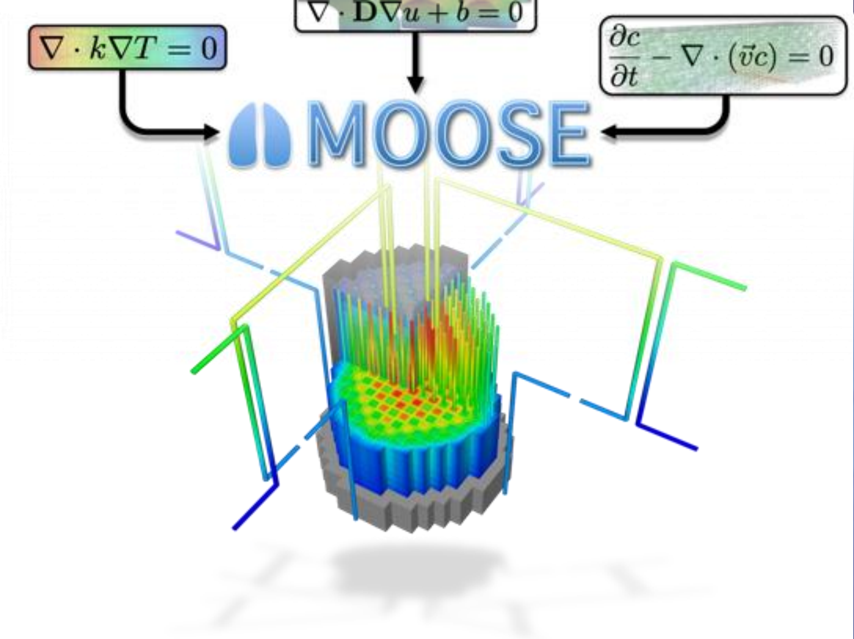

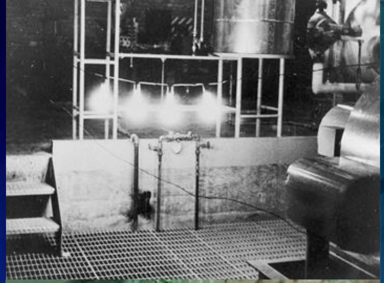

September 12, 2023

Pattrick Calderoni
Senior Technical Advisor, Fusion Safety Program

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Masashi Shimada, Chase N. Taylor, Thomas F. Fuerst, Adriaan A. Riet, Matthew D. Eklund, Hanns Gietl, Fusion Safety Program

Leveraging INL nuclear energy capabilities to support the acceleration of commercial fusion power deployment

ISFNT15
10-15 Sept 2023
Auditorio Alfredo Kraus, Las Palmas de Gran Canaria, Spain

The private fusion industry in the US is a reality

Commonwealth Fusion Systems · ZAP ENERGY · tae · generalfusion · HELION · TYPE ONE ENERGY

FOCUSED ENERGY · HB11 ENERGY LASER BORON FUSION · first light · KYOTO FUSIONEERING · Tokamak Energy

GAUSS FUSION · AVALANCHE · XCIMER ENERGY CORPORATION · fuse · EX-Fusion · STELLAREX

Helical Fusion · MarvelFusion · RENAISSANCE FUSION · nT-tao Compact Fusion Power · HelicitySpace

nearstar FUSION · THEA ENERGY · SHINE · BLUE LASER FUSION · Proxima Fusion · LPP FUSION

MIFTI · ELECTRIC FUSION SYSTEMS · HORNE TECHNOLOGIES · REALTA FUSION

NOVATRON · LONGVIEW FUSION ENERGY SYSTEMS · NK · PrincetonSATELLITE SYSTEMS · LaserFusionX

FUSION INDUSTRY ASSOCIATION

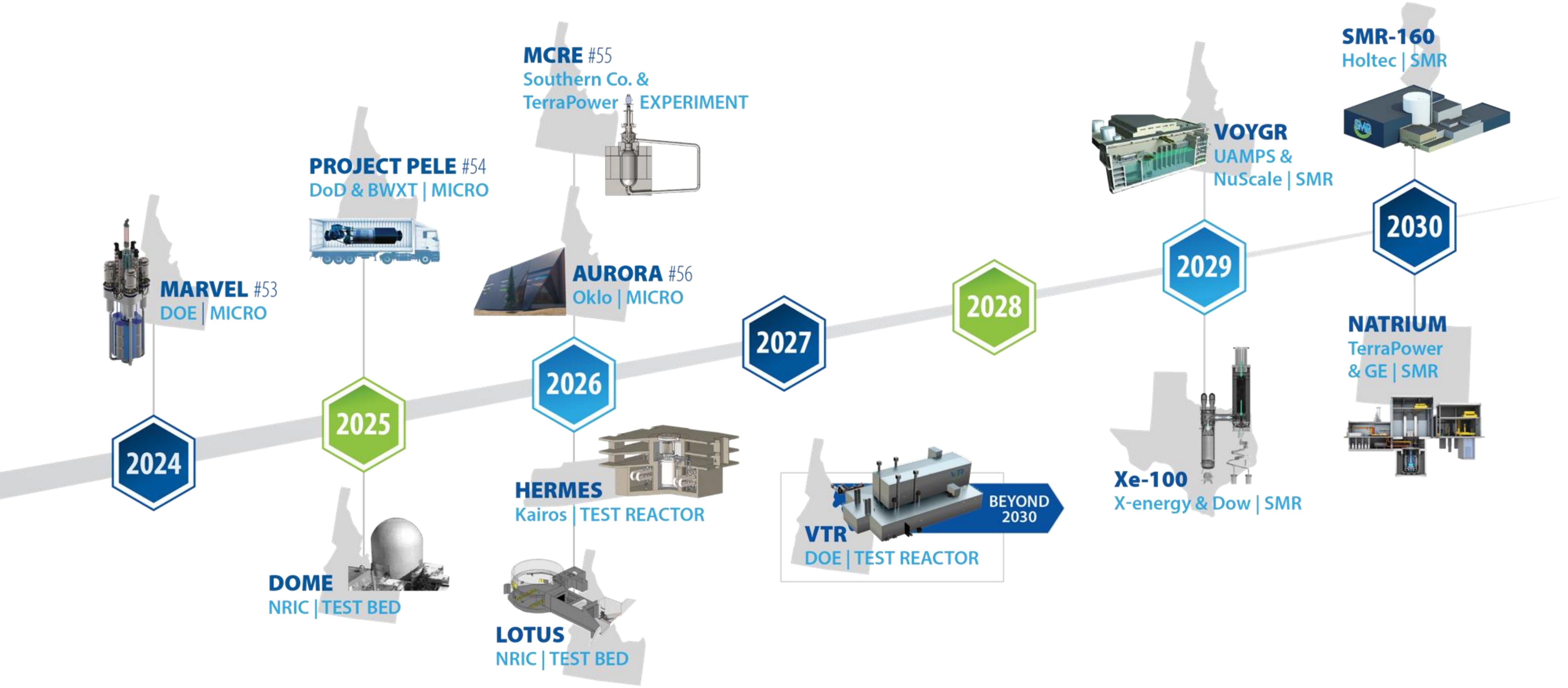
$5 billion+

Dollars invested in fusion research to date

Early 2030s

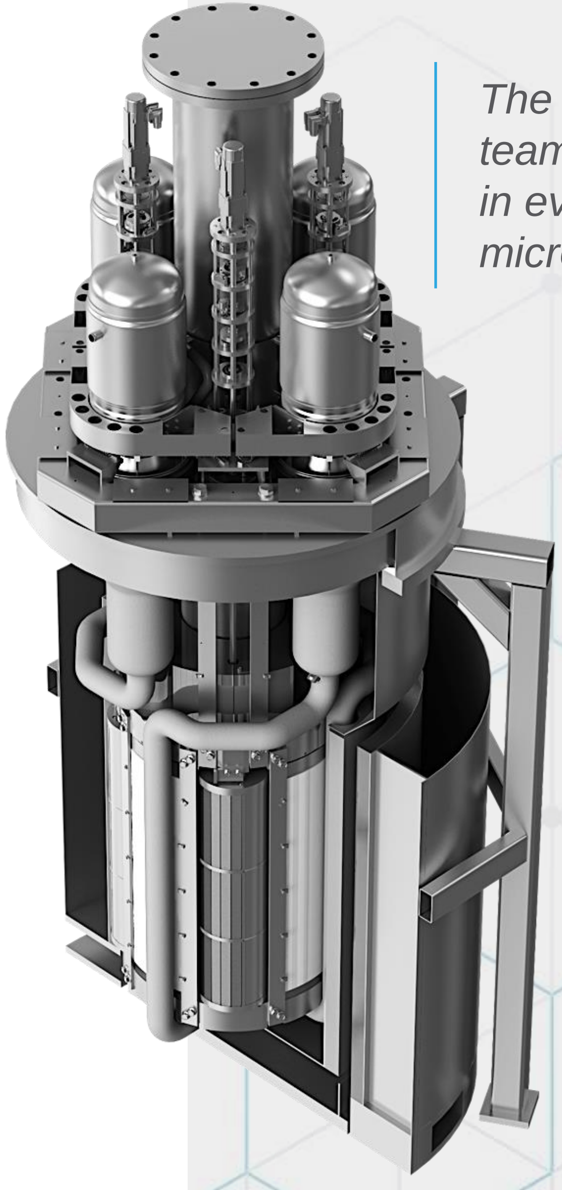
Target date for first fusion power plants

Accelerating advanced reactor demonstration & deployment



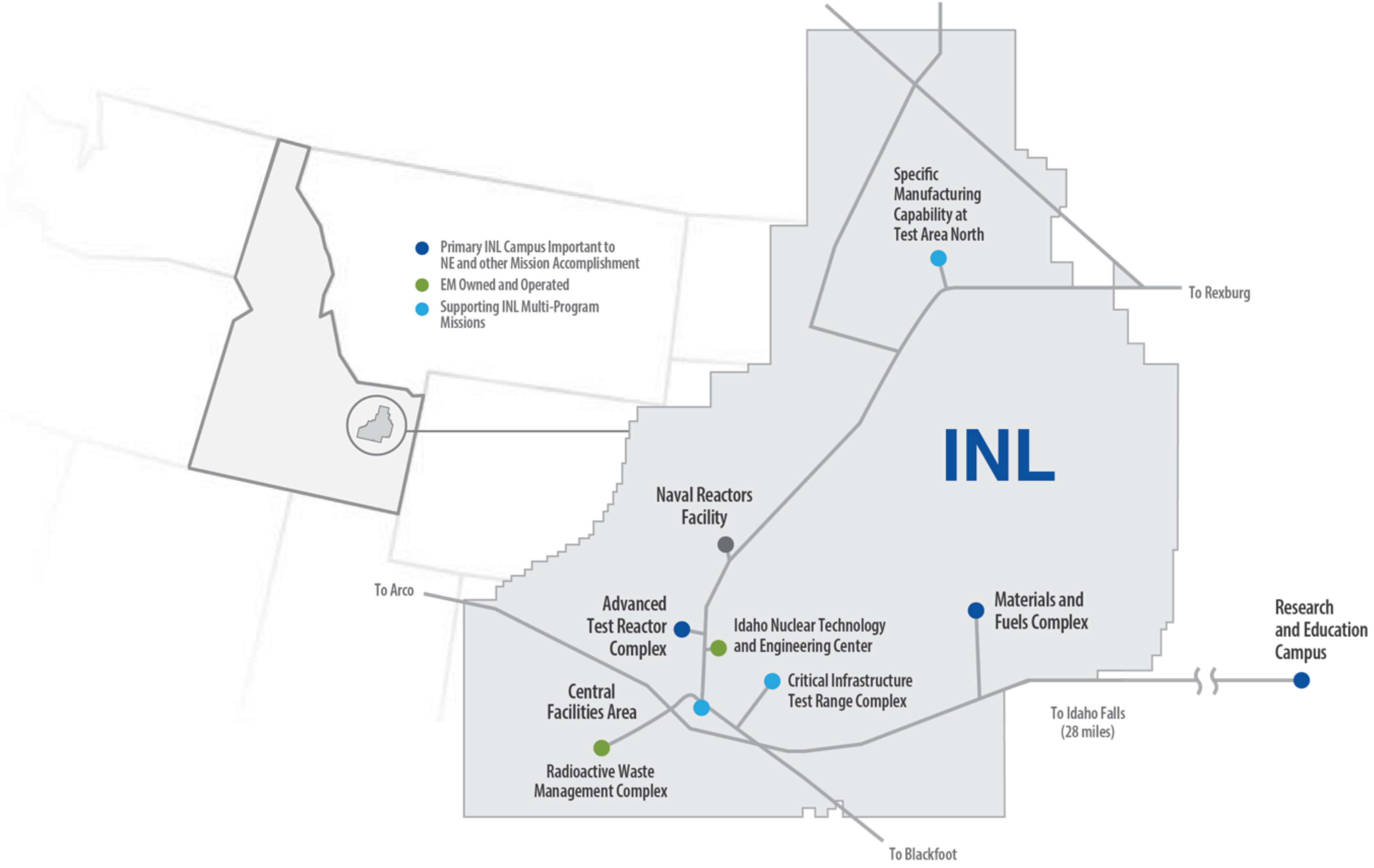
MARVEL

Microreactor Application Research, Validation and EvaLuation Project



*The **MARVEL** team is innovating in every area of a microreactor*

Unique site, infrastructure, and facilities enable energy and security RD&D at scale



4 Operating reactors

22 Hazard Category II & III non-reactor facilities/ activities

49 Radiological facilities/activities

17.5 Miles railroad for shipping nuclear fuel

44 Miles primary roads (125 miles total)

9 Substations with interfaces to two power providers

128 Miles high-voltage transmission & distribution lines

3 Fire Stations

Our core capabilities provide the foundation for our RD&D

- Advanced computer science, visualization, and data
- Applied materials science and engineering
- Biological and bioprocess engineering
- Chemical and molecular science (emerging)
- Chemical engineering
- Condensed matter physics and materials science (emerging)
- Cyber and information sciences
- Decision science and analysis
- Earth, environmental, and atmospheric science
- Isotope science and engineering
- Large-scale user facilities/ R&D facilities/advanced instrumentation
- Mechanical design and engineering
- Nuclear and radiochemistry
- Nuclear engineering
- Plasma and fusion energy sciences
- Power systems and electrical engineering
- Systems engineering and integration

Pioneering new nuclear technologies

Advanced Fission Energy Systems

- Fuels and materials development
- Advanced reactor test beds and demos
- Digital engineering and advanced M&S
- Fission battery initiative
- Space power systems

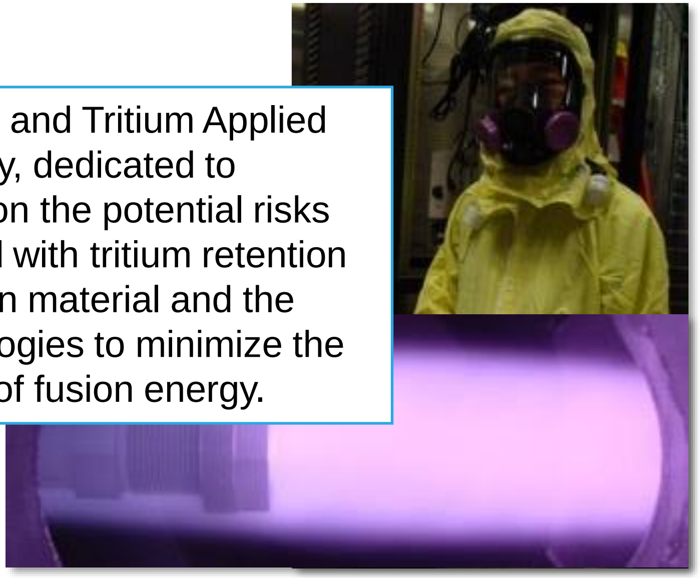
Fusion Energy Systems

- Blanket and fuel cycle technologies

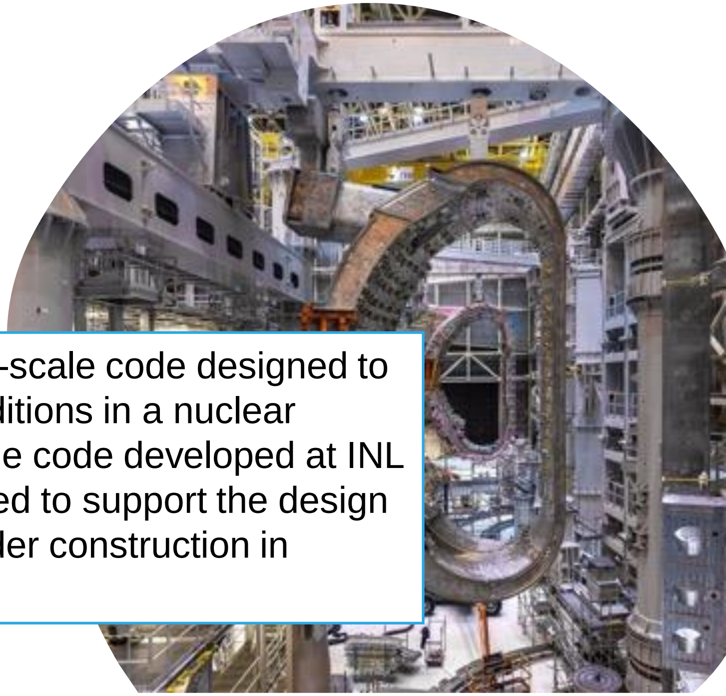
NSUF Nuclear Science User Facilities | GAIN Gateway for Accelerated Innovation in Nuclear | NRIC National Reactor Innovation Center

The INL Fusion Safety Program

- In the last 30 years INL has provided an essential contribution to the Office of Fusion Energy Science by providing safety analysis in support of the design of fusion energy systems.
- Experimental and analytical activities focus on the potential risks and hazards associated with fusion energy and the safety assessment of magnetic fusion energy systems.
- Current work supports the Department of Energy ‘Bold Decadal Vision for Commercial Fusion Energy’ and the engagement with the emergent fusion private sector.



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



MELCOR is an engineering-scale code designed to model severe accident conditions in a nuclear environment. A version of the code developed at INL for fusion applications is used to support the design and fabrication of ITER, under construction in southern France.

The INL Fusion Safety Program

Experimental research

- Tritium technology
  - Safety relevant components/processes (inventories, separation, storage, detection)
  - High temperature operation (fusion blanket)
- Breeder materials
  - Tritium/materials interactions (transport properties, extraction)
  - Liquid metals (Pb-Li, Li), molten salts (FLiBe)
- Plasma Facing Components
  - Tritium/materials interactions (retention, permeation)
  - Neutron damage

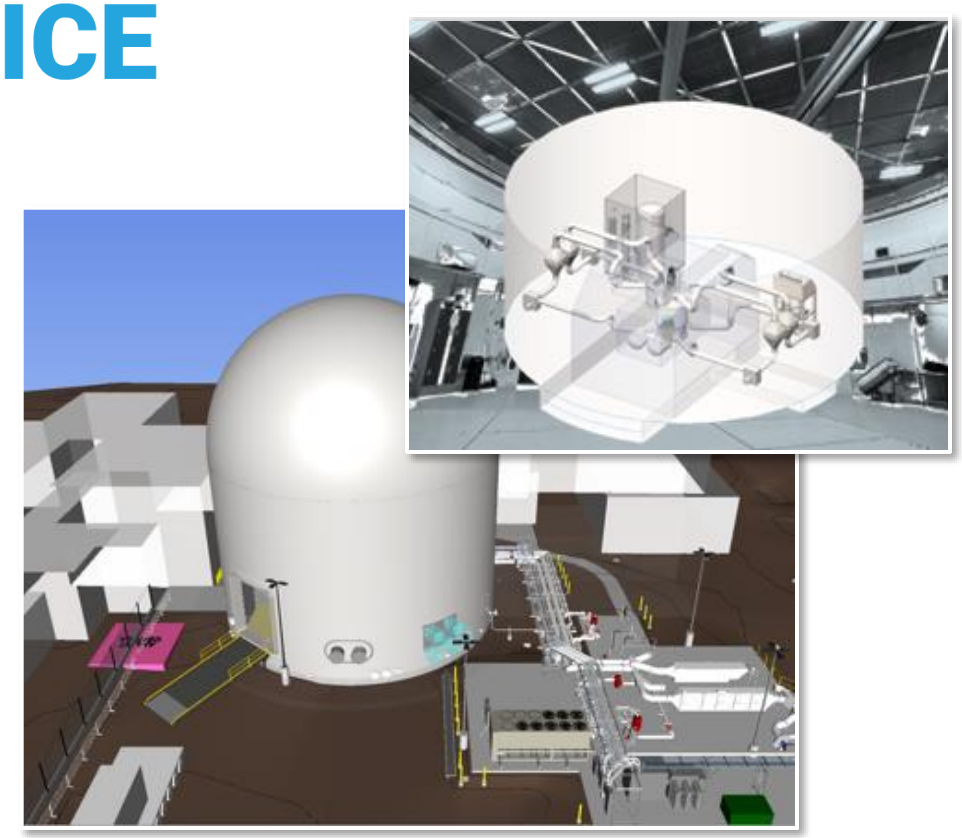
Analytical research

- Safety analysis
  - MELCOR-TMAP development/validation
  - Safety analysis of PPP blanket concepts (magnetic and inertial)
- Multi-physics modeling and simulation
  - TMAP8 validation and integration in MOOSE
  - Development of MOOSE tools for blanket high-fidelity modeling and simulation

Leveraging INL capabilities for fusion

Digital Innovation Center Of Excellence (DICE) - Home (inl.gov)

DICE



Digital engineering *principles are predicted to save up to 25% of costs in complex vertical construction and are already realizing multiple years in reduced schedules at the Department of Defense.*

Analytical research

- FPP safety assessment
  - Couple MELCOR and MOOSE fusion analysis for FPP safety assessment
- FPP modeling and simulation
  - Develop an integrated whole-device multi-physics modeling tool based on the MOOSE framework
- Digital engineering for FPP design
  - Integrate digital engineering processes in MOOSE fusion to accelerate design iterations
  - Exploit MOOSE fusion for Digital Twin development and couple with experiments (Hardware In the Loop)
  - Integrate RAMI fusion data in Probabilistic Risk Assessment (PRA)

Impact of INL MOOSE-based modeling & simulation tools

By the numbers:

- Citations for Multiphysics Object Oriented Simulation Environment (MOOSE): 1,240
- 2020 MOOSE paper is the most cited paper in Elsevier Software-X
- INL papers using MOOSE: ~200
- Citations of INL papers using MOOSE: ~3,000
- 5,000+ unique visitors a month to the MOOSE website

Nuclear Entities Using INL MOOSE-Based Applications:

U.S.NRC United States Nuclear Regulatory Commission Protecting People and the Environment · RADIANT · BWXT Nuclear Energy Canada Inc. · Structural Integrity Associates, Inc.® · Kairos Power · EPRI · Westinghouse

MOOSE · BISON · Blackbear · Falcon · Griffin · Grizzly · Magpie · Marmot · Mastodon · RELAP-7 · Sockeye · Pronghorn

MOOSE (Multiphysics Object-Oriented Simulation Environment)

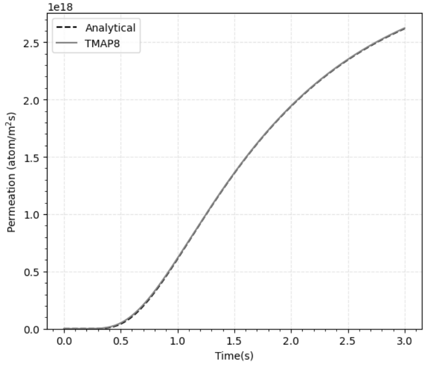
- Open-source framework for development of Multiphysics simulation software.
- Allows rapid development of new simulation tools and meets NQA-1 requirements.
- Massively parallel computations and leverages on nuclear energy validations in synergistic areas such as thermal-hydraulics, CFD, Heat transfer, mechanical/structural, Multiphysics coupling.
- Tritium Migration Analysis Program version 8 (TMAP8) is MOOSE based
- Lab directed projects started in FY23: plasma facing components, EM structural mechanic coupling

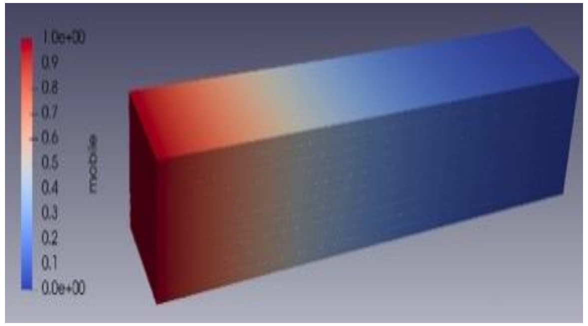
Verification example: Ver-1d, "Permeation Problem with Trapping"

A trapping parameter is defined by $\zeta = \frac{\lambda^2 \nu}{\rho D_0} exp\left(\frac{E_d - \varepsilon}{kT}\right) + \frac{c}{\rho}$

$\zeta = 91.47\, c/\rho$

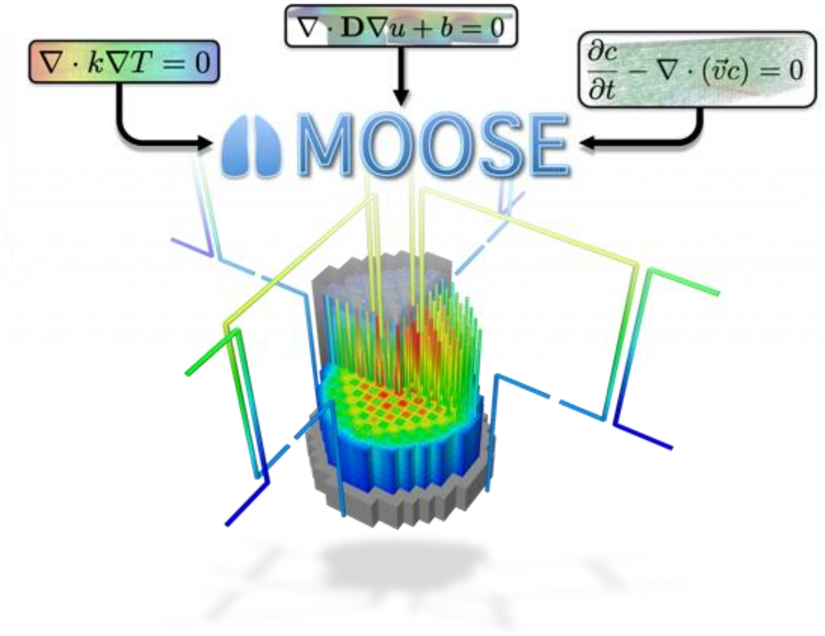
1D





3D

$\zeta = 91.47\, c/\rho$



References:

"MOOSE Framework - Open Source Multiphysics". Idaho National Laboratory. https://mooseframework.inl.gov/

Permann, Cody J., et al. "MOOSE: Enabling massively parallel multiphysics simulation." SoftwareX 11 (2020): 100430.

"TMAP8 Tritium Migration Analysis Program Version 8", https://mooseframework.inl.gov/TMAP8/

Leveraging INL capabilities for fusion

Experimental research

- Blanket components development and testing
  - Single effect (high temperature, tritium) and large-scale integrated testing for safety/accident scenarios characterization
  - Neutron irradiation in MTRs with modified spectrum test rigs/loops
- Blanket materials characterization
  - AM solid breeder materials
  - Liquid breeders
  - PFC and blanket structure
- Host test and demonstration facilities
  - Integrated testing of FPP concepts with D-T fuel
  - Accelerator-based facility for fusion materials development
- FPP instrumentation and controls
  - Sensors for blanket and fuel cycle components
  - Integration of plasma diagnostics in plant controls
  - Development of control schemes for FPP

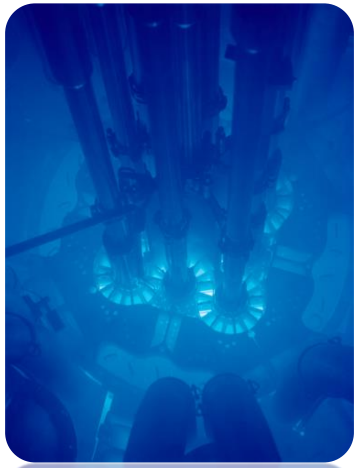
Advanced Materials and Manufacturing for Extreme Environments

GOALS

- Develop advanced manufacturing process-informed material design
- Expand advanced manufacturing process development
- Enable rapid material characterization and testing designed for advanced manufacturing
- Integrate comprehensive data analytic and modeling and simulation techniques

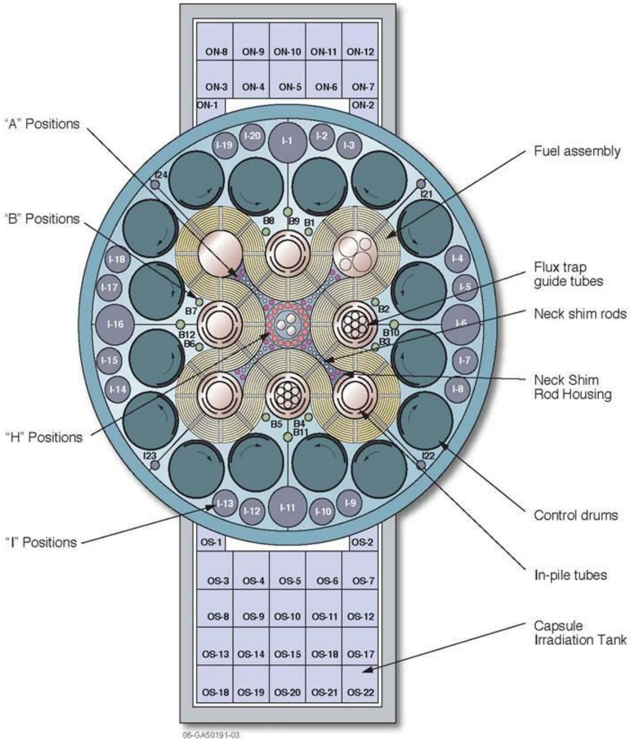
The Advanced Test Reactor

- Material test reactor started 1967, still one of the newest and most advanced test reactors in the world
- Core in 2.7 MPa pressure vessel, 70°C light water coolant, plate type driver fuel enables high power/flux density
- Serpentine driver core creates nine flux traps and numerous other test positions
- Rich history of capsule, water loop, and instrumented lead out irradiation tests
- High flux, large useable test geometries (1.2 m long core, test positions up to 13 cm dia)
- Fluxes ranging from ~5E14 n/cm^{2}s (inner core) to ~5E13 n/cm^{2}s (outer reflector)
- Without modification, fast to thermal ratios ranging from 1:1 (inner core) to 1:100 (outer reflector)
- Collocated with world class suite of properties testing and characterization equipment in shielded hot cells



ATR Core

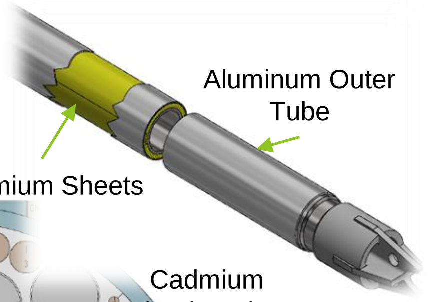
Hot Fuel Exam Facility

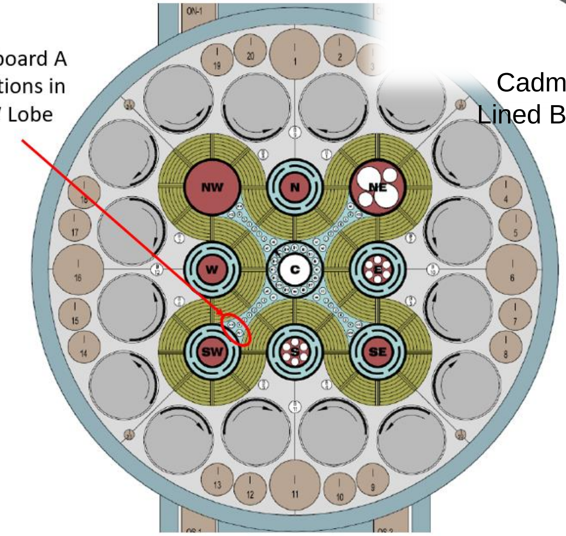


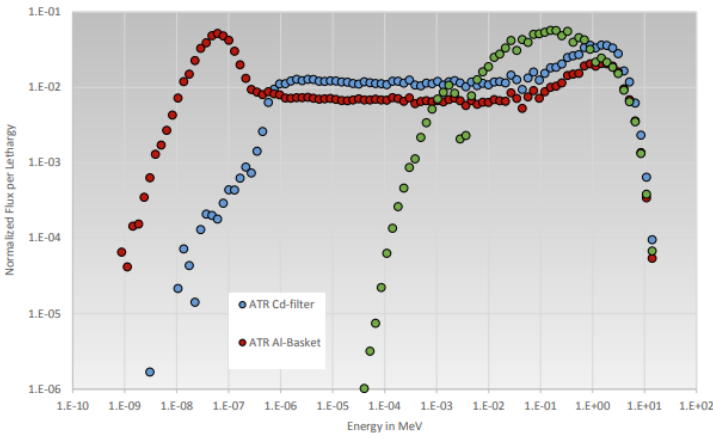
A modified closure plate with 9 additional penetrations was installed in 2022 to expand irradiation capabilities

Modified spectrum irradiations in ATR

- The DOE testbed infrastructure for fast reactors demonstration (EBR-II, FFTF) shut down in mid 1990’s
- Fast neutrons (> 0.1 MeV) testing is needed to:
  - Achieve representative damage mechanisms in structural materials (atom displacement, spallation, etc.)
  - Minimize spurious effects from thermal-neutron capture transmutation
  - Create representative self shielding, thermal/burnup gradients, and isotopic breed/burn evolutions
- Metallic fuel testing re-started in ATR to support VTR and private industry (Terrapower, Oklo, ARC)
  - Long-running AFC capsule in cad basket irradiation series completed prior to ~2021 ATR beryllium replacement
  - FAST irradiation of smaller rodlets (half diameter/length of AFC rodlets) commenced to evaluate boosted fission rate testing
  - Focused on high burn-up only, must supplement with full-size tests to support advanced fuel technology deployment

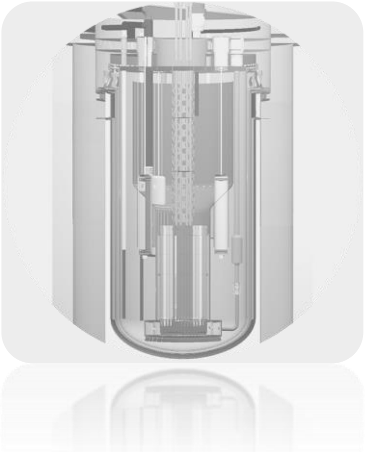






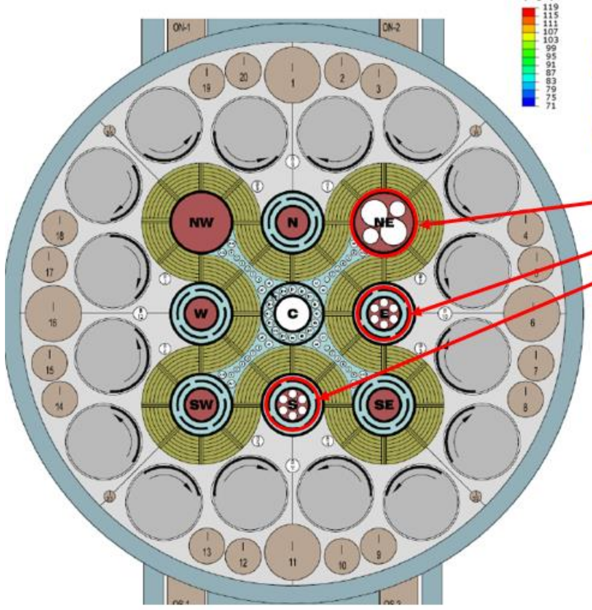
Thermal test reactor (with and without filter) vs fast fission [2]

[2] Jason M. Harp, Steven L. Hayes, Pavel G. Medvedev, and Luca Capriotti, “Testing Fast Reactor Fuels in a Thermal Reactor: A Comparison Report”, INL document INL/EXT-17-41677, 2017.

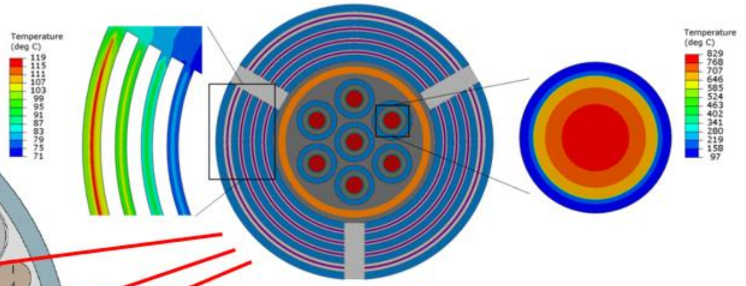


Boosted Energy Advanced Spectrum Test (BEAST)

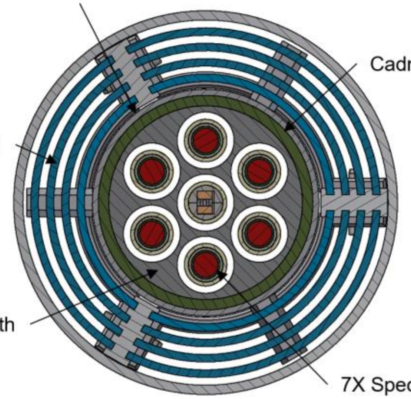
- New device "BEAST" under development
  - 1E15 n/cm^{2}s fast flux (>0.1 MeV), 10 dpa/yr achievable with HEU booster based on historic designs INL/EXT-05-00263
  - Recent calcs show ~7E14 n/cm^{2}s fast flux with LEU booster design, 53.7 fast to thermal ratio and 1.04 dpa/30days
    - Broadens booster fuel supplier options, preferred option to reduce cost
  - fuel pins 300-500 W/cm linear heating rates, thermal insulation in capsules elevates fuel/cladding temperature to 600-650 C
- Cd and Eu filtered baskets give fast-to-thermal ratios of ~50:1 and ~100:1, respectively
  - Cadmium option preferred based on higher fast flux peak and years of economical/successful use in ATR
- Booster fuel plates 250 W/cm^2 surface heat flux, well within ATR thermal hydraulic limits



Potential flux traps that could house BEAST



Thermal predictions for booster fuel plates and test pins in BEAST



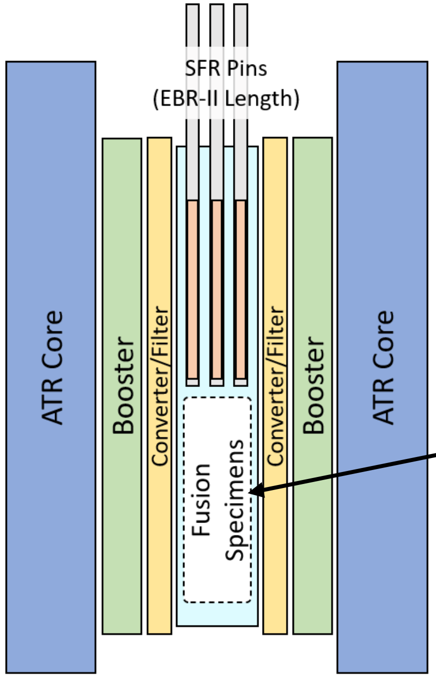
Nuclear Engineering and Design 387 (2022) 111623

Opportunity for fusion material testing - today

- Modified neutron spectrum irradiations in Material Test Reactors are only a complement to testing in prototypical conditions (VTR, FPNS)
  - He generation rate is not prototypical for plasma facing components
- Irradiation data for fusion materials is needed in the next 3 years to support the accelerated phased demonstration approach proposed by fusion private industry
- BEAST offer large test volume for material specimens with shared overhead costs

APPM/30 Days H	APPM/30 Days He	DPA/30 Days
Tungsten		
0.001	0.001	0.47
Iron		
0.037	5.786	1.06
Nickel		
660.066	44.860	1.04
Silicon Carbide		
26.880	18.958	1.3

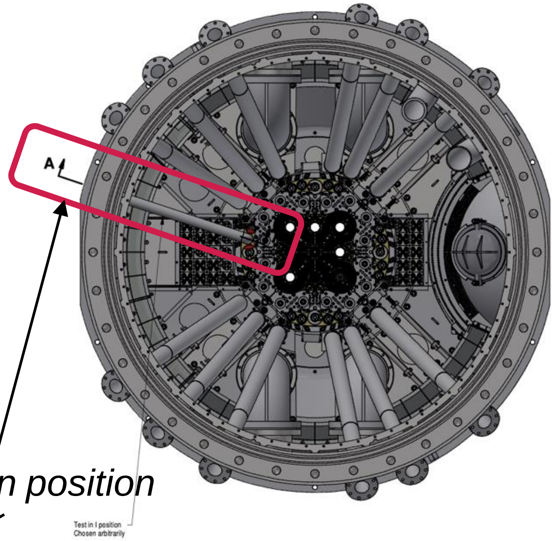
Predictions for gas generation and dpa in BEAST

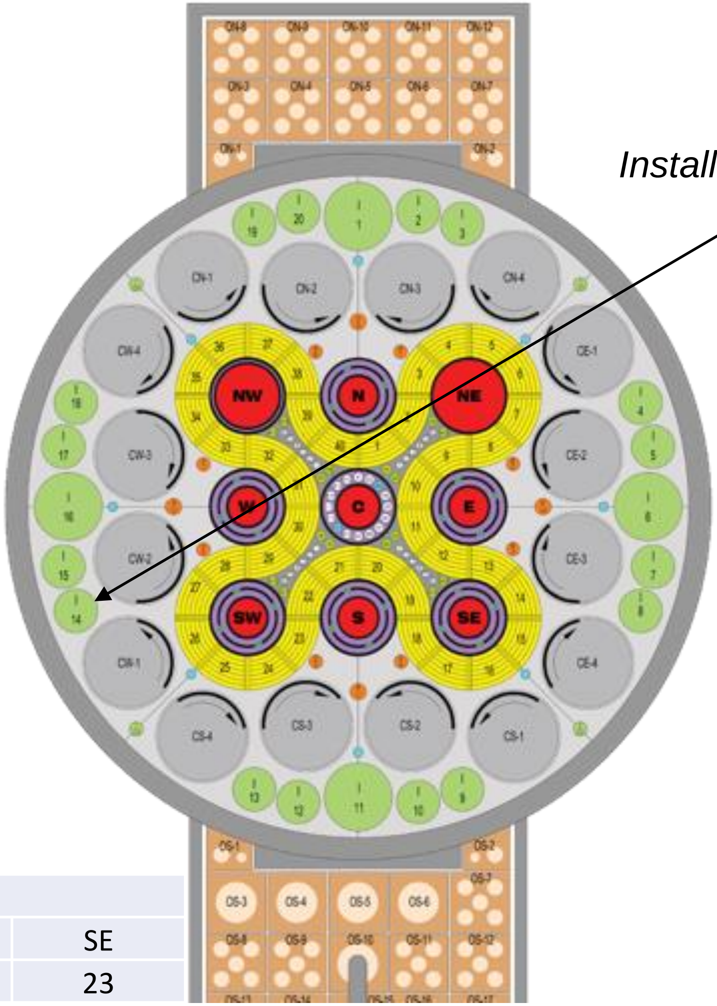


~800 cm^3
test volume

Tritium breeding integral test in ATR

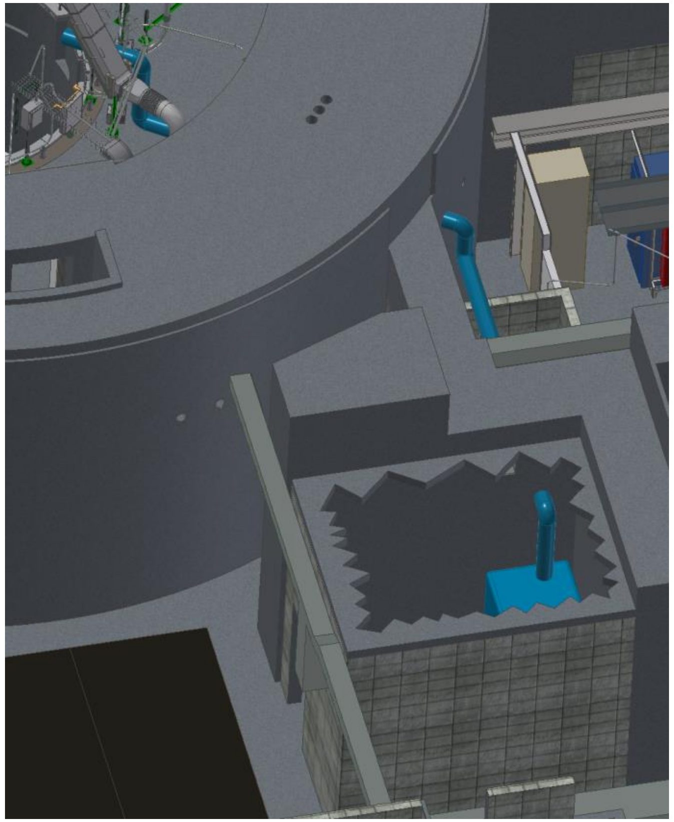
- **Lead lithium alloy forced convection loop for the characterization of tritium production and extraction + materials integral testing** under relevant nuclear conditions.
- Conceptual design study performed for PbLi but adaptable to other liquid breeder materials:
  - 600ºC operation
  - Li-6 natural enrichment
  - tritium generation calculated from Li-6 with (n,alpha) reaction and Li-7 with (n,n'alpha) reaction
  - two 60 days cycle irradiation
- Predicted generation rate from neutronic calculations are compatible with expected equilibrium concentrations in established blanket concepts (WCLL/HCLL and DCLL)

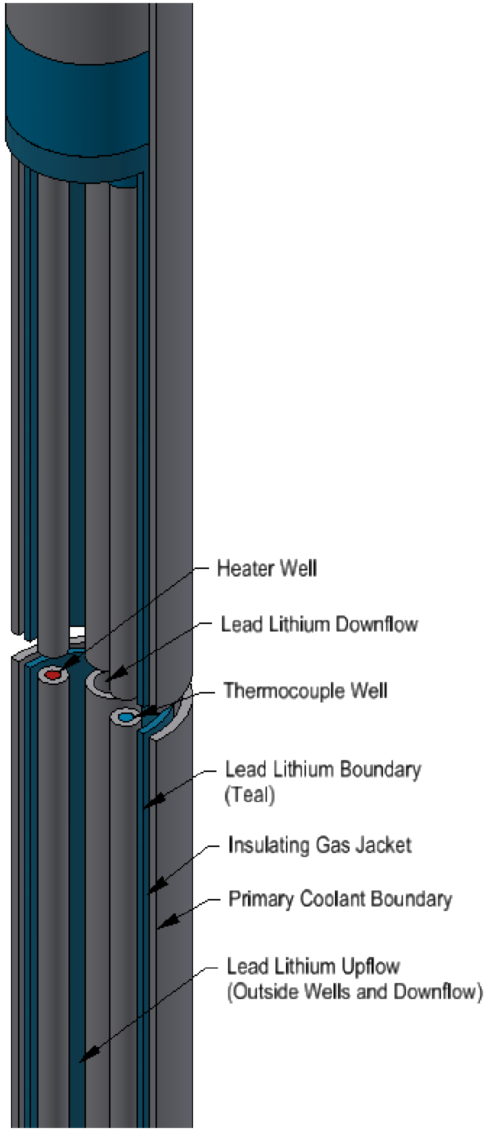


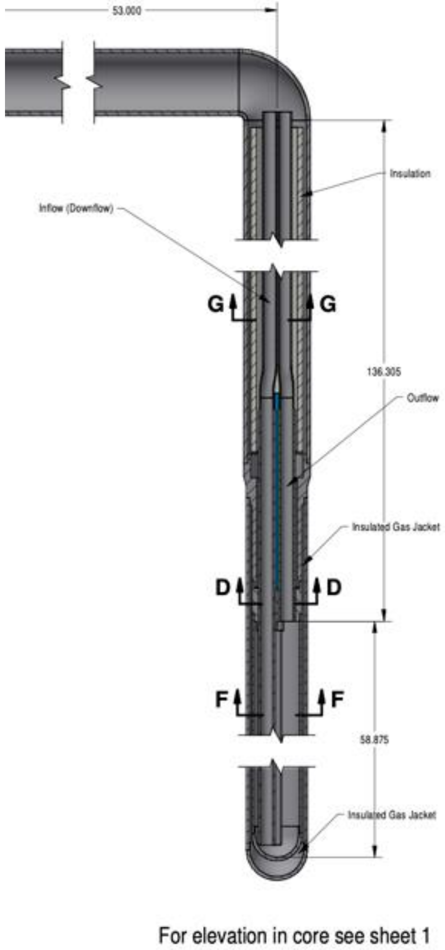


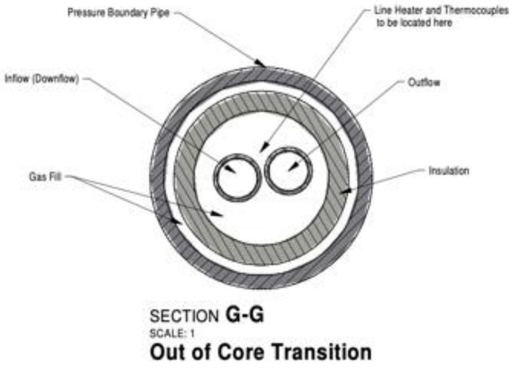
Lobe Power (MW)				
NW	NE	C	SW	SE
20	18	20.66	23	23

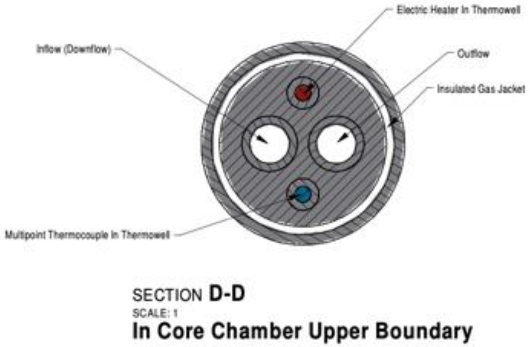
Tritium breeding integral test in ATR

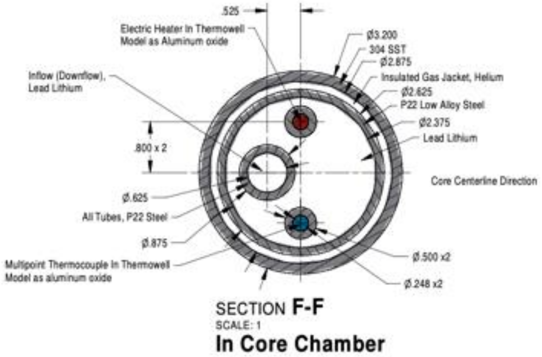












Idaho National Laboratory

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.