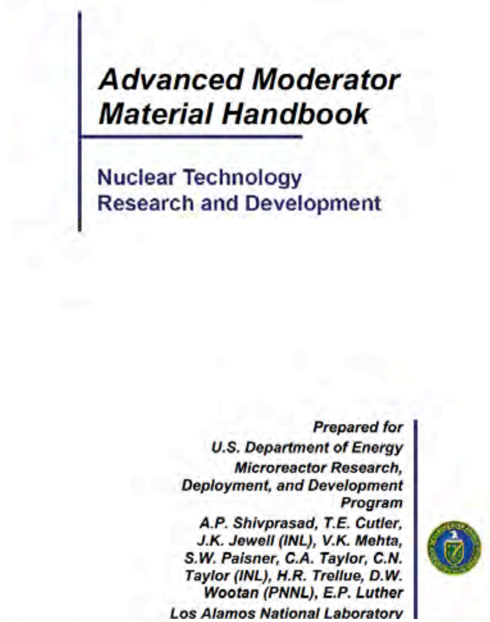
LANL High Temperature Moderator update

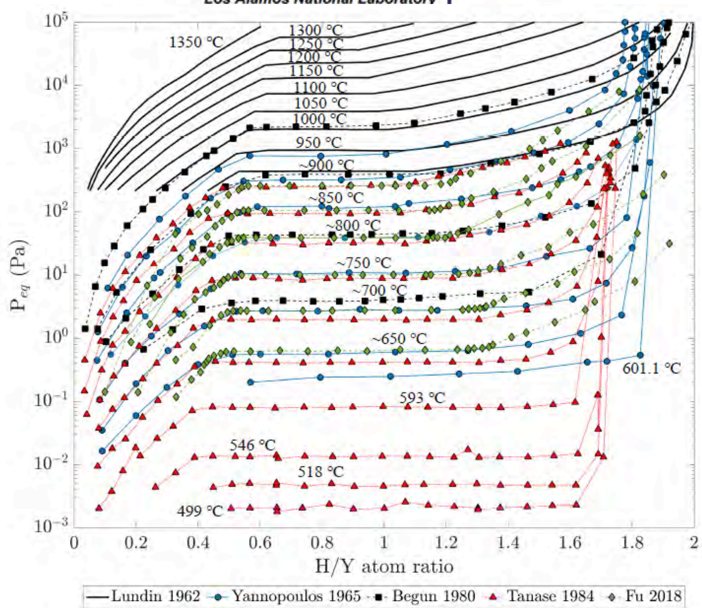
03/06/2024

A.P. Shivprasad

LA-UR-24-21660

Advanced Moderator Material Handbook overview





The original scope of the Handbook was to provide scientists and reactor designers with a set of physical and thermal property data for yttrium hydride. It originally included the following:

- Yttrium-hydrogen phase crystallography and thermodynamics of formation
- Yttrium hydride thermophysical properties including heat capacity, thermal expansion, and thermal conductivity
- Yttrium hydride mechanical properties
- Summary of hydrogen diffusion properties
- Neutronic considerations
- Fabrication techniques
- Historical irradiations in FFTF
- Introductions to ATR irradiations and NCERC critical test

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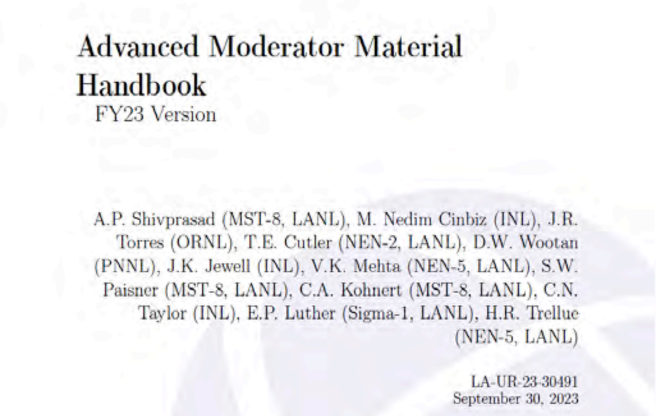
Advanced Moderator Material Handbook update, FY23 version



Advanced Moderator Material Handbook
FY23 Version

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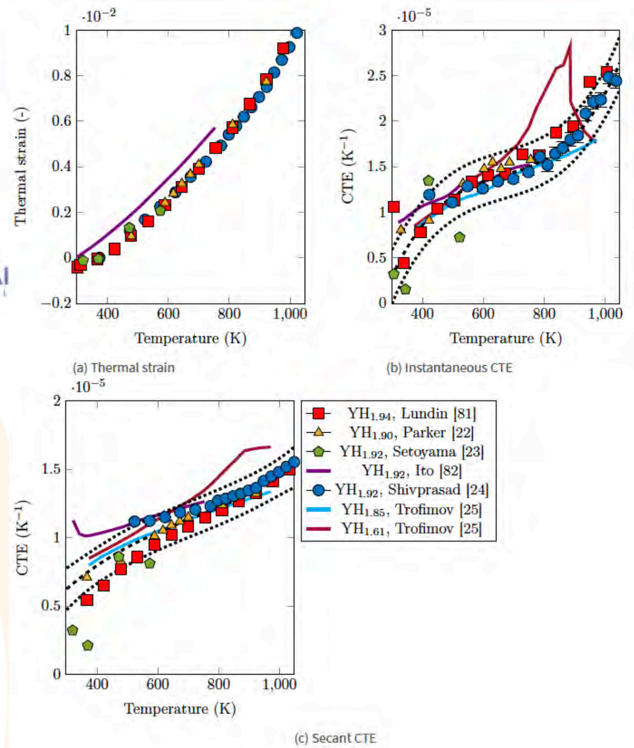
LA-UR-23-30491
September 30, 2023



The Advanced Moderator Material Handbook FY23 update focused on adding the following

- PIE data from ATR irradiation
- Summary of the NCERC critical experiment
- New sections summarizing critical manufacturing and research needs to advance the MRL and TRL of yttrium hydride
- New sections describing physical properties in greater detail based on feedback from researchers
- Newly published data between Sept. 2022 and Sept. 2023 including elastic moduli as a function of temperature
- Expanded H diffusion section to include the state of knowledge for metal hydrides in general

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Post Irradiation Examination of Yttrium Hydride Moderator

March 6, 2024

Chase N. Taylor, M. Nedim Cinbiz, Thomas A. Johnson

Idaho National Laboratory

Acknowledgments

- **Joey Charbonneau and Dr. Ian Hobbs** for specimen management, physical property measurements, and hydrogen content measurements at Analytical Research Laboratory (ARL)
- **Jatu Burns, Kourtney Wright** for metallography and microstructure characterization at Electron Microscopy Laboratory
- **Dr. Scott Middlemas, Dr. Poudel Narayan, Dr. Tsvetoslav Pavlov** for thermal property measurements at ARL and Irradiated Materials Characterization Laboratory (IMCL)
- **Glen Papaioannou** for neutron radiography at Hot Fuels Examination Facility
- **Rafael Garcia** for x-ray diffraction measurements at IMCL
- **John Stanek** for capsule disassembly and sample retrieval from the irradiation vehicles

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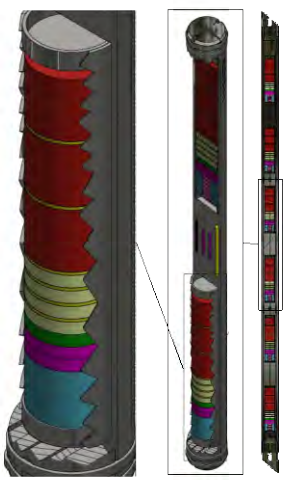
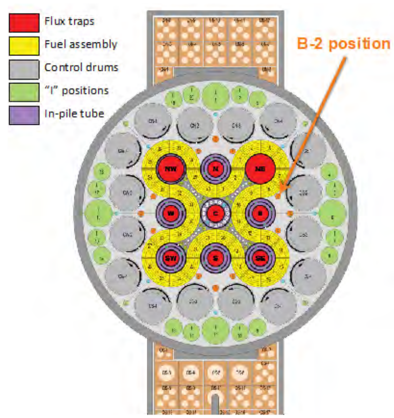
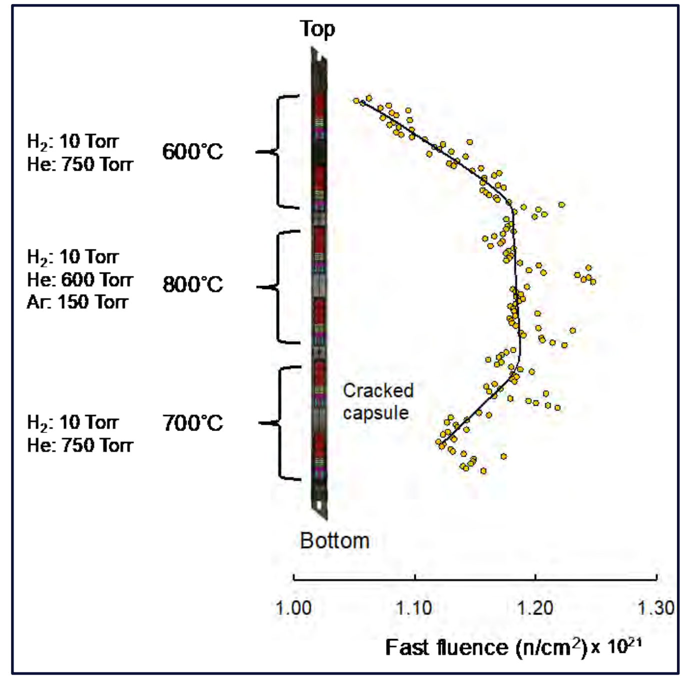
Advanced Test Reactor Irradiation (ATR) (FY'21)

- ***Samples* | *102 yttrium hydride specimens* | *36 TZM foils***
- ***Two fabrication paths* | *Direct hydriding and Powder metallurgy***
- ***Target temperatures* | *600, 700, and 800˚C***
- ***Irradiation conditions* | *60 full power days***







PIE focuses on the structural stability and predictable behavior of moderator

Post-Irradiation Examination Activities

1- Geometrical and structural stability

- Neutron radiography, visual examination of assemblies, capsules, and samples
- Metallography and electron microscopy of yttrium hydride

2- Predictable behavior

Assessment of hydrogen behavior/content

- Hydrogen content measurement to assess hydrogen content
- X-ray diffraction measurements to assess hydride and metal phases

Thermal properties

- Thermal diffusivity and heat capacity investigations
- Dilatometry for thermal expansion measurements were not included in the PIE due to dose limitations of the facilities

Major goal is to determine a hydrogen assessment metric for irradiated yttrium hydride

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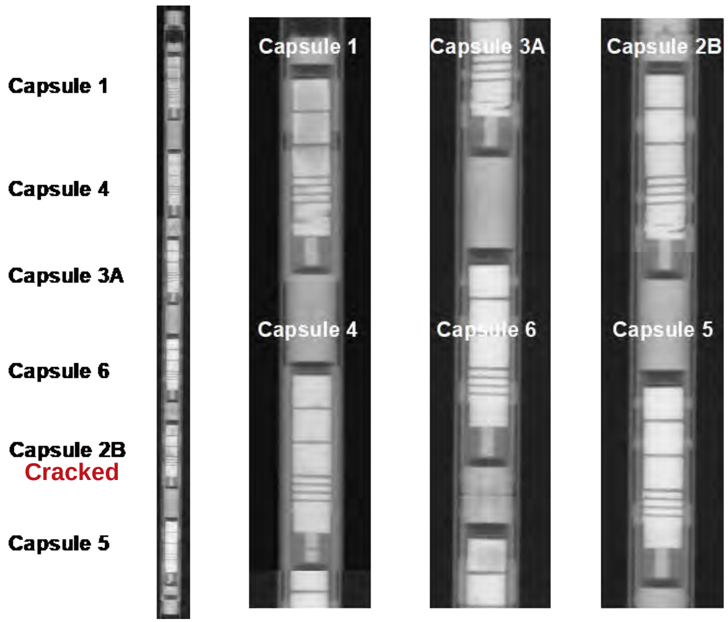
Geometrical and Structural Stability: Neutron Radiography & Visual Examinations



After capsule opening

Specimen name	Capsule identifications					
	600-1	700-2B	800-3A	600-4	700-5	800-6
RUS1	Intact	Intact	Intact	Intact	Intact	Intact
RUS2	Intact	Intact	Intact	Intact	Intact	Intact
RUS3	Intact	Intact	Intact	Intact	Intact	Intact
GDOES1	Intact	Intact	Intact	Powdered	Intact	Intact
GDOES2	Intact	Intact	Intact	Powdered	Intact	Intact
GDOES3	Intact	Intact	Intact	Powdered	Bonded to TZM	Intact
GDOES4	Intact	Intact	Intact	Powdered	Intact	Intact
GDOES5	Intact	Intact	Broken	Powdered	Intact	Intact
TEM1	Intact	Intact	Intact	Intact	Intact	Intact
LFA1	Intact	Intact	Broken	Intact	Intact	Intact
LFA2	Intact	Intact	Intact	Intact	Intact	Intact
DSC1	Intact	Intact	Bonded together	Intact	Intact	Intact
DSC2	Intact	Intact		Intact	Intact	Intact
DSC3	Intact	Intact		Intact	Intact	Intact
DSC4	Intact	Intact	Bonded together	Intact	Intact	Intact
DSC5	Intact	Intact		Intact	Broken	Intact
DSC6	Intact	Intact	Intact	Intact	Intact	Intact

INL-RPT-22-68084

Neutron radiography provides an essential information on the geometrical and structural stability

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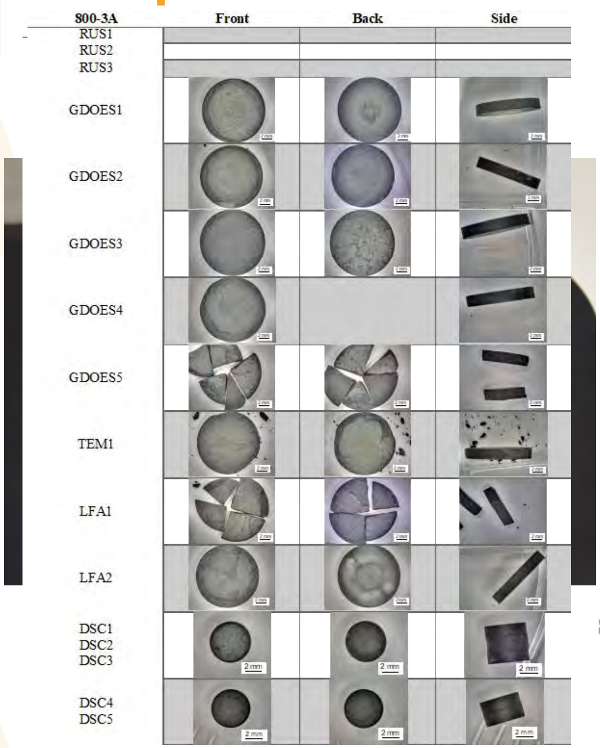
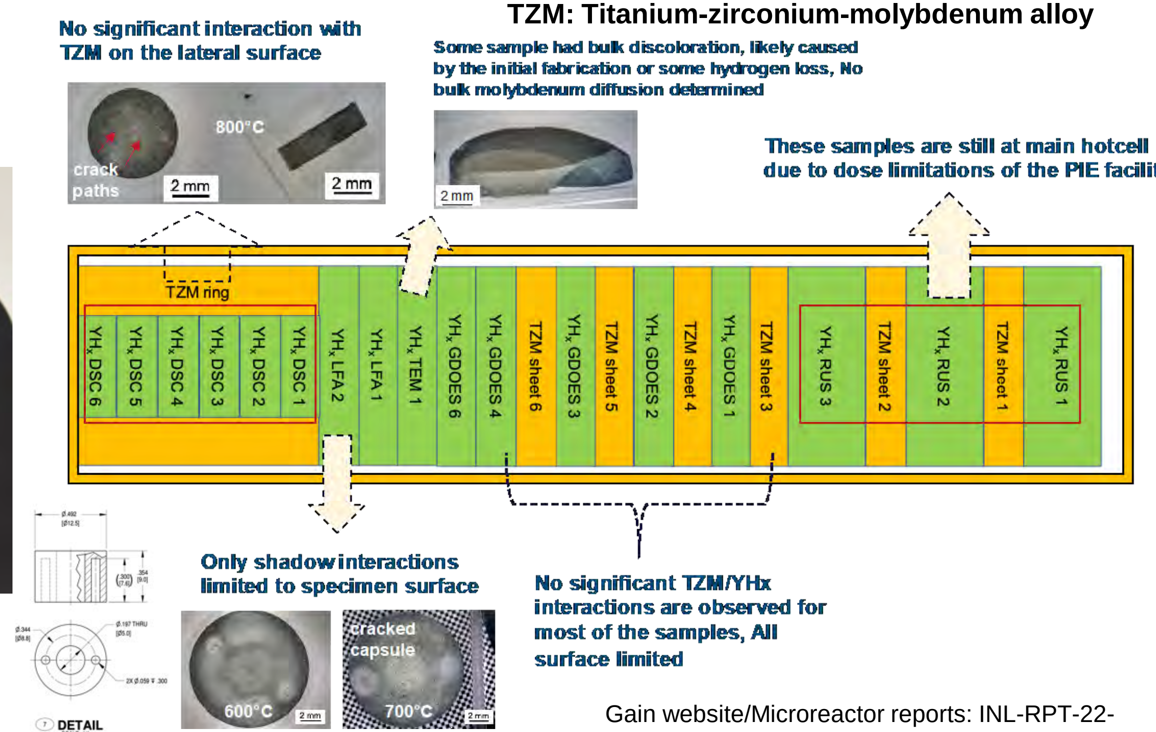
Geometrical and Structural Stability: Optical Examinations of Samples



TZM: Titanium-zirconium-molybdenum alloy



Gain website/Microreactor reports: INL-RPT-22-68084

No critical TZM/YHx interaction was determined, most of the interaction was limited to the hydride surface

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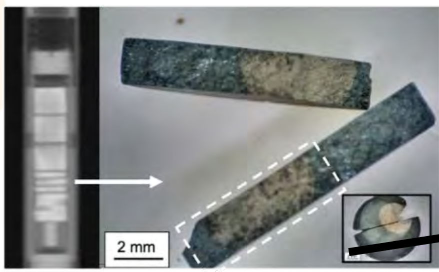
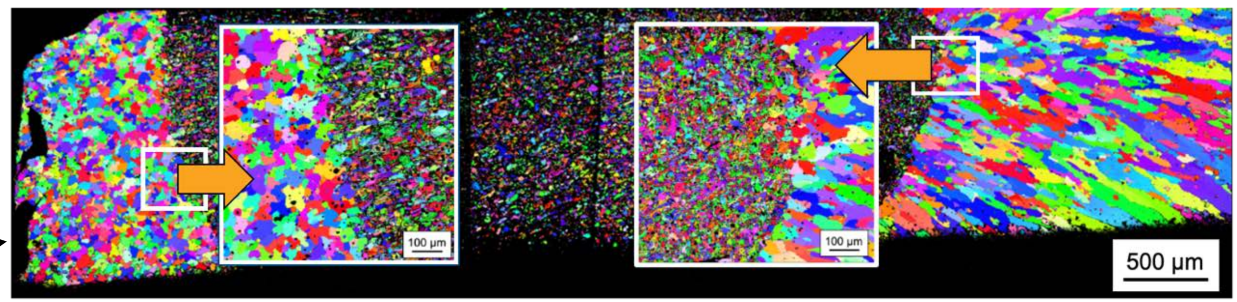
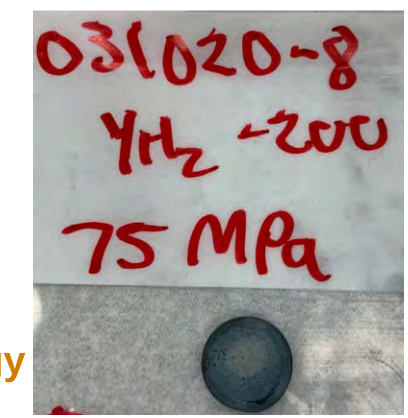
Neutron Radiography → Visual Examinations → Electron Microscopy

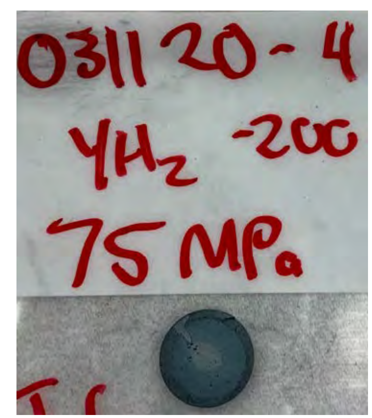
Grain shape and size abruptly changes at regions where color alteration is observed





Neutron radiography suggests these locations are the same regions where less H is present in the hydride





Color variations are related to the grain morphology and hydrogen content

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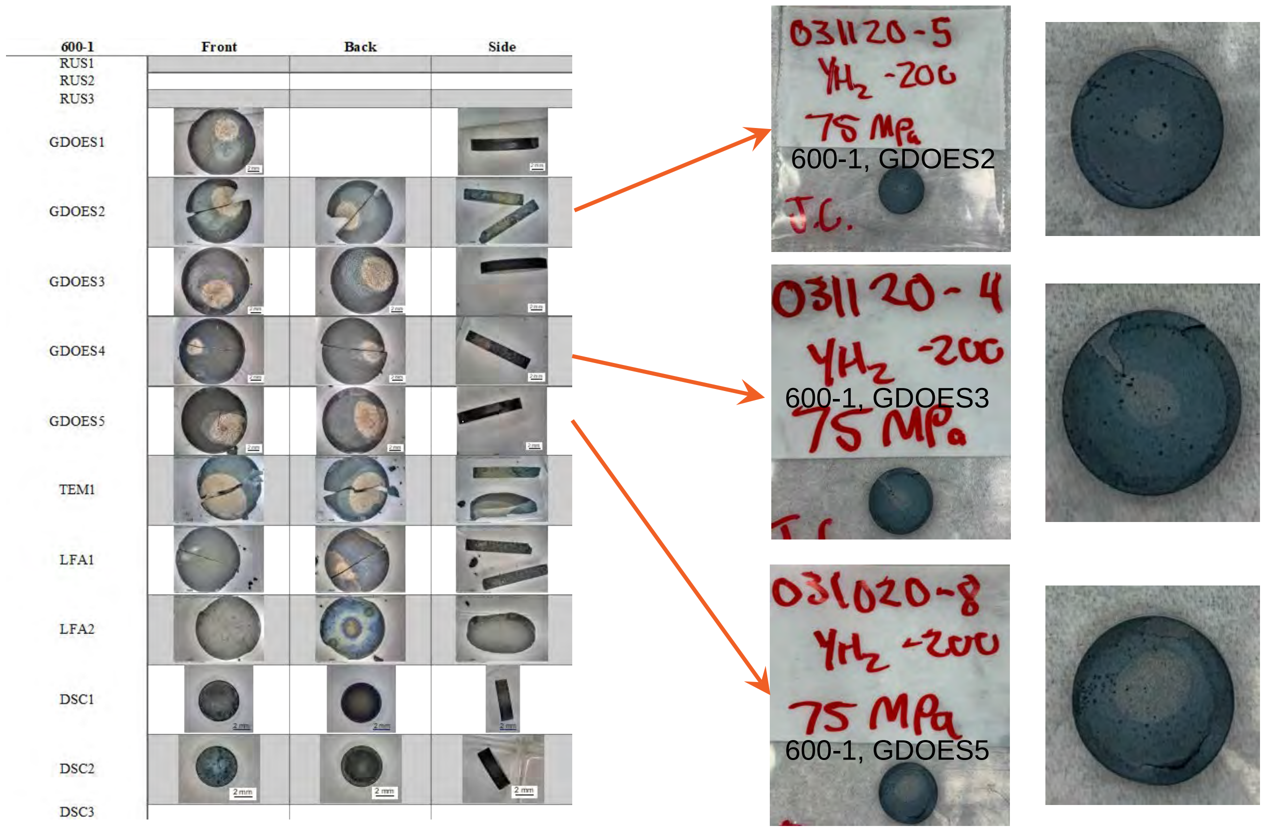
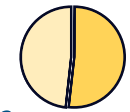
Sample discoloration observed in as-fabricated condition

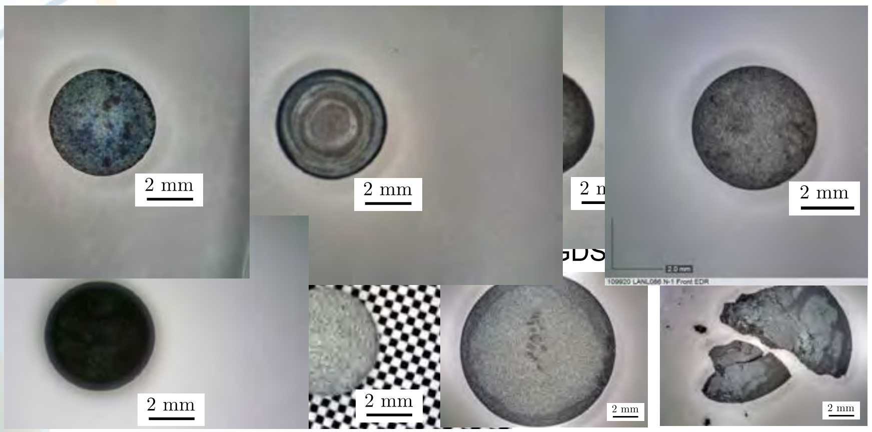


Color variations are related to the grain morphology and hydrogen content

Hydrogen Content Measurements Using Inert Gas Fusion (IGF) Results



Hydrogen content measurements and XRD performed on the same specimen



Capsule	Sample	T (°C)	Fabrication	Initial H (ppm)	Final H (ppm)	XRD Volume fractions (%)			
						YOF	Y_2O_3	Y	YH_2
600-1	DSC2	600	PM	—	22400	11.01	11.98	2.42	73.38
600-4	DSC2	600	MH	20605	22100	0.13	16.41	9.28	74.18
700-2B	DSC2	800	PM	—	18200	2.40	6.19	23.58	67.04
700-2B	GDS2	800	PM	—	15400	0.86	21.52	23.97	53.41
700-5	DSC2	800	MH	18377	22400	0.90	3.40	45.81	49.90
800-3A	DSC2	800	PM	—	17000	4.85	32.87	12.08	49.23
800-6	DSC2	800	MH	—	16300	1.03	0.98	79.15	18.83
800-6	GDS2	800	MH	20493	21200	3.40	2.10	14.65	79.08

- H content highly variable.
- Good correlation between XRF and IGF results.

Uncertainty (6-14%) reduction for the hydrogen content measurements is important to assess hydride moderators

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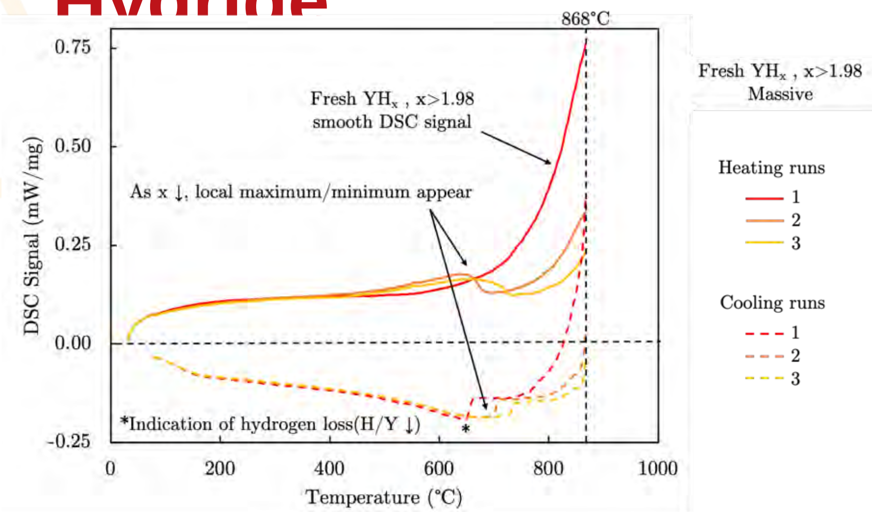
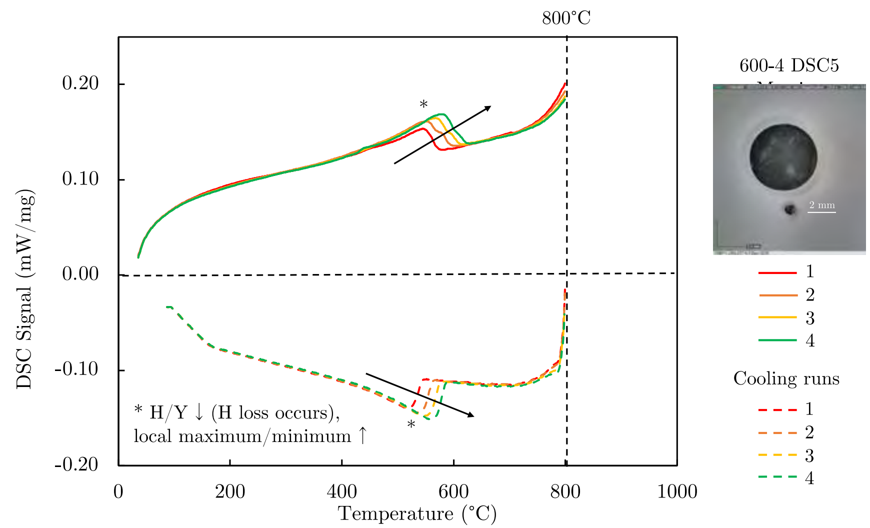
Typical Differential Scanning Calorimetry (DSC) Data of Fresh and Irradiated Yttrium Hydride





Thermal diffusivity data was also measured and reported

Observed local maximum or minimums in the DSC signal is due to hydrogen loss where H/Y reduces

Main Takeaways Are:

- *PIE indicates yttrium hydride maintains good structural stability under irradiation.*
- *A metric is needed to understand hydrogen retention in irradiated hydride which informs the hydrogen permeation resistant cladding development*
- *Hydrogen redistribution needs attention depending on the moderator design*
- *Each hydrogen assessment method has its own challenges, like IGF and lab-XRD*
- *Hot-vacuum extraction with mass spectroscopy is preferred for direct hydrogen measurements*
- *It is promising that thermal properties can be used as hydrogen retention signature for bulk irradiated samples*

Cladding technologies are needed to ensure the long-term moderator performance