High Temperature Moderator Containment:

Advanced Moderator Module (AMM) Concept

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Idaho National Laboratory | Oak Ridge National Laboratory | MRP Microreactor Program | Los Alamos National Laboratory | Argonne National Laboratory

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MRP Microreactor Program

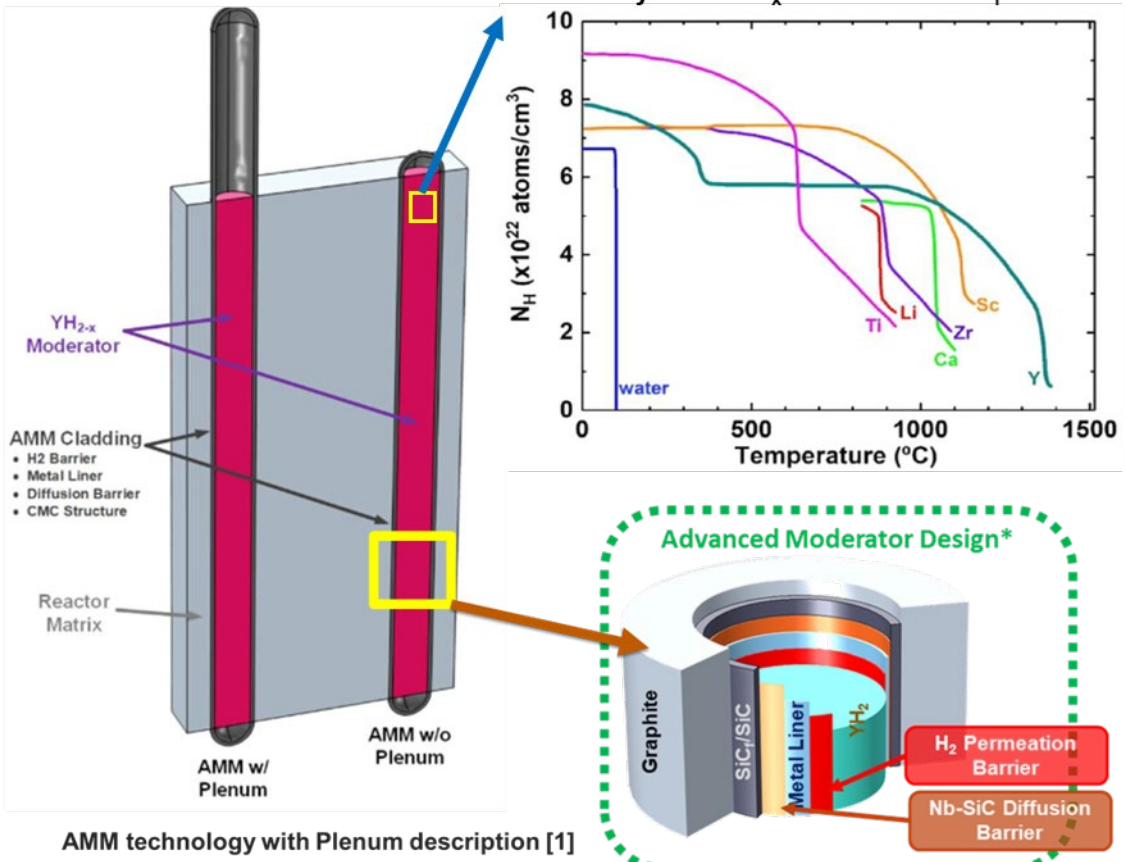
Advanced Moderator Module (AMM) Concept

Argonne National Laboratory is developing an AMM featuring a YH_{2-x} metal hydride, encased in a niobium (Nb) liner with a H_2 barrier to contain hydrogen at high temperatures, and a silicon carbide (SiC) composite cladding for structural integrity.

Advantages

- Utilizing metal hydrides, like YH_{2-x}, allows for optimal moderation.

- AMM's encapsulation method promises an improved performance:
  - Improved H_2 retention.
  - Reduced thermal neutron absorption compared to other approaches (e.g., thicker SS, high temp. alloys, ..)
  - Successful deployment will support compact microreactor cores with extended operational lifetimes.



AMM technology with Plenum description [1]

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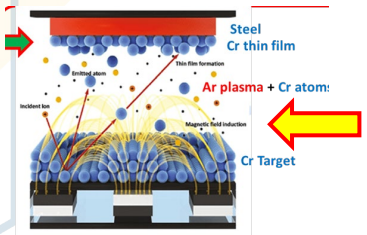
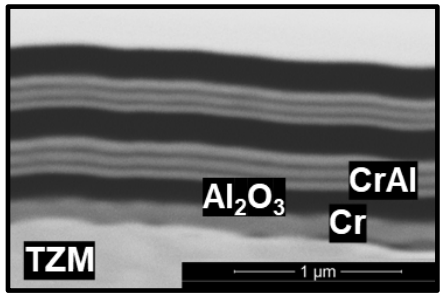
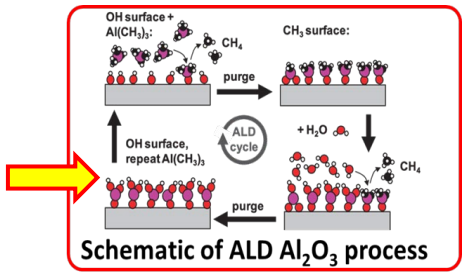
H_2 Barrier Coating (Thermal & Radiation Performance)

FIB cross section of as prepared coating



Schematic of PVD Cr sputtering



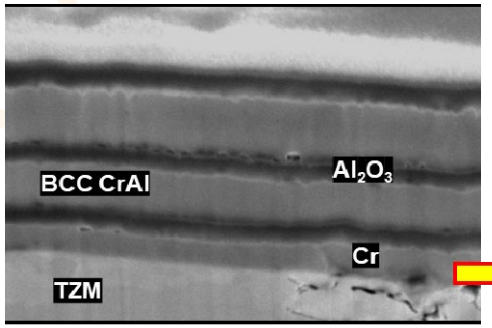


Schematic of ALD Al_2O_3 process

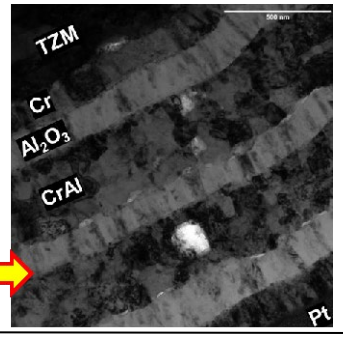
Developed Multilayer Permeation Barrier Design

- Optimal design: thin layers of Al_2O_3 combined with thin Cr_xAl_y most stable.
- Combination of ALD and PVD has been used to generate the metal ceramic architecture.

10 Thermal cycles (900°C)

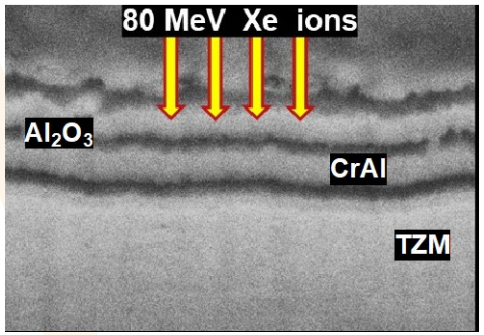


TEM showing interface conditions

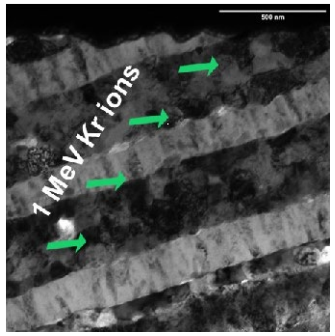


High Temperature Performance of the Functional design

- No surface cracks.
- No separation at the interfaces.
- No interaction between metal/ceramic layers.



~10 dpa (5E16 ions/cm²), AMIS facility



~11 dpa (4E15 ions/cm²) IVEM facility

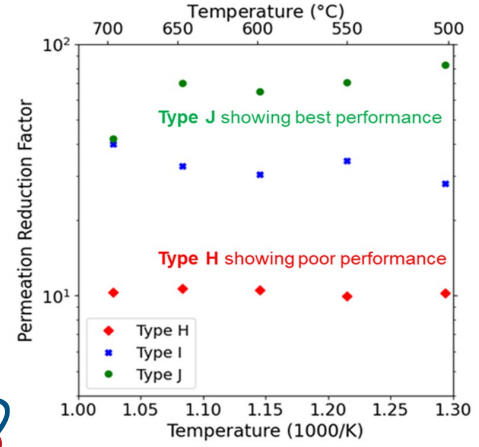
Radiation Tolerance of Developed Permeation Barrier.

- Microstructure and material phases intact
- No observable diffusion & void formation between multilayers

Static Gas Absorption and Permeation (SGAP) Testing at INL:

- Permeation reduction factor (PRF) quantifies hydrogen permeation reduction, serving as a metric for the coating's success.
- **~50 times PRF** is achieved with the multilayer design, measured at 700 °C, against pure H2 (100 Kpa)

PRF of best performing coating at different temp.



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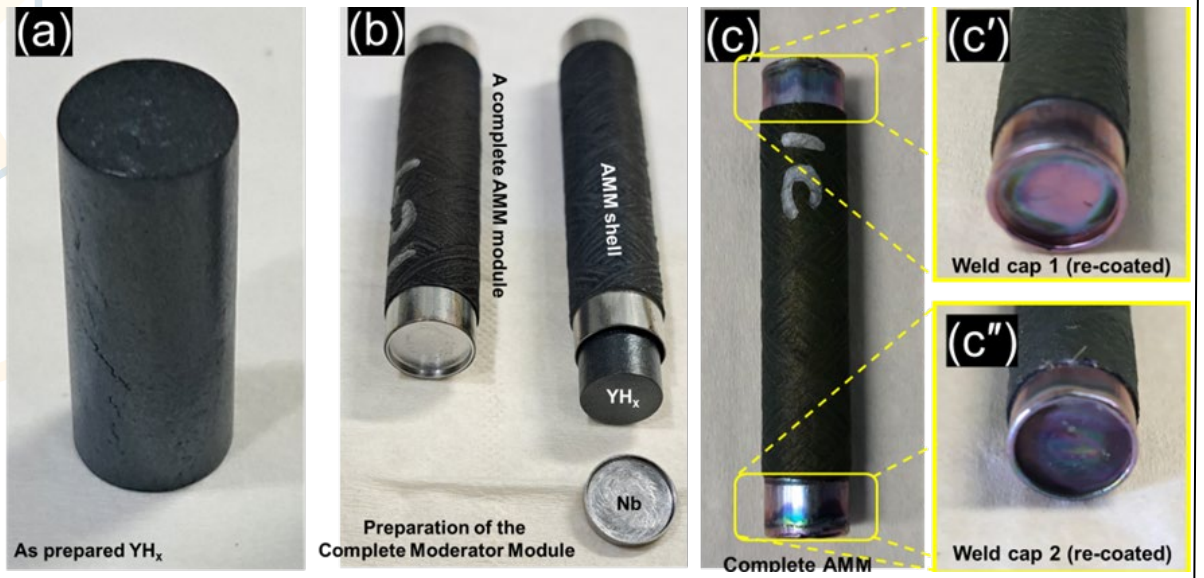
Overview: High Temperature Moderator Containment (Progress)

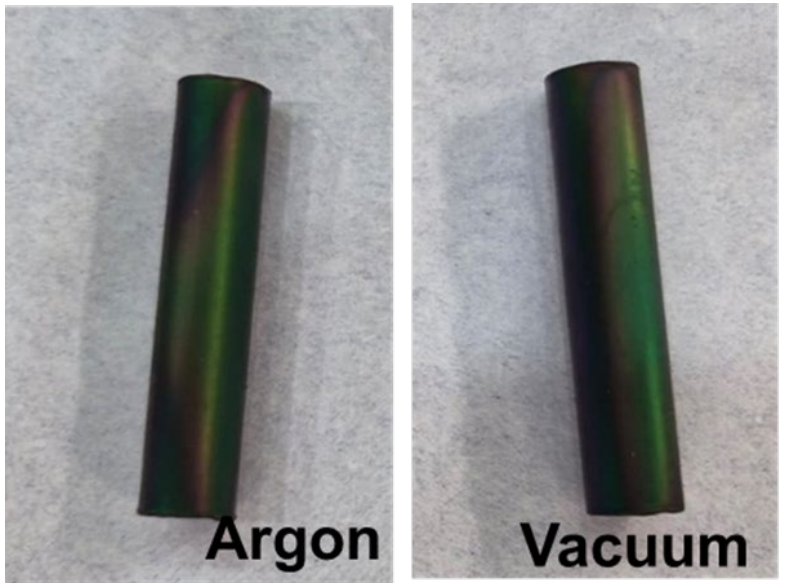
(FY 25-26)

Module Fabrication



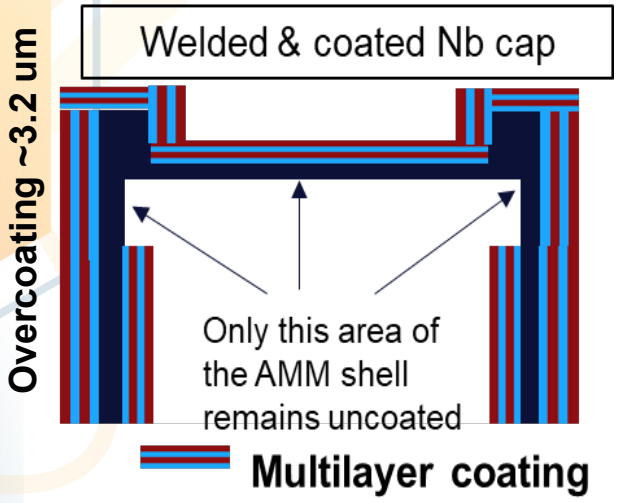
- ***Manufacturing AMM modules:***
  - YHx pellet loading and end cap hermetic seal (TIG weld)
  - Multiple modules produced
- ***AMM performance:***
  - High temperature long term performances (LANL/ANL)
- ***Improvements:***
  - SiC outer **shell degassing** → shell annealing pre-fab.
  - W**eld area coating issues** → Additional weld coating

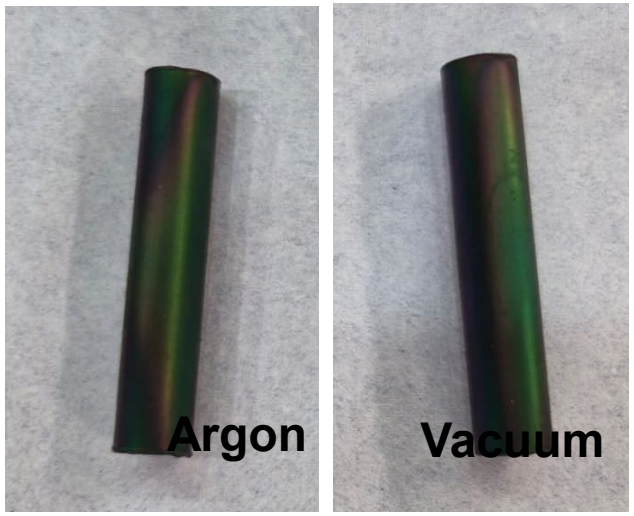
Module Optimization

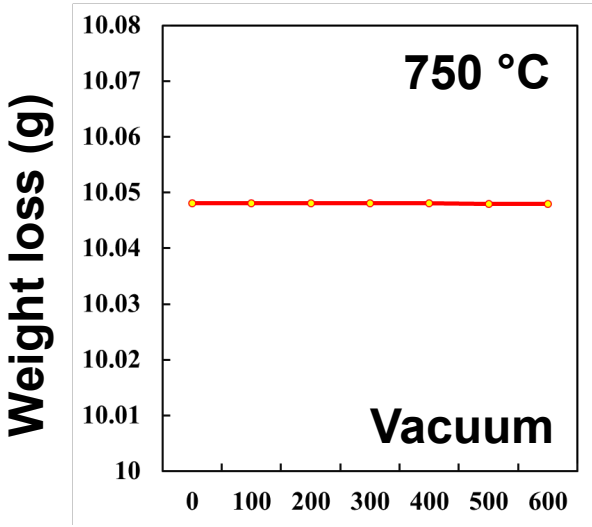


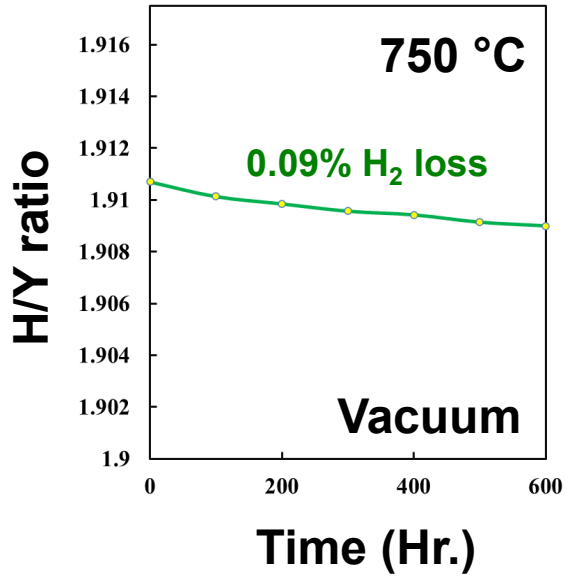
- ***Optimizing AMM modules:***
  - Welded end cap coating design optimized.
- ***Confirmation of AMM performance:***
  - Short term studies shows low H2 losses.
  - Long-term high temperature performances (Ongoing at ANL and collaboration with LANL)
- ***Performance evaluation of liner modules***
  - Coated Nb/Nb-Zr without the SiC composite shell

Optimized Advanced Moderator Module (Tests)

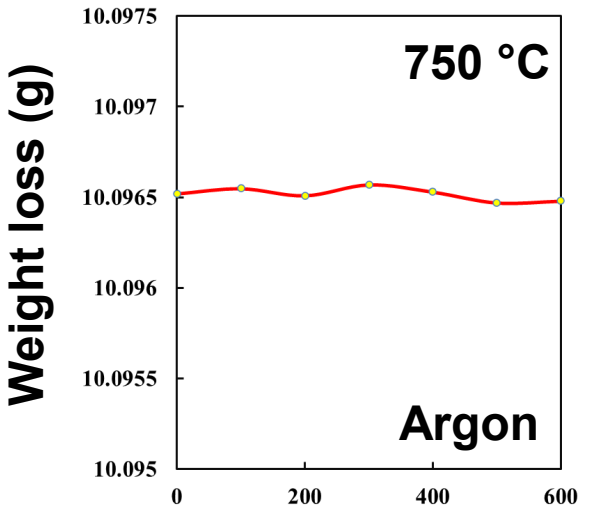


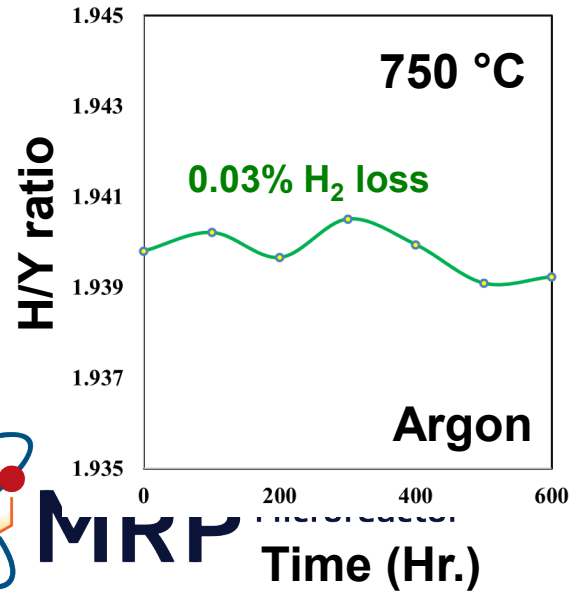






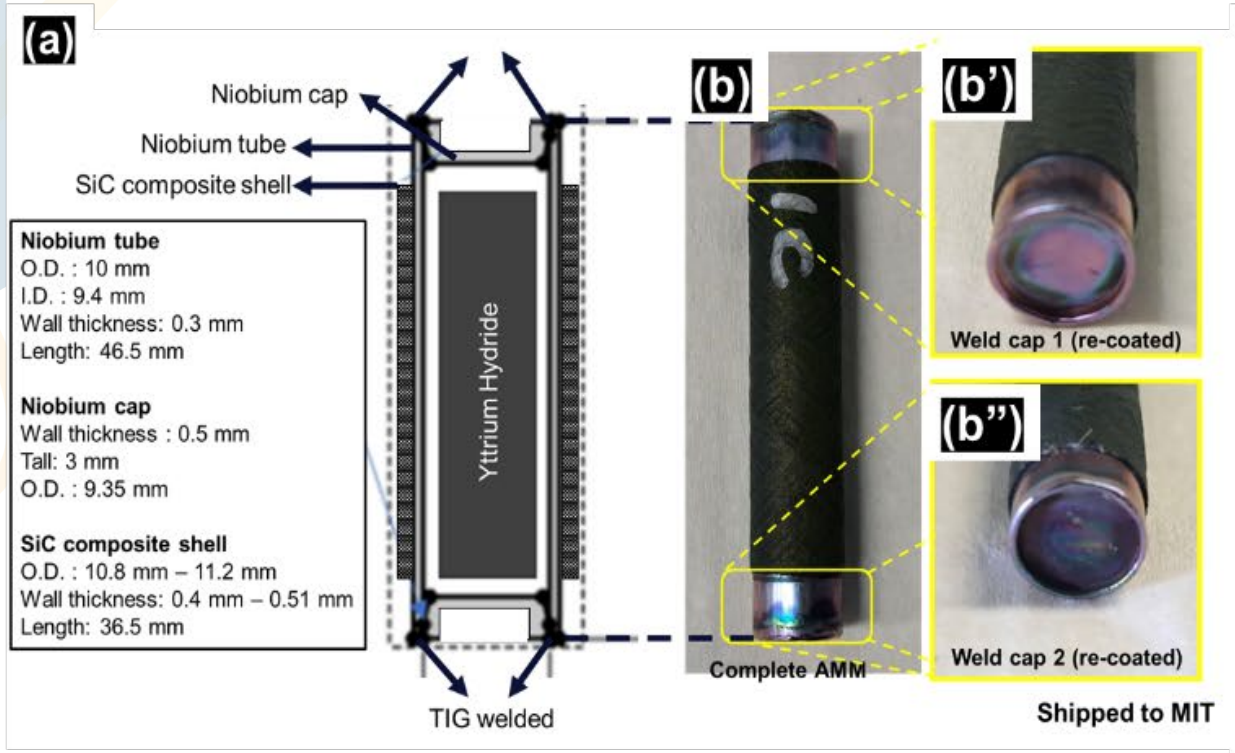
- **Long-duration thermal aging at 750 °C in vacuum/Argon ongoing to emulate high-temperature service conditions.**
  - **Primary intent:** stress the hydrogen-retention/containment architecture under a conservative low–external H_2 partial pressure boundary condition.
  - **Enables side-by-side comparison vs vacuum** aging to separate **intrinsic hydrogen loss** from **environment/handling-driven** contributions
- **Measured mass change & Hydrogen stoichiometry is being quantified during this ongoing study.**
  - Encouraging performance documented





Optimized AMM design showing resilience

PIE for the AMM module irradiated in MIT-R



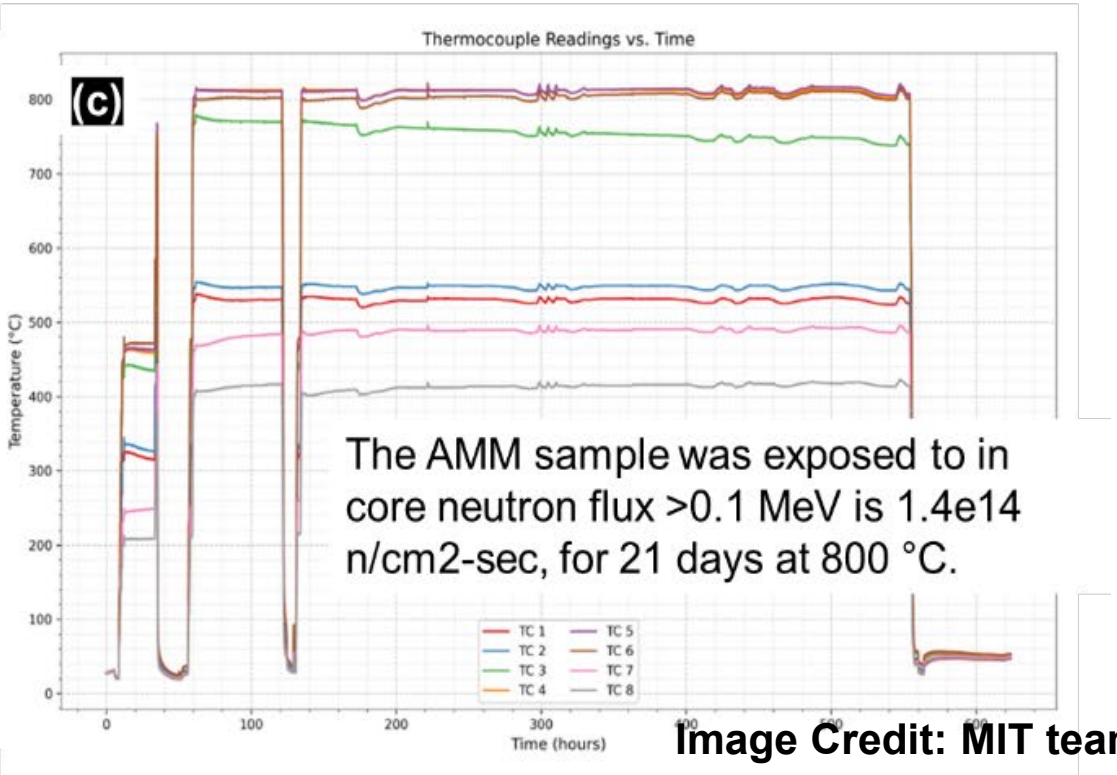


Image Credit: MIT team

- AMM configuration, as-fabricated module images, and MITR irradiation conditions.
- Thermocouple-based temperature history during irradiation, corresponding to a 21-day exposure under fast neutron flux (>0.1 MeV) of ~1.4×10^{14} n·cm^{-2}·s^{-1} with a target T ~ 800 °C.
- NSUF RTE proposal submitted for PIE at INL IMCL facility (**RTE outcome mid May 2026**)
  - Evaluate H2 permeation and characterize radiation damage to coating and interfaces

Acknowledgement for the MITR opportunity: Dr. Caitlin Anne Kohnert

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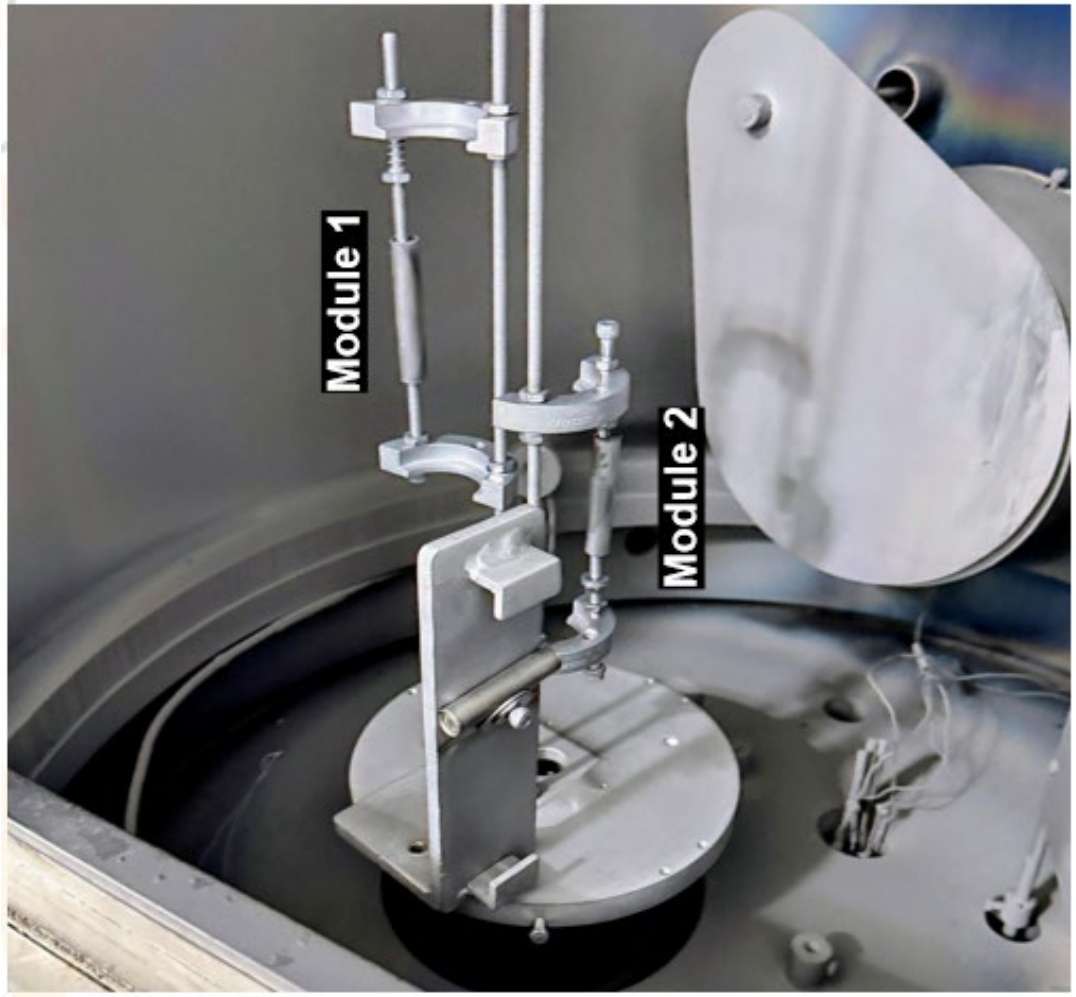
AMM Samples for LANL for 800 °C long term study



PVD setup for coating liner outer surface

- **2x AMM modules prepared for LANL.**
- **Expected to be shipped by end of February.**
- **Long-term high performances (800 °C under high vacuum).**
  - Measured weight changes.
  - Evolution of the H/Y ratio.
  - ND studies to evaluate the YH pellet and the welding status.

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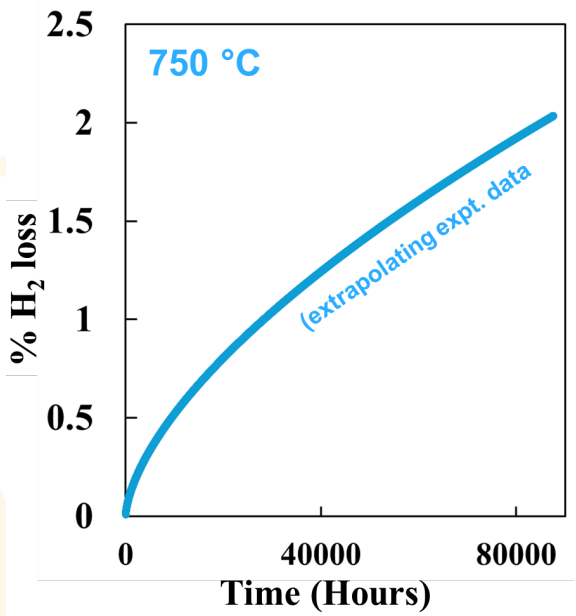
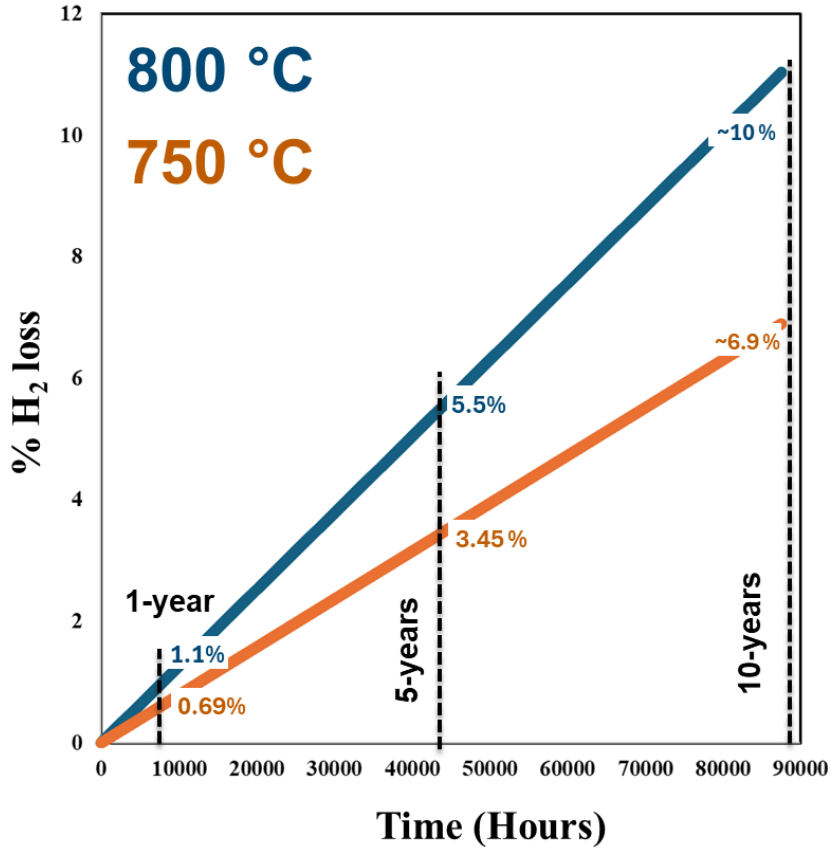
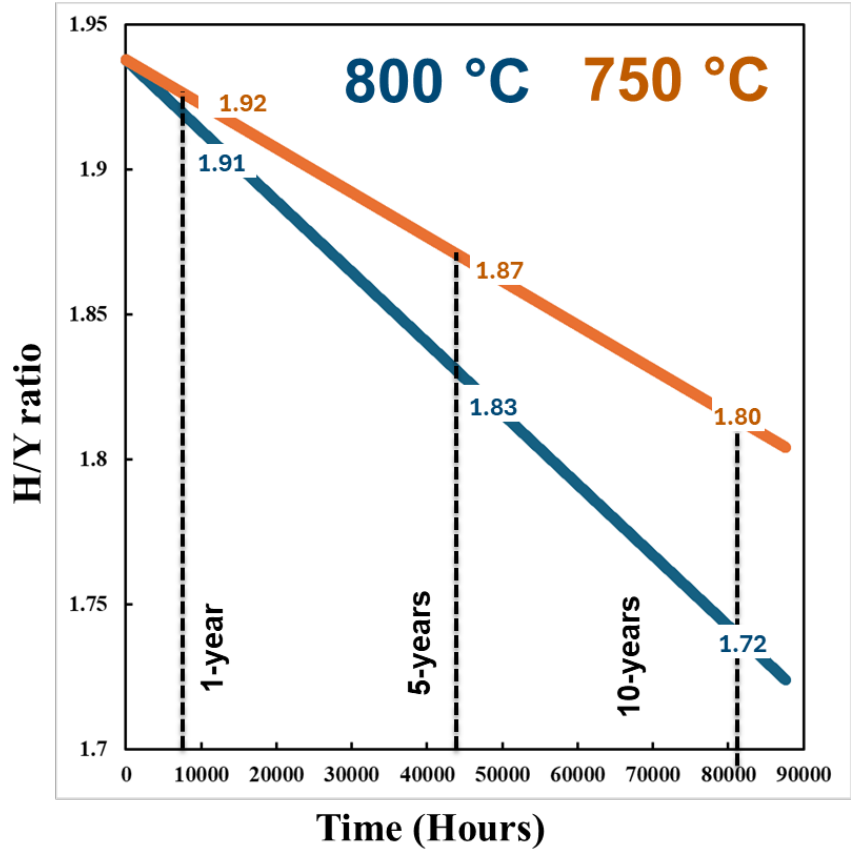
Long term performance of developed AMM at 700 °C, 750 °C, 800 °C

(10 years, with conservative estimates (**Linear fit**))

Best case scenario







800 °C (after 10 years): final H/Y = 1.723968, final %H loss = 10.039%

MRP Microreactor Program

Summary: Advanced Moderator Module (AMM) Concept

Successfully optimized AMM design to improve performance

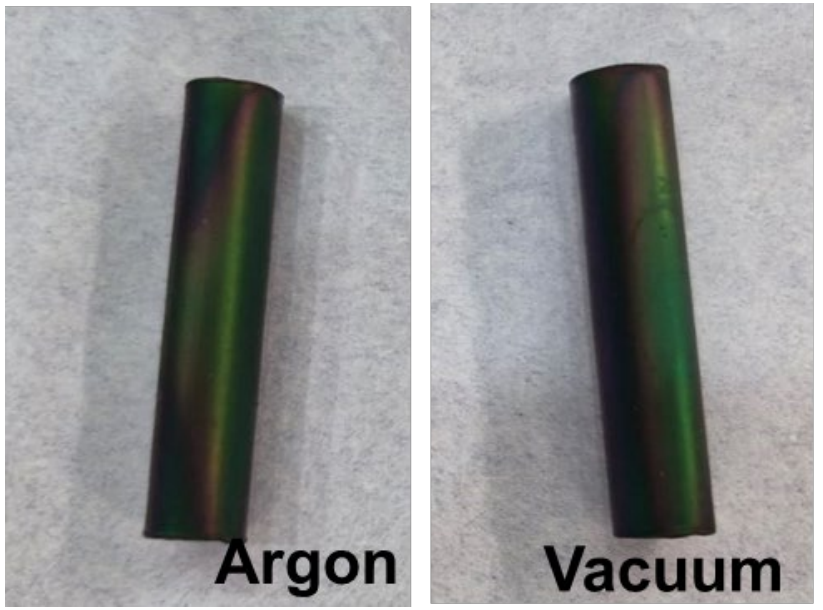
- Identified issue with stability thinner weld cap coating.
  - Implemented thicker multilayer approach
- Standalone Nb liner can withstand 700-800 °C with optimized coating.

High temperature performance (Ongoing with LANL)

- Long term thermal testing (*Ar and Vacuum environment*).
- Non uniform heating of the AMM.
- X-ray computed tomography to verify the status of the YH pellets, Nb liner and weld.

FY26 Remaining Goals:

- Demonstrate optimized AMM perform under prototypic thermal conditions & accumulate data from post testing characterizations:
  - Nb liner and coating,
  - Weld status
  - YH pellets
- Perform PIE of the AMM module that was irradiated in MITR in 2025



Advanced Moderator Module (AMM) (optimized)

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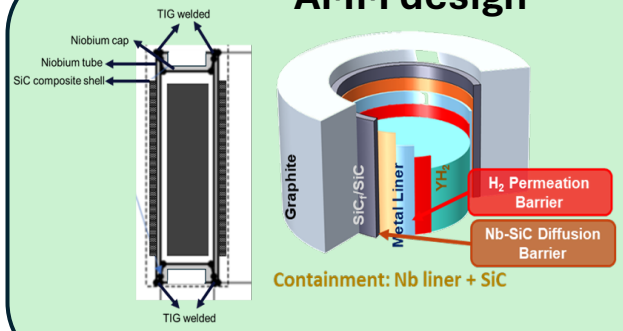
BACKUP

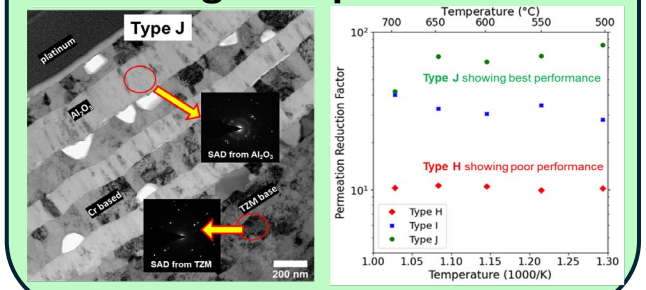
MRP Microreactor Program

Advanced Moderator Module (AMM) development progress timeline

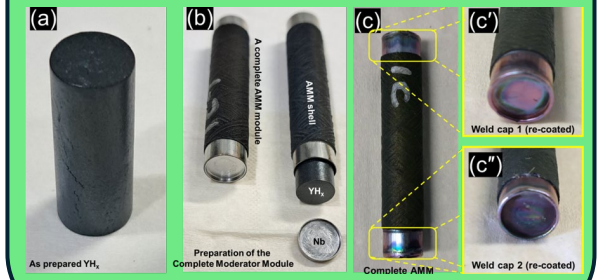
AMM design



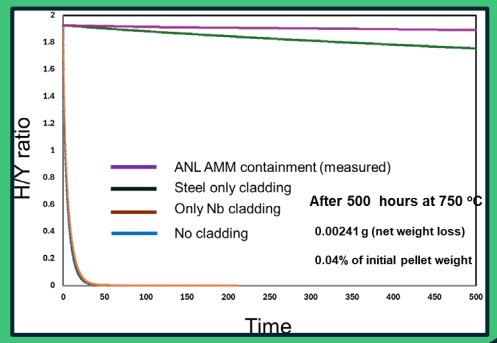
H_2 permeation barrier for high temperature



AMM module manufacturing



H/Y ratio vs. Time (hrs.)



FY-22 (TRL 0-2)

- **AMM containment Design conceived.**
- Intellectual property filed.
  - Neutron moderation modules **US patent # 11,443,858**
  - Hydrogen permeation barrier coatings and methods of making the same, **US patent application # US16925782**

FY 23-24 (TRL 2-3)

H_2 permeation barrier materials and architecture development:

- Metal ceramic multilayer architecture.
- Thermal cycling resistant
- Resistant against radiation damages.
- Significant reduction in H_2 permeation.

~50 times PRF is achieved with the multilayer design, measured at 700 °C, against pure H2 (100 Kpa)

FY 24-25 (TRL 4-5)

Manufacturing AMM modules:

- YH_x pellet loading within prepared AMM shells (Nb liner with SiC CMC).
- Hermetic seal to generate the module (TIG welding).

Multiple size modules manufactured.

Current capability: Manufacture modules with up to 1 meter (L) with 45 mm (O.D.)

FY 25 (TRL 6-7)

Long term thermal testing and MIT-Reactor insertion:

- Weight loss tracking of manufactured AMM, measured at 750 °C
  - **Loss of only 0.1% of H_2**
- **AMM module inserted in MIT-reactor in February 2025.**
  - 800 °C, 3 dpa
  - Sample expected recovery in May 2025.