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Enabling Future Fusion Energy Systems

2024 FPA Annual Meeting

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

Idaho National Laboratory

*For 30 years INL contributed to DOE SC **Fusion Energy Science** by providing **fusion energy systems safety analysis**.*

***Experimental and analytical** activities focus on the potential **risks and hazards associated with fusion energy**.*

*Support DOE '**Fusion Energy Strategy 2024**', the new administration vision for **US energy dominance** and the engagement with the emergent **fusion private sector**.*

INL operates the Safety and Tritium Applied Research (STAR) facility, a facility dedicated to experimental research on potential risks associated with tritium retention and permeation in fusion material and technology development to minimize fusion energy's environmental impacts.

MELCOR is an engineering-scale code designed to model severe nuclear accident conditions. A version of the INL-developed code for fusion applications is being used in the design and fabrication of ITER, the world's largest fusion experiment under construction in France.

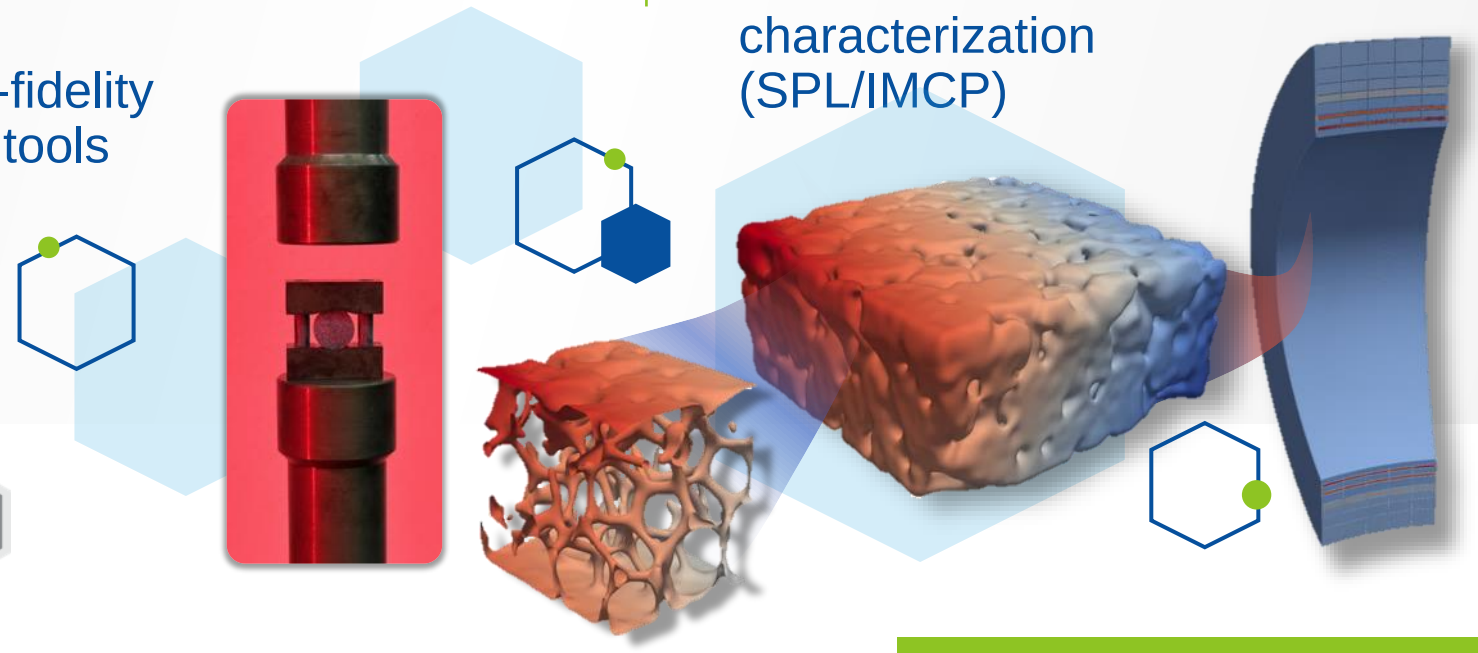
Enabling future fusion energy systems

Safety analysis and high-fidelity modeling and simulations

- MELCOR fusion for plant safety assessment
- Modern probabilistic risk assessment to support design and regulatory approaches
- MOOSE high-fidelity multi-physics tools

Experimental capabilities

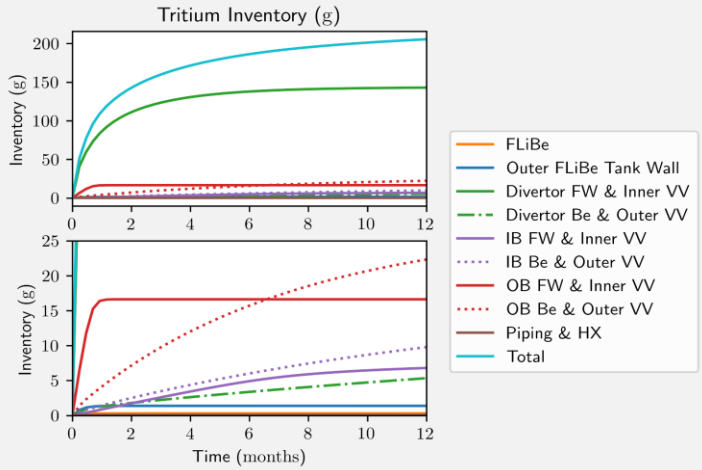
- Tritium production, transport and inventories (STAR facility)
- Blanket components nuclear testing (ATR, NRAD)
- Irradiated/tritium materials characterization (SPL/IMCP)



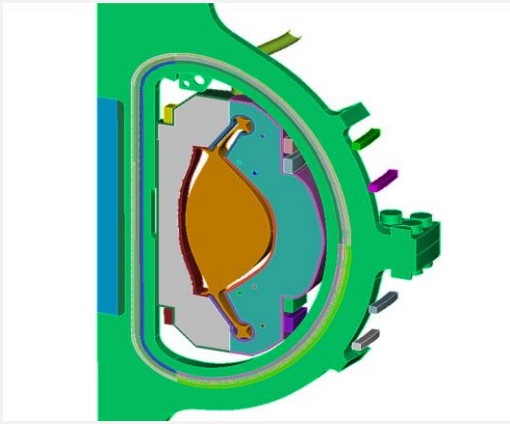
✓ 2022: Lab core capability

✓ 2025: Lab wide initiative launch

Risk informed design and safety analysis



Tritium inventory in ARC-class device over the course of one year from MELCOR-TMAP model – INFUSE project with CFS



Integrate modern PRA tools (RAVEN) and reduced order models for risk assessment and derive technical guidance for regulatory approaches

- MELCOR (melting core) is a US NRC code developed by SNL to analyze accidents and transients in nuclear pp
- MELCOR-fusion is INL modified versions for application to fusion devices

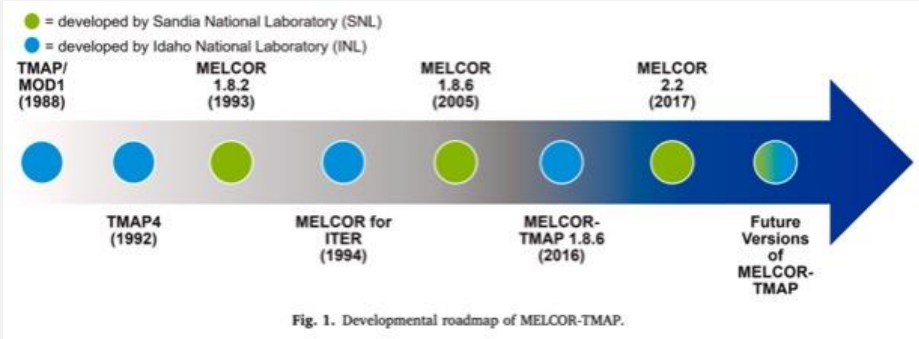


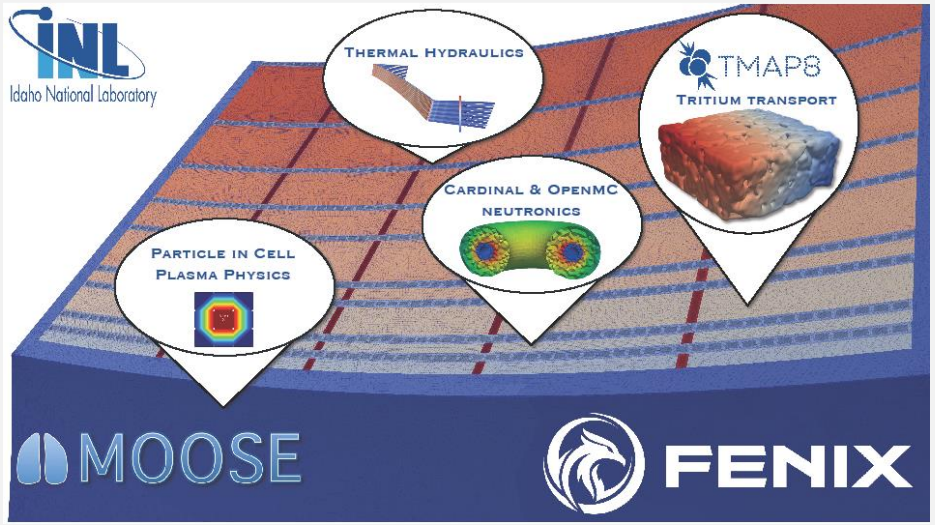
Fig. 1. Developmental roadmap of MELCOR-TMAP.

* https://doi.org/10.1016/j.fusengdes.2023.113743 *

FES Nuclear Science and Enabling R&D project: Foundational research to support fusion systems safety assessment

Supporting development of whole-device modeling for fusion

Leveraging MOOSE capabilities for high-fidelity simulation of fusion coupled physics

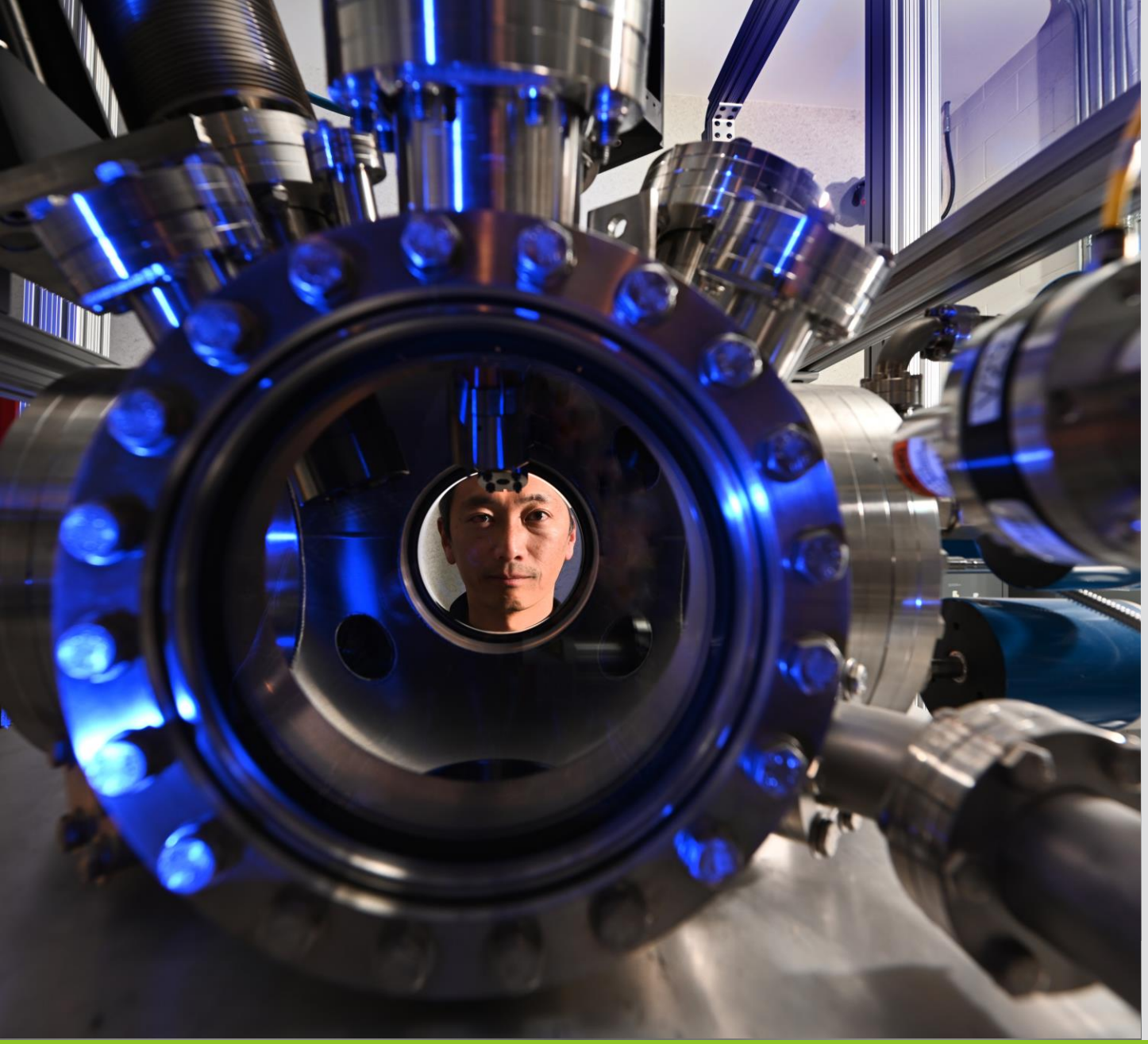


Fusion ENergy Integrated multiphys-X (FENIX): adding kinetic plasma simulation capability using a particle-in-cell (PIC) scheme to existing MOOSE capabilities to model Plasma Facing Components

Through LDRD investment, INL is developing high-fidelity MOOSE-based predictive simulation capabilities. The goal is an open-source, exascale-capable engineering platform for modeling of fusion devices.

New analysis tools that address fusion coupled physics: neutronics, plasma/materials boundaries, tritium transport, radiation effects in materials, electro-magnetics

FES Materials R&D project: Integrating advanced characterization into modeling and simulations to predict irradiation and tritium effects in fusion materials



STAR

Tritium handling (1.6 gram ~ 15,390 Ci)
Radioactive material handling (< 100 mrem/hr at 30 cm)
Surface and bulk materials characterization capabilities

Tritium/materials interactions

- Plasma Facing Components – irradiated W
- Tritium transport
- Super permeable membranes for direct internal recycling

FES NSE R&D project: Fundamental research to enable reducing tritium inventory

General Atomics INFUSE: Metal “Film” Pump for Direct Internal Recycling of Fusion Fuel

AMES Lab ARPA-E: Refractory Alloys with Ductility and Strength

Tokamak Energy milestone project and TPBAR program support

Fusion Blanket Technology

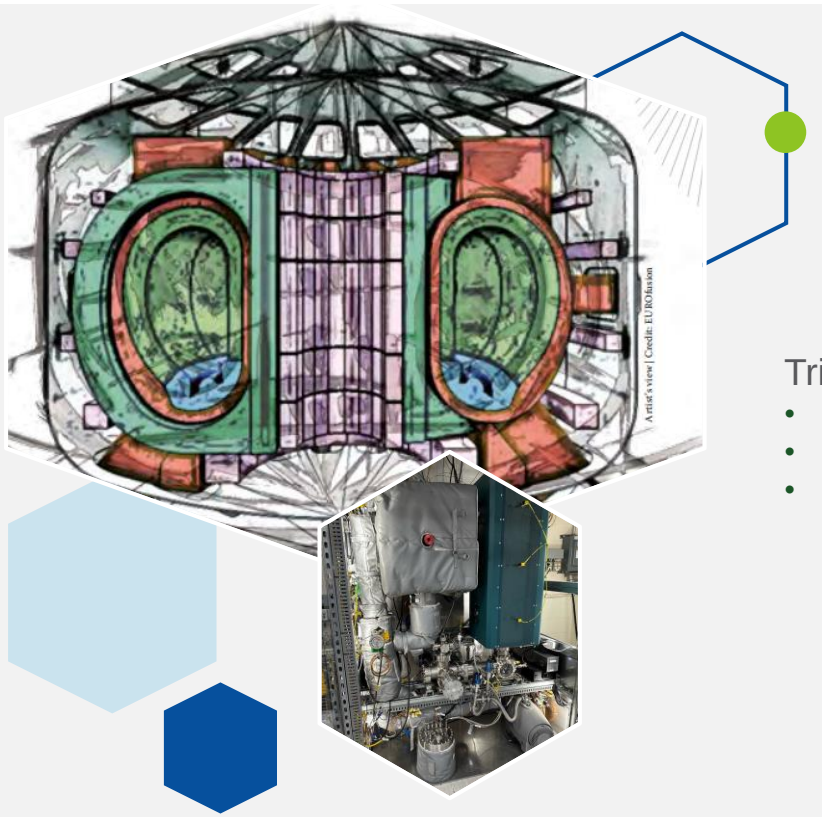
Tritium extraction from breeder materials

- Lead-lithium eutectic (vacuum permeator)
- FLiBe eutectic
- Advanced manufactured solid breeders
- Li metal

FES NSE R&D project: Foundational research on tritium transport phenomena in liquid breeder blankets

Kyoto Fusioneering INFUSE: Li-6-enriched Lithium-Lead Samples Neutron Irradiation

FES NSE R&D project (SRNL): Development and De-risking of Li Electrolysis and CoRExt Process by Flow-Loop Integration



Power harnessing:

- Thermo-hydraulic models
- Thermodynamic efficiency
- Balance of Plant integration
- Cost of electricity

Tritium breeding:

- Breeder materials properties
- Li-6 enrichment
- Tritium transport models

Shielding:

- Cross section measurement
- Validation of neutronic models
- Plant I&C / safety

Blanket components nuclear testing

Strategic initiatives

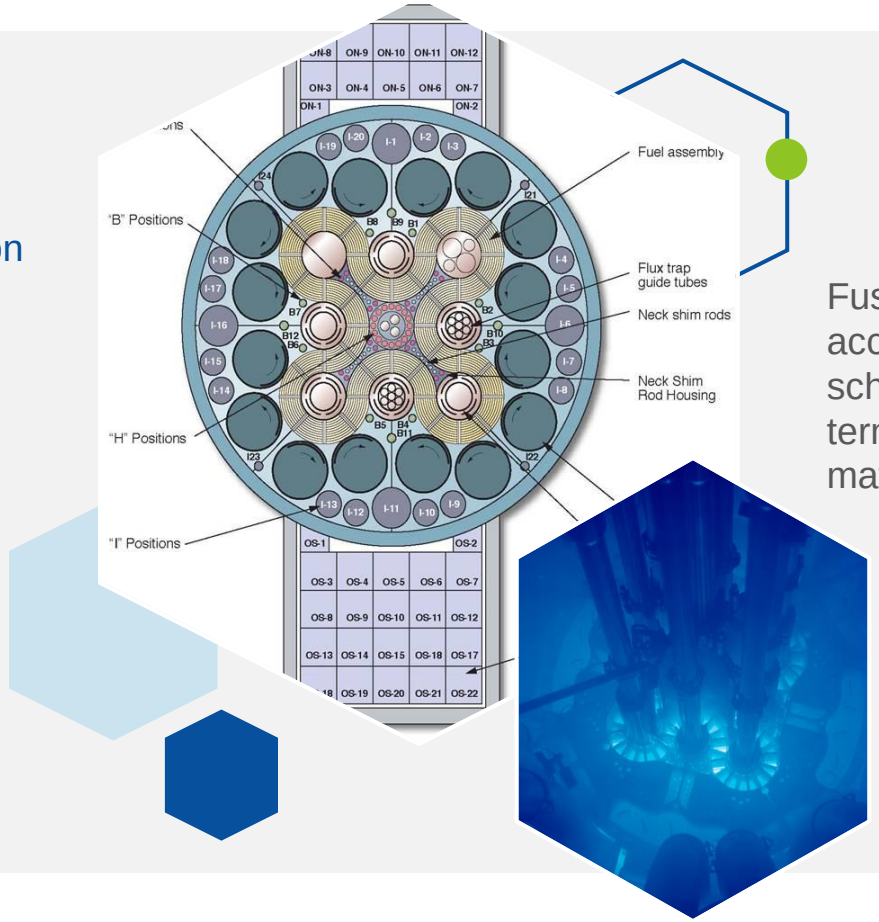
Science/Technology gap:

- Test scaled blanket components in relevant radiation environment to advance TRL beyond engineering demonstration

Spectral filters to simulate targeted effects

- Cadmium basket and HEU/LEU booster for fast fission neutrons
- ^{10}B doping for He production
- ^{6}Li for 3H permeation studies
- ^{235}U fission to drive high heat flux testing

Coupled with INL capability for materials handling and characterization (STAR, Sample Preparation Lab)

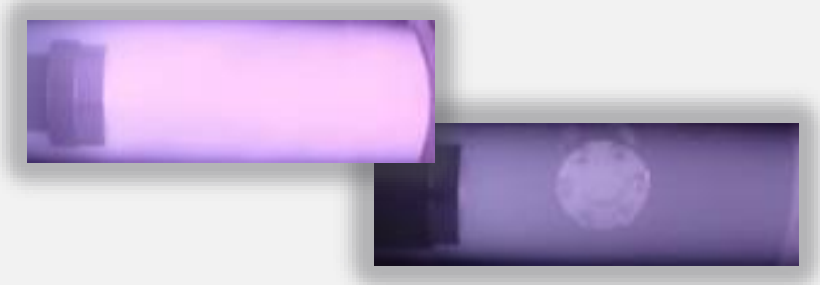


Fusion industries with accelerated development schedule interested in near term solutions for phased materials development

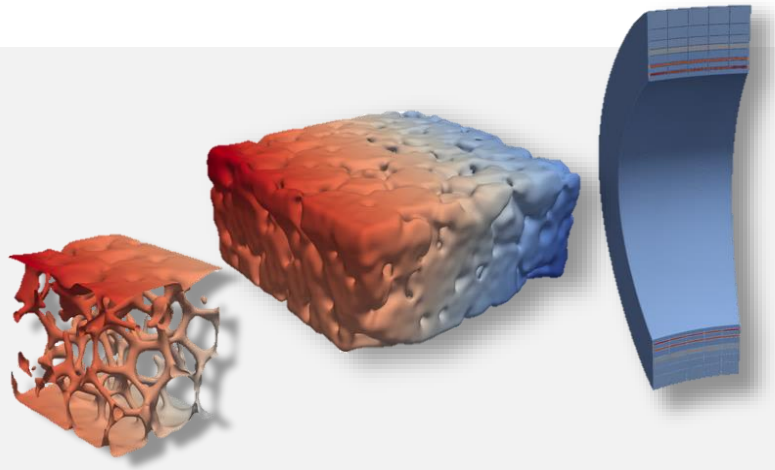
Fast fission spectrum relevant to blanket components behind the first wall, magnets, I&C and other systems functional materials

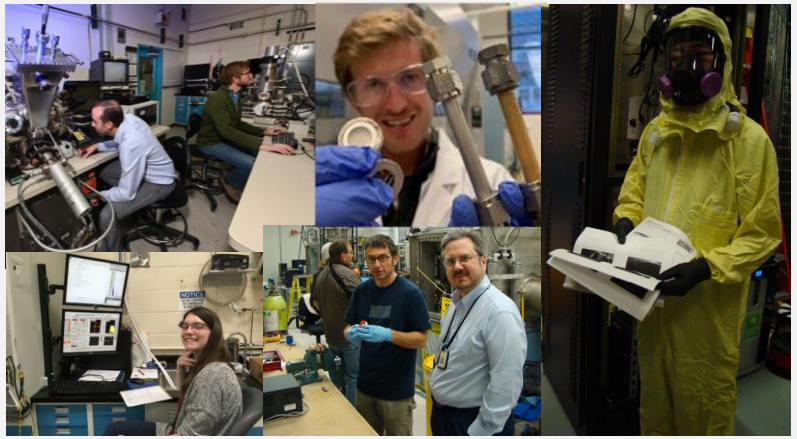
Turning Challenges into Opportunities

Tritium Plasma Experiment (TPE):
High flux (>10^{22} $m^{-2}s^{-1}$) plasma for PMI study



Tritium Plasma Experiment (TPE):
Low flux (~10^{21} $m^{-2}s^{-1}$) plasma for MFP testing





INFRASTRUCTURE

Testbeds to address some of the nation's most immediate capability shortfalls

- Tritium and irradiated materials testing and characterization
- Neutron testing for fusion blanket materials and components

SCIENCE & TECHNOLOGY

Expanding portfolio to address FES and fusion industry strategic priorities

- MOOSE based multi-physics modeling
- Fusion safety and risk informed design
- Tritium transport in breeder blankets
- Advanced materials and processes to reduce tritium inventories

WORKFORCE DEVELOPMENT

Foster and grow competencies through hands on demonstrations, knowledge transfer, and mentorship

- Fusion workforce accelerator workshop
- Academic engagement to provide fusion relevant skill set,
- Build the fusion industry nuclear workforce
- DOE Laboratories and international collaboration

16th International Symposium on Fusion Nuclear Technology
November 9-14, 2025, Knoxville, Tennessee, USA
FIRST ANNOUNCEMENT

https://isfnt-16.ornl.gov

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.