DOE Microreactor Program:

High Temperature Moderator and Structural Material

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Idaho National Laboratory · Oak Ridge National Laboratory · Microreactor Program · Los Alamos National Laboratory · Argonne National Laboratory

High Temperature Moderator Material

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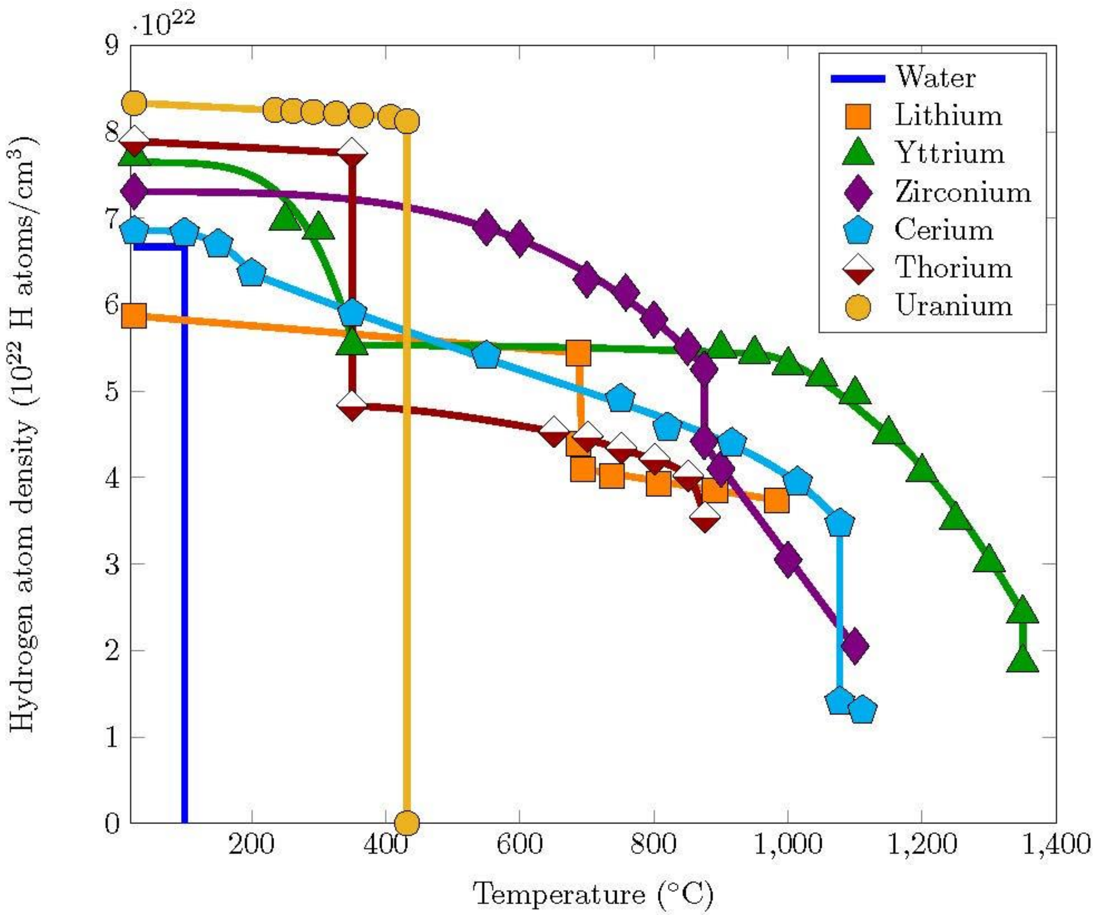
High Temperature Moderator Material

- Moderating material reduces fuel mass requirements in advanced reactors such as microreactors significantly
- Reactors are most efficient at high temperatures
- H is the ideal moderator but solid, stable forms for reactors are needed
- Yttrium hydride is the most thermally stable hydride known
- The focus is to perform activities to qualify YH for use as a moderator
- Efforts follow the needs identified in the moderator development plan

Moderator can decrease the fuel mass of low-enriched uranium by an order of magnitude and make it closer to high-enriched values



Shivprasad et al. “Elastic moduli of high-density, sintered monoliths of yttrium Dihydride” J Alloys and Compounds, 2021

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Moderator Research Plan

Material Form	*Thermophysical properties*	Cladding/Containment
Stoichiometry	**Phase formation thermodynamics**	*Hydrogen over pressure*
Fabrication methods and processes	Phase-formation kinetics	*H2 hermiticity*
Purity	**Heat capacity**	H2 transport properties
Quality	Coefficient of thermal expansion (CTE)/density	H2 embrittlement
Operating Conditions	**Hydrogen partial pressure**	Chemical compatibility
Temperature range	Thermal conductivity	Neutronics
Fluence lifetime	**Mechanical properties**	H2 transport properties
Neutronics	Structural properties	H2 embrittlement
Kinetic/transient performance	*Hydrogen mobility*	Thermophysical properties

Ongoing/Planned - italics

Completed - bold

Still needed

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Accomplishments

- Established large-scale fabrication capability (LANL)
- Placement of samples in Advanced Test Reactor (INL)
  - Irradiation completed on 4/23
  - Post Irradiation Examination planned in near future
- Integral critical experiment with yttrium hydride at National Criticality Experiments Research Center (NCERC - LANL)
  - Completed January
- Cladding/Containment work is underway and on schedule for the end of the fiscal year

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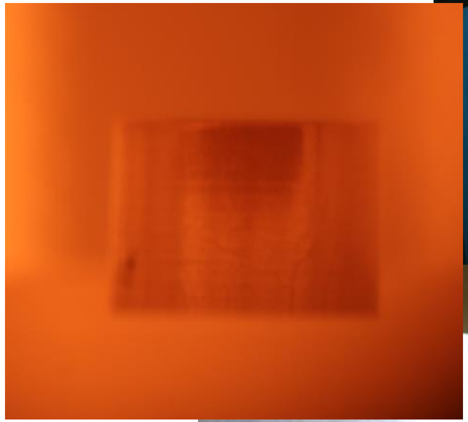
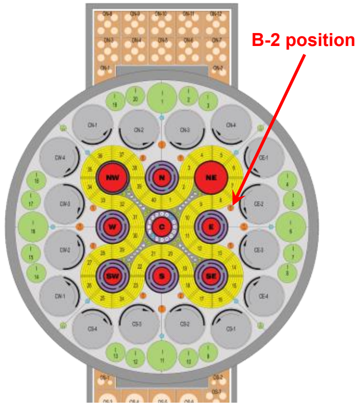
Large-scale Fabrication Capability

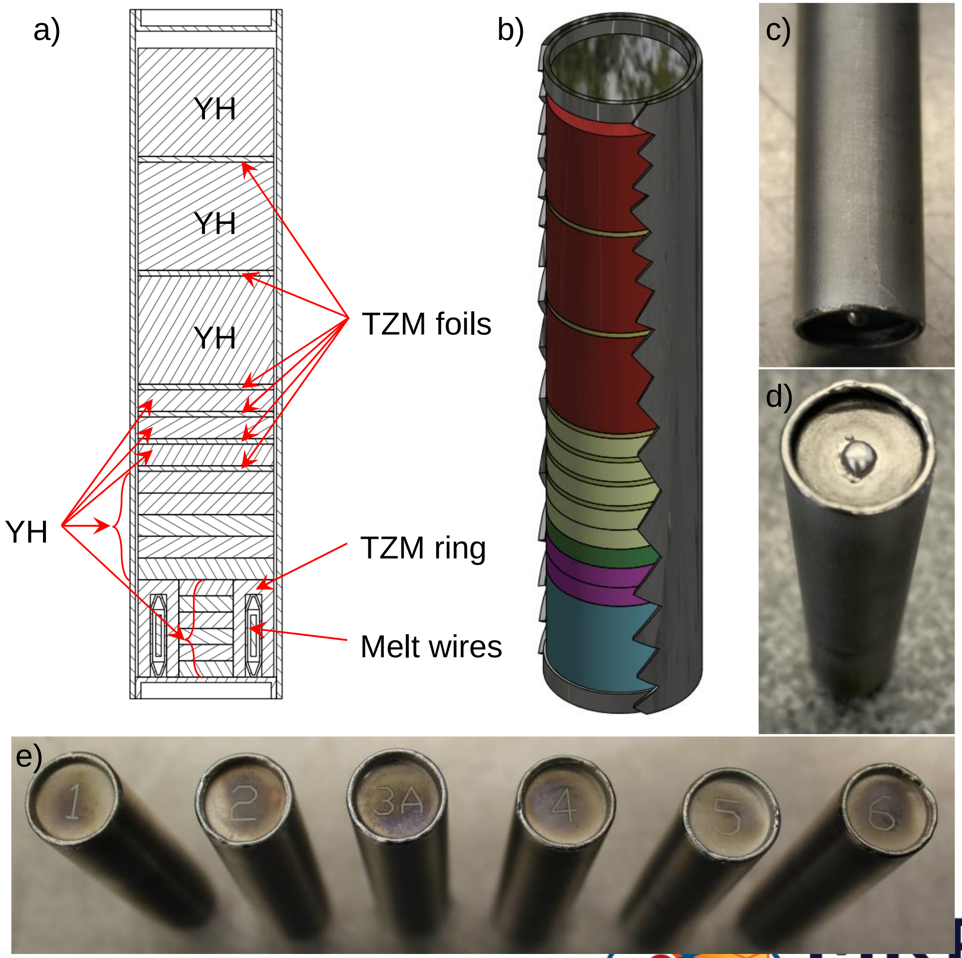
- Direct hydriding and powder metallurgy methods
  - Up to ~10” and kgs of material
- Installed glovebox, milling, pressing and sintering/hydriding equipment
- Initiated tests to measure size effects on hydride kinetics



Design, fabrication, assembly of ATR irradiation experiment

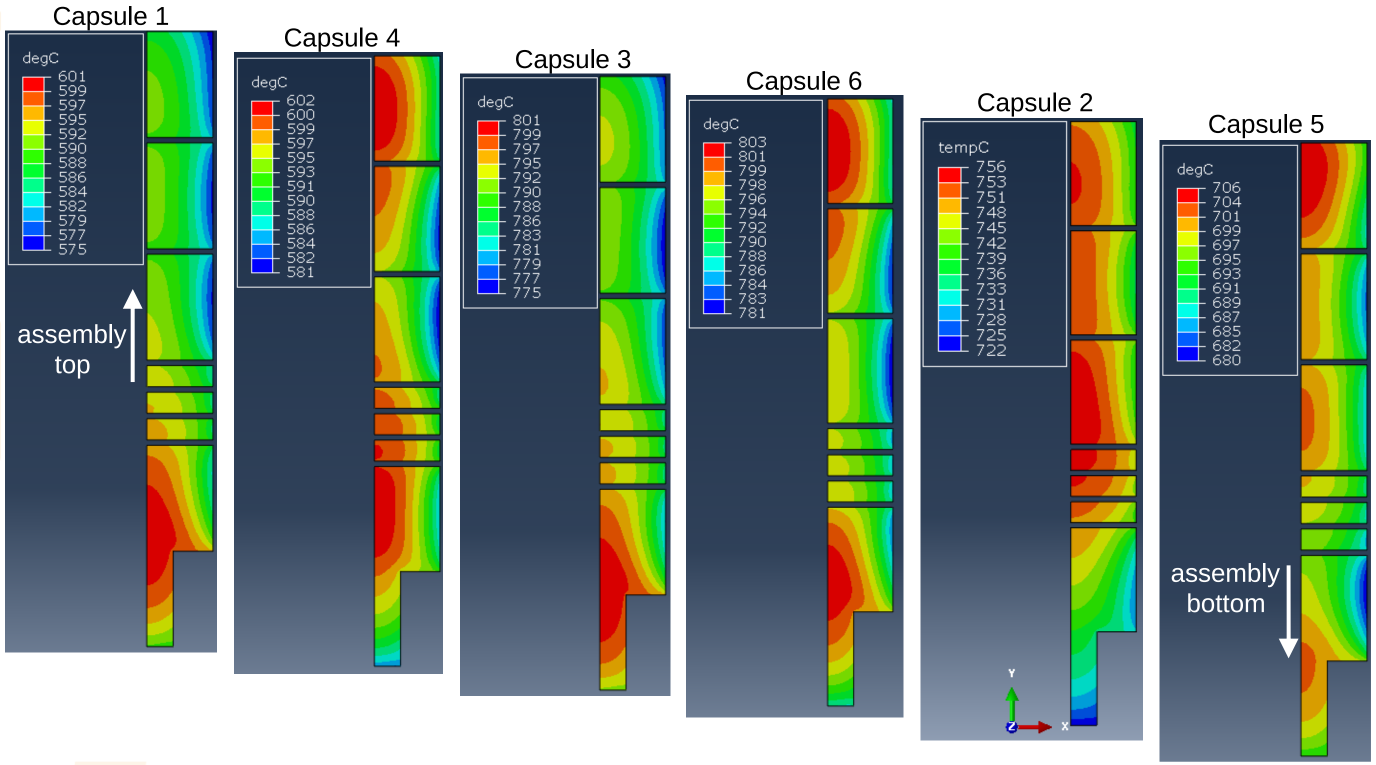


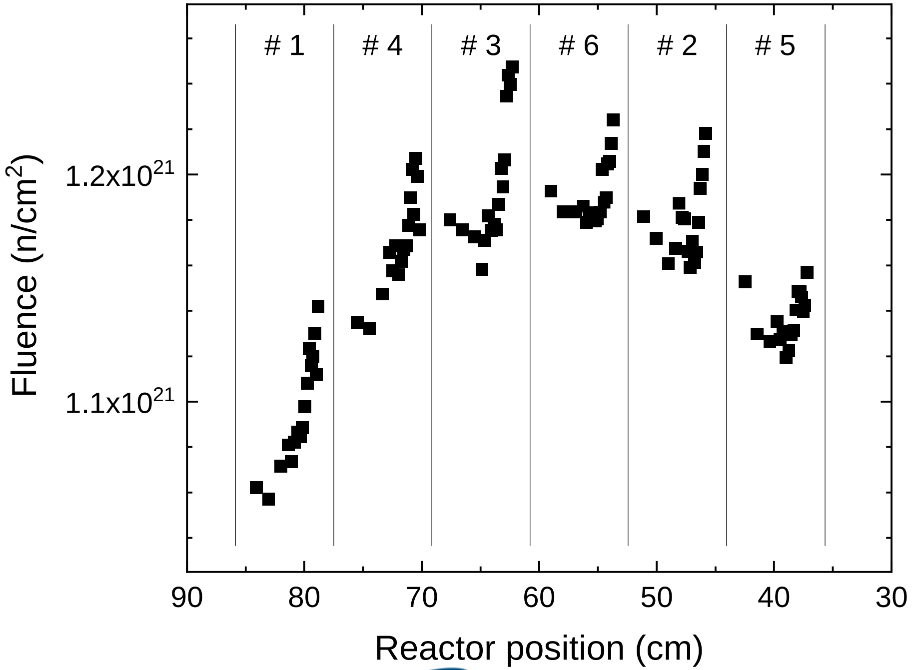
- Motivation: YH has been used before but nearly no irradiation data is available in literature
  - Nuclear quality assurance 1 (NQA-1) certification:
    23 Dec 2020
  - Irradiation start: 19 Feb 2021
  - Irradiation end: 23 Apr 2021
  - Post irradiation examination
  - Shipping: 9 Jun 2021 (projected)
  - Disassembly, visual and dimensional examination: July-Sept 2021



Thermal and neutronics analysis

- Variables: Temperature and YH fabrication method
  - 600, 700, 800ºC
  - Direct hydriding and powder metallurgy
- Temperature gradients within capsule vary by < 26˚C
  - capsule 2 <34˚C
- Average fast fluence (E ≥ 0.1 MeV)
  - 1 x 10^{21} n/cm2
  - 8% variation in neutron flux/fluence across all samples
- Melt wires to verify actual temperature in cans
- Two fluence wires in capsule





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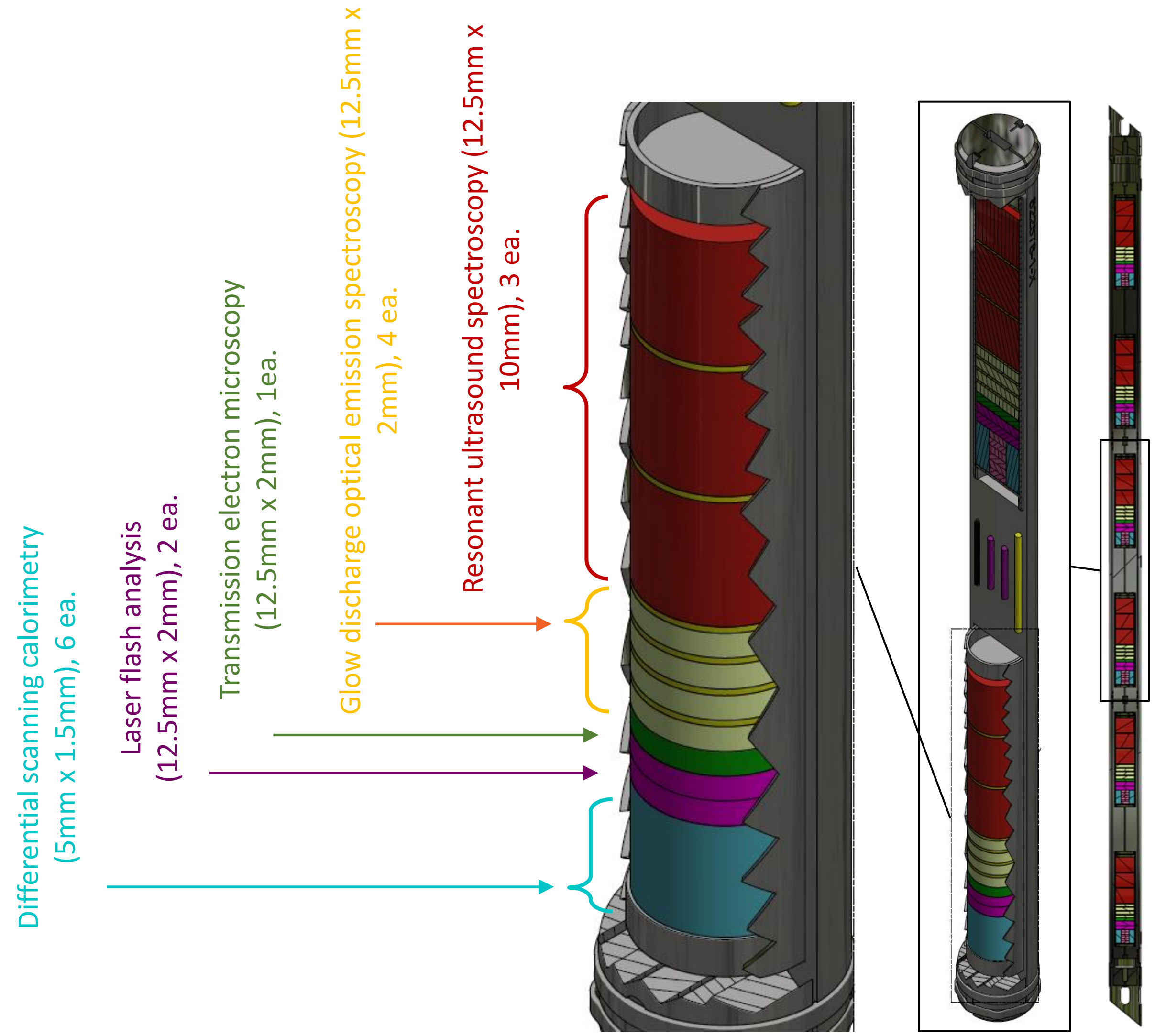
Post irradiation examination



- Most important:
  - Hydrogen stability with temperature and fluence
  - General integrity of samples
- Determine thermophysical/ mechanical properties
  - Swelling
  - Elastic properties
  - Heat capacity
  - Thermal diffusivity
  - Microstructure
  - Thermal expansion
  - Hardness

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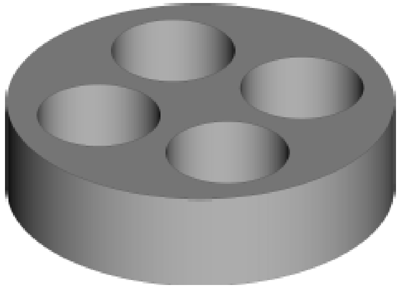
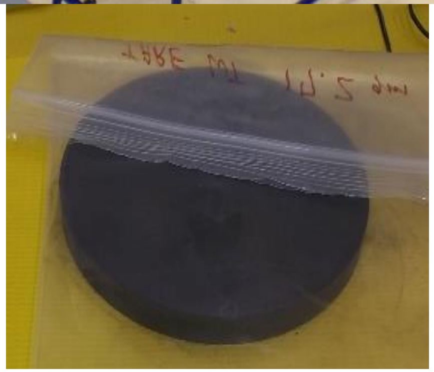
Critical Experiment

- Motivation
  - No critical experiments for validation
  - Ongoing differential measurements need validation
  - **Expect Positive Temperature Coefficient**
- Purpose: Validate temperature dependent feedback in YH_2 in a critical experiment
  - Demonstrate renewed capability to do electrically heated test at NCERC (no nuclear heating)
- Conducted at NCERC Jan 11-21, 2021
- 15 unique measurements, based on **two** different core column configurations (two and four cans of $YH_{1.9}$)
  - Materials
    - HEU (C-discs)
    - Beryllium radial reflector
    - **$YH_{1.9}$ canned in molybdenum**
    - **Alumina Heaters and Spacers**



Alumina Spacer

$YH_{1.9}$ discs inside moly can (without welded lid)



HEU C-disc

Structural Materials

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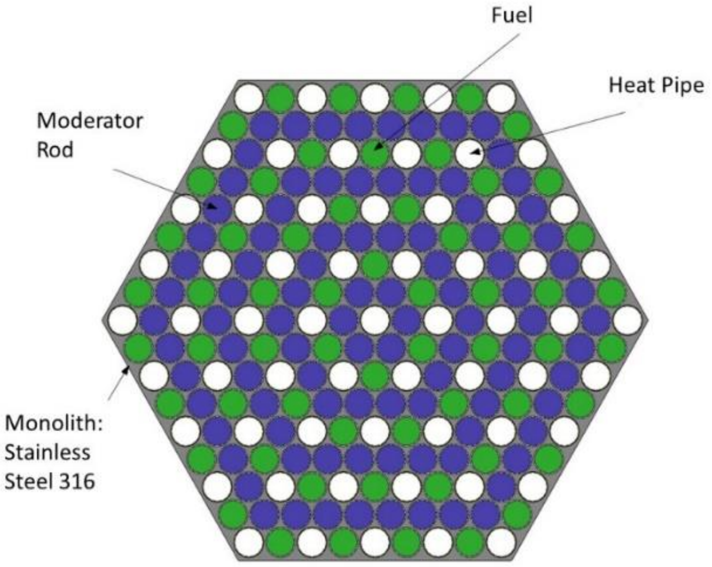
Structural Materials

- Microreactor cores comprise the following materials:
  - Fuel + Cladding   Structure   Moderator (reduces fuel mass)
- Structural options include: solid metals, ceramics and composites
- Determine integrity of structural materials used in microreactors
- Completion of code cases for licensing of materials is required

Monolith Material	Pros	Cons
Stainless Steel 316	Well proven and corrosion resistant	Neutron absorber, cannot handle temperatures > 600 C
Grade 91 Stainless Steel	Structurally preferred for reactors	Neutron absorber, not as well proven
Molybdenum	Operated $\geq$900°C	Neutron absorber
Aluminum Nitride (AlN)	Ceramic - slows neutrons down, decreasing fuel requirements	Structurally less stable than steel
Silicon or Zirconium Carbide (SiC, ZrC)	Ceramic - slows neutrons down, decreasing fuel requirements	Structurally less stable than steel
Graphite	Proven ceramic material, decreasing fuel requirements	Potential C migration to heat pipes



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Structural Materials Overview

- Identify candidate materials of interest to industry that meet basic property and material requirements for a given application. (TRL <=3)
- ORNL/ANL/INL/LANL collaborative effort:
  - Material (manufacturing processes [TRL])
  - 316 SS (powder metallurgy (PM) [3] / additive manufacturing (AM) [3])
    - Purpose: Applicability of current code requirements to new manufacturing processes
  - Grade 91 (wrought [5] / AM [2])
    - Purpose: Provide material option with enhanced high temperature strength / higher creep strength (thinner ligaments)
  - Molybdenum Alloys (AM [2])
    - Purpose: Provide material option with higher potential operating temperature
  - Graphite (AM [1])
    - Purpose: Provides material option to combine moderator with structural material

Impact: Enable new manufacturing methods

Impact: Disruptive for Engineering Design

Impact: Disruptive for Operating Temperature Design

Impact: Disruptive from a Neutronic Design

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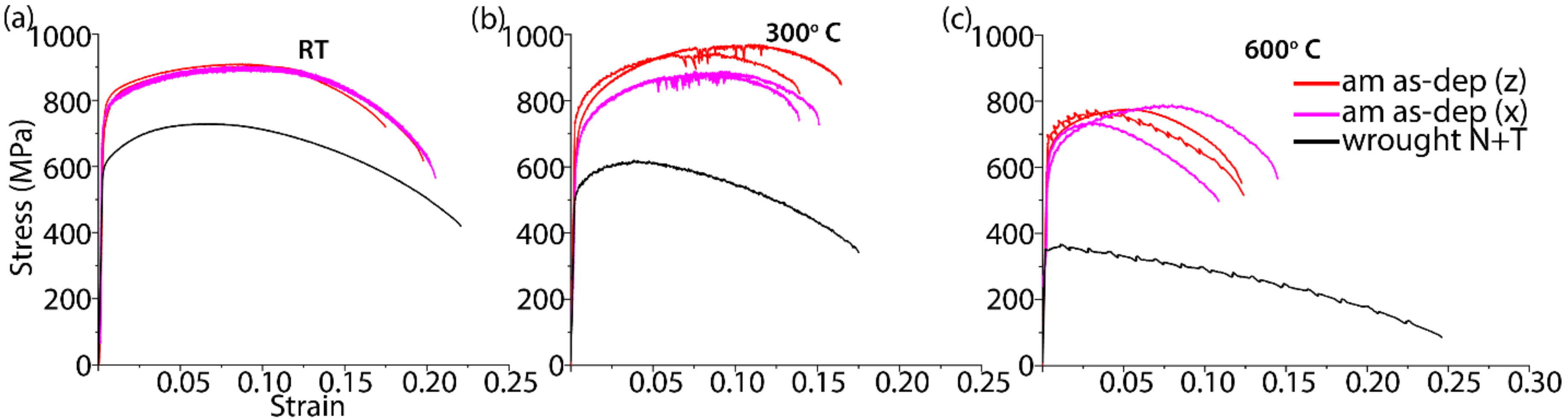
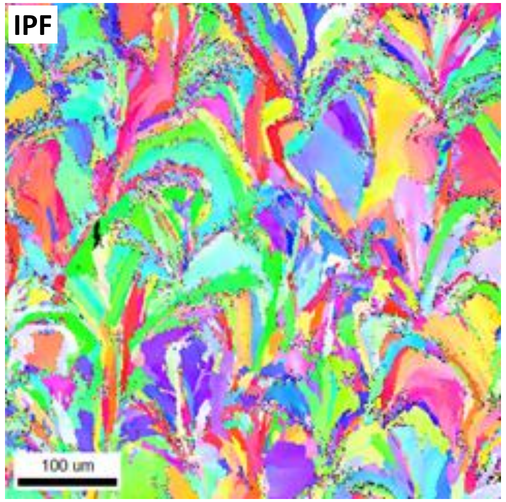
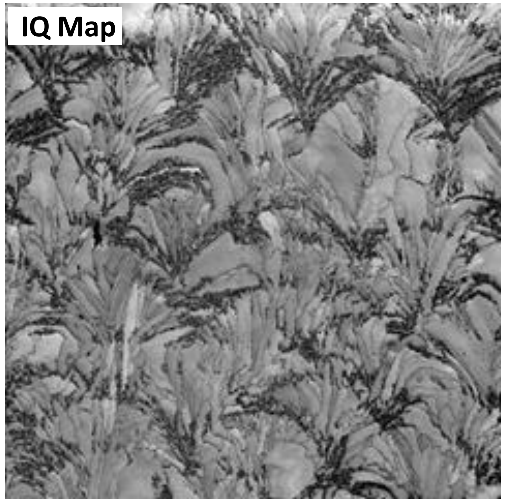
Expanding the Potential Materials for Use with Technology Enabling Manufacturing Processes

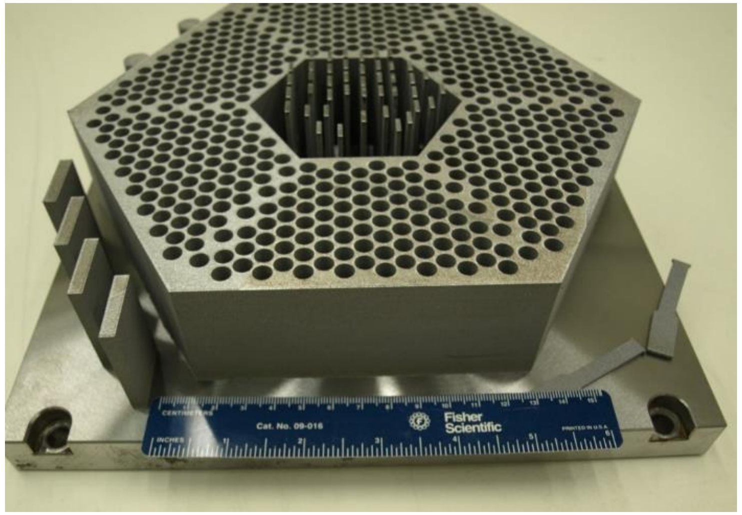
- Tensile testing of AM Grade 91 as-deposited shows enhanced high temperature properties
- Strength is over 200 MPa higher than wrought at 600C and ductility is improved
- Complex semi-bainitic microstructure

Next Step: Identify property limits under creep and temperature for AM Grade 91 steel.









All materials developed on EOS M290 AM Machine

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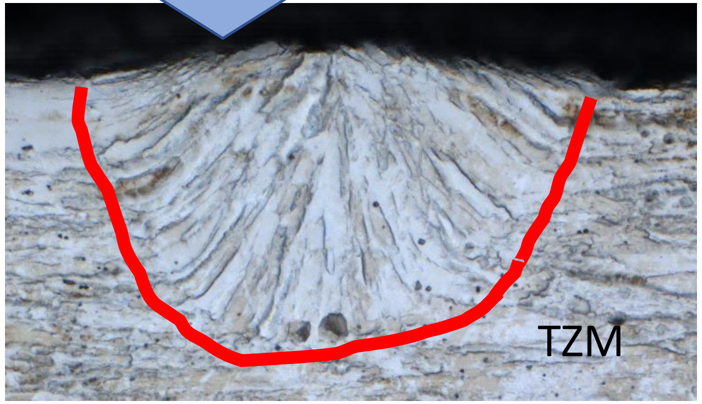
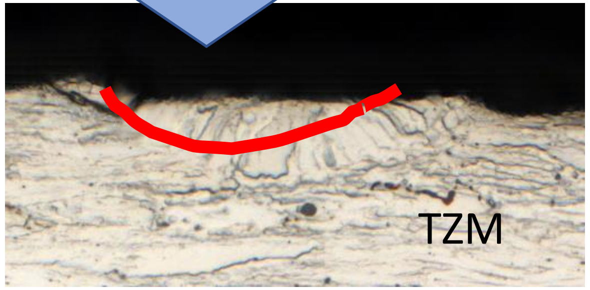
Expanding materials and processes for higher temperatures

- Initial study of weld pool study for additive manufacture of TZM
- Process parameter optimization of TZM indicates AM is possible

Predictable, stable molten pool shown below will provide adequate bonding between layers with minimal lack-of-fusion defects

Without optimization, process parameters that provide a low linear energy density (similar to steels) are seen to lack appropriate penetration





40 um

Next Step: Begin fabrication of test coupons of AM TZM to begin identifying properties

All materials developed on EOS M290 AM Machine
Results courtesy of M Brand (2021)

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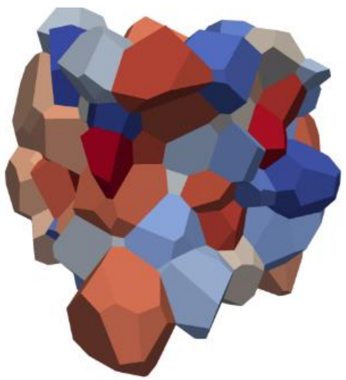
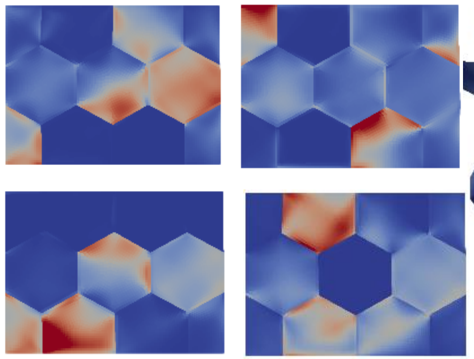
Directly experimentally assessing the life of Grade 91 under cyclic thermal loads is extremely challenging

- **Creep-fatigue damage will likely control the design life of microreactor components**
- Complex thermal stresses
- Likely more cyclic service compared to conventional reactor designs
- **Realistic hold times and strain ranges would take years to experimentally determine**
- A physically-based model to predict cyclic life will improve design efficiency and better quantify component safety

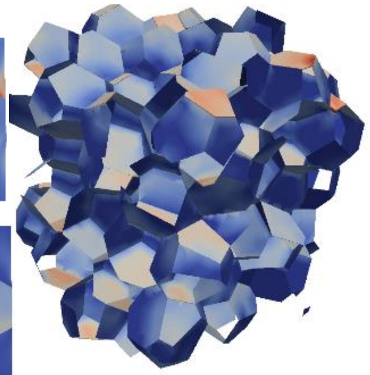
Extend framework to model creep-fatigue conditions



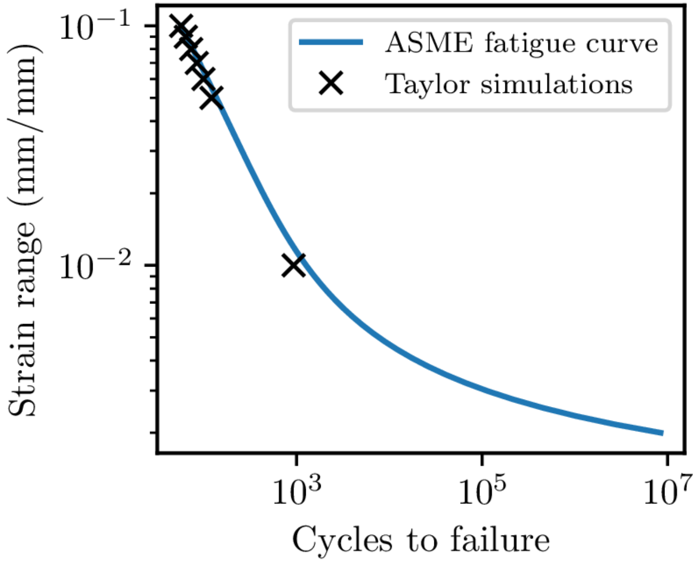
Representative microstructure



Physically-based grain bulk deformation *and damage* model

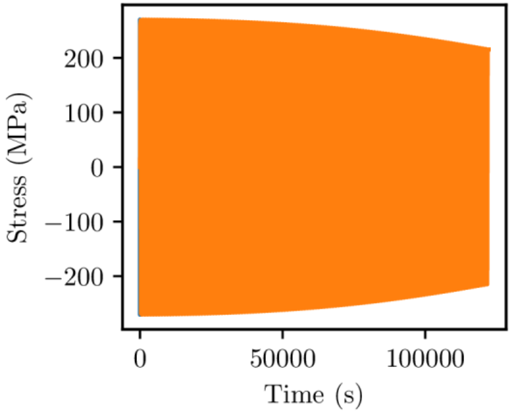


Physically-based boundary deformation/damage model



Model predicts high cycle fatigue curve with minimal calibration

Key result: simulated cyclic life predictions under realistic conditions



Stress vs time for fixed strain range (creep-fatigue)

Tests conventionally stopped at 20% load drop

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Conclusions

- Progress is being made to qualify YH for reactor applications
  - Scale up to support testing
  - Fundamental properties measurements
- Identifying candidate structural materials for applications
  - Enabling new manufacturing methods
  - Expanding potential materials pool
  - Creating a framework for simulating life cycle of candidate materials

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