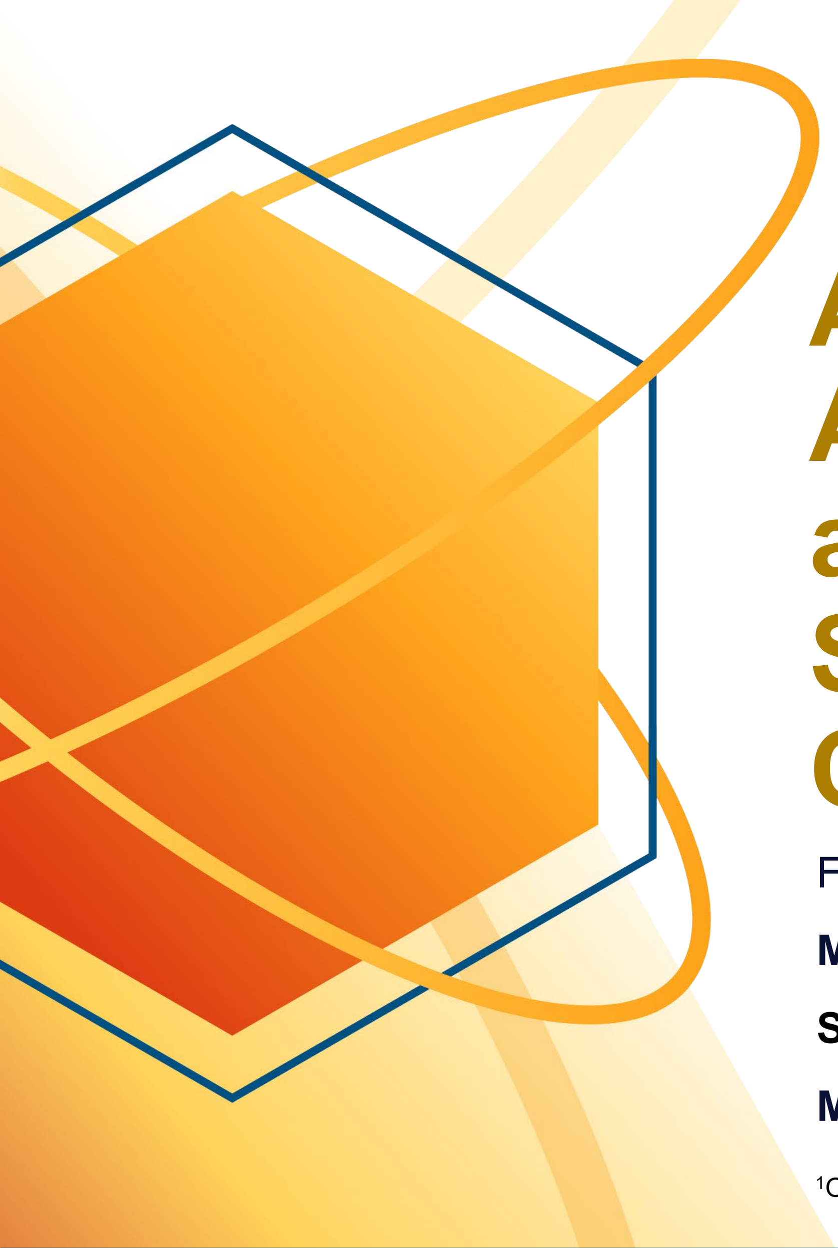


An Overall Assessment of ATR and HFIR Irradiated Samples and Conclusions

February, 2026

M Nedim Cinbiz[1], Annabelle Le Coq[1], Kory Linton[1],

Shaileyee Bhattacharya[1], Yan-Ru Lin[1],

Mobashera Saima Haque[2], David Sprouster[2]

[1]Oak Ridge National Laboratory, [2]Stony Brook University

INL Idaho National Laboratory

Oak Ridge National Laboratory

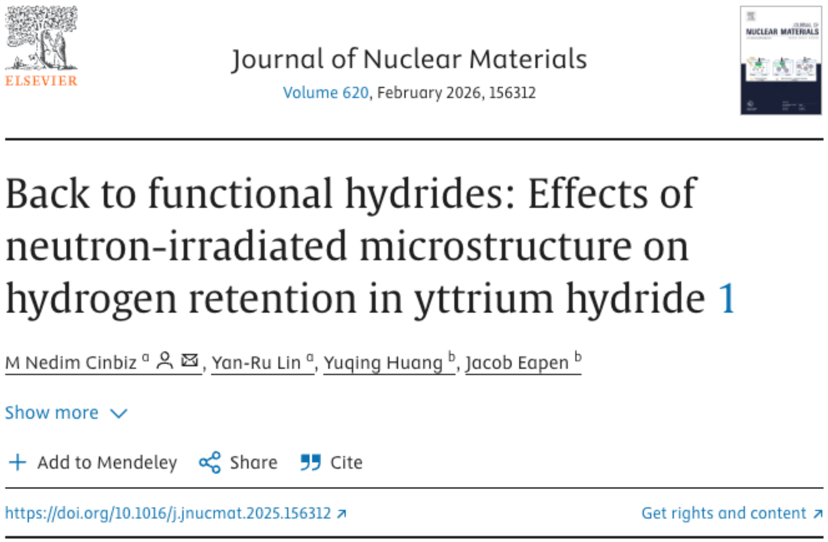
MRP Microreactor Program

Los Alamos National Laboratory

Argonne National Laboratory

POST-IRRADIATION EXAMINATIONS WERE SUCCESSFULLY COMPLETED !

- Level 2 milestone was completed
- 1 paper is published in JNM
- 3 additional papers are in preparation



ELSEVIER

Journal of Nuclear Materials

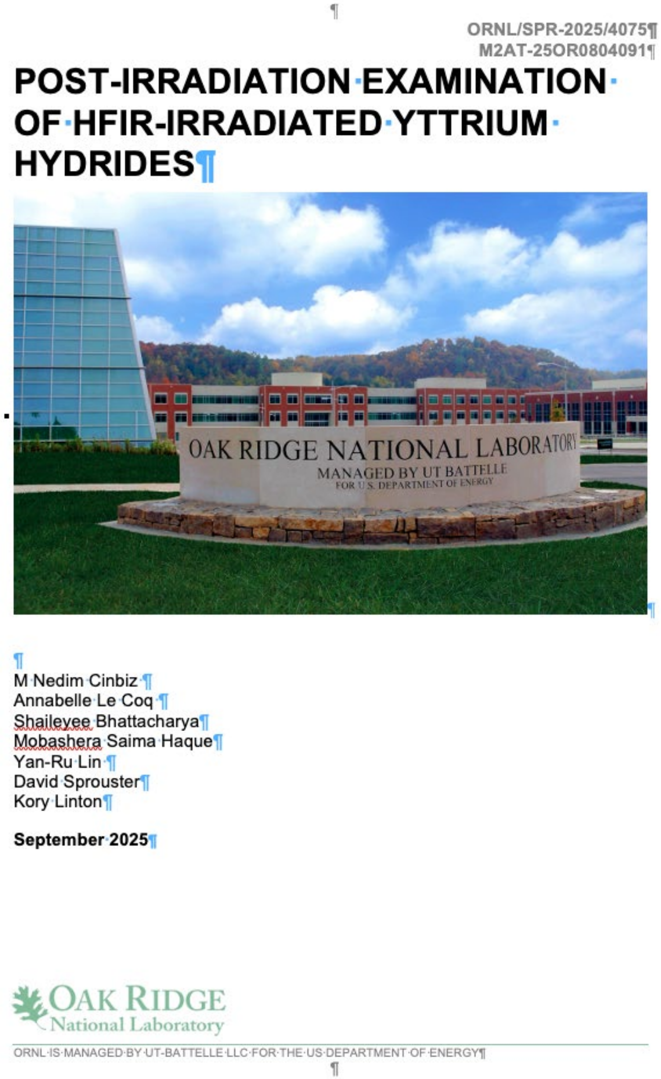
Volume 620, February 2026, 156312

Back to functional hydrides: Effects of neutron-irradiated microstructure on hydrogen retention in yttrium hydride 1

M Nedim Cinbiz [a], Yan-Ru Lin [a], Yuqing Huang [b], Jacob Eapen [b]

Show more

https://doi.org/10.1016/j.jnucmat.2025.156312



ORNL/SPR-2025/4075
M2AT-25OR0804091

POST-IRRADIATION EXAMINATION OF HFIR-IRRADIATED YTTRIUM HYDRIDES

M Nedim Cinbiz
Annabelle Le Coq
Shaileyee Bhattacharya
Mobashera Saima Haque
Yan-Ru Lin
David Sprouster
Kory Linton

September 2025

OAK RIDGE
National Laboratory

ORNL IS MANAGED BY UT-BATTELLE LLC FOR THE US DEPARTMENT OF ENERGY

WHERE ARE WE AT ON THE DEVELOPMENT YTTRIUM HYDRIDE MODERATORS AT DOE?

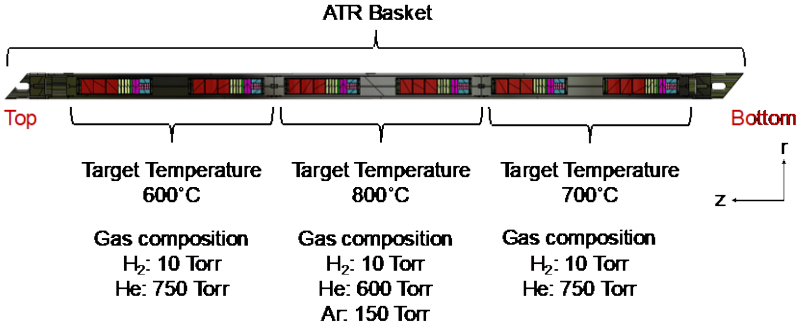
OUR FOCUS: ATR & HFIR IRRADIATION CAMPAIGNS AND PIE

MRP Microreactor Program

ATR & HFIR IRRADIATIONS

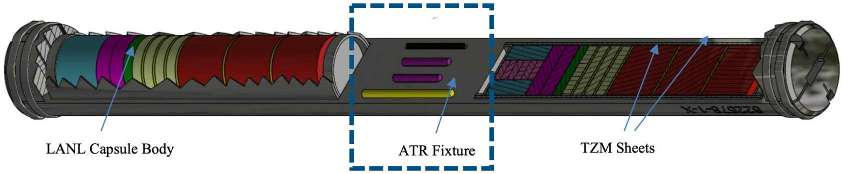
ATR IRRADIATIONS

- ***Samples* | *102 yttrium hydride specimens | 36 TZM foils***
- ***Target temperatures* | *600, 700, and 800˚C***
- ***Irradiation conditions* | *60 full power days***



Cinbiz et al, 2020

ATR handbook



Melt bar
Fluence wires
SiC rods for thermometry

Cinbiz et al, 2020

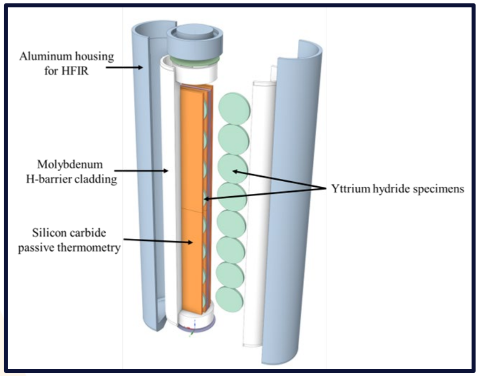
NEUTRON RADIOGRAPHY INDICATED HIGH STRUCTURAL STABILITY

HFIR IRRADIATION

- ***Samples* | 16 yttrium hydride disks per capsule**
- ***One fabrication path* | *Direct hydriding***
- ***Target temperatures* | *~600 and 800˚C***
- ***Irradiation conditions* | *Max.* 22 days | *Min.* ~ 2 days**

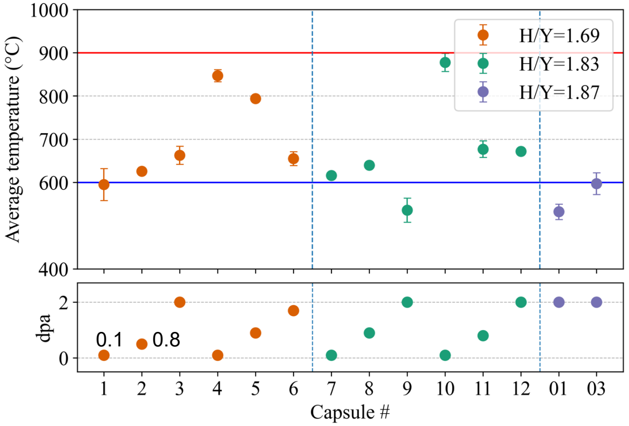
HFIR handbook

Schematics of the HFIR capsule



HFIR capsule components

Passive thermometry results



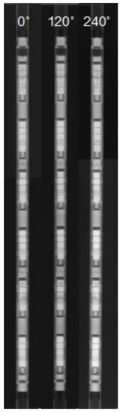
IRRADIATION DESIGN ENCOMPASSED MULTIPLE DOSE LEVELS

HYDRIDE IRRADIATIONS IN ADVANCED TEST REACTOR (ATR) AND HIGH FLUEX ISOTOPES REACTOR (HFIR)

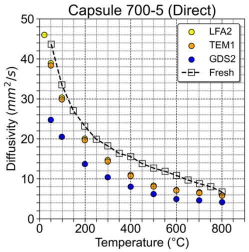
POST-IRRADIATION EXAMINATIONS

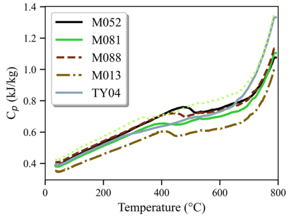
PIE EXAMINATIONS ENCOMPASSED VARIOUS TECHNIQUES

Neutron Radiography To Assess Mechanical Integrity



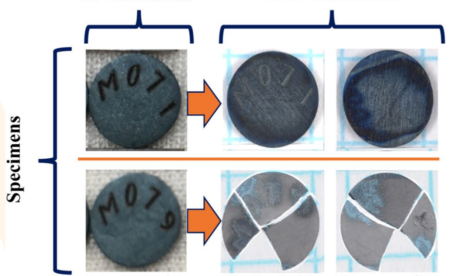
Differential Scanning Calorimetry Laser Flash Analysis To Assess Thermal Transport





Microscopy To Assess Defects & Phase Stability

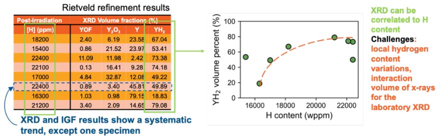
Dimensional, visual, mass to assess drastic changes



Cinbiz et al. , Materalia, 2023

PIE is to determine hydrogen in hydride

Lab X-ray diffraction (XRD), Inert Gas Fusion, Synchrotron Radiation Diffraction To Assess Local & Global Phase Fractions



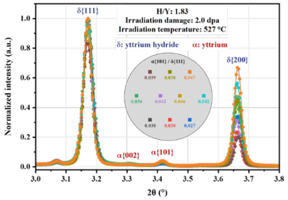
Rietveld refinement results

Post-Irradiation	XRD Volume fractions (%)			
[H] (ppm)	YOF	Y_2O_3	Y	YH_2
18200	2.40	6.19	23.58	67.04
15400	0.86	21.52	23.97	53.41
22400	11.09	11.98	2.42	73.38
22100	0.13	16.41	9.28	74.18
17000	4.84	32.87	12.08	49.22
22400	0.89	3.40	45.81	49.89
16300	1.03	0.98	79.15	18.83
21200	3.40	2.09	14.65	79.08

XRD and IGF results show a systematic trend, except one specimen

XRD can be correlated to H content

Challenges: local hydrogen content variations, interaction volume of x-rays for the laboratory XRD



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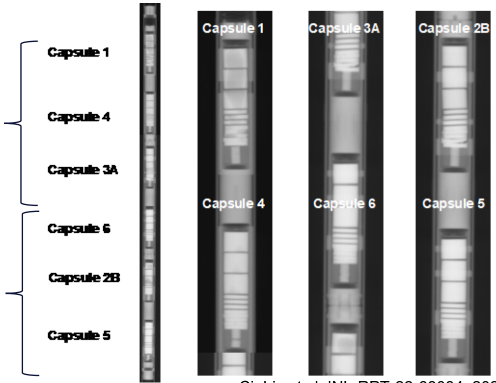
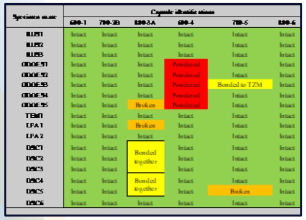
EXAMPLES OF POST-IRRADIATION MECHANICAL STABILITY THRU VARIOUS METHODS

Pow-Met

Direct



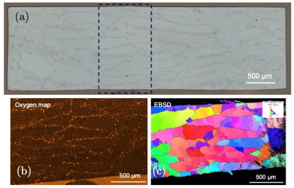
Cinbiz et al, INL-RPT-22-68084, 2022



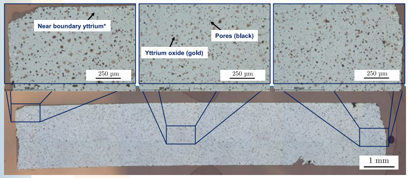
Specimen name	Capsule identification					
	600-1	700-2B	800-3A	600-4	700-5	800-6
ILUS1	Intact	Intact	Intact	Intact	Intact	Intact
ILUS2	Intact	Intact	Intact	Intact	Intact	Intact
ILUS3	Intact	Intact	Intact	Intact	Intact	Intact
ODOES1	Intact	Intact	Intact	Powdered	Intact	Intact
ODOES2	Intact	Intact	Intact	Powdered	Intact	Intact
ODOES3	Intact	Intact	Intact	Powdered	Bonded to TZM	Intact
ODOES4	Intact	Intact	Intact	Powdered	Intact	Intact
ODOES5	Intact	Intact	Broken	Powdered	Intact	Intact
TEM1	Intact	Intact	Intact	Intact	Intact	Intact
LPA1	Intact	Intact	Broken	Intact	Intact	Intact
LPA2	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

Cinbiz et al, INL-RPT-22-68084, 2022

Oxide decoration around grain boundaries may cause failure for long duration



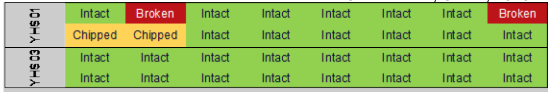
Cinbiz et al, INL/RPT-23-71531,2023



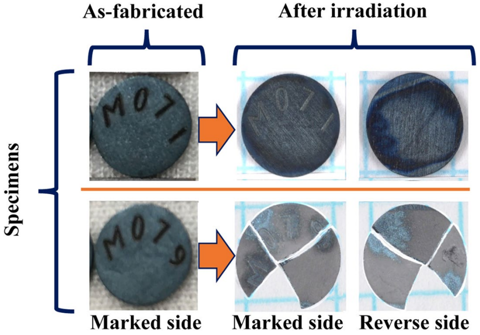
Cinbiz et al, INL/RPT-23-71531,2023

No network of oxides in powder met specimens, but large pores were present

Cinbiz et al. , ORNL, 2025

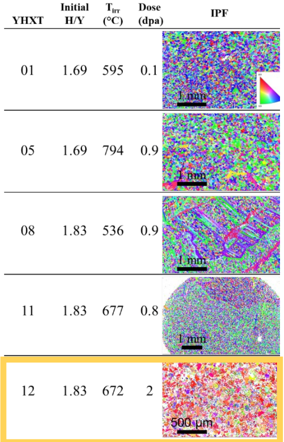


YHS01	Intact	Broken	Intact	Intact	Intact	Intact	Intact	Broken
	Chipped	Chipped	Intact	Intact	Intact	Intact	Intact	Intact
YHS03	Intact	Intact	Intact	Intact	Intact	Intact	Intact	Intact
	Intact	Intact	Intact	Intact	Intact	Intact	Intact	Intact



SiC/YH$_x$ interaction around ~ 800°C at 2dpa

Cinbiz et al. , Materalia, 2023



YHXT	Initial H/Y	T_{irr} (°C)	Dose (dpa)	IPF
01	1.69	595	0.1	1 mm
05	1.69	794	0.9	1 mm
08	1.83	536	0.9	1 mm
11	1.83	677	0.8	1 mm
12	1.83	672	2	500 µm

Le Coq et al. , JNM, 2025

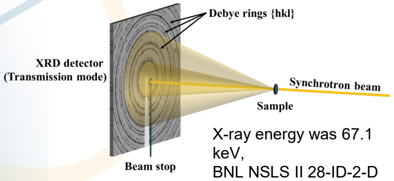
Samples in 1.5 HFIR capsules were completely powdered

Hydrogen loss

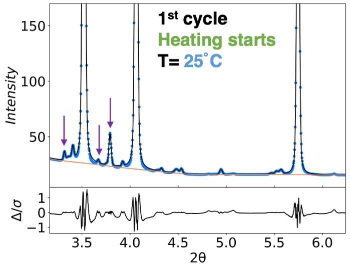
Structural stability after irradiation was good. However, there are exceptions related to the fabrication processes for both campaigns

MRP Microreactor Program

ADVANCED CHARACTERIZATION TECHNIQUES OFFER IN-DEPTH UNDERSTANDING OF MICROSTRUCTURE AND H RETENTION BEHAVIOR



X-ray energy was 67.1 keV, BNL NSLS II 28-ID-2-D beamline

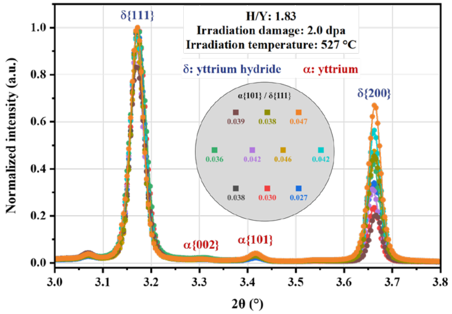


Cinbiz et. al, 2025

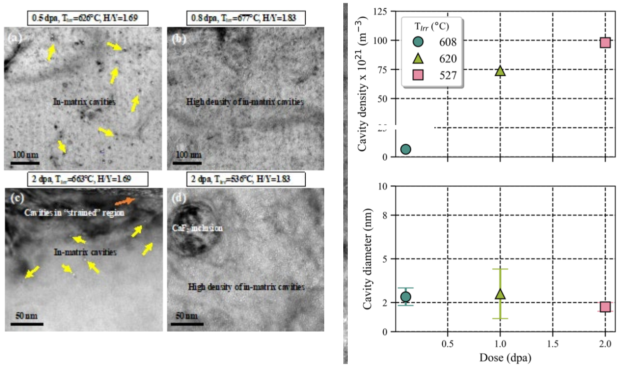
In situ XRD during heating-cooling tests showed fading α-Y peaks rather than increase due to H loss

Excess H is likely from:

Local H/Y variations



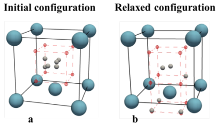
Irradiation-induced cavities



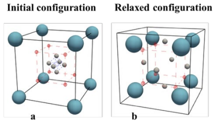
H/Y also effects on the cavity μ-structure

Density Functional Theory (DFT) calculations indicated H/Y variation and H trapping can occur with the presence of 5 Y-atom size vacancies or larger

5 Y-ATOM VACANCY



6 Y-ATOM VACANCY



Cinbiz et. al, JNM, 2026

Irradiation-induced μ-structure has positive outcome on the H retention behavior of yttrium hydrides

MRP Microreactor Program

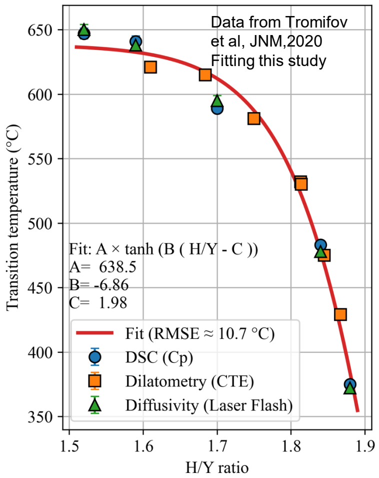
THERMAL PROPERTIES ARE CRITICAL TO DETERMINE MODERATOR TEMPERATURE DURING OPERATION

Thermal diffusivity exhibits 1/(A+BT) behavior

Adapted from Cinbiz et al, INL/RPT-23-71531,2023

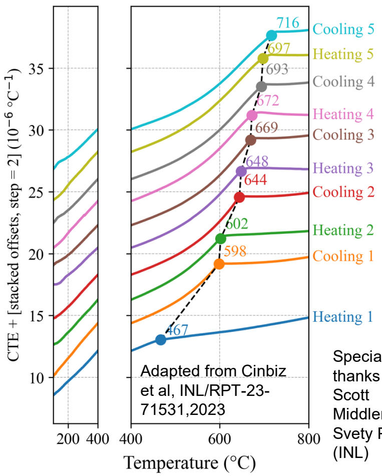
Heat capacity shows 2nd order transition

T_{tr} vs H/Y ratio



Data from Tromifov et al, JNM,2020
Fitting this study

Thermal expansion indicates 2nd order transition



Adapted from Cinbiz et al, INL/RPT-23-71531,2023

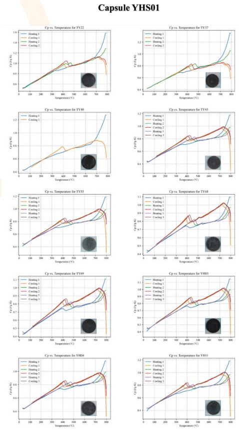
Special thanks to Scott Middlemas & Svety Pavlov (INL)

The 2nd order transition is related to loss of H sublattice order with increasing temperature which creates resistance to phonon scattering in yttrium hydride

MRP Microreactor Program

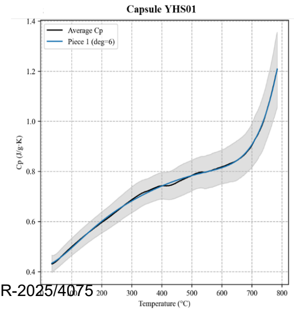
A PRACTICAL ENGINEERING APPROACH: USE CAPSULE AVERAGED VALUES (1^{ST} CYCLE HEATING ONLY) FOR FITTING

Individual specimens



H/Y=1.87

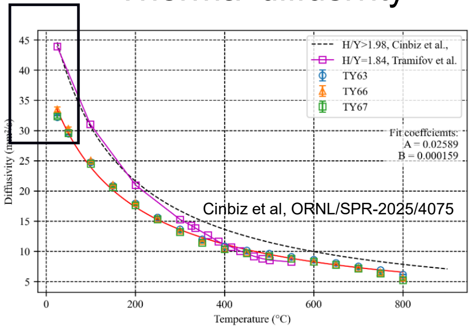
Capsule-averaged heat capacity



Cinbiz et al, ORNL/SPR-2025/4075

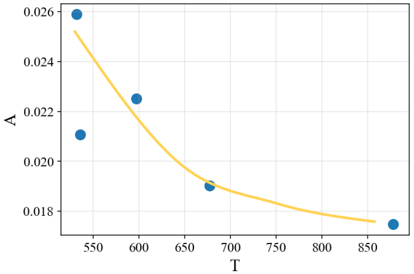
$c_p(T)=aT^6+bT^5+cT^4+dT^3\ eT^2+fT+g$

Capsule-averaged Thermal diffusivity



Cinbiz et al, ORNL/SPR-2025/4075

Lattice resistivity (A) decreases with increasing irradiation temperature



Lattice resistance (A) term is affected by the competition b/w irradiation temperature and displacement damage

$$A \approx 2.15951\times10^{-2}\ -\ 4.41912\times10^{-6}\,T_{irr}\ +\ 3.30943\times10^{-3}\,dpa$$

This model will be further updated

ENGINEERING APPROACH ENABLES FAST IMPLEMENTATION BUT PHYSICS BASED MODELS ARE CRITICAL TO REDUCE UNCERTAINTIES

MRP Microreactor Program

MAIN TAKEAWAYS FROM PIE

- High hydrogen retention and structural stability
- Defect-driven H retention mechanisms
- Non-uniform hydrogen redistribution
- H retention metric for irradiated specimens via thermal properties

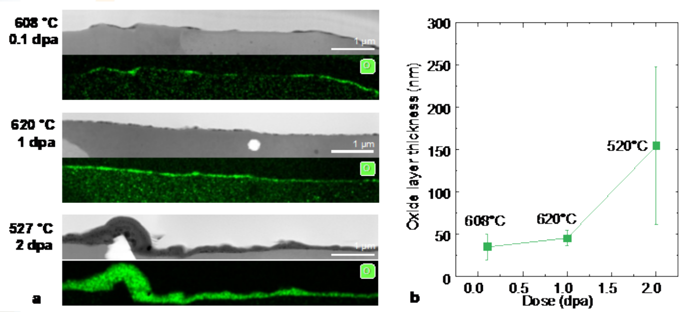
DIRECTIONS TO ACCOMPLISH READINESS & DEPLOYMENT

- LONG TERM IRRADIATIONS OF NEAR FINAL GEOMETRY MODERATOR
- UNITCELL IRRADIATIONS ENABLING MATERIALS COMPATIBILITY

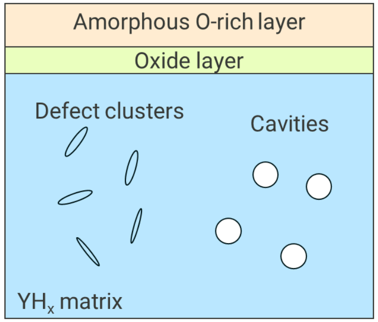
MRP Microreactor Program

MICROSTRUCUTRE EVOLUTION UNDER IRRADIATION IMPROVES H RETENTION IN YTTRIUM HYDRIDE

Formation continuous oxide with increasing dpa (?)



H retention enhancing features



H transport under irradiation may need an update as follows, which may impact criticality condition

$$\frac{\partial C_H}{\partial t} = \text{FickianTerm} + \text{Soret Term} + \text{Sorption Term} - \text{Cavity Bias}\,\frac{\partial C_{cavity}}{\partial t}$$

Helium production in real application needs to be considered with impurities, like oxygen

TO INCREASE THE TECHNOLOGICAL READINESS, WELL-DEFINED FABRICATION TECHNIQUES NEED TO BE DEVELOPED WITH POTENTIAL QUALITY ASSURANCE AND CONTROL

- Initial material feedstock quality and pedigree are ranked as LOW, final product quality is not clear
- Initial feed stock material requires additional processing to reduce unwanted elements such as Sc, F, La
- Post-hydriding analysis and non-destructive methods needs to be developed

ORNL have new recipes, enabling higher manufacturing readiness levels

MRP Microreactor Program

ACKNOWLEDGEMENTS

- Diana Li (DOE), John Jackson (INL), Kurt Terrani (ORNL), Holly Trellue and Erik Luther (LANL), Thomas Johnson and Chase Taylor (INL), Mehmet Topsakal at NSLS-II at BNL
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- IMET and LAMDA Staff at ORNL
- Tim Lach, Yan-RU Lin (ORNL)
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- the High Flux Isotope Reactor, a DOE Office of Science User Facility operated by the Oak Ridge National Laboratory. The beam time was allocated to MARS and WAND2 on proposal numbers IPTS-33637.1 and IPTS-33813.1.
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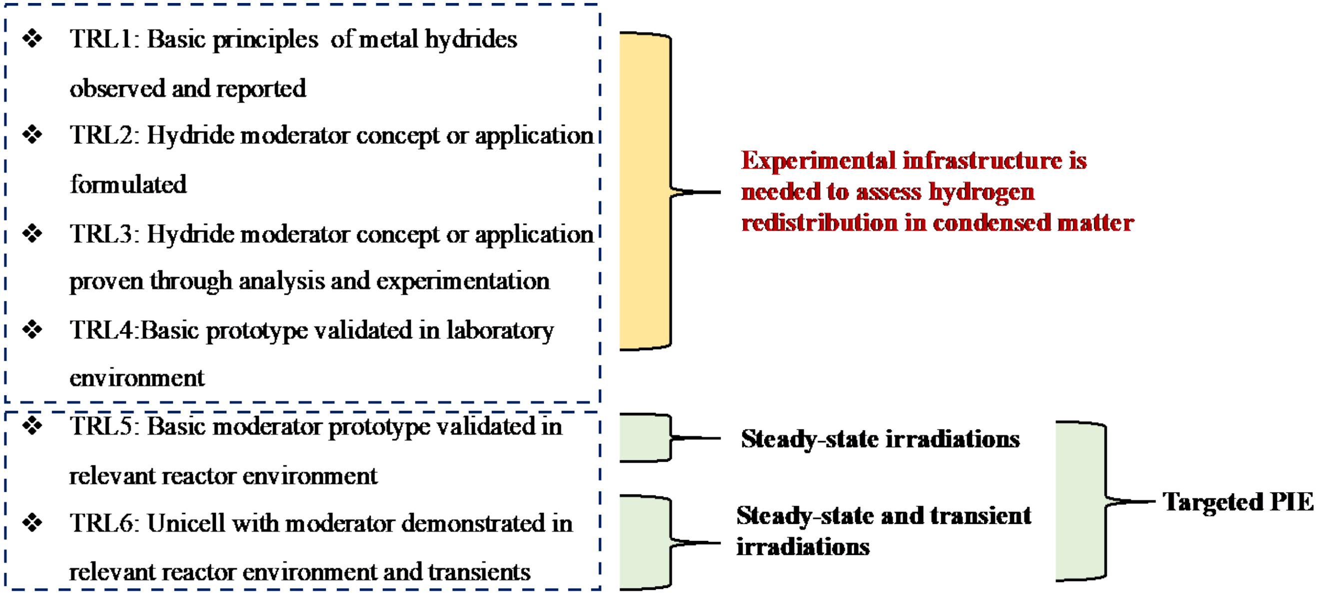
MRP Microreactor Program

TRLs



- ❖ TRL1: Basic principles of metal hydrides observed and reported
- ❖ TRL2: Hydride moderator concept or application formulated
- ❖ TRL3: Hydride moderator concept or application proven through analysis and experimentation
- ❖ TRL4:Basic prototype validated in laboratory environment

Experimental infrastructure is needed to assess hydrogen redistribution in condensed matter

- ❖ TRL5: Basic moderator prototype validated in relevant reactor environment
- ❖ TRL6: Unicell with moderator demonstrated in relevant reactor environment and transients

Steady-state irradiations

Steady-state and transient irradiations

Targeted PIE

MRP Microreactor Program