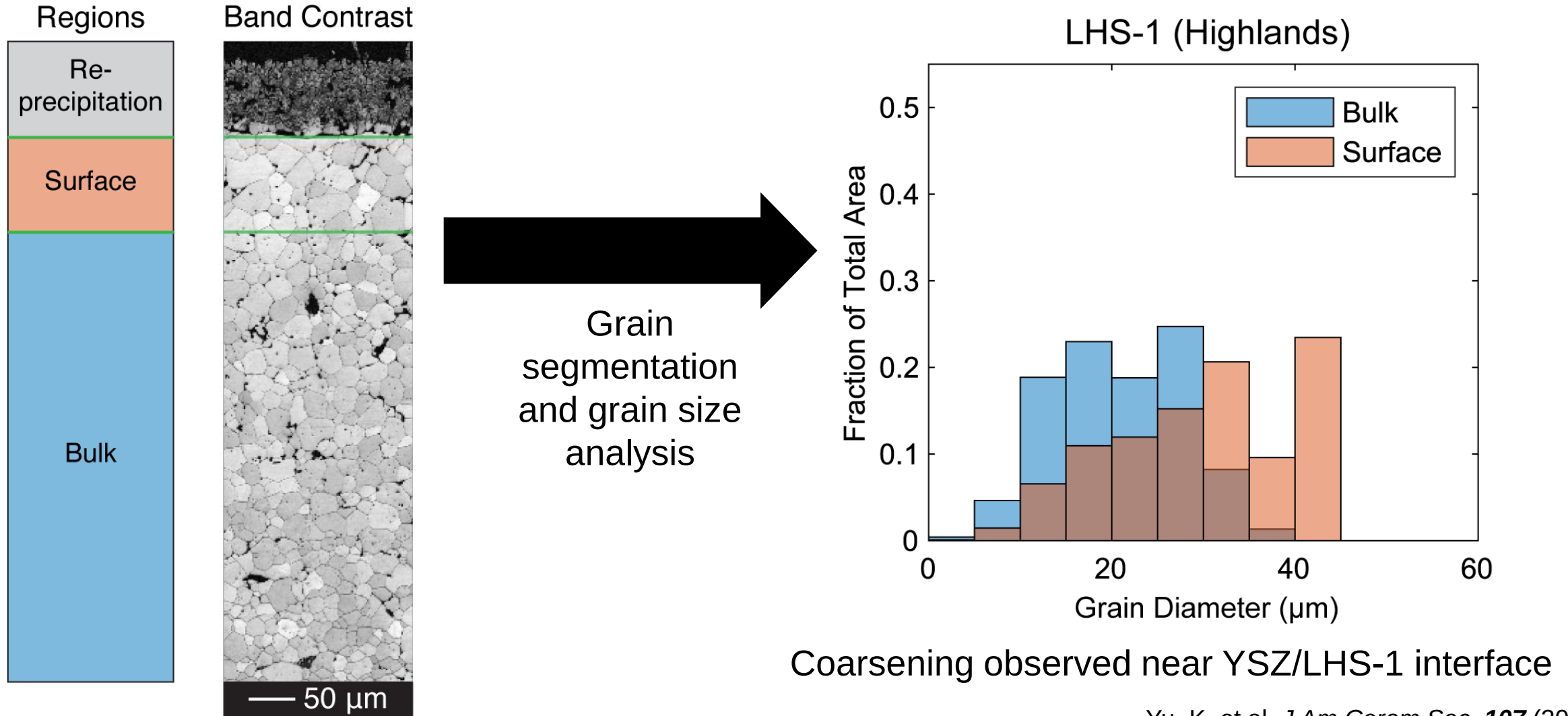


- EDS detected Y-depletion in reprecipitation region
- Y-depletion causes reprecipitated YSZ to become monoclinic on cooling
 - Confirmed with EBSD
 - YSZ cracks on cooling



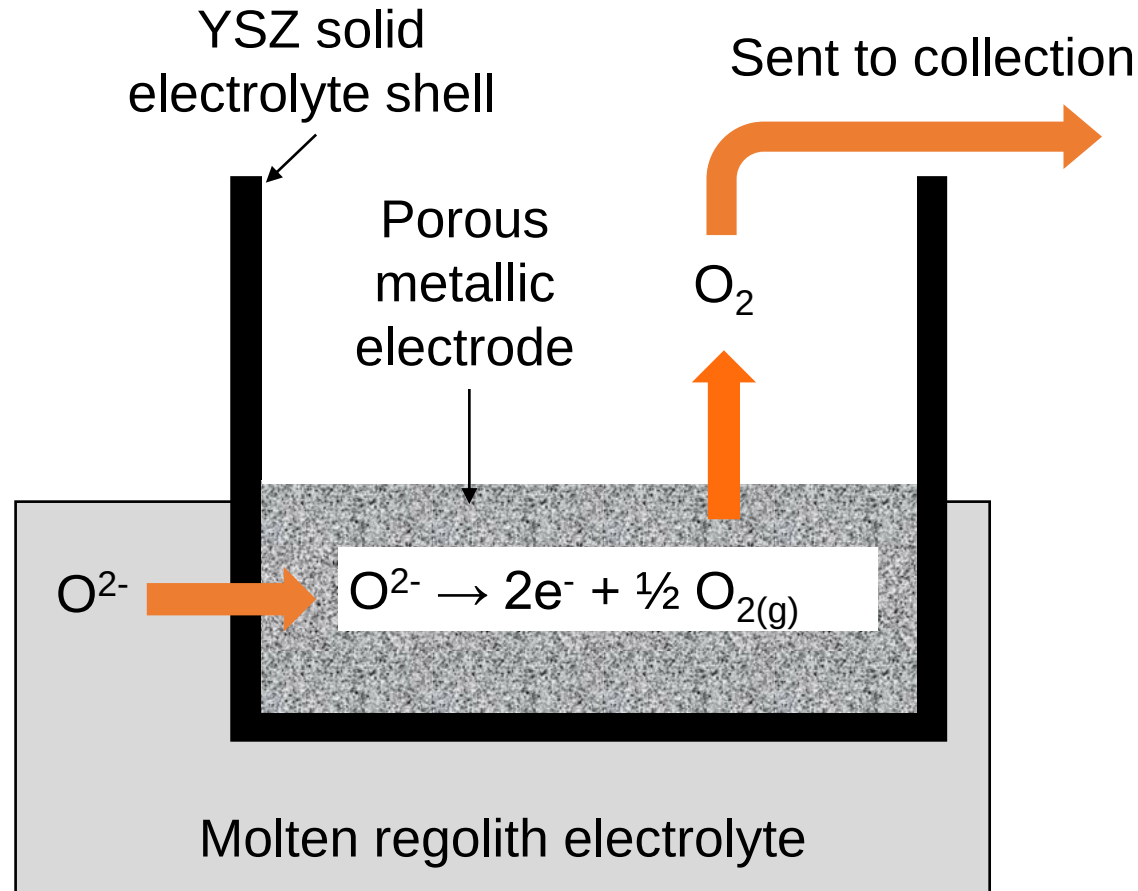
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Grain coarsening – LHS-1 (Highlands)



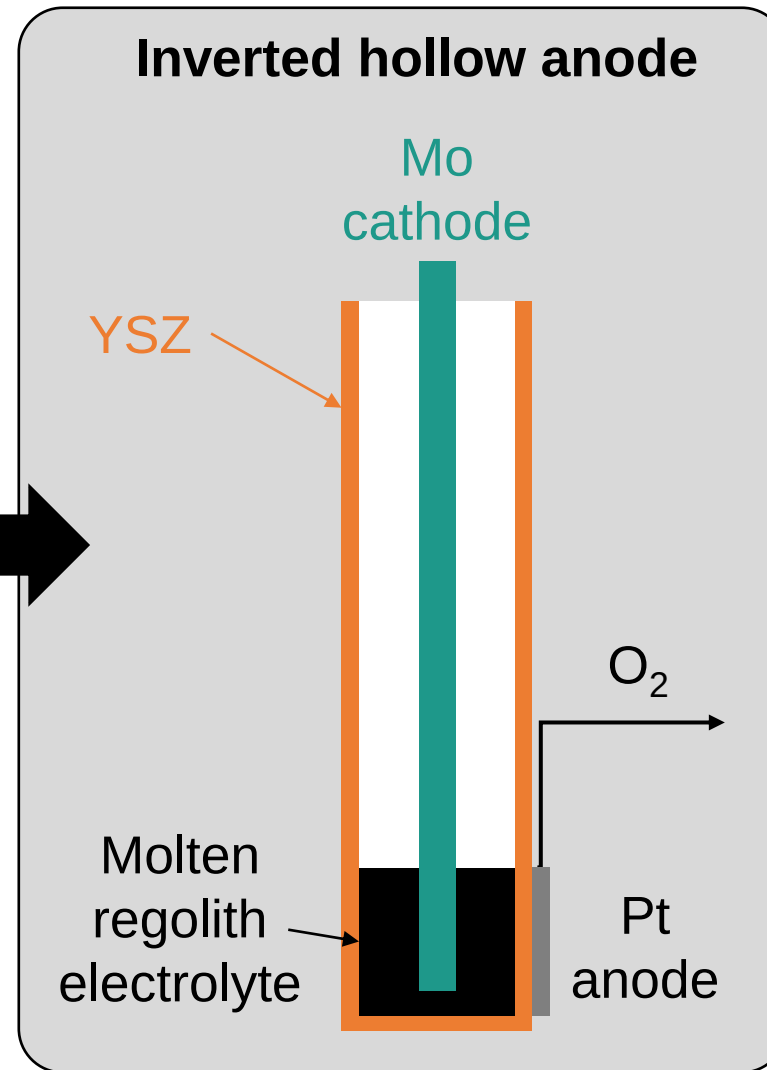
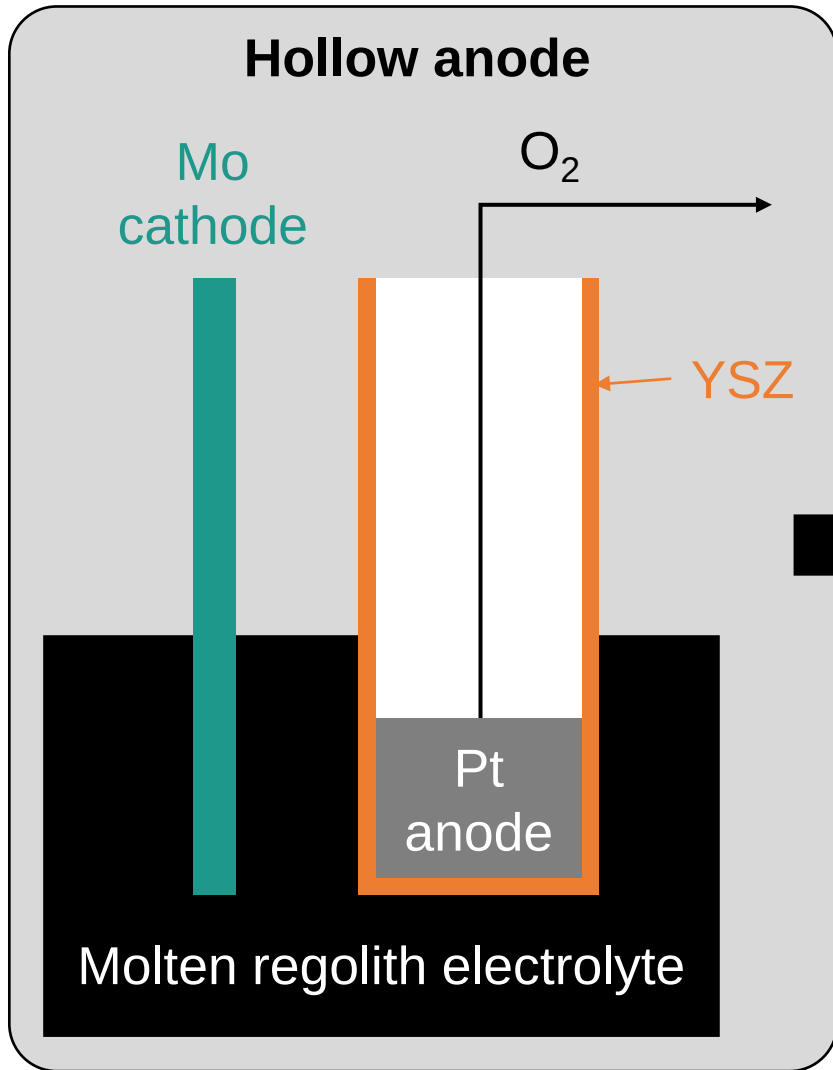
Yu, K. et al. *J Am Ceram Soc.* **107** (2024).

Hollow anode for MRE



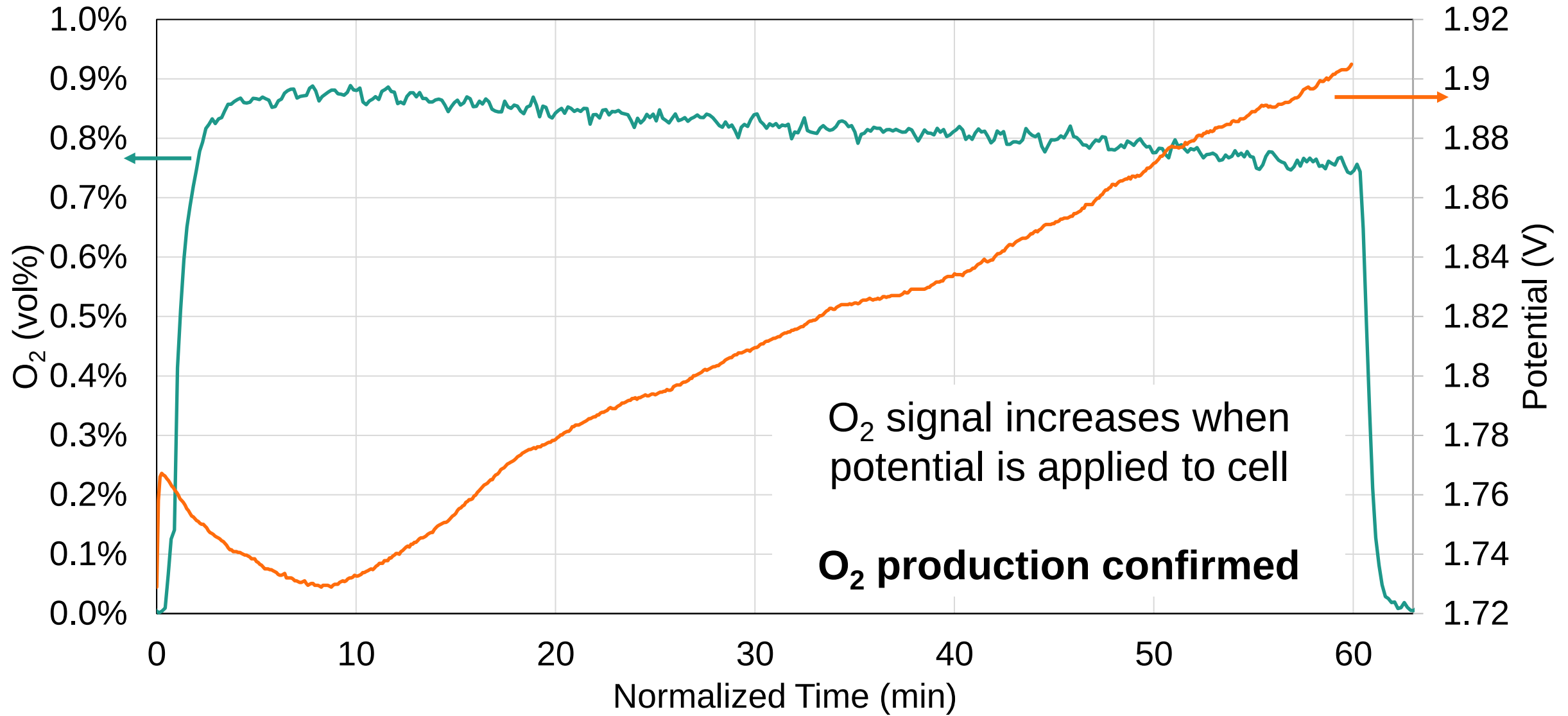
- Use dense YSZ as a solid electrolyte and protective shell
- Designed to enable facile collection of O_2
- Effect on efficiency:
 - ↓ Additional mass transport resistance from solid YSZ
 - ↑ O_2 removed from system without bubbling through molten regolith

Inverted hollow anode for small-scale testing

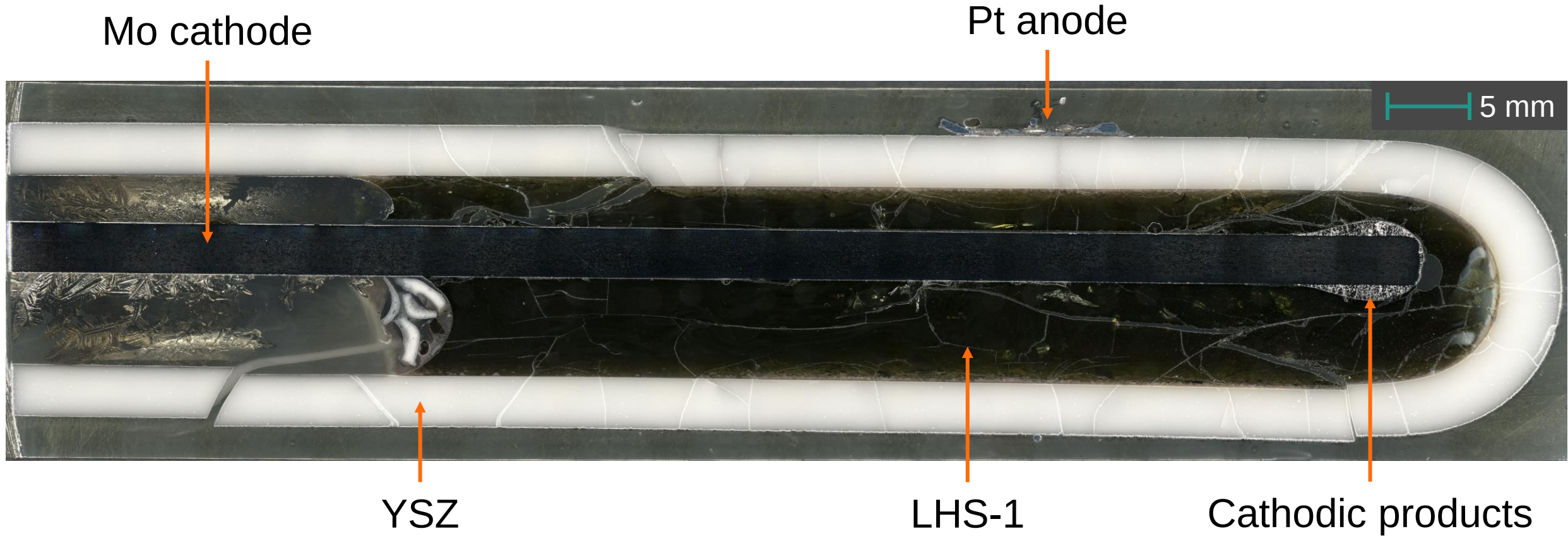


- Designed and built small-scale MRE reactor utilizing inverted hollow anode design
- Test conditions:
 - 1600°C under flowing argon
 - Constant current of 0.5 A
 - Outlet gas composition measured using residual gas analysis

Hollow anode proof-of-concept experiment

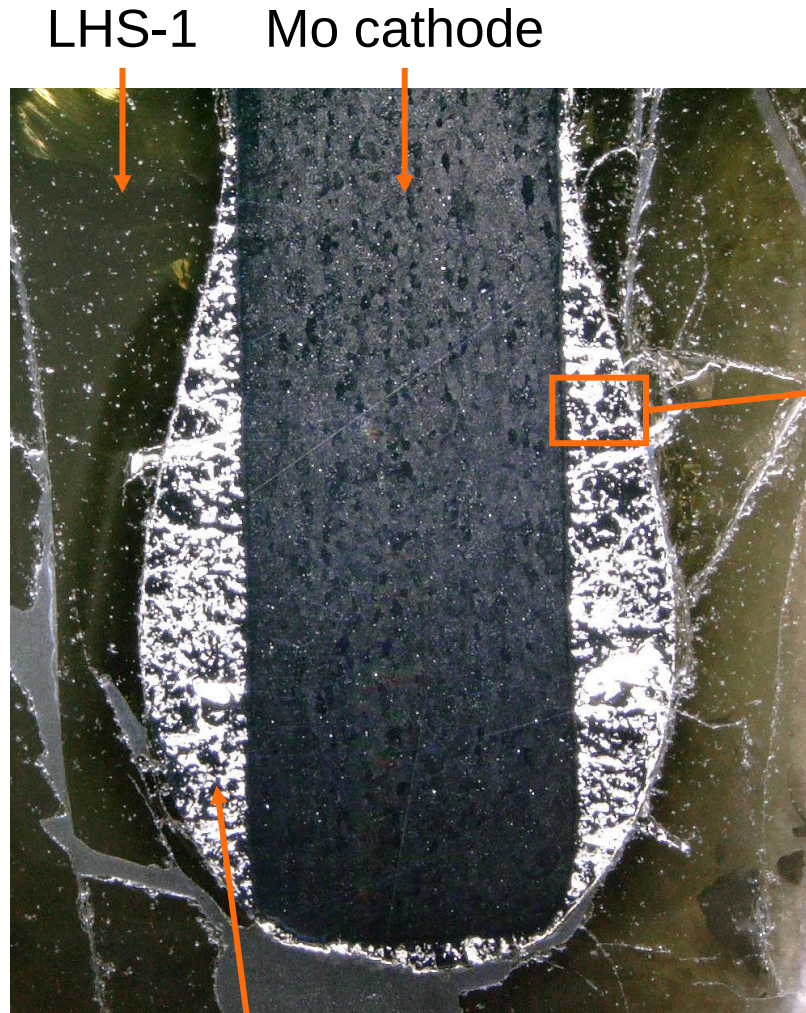


Post-electrolysis microscopy



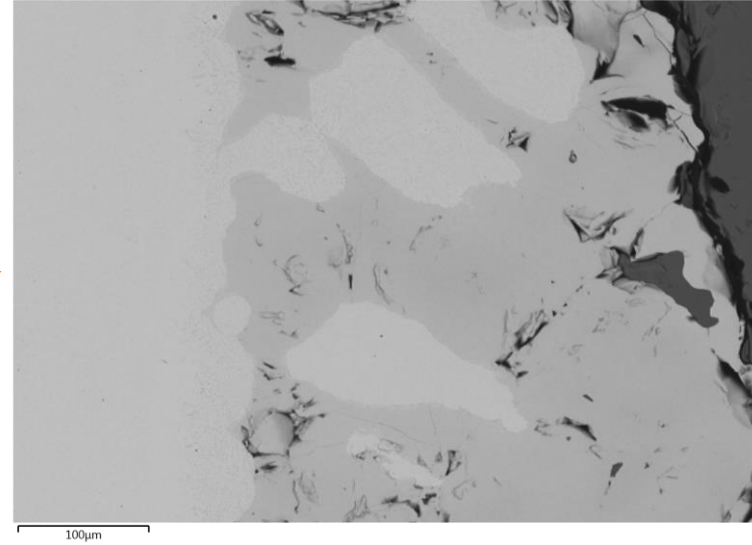
YSZ cracks on cooling due to monoclinic phase transformation (similar to crucible)
YSZ is limited to single-use applications for MRE

Cathodic products

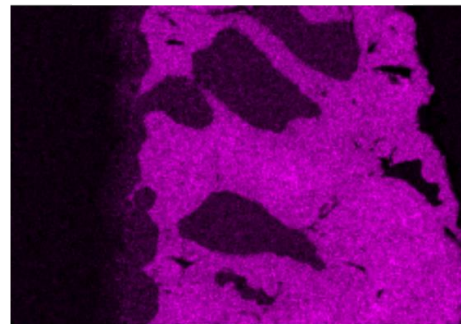


Cathodic products

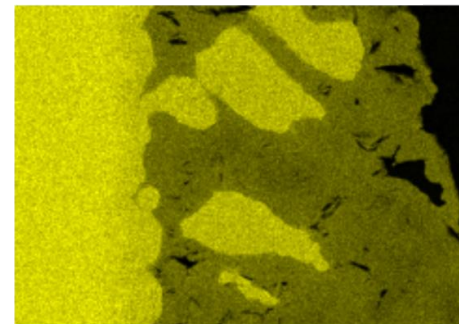
Backscattered electron image



Fe EDS map



Mo EDS map



Fe detected in
cathodic product
(alloyed with Mo)

**Fe production
confirmed**

Summary

Molten regolith containment

- YSZ dissolution and Y-depletion are primary degradation mechanisms
 - Y-depletion causes YSZ to become monoclinic on cooling, leading to cracking
- YSZ can be used to contain molten regolith for limited durations and for a single thermal cycle
- YSZ near interface with molten regolith undergoes grain coarsening
 - May slow rate of regolith penetration along grain boundaries

Hollow anode for MRE

- Proof-of-concept experiment successfully demonstrated O_2 (anode) + Fe (cathode) production
- Hollow anode allows O_2 to be easily collected after being produced through MRE
 - Avoids secondary reactions from bubbling O_2 through molten regolith
- YSZ can be used as a solid electrolyte in the hollow anode design for limited durations and single thermal cycle
 - Future work will focus on extending MRE durations

Acknowledgements

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Summary

Molten regolith containment

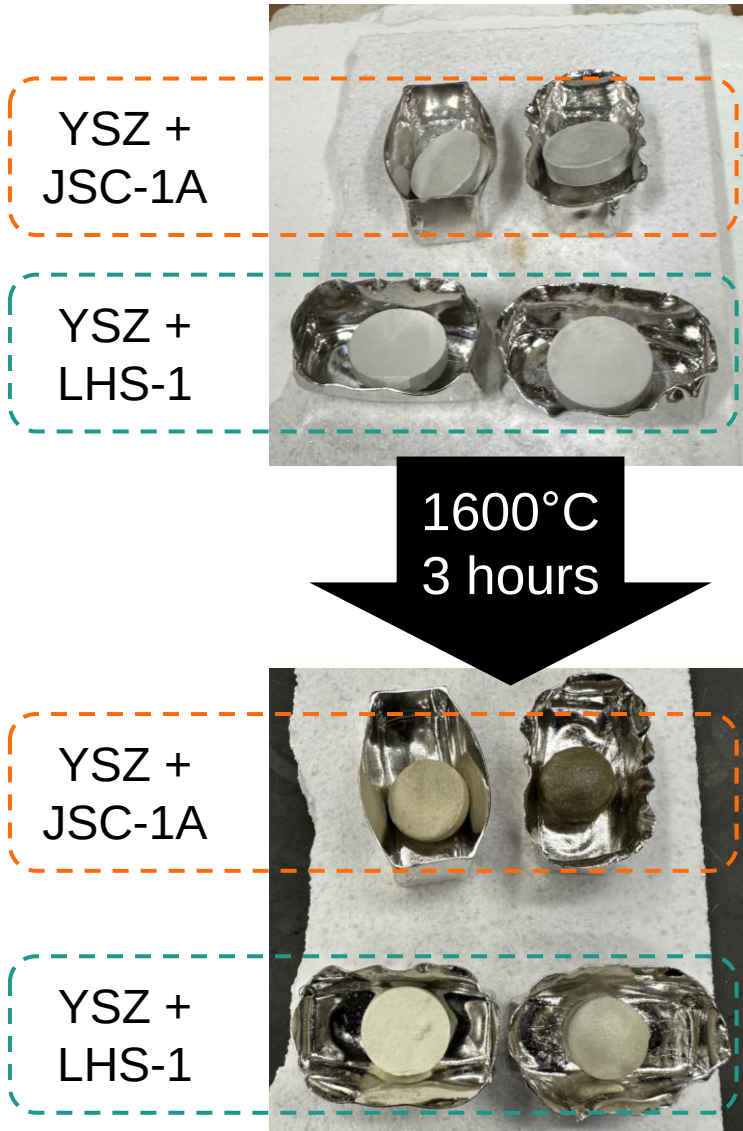
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Backup

Powder compact summary



Interactions observed:

- YSZ dissolution
- Y depletion from YSZ

Not observed:

- High temperature reaction phase (ZrSiO_4)

	LHS-1 (Highlands)		JSC-1A (Maria)	
	Zr at%	Y at%	Zr at%	Y at%
Measured	1.38	1.27	1.65	1.38
FactSage	1.96	-	1.95	-

Similar Zr/Y solubilities for LHS-1 and JSC-1A

FactSage viscosity model (melts)

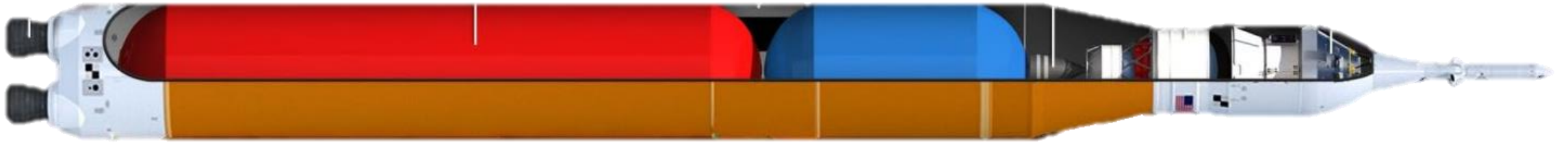


LHS-1: 6.7 Pa*s

JSC-1A: 0.7 Pa*s

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Space Launch System – Artemis 3



Dry mass { **Payload: 2.5% (27 mt)**
Dry Core Stage: 7.8% (85.3 mt)

Propellants { **Oxygen: 76.7% (843.7 mt)**
Hydrogen: 13.1% (143.8 mt)

Refueling 27 mt (3%) with lunar-derived oxygen → Drops \$/kg of payload by half

<https://www.nasa.gov/humans-in-space/space-launch-system/sls-fact-sheets/>

Oxygen production from lunar regolith

	H ₂ reduction	Carbothermal reduction (CH ₄)	Molten regolith electrolysis
Site specificity	Moderate to high (ilmenite/pyroclasts)	Low to moderate (iron oxides and silicates)	
Extraction temp.	Moderate (900°C)	High (1600°C)	High (1600°C)
Energy per kg	High	Moderate	Moderate
Extraction efficiency	1-5%	5-15%	20-40%
TRL	4-5	4-5	2-3

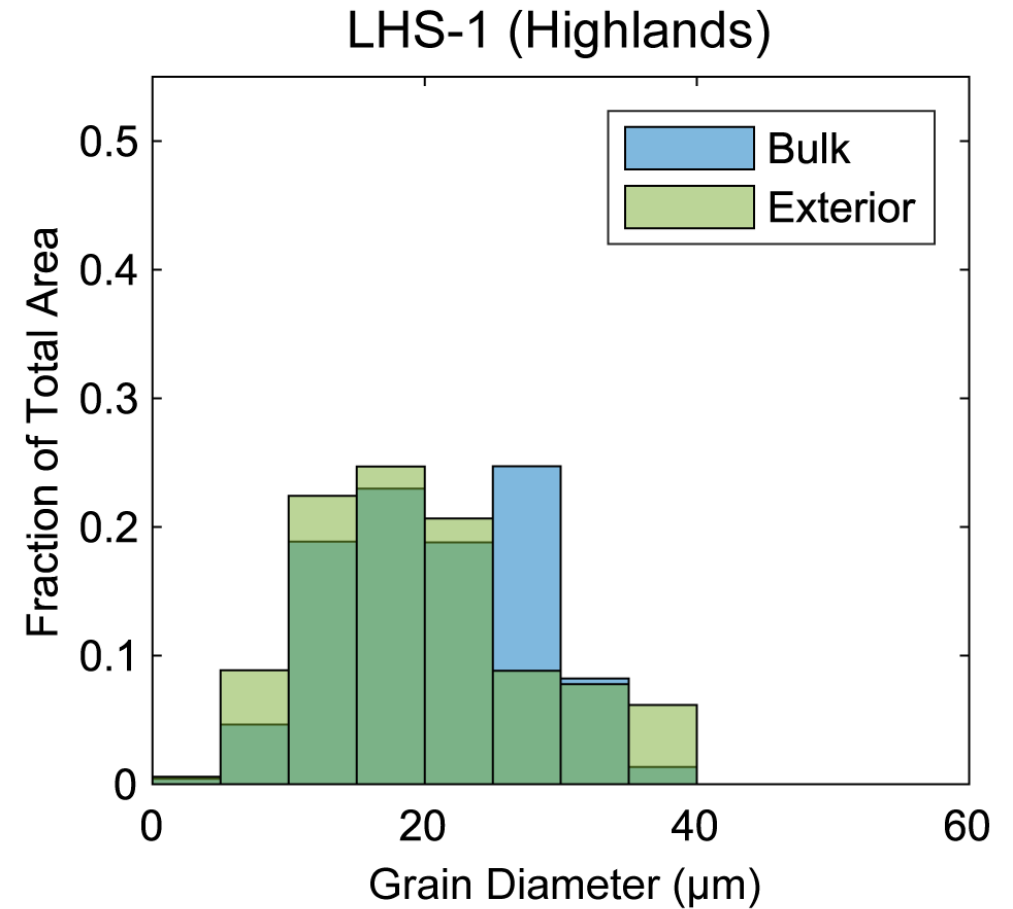
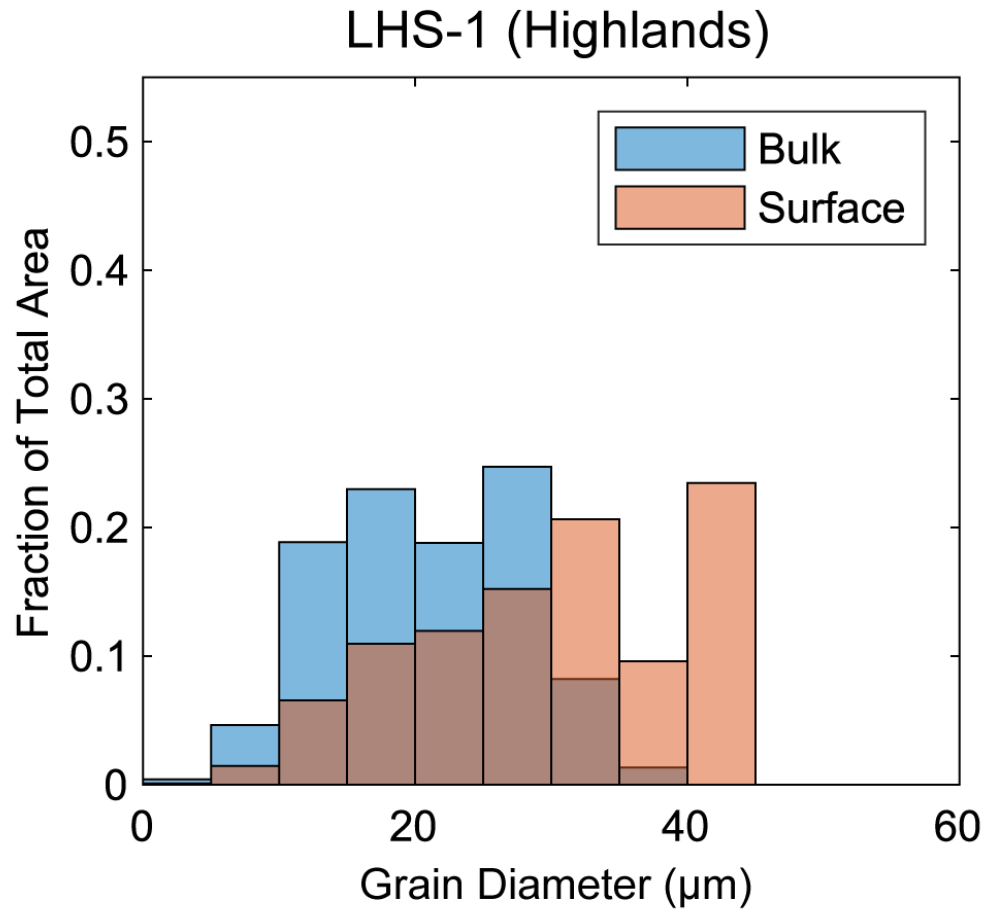
Increasing extraction efficiency



What material can withstand 1600°C and contact with corrosive molten regolith?

YSZ is a promising option based on preliminary testing

Grain size – Exterior/Bulk/Surface



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