High Temperature Moderator Containment:

Advanced Moderator Module (AMM) Concept

March 5, 2025

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Introduction: Yttrium Hydride based Moderator designs

Advanced neutron moderators are required for microreactors due to the:

- − Lower fuel enrichment of HALEU (<20%) instead of high enriched uranium.
- − Compact size.
- − High efficiency/high temperature requirements.

Hydrogen is the best moderator as it has a low Z number. So, materials with high H_2 density will be ideal candidate, such as metal hydrides.

− **Yttrium hydride YH_x** (out of all metal hydrides) shows the best potential, because:

- Exceptional high H_2 concentration (figure a),
- Low neutron absorption cross section,
- Can sustain high temperature with low H_2 dissociation pressure (figure b),
- Good thermal conductivity and high melting point.

− **Even with low H_2 dissociation for YH_x, it is still ~1 atm at ~850 ^{o}C** (see, Figure (b)). Consequently, it needs to be encapsulated to prevent H_2 loss during long term operations.

− ANL is using a SiC/Nb based moderator design to encapsulate the YHx.

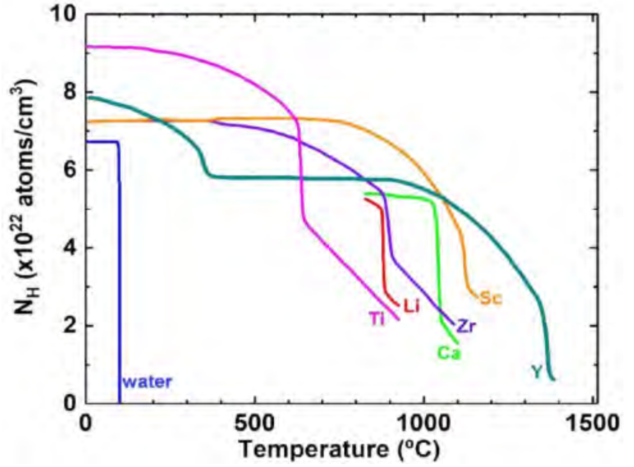


Figure (a)

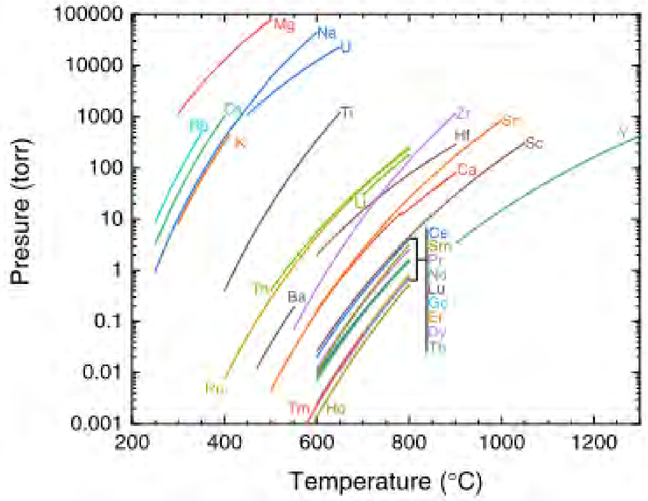
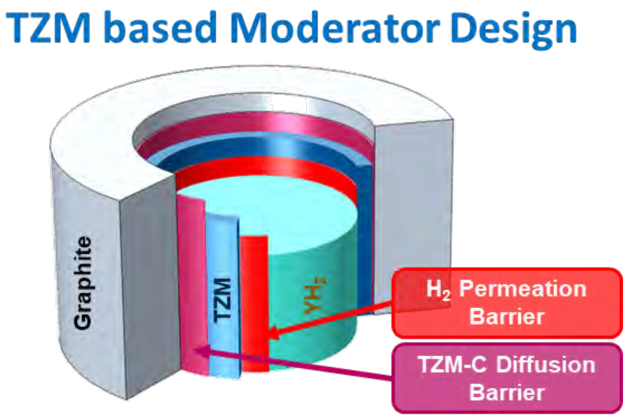


Figure (b)

MRP Microreactor Program

Overview: High Temperature Moderator Containment (ANL contributions)

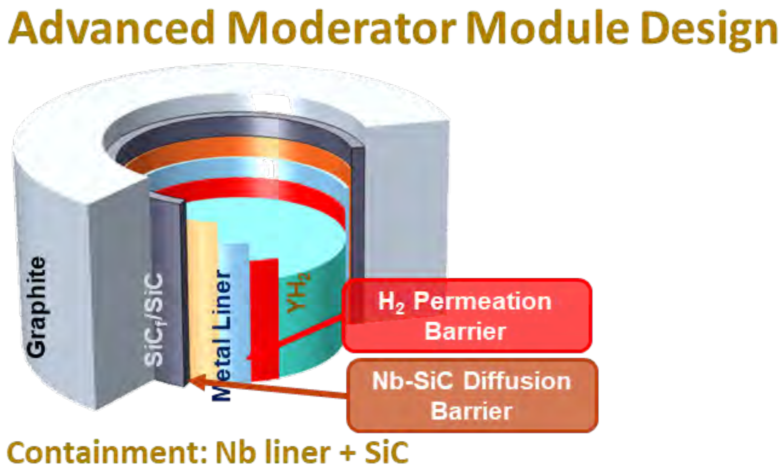
Heat & radiation resistant high temperature barrier coating



- ***H_2 permeation barrier and graphite interaction barrier materials and architecture selection:***
  - Metal ceramic multilayer architecture.
  - Cr_xAl_y /Al_2O_3 based design.
  - Optimized individual layer thickness.
- ***Confirmation of desired barrier properties:***
  - Thermal cycling resistant
  - Resistant against radiation damages.
  - Significant reduction in H_2 permeation.
  - Prevents high temperature graphite interactions

(FY-23, completed)

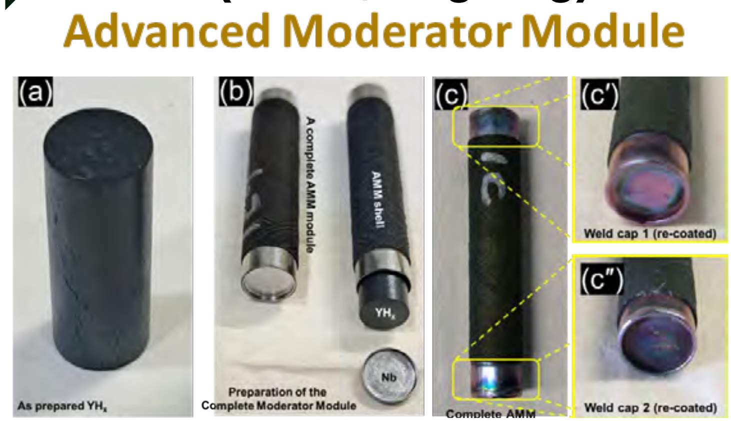
Advanced Moderator Module (AMM) concept



- ***Preparation of AMM modules:***
  - Implementation of developed H_2 barrier design within Nb tubes.
  - Confirmation of mechanical and thermal properties of the implemented barrier coating.
  - Manufacturing outer SiC shells.
  - Shrink fitting SiC shells over coated Nb liners.
  - Hermetic sealing of coated Nb liners (welding).

(FY-24, completed)

Advanced Moderator Module (AMM) concept
(FY-25, ongoing)

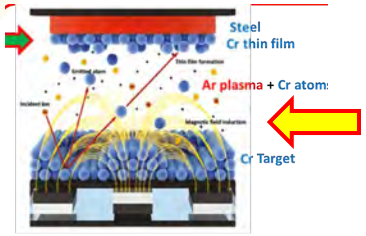


- ***Manufacturing AMM modules:***
  - YHx pellet loading within prepared AMM shells (Nb liner with SiC CMC) in FY24.
  - Hermetic seal to generate the module (TIG welding).
  - Successfully created multiple modules.
- ***Confirmation of AMM performance:***
  - High temperature long term performances (Ongoing collaboration with LANL)

MRP Microreactor Program

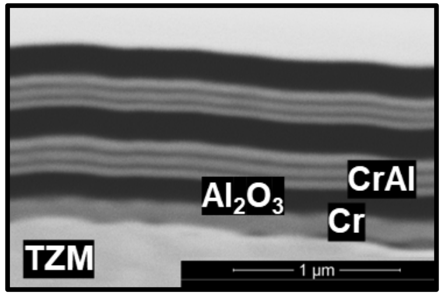
Recap of properties of the developed H_2 permeation barrier in FY 23

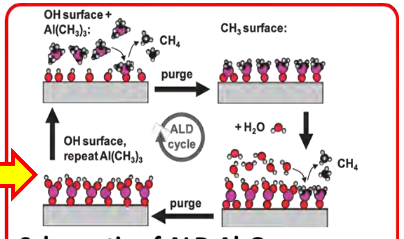
H_2 Barrier Coating (Thermal & Radiation Performance)



Schematic of PVD Cr sputtering

FIB cross section of as prepared coating



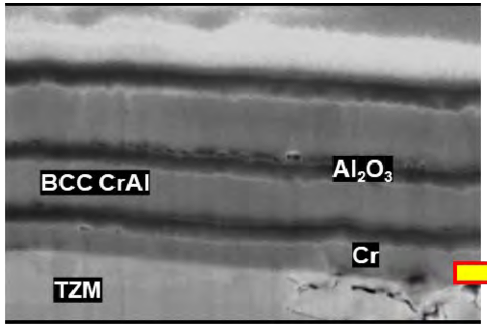


Schematic of ALD Al_2O_3 process

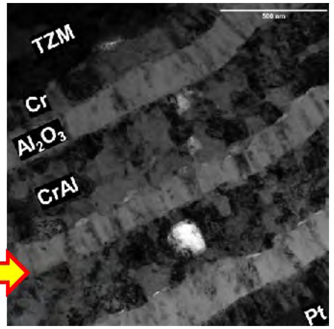
Developed Multilayer Permeation Barrier Design

- 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^{o}C)



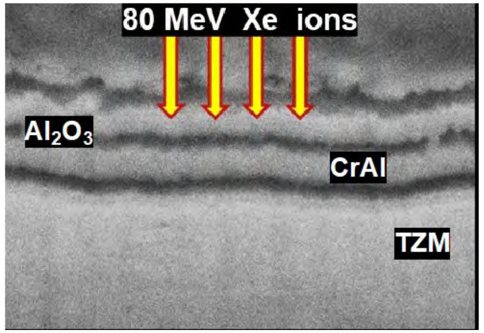
TEM showing interface conditions



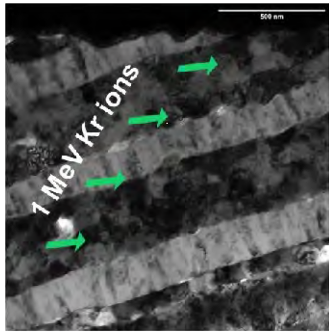
High Temperature Performance of the Functional design

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

ATLAS Materials Irradiation Station (AMIS)



~10 dpa (5E16 ions/cm^2), AMIS facility



~11 dpa (4E15 ions/cm^2) IVEM facility

Radiation Tolerance of Developed Permeation Barrier.

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

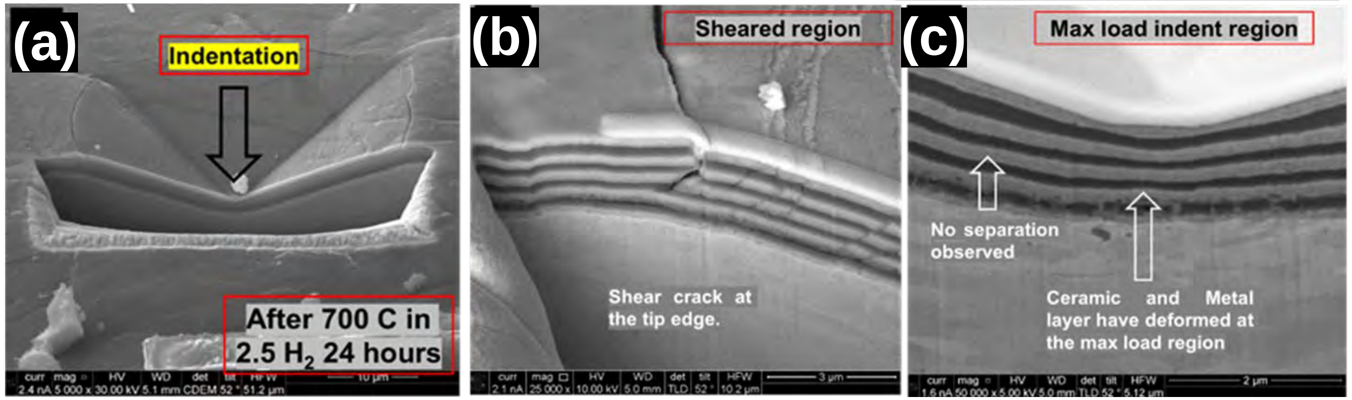
MRP Microreactor Program

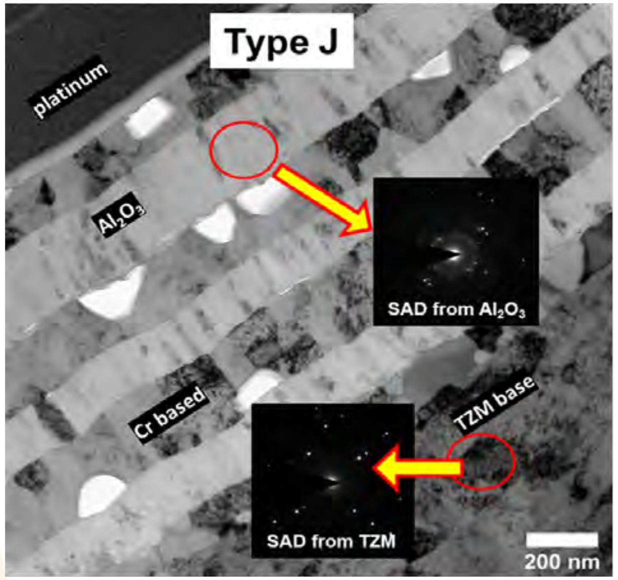
H_2 Barrier coating (Mechanical & Permeation Performance)

Mechanical behavior (localized deformation via micro indentation)

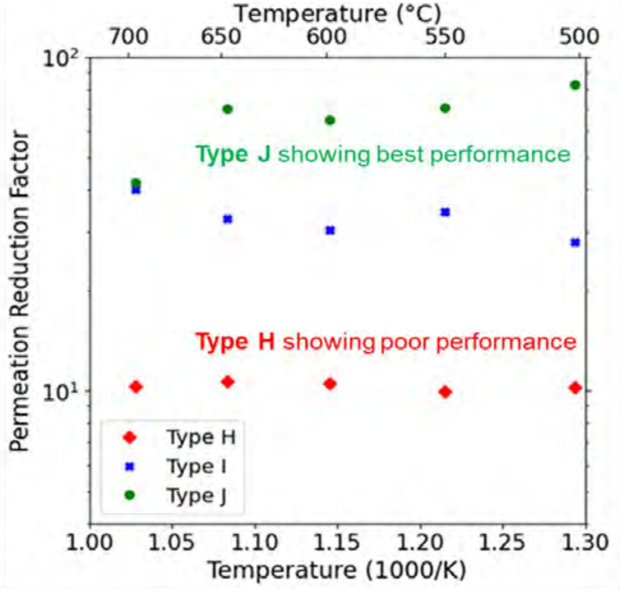
- At max load region, Al_2O_3 and CrAl deformed, but no layer cracks or separation at other coating regions
- Crack traveled through first few layers, but stopped at one of the CrAl layer

500g-force/15 seconds





TEM image taken from multilayer cross section after exposure to **pure H_2 (100 Kpa) at 700 °C**



PRF of best performing coating at different temp.

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)

MRP Microreactor Program

Recap of AMM design and step by step preparation in FY 24

MRP Microreactor Program

Advanced Moderator Module (AMM) Concept

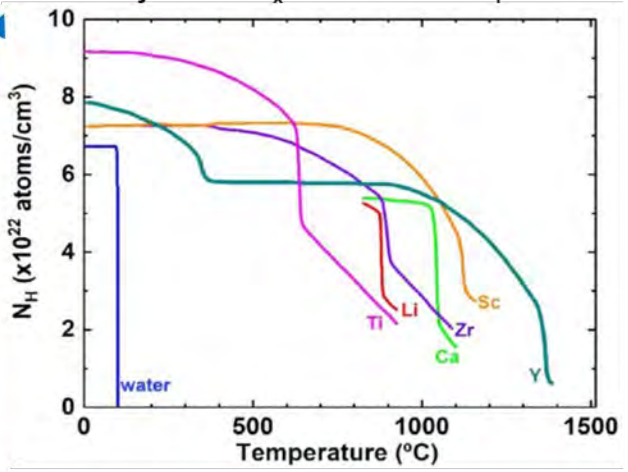
Argonne National Laboratory is developing an AMM featuring a YH_{2-x} metal hydride, encased in a niobium (Nb) liner with a H_2 barrier to contain hydrogen at high temperatures, and a silicon carbide (SiC) composite cladding for structural integrity.

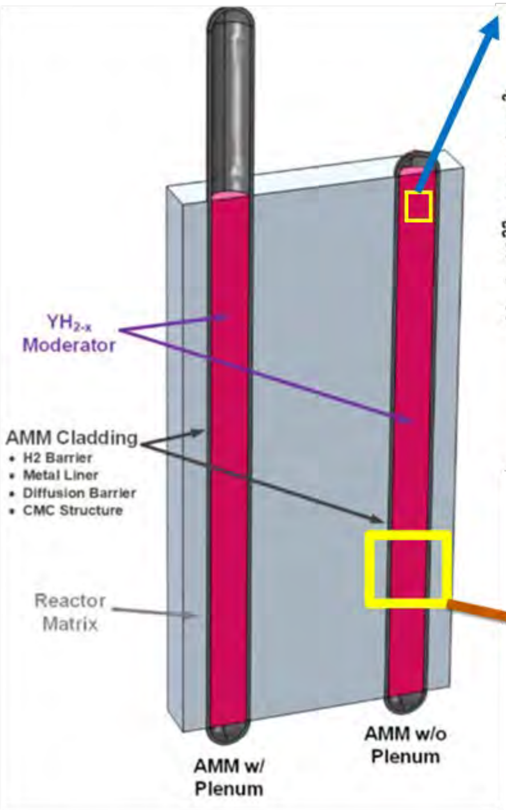
Advantages

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

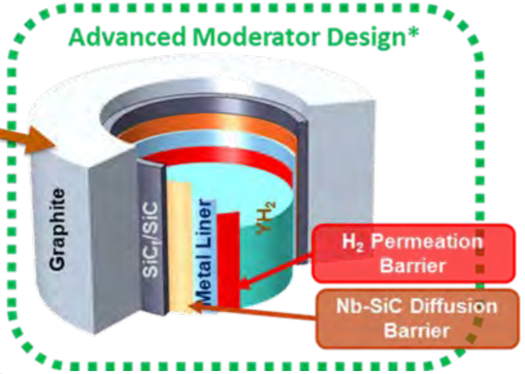
- AMM's encapsulation method promises an improved performance:
  - Improved H_2 retention.
  - Reduced thermal neutron absorption compared to other approaches (e.g., SS, high temp. alloys, ..)
  - Successful deployment will support small microreactor cores with extended operational lifetimes.

Yttrium hydride YH_x shows the best potential





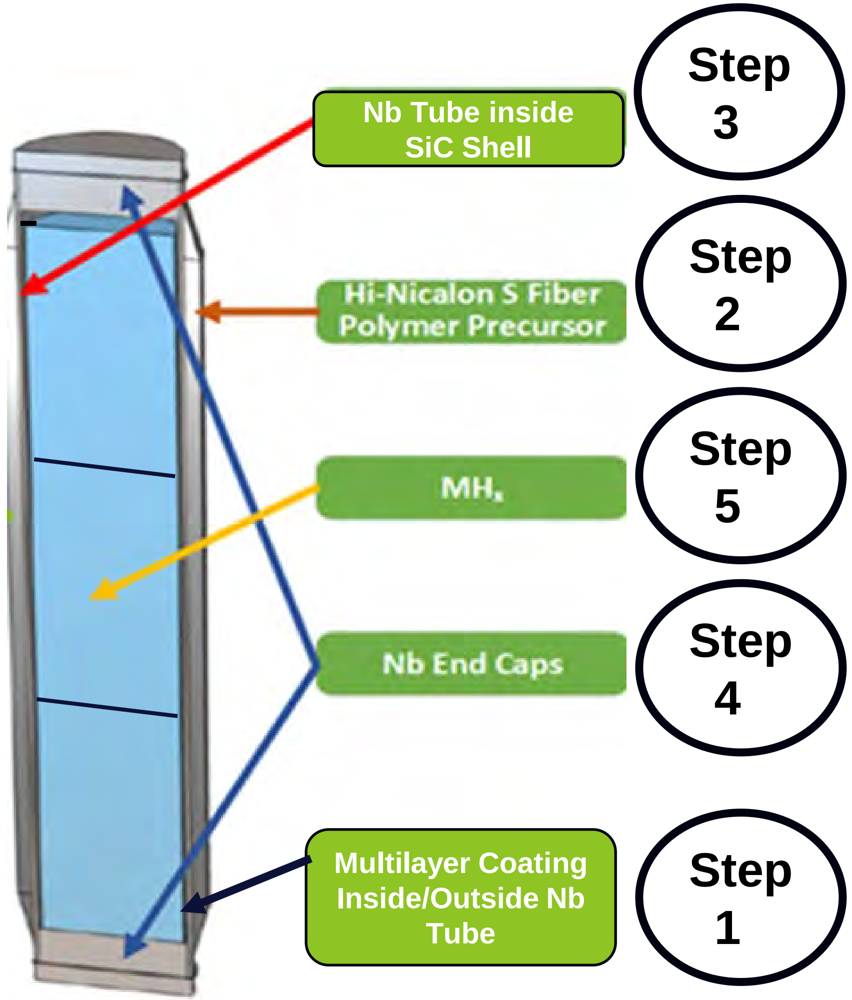
AMM technology with Plenum description [1]



MRP Microreactor Program

Advanced Moderator Module (AMM) manufacturing steps

1. **Implementation of developed H_2 barrier design inside & outside of 10 mm O.D. Nb liners/tubes** – Implementation completed
2. **Manufacturing outer SiC composite shells via polymer impregnation and pyrolysis (PIP)** – Manufacturing completed
3. **Form SiC composite shells on Nb tubes** – Manufacturing completed
4. **Welding end caps** – Trial completed
5. **Loading of YH_{2-x} pellets (from LANL)**- completed



Schematic of the AMM Cross section , showing the metal hydride pellet within Nb liner, and enclosed by two Nb caps, welded on both ends.

AMM prototype manufacturing – Ongoing in FY25

MRP Microreactor Program

Step-1 H_2 barrier

Summary of Processes

As-Received Nb Tubes (50 cm × Φ1 cm)

↓

ALD Al_2O_3 (inside & outside)

↓

PVD CrAl (inside & outside)

↓

ALD Al_2O_3 (inside & outside)

↓

PVD CrAl (inside & outside)

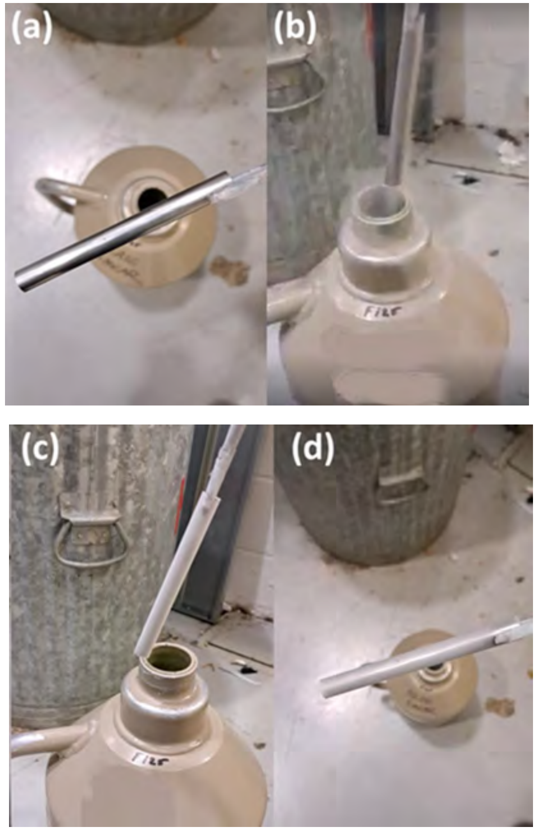
Step-2

SiC shells prepared via PIP technique where the polymer infiltrated SiC fiber pre-form prepared over graphite mandrel.

In collaboration with **Ceramic Tubular Products (CTP)**

Step-3

Cryogenic Shrink fitting

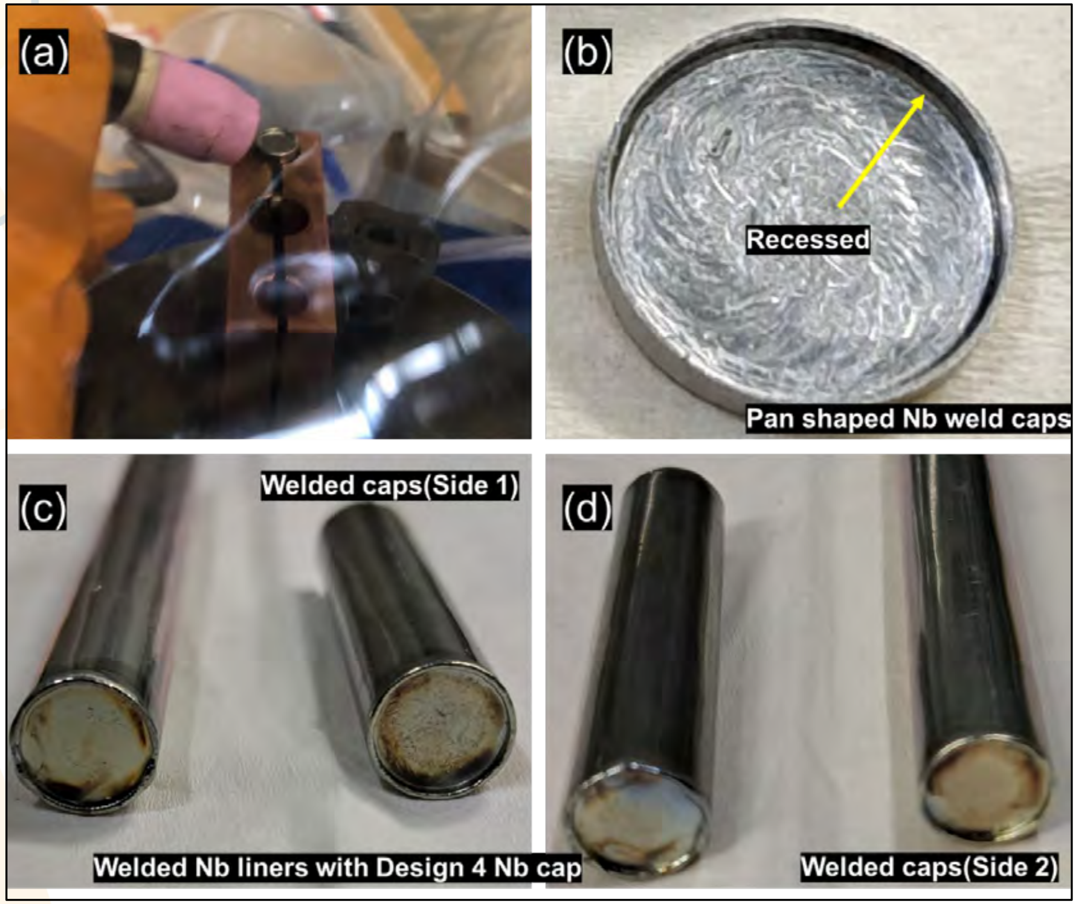


Despite extreme low temperatures & stresses of rapid contraction/ expansion, Cr_xAl_y /Al_2O_3 coating remain adherent to Nb substrate.

MRP Microreactor Program

Step-4

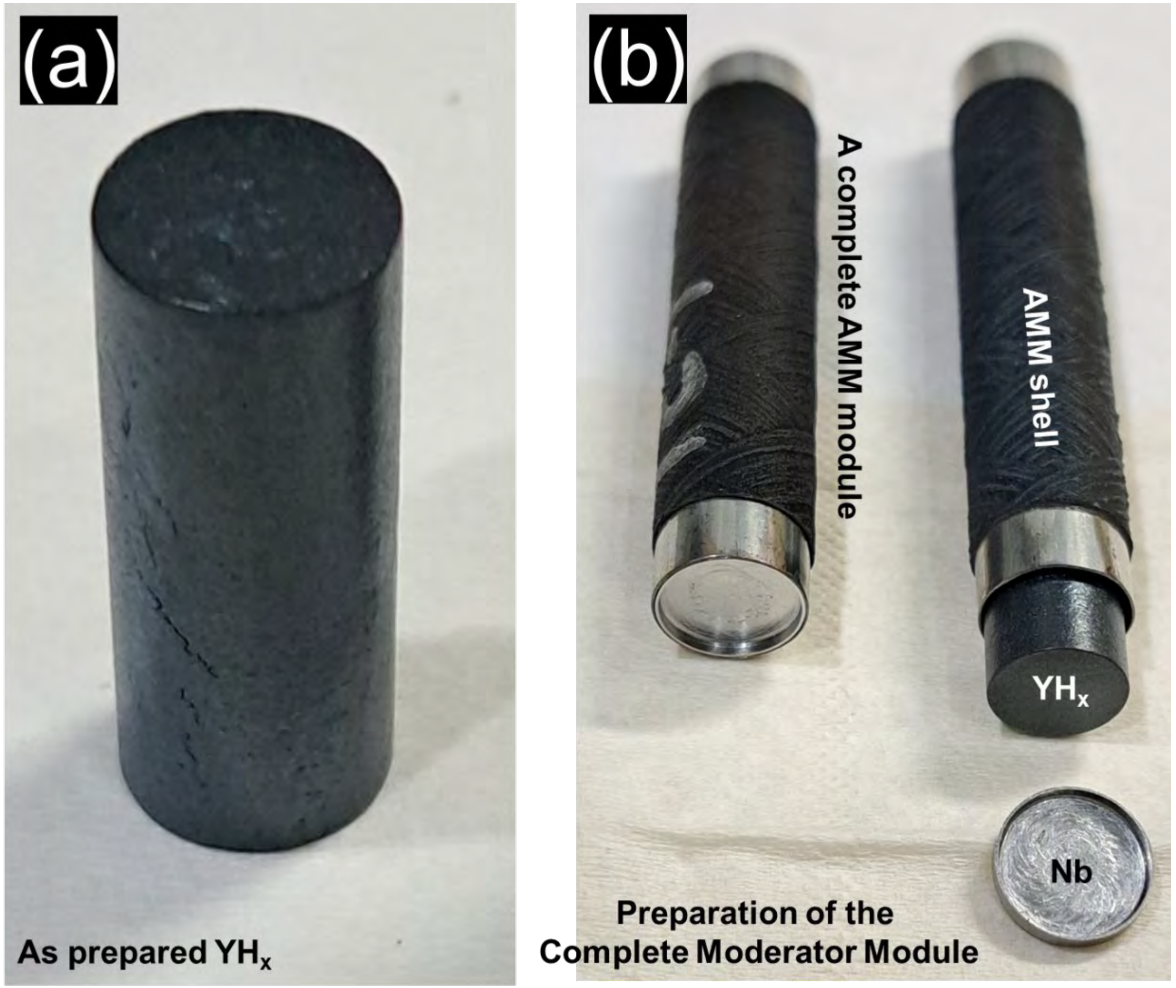
End cap weld development



The TIG weld has generated a secure and consistent weld joint.

Step-5

Loading YH_{2-x} pellets and welding end caps



More details on individual steps can be found in our earlier reports and Microreactor program review presentations

MRP Microreactor Program

FY 25 AMM Proof of Concept: manufacturing & testing activities

MRP Microreactor Program

Work scope for FY25 and progress made

1. Manufacturing AMM modules (Completed):

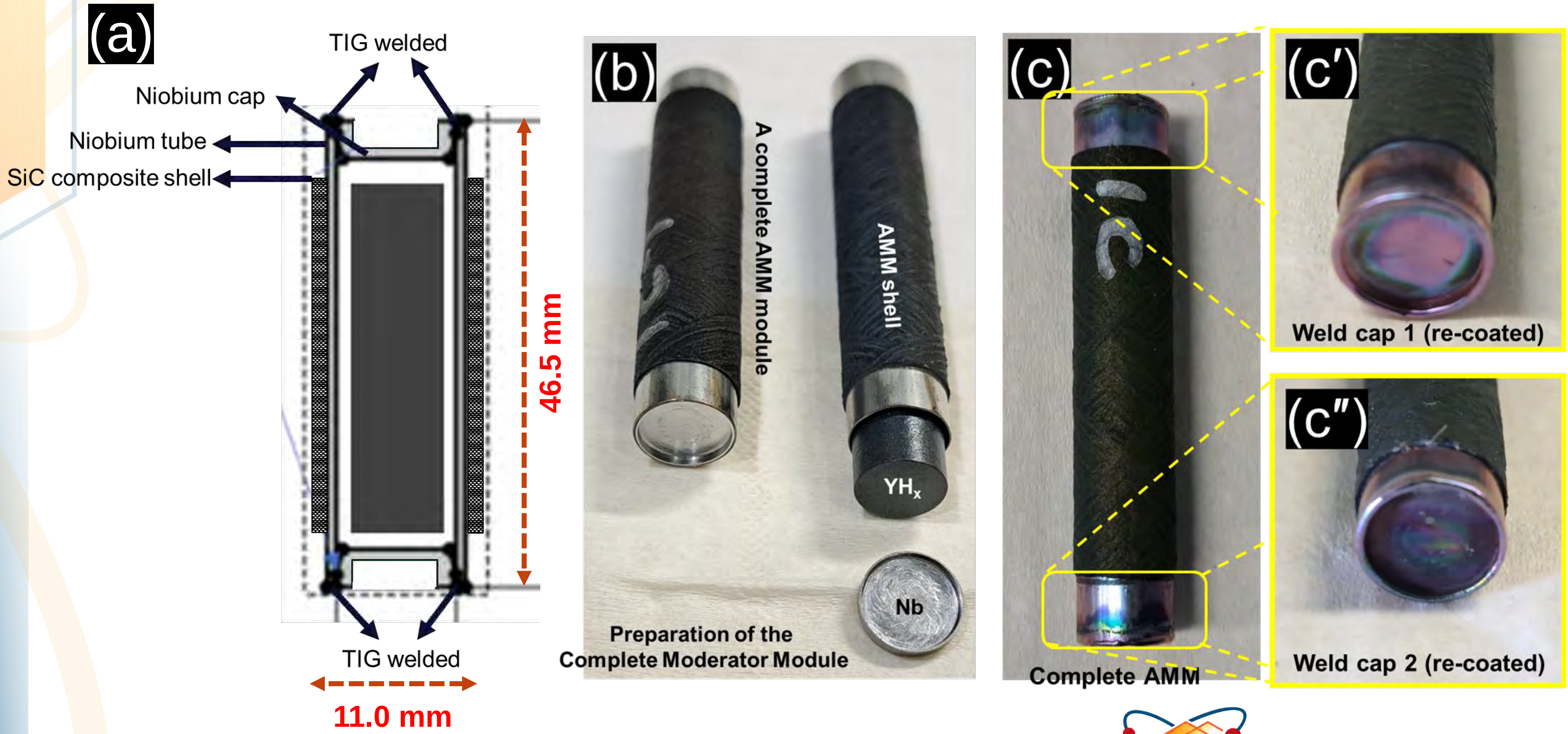
- AMM shells (Nb liner with SiC CMC): prepared in FY24
- YH_{2-x} pellet loading
- Hermetic sealing (TIG welding)

2. High temperature performance (Ongoing collaboration with LANL)

- Long term thermal testing (*Ar and Vacuum environment*).
  - Weight change tracking (H_2 loss)
  - X-ray computed tomography to verify the status of the YH pellets, Nb liner and weld.
- Non uniform heating of the AMM.
  - Thermal gradient impact
- Analysis after thermal studies.
  - Evaluate status of the different components: SiC CMC, Nb liner, Welding and YH pellets

MRP Microreactor Program

Advanced Moderator Module Manufacturing

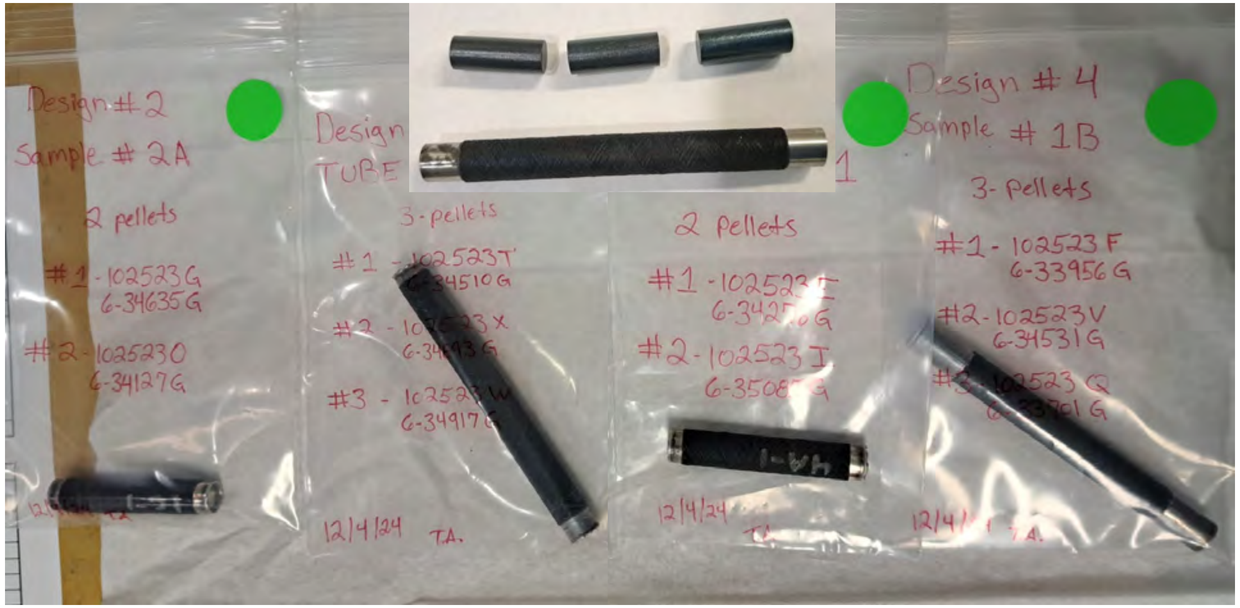


Images of the first completed ANL made moderator module.

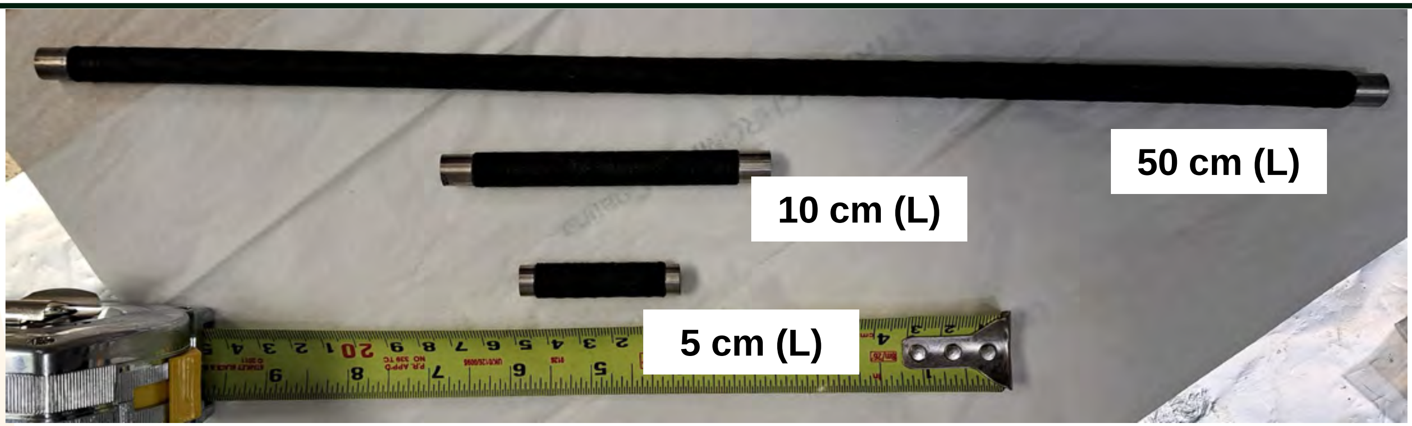
MRP Microreactor Program

AMM Manufacturing (continued)

Demonstrated manufacturing of different size modules



Capability to manufacture modules up to 1 m long & 45 mm (O.D.)



He leak check inspections

CS/IN FORM: 700	CENTRAL SHOPS INSPECTION MSLD TECHNIQUE RECORD	PAGE 1 OF 1

INSPECTION REQUIREMENTS

DIVISION: CFC	PERSON: SUMMIT BHATTACHARYA	JOB NO.: [illegible]
INSPECTION CODE:	ACCEPTANCE CRITERIA: [illegible] std. cc/sec	PART INT. VOLUME: / MAX. PRESSURE:
PART NAME: NIOBIUM TUBES	JCP#: N/A	DWG. NO.: N/A
PART NUMBER(S): LISTED BELOW		

PART DESCRIPTION, IDENTIFICATION OF PART AREA(S) TO BE INSPECTED & SPECIAL INSTRUCTIONS: *(type component, weld joint number, specific part area, etc.)*

INSPECT WELD JOINTS FOR LEAKS USING PROVIDED VACUUM CYLINDER TO INSERT TUBE AND VERIFY NO HELIUM LEAKS OUT OF PELLET TUBES.
TUBES TESTED: DESIGN #1 / TUBE #3, DESIGN #2 / TUBE #2A, DESIGN #4 / TUBE #1B, DESIGN #4 / TUBE #4A-1.

ATTACHMENTS: (X) SKETCH [ ] DRAWING [ ] OTHER

FOR CS/IN USE ONLY

PART IDENTIFICATION: NIOBIUM TUBES		INSPECTION DATE: 01/10/25
		PROCEDURE: Q-005
MSLD MFG.: Adixen	MODEL: ASM 390	PUMPING RATE: 5 L/S
AUX. ROUGHING PUMP MFG.: N/A		PUMPING RATE: N/A
AUX. VALVE(S) TYPE: N/A	SIZE: N/A	
HOSE OR AUX. MANIFOLD TYPE: N/A	LENGTH: N/A	MIN. I.D.: N/A
MARKING & SEALING MATERIAL: N/A		
METHOD OF REMOVING MARKING & SEALING MAT'L: Acetone and Alcohol		
STANDARD CALIBRATED LEAK MFG.: Adixen	TYPE: EXTERNAL	
STD. CAL. LEAK RATE: 9.36E-8 mbar l/s	DATE LAST CALIBRATED: 01/10/25	
LEAK TEST METHOD: VACUUM TUBE		
RESPONSE TIME OF CAL. LEAK: ~1 sec	TRACER GAS CONCENTRATION: 99.99%	
APPLICATION TIME OF He TO PART: [illegible]	TEST TIME: 15 MIN. EACH	
SYSTEM SENSITIVITY: 1.0 X 10[illegible] mbar L/S	TEST SENSITIVITY: 1.5 X 10[illegible] std. cc/sec	

INSPECTION RESULTS: [X] ACCEPT	[ ] UNACCEPT	[ ] OTHER*:	NCR NO.:

COMMENTS *(reportable indications, etc.)*:

No helium response at 1.0 X 10[illegible] std. cc/sec.

INSPECTOR: *Jonathan Torres*	CERT. LEVEL: II	DATE: 01/10/25

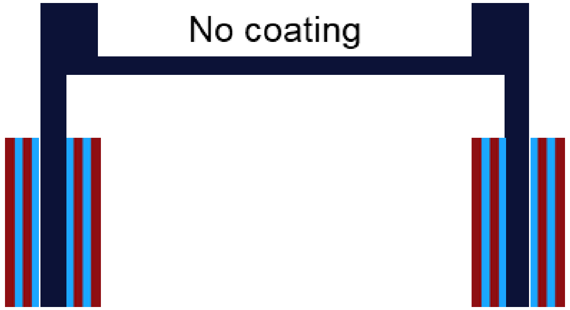
(05/09)

MRP Microreactor Program

Suppression of possible H_2 permeation through weld HAZ areas

Issue: Affected weld zone as H_2 permeation weak spot

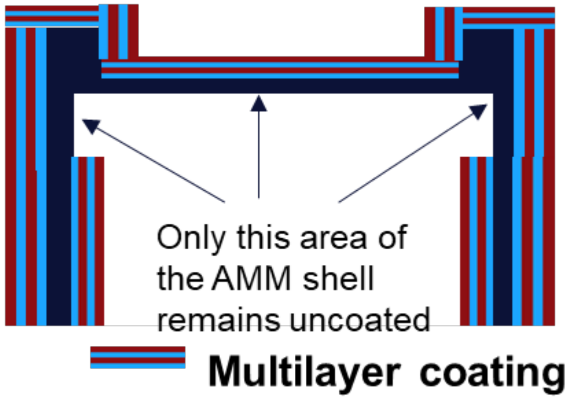
Welded Nb cap on the Nb tube



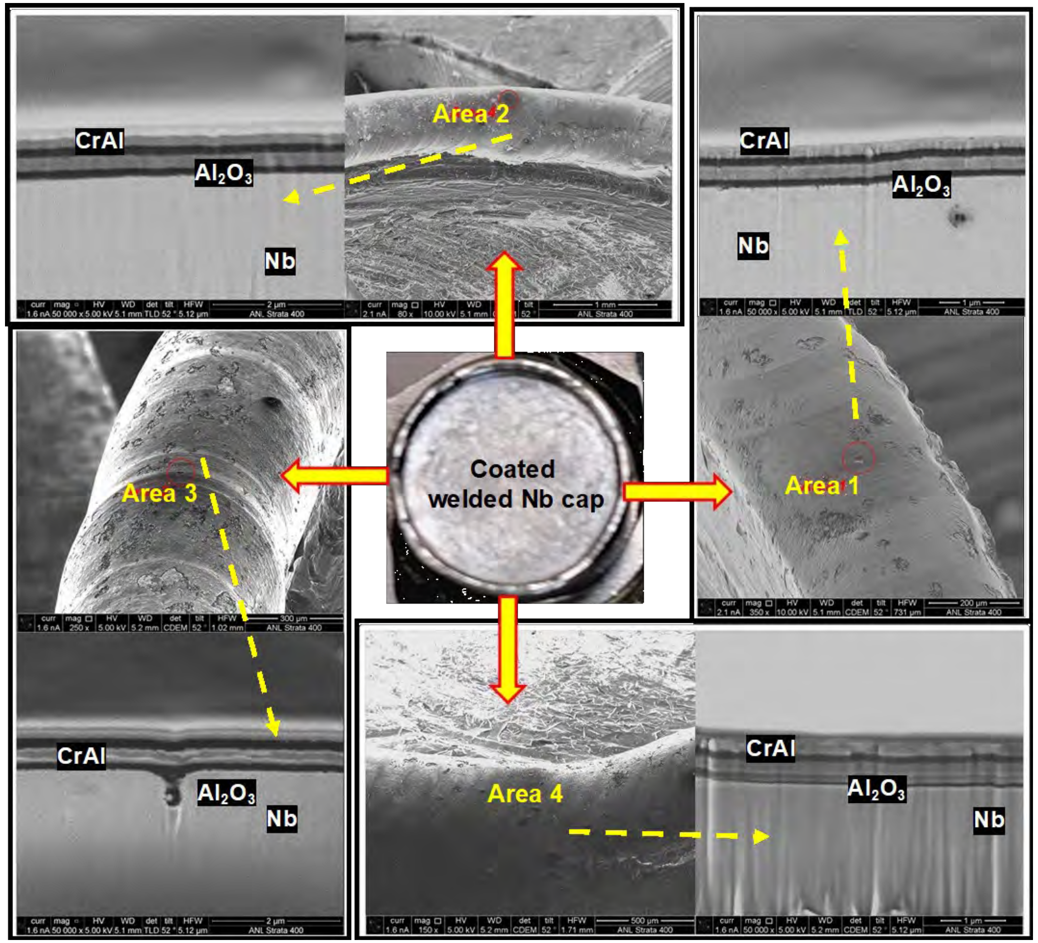
Resolution: Applied external multilayer coating

Welded & coated with only Al_2O_3

Welded & coated Nb cap



FIB analysis after welded region has been coated and HT at 800 ^{o}C



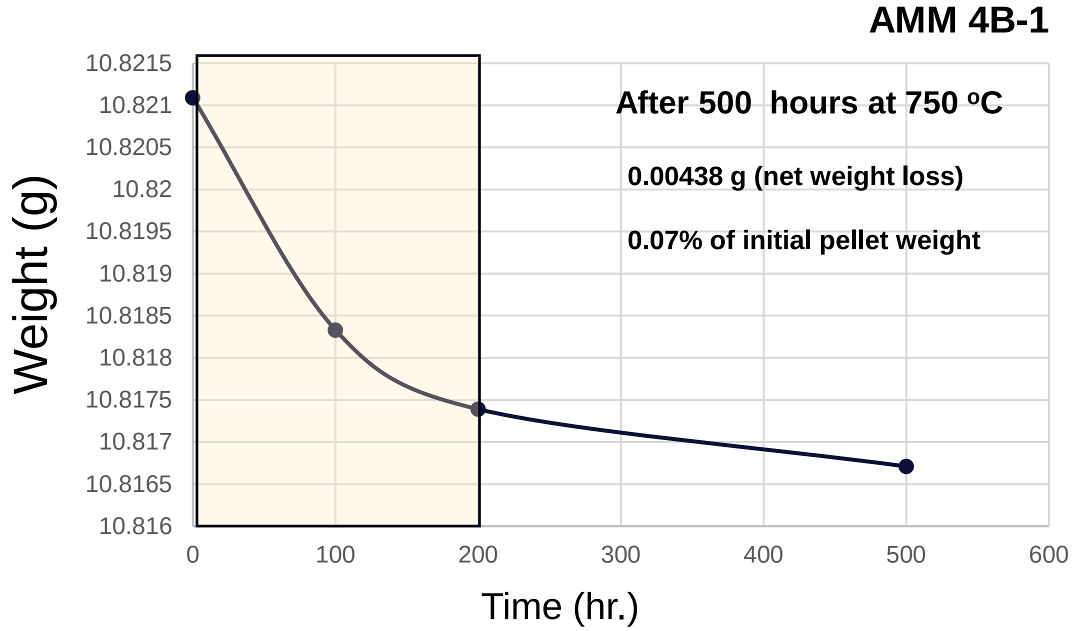
MRP Microreactor Program

Currently Tested AMMs

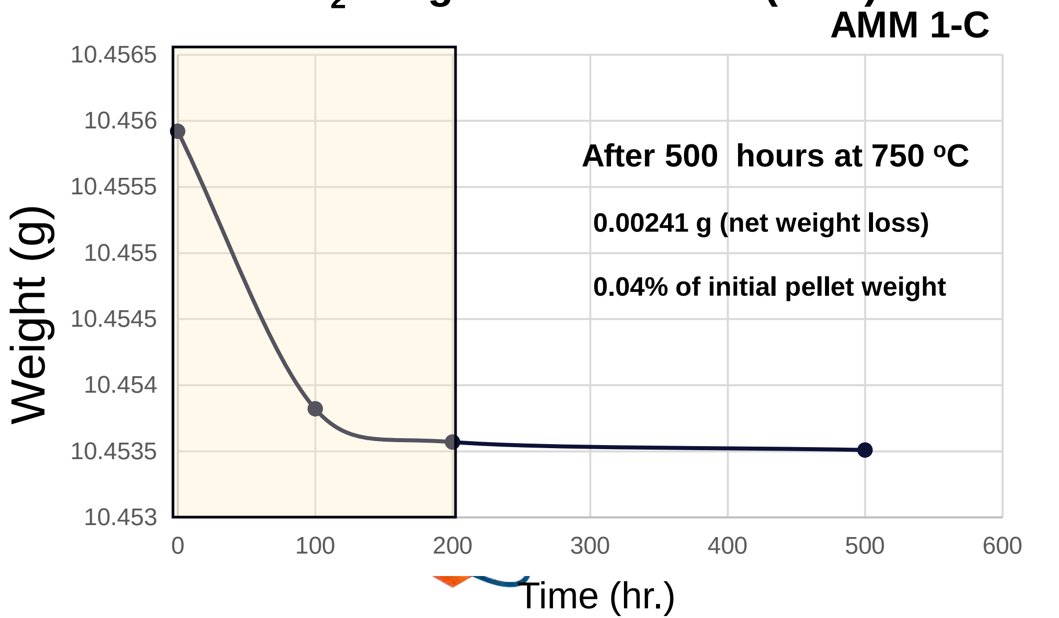
AMM ID	YH pellet ID and as received Wt.	H_{mass} & H/Y ratio	Weld cap coating	Studies (LANL/ANL)	
Tube design 4, Sample 4A-1	#102523I- 6.3512 g #102523E- 6.3431 g	0.1363g & 1.9343 0.1366g & 1.9412	500 nm Al_2O_3	**Tested at ANL for 100 Hrs. at 800 °C under vacuum.**	Shipped to LANL (HT 800 °C) Under vacuum
Tube design 2, Sample 2A	#102523O- 6.3415 g #102523G- 6.3466 g	0.1363g & 1.9374 0.1317g & 1.9300	500 nm Al_2O_3	**Tested at ANL for 100 Hrs. at 800 °C under vacuum**	Shipped to LANL (HT 800 °C) Under vacuum
Tube design 4, Sample 1B	#102523F- 6.3397 g #102523V- 6.3503 g #102523Q- 6.3374 g	0.1357g & 1.9292 0.1364g & 1.9361 0.1358g & 1.9314	**2X** 300 nm Al_2O_3/300 nm CrAl	ANL (Thermal Cycling 800 °C) Under vacuum	
Tube Design 5, Sample 3	#102523T- 6.3456 g #102523X- 6.3493 g #102523W- 6.3496 g	0.1365g & 1.9390 0.1364g & 1.9364 0.1363g & 1.9348	**3X** 300 nm Al_2O_3/300 nm CrAl	ANL (Thermal cycling 800 °C) Under vacuum	
Tube Design 4, Sample 4B-1	#102523N- 6.3391 g	0.1360g & 1.9338	300 nm Al_2O_3	**Tested at ANL for 500 Hrs. at 750 °C under Argon**	Shipped to LANL (being tested at 800 °C) Under vacuum
Tube Design 2, Sample 1C	#102523C1- 6.3682 g	0.1362g & 1.9276	300 nm Al_2O_3	**Tested at ANL for 500 Hrs. at 750 °C under Argon**	**Shipped to LANL**

AMM Heat Treatment at 750 ^oC (UHP Ar gas)

Time (750 ^oC)	AMM 4B-1 (weight measured)	H/Y ratio	AMM 1-C (weight measured)	H/Y ratio
0 hrs.	10.82109g	**1.9338**	10.45592g	**1.9276**
100 hrs.	10.81833g (0.00276g)	**1.8945***	10.45382g (0.0021g)	**1.8979***
200 hrs.	10.81739g (0.00094g)	**1.8811***	10.45357g (0.00025g)	**1.8944***
500 hrs.	10.81671g (0.00068g)	**1.8714***	10.45341g (0.00016g)	**1.8921***



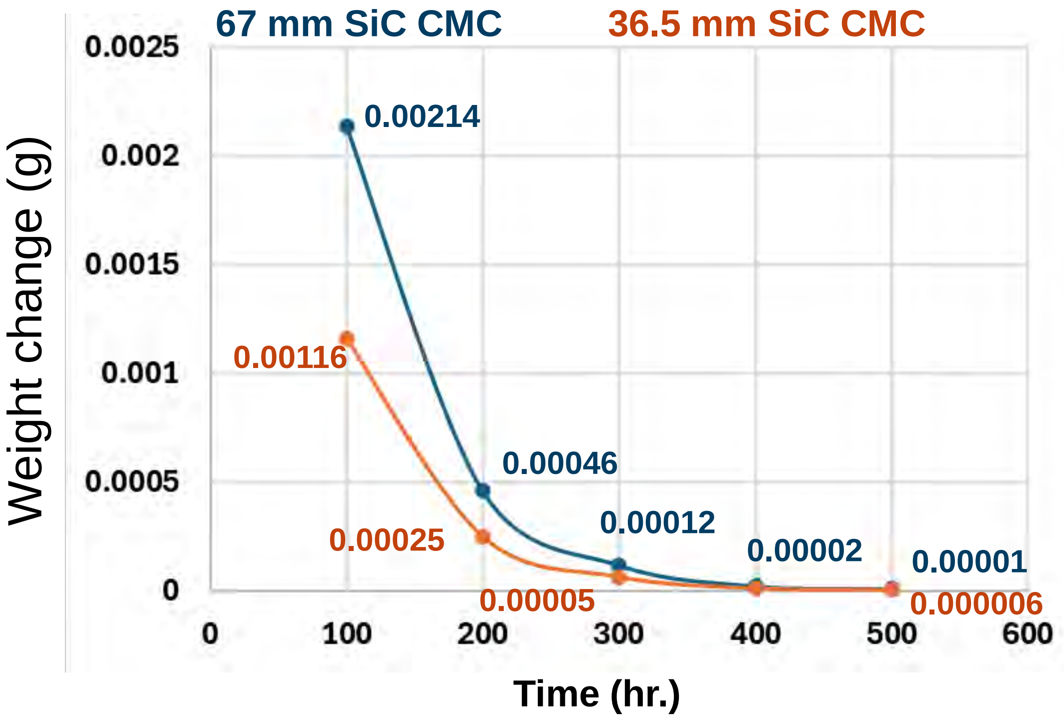
H_2 weight loss studies (ANL)



SiC CMC shell behavior at 750 ºC (UHP Ar gas)

Purpose: Understand potential contributions to weight loss from de-gassing of the modules SiC CMC component

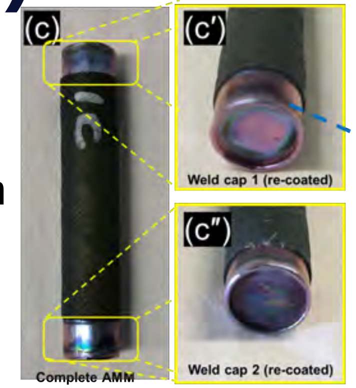
SiC composite shell
O.D. : 10.8 mm – 11.2 mm
Wall thickness: 0.45 mm
Length: 67.0 mm



Conclusion

- Initial indications show contributions to weight loss from SiC CMC de-gassing
- More detailed weight to establish an accurate relationship between measured weight loss and SiC CMC shell length.

SiC composite shell
O.D. : 10.8 mm – 11.2 mm
Wall thickness: 0.45 mm
Length: 36.5 mm



AMM 1-C (wt. in g)	H/Y ratio	H/Y ratio (corrected*)
10.45592g	**1.9276**	**1.9276**
10.45382g (100 hr.)	**1.8979***	**1.9149**
10.45357g (200 hr.)	**1.8944***	**1.9148**
10.45341g (500 hr.)	**1.8921***	**1.89217**

MRP Microreactor Program

Summary: Advanced Moderator Module (AMM) Concept

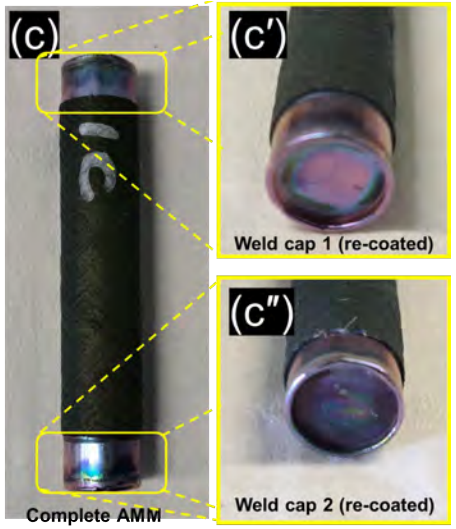
Successfully completed manufacturing different size AMM samples

- Using 10 mm O.D. Nb tubes with 0.3 μm wall thickness.
- AMMs with various lengths manufactured
- **Current capability: can manufacture modules with up to 1 meter (L) with 45 mm (O.D.)**

High temperature performance
(Ongoing collaboration 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.

Images of the first completed ANL made moderator module.



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10.45357g (200 hr.)	**1.9148**
10.45341g (500 hr.)	**1.89217**

Initial thermal testing results

FY25 Remaining Goals: Demonstrate working AMM samples under prototypic thermal conditions & accumulate performance data for their components

- Post testing characterizations:
    - SiC CMC, Nb liner and coating, Welding and YH pellets

MRP Microreactor Program

Acknowledgement

- (ANL) Yinbin Miao, Nicolas Stauff, Dean R. Walters, Greg Fletcher, William F. Toter
- (INL) Chase N. Taylor
- (LANL) Erik P. Luther, Caitlin Anne Kohnert, Michael A. Hahn, Tom Nizolek, Holly R. Trellue