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Transforming Microreactor Economics Through Hydride Moderator Enabled Neutron Economy

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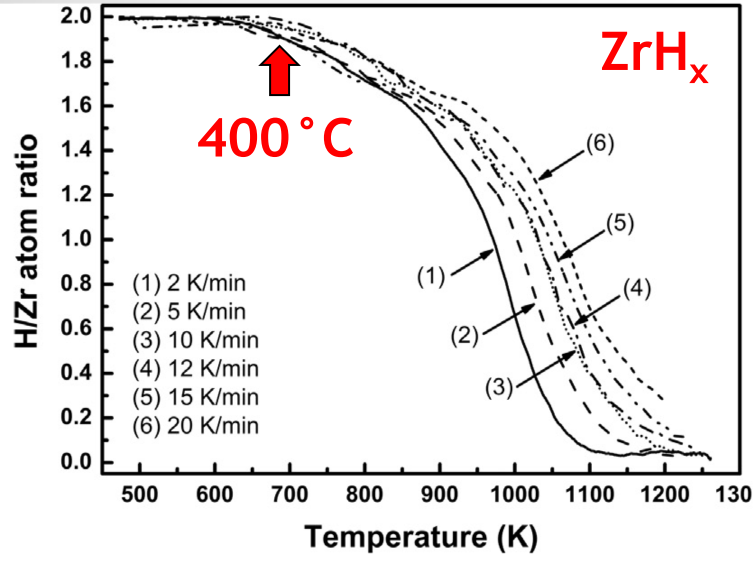
Combating the intrinsic thermodynamic limitations of hydrides

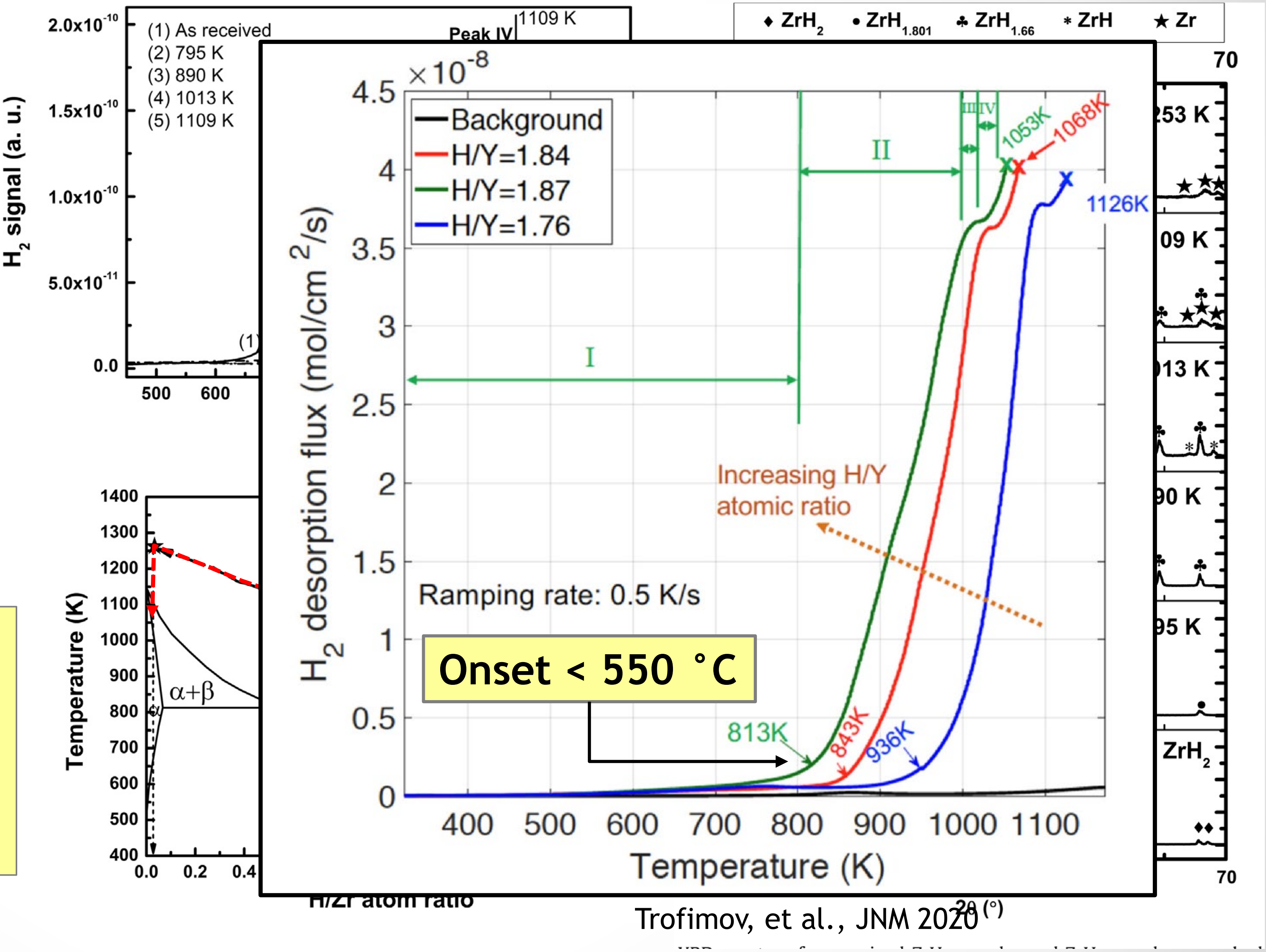


400 °C

$$\varepsilon \rightarrow \delta+\varepsilon \rightarrow \delta \rightarrow \beta+\delta \rightarrow \beta$$

Hydride stability is intrinsically limited by thermodynamics, but what if we can suppress the desorption of hydrogen?

Ma et al. JAC 2015



Onset < 550 °C

Trofimov, et al., JNM 2020

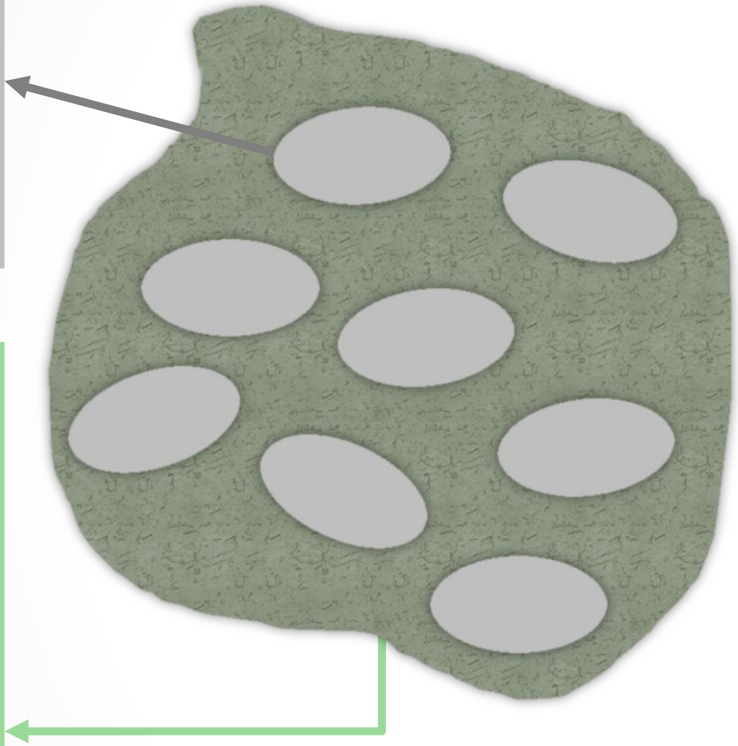
Ceramic composites as engineered moderator/reflector materials

Entrained Phase

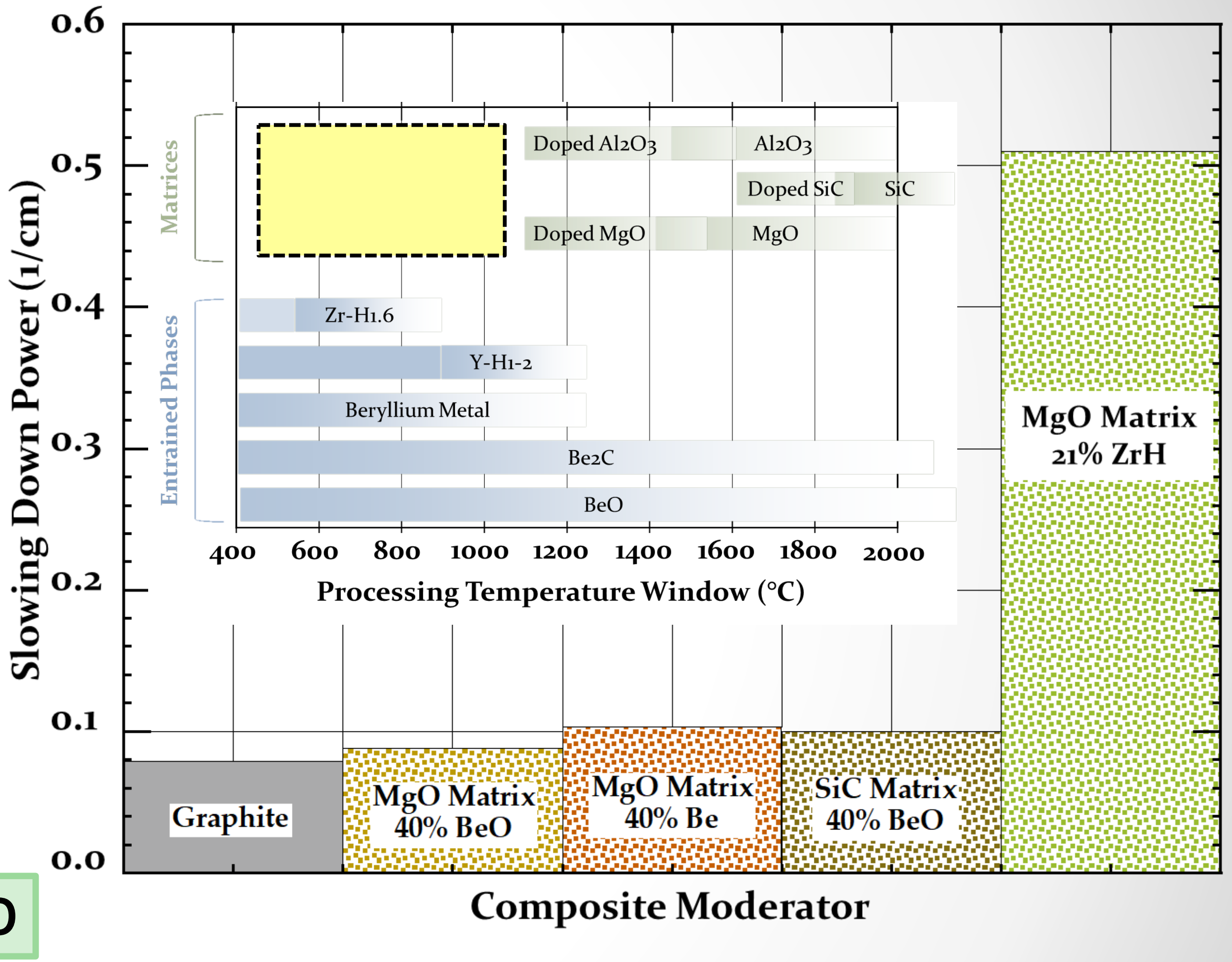
- → High Moderation
- → Low Neutron Absorption
- → Fair Radiation Stability
- → Low Transmutation

Matrix Phase

- → Fair Moderation
- → Low Absorption
- → Good Radiation Stability
- → Good Thermal Conductivity
- → Good Compressive Strength
- → Low Permeability



Magnesium Oxide, MgO



Manufacturing: ideally no chemical reactivity between the two phases with processing temperatures that do not decompose either phase and offer a pathway to economy of scale.

Project goals and objectives

Goals

- Demonstrate significantly reduced fuel costs through novel microreactor designs enabled by the technical advancement of engineered hydride ceramic composite moderators.

Objectives

1. Fabricate stabilized entrained hydride moderators for continuous operation at 800 °C through neutronics informed optimization
2. Enhance the performance of an annular, spherically-shaped, and reflected core through these moderators and integrated design optimization
3. Produce entrained hydride composites up to 10 cm in diameter via DCS and map the spatial distribution of microstructure and properties,
4. Measure H desorption from the entrained hydride composites with a migration model developed for hydrogen transport in MgO
5. Quantify the trade-off cost with savings realized through reduced uranium loading and other factors pertinent to microreactors.

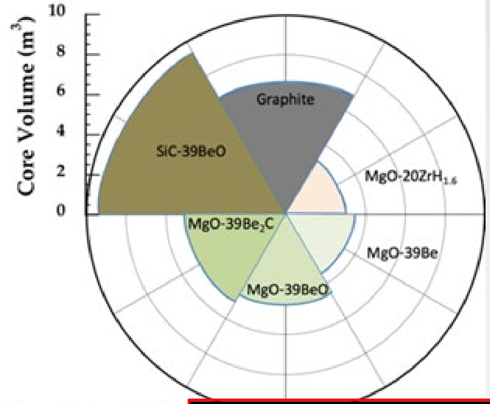
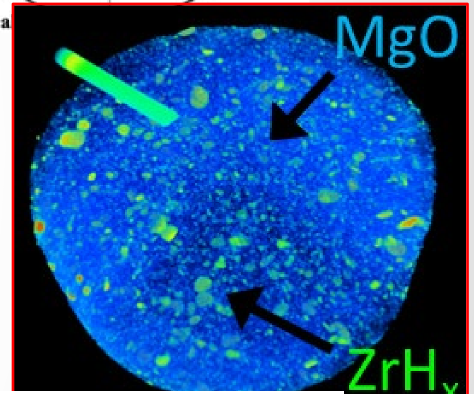
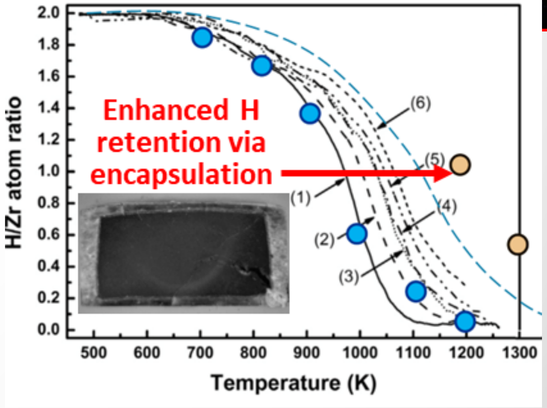
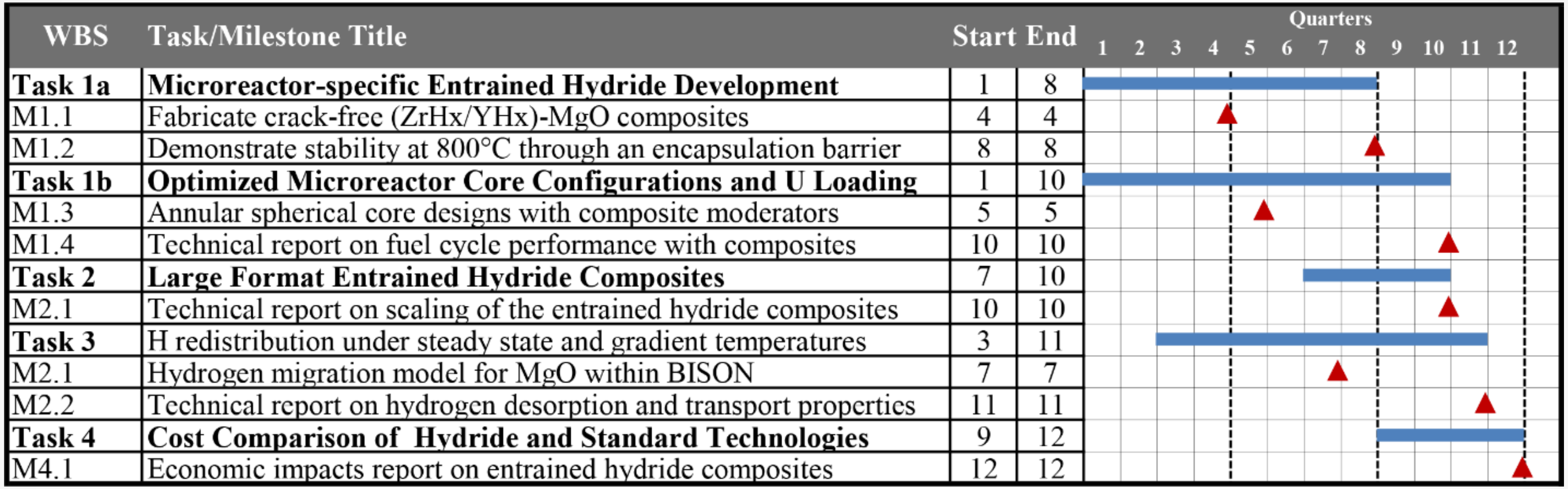


Figure 4: Core Critica





Project schedule and milestones



				Quarters											
WBS	Task/Milestone Title	Start	End	1	2	3	4	5	6	7	8	9	10	11	12
Task 1a	**Microreactor-specific Entrained Hydride Development**	1	8	▬	▬	▬	▬	▬	▬	▬	▬				
M1.1	Fabricate crack-free (ZrHx/YHx)-MgO composites	4	4				▲								
M1.2	Demonstrate stability at 800°C through an encapsulation barrier	8	8								▲				
Task 1b	**Optimized Microreactor Core Configurations and U Loading**	1	10	▬	▬	▬	▬	▬	▬	▬	▬	▬	▬		
M1.3	Annular spherical core designs with composite moderators	5	5					▲							
M1.4	Technical report on fuel cycle performance with composites	10	10										▲		
Task 2	**Large Format Entrained Hydride Composites**	7	10							▬	▬	▬	▬		
M2.1	Technical report on scaling of the entrained hydride composites	10	10										▲		
Task 3	H redistribution under steady state and gradient temperatures	3	11			▬	▬	▬	▬	▬	▬	▬	▬	▬	
M2.1	Hydrogen migration model for MgO within BISON	7	7							▲					
M2.2	Technical report on hydrogen desorption and transport properties	11	11											▲	
Task 4	**Cost Comparison of Hydride and Standard Technologies**	9	12									▬	▬	▬	▬
M4.1	Economic impacts report on entrained hydride composites	12	12												▲

Milestones

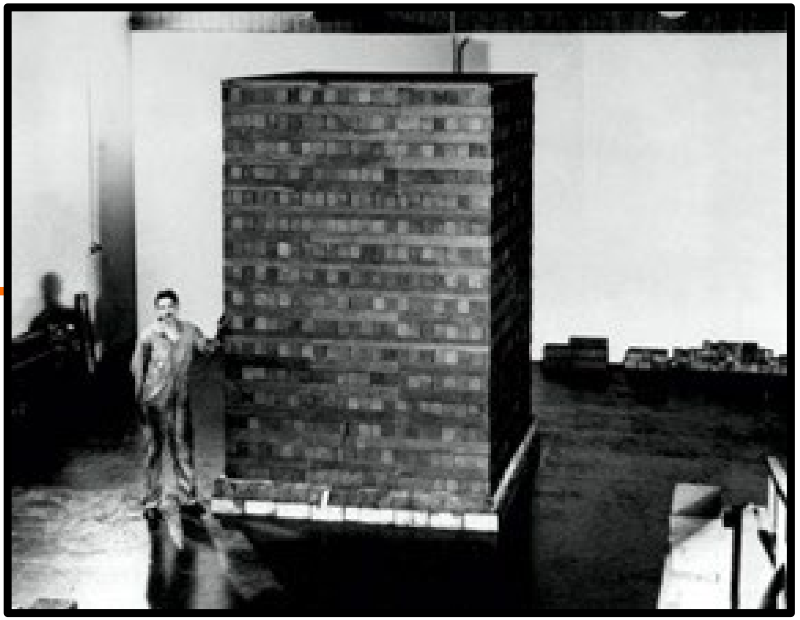
1. Report on the fabrication of stabilized entrained hydride ceramic composites with hydride loading optimized based on the annular spherical core models and stability up to 800°C. - Submitted
2. Report on fuel cycle performance of the spherical cores optimized to exploit the enhanced neutron economy enabled by the hydride-entrained composite moderators and reflectors. – Due 3/31/26
3. Report on hydrogen transport in the entrained hydride composites coupled with a hydrogen migration model for MgO and its impact on fuel cycle performance under transients. – Due 9/30/26
4. Technical Report on Large Format Production of Entrained Hydride Composites. - Due 9/30/26

Spherical Micro HTGR

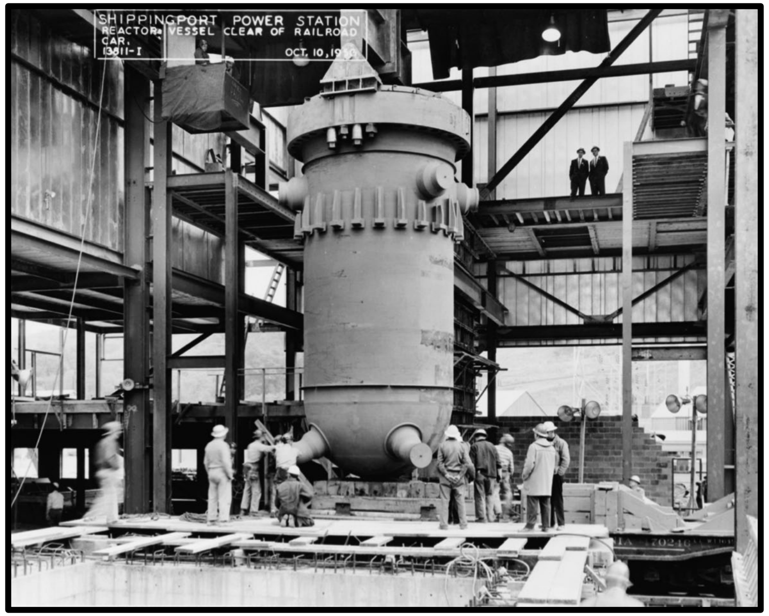
Graduate Student: Donald Doyle
Co-PI: Dr. Nicholas Brown

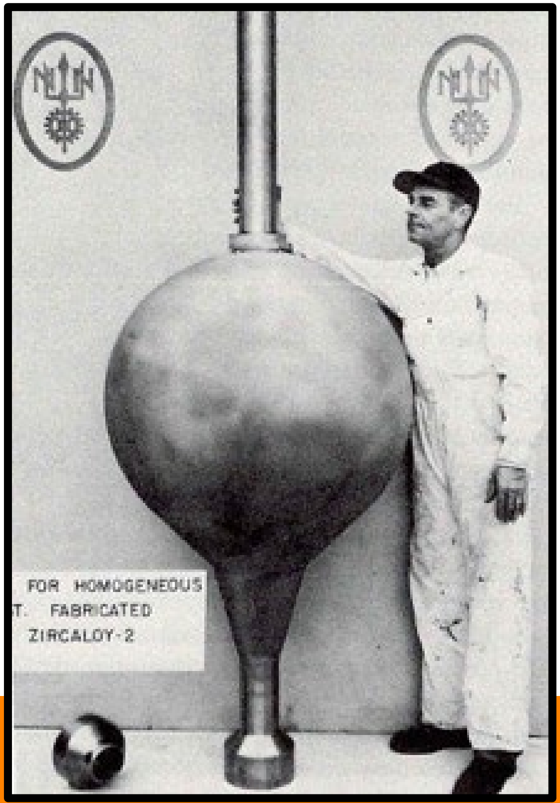
THE UNIVERSITY OF
TENNESSEE
KNOXVILLE

Past Reactor Designs



- First nuclear reactor Chicago Pile 1 was rectangular parallelpiped.
- Reactors quickly moved to cylindrical for reduced leakage.
- Spherical have been produced but limited by manufacturing and operational constraints.



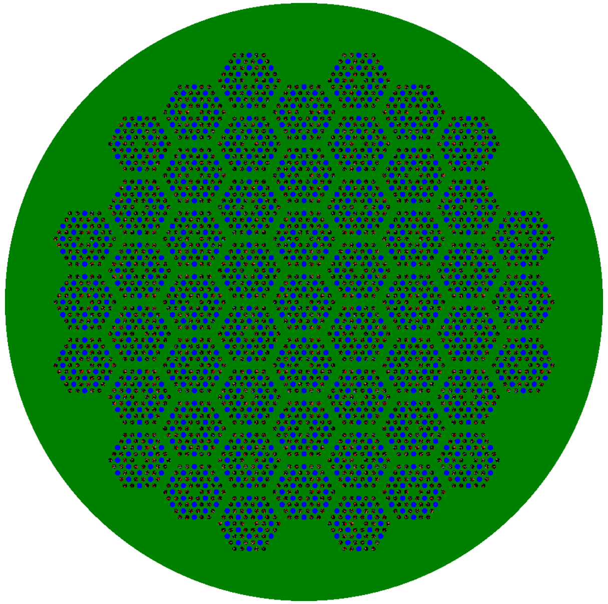


"Chicago Pile-1 - Nuclear Museum." *Https://Ahf.nuclearmuseum.org/*, 1 Dec. 2016, ahf.nuclearmuseum.org/ahf/history/chicago-pile-1/.
Sierchuła, Jakub. (2018). Analysis of reactivity changes during the operation of a nuclear power plant. 61-66. 10.1109/IIPHDW.2018.8388326.
"Cesium-137 Recovered from Homogeneous Reactor Fuel (1962)." *Museum of Radiation and Radioactivity*, July 2024, orau.org/health-physics-museum/collection/reactors/cesium-137-recovered-from-homogeneous-reactor-fuel.html. Accessed 5 Aug. 2024.

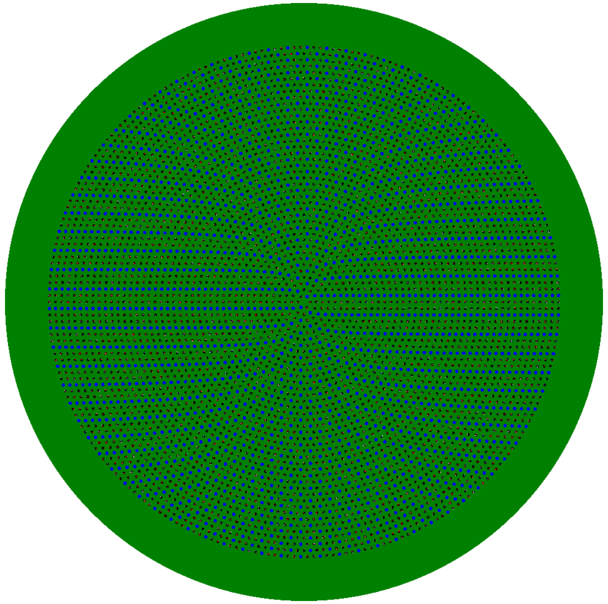
Cylindrical vs. Spherical Microreactor Design

XZ cut

XY cut

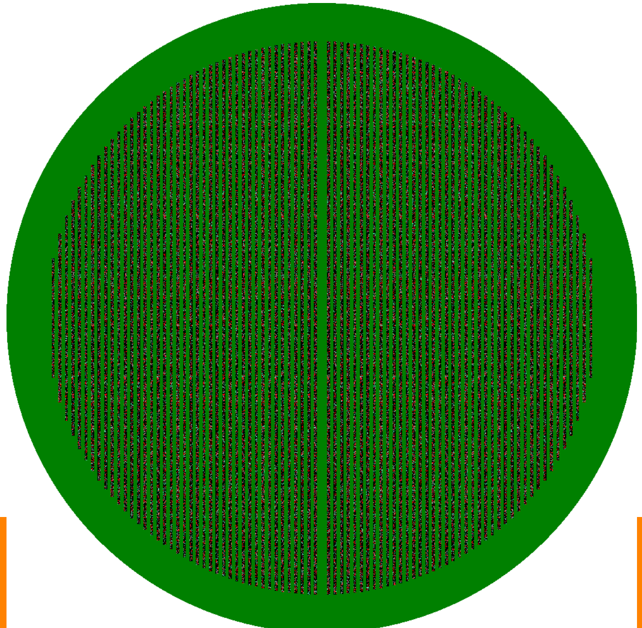


XY cut



🟩 Green: Moderator
⬛ Black: Fuel matrix
🟦 Blue: Helium
🟥 Red: Fuel

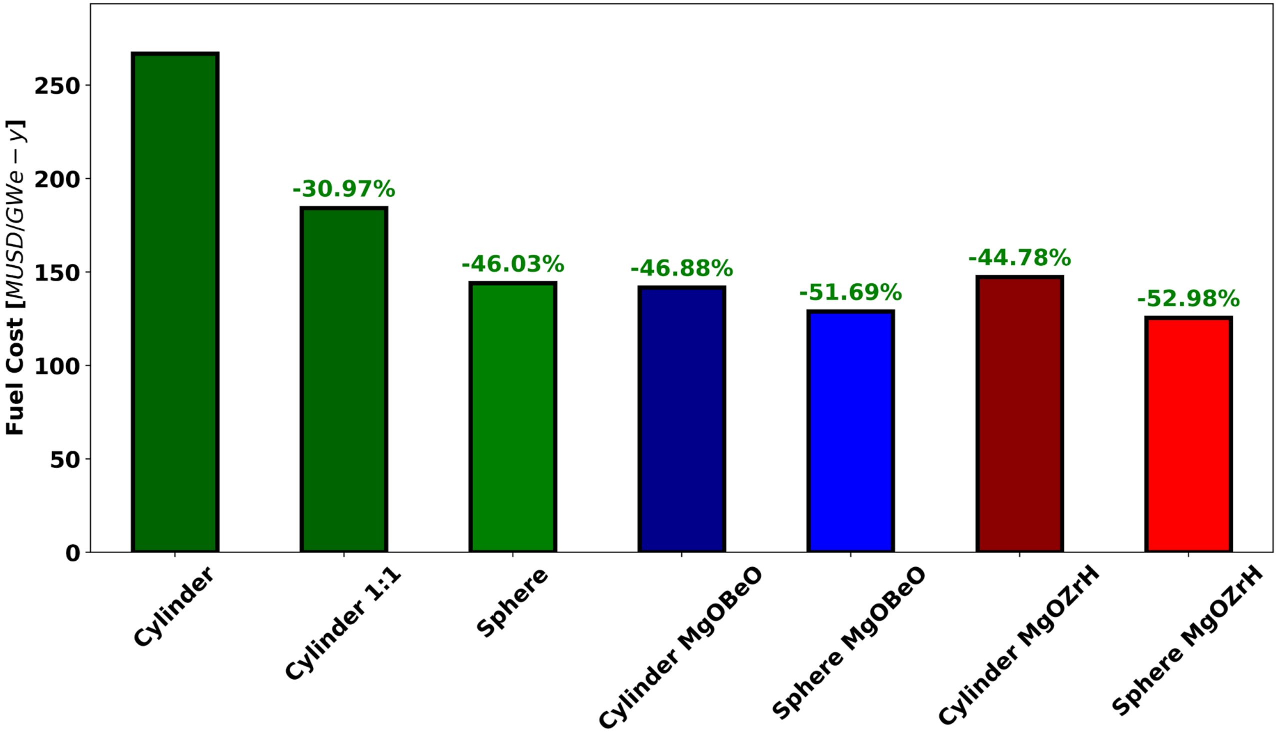
XZ cut



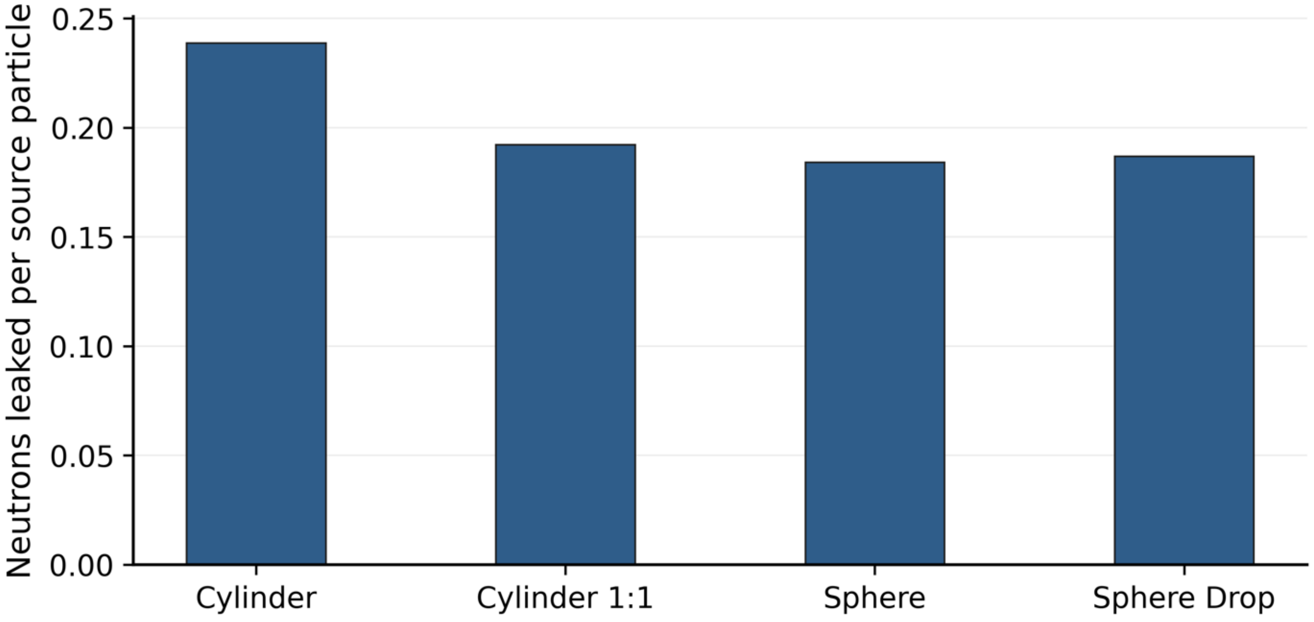
- Same volume of fuel, moderator, and coolant
- Same volume of total reactor system
- Coolant channel diameters adjusted to equalize pressure drop and maintain adequate cooling

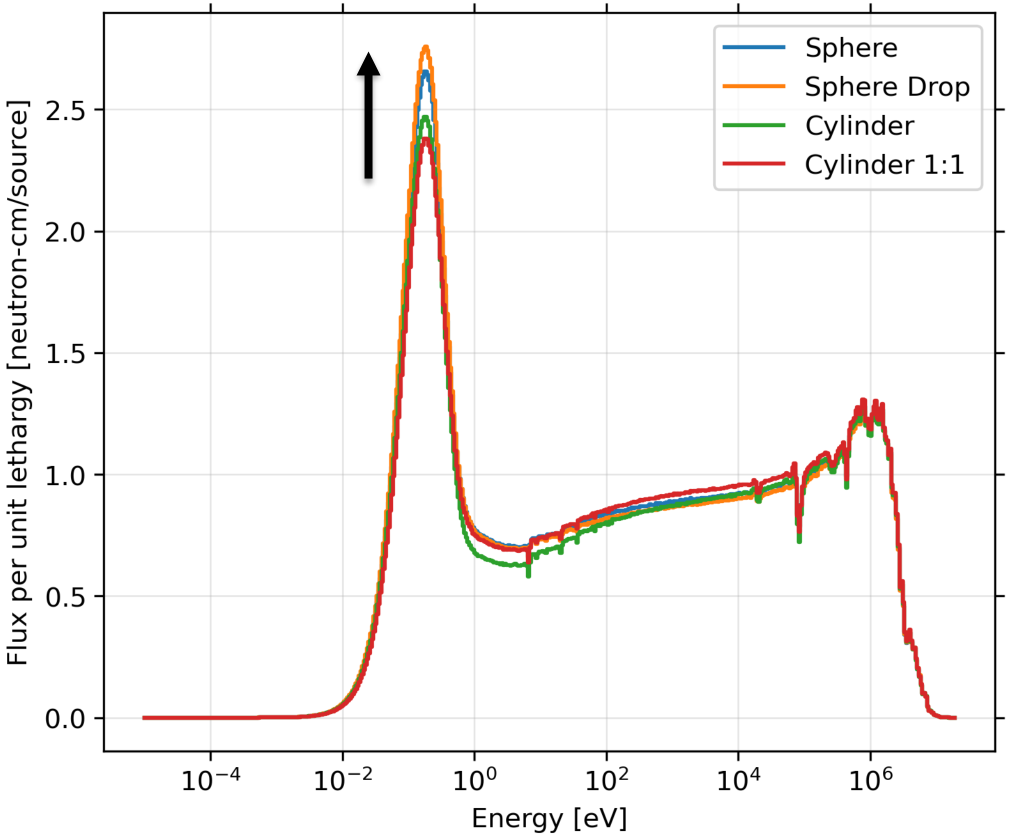
Spherical microreactor advantages

- A sphere has the smallest surface-area-to-volume ratio, improving neutron economy and fuel utilization.
- Tri-structural isotropic (TRISO) particles and HALEU fuel enable high burnup and stable operation without refueling for sealed spherical cores.



Neutron spectrum and leakage impacts





Reduced leakage in sphere results in higher thermal peak

Takeaways

- Purpose-built microreactor designs (e.g., spherical cores) may offer benefits versus scaling down large cylinder reactor geometries:
  - Reduced neutron leakage,
  - higher fuel burnup,
  - optimized neutron economy, and
  - sealed cores for remote deployment.

Altamimi, R., Doyle, D., Trelewicz, J. R., & Brown, N. R. (2025). Equilibrium Core Model for Micro Pebble Bed Reactors Using OpenMC. Nuclear Science and Engineering, 1–15

Spherical Reactor Geometry in Micro-High Temperature Gas Cooled Reactors with Composite Moderating Materials

Donald L. Doyle[1], Jason R. Trelewicz[2, 3], Nicholas R. Brown[1]

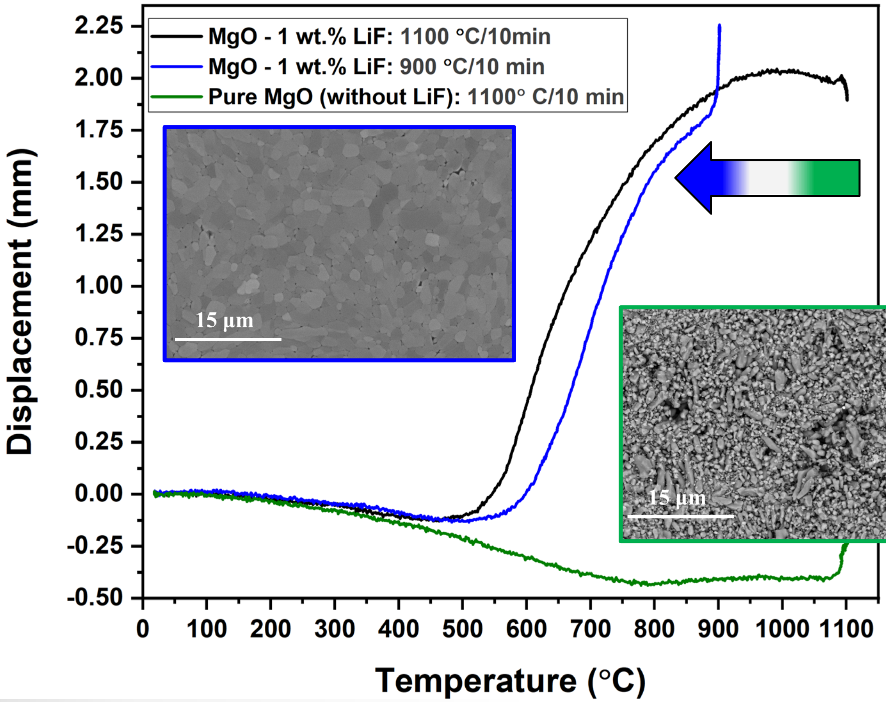
Composite Moderator Development

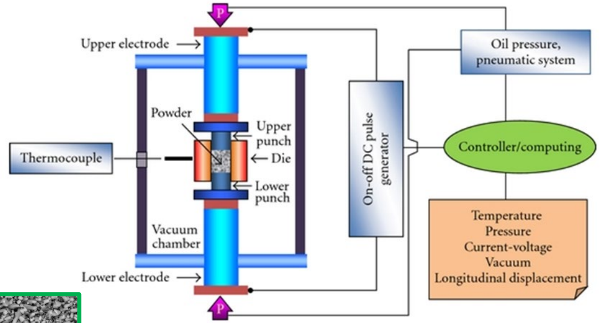
Postdoc: Luv Gurnani
Graduate Student: Mirza Shawon
Research Scientist: Spencer Thomas
Co-PI: Dr. Nicholas Brown

INL Lead: Chase Taylor
Hot Vacuum Extraction & Permeation Measurements

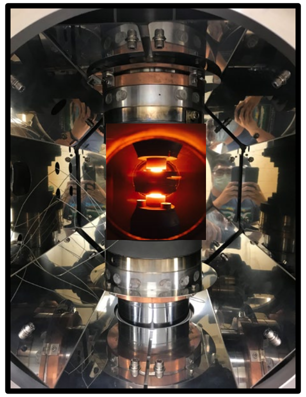
ORNL Collaborator: Weicheng Zhong
Thermal Desorption Spectroscopy

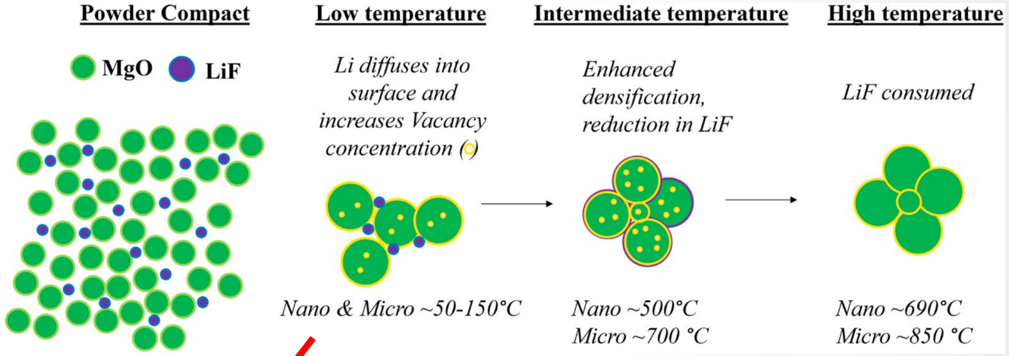
Enabling hydride composites through MgO sintering technology

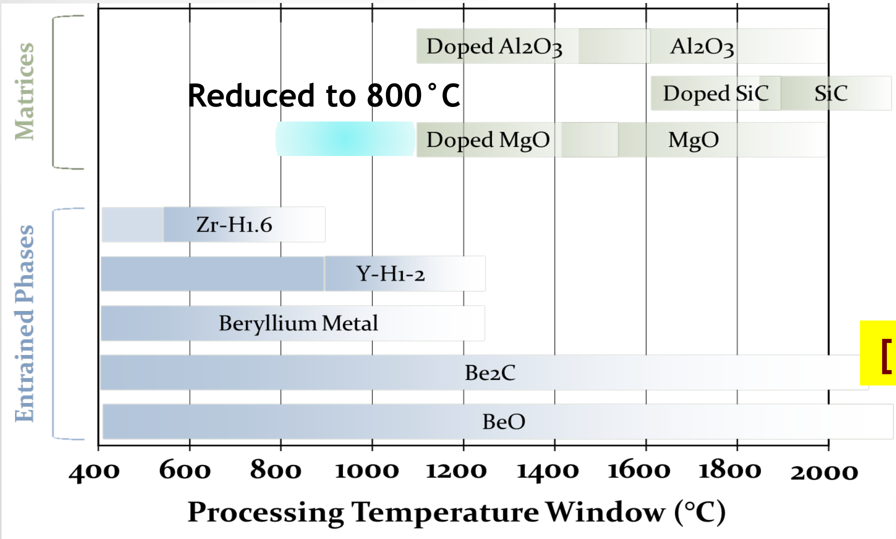




LiF suppresses the onset temperature for sintering by ~500 °C (w.r.t pure MgO) with ~99% densification achieved at 900 °C





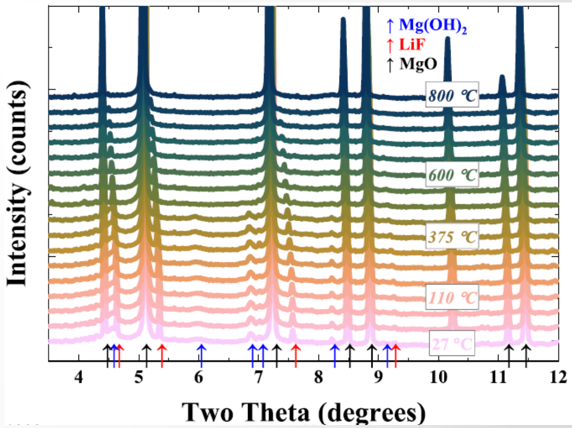


Mg^{2+} vs. Li^{1+} => charge balance requires oxygen vacancies

$$2\,LiF + O_O^{\times} \rightarrow 2\,Li_{Mg}^{'} + V_O^{\bullet\bullet} + 2\,F^{-}$$

(segregation/GB)

[Sprouster *et al.*, *J. Eur. Ceram. Soc.* 46 (2026) 118043]



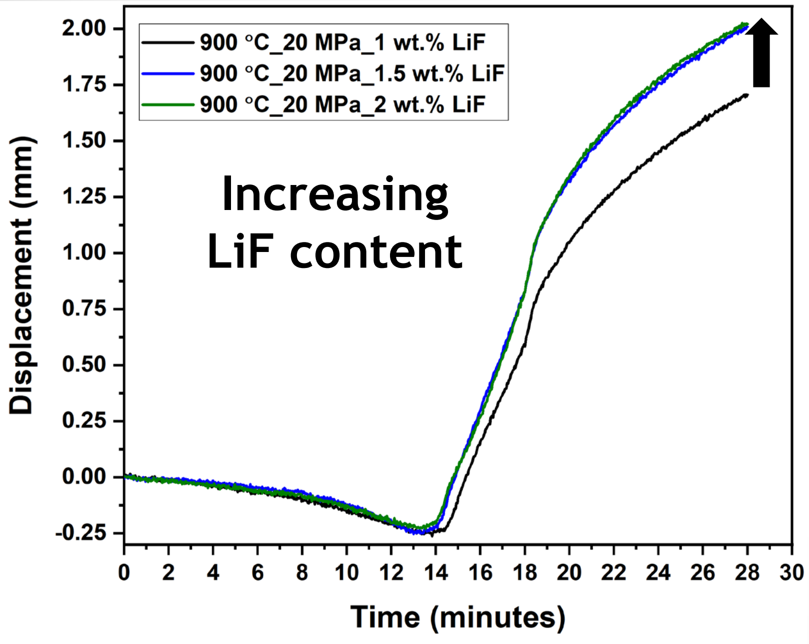
Systematic variation of process parameters for MgO-ZrHx

Parameters varied:

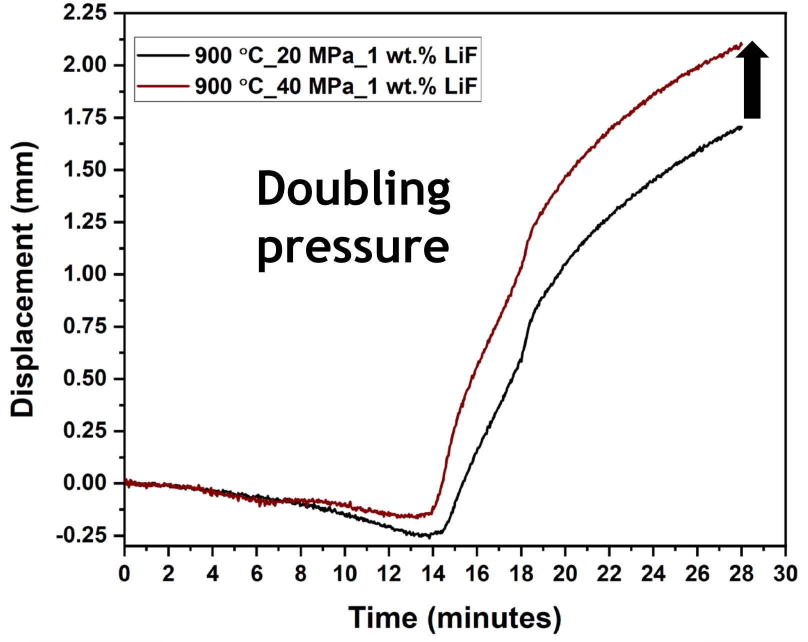
- LiF content
- Sintering pressure
- Sintering temperature

Fixed conditions: 50 °C/min heating rate, 10 min hold, 25 mm graphite die, Ar–5%H_2 atmosphere

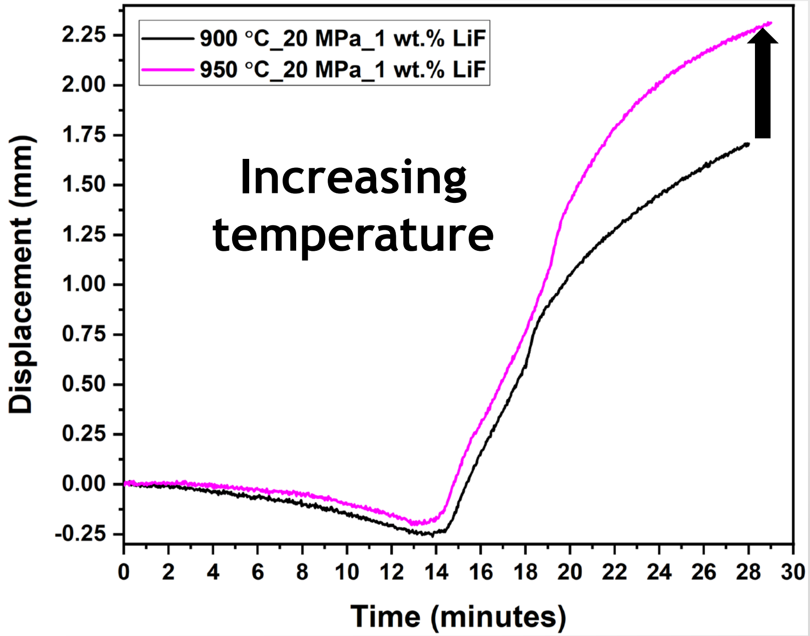
Sintering temperature (°C)	LiF Content (Wt.%)	Sintering pressure (MPa)	Density (g/cm^3)	Relative density (% of ρ_{th}); ρ_{th} = 3.98)
900	1.0	20	3.29	82.66
900	1.5	20	3.40	85.42
900	2.0	20	3.44	86.42
900	1.0	40	3.51	88.19
950	1.0	20	3.70	92.96



Increasing LiF content

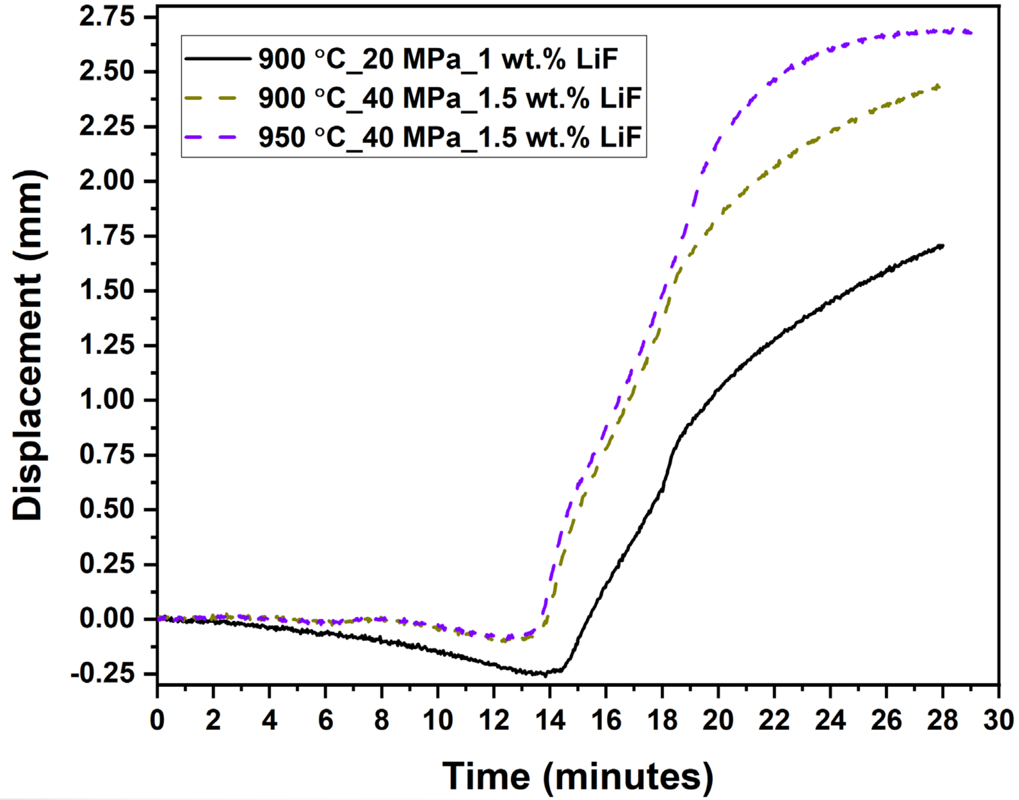


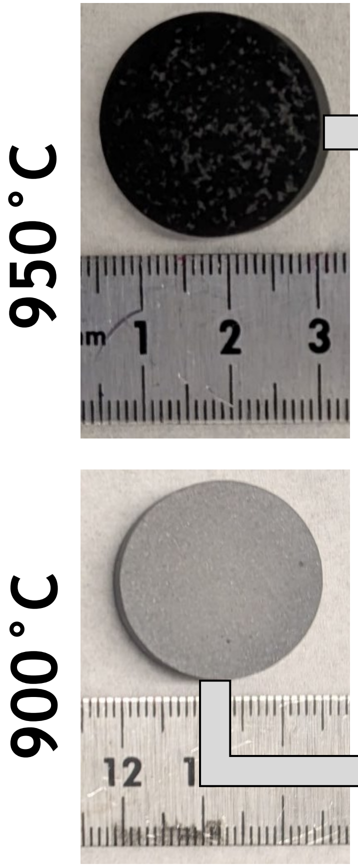
Doubling pressure

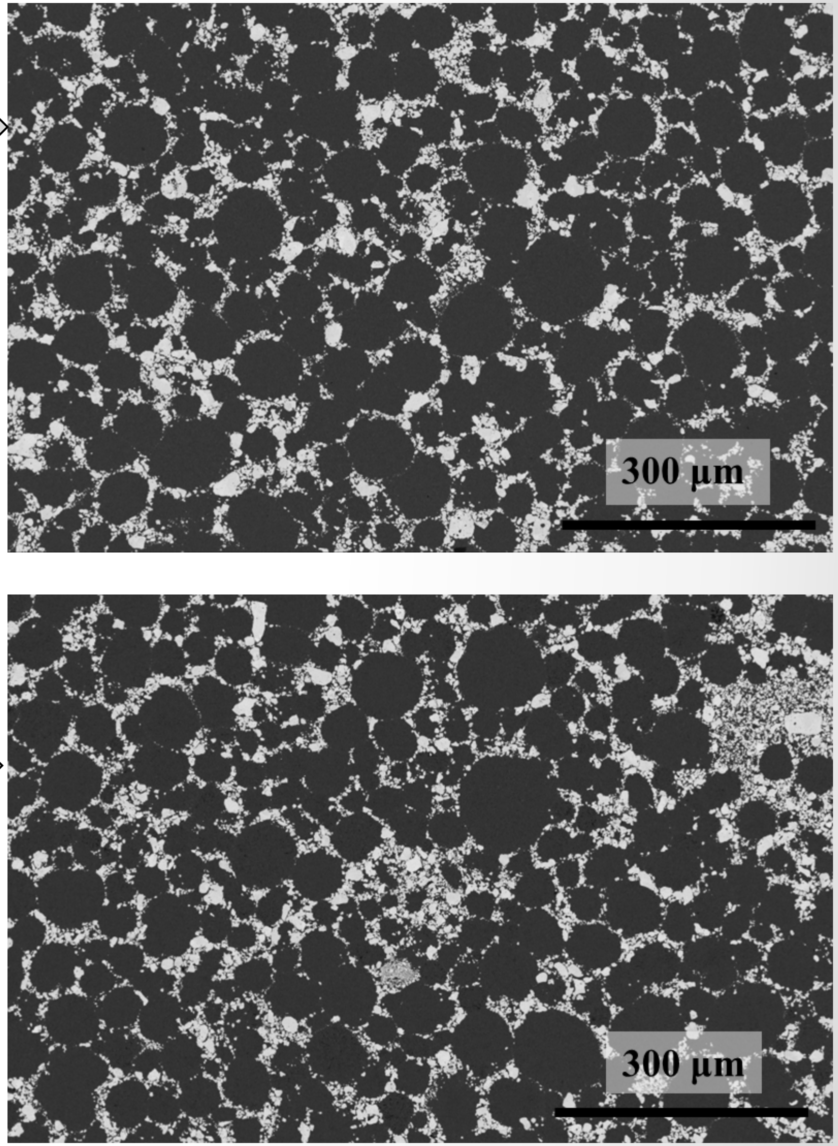


Increasing temperature

Optimized MgO-ZrH_x composites



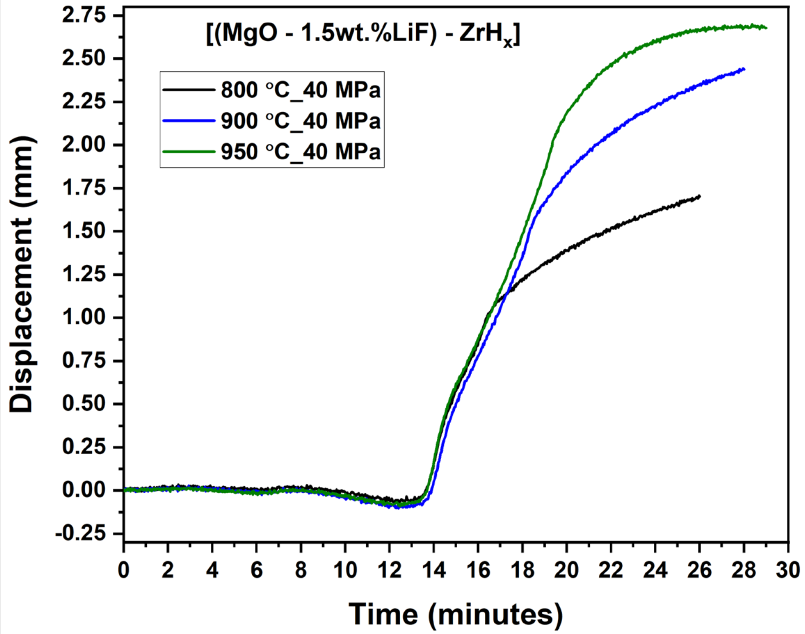


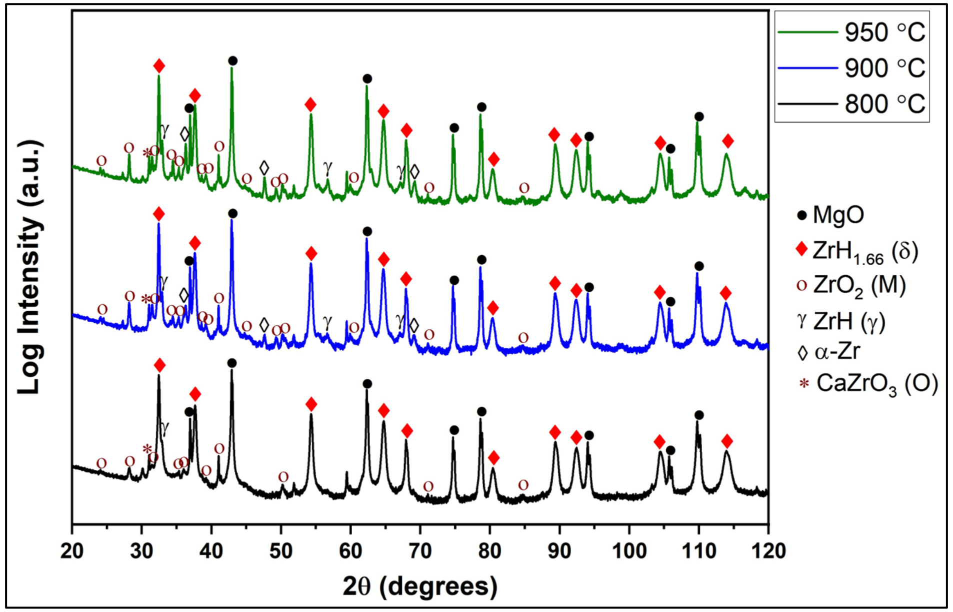


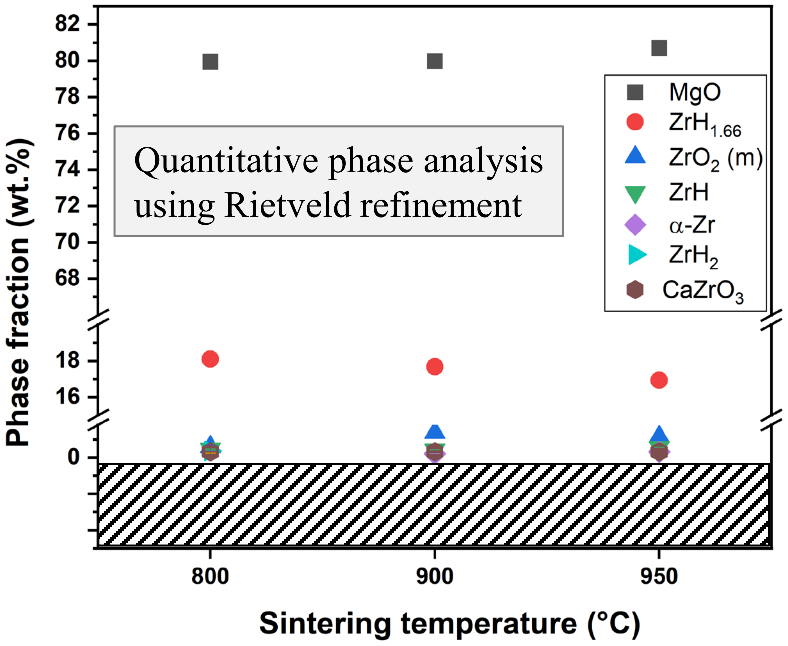
Sintering temperature (°C)	Wt.% LiF (w.r.t. MgO)	Pressure (MPa)	Density (g/cm^3)	Relative Density (%)
900	1.0	20	3.29	82.66
900	1.5	40	3.76	94.47
950	1.5	40	3.93	98.74

Mapping hydride phase stability with sintering temperature

Sintering temperature (°C)	Wt.% LiF (w.r.t. MgO)	Sintering pressure (MPa)	Density (g/cm^3)	Relative Density (% of ρ_{th})
800	1.5	40	3.12	78.39
900	1.5	40	3.76	94.47
950	1.5	40	3.93	98.74





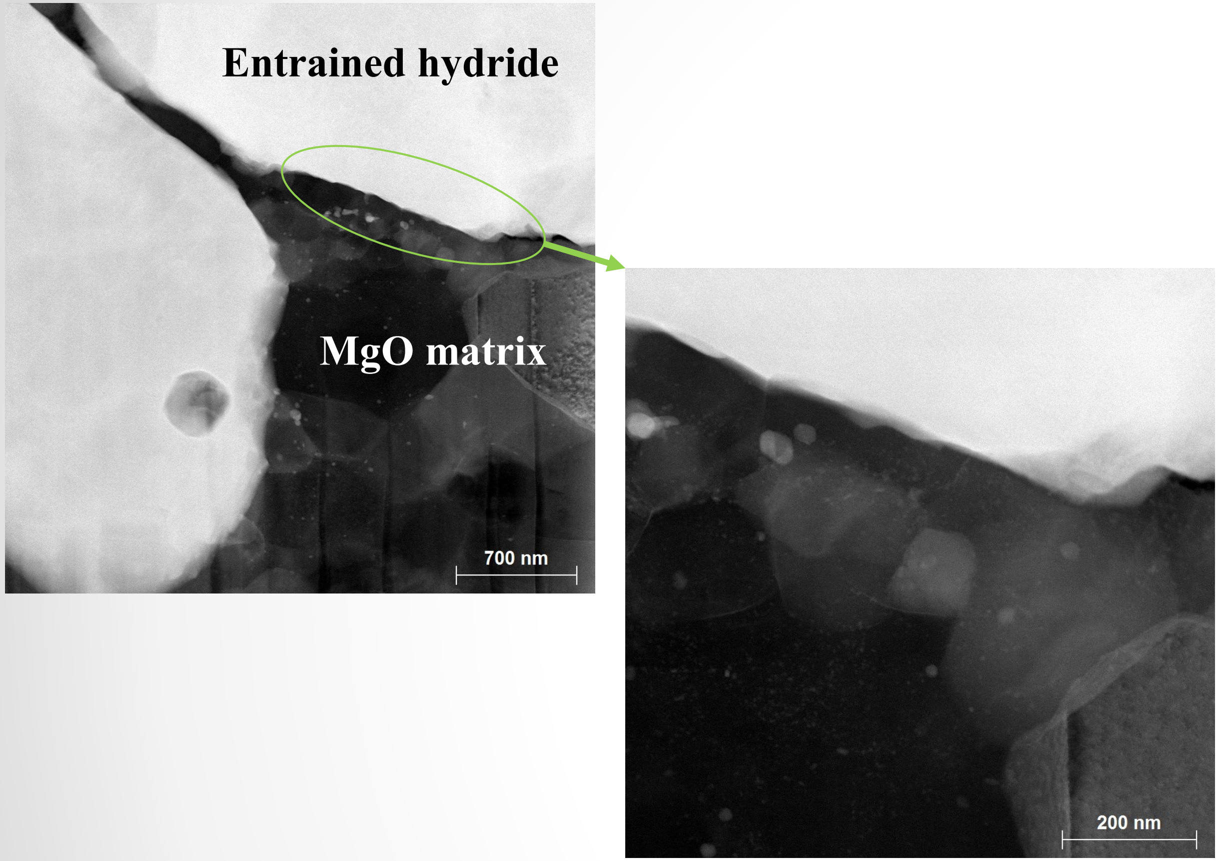


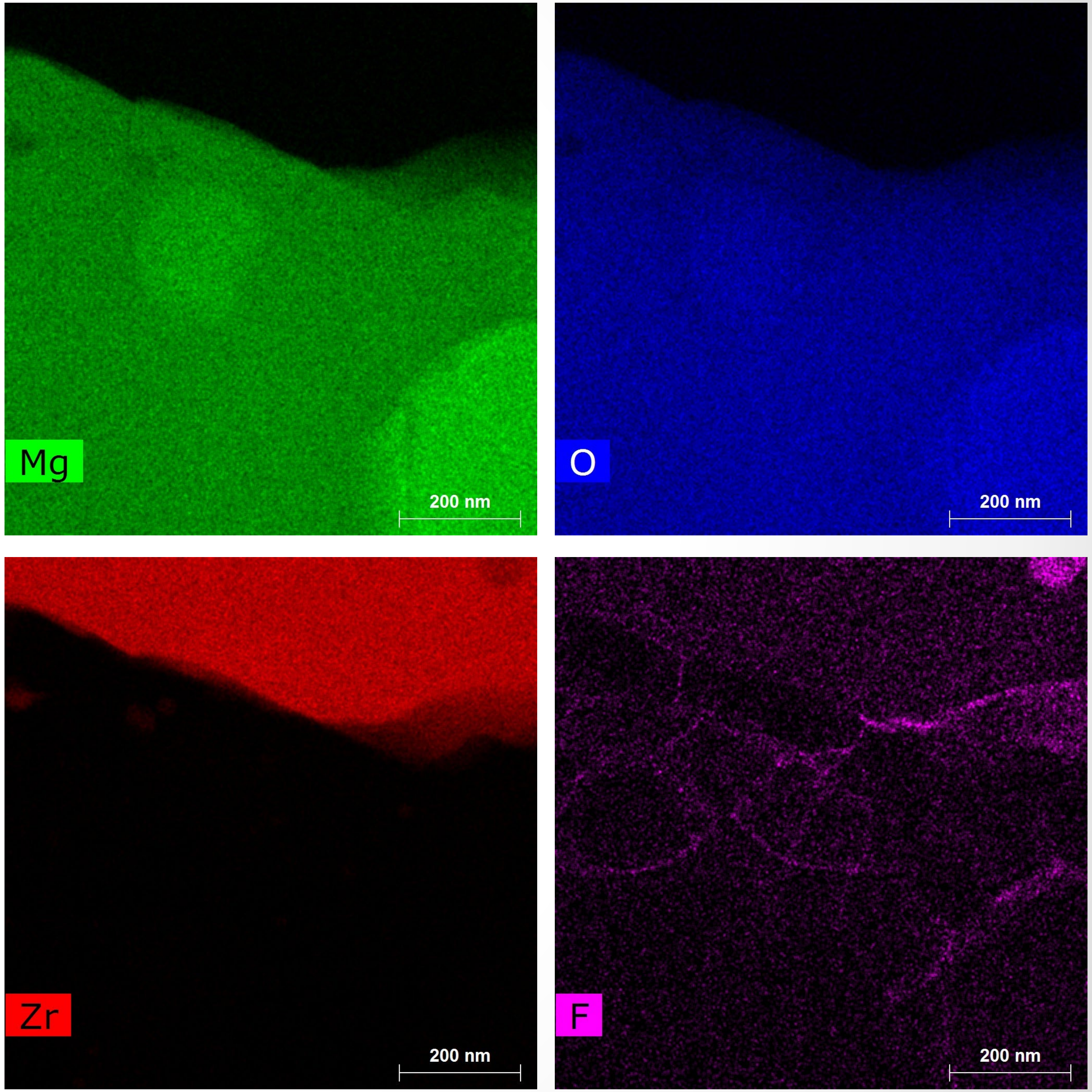
Quantitative phase analysis using Rietveld refinement

ε-ZrH$_2$ (in starting powders) ⟶ δ-ZrH$_{1.66}$ (in as-sintered composites)

Significant hydride retention (~17 wt.%), while achieving near-complete densification (~99%) at 950 °C.

Probing the nature of MgO/hydride interfaces using STEM-EDS

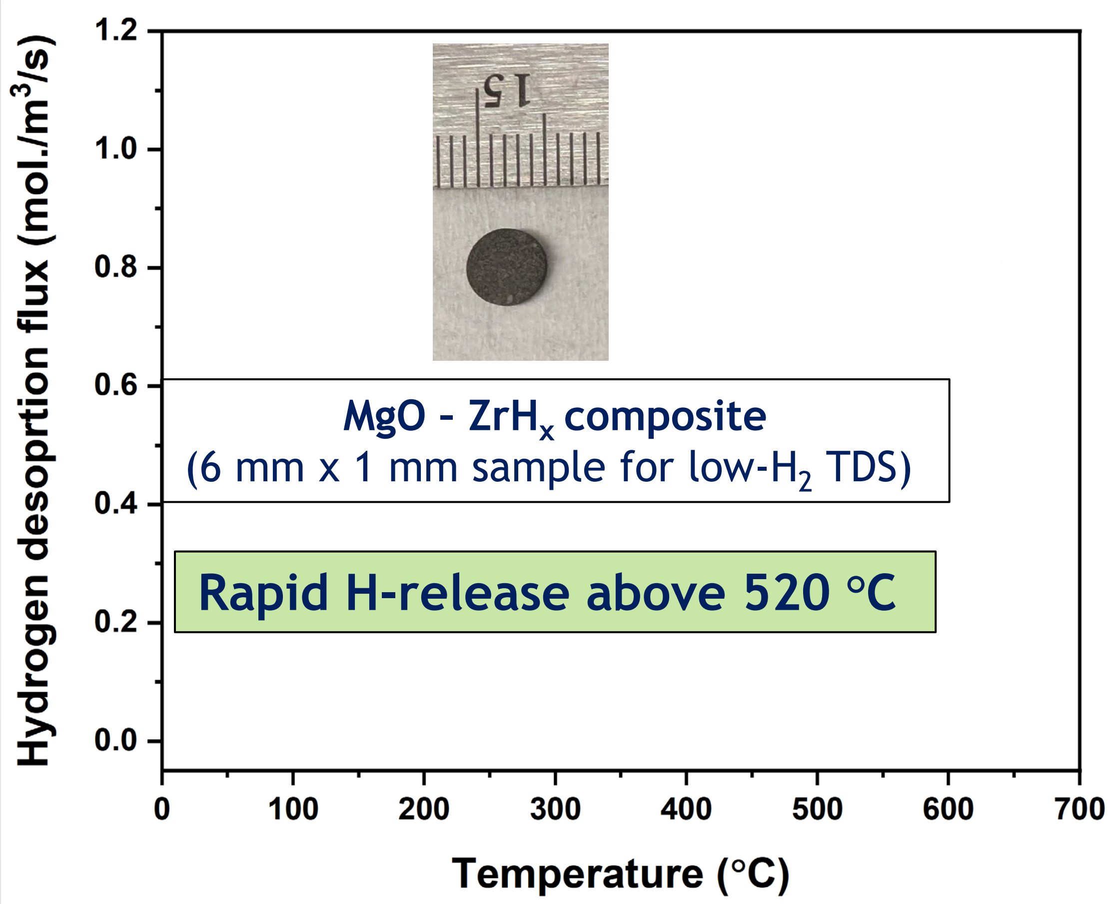




- Interfaces are free of cracking.
- No chemical reaction between MgO and ZrH_x at the phase boundaries interface.

Mitigating H-desorption from surface hydrides of composite moderators

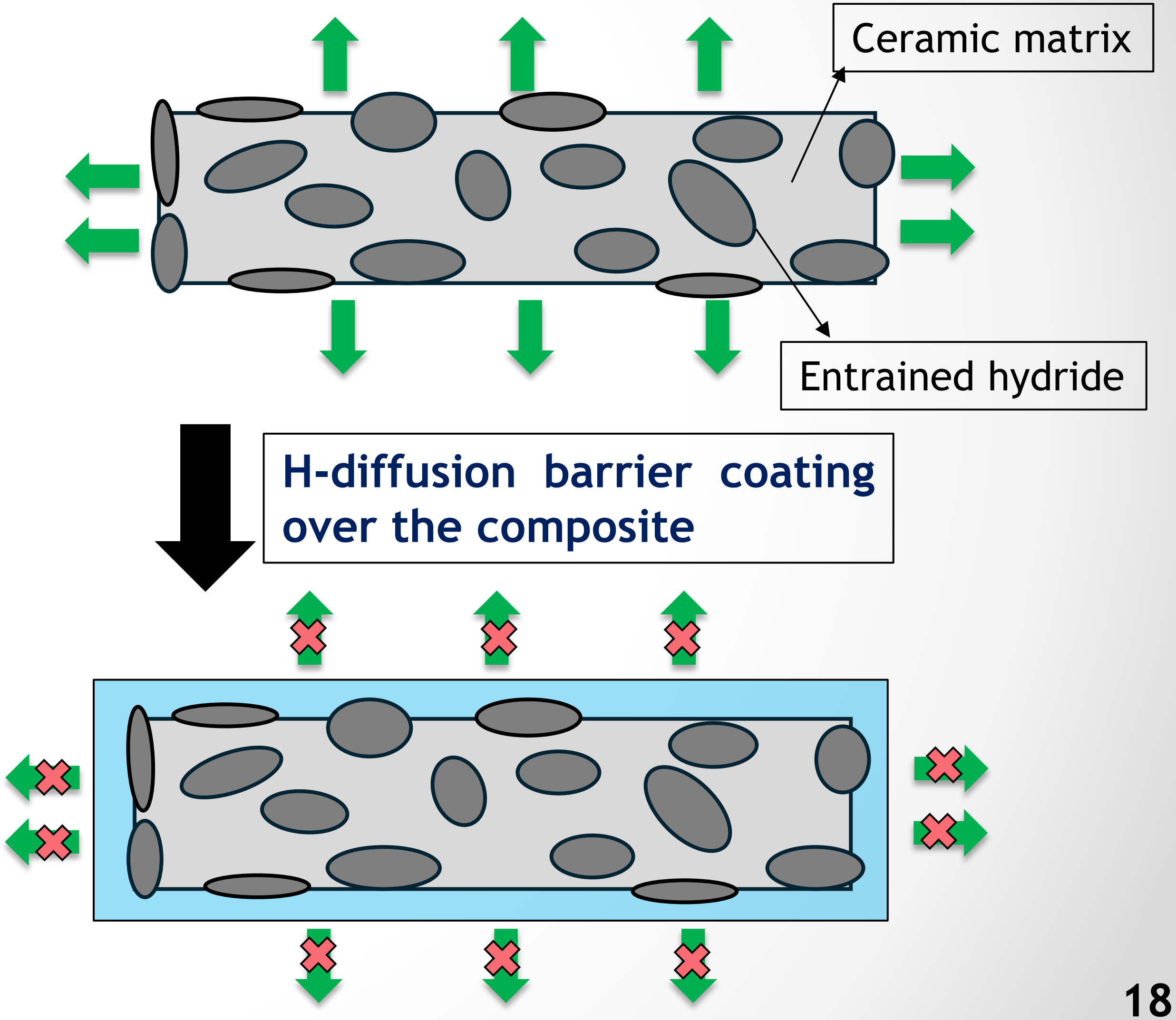
Thermal desorption spectroscopy (TDS) for mapping H-release



MgO - ZrH_x composite
(6 mm x 1 mm sample for low-H_2 TDS)

Rapid H-release above 520 °C

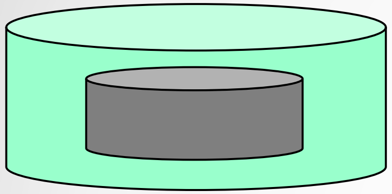
H_2 outgassing from surface-exposed hydrides



H-diffusion barrier coating over the composite

In-situ encapsulation of MgO – ZrHx composites

Cylinder-in-cylinder geometry

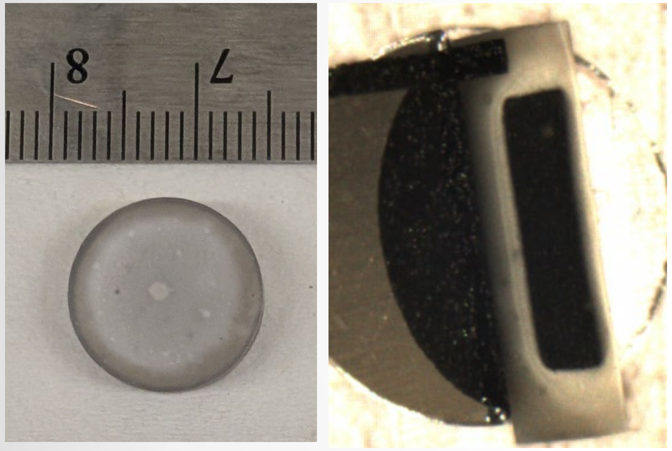


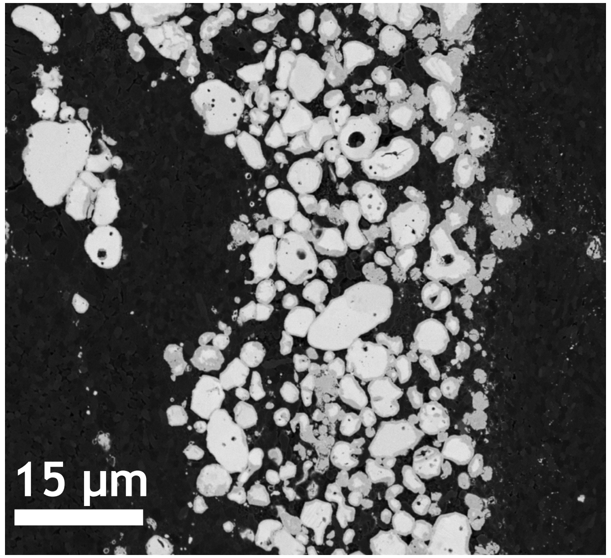
Outer layer: MgO – 1.5 wt.% LiF

Inner core: [(MgO – 1.5 wt.% LiF) – 20 vol.% ZrH_2]

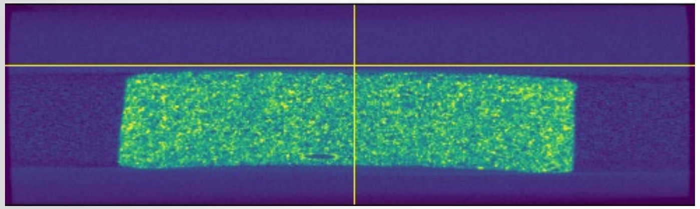
(co-sintered at 950 °C/40 MPa for 10 min)

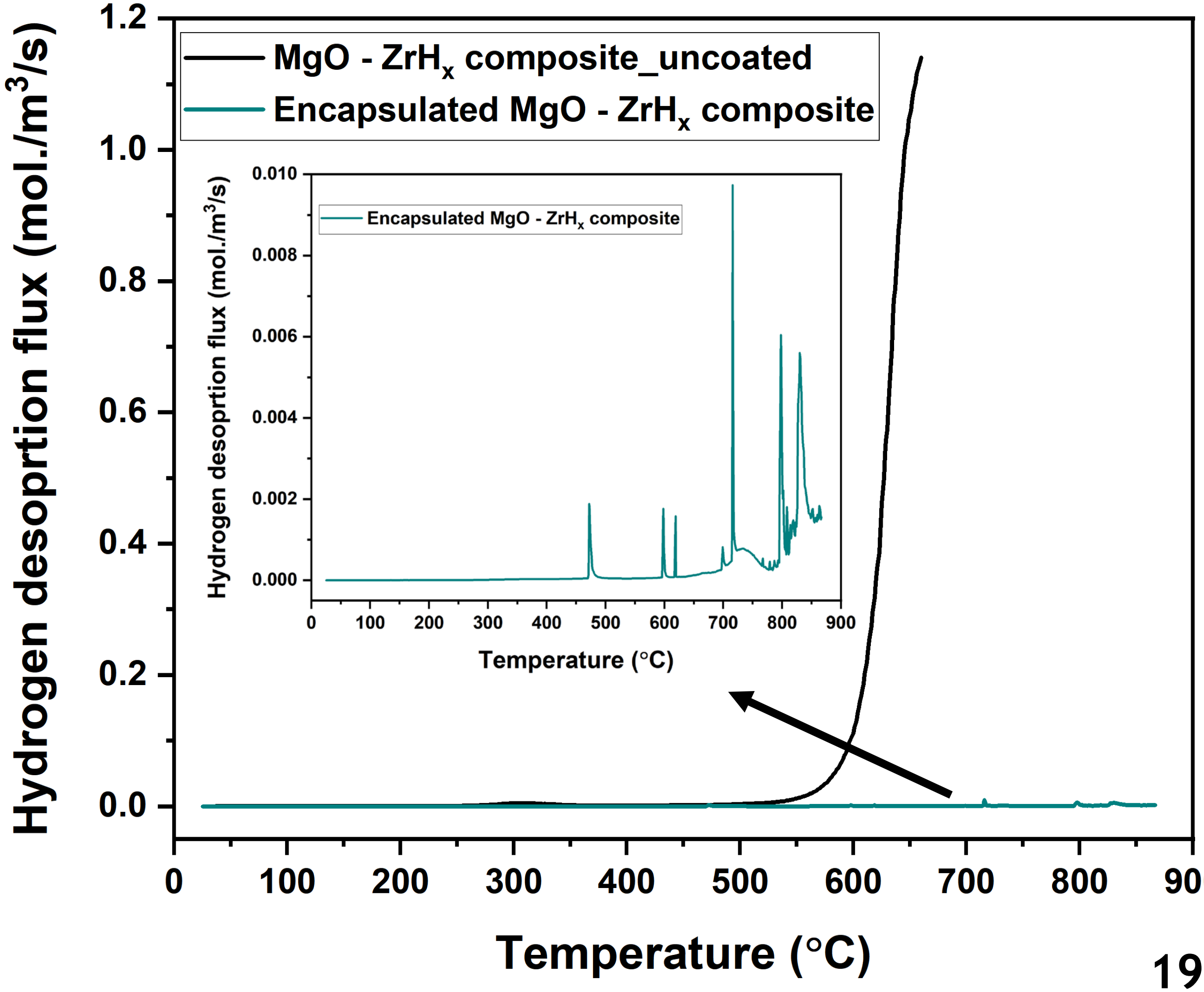
Expanding the operating temperature window to >800 °C





X-ray CT image





Hydrogen migration model in MgO

Stony Brook University

Solid Solution

c_{SS} Concentration gradient (Fick's Law)

T Temperature gradient (Soret Effect)

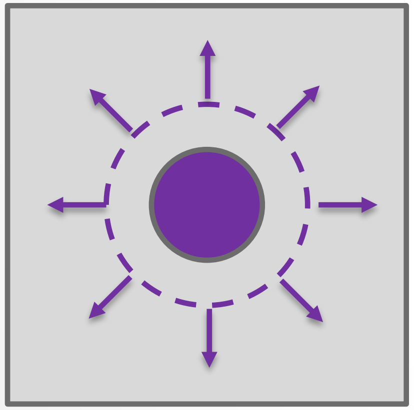
Heat of transport

$$J_{Tot} = J_{Fick} + J_{Soret}$$

$$= -\boldsymbol{D_H}\left(\nabla C_{SS} + \frac{C_{SS}\boldsymbol{Q}^*}{RT^2}\nabla T\right)$$

H interdiffusion coefficient

Hydrides



Kinetic Parameters

Solubility Limit

$$\frac{\partial C_{SS}}{\partial t} = \begin{cases} -K_D(C_{SS} - TSS_D)\,, & C_{SS} < TSS_D \\ -K_G(C_{tot} - TSS_D)p(1-x)\big(-ln(1-x)\big)^{1-1/p}, & TSS_D < c_{SS} < TSS_P \\ -K_N(C_{SS} - TSS_P), & TSS_P < C_{SS} \end{cases}$$

Dissolution

Growth

Nucleation

Super-solubility Limit

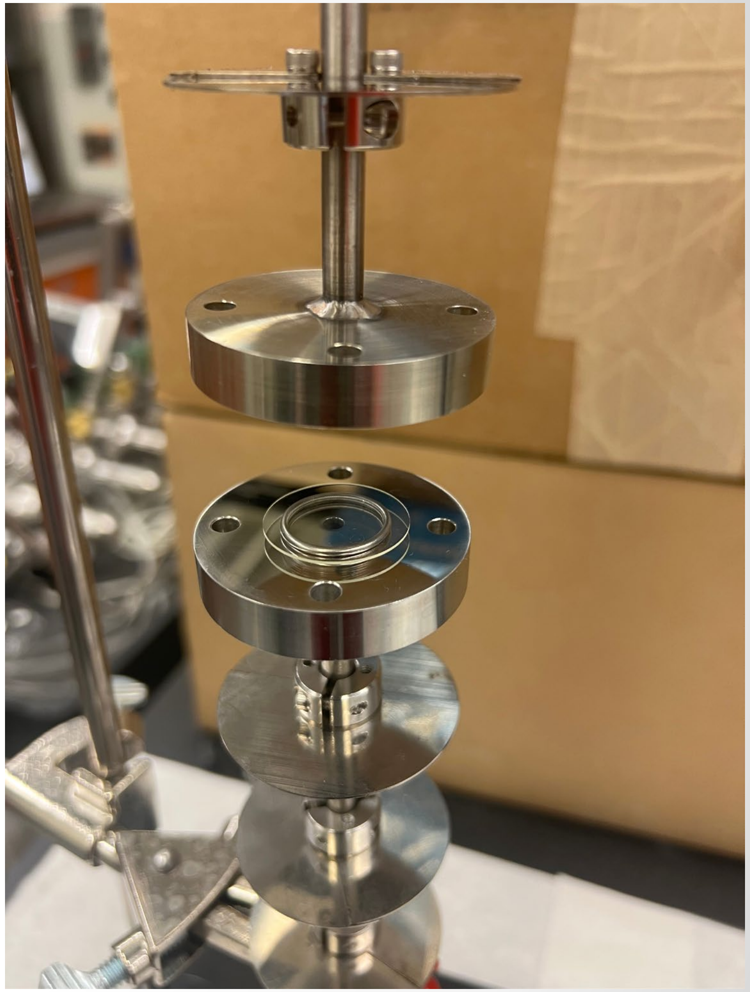
$$x = \frac{C_{tot} - C_{SS}}{C_{tot} - TSS_D}$$

Passelaigue, F., Simon, P. C. A., & Motta, A. T. (2022). Predicting the hydride rim by improving the solubility limits in the Hydride Nucleation-Growth-Dissolution (HNGD) model. *Journal of Nuclear Materials*, *558*, 153363.

Quantifying hydrogen transport: H/D - permeation experiments

Stony Brook University

- The hydrogen permeability is the product of solubility and diffusivity.
- Permeation Side (Permeability):
  - 25 mm sample sandwiched between two SS test sections and two O-rings.
  - Sample contacting K-type TC controls heater
  - Primary pressure recorded with 1000, 30, 1 Torr
  - Permeation measured via pressure build up or dynamically with QMS on secondary side
- Experiments currently being performed for H-transport in MgO single crystals of three different orientations [(100), (110) and (111)].
  - Feb 2026



SGAP test section with MgO single crystal sample (it's transparent!)

Courtesy: Dr. Chase N. Taylor

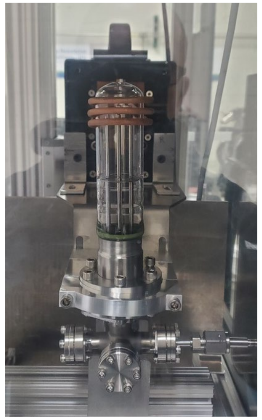
Idaho National Laboratory

Samples provided to INL for hot vacuum extraction

- Goal to measure hydrogen concentration (# of moles of H_2 released) across a range of concentrations.
- Scheduled for April 2026

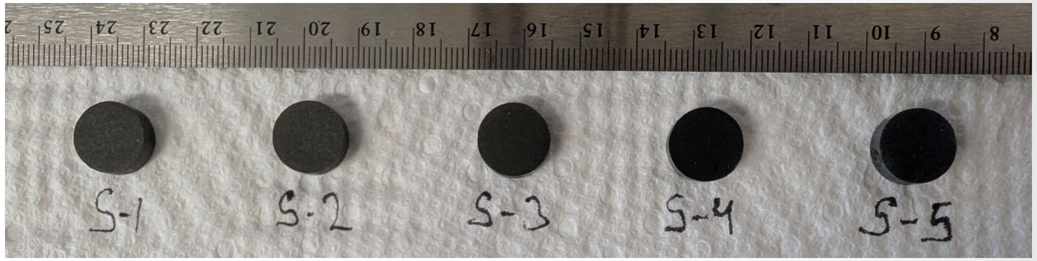
How it works: $n = \frac{RT}{PV}$ (ideal gas)

Measure gas temperature (T)
Calibrated system volume (V)
➢Calculate the number of moles (n) of H_2 released from sample.



HVE furnace

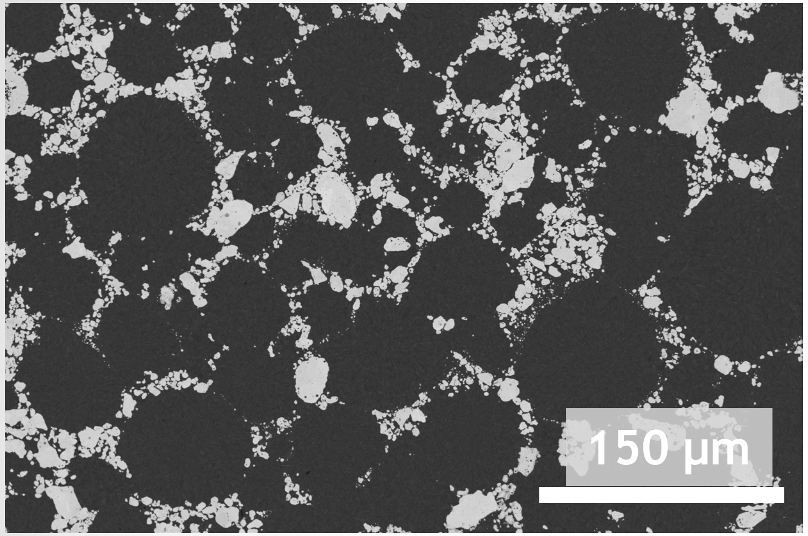
- As-sintered samples (13 mm dia. and 5.4 mm height) were ground and roughly polished on both sides to reduce the thickness to ~4 mm
- 5 test samples have been sent to INL for the HVE experiments



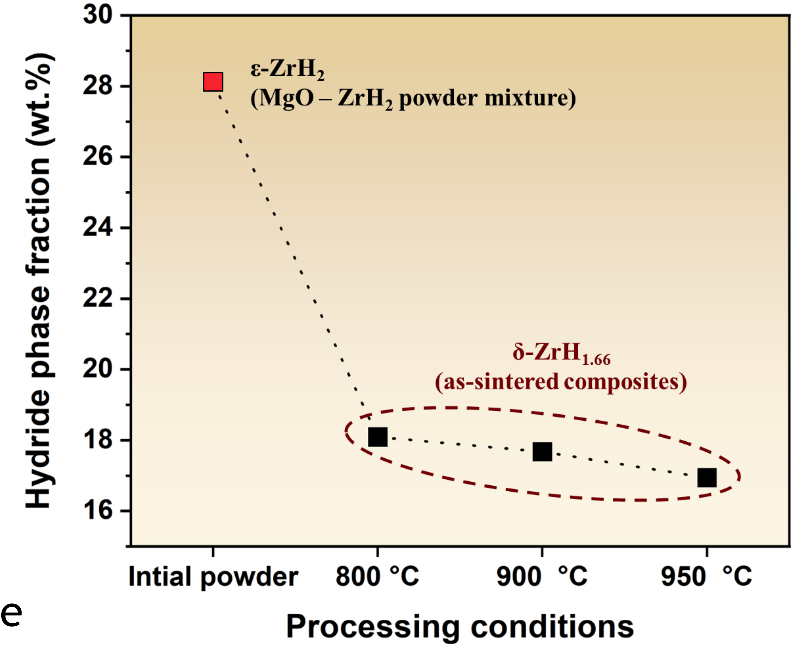
	Diameter (mm)	Height (mm)	Archimedes' Density (g/cm^3) (ρ_{th} = 3.98 g/cm^3)
S1	13.10	4.09	3.94 (99 % ρ_{th})
S2	13.08	3.90	3.94 (99 % ρ_{th})
S3	13.10	3.93	3.94 (99 % ρ_{th})
S4	13.04	4.06	3.91 (98 % ρ_{th})
S5	13.07	4.07	3.92 (98 % ρ_{th})

Summary: Composite Solutions for Enabling Hydride Moderators

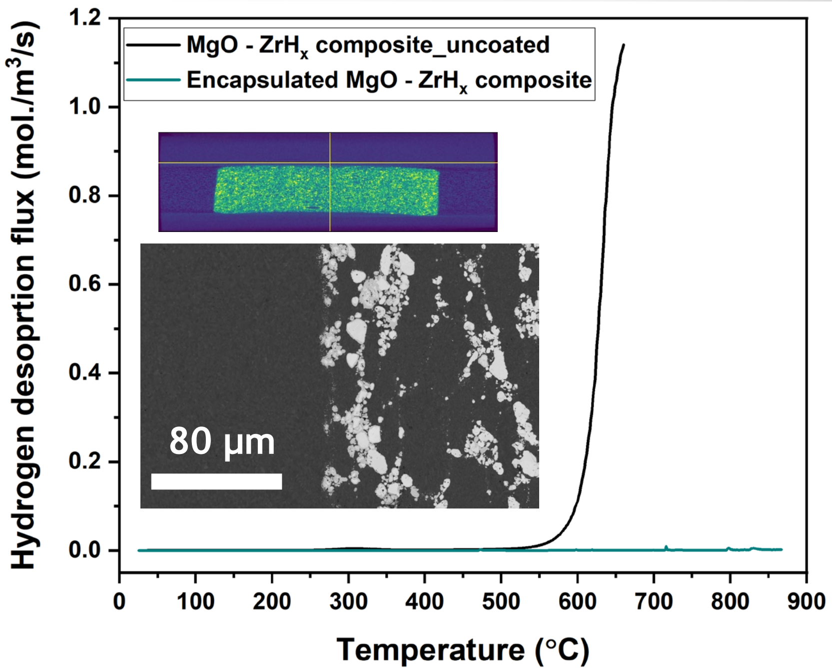
A viable processing pathway toward development of robust entrained-hydride ceramic composite moderator has been successfully demonstrated with engineered barriers to hydrogen release.



Dense (~99% ρ_{th}) and uniform microstructure



Retention of ~17wt.% $ZrH_{1.66}$ under optimized processing conditions



Prevention of H-outgassing via encapsulation, enabling high temperature moderator applications.

[Gurnani *et al.*, Manuscript to be submitted, *J. Nucl. Mater.*]

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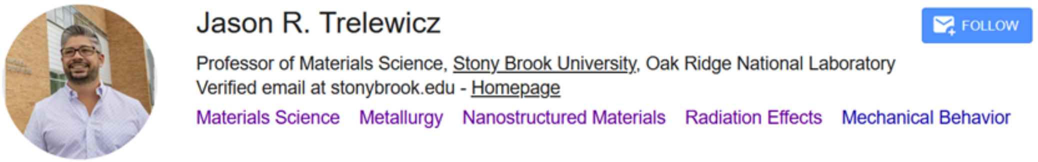

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