

X·ENERGY

XPeRT Experiment Data – Fuel Qualification

Clean • Safe • Secure • Affordable

Feldon Barlow, Manager Fuel Systems Engineering

X-Energy Fuel Qualification Status

Status:

X-energy submitted Revision 3 of the “Xe-100 Topical Report: TRISO-X Pebble Fuel Qualification Methodology” to the U.S. NRC on July 29, 2022 (ML22216A179).

U.S. NRC issued a Safety Evaluation on Revision 3 of the TR on March 9, 2023 (ML22327A201).

Submitting Revision 4 of the “Xe-100 Topical Report: Pebble Fuel Qualification Methodology - May 2026

Fuel qualification testing:

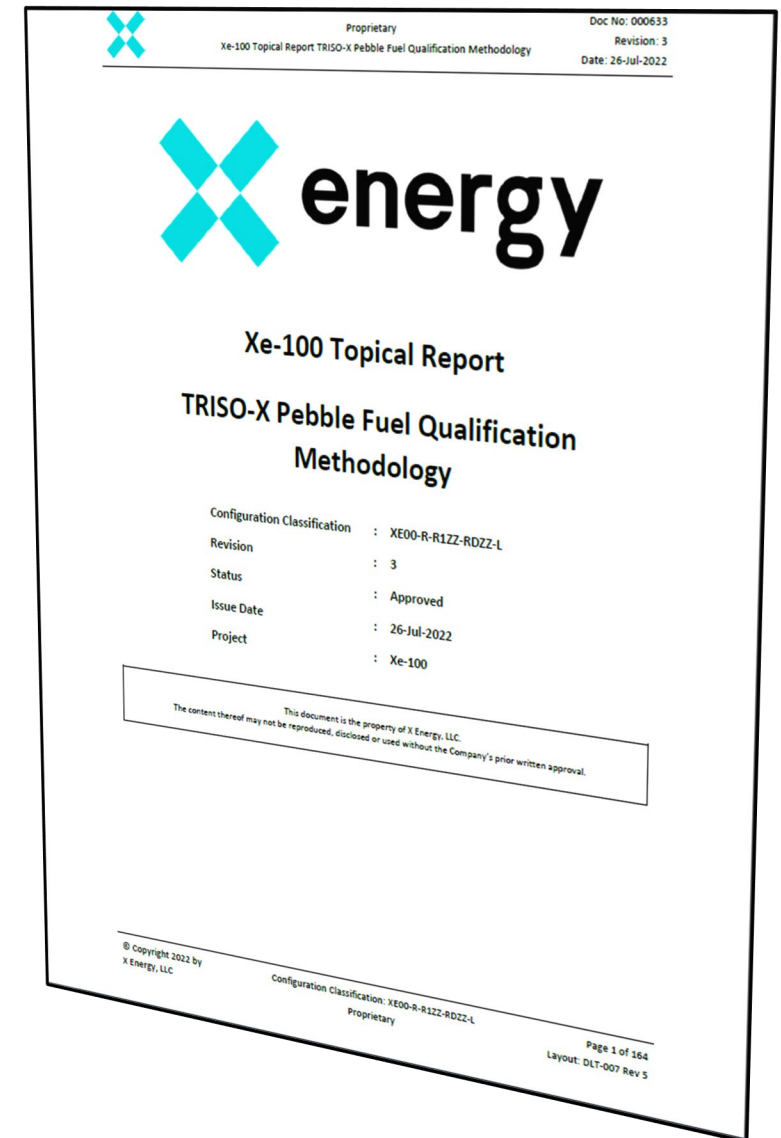
XPeRT (X-energy Pebble Reactor Test): Irradiation campaign currently running TRISO-X fabricated test fuel to conditions consistent with Xe-100’s operating envelope in ATR and perform post-irradiation examinations (PIE) – Cycle 1 completed, Cycle 2 to complete 4/27/26

XPLoRE (X-energy Pebble Loading Results Examination): Thermal-mechanical performance and material properties testing ongoing at various vendors.

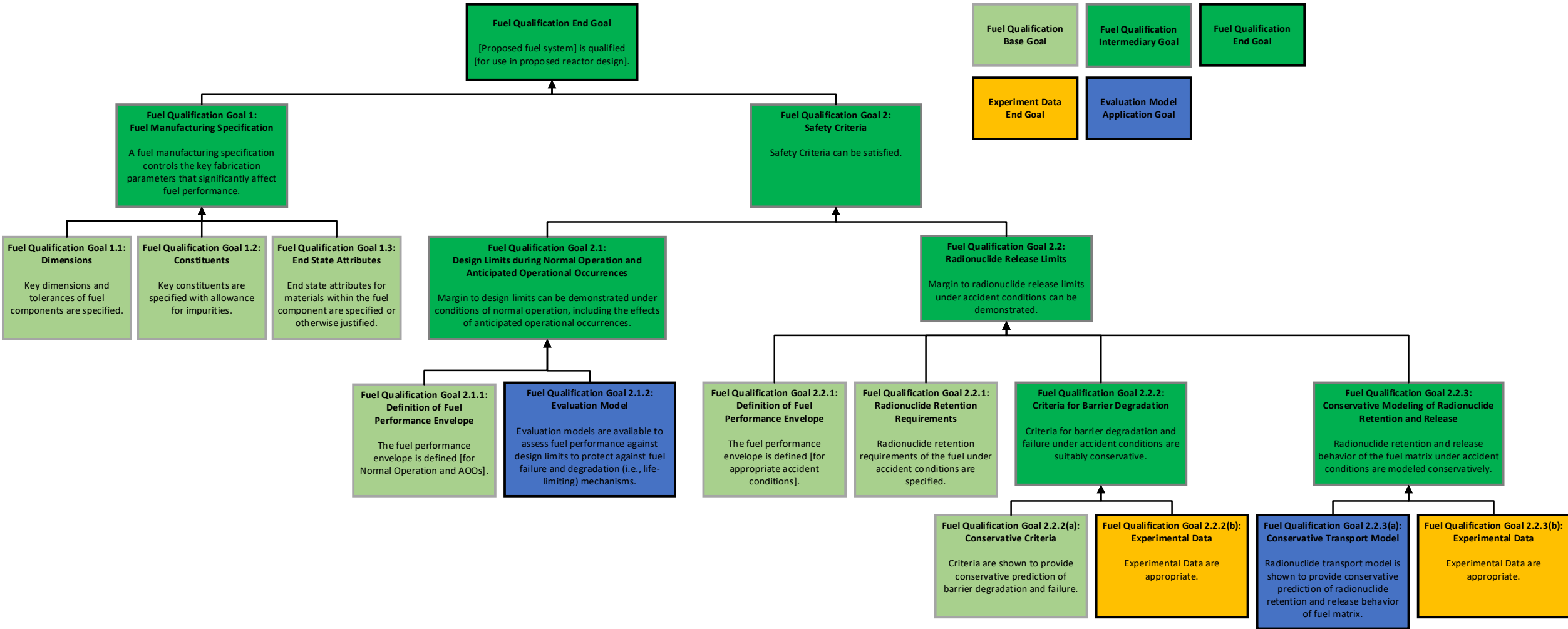
NUREG-2246: Fuel Qualification for Advanced Reactors

U.S. NRC guidance was released during the development of the first submission of the Fuel Qualification TR.

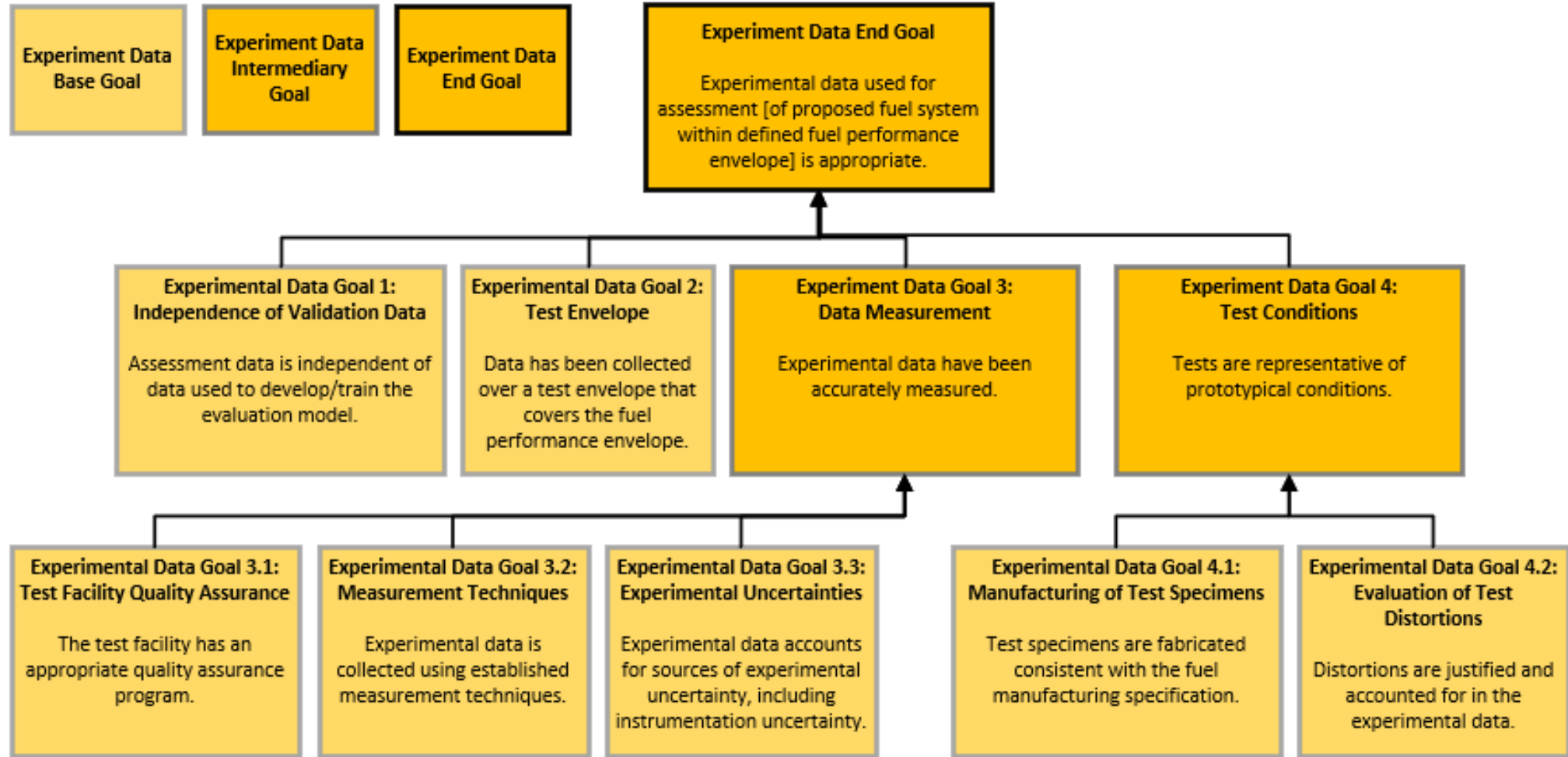
Next revision to the Fuel Qualification TR includes structural changes to leverage NUREG-2246 framework



NUREG-2246 Fuel Qualification for Advanced Reactors Framework



NUREG-2246 Experiment Data Framework



Incorporating NUREG-2246 Experiment Data Framework in XPeRT

Base Goals

- ED Goal 1: Independence of Validation Data
 - XPeRT data not planned to develop models for safety analysis, only employed in model validation.
- ED Goal 2: Test Envelope
 - Iteration over program requirements to align with Xe-100 conditions at every stage of XPeRT design.
- ED Goal 3.1: Test Facility Quality Assurance
 - INL held an ASME NQA-1 Certification (#NQA-125). Their quality program maintains adequate controls on the implementation of programmatic elements which quality experiment data is required to have.
 - X-energy is additionally performing Commercial Grade Dedication (CGD) on the irradiation and PIE data.
- ED Goal 3.2: Measurement Techniques
 - Leveraging INL's proven track record of particle fuel testing from AGR including experimental facilities and personnel.
- ED Goal 3.3: Experimental Uncertainties
 - INL Quality Assurance Program elements provide programmatic controls.
 - Critical characteristics in XPeRT CGD dealing specifically with quantification of experimental uncertainties.
- ED Goal 4.1: Manufacturing of Test Specimens
 - TRISO-X fabricated test fuel elements
 - Consistent with Condition 1 of the EPRI UCO TRISO-Coated Particle Fuel Performance TR, X-energy is responsible for evaluation of discrepancies between tested fuel
- ED Goal 4.2: Evaluation of Test Distortions
 - Consistent with Condition 2 of the EPRI UCO TRISO-Coated Particle Fuel Performance TR, X-energy is responsible for evaluation of distortions between fuel operating conditions and experiment conditions.
 - Critical characteristics in XPeRT CGD dealing specifically with irradiation test distortions

BWXT **ADVANCED** TECHNOLOGIES

From Concept to Reality
Design, build and test new nuclear

Daniel Galicki, Ph.D.

Technical Integrator
BWXT Advanced Reactor Development Program
BWXT Advanced Technologies LLC



Andrew Davidson

UP&RR Director, Uranium Processing and Research Reactors
BWXT Nuclear Operations Group, Inc.

*NRIC Annual Program Review
May 2026*

Agenda

- BWXT Overview
- BANR – ARDP Program Overview
- BANR – UN TRISO Fuel Development Update
- BANR-1 Irradiation Experiment
- BANR-1 Irradiation Specimen Manufacturing
- Acknowledgements
- Questions

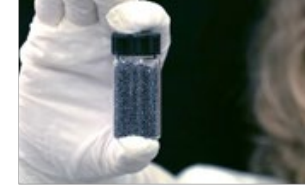
Government Operations (GO)

Global defense



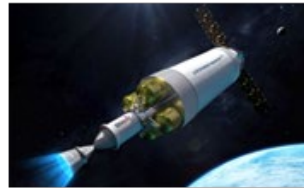
- Naval nuclear propulsion components for the U.S., U.K. and international navies
- Highly skilled manufacturing capabilities

Special materials



- Uranium & other national security materials handling and processing
- Production of naval and coated fuels (Including TRISO)
- Uranium down blending, conversion and purification

Space and defense microreactors



- Power, propulsion and fuel
- Design, prototype and production of flagship programs with U.S Government & industry partners

Technical services



- Nuclear Environmental Management
- Management & Operations
- U.S. Department of Energy (DOE) and Government sites

Commercial Operations (CO)

Energy security



- Component Manufacturing
- Fuel
- Field Services

Nuclear medicine



- Manufacturing and processing radioisotopes
- Diagnostic and therapeutic radiopharmaceutical products for nuclear medicine



Operations

BWXT Sites



Manufacturing Sites

- Lynchburg, VA
- Barberton, OH
- Euclid, OH
- Mount Vernon, IN
- Erwin, TN
- Jonesborough, TN
- Long Beach, CA
- Cambridge, Ontario
- Toronto, Ontario
- Peterborough, Ontario
- Arnprior, Ontario
- Oakville, Ontario
- Brampton, Ontario
- Vancouver, British Columbia
- Oldham, United Kingdom

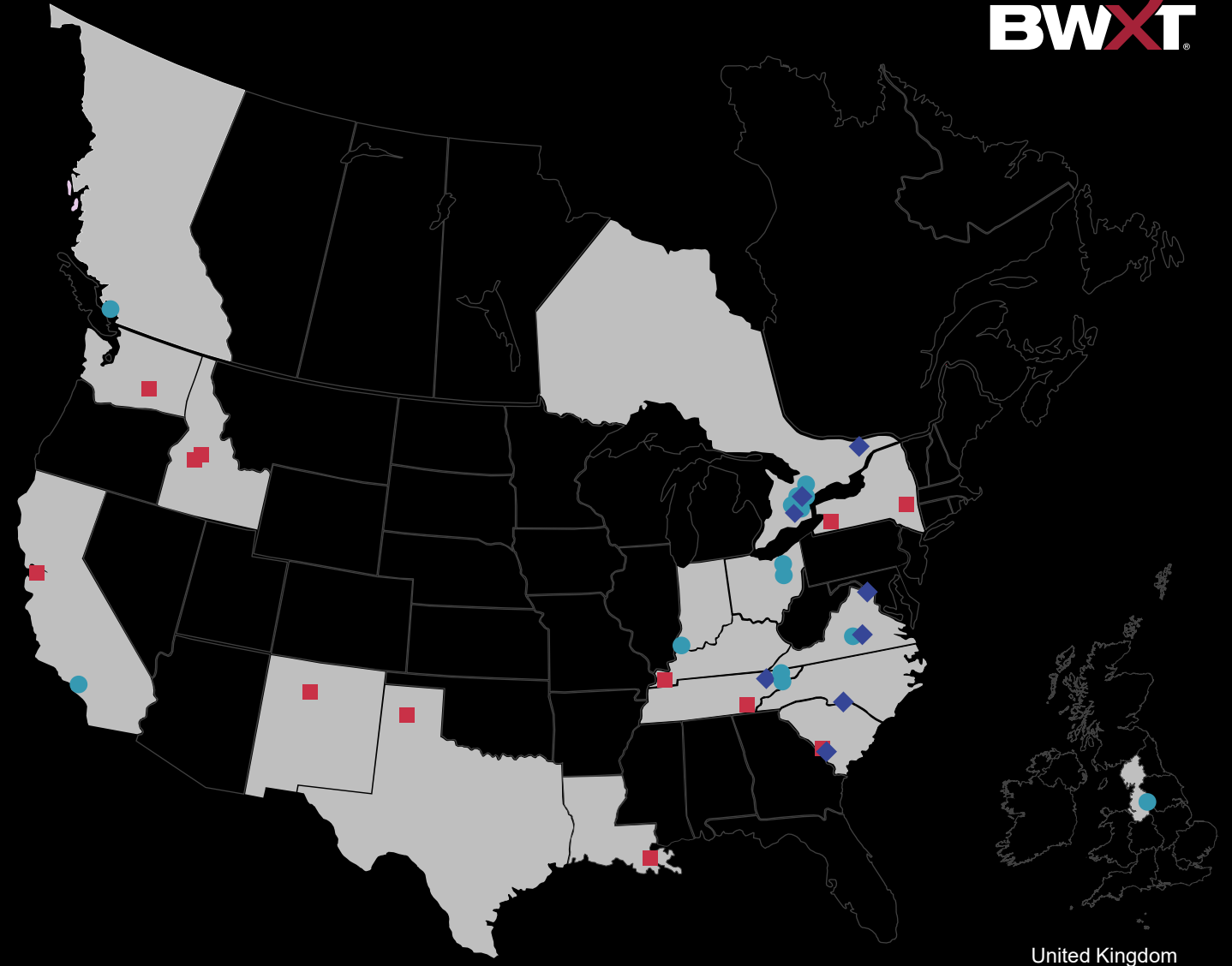
Key Offices / Operations

- ◆ Lynchburg, VA*
- ◆ Charlotte, NC
- ◆ Oak Ridge, TN
- ◆ Aiken, SC
- ◆ Washington, DC
- ◆ Cambridge, Ontario
- ◆ Peterborough, Ontario
- ◆ Ottawa, Ontario

Joint Ventures

- BWSR – Kesselring Site Operations, NY
- BWSR -- Naval Reactors Facility, ID
- West Valley Cleanup Alliance, LLC – NY
- Four Rivers Nuclear Partnership, LLC – KY
- Battelle Energy Alliance, LLC – ID
- Lawrence Livermore National Security, LLC – CA
- UT-Battelle, LLC – TN
- Isotek Systems, LLC – TN
- Savannah River Mission Completion, LLC – SC
- Strategic Storage Partners, LLC – LA
- Newport News Nuclear BWXT-Los Alamos, LLC – NM
- PanTeXas Deterrence, LLC – TX
- Hanford Tank Waste Operations and Closure, LLC - WA

* Corporate headquarters



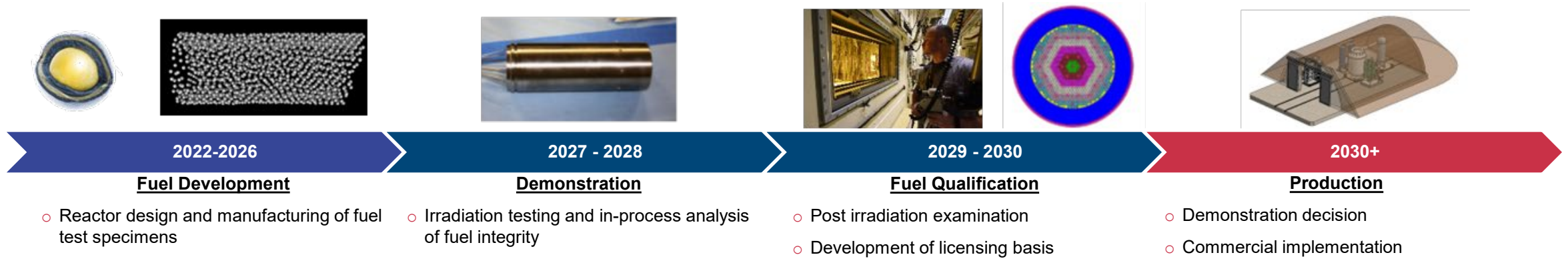
United Kingdom

TRISO Fuel Delivered by BWXT

- Full core of TRISO compacts for PELE
 - Delivered to INL Nov. 2025
- TRISO compacts to NCERC
 - Dec. 2025, Feb. 2026
- TRISO compacts for Antares



BANR ARDP Program Scope



Risk Reduction Program Scope

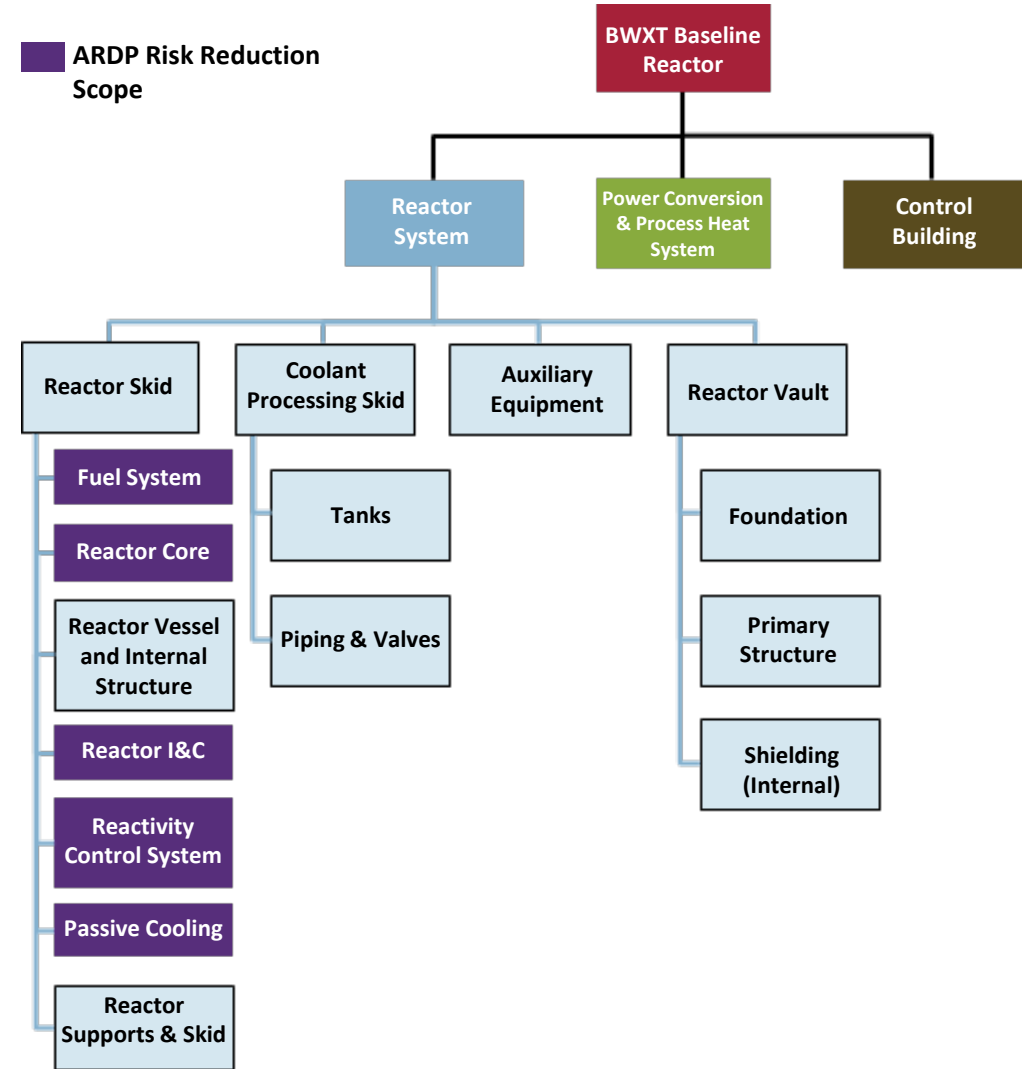
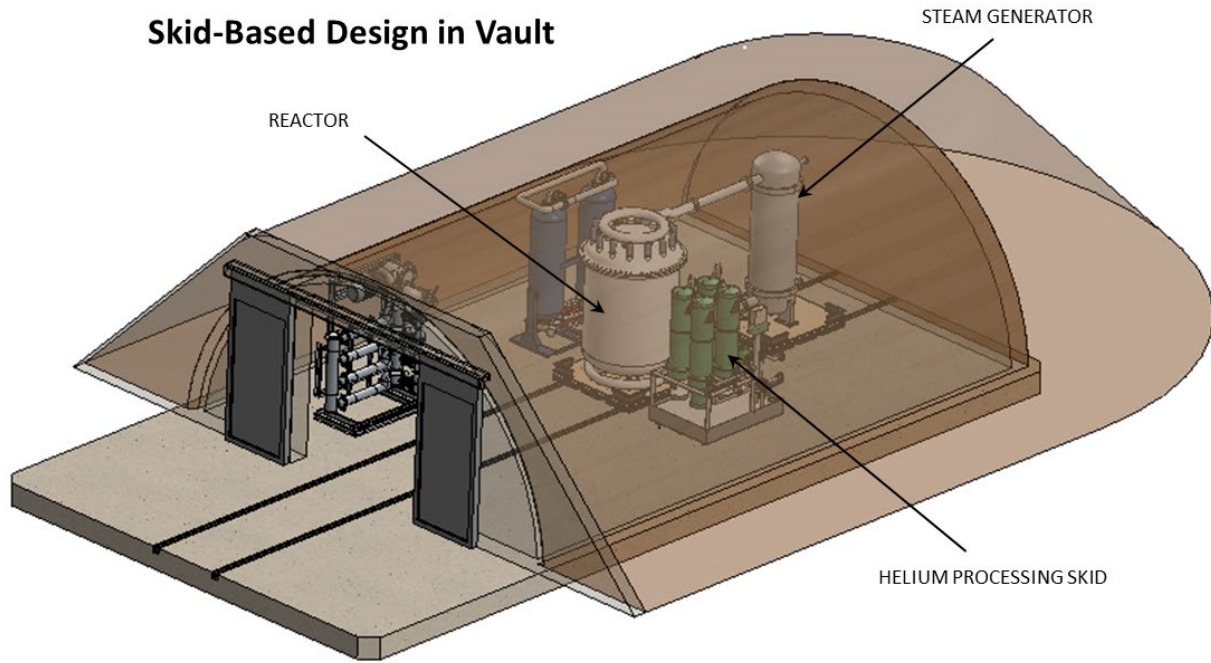
- Mature design and manufacturing technologies, improving commercial viability
- Demonstrate advanced technology applications to reduce reactor costs
- Develop and demonstrate high-power density TRISO fuel form for microreactors
- Focus on reactor skid: fuel system, core design, reactivity control, passive cooling, I&C

Fuel-Specific Scope

- HALEU fuel acquisition; TRISO fuel production
- Knowledge transfer from INL's AGR program and ORNL's TCR program
- Iterative manufacturing and testing of fuel elements, e.g. AM using CVI densification, element testing and characterization
- Irradiation (INL) and examination (ORNL) to advance UN fuel performance
- Licensing activities to advance fuel form regulatory case

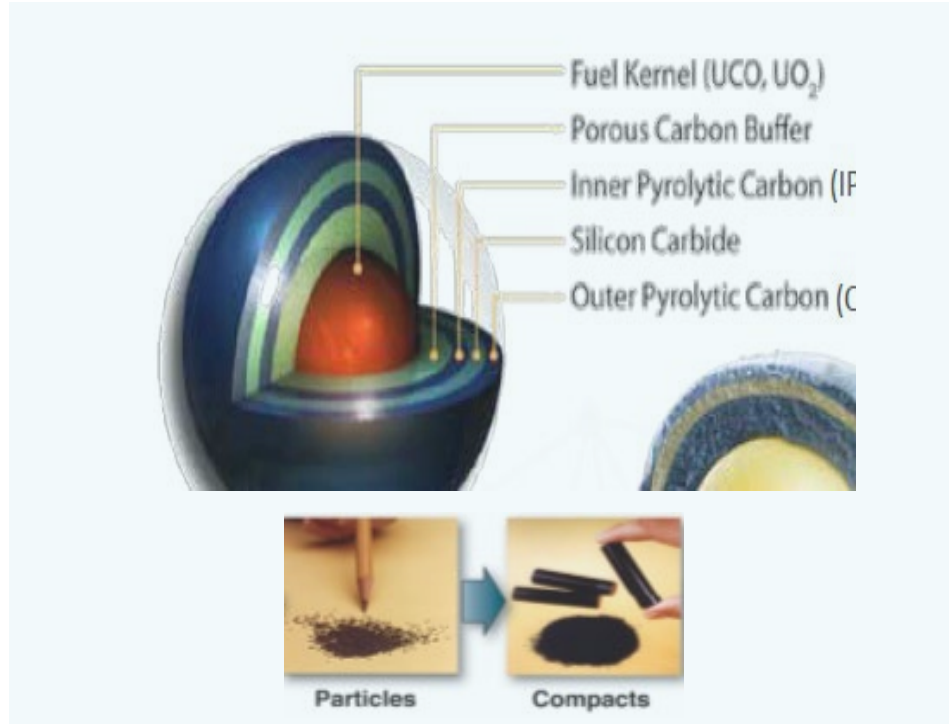
Technology Assessment - BANR Design

Skid-Based Design in Vault



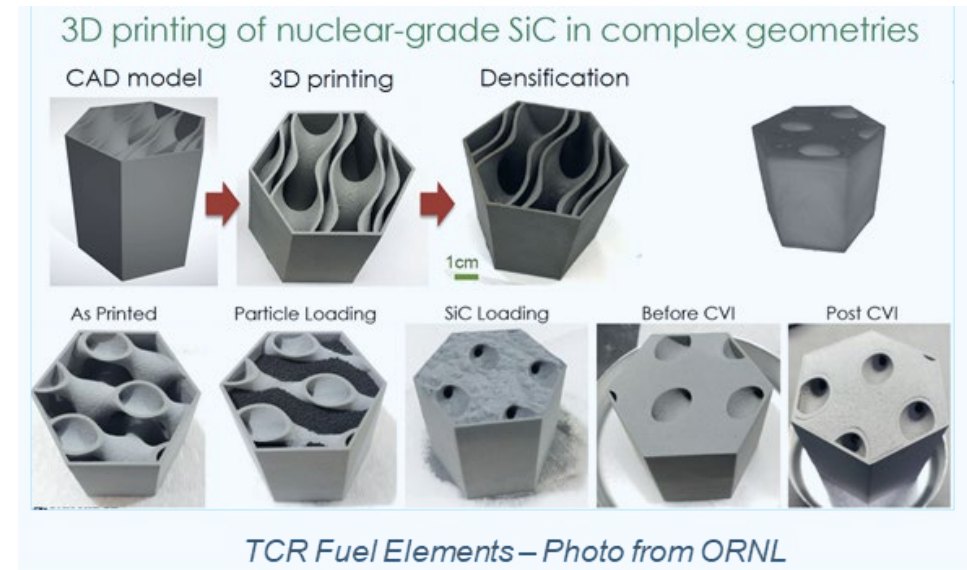
Qualifying New Fuel Form is Major Focus

Baseline based on Advanced Gas Reactor (AGR) TRISO Fuel



- UCO fuel kernel coated with multiple layers of pyrocarbon (PyC) and Silicon Carbide (SiC)
- Can withstand extreme temperatures well beyond the threshold of current nuclear fuels
- Each particle acts as its own containment, retaining fission products under all conditions

BWXT's ARDP Award upgrades BANR to a higher density UN TRISO Fuel



- UN fuel kernel contains ~+30% U235 density compared to UCO kernel
- UN-TRISO increased kernel U density combined with higher particle packing fraction (~60 vol%) provides for ~2X fuel form U-density compared to UCO...increasing power and extending core life
- Advanced manufacturing optimizes design, reduces cost & improves throughput
- Commercializes previous DOE fuel development work



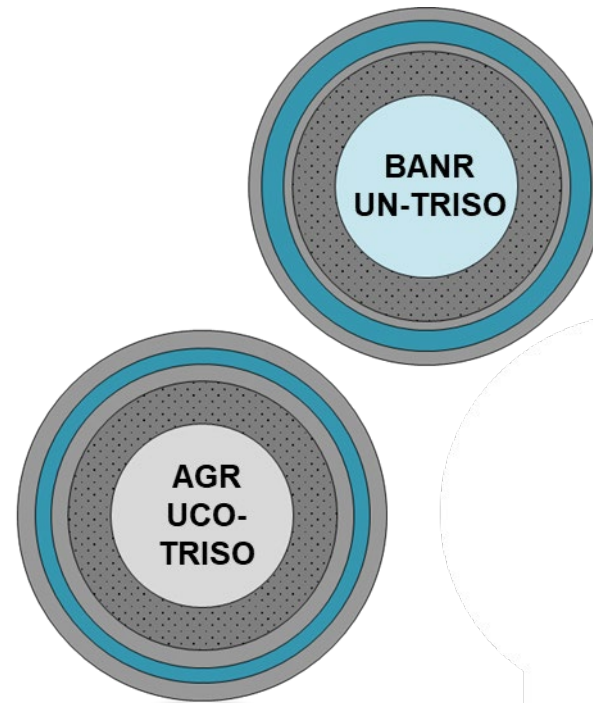
UN-TRISO Development



BWXT ARDP UN-TRISO Particle Design

- **Design Goal:** Optimize the uranium density (gU/cc) within a BANR fuel element, while maintaining low particle failure rate during operation.
- BWXT AT sampled >1,000 UN-TRISO/Operating-Condition pairs and performed >134,400 2D TRISO particle BISON models

	Metric	BANR UN-TRISO [um]	AGR UCO-TRISO [um]
	Kernel diameter	425 ± 10	425 ± 10
thickness	C-Buffer	100 ± 15	100 ± 15
	IPyC	20 ± 4	40 ± 4
	SiC	50 ± 3	35 ± 3
	OPyC	30 ± 4	40 ± 4
	Particle diameter (nominal)	825	855
	Kernel/Particle volume ratio	0.1367	0.1228

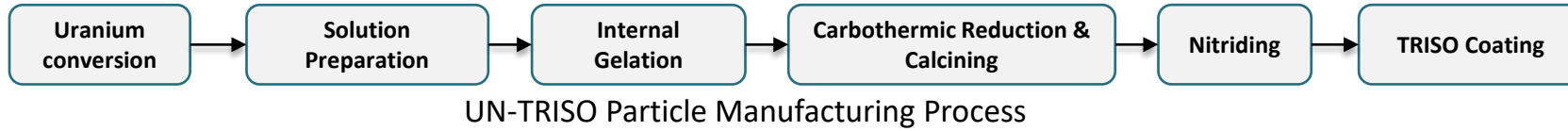


Particles to scale, relative to each other

Attractive Attributes of UN

- Higher U-loading than UCO
- Increased thermal conductivity
- Potentially improved fission product retention

BWXT UN-TRISO Particle Design & Manufacturing Progress

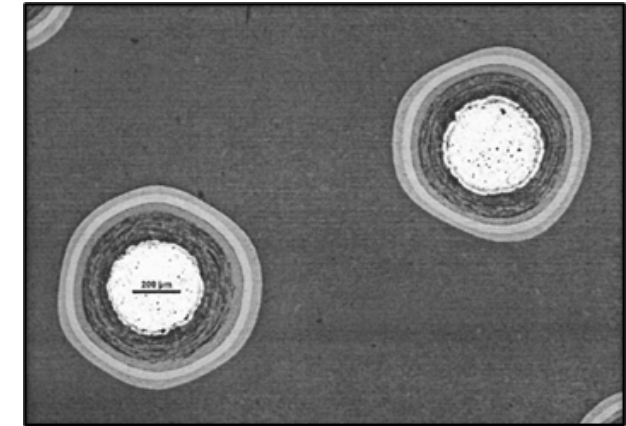


2021 – 2022

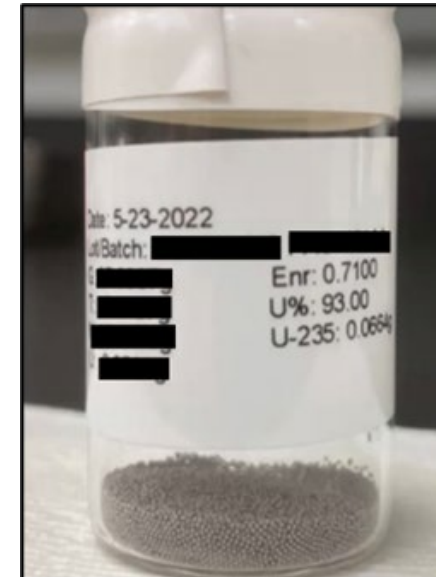
- ✓ UN-TRISO design optimization

2022 – 2025

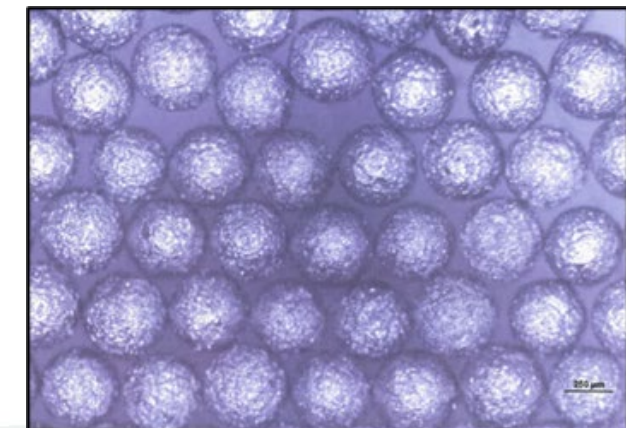
- ✓ UN kernel nitride conversion (**natU**)
- ✓ UN-TRISO coating development (**natU**)
- ✓ UN kernel nitride conversion (**HALEU**)
- ✓ UN kernel coating (**HALEU**)
- ✓ UN-TRISO tabling (**HALEU**)
- ✓ UCO-TRISO acquisition (**HALEU**)



BWXT-manufactured, naturally-enriched UN-TRISO particles



Naturally-enriched UN kernels



HALEU UN Loose Kernels

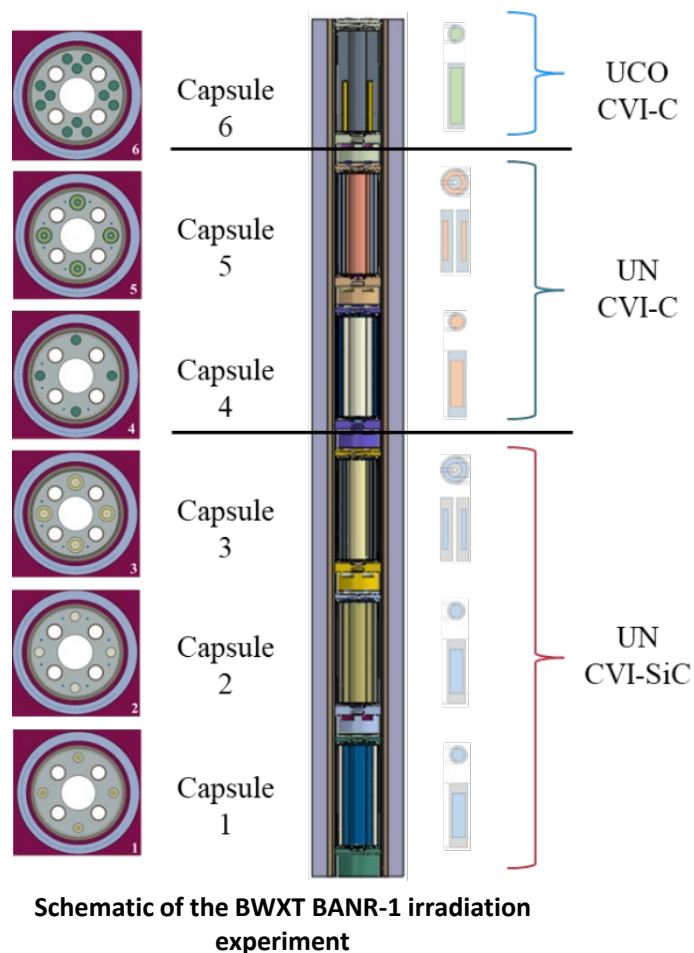


BANR-1 Irradiation Experiment

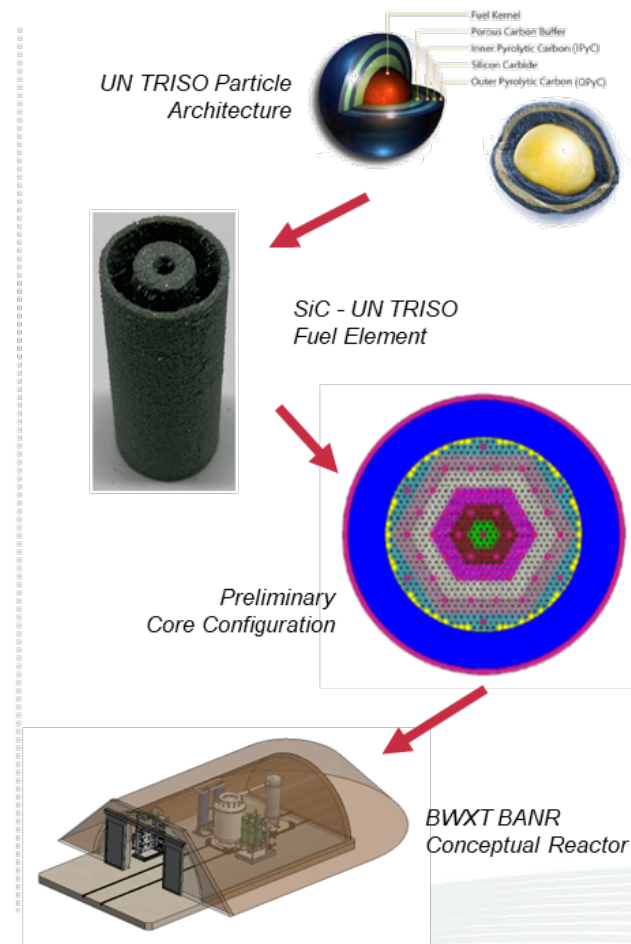


BANR-1 Irradiation Experiment - Goal

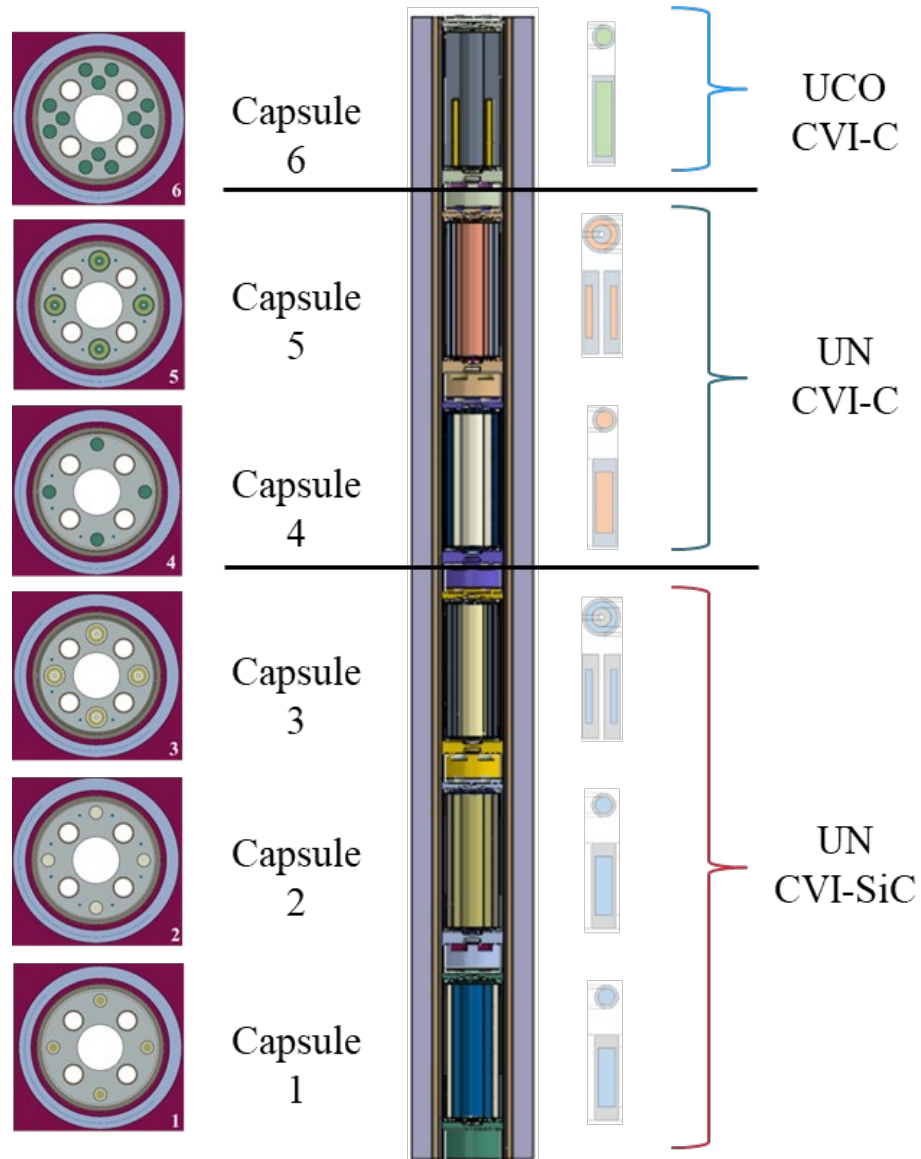
- Qualify UN-TRISO fuel by testing and evaluating the performance of the fuel form at normal and off-normal BANR operating conditions.



Schematic of the BWXT BANR-1 irradiation experiment



BANR-1 Irradiation Experiment – Test Train Capsule Design



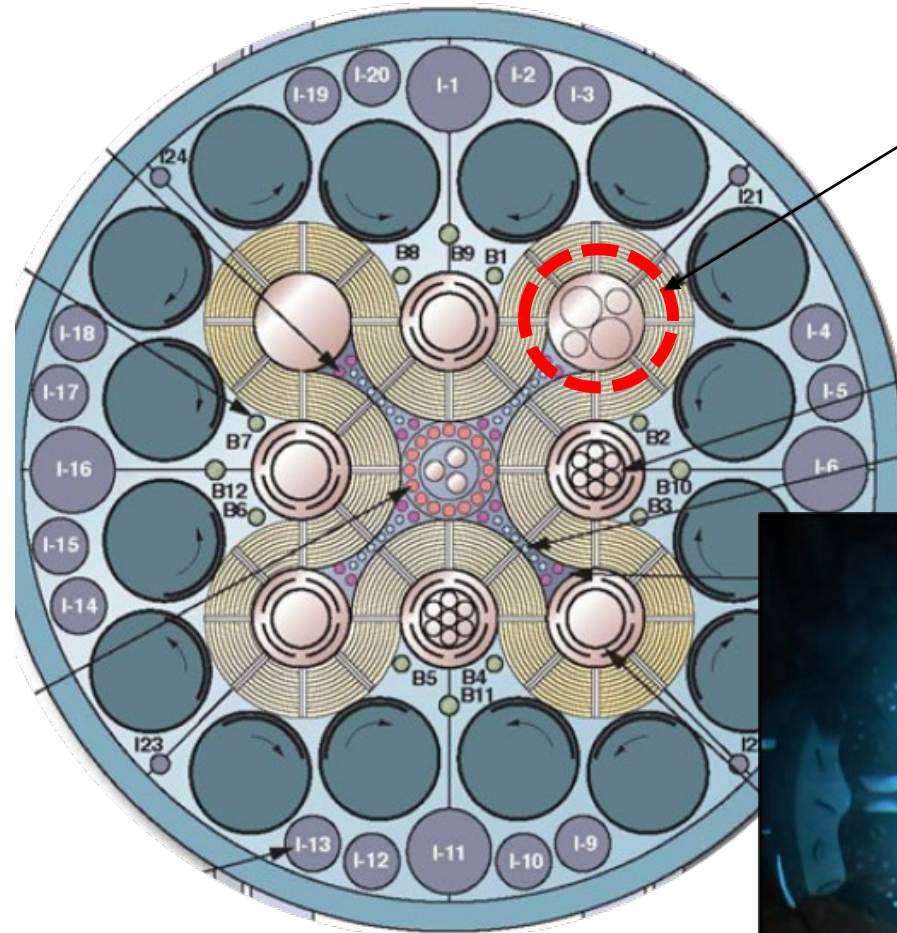
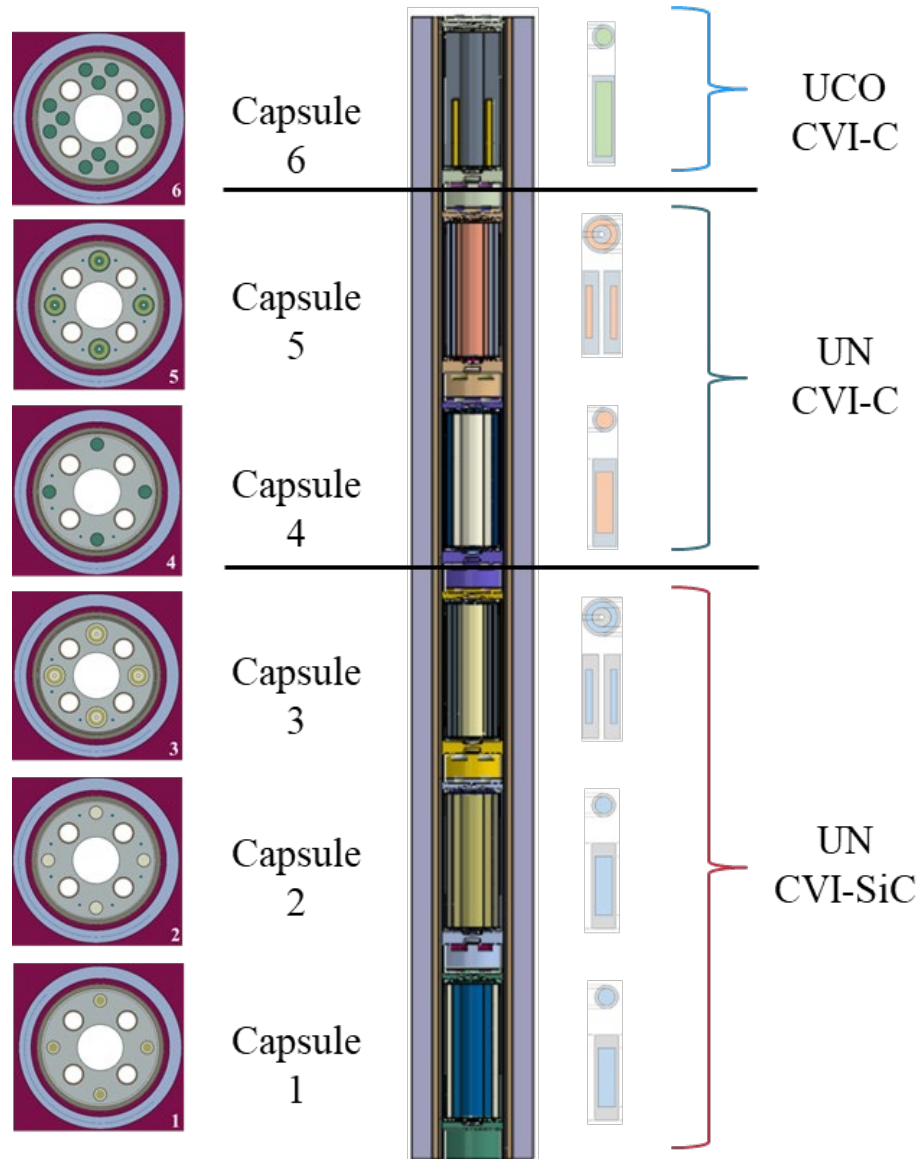
BANR-1 Experiment Objectives

1. Burnup – amount of uranium that has fissioned (max 15% FIMA)
2. Fast Fluence ($E > 0.18 \text{ MeV}$) – neutron damage to materials ($2.2\text{-}5.6 \text{ E}25 \text{ n/m}^2$)
3. Temperature (550-1250 C)
4. Time at Temperature ($\sim 300 \text{ EFPD}$)

Capsule number	Purpose	TRISO Type (UCO/UN)	Matrix Material	Pellet geometry
6	Tertiary Fuel Form	UCO	CVI-carbon	solid
5	Secondary Fuel Form	UN	CVI-carbon	annular
4		UN	CVI-carbon	solid
3	Primary Fuel Form for BANR 2.0	UN	CVI-SiC	annular
2		UN	CVI-SiC	solid
1		UN	CVI-SiC	solid

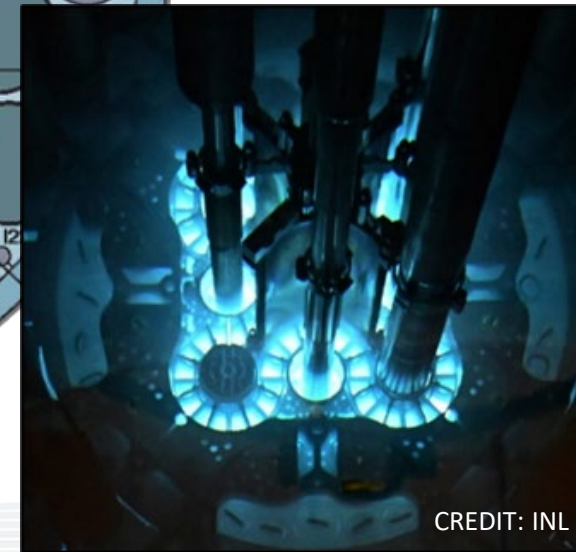
BANR-1 Irradiation Experiment - Test Train Capsule Descriptions

BANR-1 Irradiation Experiment – Test Train Capsule Design



ATR northeast lobe
 Each of the four lobes of the reactor can be controlled somewhat independently of the others

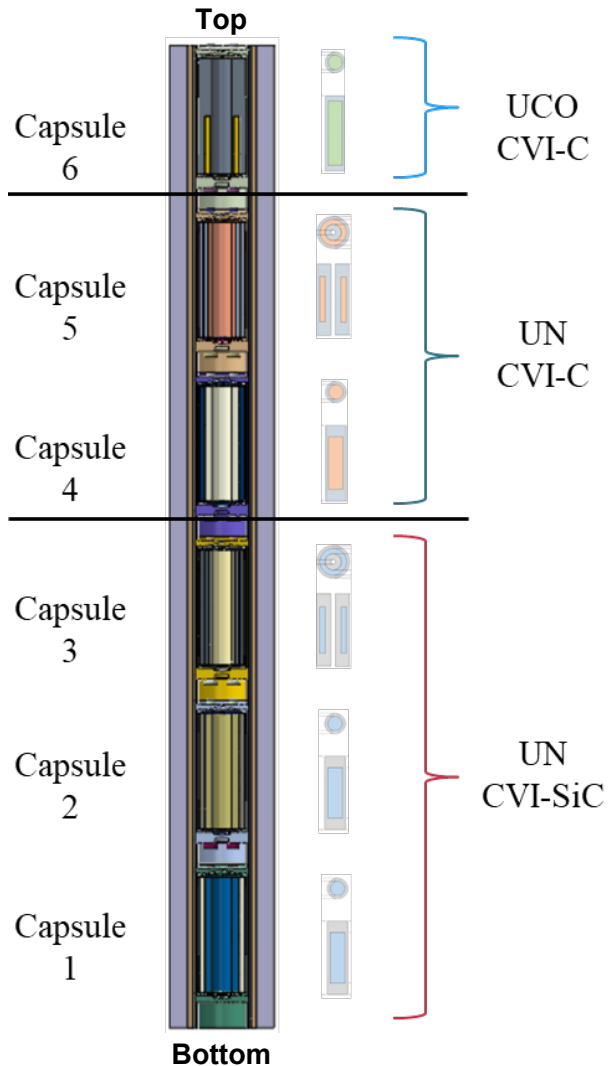
CREDIT: INL



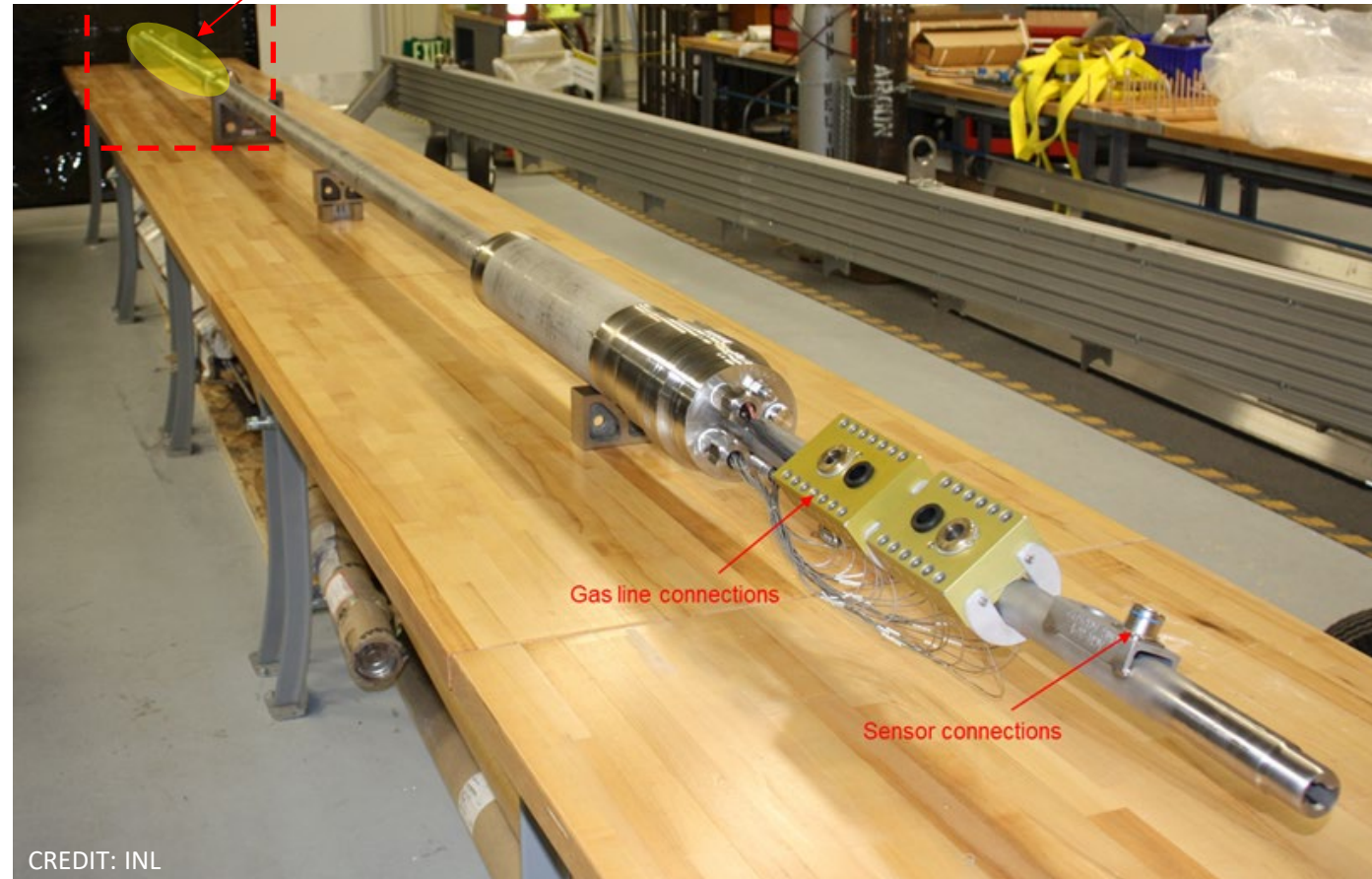
CREDIT: INL

INL's [Advanced Test Reactor \(ATR\)](#)

BANR-1 Irradiation Experiment – Test Train Capsule Design



Test Train Capsules



- BANR-1 test train based on the AGR-5/6/7 test train.

- Experiment located in bottom ~4 feet of test train.

- In-pile gas and temperature monitoring

- Advanced sensor testing

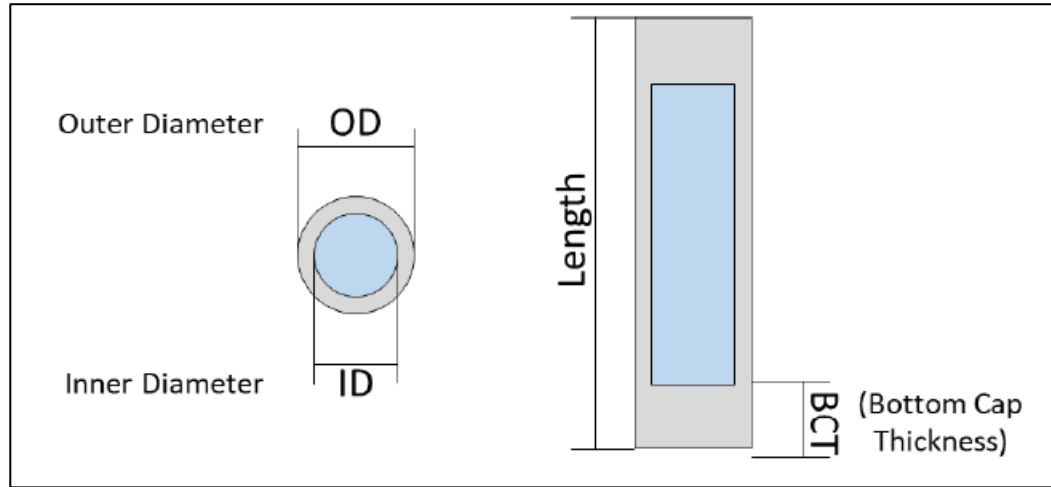
pressure
thermal conductivity
neutron fluence
temperature



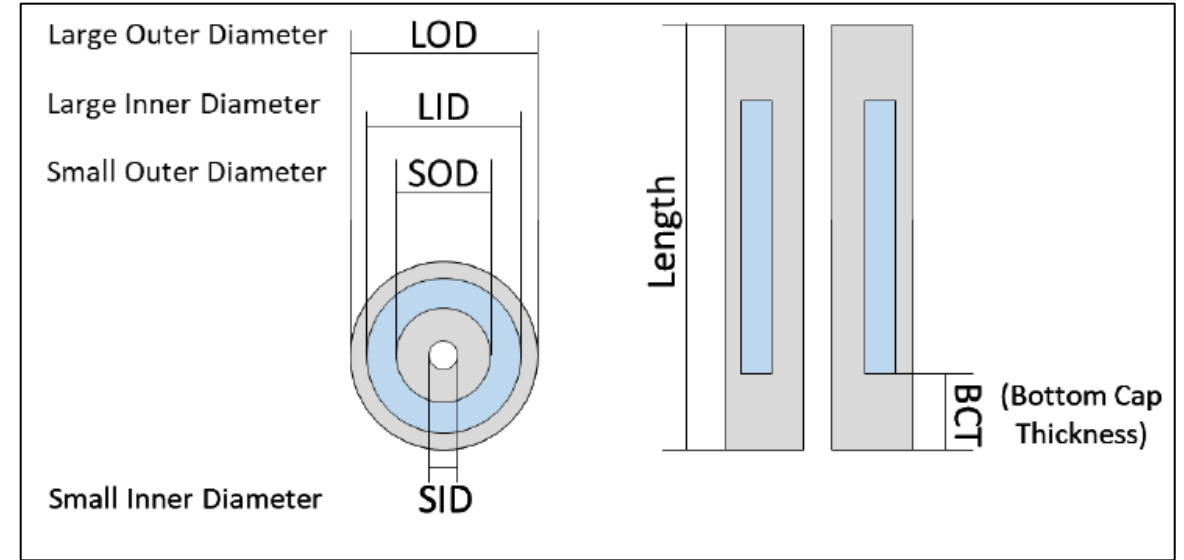
Manufacturing the ARDP Fuel Form



BANR-1 Irradiation Specimen Geometries



Solid Pellet Design

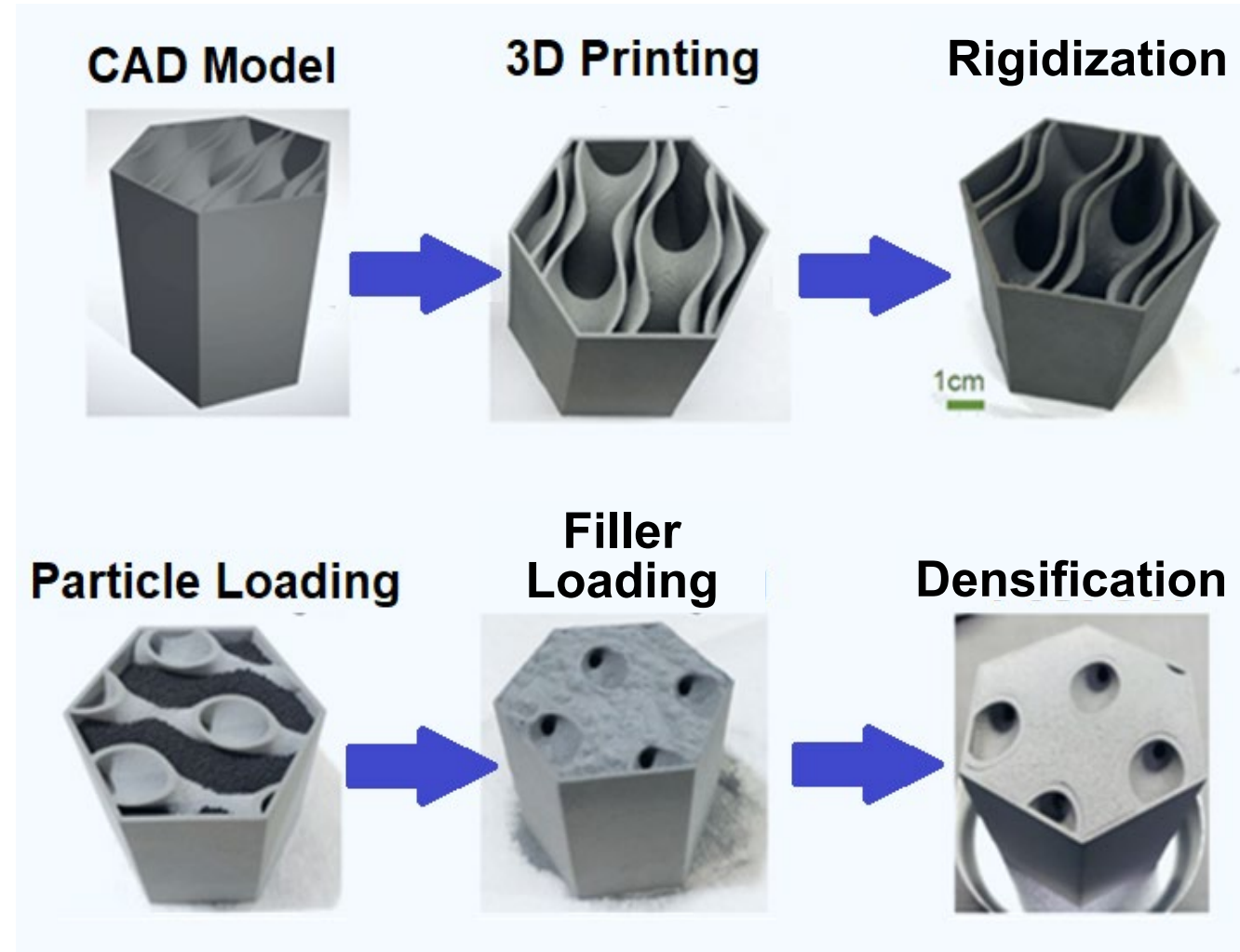


Annular Pellet Design

- Gray – unfueled preform “shell”
- Blue – fueled volume (packed TRISO particles; SiC or carbon matrix)

Fuel Element Fabrication

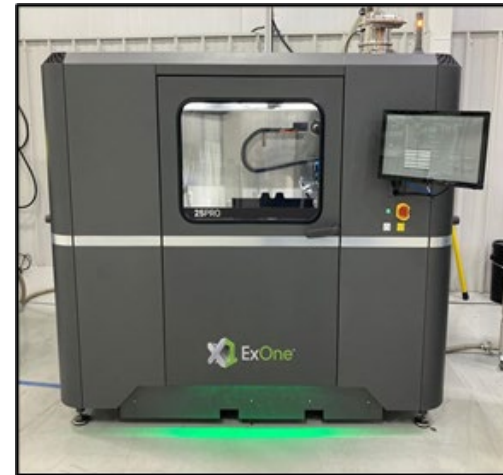
1. **CAD Model:** A fuel element shell geometry is created in modeling software.
2. **3D Printing:** Using a 3D binder jet printer, the fuel shell is built by selectively depositing a liquid binding agent onto a thin layer of powder particles. This is repeated layer by layer until the fuel element shell is complete.
3. **Rigidization:** Partial CVI densification step provides strength to the fuel element shell so that fuel can be loaded.
4. **Particle Loading:** TRISO particles are placed into the empty fuel element shell.
5. **Filler Loading:** Filler powder is packed into the fuel element, filling the spaces around the TRISO particles.
6. **Densification:** The interior structure is densified into an immobile matrix, via CVI.



TCR Fuel Element Photos, courtesy of ORNL

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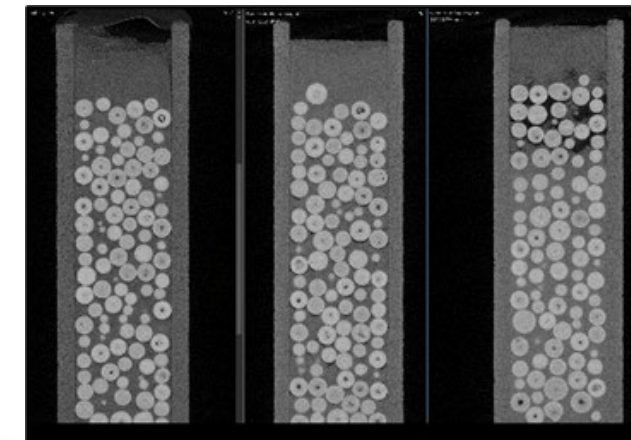
BWXT's Binder Jet



BWXT CVI Furnace



BWXT CVI furnace retort loaded with carbon matrix HALEU specimens.



XCT of development carbon pellets loaded with surrogate particles

BANR Fuel Development: Current Status

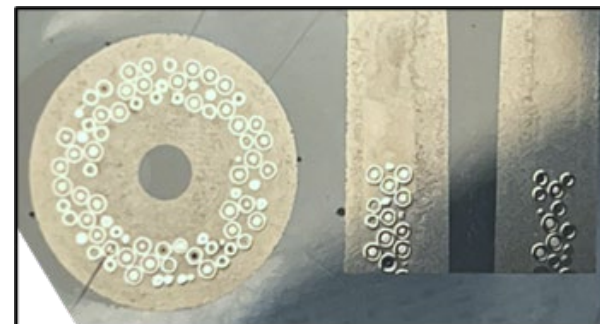
- BWXT has a mature irradiation sample manufacturing process that has been stress-tested.
- BWXT's CVI furnace is operational and carbon-matrix HALEU irradiation specimen production has begun.
- BWXT SiC-matrix HALEU irradiation specimen production to follow completion of carbon-matrix specimen production.
- ORNL's CVI furnace is in the process of being commissioned. ORNL will verify SiC CVI parameters and produce SiC samples for thermal and mechanical testing.



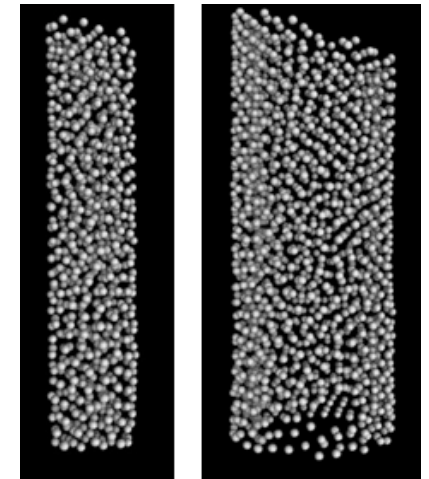
Development Carbon pellet preforms loaded onto tooling racks for insertion into BWXT's CVI furnace



SiC preforms loaded into the BWXT CVI furnace



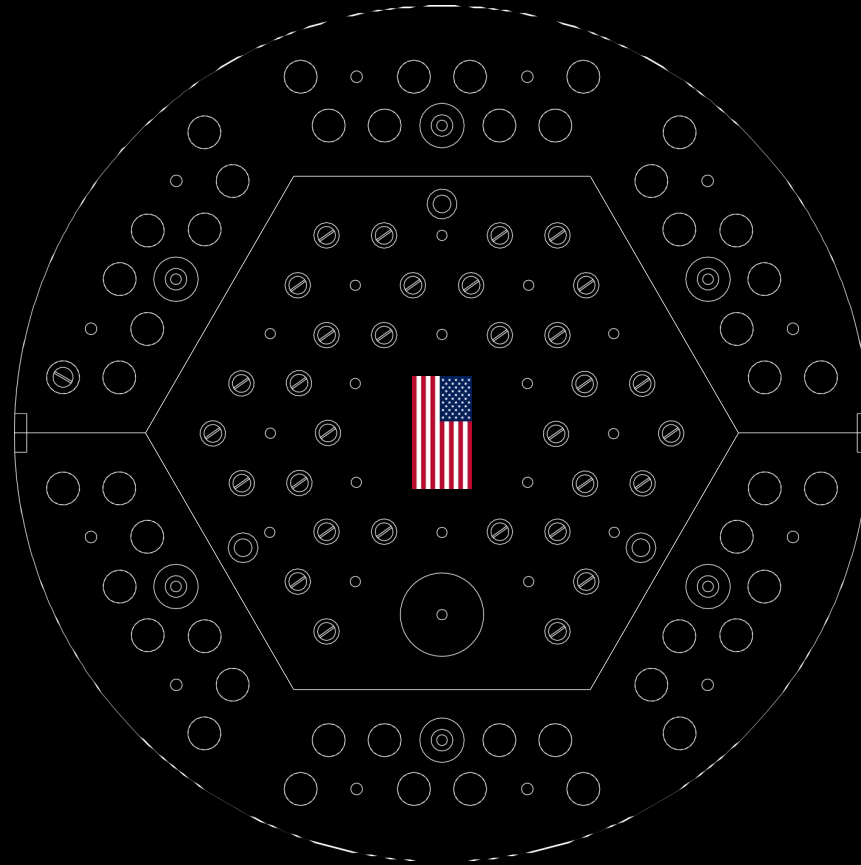
Cross section of a naturally-enriched UN-TRISO filled, annular geometry specimen.



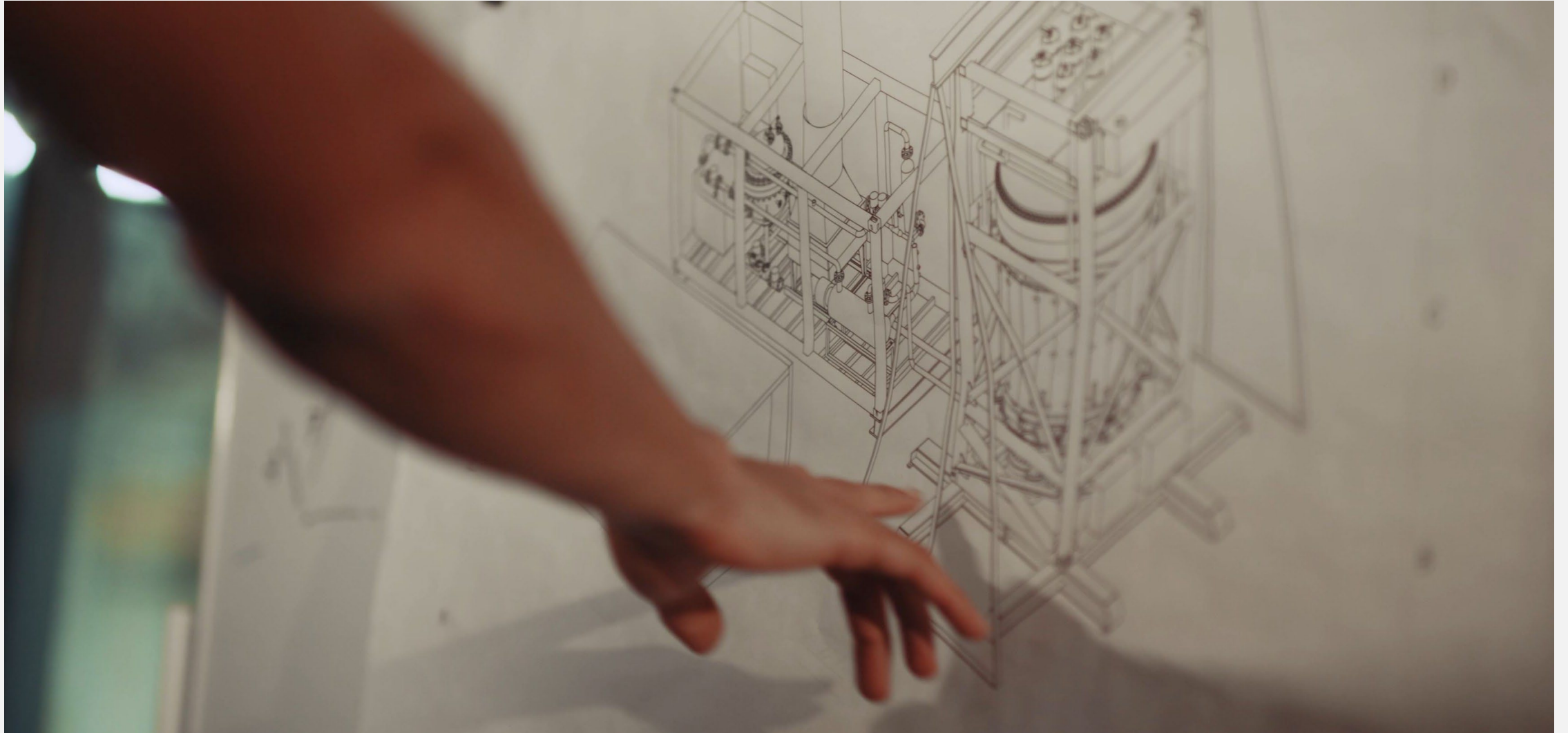
XCT of Printed preforms filled with natU UN-TRISO particles

Acknowledgement and Thanks

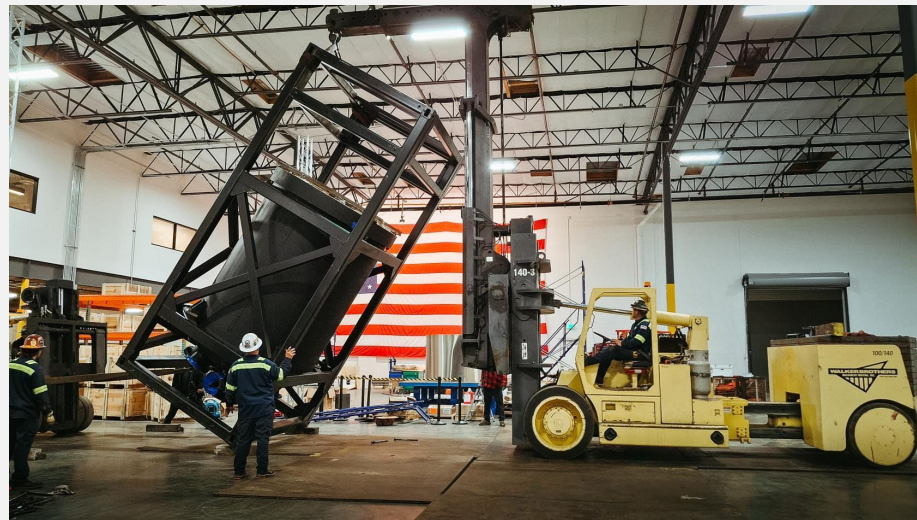
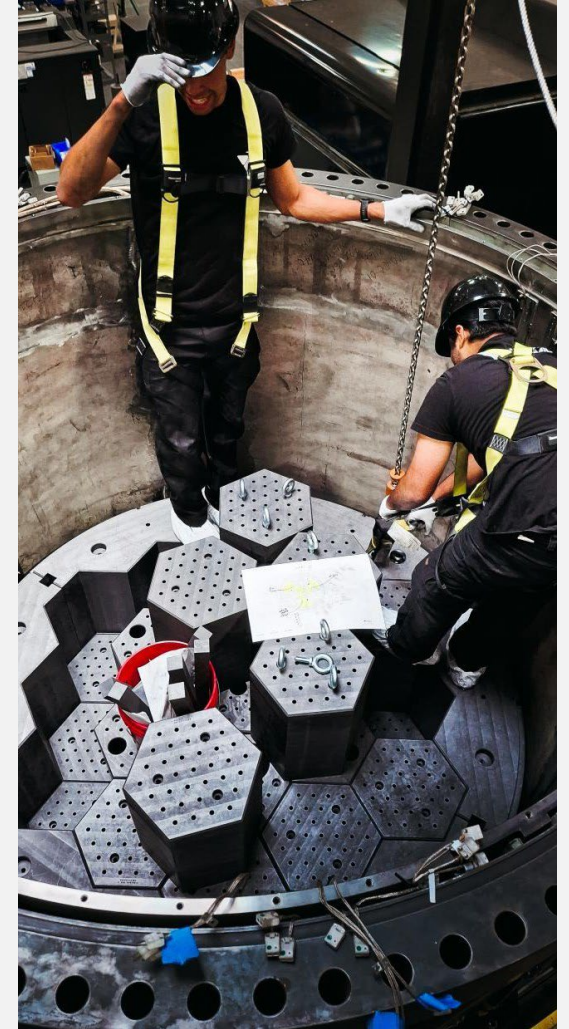
- U.S. Department of Energy
- Idaho National Laboratory
- Oak Ridge National Laboratory
- National Reactor Innovation Center



CONCEPT TO THERMAL PROTOTYPE



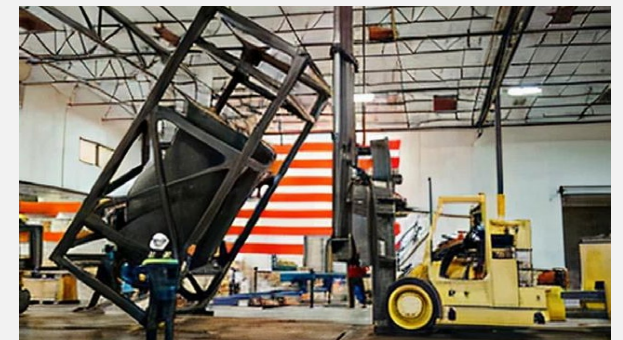
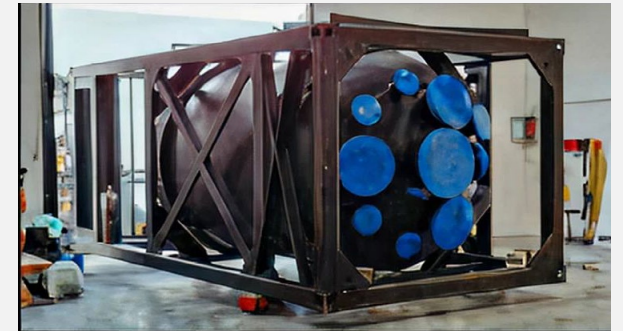
CONCEPT TO THERMAL PROTOTYPE



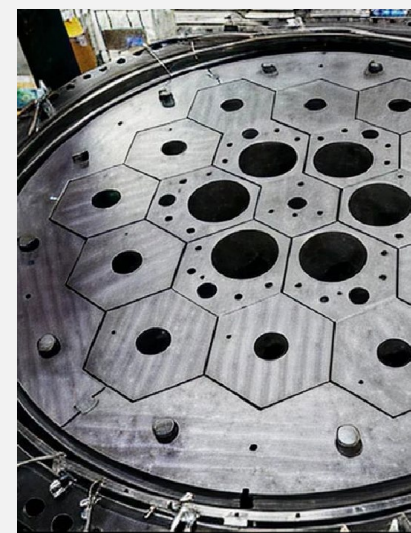
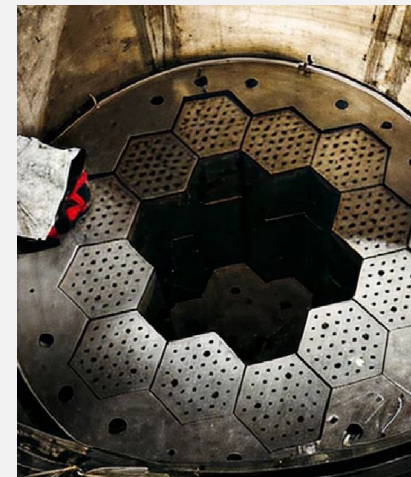
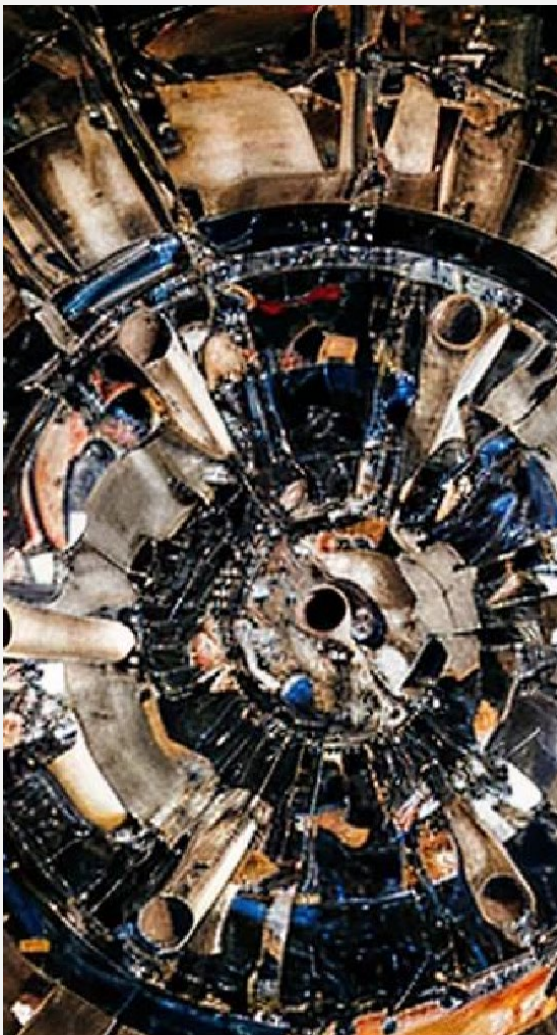
CONCEPT TO THERMAL PROTOTYPE



CONCEPT TO THERMAL PROTOTYPE



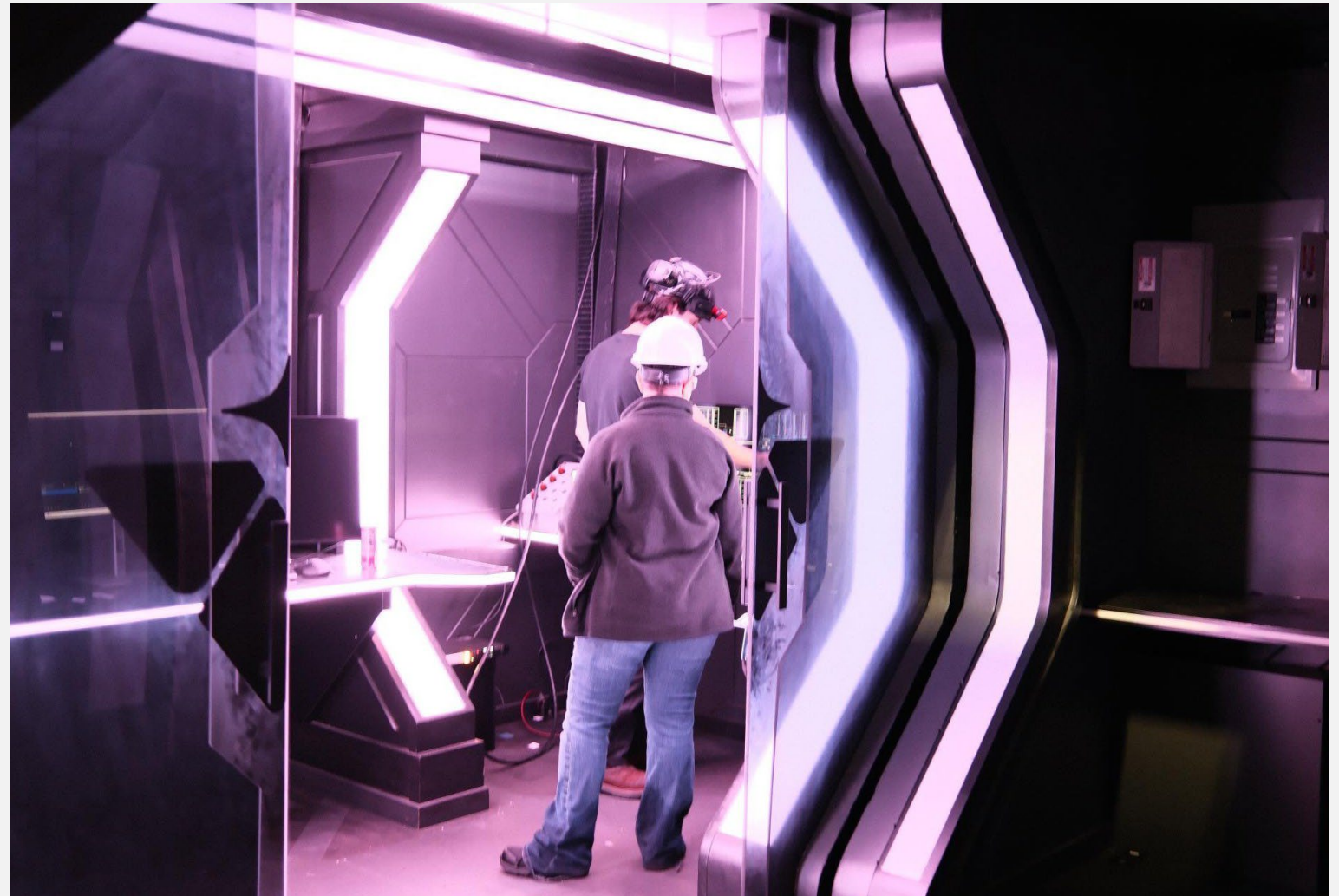
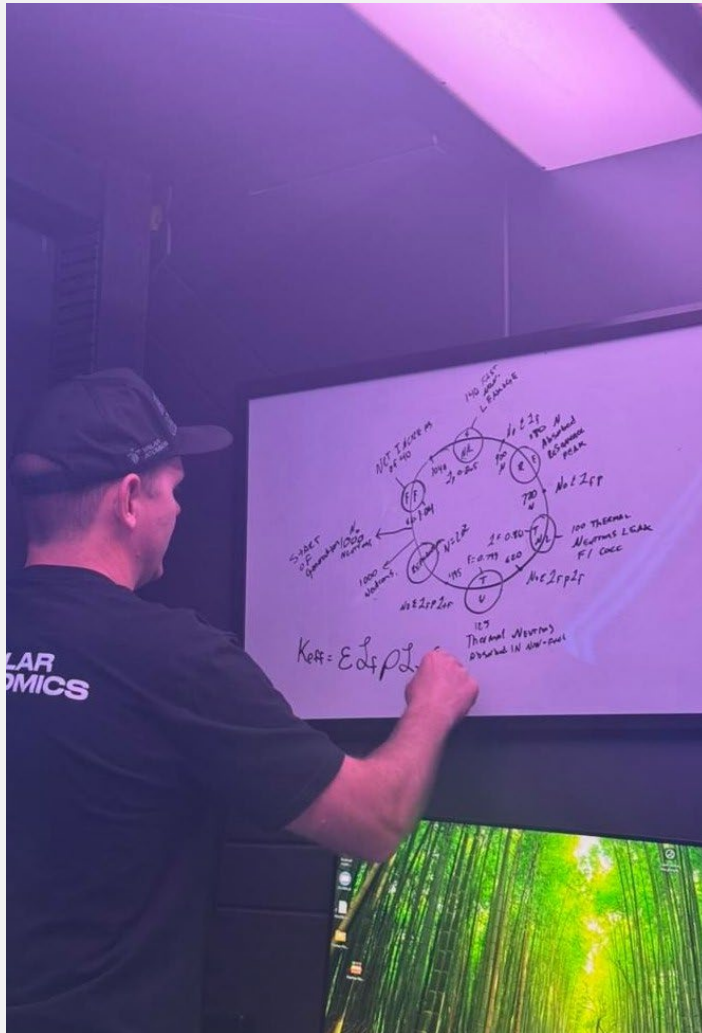
CONCEPT TO THERMAL PROTOTYPE



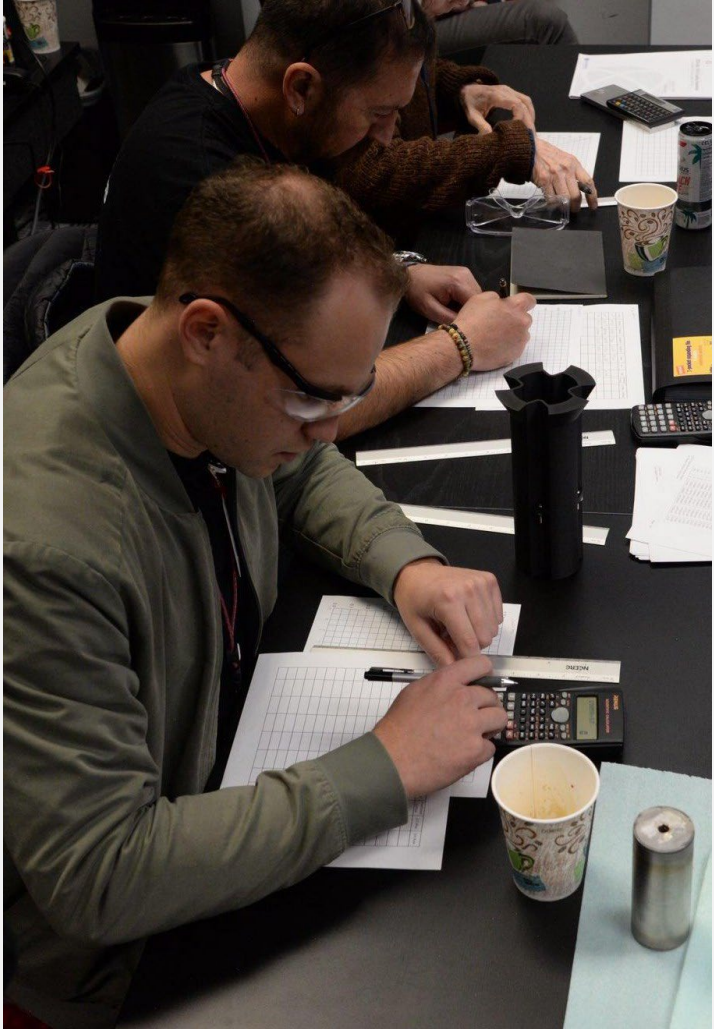
10 MONTHS



REACTOR TESTING



CRITICALITY



REACTOR TRANSPORT



REACTOR TRANSPORT



WARD 250 SITE



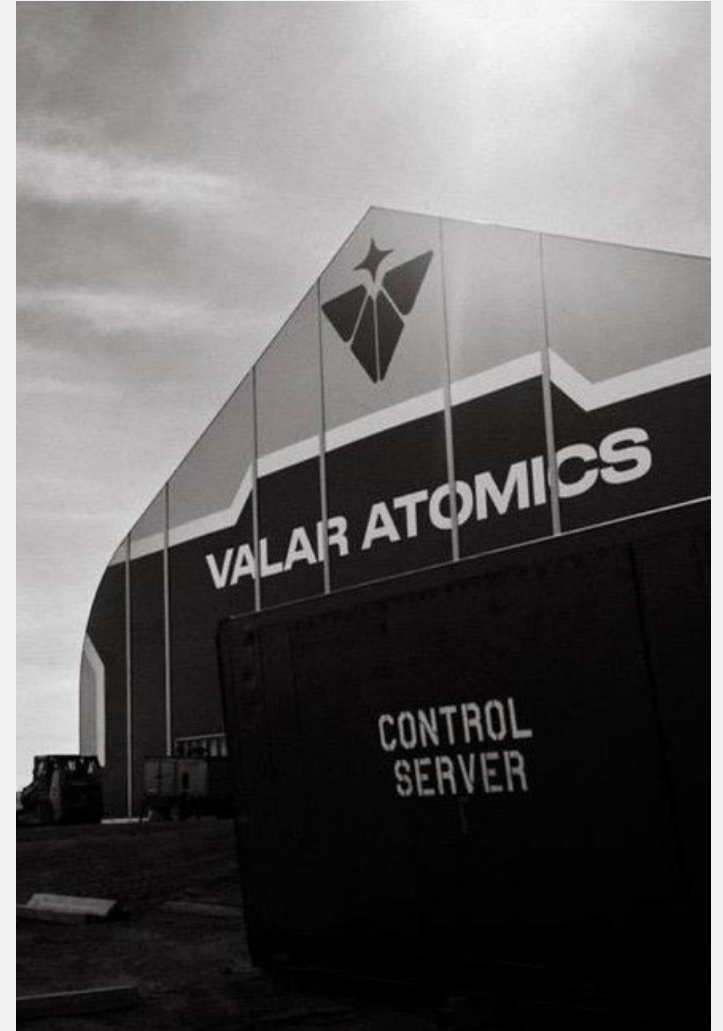
WARD 250 SITE



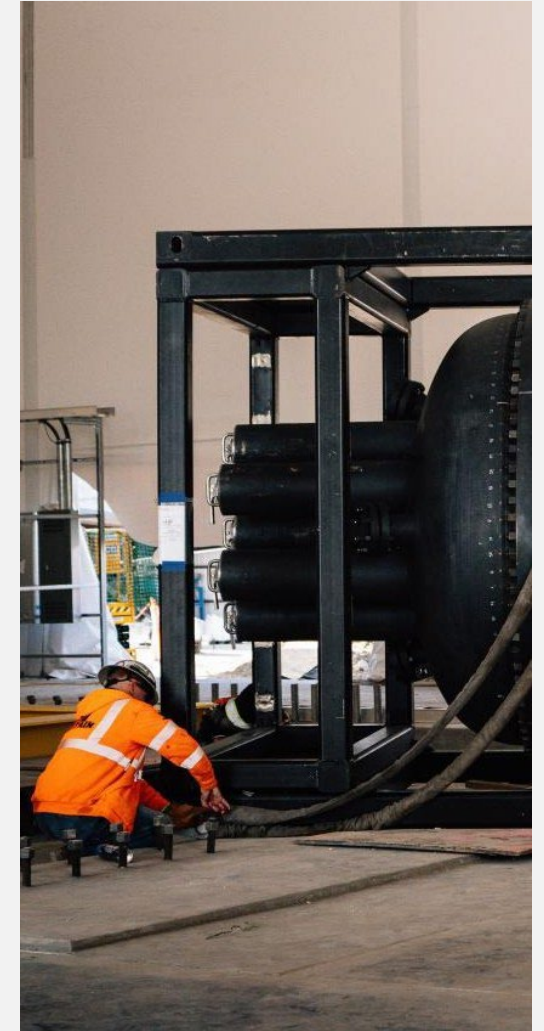
WARD 250 SITE



WARD 250 SITE



WARD 250 SITE



Valar Video

[Click Here to Watch](#)



Peter Suyderhoud
Scientific Computing & AI

AI for Nuclear Energy



Collaborative Computing Center
955 MK Simpson Boulevard

MIS-25-89334

Battelle Energy Alliance manages INL for the
U.S. Department of Energy's Office of Nuclear Energy



Idaho National Laboratory



Genesis Video

[Click Here to Watch](#)

Genesis Mission: A National Mission to Accelerate Science Through Artificial Intelligence



Applied Energy

AI will be used to accelerate sustainable fusion power, optimize advanced nuclear reactor design and operation, and enable a more intelligent and resilient electrical grid.



Discovery Science

AI will be used to illuminate molecular dynamics, unify data to understand the universe from quarks to cosmos, and generate new quantum algorithms.



National Security

AI will be used to secure critical materials, accelerate advanced manufacturing, and discover mission-ready materials for defense and industry.

Utilizing GenAI Tools and APIs Across INL

2.5

THOUSAND

Microsoft Copilot
(integrated with Microsoft Office productivity tools)

288

HPC AI APIs
(e.g. OpenAI GPT OSS, Meta LLAMA)

488

Anthropic Claude
(with access to Claude Code)

100

Advanced Cloud Frontier Model API Access

458

OpenAI ChatGPT
(with access to Codex)

3

THOUSAND

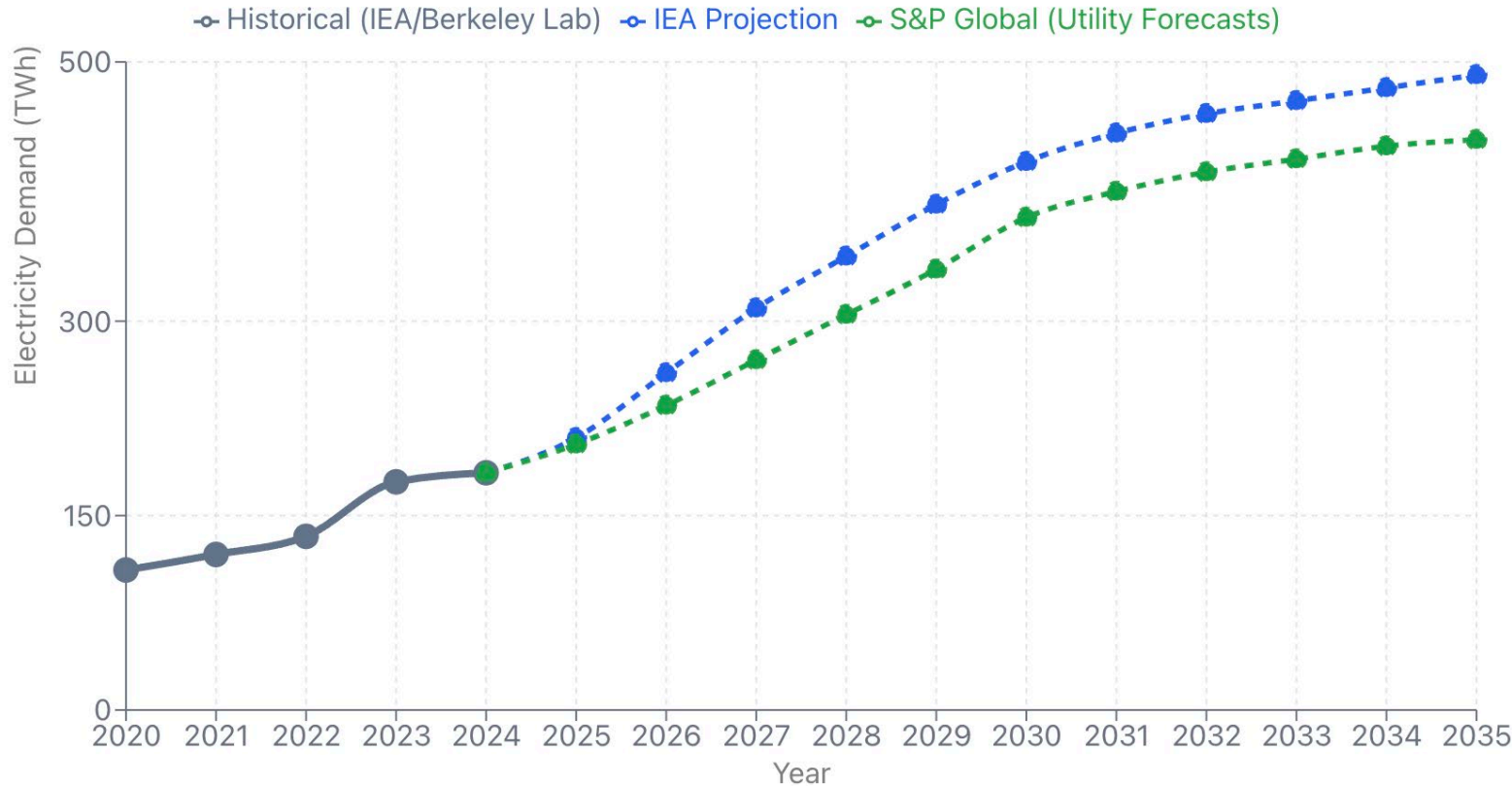
Unique employees use advanced AI tools each week (on average)



~4,200 Utilize Generative AI in Some Way

~300 AI Champions Across INL

The Demand for AI Electricity is Growing Rapidly



Massive Multitask Language Understanding

Human: 89.8%

OpenAI

GPT-3 (2020): 43.9%
GPT-3.5 (2022): 70%
GPT-4 (2023): 86.4%
GPT-4o (2024): 88.7%
GPT-5 (2025): 91.4%

Anthropic Claude

Claude 2 (2023): 78.5%
Opus 3 (2024): 86.8%
Opus 4.5 (2025): 90%

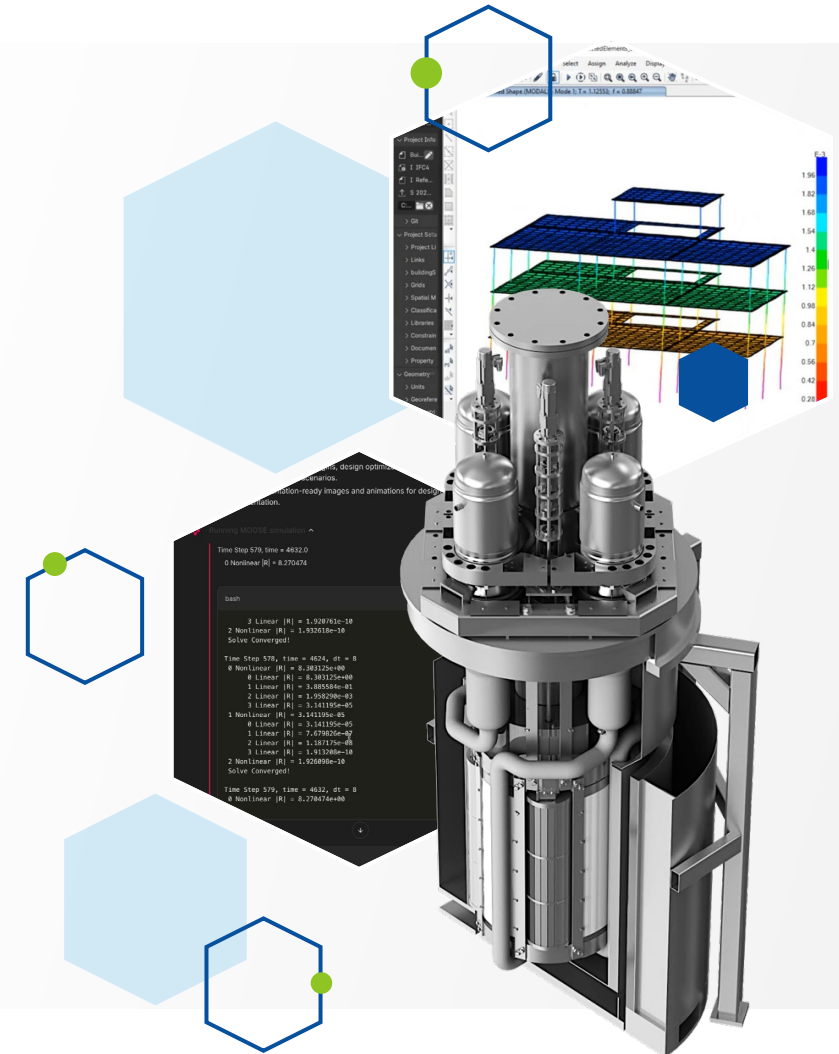
MMLU measures AI knowledge across 57 academic subjects—from law to physics—like a comprehensive college entrance exam for machines. Higher scores indicate broader, more accurate understanding.

Genesis Mission: *Prometheus Challenge*

AI-First Nuclear Paradigm

First-of-its-kind autonomous nuclear reactor designed, safety analyzed, built, and operated with <5% human intervention

- **Strategic Impact:** Supports U.S. goal to reach 400 GW nuclear capacity by 2050; enables **2–5x schedule acceleration** and **up to 70% OPEX** reduction.
- **Born-Certified Manufacturing:** Digitally certified, AI-augmented fabrication with in-situ quality control.
- **Public-Private Partnership:** Uniting national labs, AI developers, and industry for shared innovation and leadership.
- **Technical Milestones:** From AI design platform (2026), limited autonomy demo (2027) to full reactor (2031).

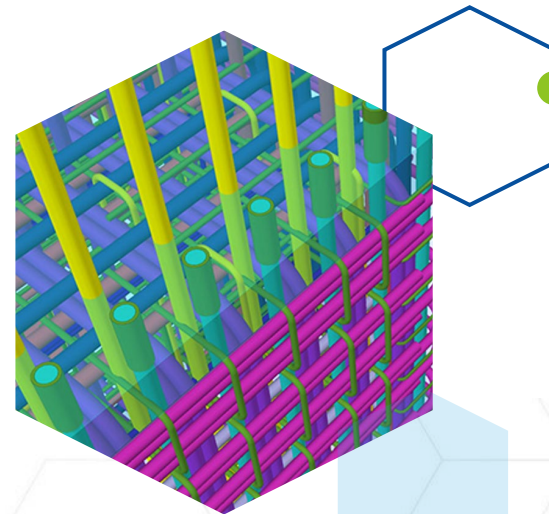
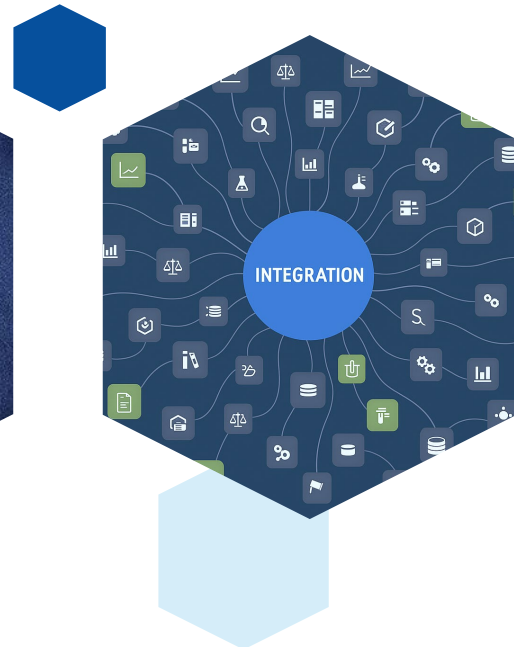
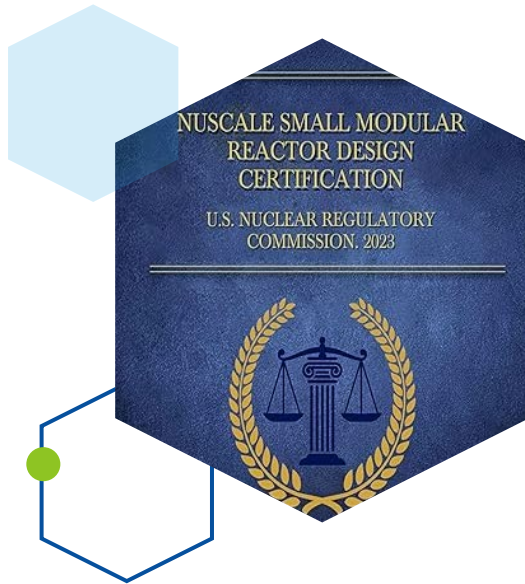


Nuclear Engineering Today

Millions of Pages of Paper¹

Cascading Risk

Complex Detailing²



Design & License Efforts

2,000,000 Pages of Supporting Engineering Documents¹

12,000 Pages in Design Certification Application (DCA)¹

\$500M DCA application Preparation Cost¹

380+ 3D BIM technicians and modelers²

12,000+ Drawings across the construction disciplines²

1: NuScale, 2: Hinkley Point C



Chainlit Video

[Click Here to Watch](#)

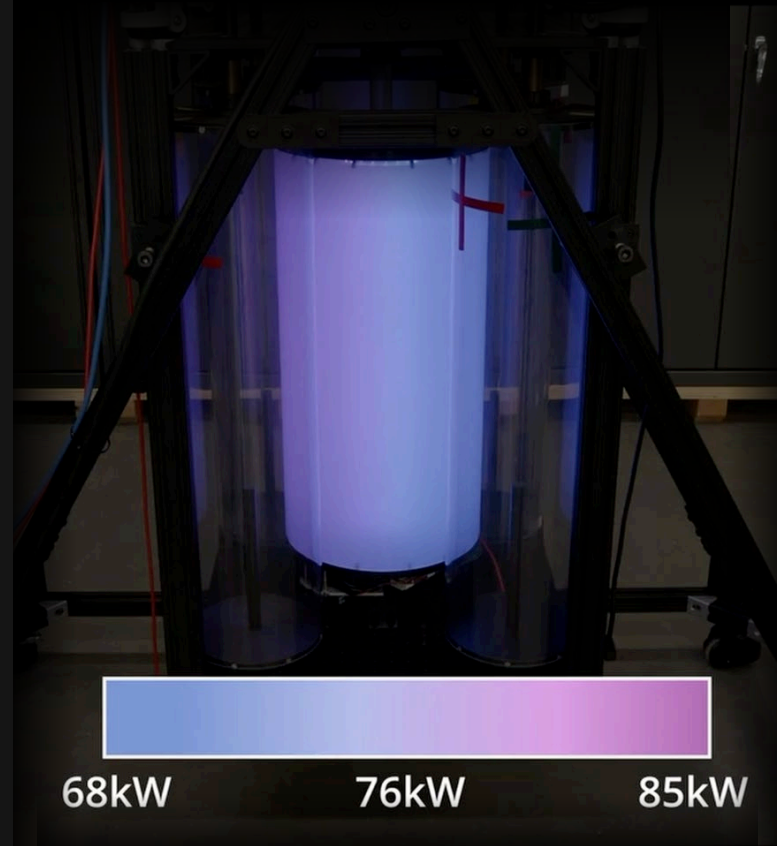
*“To avoid the prospect that high staffing levels relative to unit power production will lead to unsustainable O&M costs for small reactors, a significantly **higher degree of automation**, to the point of **near autonomy**, is necessary. Essentially, the **economy of automation** is needed to offset the **loss of economy of scale**.”*

Richard Wood, Nuclear News (July 2021)

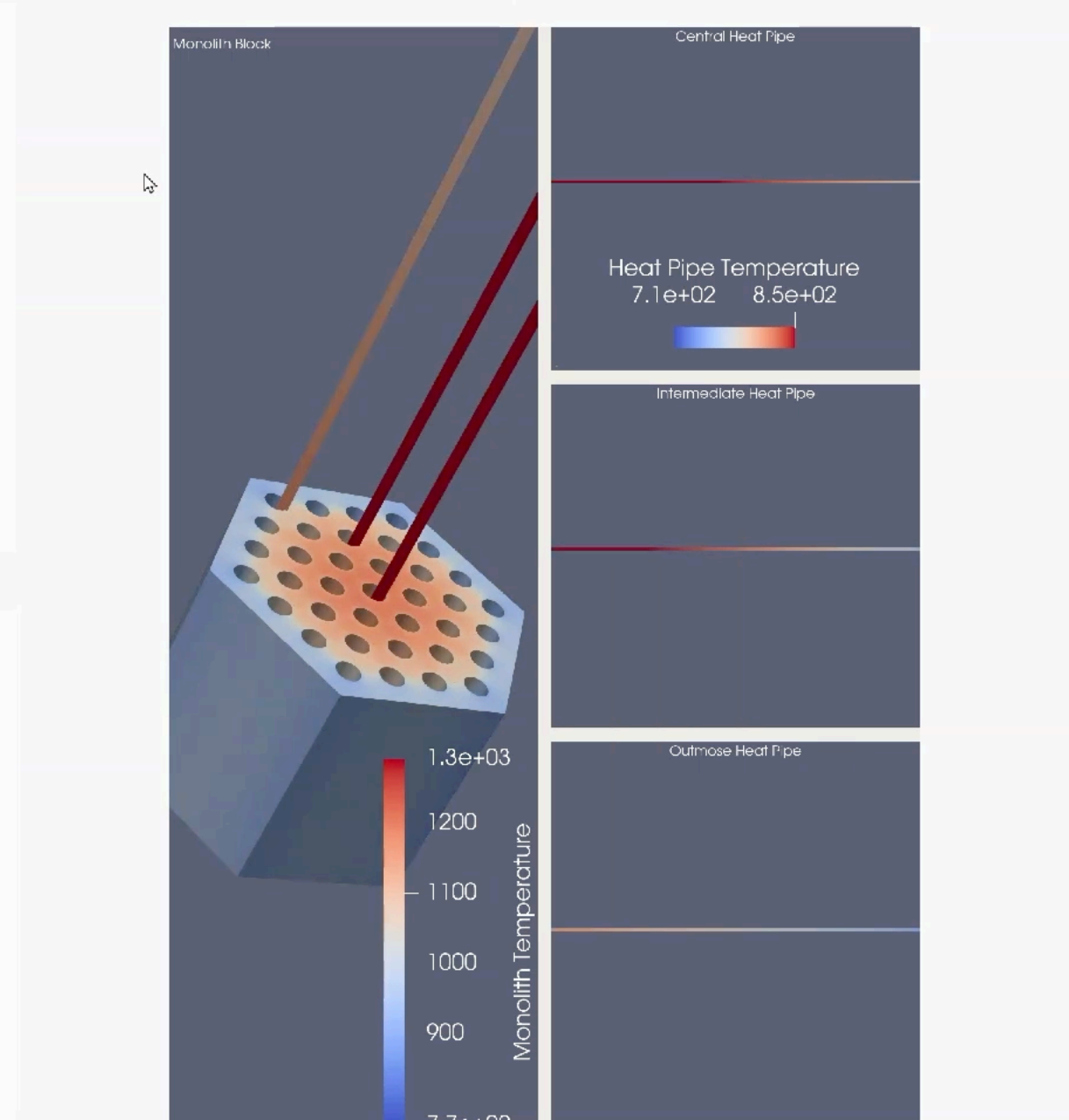
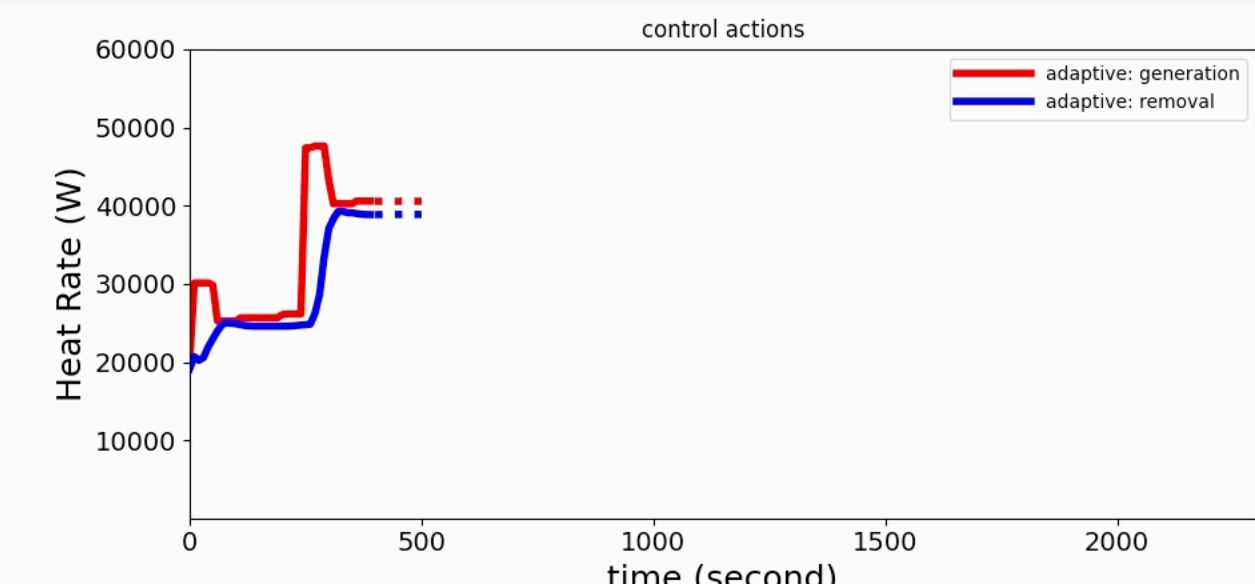
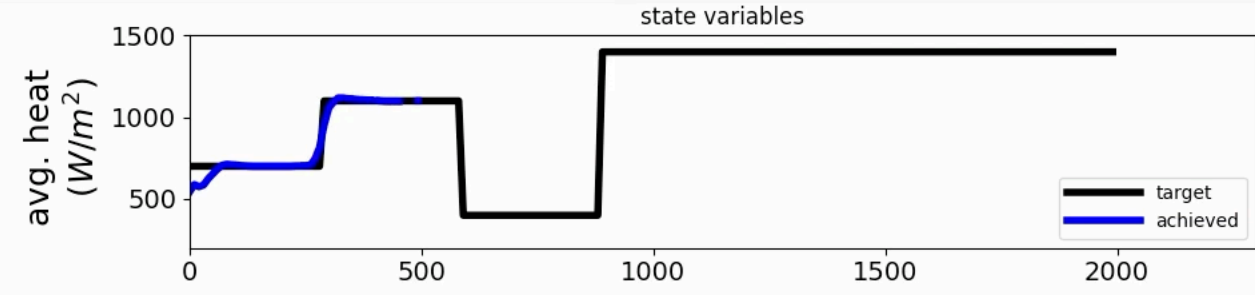
Autonomous Operations and Maintenance

First Autonomously
Controlled Non-Nuclear
Microreactor

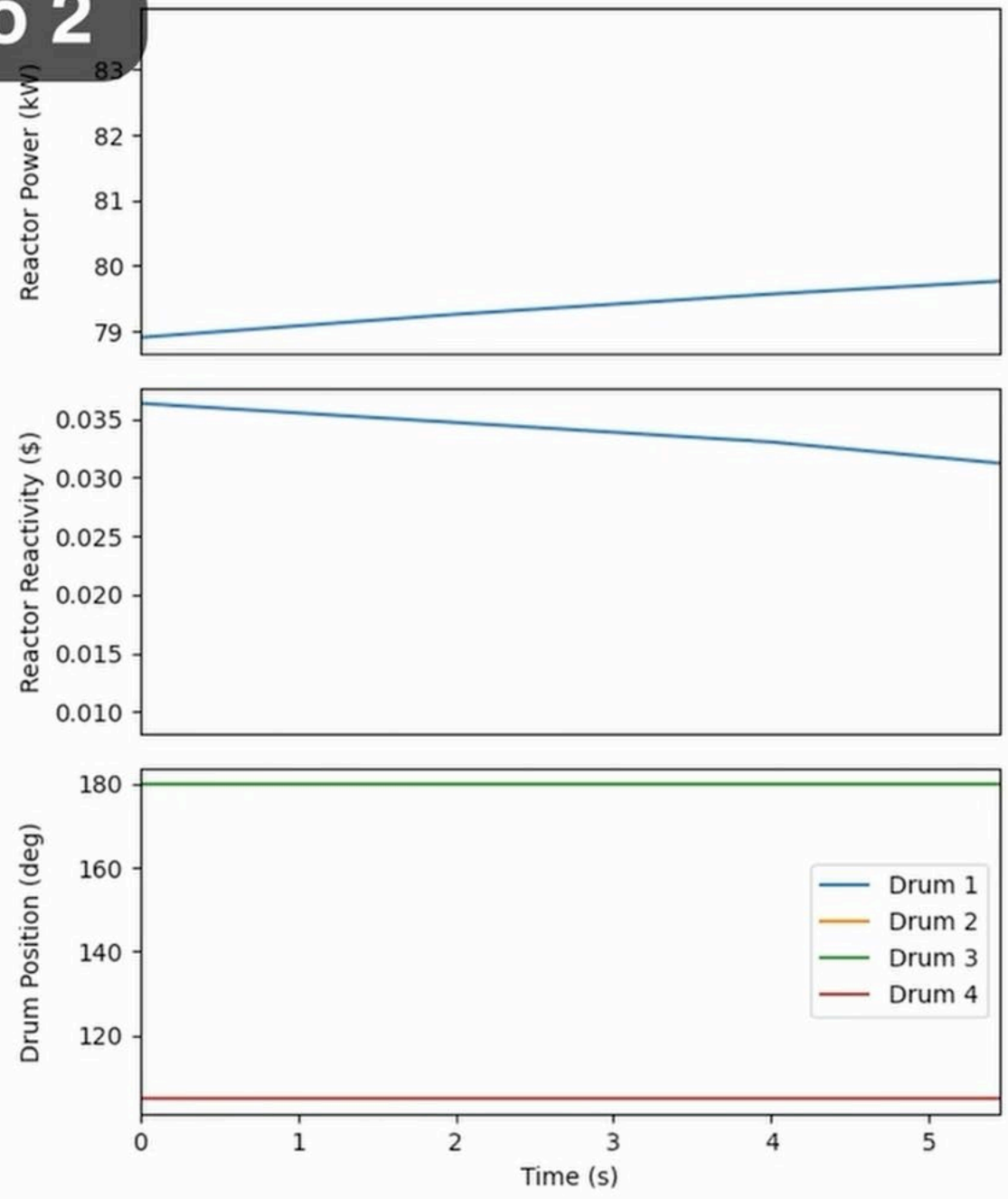
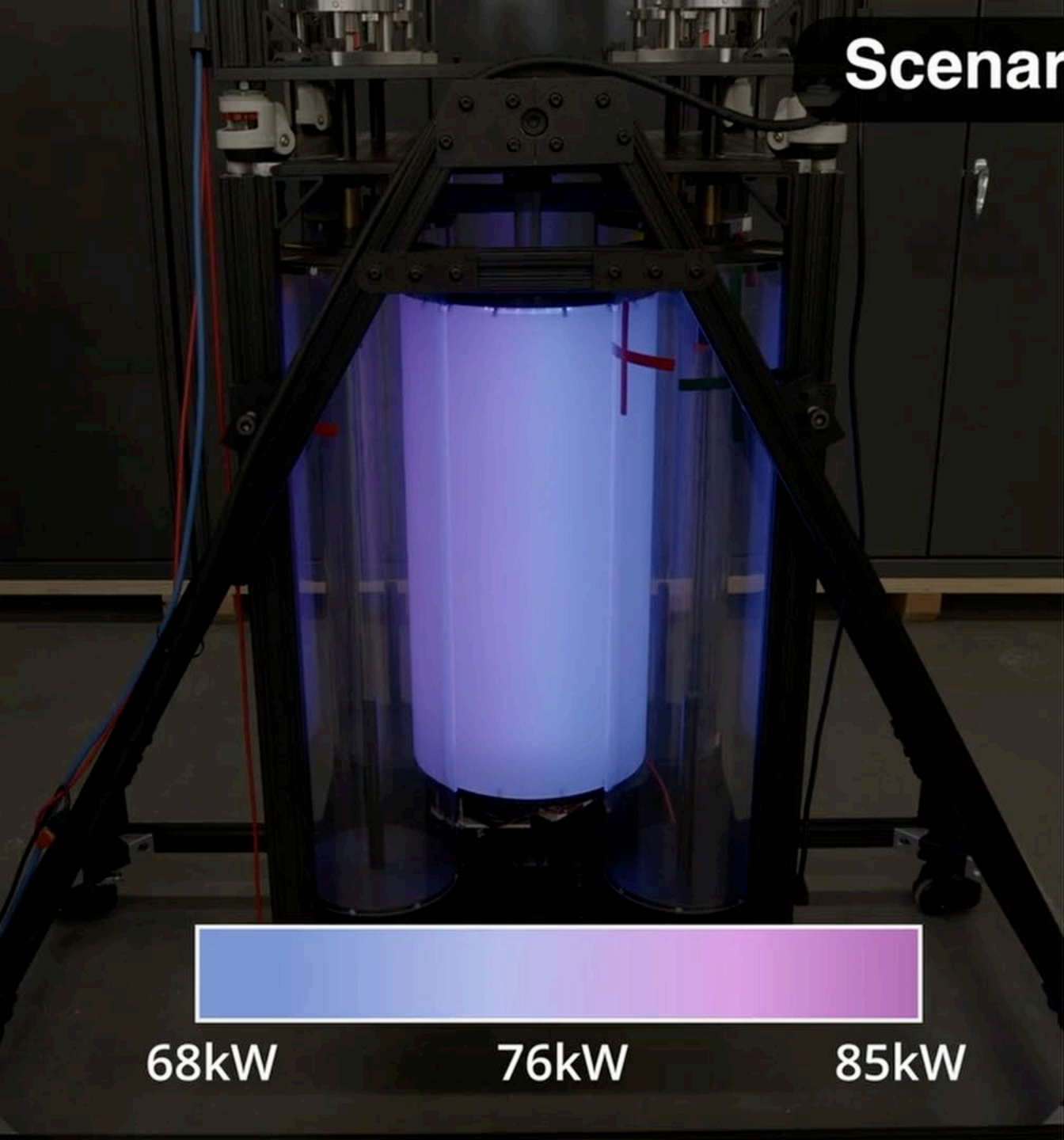
First Real-time, Real-
world **Digital Twin** of a
Nuclear Reactor



normal START RESET EXIT



Scenario 2





Genesis Mission: *VULCAN Challenge*

AI-Driven Nuclear Materials Revolution

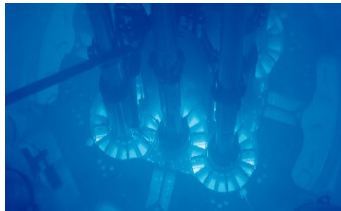
Autonomous pipeline for nuclear materials discovery, qualification, and deployment—compressing decades into years

- **Historic Data Foundation:** Digitizes 25,000+ irradiation experiments; LLMs guide optimal testing using legacy data from EBR-II, HFIR, ATR.
- **AI-Driven Materials Design:** Predicts qualified materials using multi-modal models aligned with ASME/NRC standards; auto-generates compliance docs.
- **High-Throughput Autonomous Experimentation:** Fabricates 100+ samples per campaign; robotics and AI vision automate irradiation and monitoring.
- **Automated Characterization & Analysis:** Robotic hot cells and AI analytics deliver real-time PIE and predictive models into ASME-compliant databases.



Nuclear Infrastructure and Data are Key for AI

Key Nuclear Infrastructure



Advanced Test Reactor



Fuel Conditioning Facility



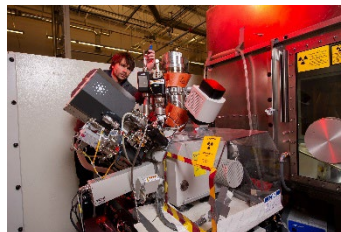
NRIC DOME



Hot Fuel Examination Facility



Sample Preparation Laboratory



Irradiated Materials Characterization Laboratory



Collaborative Computing Center



Transient Reactor Test Facility

Rich Data Assets at INL for AI

- **Legacy data** from decades of reactor, fuels, and materials tests
- ATR and TREAT experimental campaigns provide **foundational fuel performance** and transient behavior data
- DOME, test bed, and pilot projects can capture **industry-relevant reactor experiment** data
- Fuels and Fuel Cycle Facilities contributes critical **material property characterization**
- Alexandria supports **non-proliferation** and **safeguards** applications (petabyte-scale)
- Near-term **microreactor** deployments (e.g., MARVEL, Pele) will generate **autonomous control**, digital twin validation, and **mobile reactor** datasets

May 6, 2026

Justin Coleman

Director – Nuclear Reactor Technology

Sebastian Corbisiero

National Technical Director – Space Reactor Program

Space Reactor Overview

MIS-26-92002

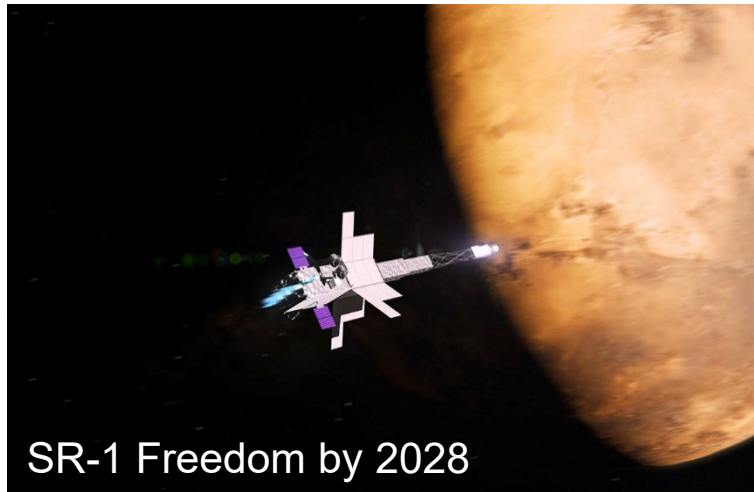
Battelle Energy Alliance manages INL for the
U.S. Department of Energy's Office of Nuclear Energy



Idaho National Laboratory

Space Reactor Updates

- Executive Order 14369: Ensuring American Space Superiority (12/18/2025)
 - “(ii) enabling near-term utilization of space nuclear power by deploying nuclear reactors on the Moon and in orbit, including a lunar surface reactor ready for launch by 2030;”
- NASA Ignition announcement (3/24/2026)
- NSTM-3 (4/14/2026)



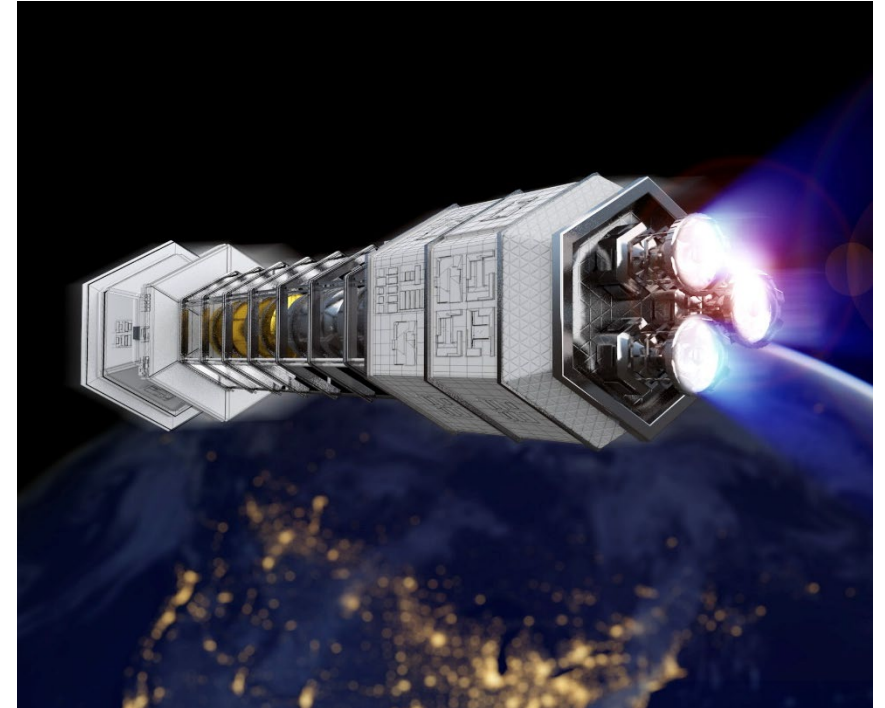
INL's Role in Space Nuclear Development

Vision

- Enable U.S. development and operation of space nuclear reactors that support American leadership in space

Role

- Advisory
 - Provide scoping support
 - Offer subject matter expertise
- Development
 - Advanced technology
 - Build supporting infrastructure
- Integration
 - Serve as lead integrator for space reactors
 - Coordinate across the national laboratories



Technology Development at the National Labs – NASA Sponsored

Instrumentation & Control

- Autonomous operation required in high-radiation, zero-maintenance environments

Metal Hydride Moderators & Encapsulation

- Moderation enables mass reduction and metal hydrides support moderated systems

Shielding

- Mass-limited systems require optimized radiation shielding, which is often the largest mass component

Nuclear Thermal Propulsion (NTP) Fuel Development

- Fuel must sustain temperatures >2850 K, far higher than terrestrial reactor temperatures

Industry Design Efforts

- SME support and contract oversight of 6 industry design efforts (FSP and NTP)



TZM Elements (LANL)



Quartz Encapsulation (INL)

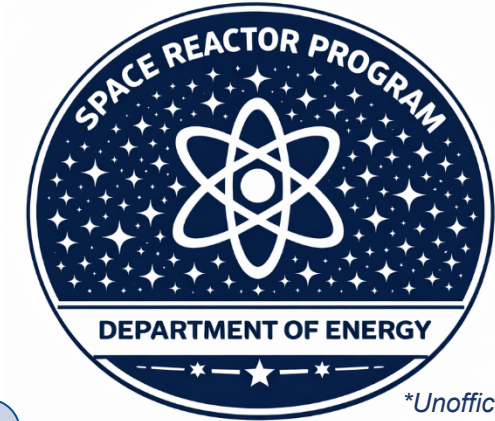
Department of Energy – Space Reactor Program (SRP)

Goals of this New Program

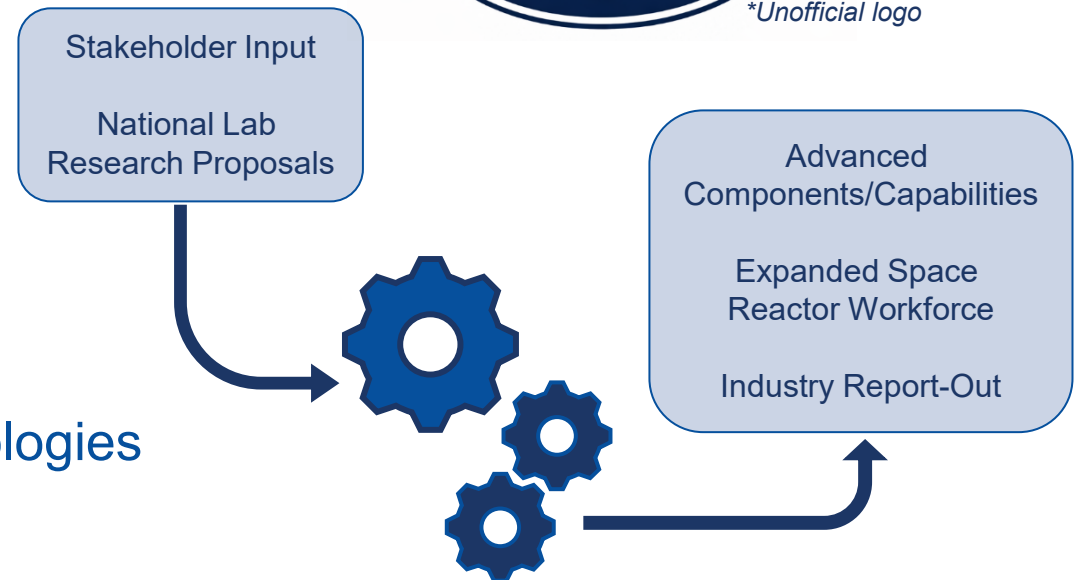
- Capability development
 - Mass reduction (20%)
 - Reactor temperatures >1200 K
- Workforce & expertise development
- Test bed development
 - Enable challenging/high-risk testing

Development Approaches

- Advance cross-cutting and forward-looking technologies
- Engage with industry partners
- Coordinate with other DOE-NE program efforts



**Unofficial logo*



Summary - INL's Leadership in Space Nuclear

Key Points

- National laboratories are developing key capabilities for future space reactors
- DOE's new Space Reactor Program is accelerating progress
- Recent national actions signal strong momentum for space nuclear deployment

Bottom line: INL is positioned to help deliver the next generation of space power systems.



Idaho National Laboratory

Battelle Energy Alliance manages INL for the U.S. Department of Energy's Office of Nuclear Energy. INL is the nation's center for nuclear energy research and development, and also performs research in each of DOE's strategic goal areas: energy, national security, science and the environment.



Anne Demma, Division Director
Anne.Demma@inl.gov

May 6, 2026

Materials Characterization and Testing Support

CON-26-92095

Why Do We Care about Materials Degradation & Characterization?

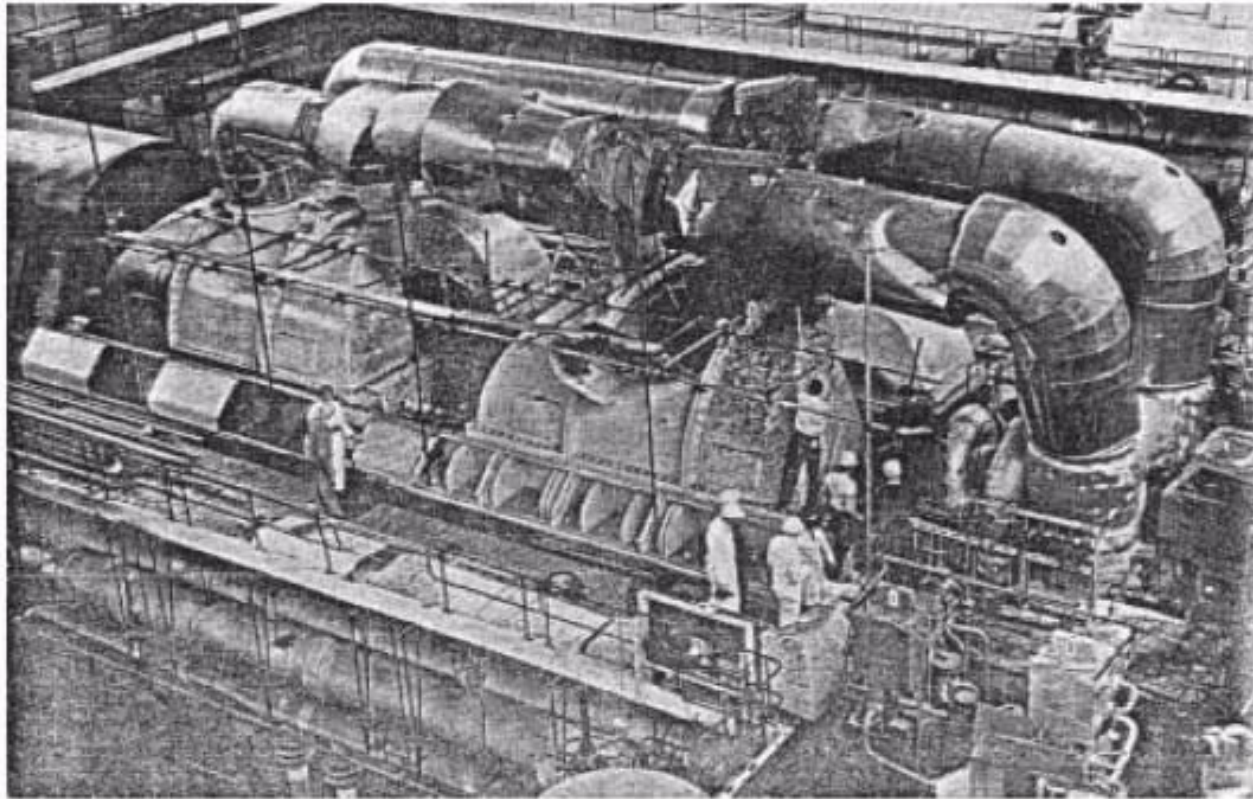


Fig. 2 Appearance of the No.5 unit after the failure.

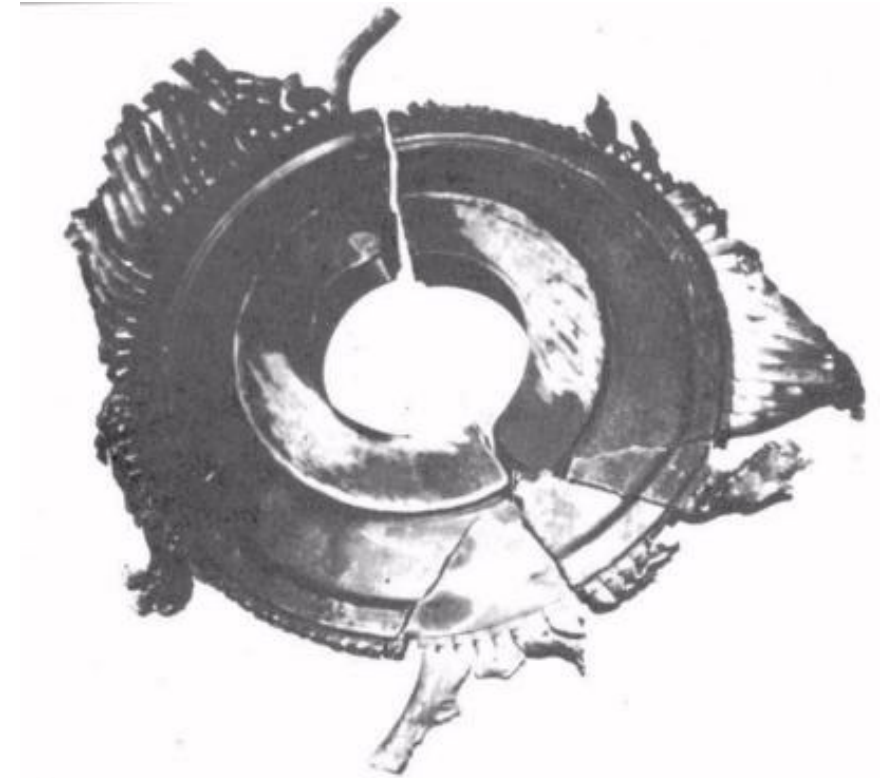


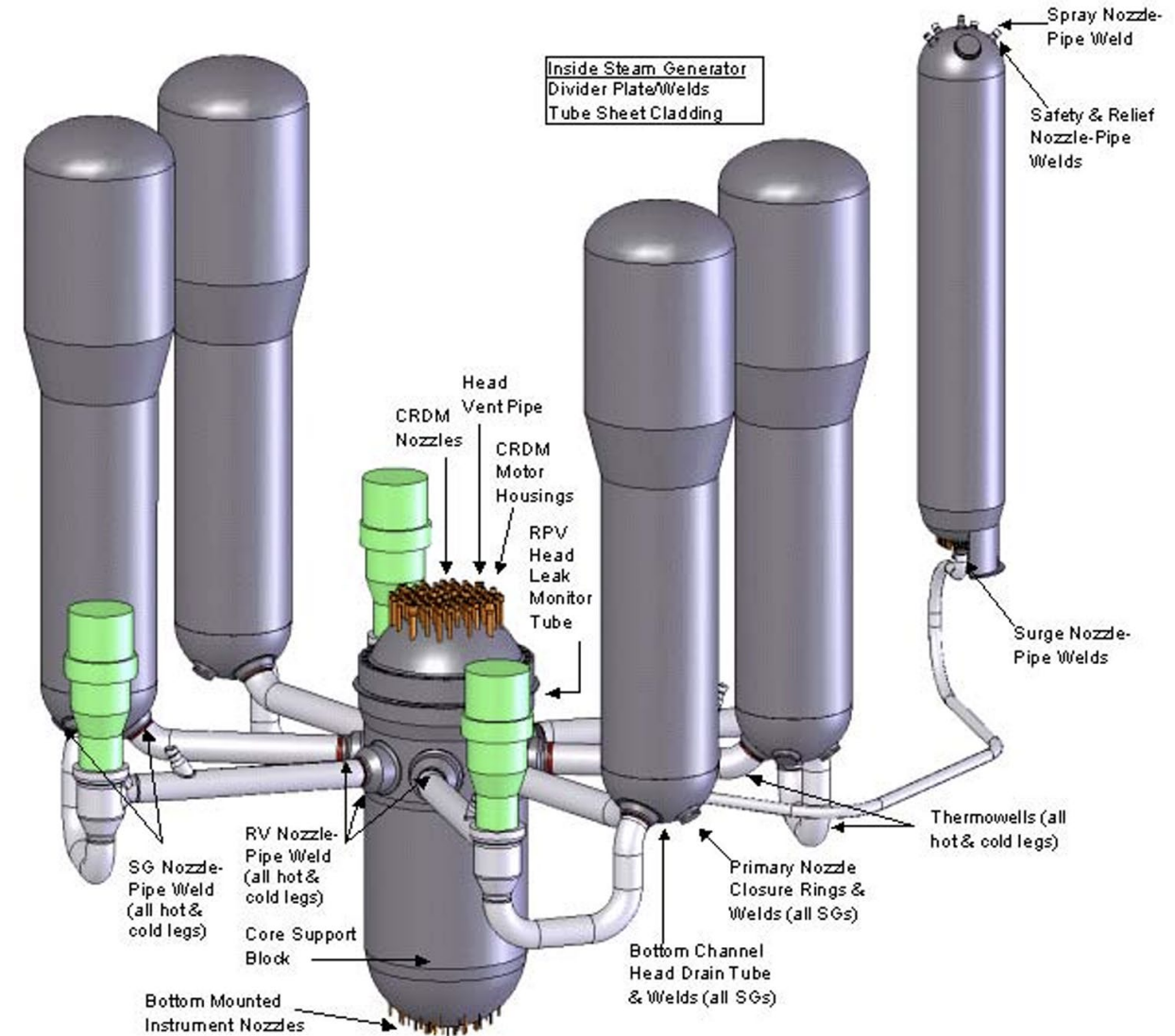
FIG.7 FRACTURED LP No3 DISC FROM 200 MW REHEAT TURBINE

- **Because of Equipment Failures!** Example: Hinkley Point Nuclear Steam Turbine Failure of 3Cr-0.5Mo steel occurred in 1969 after 1.6 mm of Stress Corrosion Cracking (SCC) growth [1]
- **Small cracks growing can destroy huge machines and can injure or kill people.**
- **Characterization helps us understand the failure mechanisms.**

[1] P. Andresen, "Environmental Cracking: History, Science, Art and Application," Presentation at Environmental Degradation of Materials in Nuclear Power Systems, Long Beach, CA, USA, 2025.

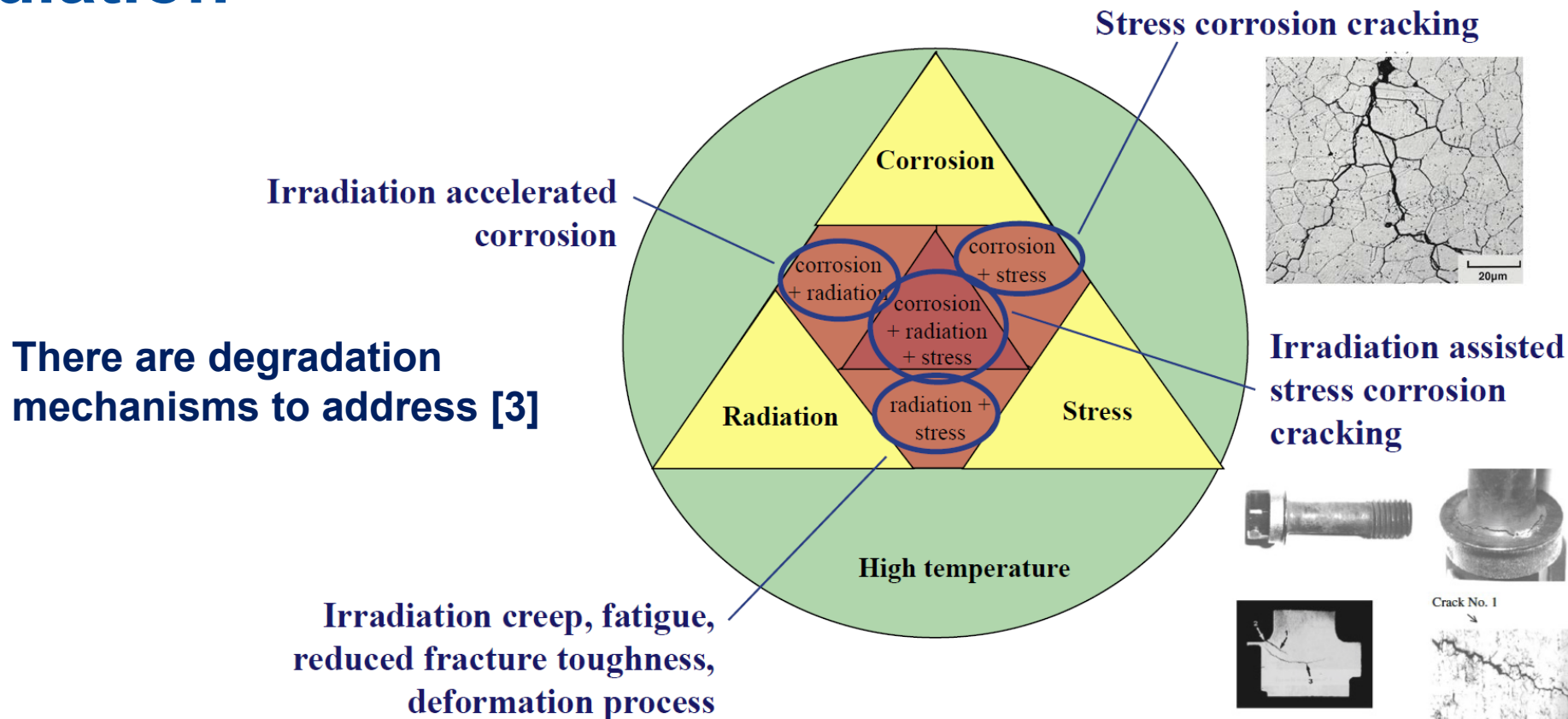
Example of Material Degradation: Alloy 600 Stress Corrosion Cracking in PWRs

- Equipment failures in plant components led to understanding of degradation mechanisms by testing and characterization in the lab.
- If we understand the degradation mechanism first by using testing and characterization, we can avoid large equipment failures at plants
 - By considering the degradation mechanisms in the design phase.
- This would result in large savings for developers, utilities, and customers.
 - Avoid large component replacement
 - Avoid electricity/heat production downtime
- Need to manage the risk to take new materials and techniques to the field!



Typical Alloy 600 Locations in Westinghouse Plants [2]

LWR Components Must Function with Corrosion, Stress & Radiation



For Small LWRs

- Similarly, **Small LWR Components** must function in a water environment with stress and radiation
 - But need to address advanced manufacturing methods: new welding techniques, additive manufacturing, etc.
 - Because these reactors are more compact, some components not previously irradiated will need to be investigated for the effects of radiation

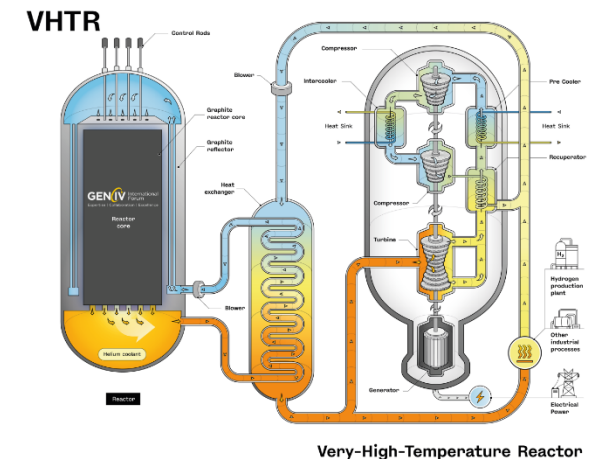
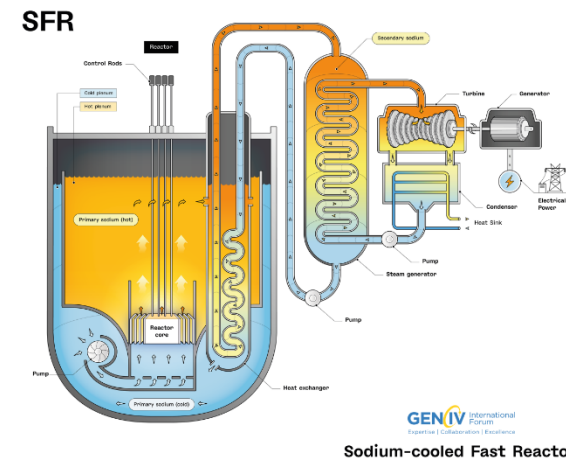
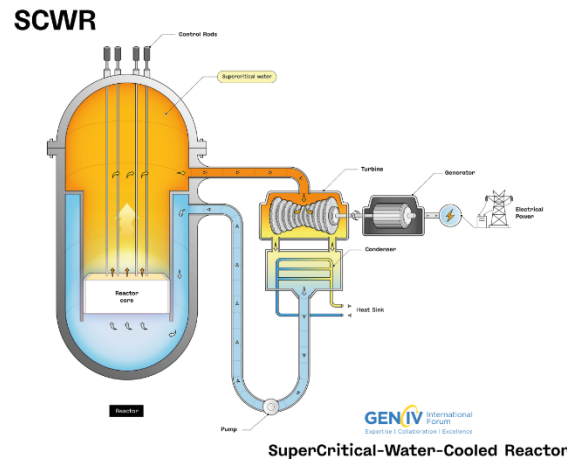
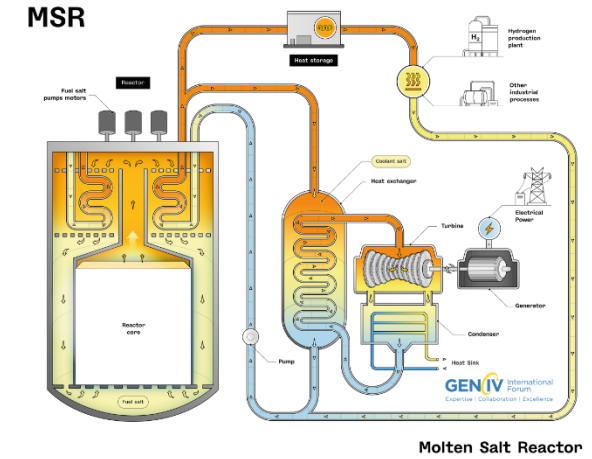
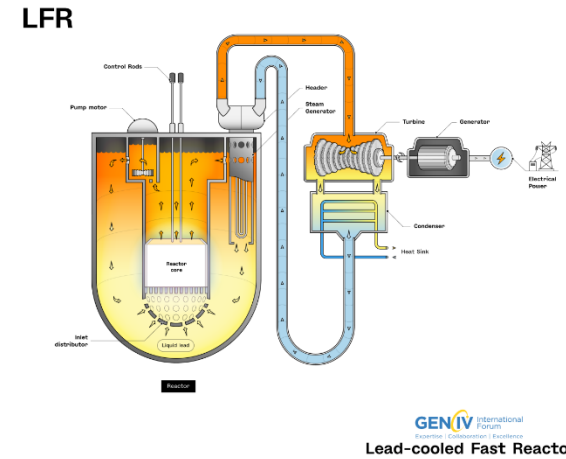
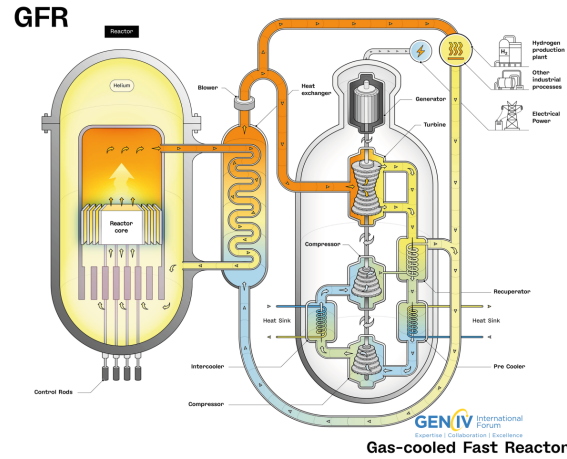
Advanced Nuclear Reactors

- Similarities

- High operating temperature
- Enhanced passive safety features

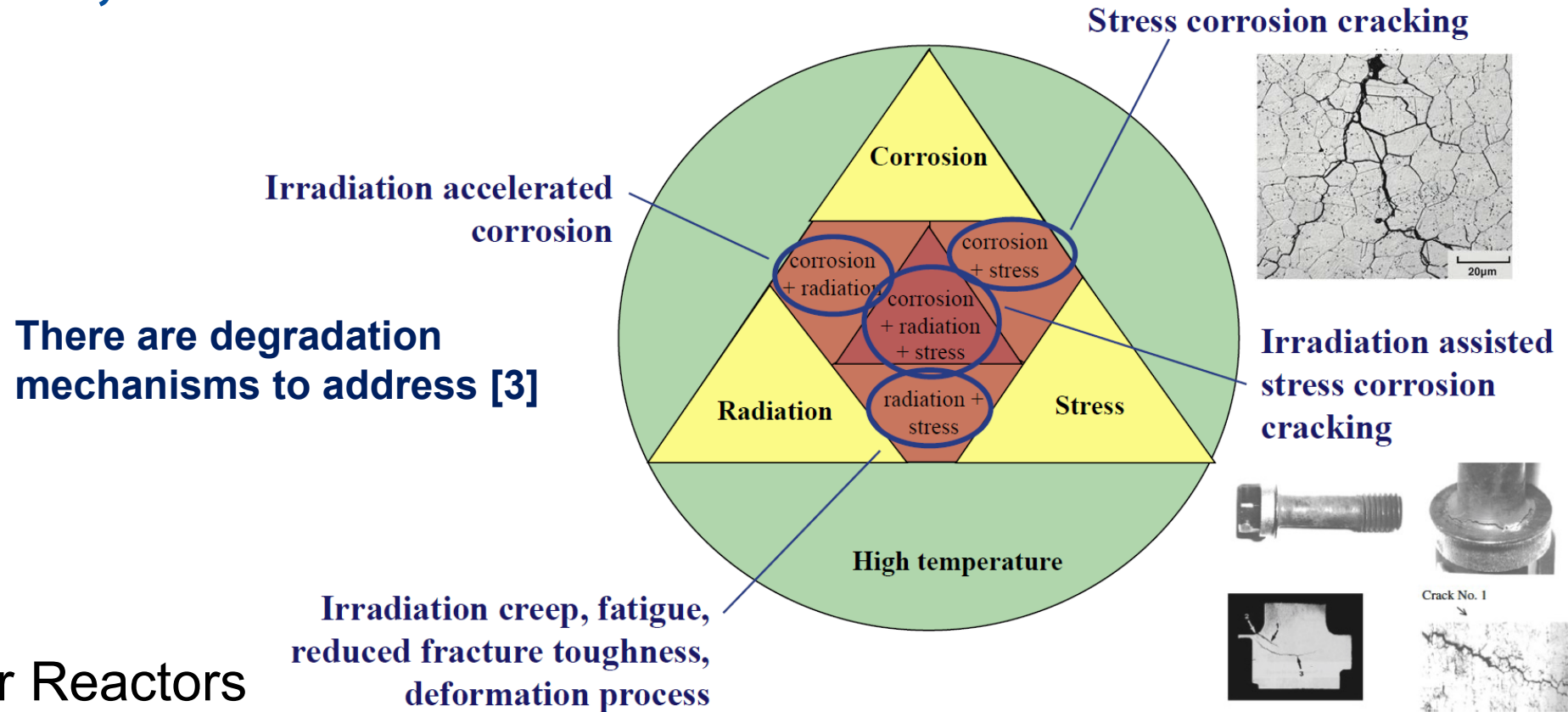
- Differences

- Operating pressure
- Fuel type
- Coolant type
- Neutron spectrum [4]



Schematic view of GFR, LFR, MS, SCWR, SFR, VHTR from <https://www.gen-4.org/>

Advanced Nuclear Reactor Components Must Function with Corrosion, Stress & Radiation like LWRs



For Advanced Nuclear Reactors

- For **Advanced Nuclear Reactor Components** (non-water), there are needs to address:
 - Additional mechanisms due to high temperatures: thermal creep, thermal aging, creep-fatigue, etc.
 - Effects of new environments: gas, sodium, lead, molten salts: fluorides, chlorides, etc.
 - Impact of new fuel: higher enrichment, manufacturing uncertainties, etc.
 - Different materials than the LWR materials
 - Advanced manufacturing methods.

Material Qualification for Advanced Reactors

- **What is Material Qualification?**
 - Process of testing and evaluating candidate materials to ensure their performance and reliability under reactor operating conditions, including mechanical loading and environmental effects
 - Subject to Codes, Standards, and Regulations
 - ASME Boiler and Pressure Vessel Code (BPVC) Section III Division 5 (III.5), etc.
 - Nuclear Authority Regulations, such as NRC

Material Qualification for Advanced Reactors

- ASME BPVC Section III.5 provides the rules and requirements for material, design, construction and fabrication of high temperature reactor systems and supporting structures; **it does not address or consider environmental effects**
- Currently there are only 6 permitted materials for Class A components, with a ballot for a 7th Alloy expected to be submitted soon

SS 304*	9Cr-1Mo-V
SS 316*	2.25Cr-1Mo
Alloy 800H	<i>Alloy 709**</i>
Alloy 617	

* Minimum carbon content of 0.04. "H" designation not used in ASME BPVC III.5

** Code Case ballot expected soon

[4]

Material Qualification for Advanced Reactors

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SS 304*	9Cr-1Mo-V
SS 316*	2.25Cr-1Mo
Alloy 800H	<i>Alloy 709**</i>
Alloy 617	

* Minimum carbon content of 0.04. "H" designation not used in ASME BPVC III.5

** Code Case ballot expected soon

[4]

- Extremely limited choices for material selection***
- Permitted materials may not be sufficiently compatible with the reactor environment***

Material Qualification for Advanced Reactors

“Mechanical” Qualification (ASME BPVC III.5)

+

“Environmental” Qualification

- Time-independent Data (HBB-Y-2100)
- Tensile reduction factors for thermal aging (HBB-Y-2110)
- Time-dependent data (HBB-Y-2200)
- Weldments data
- Isochronous stress-strain curves
- Creep-fatigue for base and weldments
- Cyclic stress-strain curves
- Etc.

- Corrosion (general, localized, galvanic)
- Thermal gradient driven degradation
- Erosion-corrosion, flow-accelerated degradation
- Environmentally assisted cracking
- Irradiation assisted degradation
 - Irradiation-assisted SCC
 - Etc.

Material Qualification for Advanced Reactors

“Mechanical” Qualification (ASME BPVC III.5)

+

“Environmental” Qualification

- Time-independent Data (HBB-Y-2100)
 - Tensile reduction factors for thermal aging (HBB-Y-2110)
 - Time-dependent data (HBB-Y-2200)
 - Weldments data
 - Isochronous stress-strain curves
 - Creep-fatigue for base and weldments
 - Cyclic stress-strain curves
 - Etc.
 - **If use one of the permitted materials for Class A components, then no additional testing needed.**
 - **If need to use a different material, then long-term testing needed, but known path using existing facilities and demonstrated test capabilities**
- Corrosion (general, localized, galvanic)
 - Thermal gradient driven degradation
 - Erosion-corrosion, flow-accelerated degradation
 - Environmentally assisted cracking
 - Irradiation assisted degradation
 - Irradiation-assisted SCC
 - Etc.

Material Qualification for Advanced Reactors

“Mechanical” Qualification (ASME BPVC III.5)

+

“Environmental” Qualification

- Time-independent Data (HBB-Y-2100)
 - Tensile reduction factors for thermal aging (HBB-Y-2110)
 - Time-dependent data (HBB-Y-2200)
 - Weldments data
 - Isochronous stress-strain curves
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 - Etc.
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- Corrosion (general, localized, galvanic)
 - Thermal gradient driven degradation
 - Erosion-corrosion, flow-accelerated degradation
 - Environmentally assisted cracking
 - Irradiation assisted degradation
 - Irradiation-assisted SCC
 - Etc.
 - **If use an ASME permitted materials or a different material, long-term & resource intensive testing**
 - **Often design specific environmental requirements**
 - **Limited testing capabilities**
 - **Requires significant development and investment**

Material Qualification for Advanced Reactors

**“Mechanical” Qualification
(ASME BPVC III.5)**

+

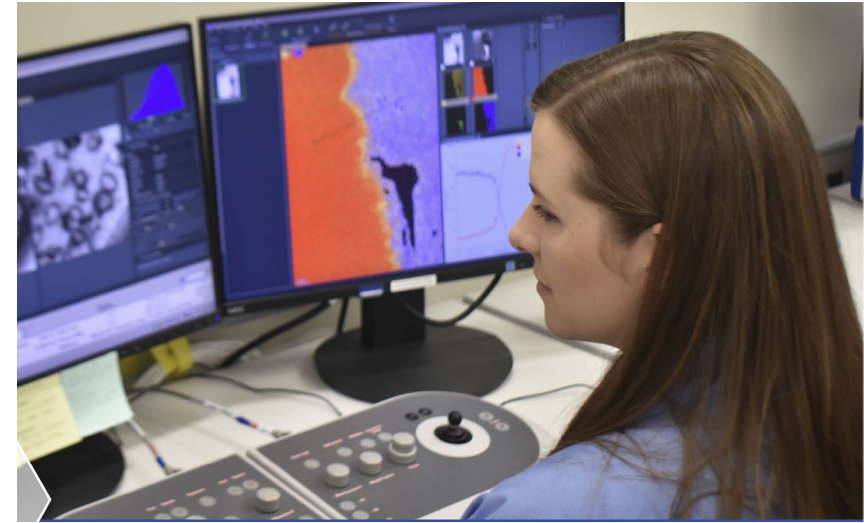
“Environmental” Qualification

Synergistic Effects: “Environmental” on “Mechanical”, etc. ?

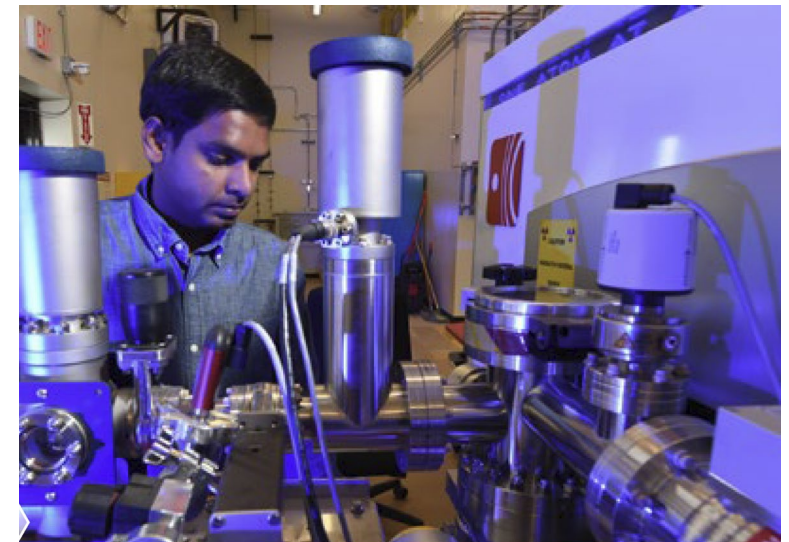
**Since limited operating experience for the advanced reactors,
there could be some unknown impacts!**

Collaboration Needed

- **Materials qualification is not a challenge that one organization can resolve individually!**
- It requires strategic collaborations between the Reactor Developers, National Laboratories, Universities and EPRI, to
 - Understand materials maturity
 - Codify additional materials
 - Develop test facilities
 - Test and characterize materials and fuel
- **INL can provide support to reach materials qualification faster!**



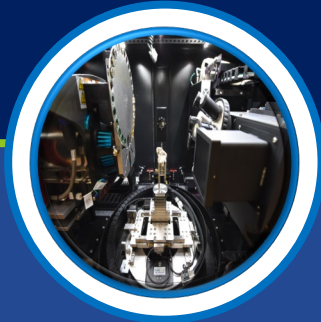
INL's Electron Microcopy Lab. (EML)



Irradiated Materials Characterization Lab. (IMCL).

Nuclear Materials Performance Division

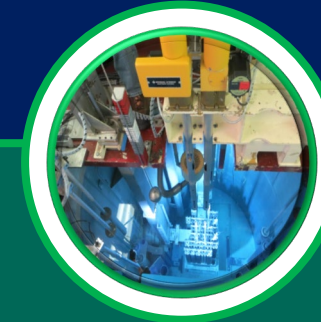
Nuclear Materials Performance



**Advanced
Materials
Characterization**



**Structural
Materials PIE
& Testing**



X-ray Sciences

Mission: To enhance the understanding of nuclear material performance under extreme nuclear environments to accelerate the development, qualification and demonstration of advanced nuclear energy systems as well as extend the life of existing nuclear power plants.

Vision: World-class facilities, world-class scientists, and world-class operations merge to establish an international hub for the development of advanced nuclear materials and fuels.

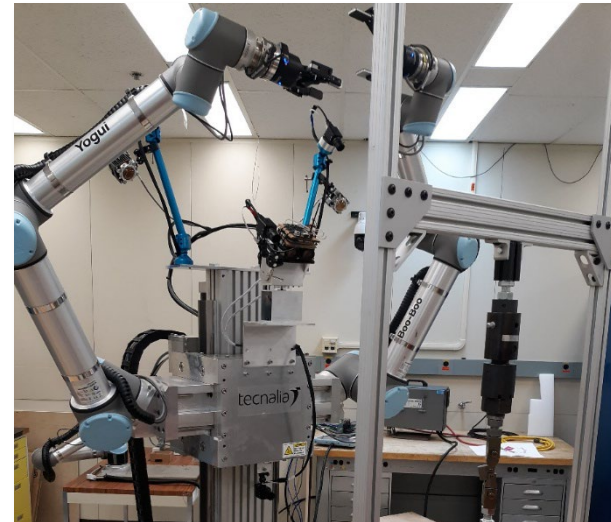
SPL Fills a Critical Gap for the Accelerated Research, Development, and Qualification of Nuclear Structural Materials

SPL received its first shipment of radioactive structural material, signaling the facility's official start of research operations.

- Hazard Category 3 non-reactor nuclear facility
- 3 story, 49,000 sq. ft facility
- Central point for DOE-NE research collaborations
 - Dedicated sample receipt and preparation capabilities for non-alpha bearing material samples
 - World class instrumentation supporting the analysis of structural materials (non-fuel)
 - Scanning Electron Microscope (SEM)
 - X-ray photoelectron spectroscopy for Surface science
 - X-ray diffraction (XRD)
 - Tensile, creep, microhardness and impact material testing
- Facility will increase overall sample throughput and analytical capabilities



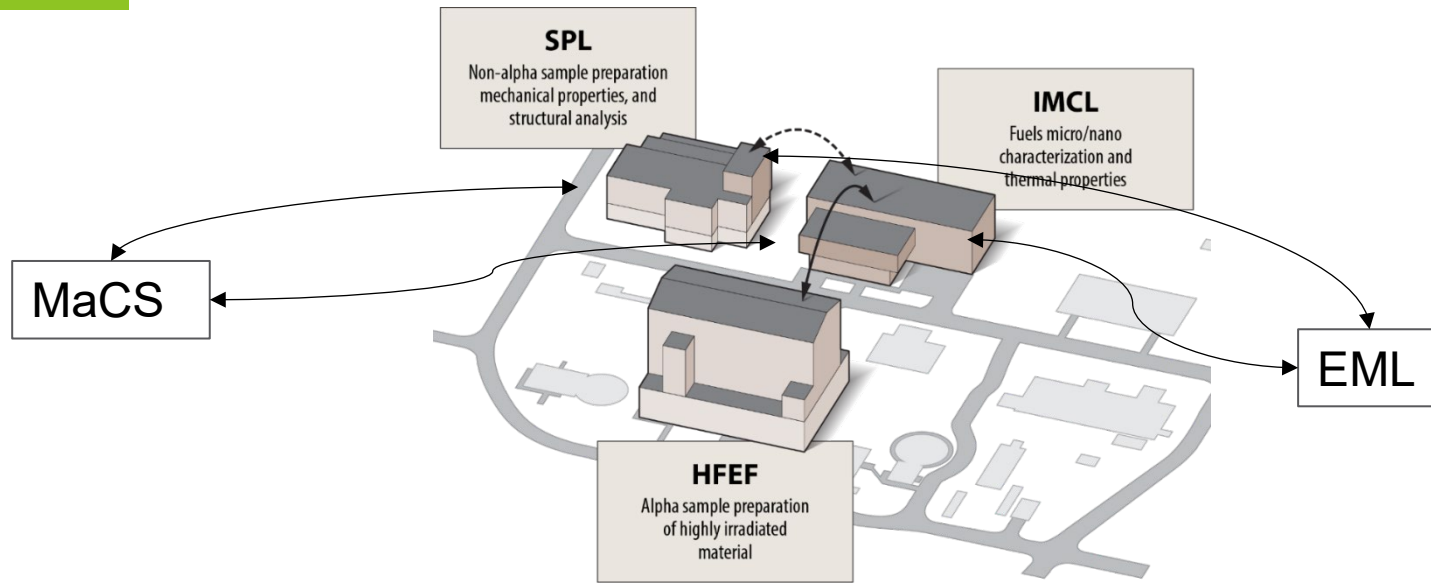
The Sample Preparation Laboratory.



An instrumentation and Controls Engineer performs mechanical properties testing on a sample in the Mechanical Properties Test Cell.

Dual Arm Robot Teleoperated System

INL Post Irradiation Examination / Materials Characterization Capability



- IMCL provides high end microscopy, thermal testing, and small-scale mechanical testing of irradiated materials including sample preparation of commercial fuel pellet sized experiments
- SPL provides engineering and microscale examination of reactor structural materials.
- IMCL, SPL, and HFEF are broadly available to the nuclear research community through the Nuclear Science User Facilities, University partnerships, DOE programs, and Strategic Partnership programs



INL Multiscale Approach Post Irradiation Examination (PIE)

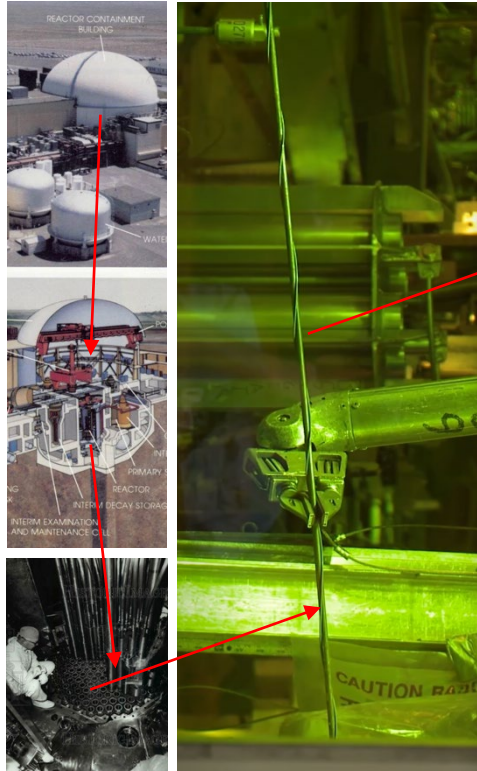
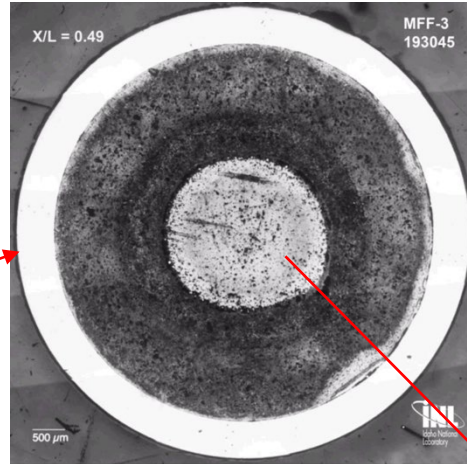
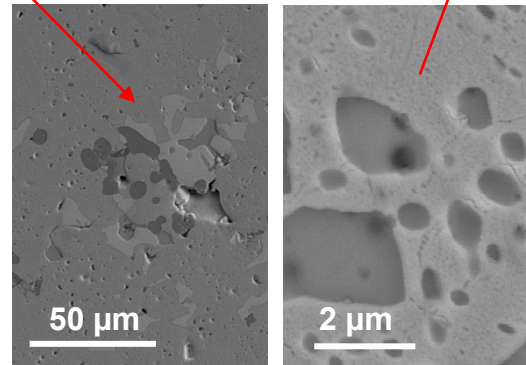


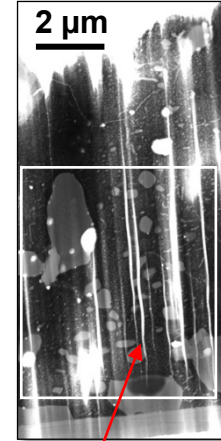
Photo observation of U-10Zr fuel pins irradiated in Fast Flux Test Facility (~1 m)



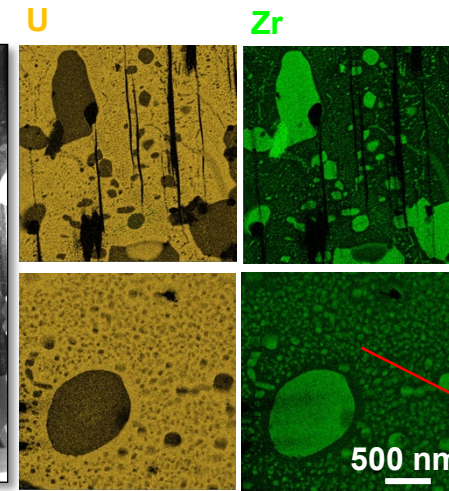
Optical microscopic examination (U-10Zr fuel) (1mm, 10^{-3} m)



Scanning electron microscopy characterization of U-10Zr grain and precipitate (1 μ m, 10^{-6} m)



Transmission electron microscopy identification of Zr nano precipitate (2-5 nm, 10^{-9} m)



Atom probe tomography study of Zr atom distribution in 3D (3 \AA , 10^{-10} m)

PIE capabilities span 10 orders of magnitude

Materials Characterization and Testing Support

- With current capabilities
 - Thermal creep testing
 - Irradiated materials creep testing
 - Irradiated materials mechanical testing
 - Characterization
 - Link between microstructure and properties.
- With future capabilities
 - Corrosion testing of irradiated materials
 - Mechanical testing of irradiated materials in environment
 - Etc.
- Learn More: [SPL](#), [IMCL](#), [EML](#)



Any Questions?



May 6, 2026

Drew Thomas

Manager, Human Factors
and Reliability

Regulatory Research and
Plant Optimization Division

Human Factors for Advanced Reactor Operation

INL Capabilities and Facilities

INL/MIS-26-91809

Battelle Energy Alliance manages INL for the
U.S. Department of Energy's Office of Nuclear Energy



Idaho National Laboratory

Advanced Reactor Human Factors

Key assumptions for advanced reactor deployments:

- New reactor designs are fundamentally different (size, safety systems, operations) than the existing fleet
- New Concepts of Operation, that are not well researched or understood, will become the new norm (remote operation, semi-autonomous and/or autonomous operation, multi-unit, remote monitoring)
 - Systems will be simplified but operations environment will likely become more complex.
- Don't repeat history (non-human factors considered designs, re-engineering, operation/performance challenges) that the existing fleet has been unwinding since 1978.

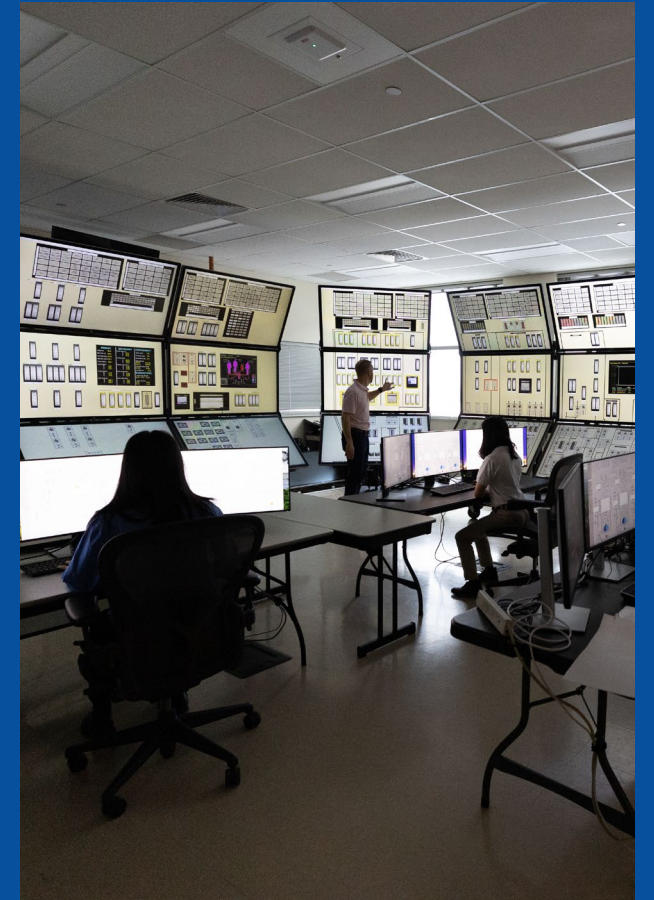


Human Factors and Reliability Research Focus

Perform cutting-edge research enabling human-centered design for nuclear plant optimization, advanced reactor deployments, and emerging artificial intelligence and automation technologies.

Supporting Deployment

- What is needed to meet regulatory requirements?
- How do I get important operational data to inform my design, concept of operation, or level of automation for my reactor?
- How do I make data-informed decisions on how I optimize the number of operators and support personnel that are needed for specific types of operations (e.g. multi-unit, multi-asset, remote, remote semi-autonomous, etc.)



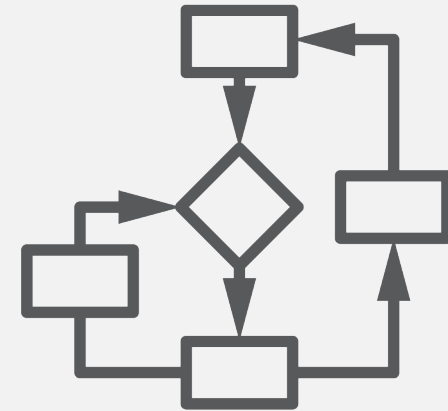
Translating Research to Operations



**Human-Machine
Interface**



**System & Human
Performance
Evaluation and Testing**



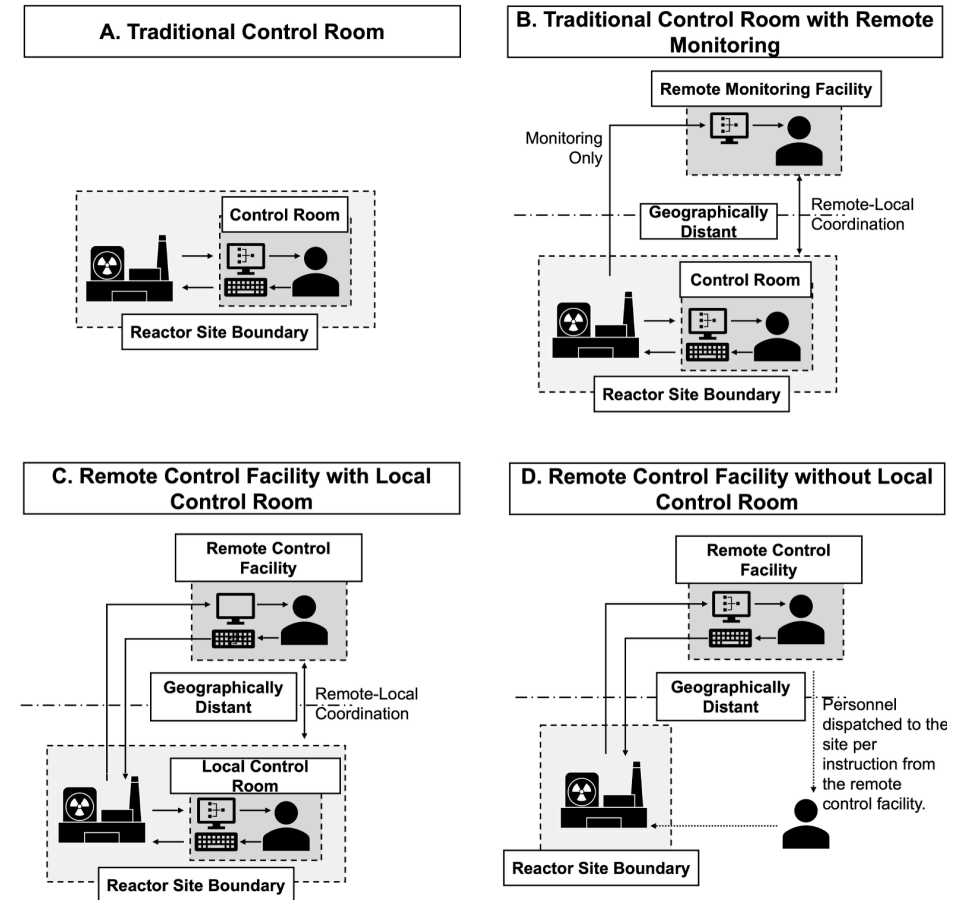
**Decision-making,
Automation, and
Concepts of Operation**

Nuclear Regulatory Commission: *Remote and Autonomous Operations Guidance*

INL Human Factors team is working with the NRC to adapt current regulations (NUREG-711, etc.) considering remote and autonomous operation environments.

Team recently released a report on remote operations (<https://www.nrc.gov/docs/ML2517/ML25175A108.pdf>)

NRC has expressed interest in INL's human factors group participating in work with advanced reactor developers to continue to inform remote and autonomous operations.



Existing Plant Safety System Digital Upgrades

- First-of-a-kind digital upgrade led by INL human factors engineers.
- Utilized INL control room simulator along with on-site integrated system validation to test the upgrades through scenario-based testing.
- Established performance baselines and measures to inform license amendment process.
- Breakthroughs on License Amendment Request (LAR) for digital upgrades on safety systems.



NRC NEWS
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No: 26-002
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January 5, 2026

NRC Approves Major Digital Upgrade for Commercial Reactor Safety System Controls at Limerick

The Nuclear Regulatory Commission has [amended the operating licenses](#) for Limerick Units 1 and 2, granting approval to replace analog safety-related instrumentation and controls systems with a modern digital system. These amendments enable Constellation to install new I&C equipment as part of Limerick's digital modernization project. Limerick's two boiling water reactors are located in Limerick, Pennsylvania.

As the nuclear industry advances toward next-generation power reactors equipped with state-of-the-art digital I&C systems, much of today's operating fleet still relies on analog controls. While reactor operators have leveraged existing regulatory flexibilities to implement targeted digital upgrades, the NRC's approval of the Limerick amendments represents a broader and more comprehensive approach. Limerick will be the first operating nuclear power plant the NRC has authorized to perform a major digital retrofit that replaces multiple analog safety systems with a single digital plant protection system. The change modernizes the control room by replacing legacy equipment with modern digital controls and displays.

The NRC's review and approval of the Limerick amendments also paves the way for future digital I&C modernization across the nation's nuclear power plants. This milestone highlights the NRC's commitment to the safe adoption of digital technologies in nuclear facilities and supporting innovation and modernization across the operating fleet.

Article link:
<https://www.nrc.gov/sites/default/files/cdn/doc-collection-news/2026/26-002.pdf>

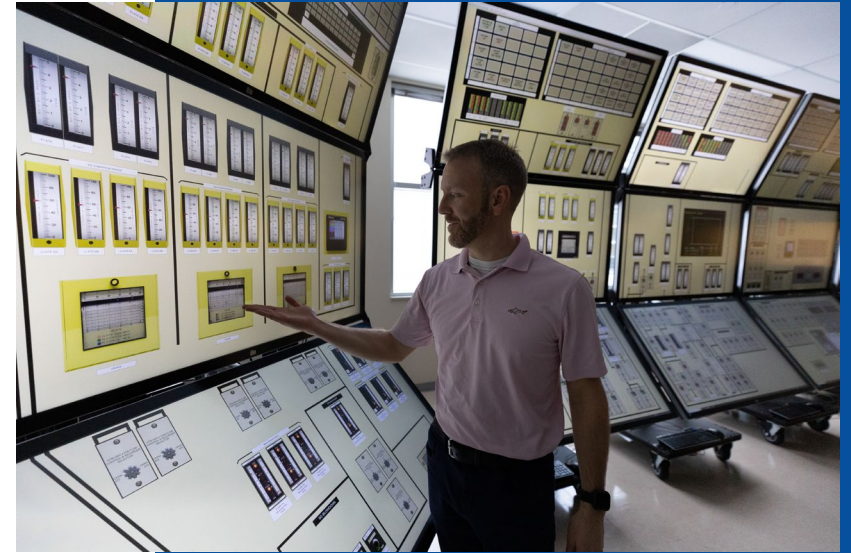
LAR approval not only modernizes Limerick's control room but also represents a pivotal moment for advancing innovation and safety in the nation's nuclear energy sector.

A decorative background featuring a light blue hexagonal grid pattern. The grid is composed of thin lines and small dots at the vertices. The pattern is more prominent on the left side and fades out towards the right. Two horizontal blue lines are positioned above and below the main title.

Simulation Labs

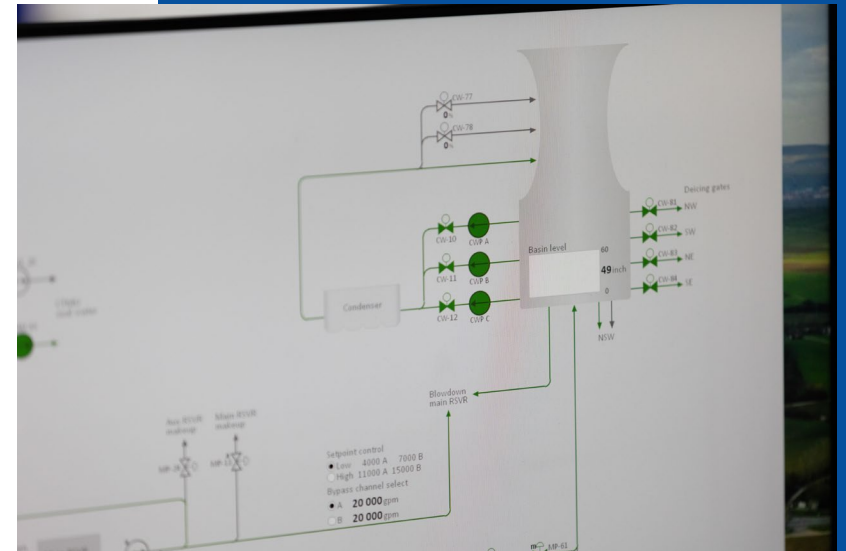
Human Systems Simulation Laboratory (HSSL)

- Full scale control room simulation environment
 - Glass-top simulation environment
 - Custom plant or developer simulator or generalized simulators
 - Replicates existing control room configurations
- Facilitates:
 - Digital upgrades testing
 - System and human performance testing through scenario-based experimentation



Advanced Reactor Human Systems Simulation Laboratory (HSSL-2)

- Fully reconfigurable workstation-based control room simulation for advanced reactors
 - Uses developer specific simulator or simplified reactor simulator that can be customized.
 - Simulators can be easily replicated to simulate multi-asset control or monitoring environments.
 - Remote monitoring lab to test control room, monitoring station, or hybrid environments.
- Capability to provide baseline operations data on how new concepts of operation will perform in real-world settings.





Contact Information

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Idaho National Laboratory

Battelle Energy Alliance manages INL for the U.S. Department of Energy's Office of Nuclear Energy. INL is the nation's center for nuclear energy research and development, and also performs research in each of DOE's strategic goal areas: energy, national security, science and the environment.

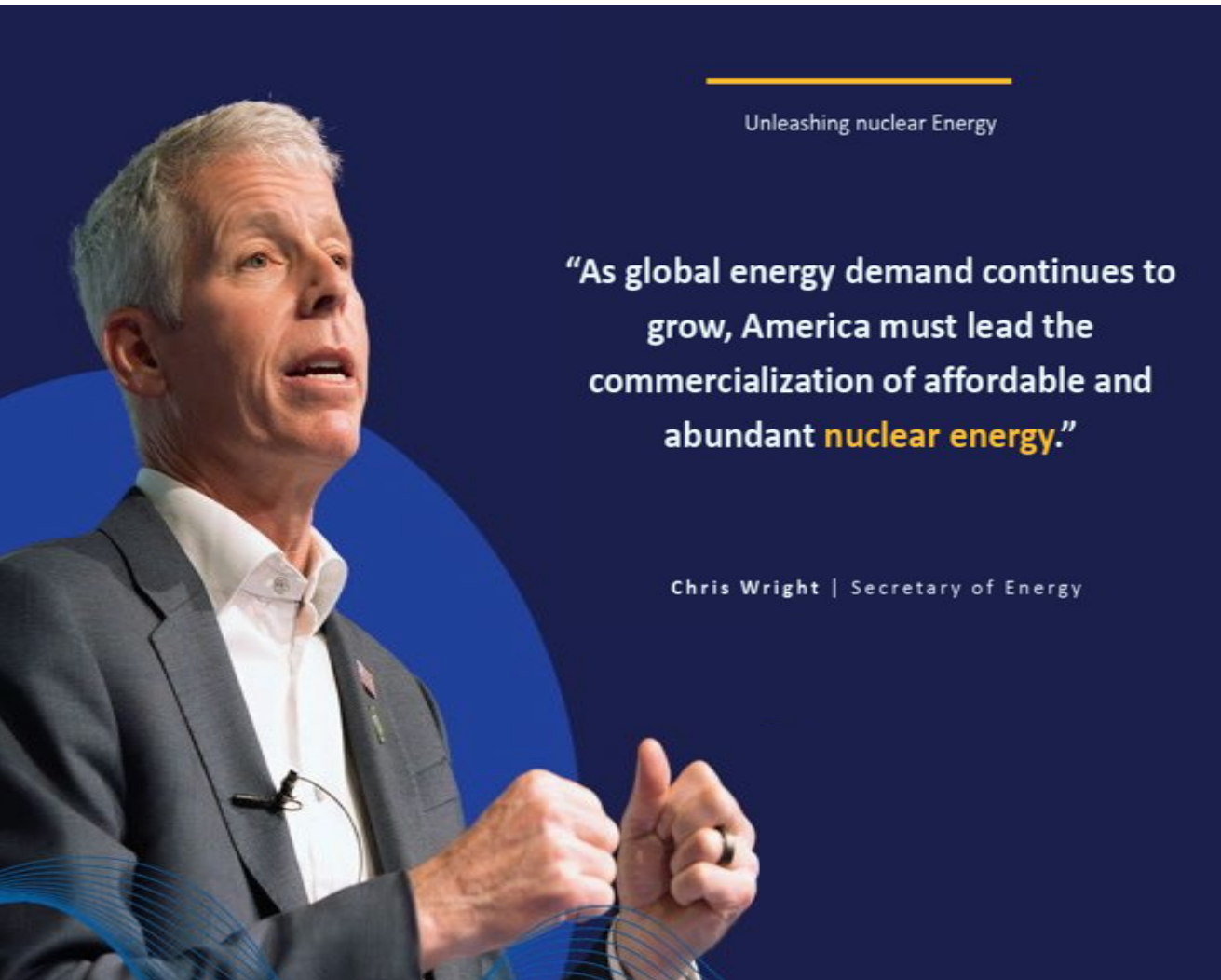


DOE:NE Regulatory Framework Modernization

Joseph Renevitz

Acting National Technical Director – Regulatory Development
Idaho National Laboratory

Focus, Research, Regulatory Reform, Support



Unleashing nuclear Energy

“As global energy demand continues to grow, America must lead the commercialization of affordable and abundant **nuclear energy**.”

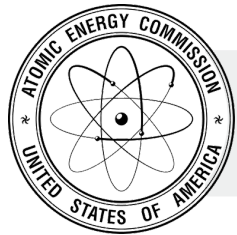
Chris Wright | Secretary of Energy



Congress made it abundantly clear that they wanted the NRC to be an agent of change ... we could no longer do things the same old way. They want us to become more efficient, and “efficient” doesn’t mean doing things with less or doing more with less. It’s okay to think outside the box and be bold. Sometimes if there’s a novel issue, it might take a heartbeat longer to get there.

Commissioner David Wright,
US NRC – American Nuclear Society Interview

Nuclear Regulatory History



Commercial Nuclear Included



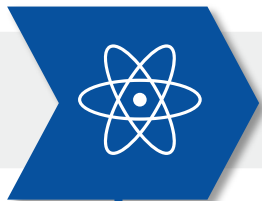
Commercial Regulation



Merged



Research & Development Promotion



1946

Atomic Energy Act (AEA) of 1946

Created the U.S. Atomic Energy Commission (AEC) to manage nuclear energy; places control under civilian authority.



1954

Revised Atomic Energy Act

Allowed for commercial nuclear power development and private sector participation, regulated by the AEC.



1957

Price-Anderson Act

Price-Anderson Act passed in the U.S., providing a liability framework for nuclear accidents.



1974

Energy Reorganization Act

Dissolved the AEC, created the NRC to regulate nuclear safety and the ERDA to manage nuclear R&D (later merged into the DOE).



2005

Energy Policy Act of 2005

Expanded NRC authority to support new reactor licensing, and reauthorized Price-Anderson.



2020 - Present

Advance Reactors and Regulatory Modernization

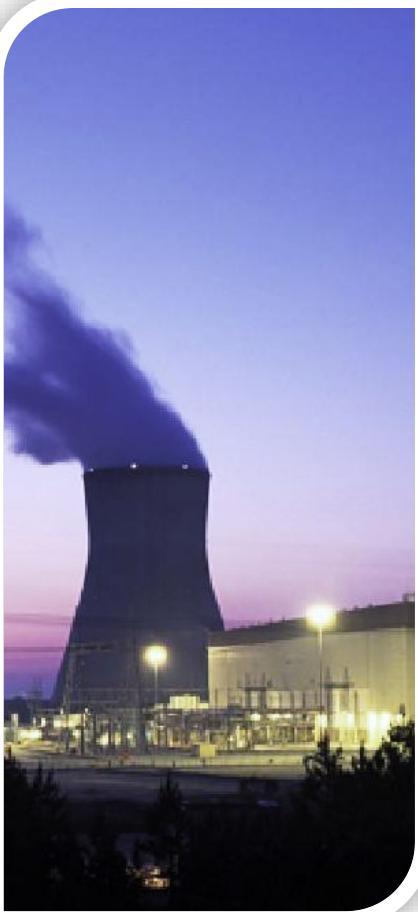
Renewed focus on advanced and small modular reactors; NRC streamlining regulations to support deployment and fuel management.

2025 Executive Orders

- **Reform of the NRC:**
 - Directs the NRC to complete rulemakings within 18 months to comprehensively revise its regulations and guidance documents
 - Directs the NRC to reform its culture and realign its organization to reflect Congress' directive to rapidly promote nuclear power while ensuring reactor safety
- **Reforming Reactor Testing at DOE:**
 - Executive Order to reform and streamline National Laboratory processes for reactor testing
 - Establishing a pilot program outside the national laboratories
 - Streamlining environmental reviews



NRC Licensing Pathways



10 CFR Part 50

(All but two commercial reactors)



Construction
Permit



Operating
License

10 CFR Part 52

(Vogtle Units 3 & 4)



Design
Certification



Early Site
Permit



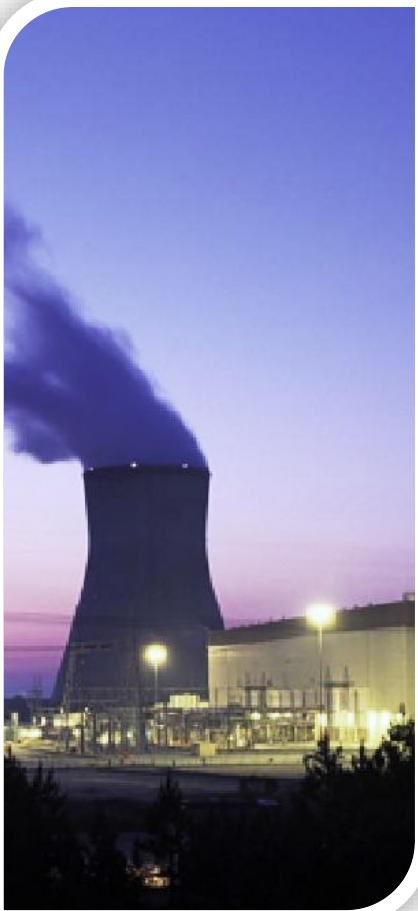
Combined
License



Manufacturing
License

NRC Licensing Pathways

Under Development



10 CFR Part 50

(All but two commercial reactors)



Construction Permit



Operating License

10 CFR Part 52

(Vogtle Units 3 & 4)



Design Certification



Early Site Permit



Combined License



Manufacturing License

10 CFR Part 53



Risk Informed,
Technology-Inclusive
Regulatory Framework
for Advanced Reactors



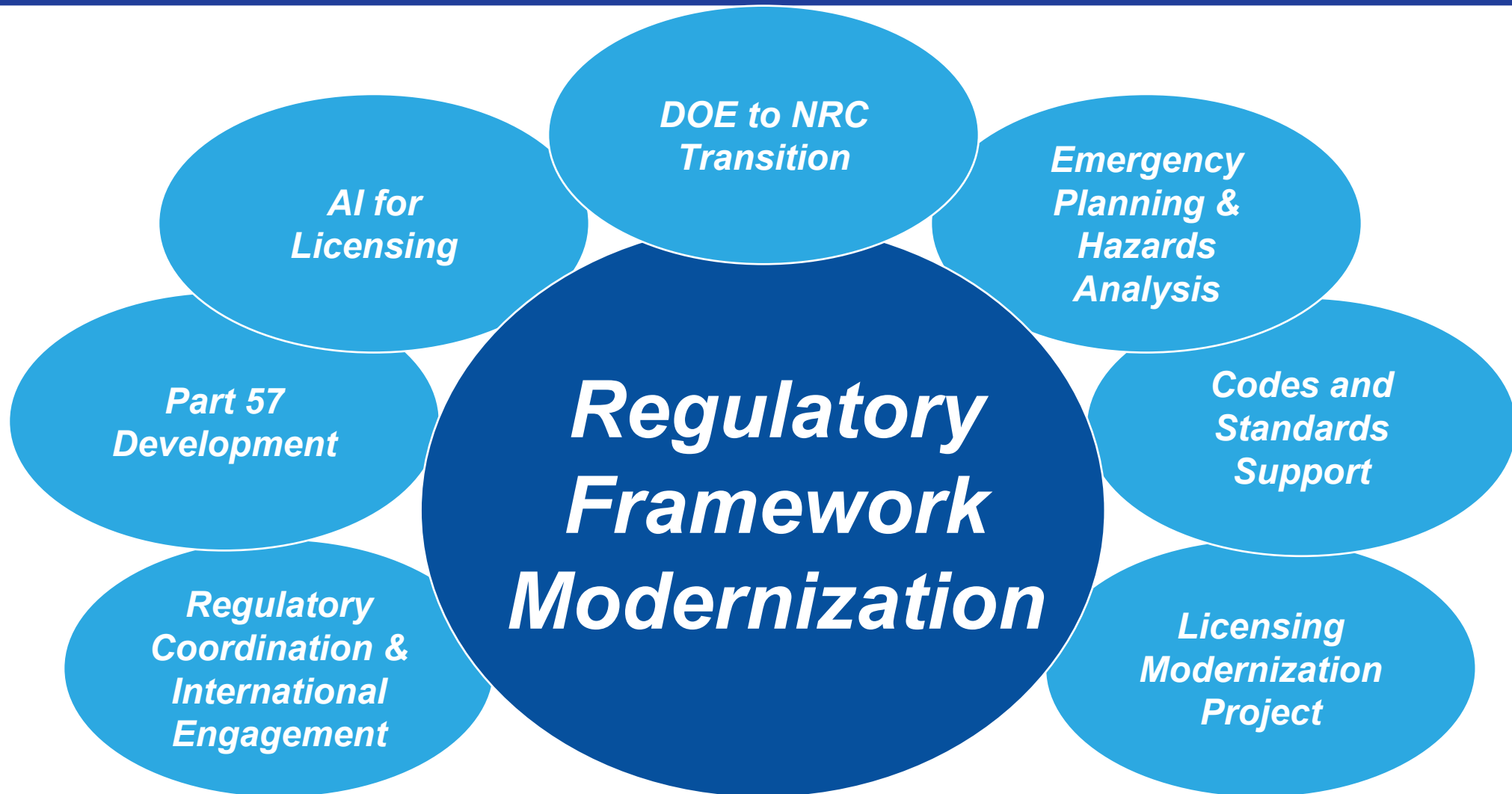
Low Dose
Consequence
Licensing for High
Volume Licensing

Key DOE Process Change Summary

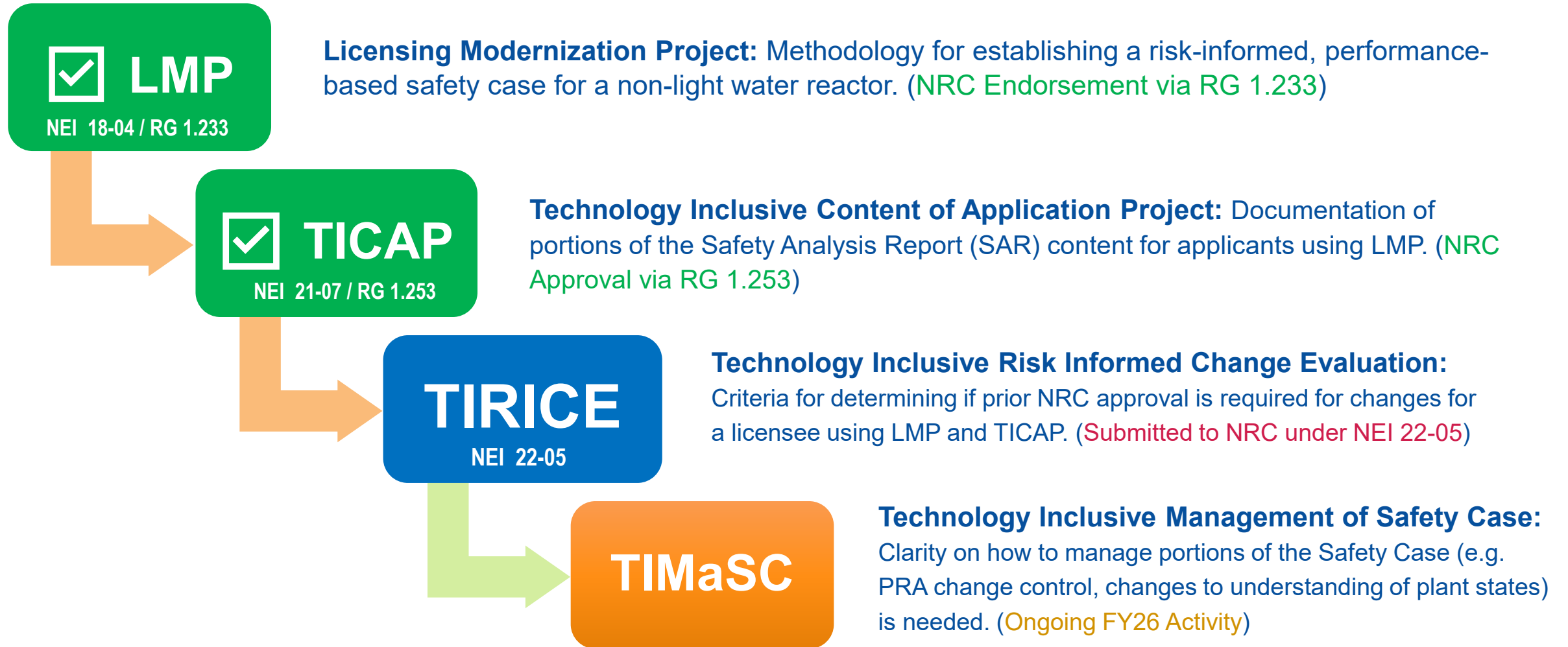
- **New STD-1271:** "Test Reactor and Fuel Cycle Facility Approach to Office of Nuclear Energy Authorization" replaces STD-1189. Design lifecycle stage gates are simplified with an upfront agreement on stage gate content. Invokes all other safety orders.
- **Rad Con Program:** The use of "ALARA" (As Low As Reasonably Achievable) is being discontinued. Shielding design graded to occupancy & risk. Raise occupational and public dose limits.
- **Readiness to Startup & Restart:** Reduce in-line reviews, return startup authority for operating facilities to the contractor; DOE retains startup authority for new reactors
- **Natural Phenomena Hazards:** 20 year update assessment. Updated codes and standards include IBC 2024. Soil structure interaction is not required for SDC-1 and SDC-2. Option for SDC-3 facilities use IBC with increased margin.
- **Facility Safety:** Remove Defense Board Recommendations. Right-size fire protection loss prevention.



Projects: Overview



Projects: Licensing Modernization Project (LMP)



Projects: DOE Authorization to NRC License Transition

- **Reactors and Fuel Cycle Facilities**
 - Responding to executive order
 - Derisking and accelerating transition from DOE authorization to NRC commercial licenses, including new DOE:NE authorization approach
 - Key aspect of DOE:NRC MOU and collaborating with NRC staff
 - Comparing regulatory requirements to identify synergies and differences
 - Examining safety and security



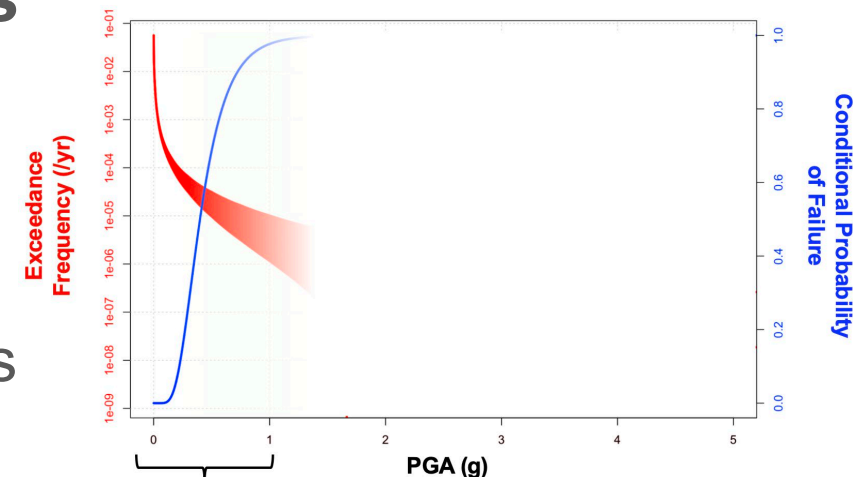
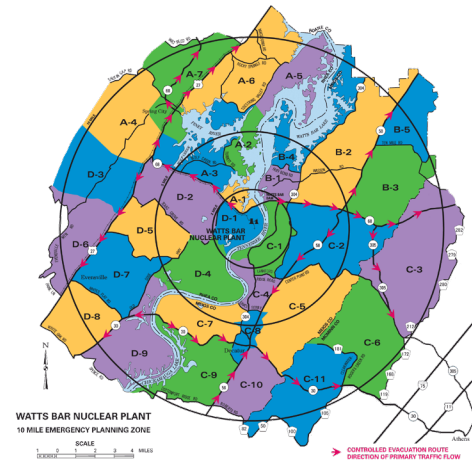
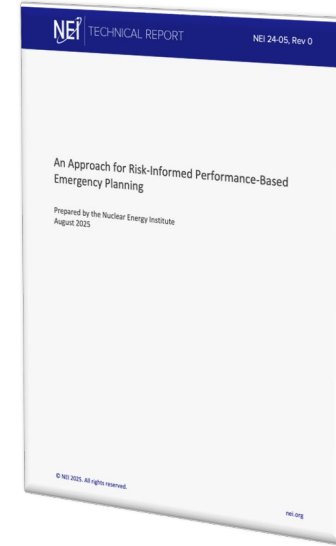
Projects: Emergency Planning & Hazards Analysis

- **Risk-Informed Performance-Based EP:**

- Aligning with new NRC rule, allows right-sizing of emergency planning zone (EPZ) based on plant risk profile (no EPZ, at site boundary, or beyond)
- NEI 24-05 currently under NRC review

- **Assessment of Low Frequency Seismic Events**

- Rare external events (earthquake, flood, etc.) are difficult to assess due to uncertainty in likelihood
- Simplified approach developed in coordination with industry, to be submitted to the NRC once 10CFR 53 is released



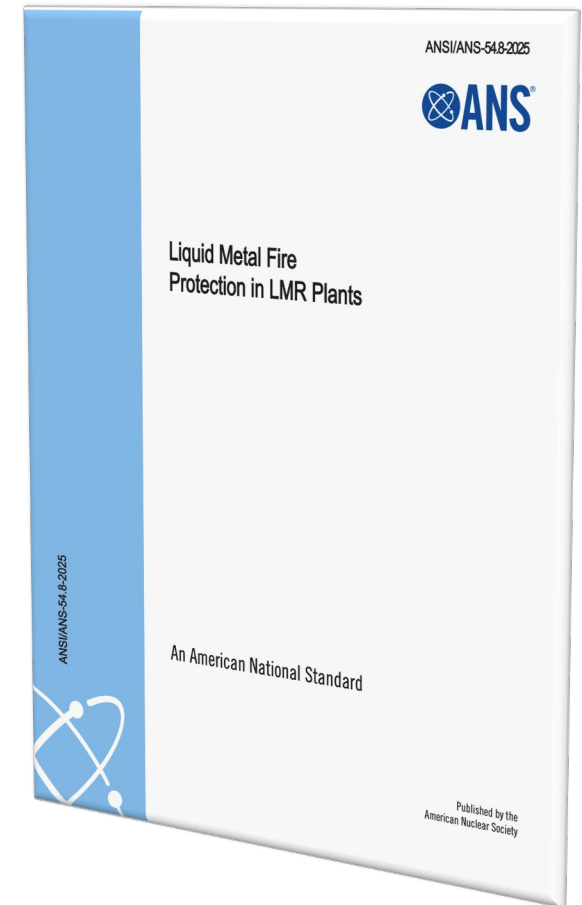
Projects: Code and Standard Support

- **Expediting C&S Development**

- Working with NRC, industry partners, and standards development organizations to identify C&Ss gaps for advanced reactors
- Collaborating with NRC to enhance the endorsement process and provide alternative pathways to use an unapproved C&S's

- **Liquid Metal Fire Protection (ANS 54.8)**

- Withdrawn in 2000, new working group established and revived/published in September
- New version being prepared with optional risk-informed pathway, target 2026 release



Projects: AI for Licensing – Building a Safety Case

- **AI Tools for Commercial Licensing**
 - Utilizing AI tools to automate license application development, including transition from DOE to NRC crosswalk
 - Collaborating with industry (Everstar Inc. and vendors) to prepare example application
 - Developing a benchmark for AI performance in regulatory space
- **AI Tools for Test Reactors**
 - Utilizing model-based systems approach with AI/ML knowledge management and licensing matters
- **AI Regulatory Context Protocol (RCP)**
 - Facilitating communication between industry and NRC AI agents
 - Expedites audits and requests for additional information

Projects: Part 57 Support

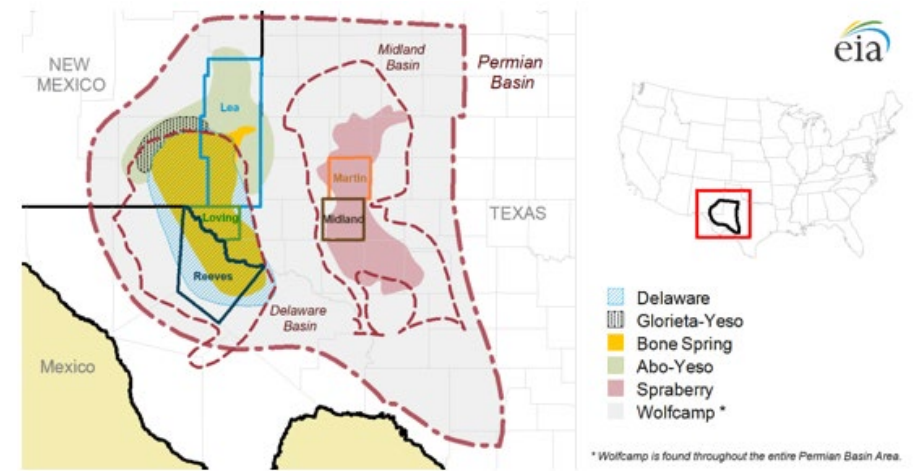
- **Entry Criteria**

- Determining the criteria and analyses necessary to demonstrate a “low consequence” facility. Targeting 1 rem at site boundary over 96 hours for maximum hypothetical accident (MHA), using NUREG-1537 approach.
- INL Transmitted recommendation to the NRC in December 2025

- MHA Framework in development with NEI

- **Expedited Licensing**

- Developing a site parameter envelope (SPE) to allow expedited siting of micros and SMRs over large areas, such as the Permian Basin in Texas to support oil/gas operations



Projects: Regulatory Coordination and International Engagement

- **Regulatory Coordination**

- Multi-lab group that leverages national laboratory expertise to review draft regulatory items and provides comments on behalf of DOE

- **International Engagement**

- Promotes global alignment on regulatory matters, support US vendor deployment internationally
- Supports US participation in GIF Risk and Safety Working Group (RSWG) and US expert participation at IAEA and other international events



Looking Ahead...

- **Evolution**

- Nuclear regulation and guidance is evolving at a rapid pace
- Indicative of the intense interest in nuclear energy

- **DOE and NRC**

- Vendors are actively pursuing DOE authorization and NRC licensing with both organizations working in close coordination

- **National Lab Support**

- Active efforts on multiple fronts to support the ongoing reforms and industry

Questions





NRIC

National Reactor
Innovation Center

INL Graphite & Nonmetallic Industry Testing Capabilities

Accelerating Advanced Reactor Deployment

Gerhard Strydom

Brandon Bolach (Brandon.Bolach@inl.gov)

Graphite: The Material That Makes Gas-Cooled and Molten Salt Reactors Possible

- Uniquely suited to the high-temperature environments advanced reactors require
- Graphite plays critical roles as a neutron moderator and reflector, and maintains core structural geometry.
- Graphite is thermally stable up to very high temperatures, has a high heat capacity, and has been used extensively in nuclear reactors since 1942.



Graphite Qualification Status

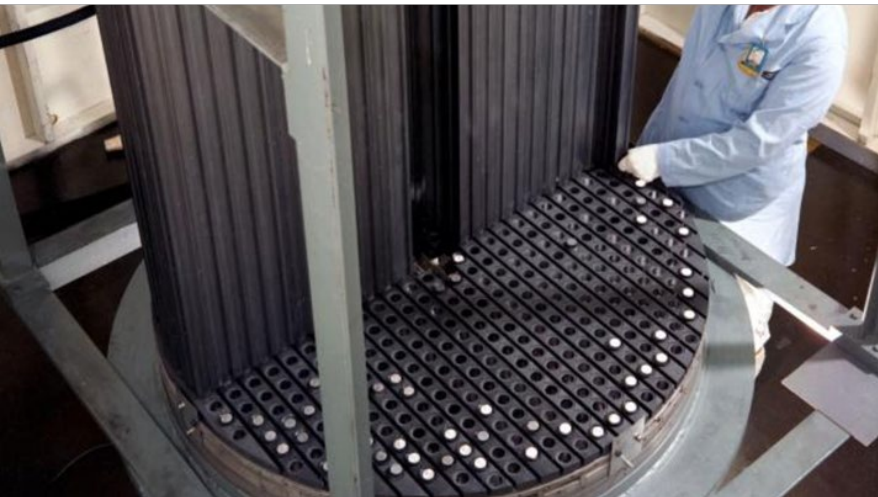
FORM MDS-1 MATERIAL DATA SHEET (SI UNITS)						
Grade Designation						
Material Grade	Material spec. ID	ASTM spec.				
Max. grain size (mm)	Designation					
Temperature-Dependent Parameters						
Property	Units	Orientation	20°C	250°C	400°C	600°C
Bulk density	kgm ⁻³	—				
Strength – tensile	MPa	WG, AG				
Strength – flexural (4-point)	MPa	WG, AG				
Strength – compressive	MPa	WG, AG				
Elastic modulus (dynamic)	GPa	WG, AG				
Elastic modulus (static)	GPa	WG, AG				
Coefficient of thermal expansion	10 ⁻⁶ °C ⁻¹	WG, AG				
Thermal conductivity	W/m·K	WG, AG				
Temperature-Independent Parameters						
Poisson's ratio	Anisotropy factor	Critical stress intensity factor K _{IC} MPa·m ^{1/2}				
Design Strength and Material Reliability Curve Values						
Ratio of compressive to tensile strength (R _c)	Ratio of flexural to tensile strength (R _f)	S _{0.05} MPa	m _{0.05}			
	S _{0.05} MPa	S _{0.05} MPa	m _{0.05}			
S ₁ (10 ⁴) MPa	S ₁ (10 ⁴) MPa	S ₁ (10 ⁴) MPa	S ₁ (10 ⁴) MPa			
Property Degradation Versus Weight Loss % in Uniformly Oxidized Graphite						
Property	Units	2%	4%	6%	8%	10%
Strength						
Elastic modulus (dynamic)						
Thermal conductivity						
Irradiated Graphite						
Property	Units	WG	AG			
Dimensional change						
Creep coefficient						
Coefficient of thermal expansion						
Strength						
Elastic modulus						
Thermal conductivity						

GENERAL NOTES:
 (a) WG, AG refers to the with- and against-grain direction of the material.
 (b) {} indicates a dimensionless quantity.
 (07/23)

NOTE:
 (1) If the maximum intended use temperature exceeds 1 000°C, then the temperature dependent data shall be extended to cover the property values at the maximum intended use temperature.

- In the USA, there is currently **ONE** grade of graphite qualified for use in a specific reactor design.
- ASME BPVC requires several thermophysical, mechanical, oxidation, and irradiation tests to fully qualify a new grade of graphite for nuclear applications.
- Thousands of material property tests are required.

Graphite Changes with Irradiation Impact Design and Licensing



- **Graphite changes volume in reactor cores** — Neutron irradiation causes it to first shrink, then swell.
- **Reactor fluence doesn't just damage graphite** — it changes its material properties entirely.
- **Every reactor design** has a maximum fluence the graphite can tolerate before it must be replaced.
- **Most modern nuclear-grade graphite have limited irradiation data** — Legacy datasets from the 1960s and 80s won't cover the new grades and design-specific operational temperatures and fluences.
- **Getting in the ATR queue early is strategic** — Irradiation campaigns are multi-year commitments; planning must start as early as possible.

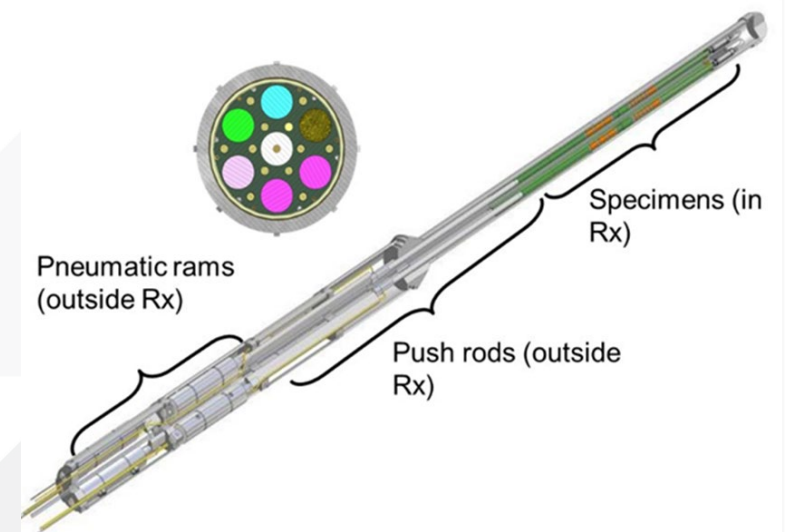
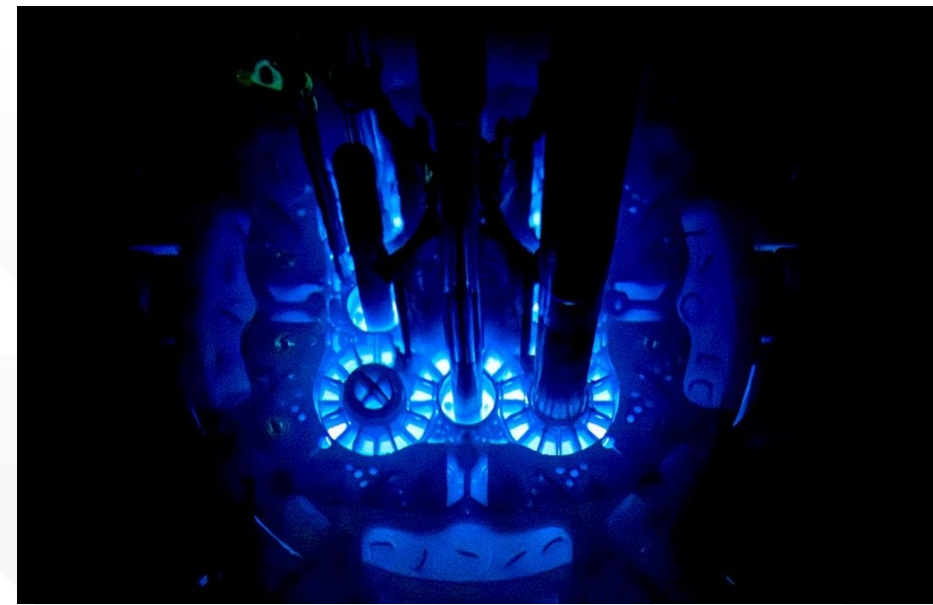


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Innovation Center

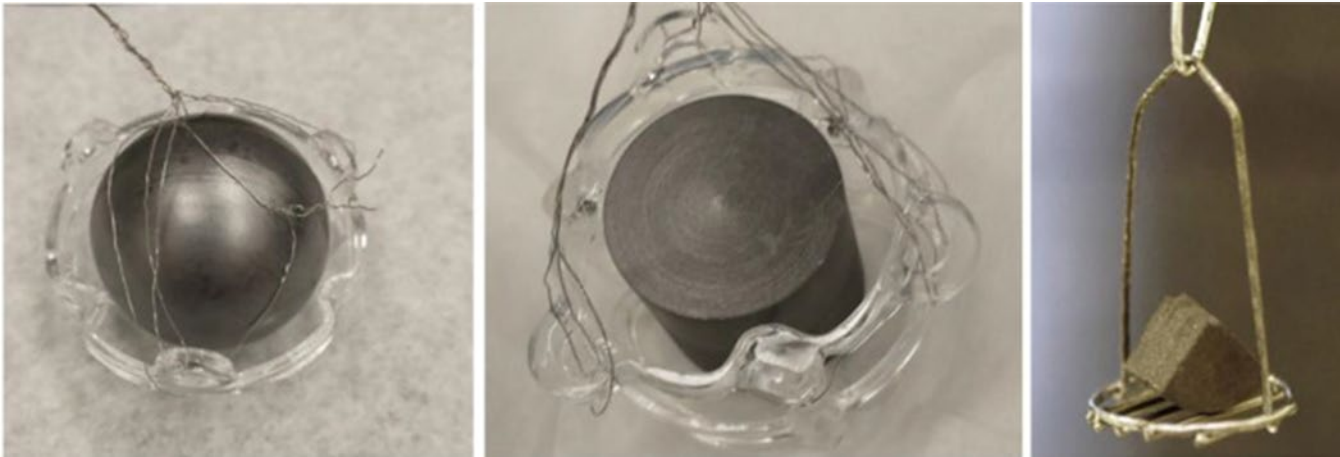
ATR and Irradiation Vehicles

- INL has developed multiple pre-designed graphite irradiation vehicles that can be tailored to specific reactor design needs
 - Advanced Graphite Creep (AGC)
 - Vendor Irradiation Capsule (VIC)
 - Neutron Irradiation as a Function of Temperature Experiment (NIFT-E)
- INL has the ability to perform all necessary Pre- and Post-Irradiation Examination assessments



Graphite Degradation from Oxidation

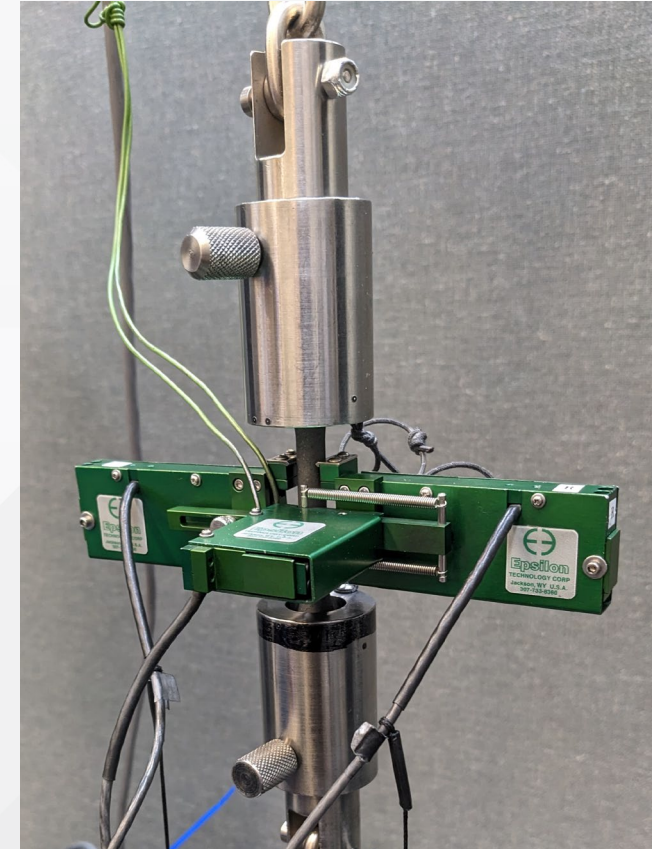
- **Oxidation degrades every structural property**— strength, stiffness, and thermal conductivity all decline, even at modest oxidation levels.
- **Air ingress is not a hypothetical** — a breach in the primary boundary introduces oxygen into a high-temperature core, and the damage is difficult to predict without test data.
- **Normal operations aren't risk-free either** — trace impurities in coolant gases cause slow, cumulative oxidation over the reactor lifetime.
- **"NQA-1 Qualified" means demonstrating oxidized graphite properties, not just pristine ones** — licensing path requires data across a range of oxidation levels.



INL's Worldclass Graphite & Nonmetallic Material Testing Lab

INL designed and executes a fully NQA-1 qualified graphite & nonmetallic testing program as part of the DOE-NE funded Gas-Cooled Reactor Program for more than 20 years.

The **goal** of this new NRIC industry engagement program is to offer these testing services to industry to accelerate advanced nuclear reactor deployment.



INL Oxidation Testing Capabilities

- INL developed ASTM-approved oxidation standards for nuclear graphite
- INL has also designed a custom large-batch oxidizing method that accelerates testing. This testing has been verified to ASTM D7542 results.
- Our hardware includes four oxidation furnaces that can do batches of 12 graphite samples at a time.

Property Degradation Versus Weight Loss % in Uniformly Oxidized Graphite

Property	Units	2%	4%	6%	8%	10%
Strength [.] ⁽²⁸⁾	_____	_____	_____	_____	_____	_____
Elastic modulus (dynamic) [.] ⁽²⁹⁾	_____	_____	_____	_____	_____	_____
Thermal conductivity [.] ⁽³⁰⁾	_____	_____	_____	_____	_____	_____

Example: Non-Irradiation Testing Needed for Section 1 of ASME FORM MDS-1

Test	ASTM Standard	Sample Geometry
Quality Assurance	-	-
Check in/Washing	C559-16(2020)	All
Bulk Density (Dimensional Inspection)	C559-16(2020)	All
Strength-Tensile Test	C749-15(2020)	Dog Bone
Strength-Split Disc	D8289-20	Split Disc
Strength-Flexural (4-point)	C651-20	Bend Bar
Strength-Compressive	C695-21	Compression
Elastic Modulus (Dynamic-Fundamental Frequency)	C747-23	Bend bars, (compression can be used)
Elastic Modulus (Dynamic-Sonic Velocity)	C769-15(2020)	Compression
Elastic Modulus (static)**	C749-15(2020), D8289-20	Dog Bone, split disc
Coefficient of Thermal Expansion (up to 1000C)	E228-22	Compression
Thermal Conductivity (up to 1000C)	E1461-13(2022)	Split Disc

**Elastic modulus is measured in the tensile testing

Same colors use the same sample geometry



The Path to Graphite Qualification Runs Through INL

- Graphite qualification is a multi-year journey — start now to have the data for licensing review.
- Oxidation and irradiation data for new grades does not exist yet — it must be generated by a qualified and certified test program.
- INL has the facilities, the expertise, and the NQA-1 infrastructure to qualify and codify new graphite grades for HTGR and MSR use.

We're ready to partner with you!

Brandon Bolach (Brandon.Bolach@inl.gov)



Questions?

NRIC

National Reactor
Innovation Center

Thank you!



NRIC National Reactor
Innovation Center