Oak Ridge National Laboratory Molybdenum-99 Program

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ORNL ^{99}Mo Program

- In response to international supply chain challenges, the US Department of Energy (DOE) established a program to evaluate and support projects for the production of ^{99}Mo in the United States without the use of highly enriched U.
- ORNL has collaborated with a variety of companies to provide R&D solutions to overcome fabrication, production, licensing, and potential operational challenges.

SHINE Medical Technologies · BWXT BWX Technologies, Inc. · NorthStar Medical Radioisotopes, LLC, A Subsidiary of NorthStar Medical Technologies · NIOWAVE Accelerating Your Particles · EDEN RADIOISOTOPES · Flibe ENERGY

- Oak Ridge National Laboratory (ORNL) support has included target material processing support, material performance evaluations, material capsule and prototypic target design, irradiation support, and core neutronic, thermal, and shielding design support.

Acknowledgement

ORNL's ^{99}Mo program is supported by the DOE National Nuclear Security Administration's Material Management and Minimization Office.

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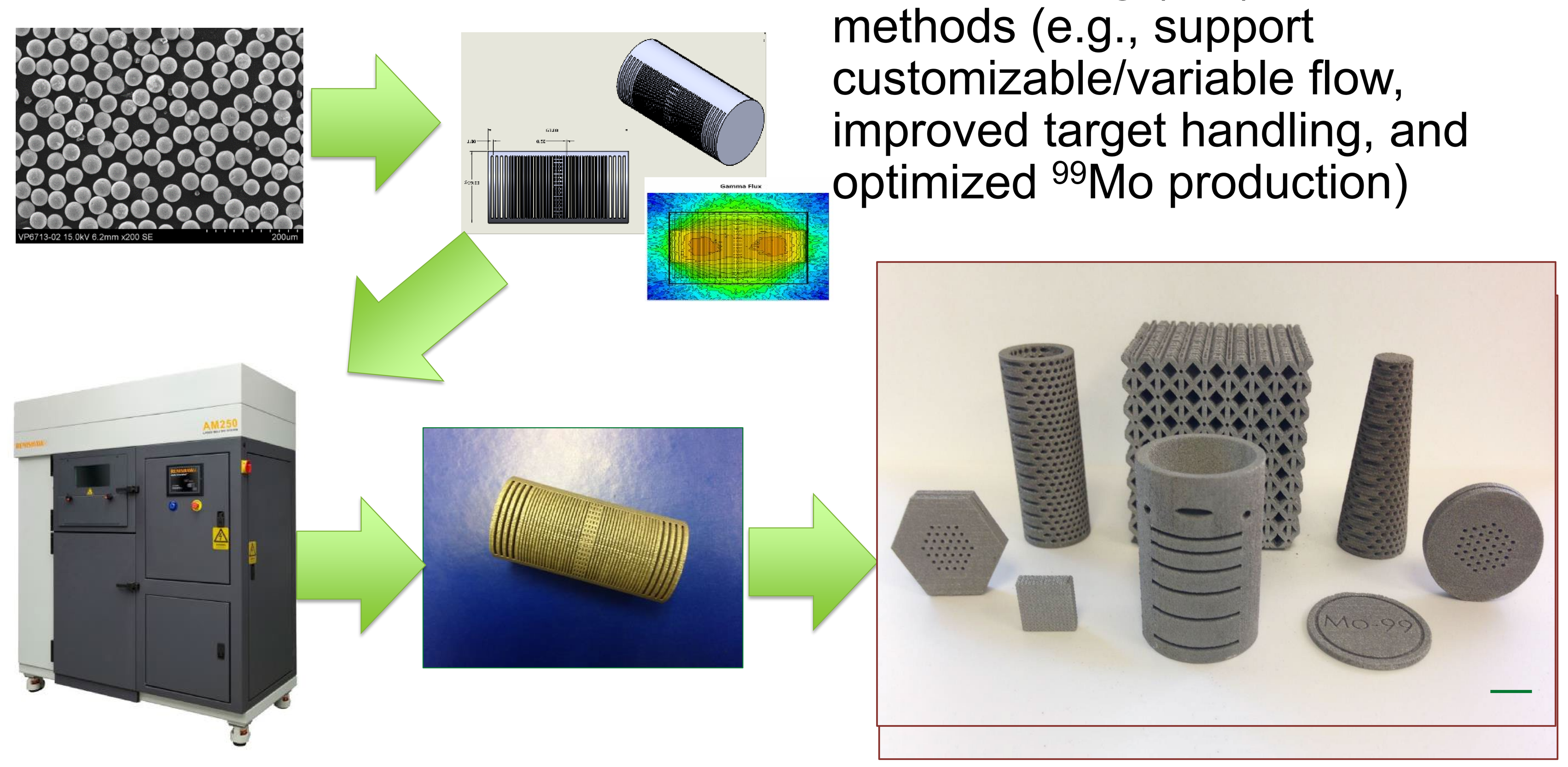
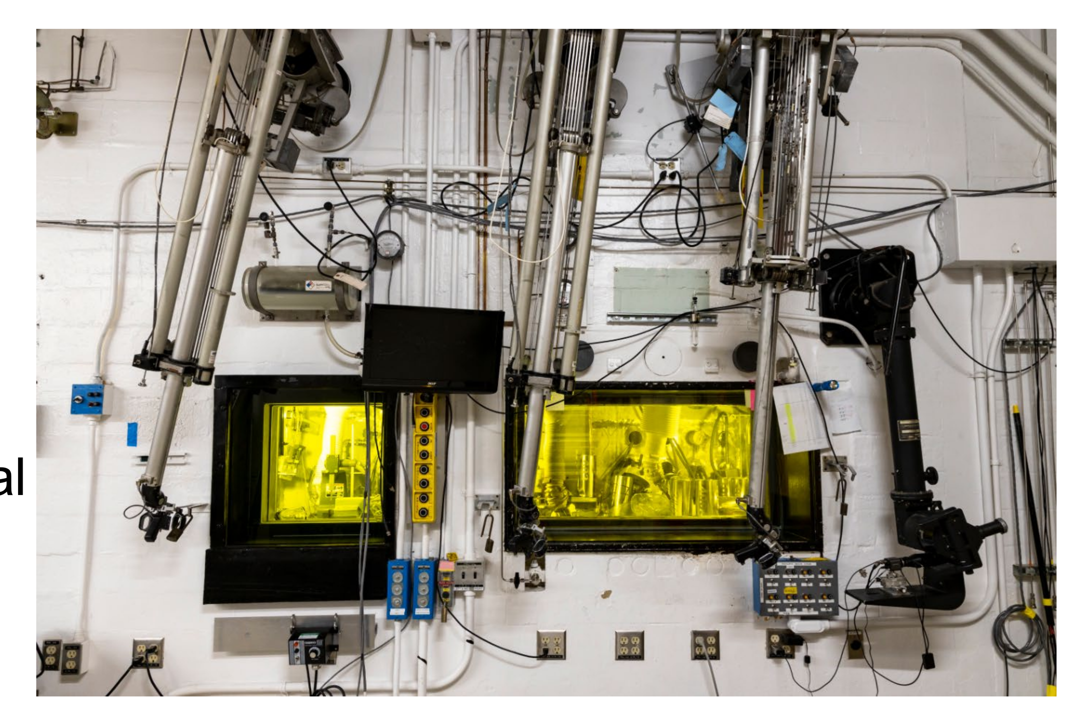
Target Material Processing & Production

- ORNL developed a die and powder system to support target disk production of Mo
- Development included press and sinter capability for enriched Mo
- ORNL also explored additive manufacturing (AM) production methods (e.g., support customizable/variable flow, improved target handling, and optimized ^{99}Mo production)



Material Performance Evaluation

- ORNL irradiated material testing, including physical and mechanical property testing, corrosion testing, and SCC testing
- Reactor vessel material development was performed with SHINE



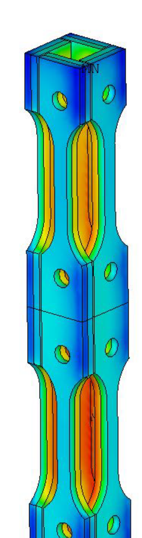
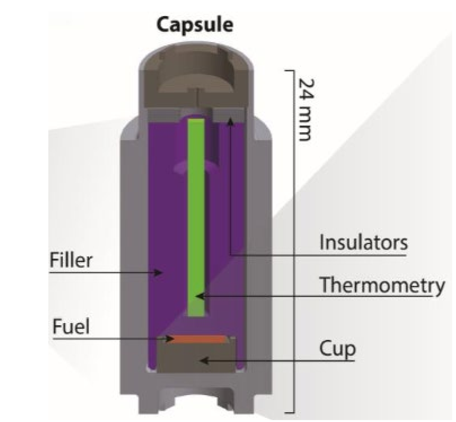


Figure 6. (Left) Tensile bar holder used for SS3 specimens. (Right) Selection of tools with manipulator fittings to be used in IMET.

Target Design & Irradiation

- Irradiation test design at ORNL in support of the ^{99}Mo program includes prototypic target design and material capsule experiment design



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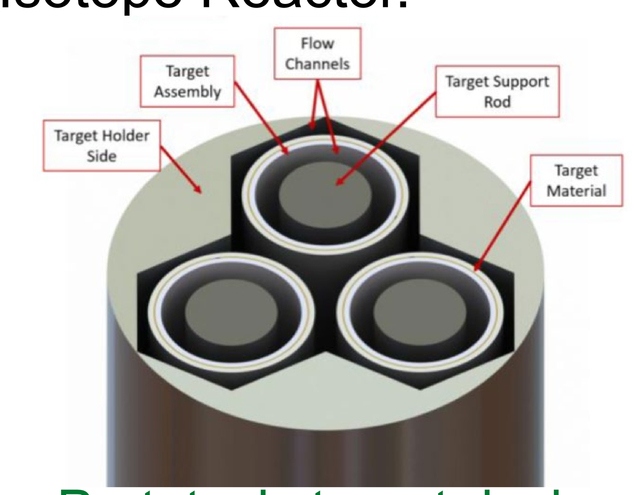
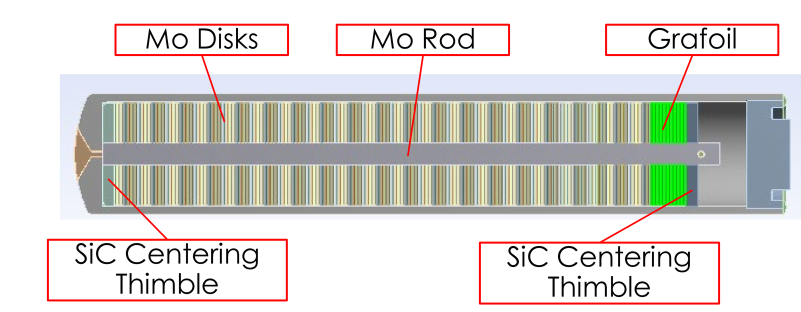
- Thermal and growth properties of low-enriched U were evaluated
- The design and analysis were completed at ORNL for irradiation in ORNL's High Flux Isotope Reactor.

Mini-Fuel Irradiation Test



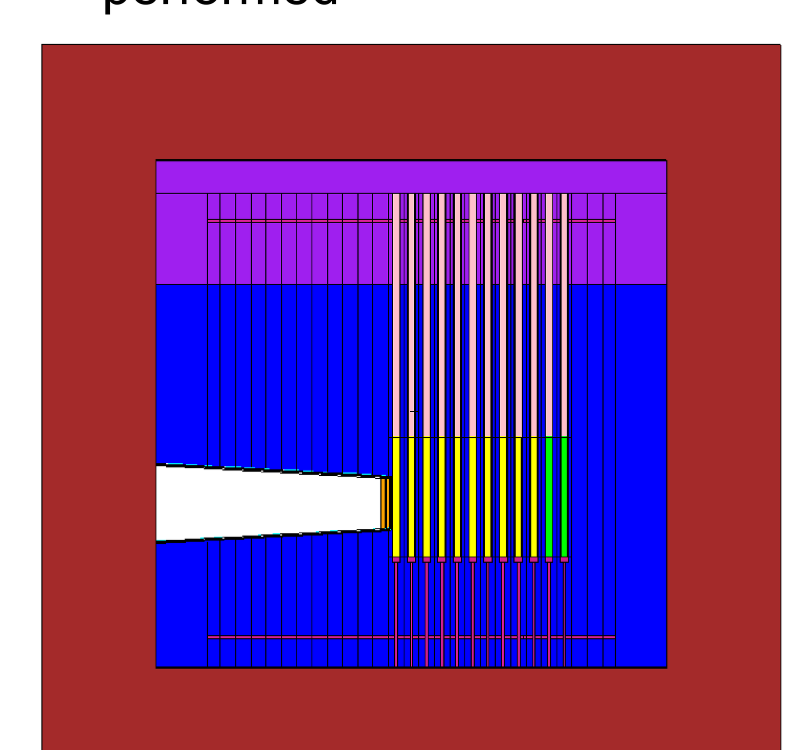
Prototypic target design

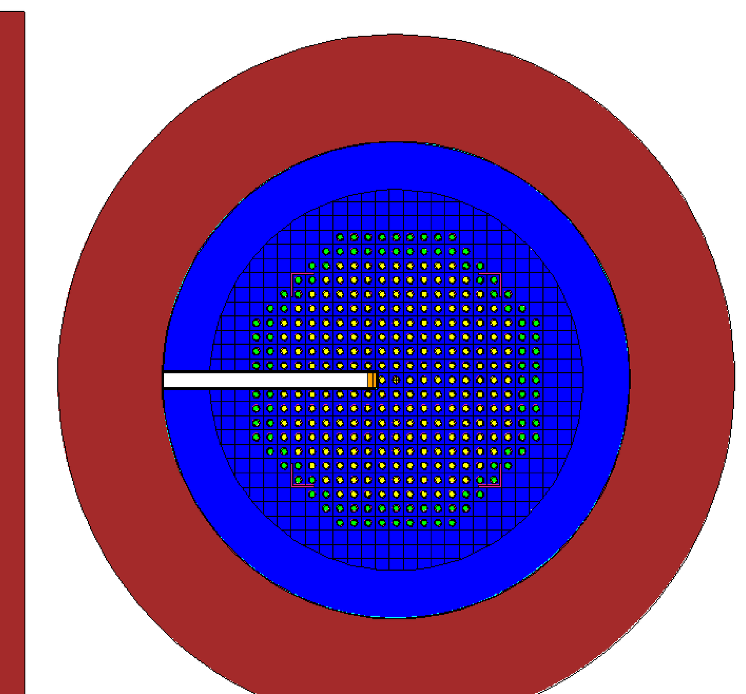


Irradiation capsule with Mo disks

Neutronics, Thermal, & Shielding Support

- Ongoing work is investigating optimal core configurations for maximizing 99Mo production with Niowave, supporting Niowave facility shielding studies
- Method development: incorporating photonuclear production calculations into SCALE framework
- Augmented data human analysis methodologies are being developed to better target the optimum space, and an initial thermal hydraulic study of the experimental system is being performed





*Irradiation design concept of the minifuel experiment-modified figure from C.M. Petrie, J. Nucl. Mater. 526 (2019)

Oak Ridge National Laboratory Design and Shielding Support for Accelerator Driven Subcritical Assembly use for Mo-99 Production

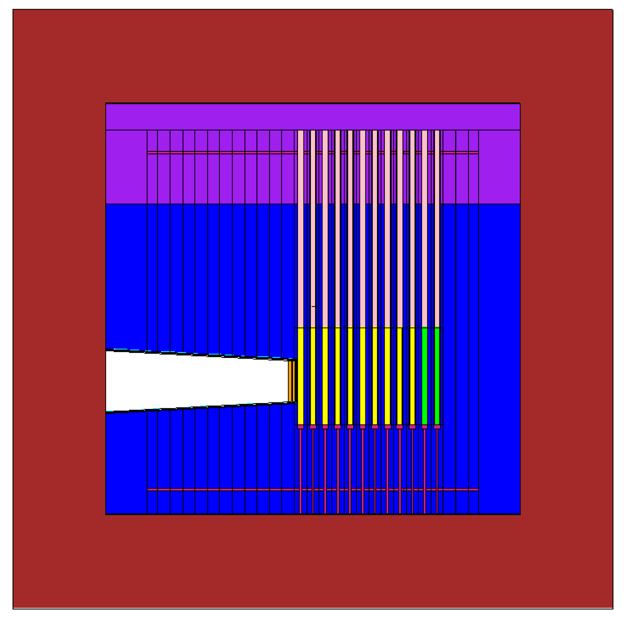
Jorge Navarro, Noel Nelson, Andrew Conant, Cory Ball, Blake Wilkerson,
Michael Smith, Zane Karriem, and Jim Nash

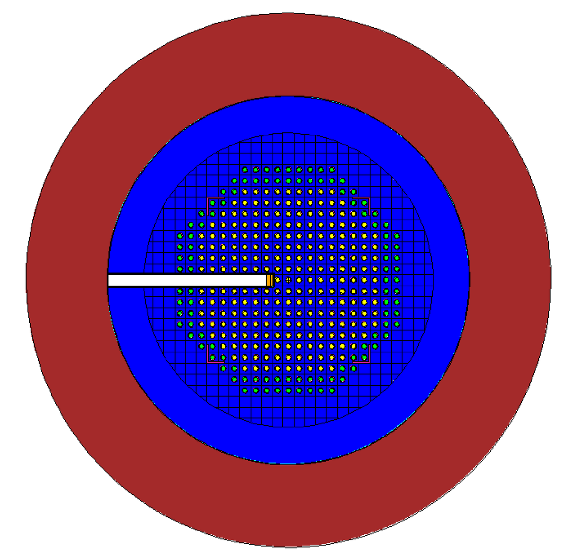
Design and Optimization

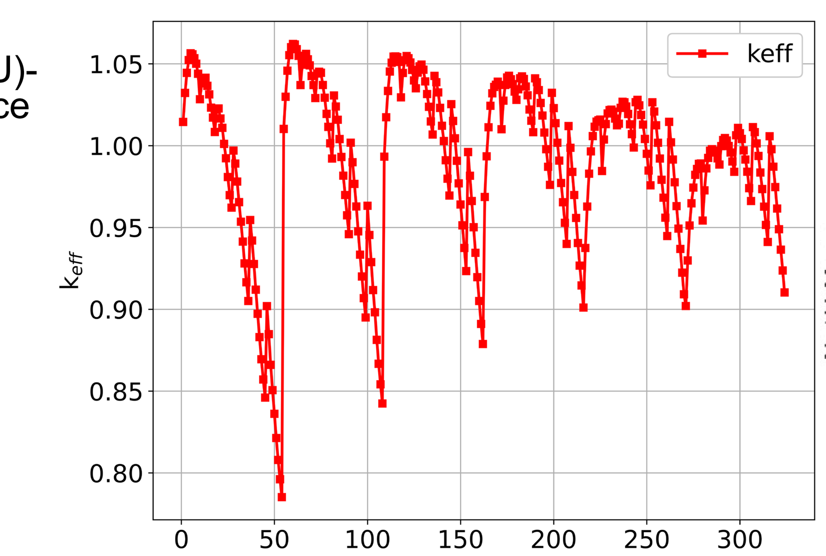
The modeling and simulation ORNL Accelerator-Driven Subcritical System (ADSS) team has followed three paths to design and optimize two Linear Accelerator (LINAC)-subcritical assembly coupled size systems for Mo-99 production

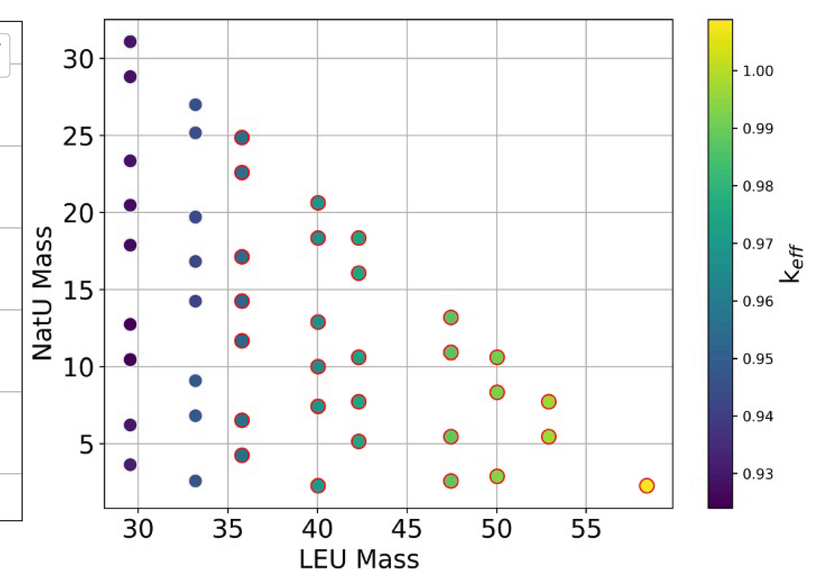
1. **Sensitivity study**
   – MCNP and PSTUDY tools for rapid iteration
2. **Machine learning**
   – Dakota implementation
     - Asynchronous search
     - Colony evolutionary algorithm
     - Efficient global optimization
     - Direct Optimization Algorithm
     - Single-objective genetic algorithm (SOGA)

- Design parameter: maximized fissions per electron
- Investigation of core configurations for mixed Low Enriched Uranium (LEU)- and Natural Uranium (NU)-fueled core with electron-driven photonuclear source with LINAC
- Optimization of k_{eff}, fissions/electrons, and fission fraction in NU-fueled vs. LEU
- Multiple stages
  1. LEU pitch and reflector material
  2. Core Height/Diameter
  3. Natural uranium-fueled pitch
  4. LINAC location

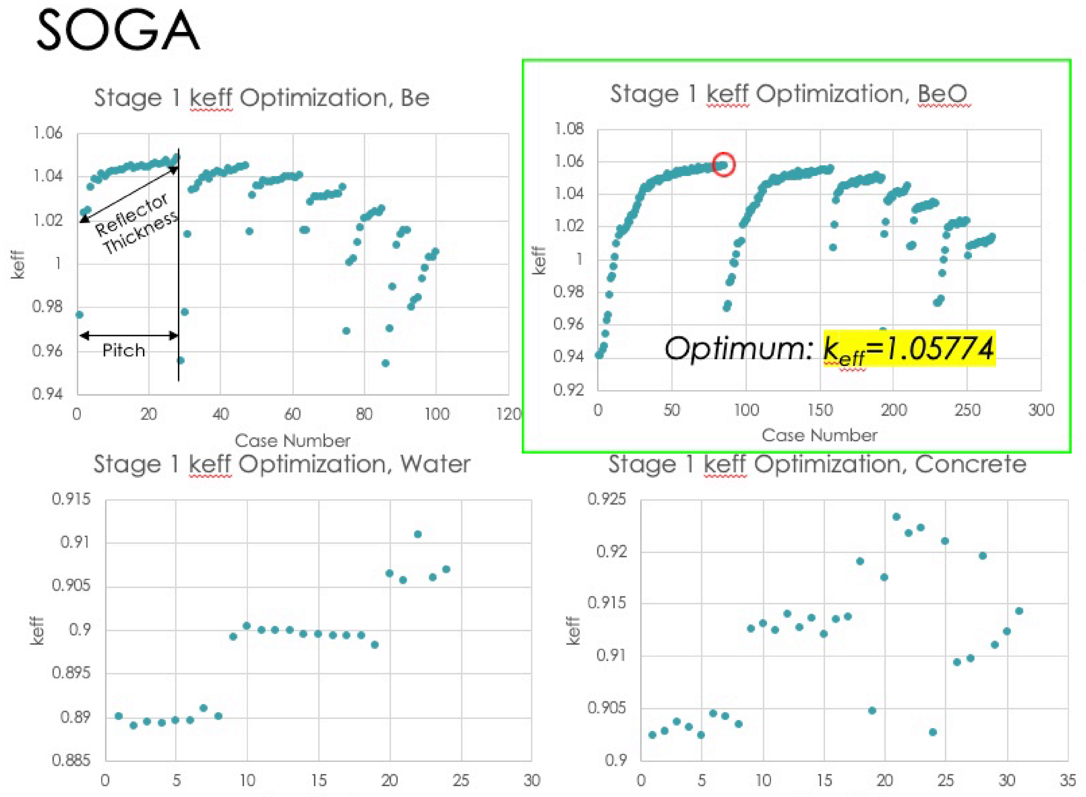




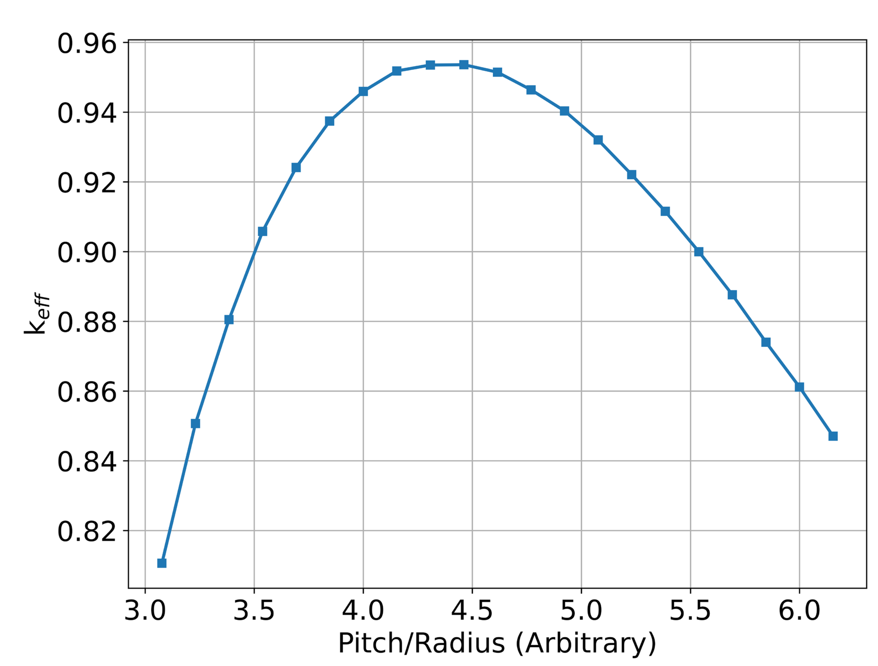




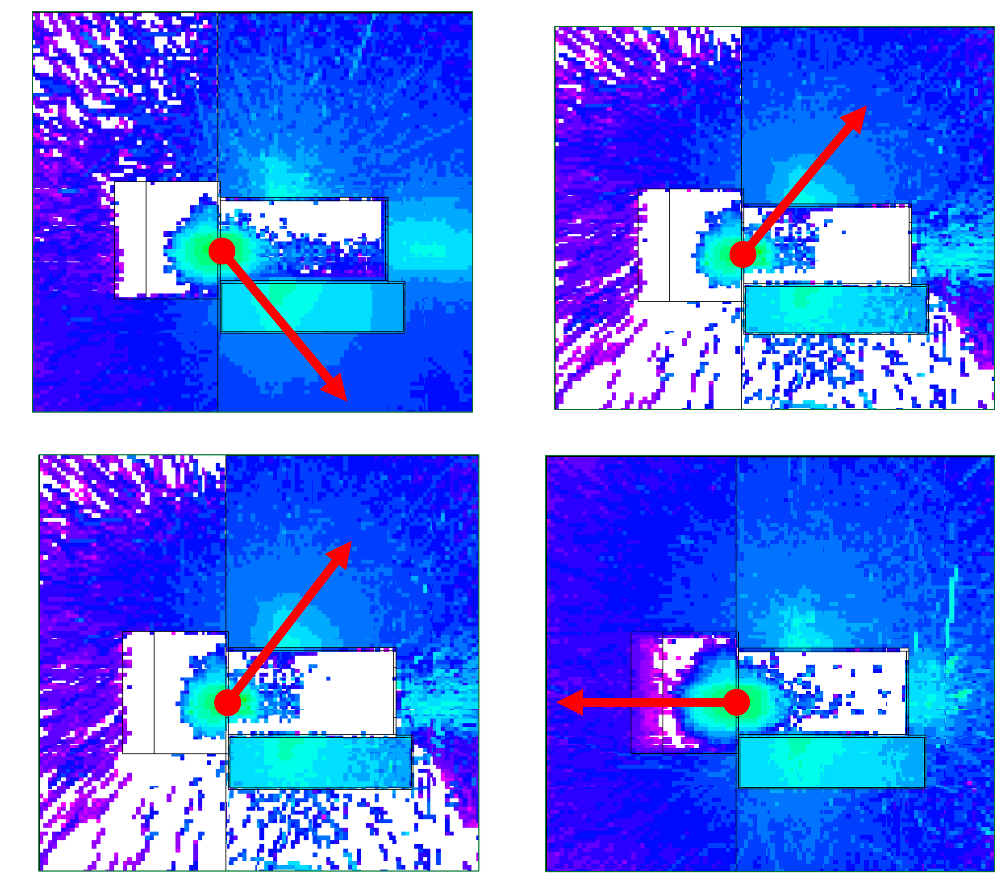
SOGA



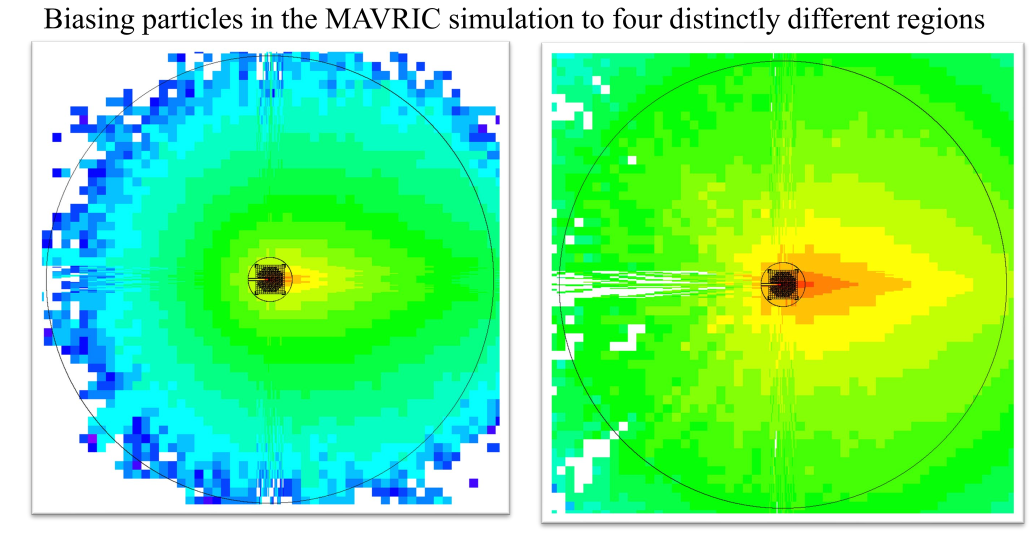
Metrics
1. Opt.: **Strong**
2. Depth: **Intermediate**
3. Time: ***6.47 hours***



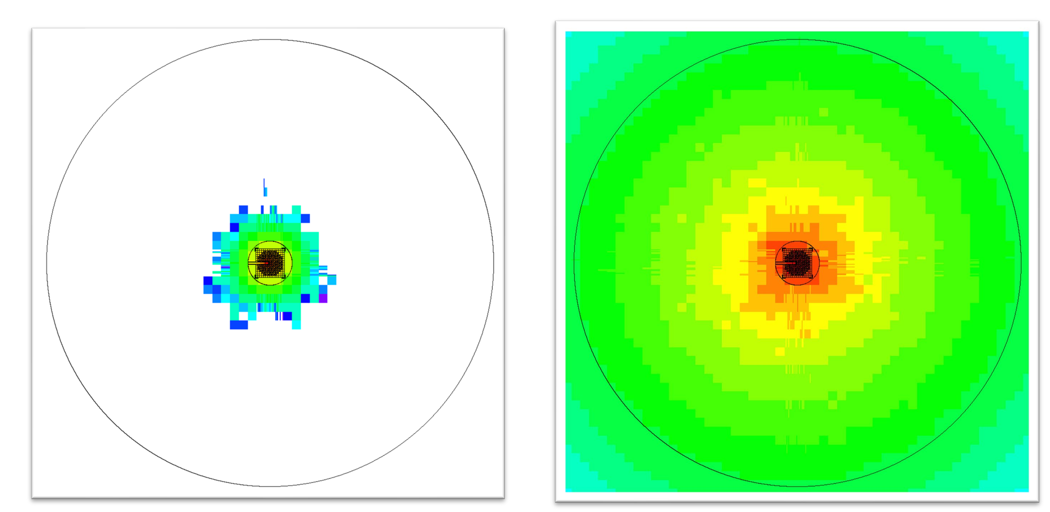
Facility Shielding



Biasing particles in the MAVRIC simulation to four distinctly different regions



Forward-Weighted Consistent Adjoint Driven Importance Sampling (FW-CADIS) acceleration, photon dose rates estimates improvement



FW-CADIS acceleration, neutron dose rates estimates improvements

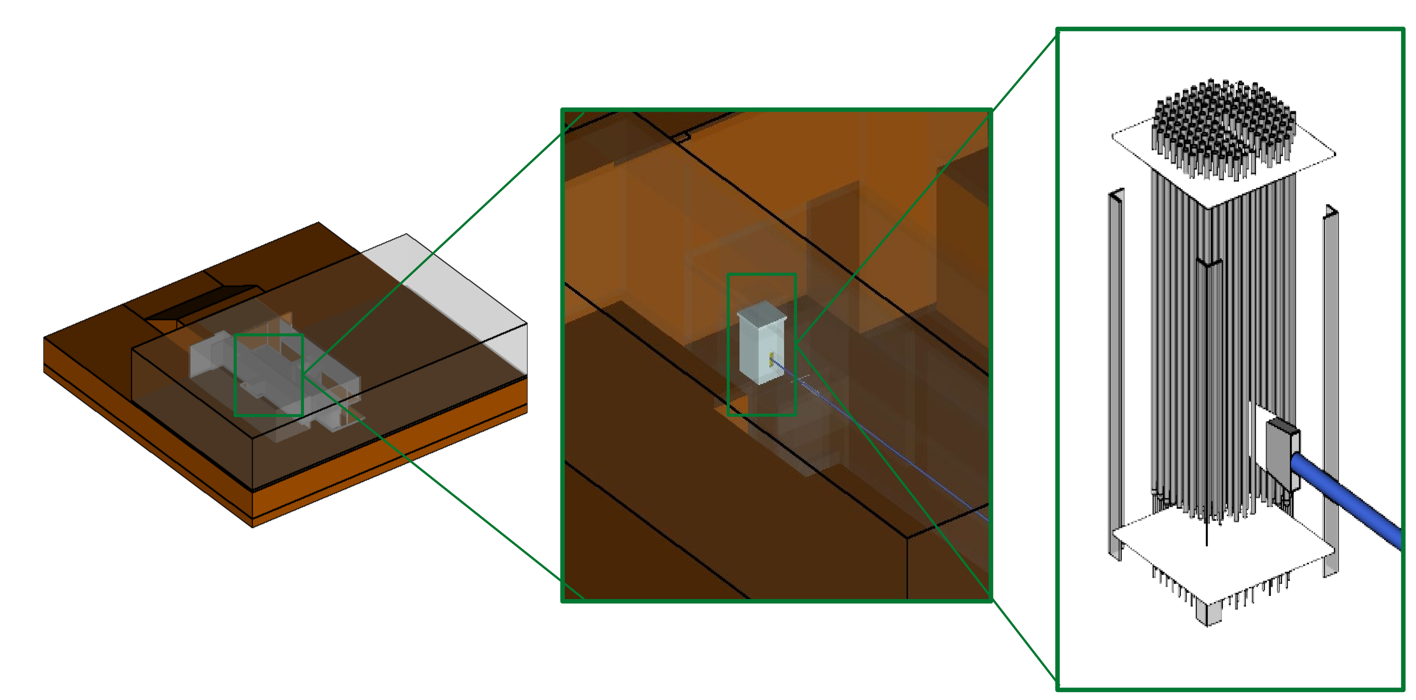
Objective: Develop a methodology that can capture the complex multiphysics environment of Accelerator Driven Subcritical System (ADSS) while still having an efficient shielding simulation.

The shielding methodology for Mo-99 ADSS production facilities has three paths:

1. The photonuclear source reduced-order model approach
   - Decouples the bremsstrahlung accelerator target physics from the subcritical assembly's photon and neutron physics
2. A secondary particle source generator (SPSG) is being developed with MCNP's PTRAC to help transport efficiency
   - CADIS implementations for radiation transport (MAVRIC or ADVANTG) accelerate neutral particle transport
   - Charged particle physics need to be converted to neutral particle sources for acceleration
   - SPSG creates a new neutral particle source using MCNP's PTRAC output
3. The ORNL ADSS team will partner with the SCALE team to add cross section–specific libraries as well as acceleration methodologies geared toward improving ADSS multiphysics capabilities

SPSG

MCNP charged particle transport with PTRAC → Tally PTRAC particle information → Data converted to neutron and photon sources in MCNP or SCALE



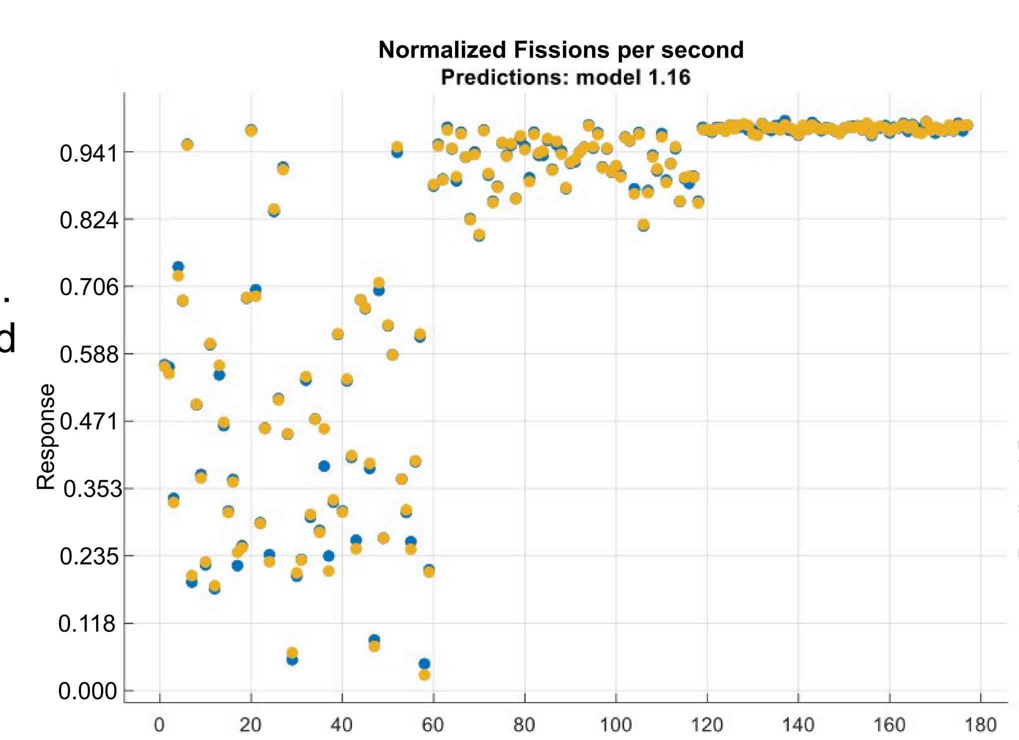
Stochastic Prediction-Based Exploration Surrogate Optimization (SPESO)

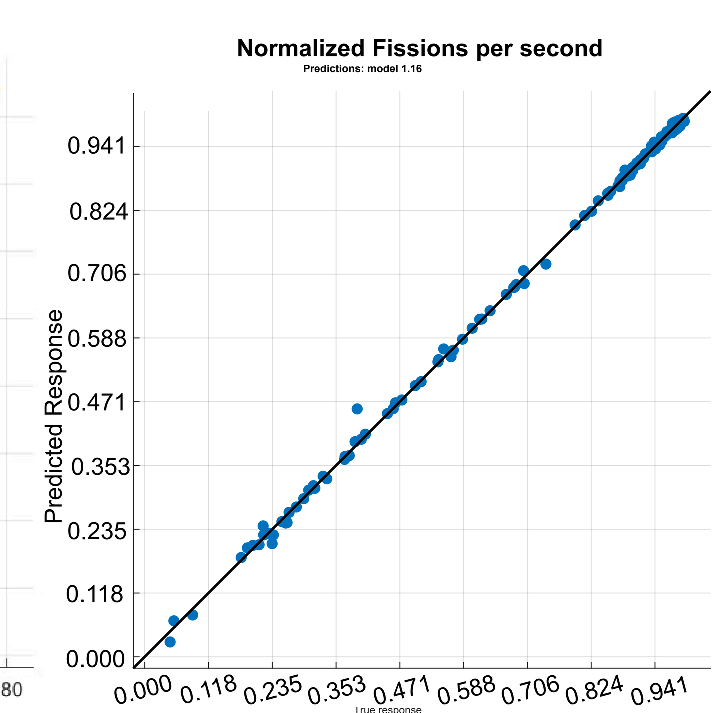
The ORNL team also developed a new optimization method. SPESO is a technique in which multiple cases are used to construct a surrogate model of the objective function.

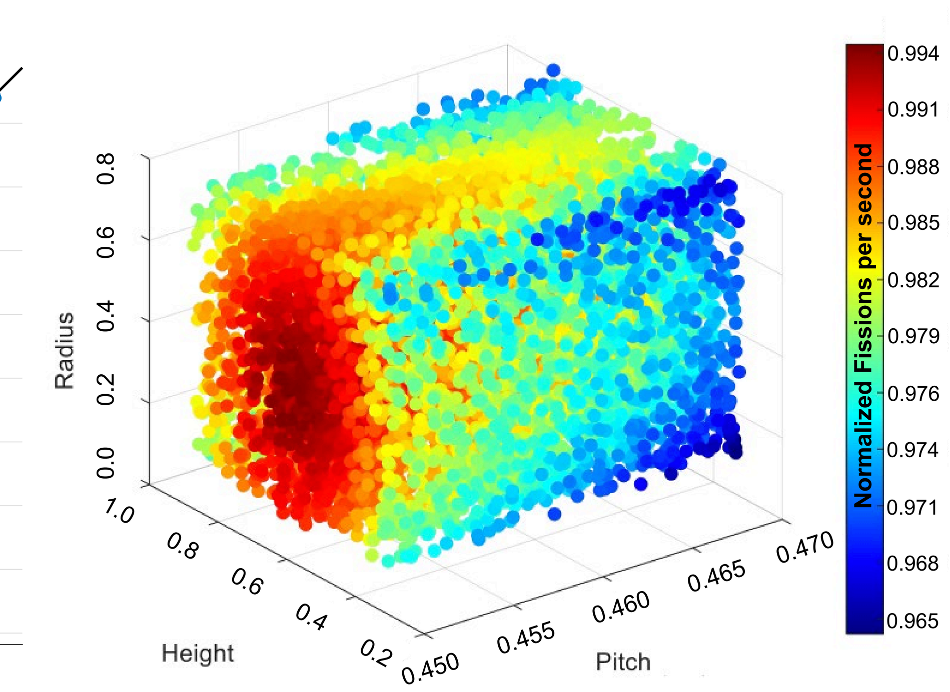
The newly created surrogate model is then optimized. The algorithm is an advancement on prediction-based exploration surrogate optimization.

The advantages to SPESO over previous methods are

- The ability to take advantage of parallel computing,
- A probabilistic quantification of the quality of the results, and
- More expansive search of the parameter space







Acknowledgments

ORNL's Mo-99 program is supported by the US Department of Energy National Nuclear Security Administration's Material Management & Minimization Office.

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References

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2. N. Nelson, et al., "A Comparison of DAKOTA Algorithms for the Optimization of an Accelerator Driven Subcritical Assembly," pending submission.
3. C. Ball, et al., "Introduction of the Stochastic Prediction-Based Exploration Surrogate Optimization (SPESO) and Application to NioWave UTA-2 Nuclear System," pending submission.

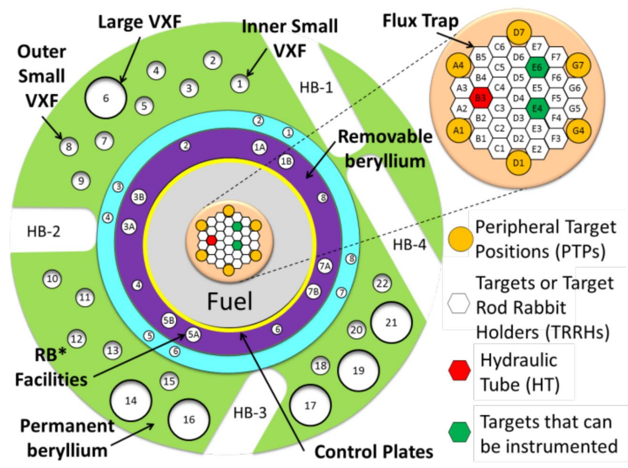
Mo-99 Target Design and Irradiation Testing in the High Flux Isotope Reactor

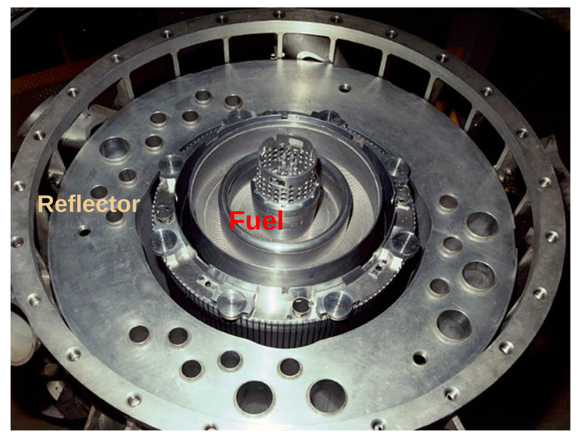
Nolan Goth, Jorge Navarro, Jim Nash, Eliott Fountain, and Chris Bryan

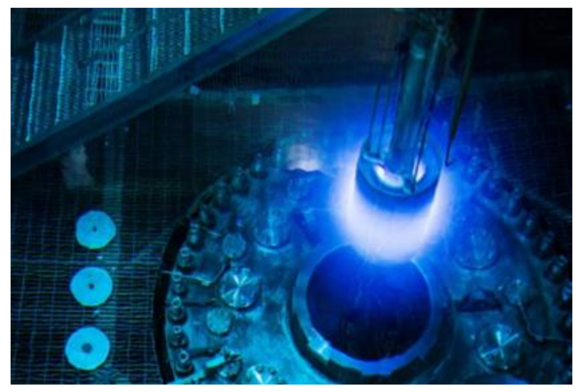
^{99}Mo Production

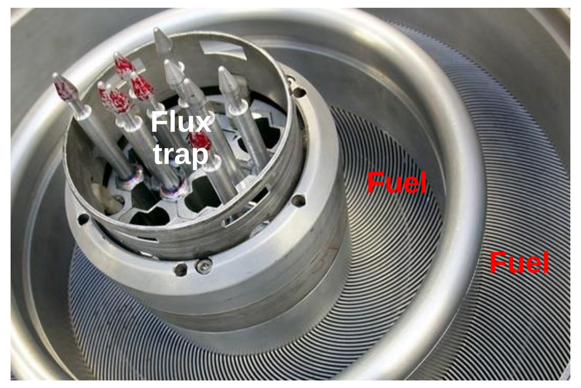
- Fueled target irradiations address the chicken and egg paradox related to reactor licensing and fuel qualification.
- ORNL's High Flux Isotope Reactor provides the neutrons for initial studies to assist industrial partners looking to design and build their own isotope production capabilities.

- Pressurized, flux-trap type, light water cooled and moderated.
- HEU fuel (U_3O_8 dispersed in aluminum) with involute plate geometry.
- Operates at a steady state 85 MW.
- Experiments in flux trap or beryllium reflector.
- 24 days/cycle, 6–7 cycles/year.





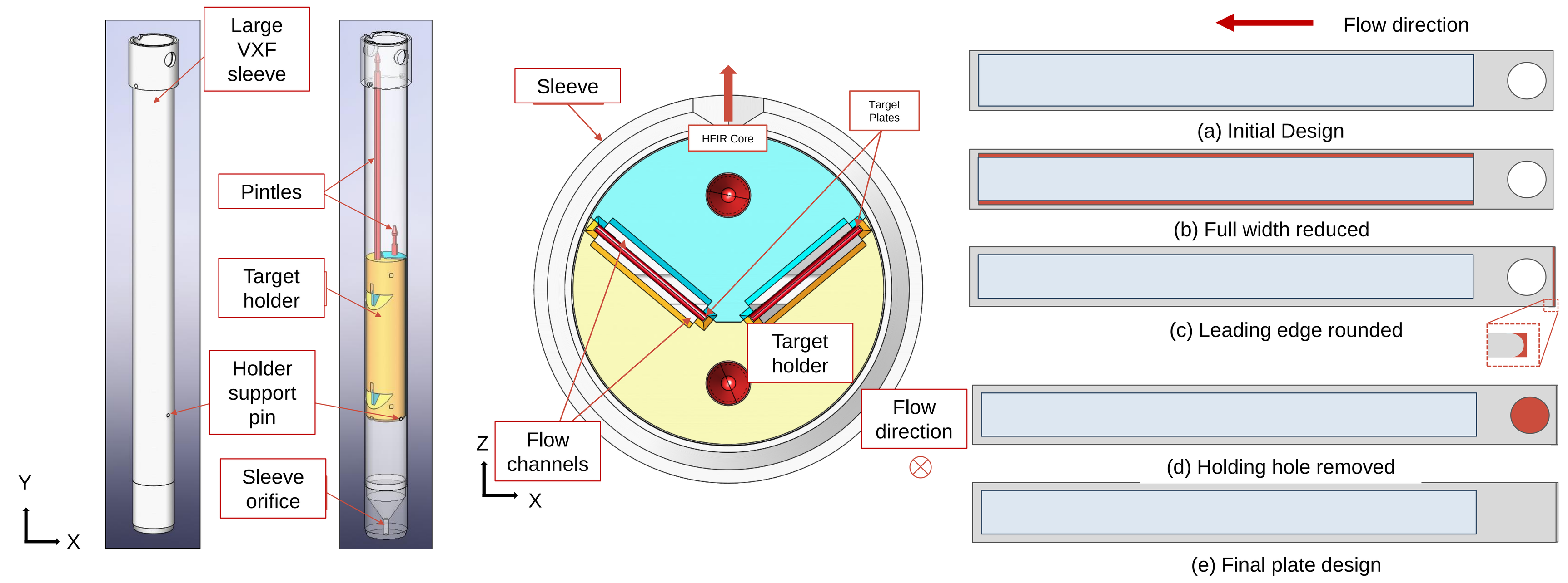




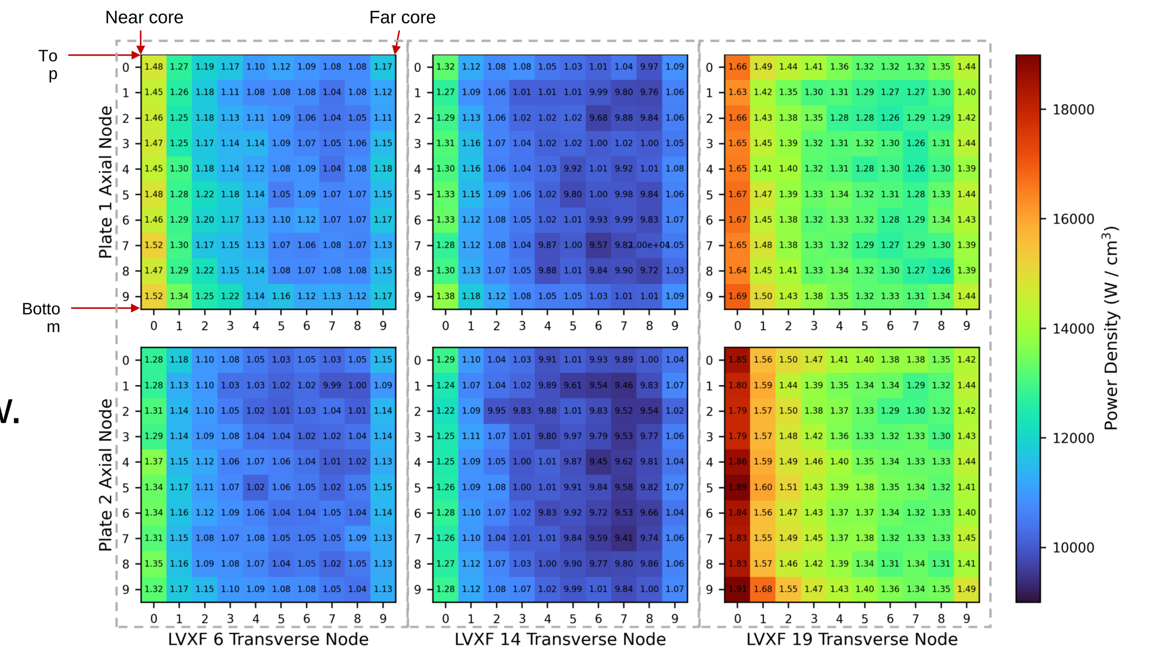
Parameter	Value
Inlet temperature	48.9°C (120°F)
Inlet pressure	3.347×10^6 Pa (485.5 psi)
Outlet pressure	2.537×10^6 Pa (368 psi)
Total pressure drop	8.101×10^5 Pa (117.5 psi)
Reactor power	85 MW_{th}
Peak thermal flux	2.1×10^{15} n/cm²/s
Peak fast flux	1.1×10^{15} n/cm²/s

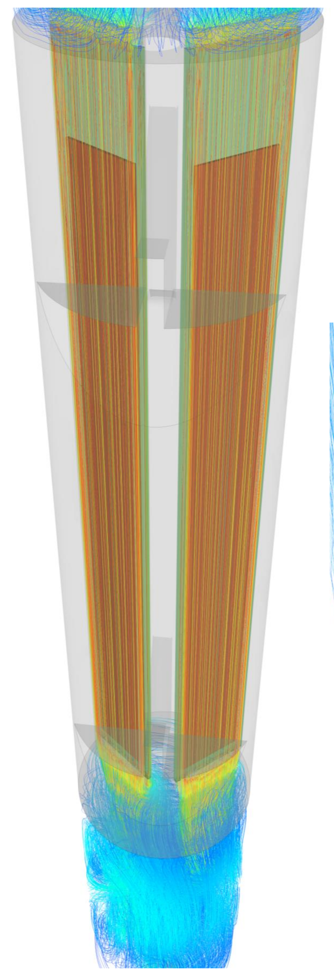
Plate-Type Targets

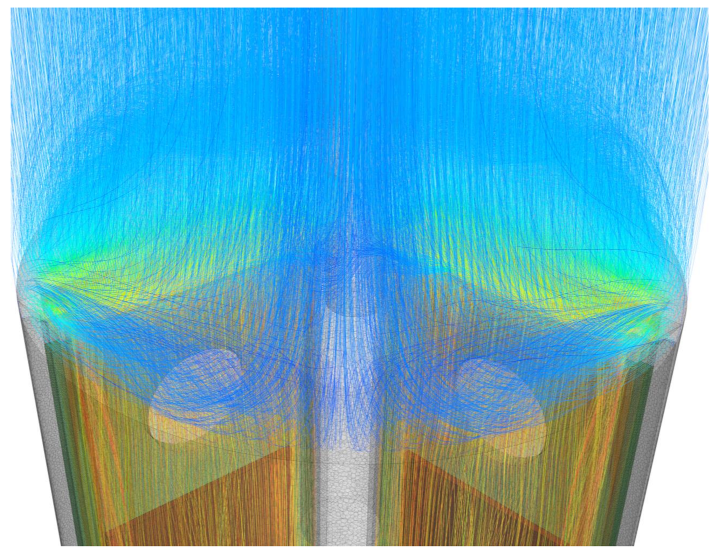
- Some partners are considering a plate-type target design.
- ORNL has completed initial scaling studies, reduced order thermall-hydraulic design, MCNP heat generation and burn calculations, and steady and transient CFD simulations on this geometry.

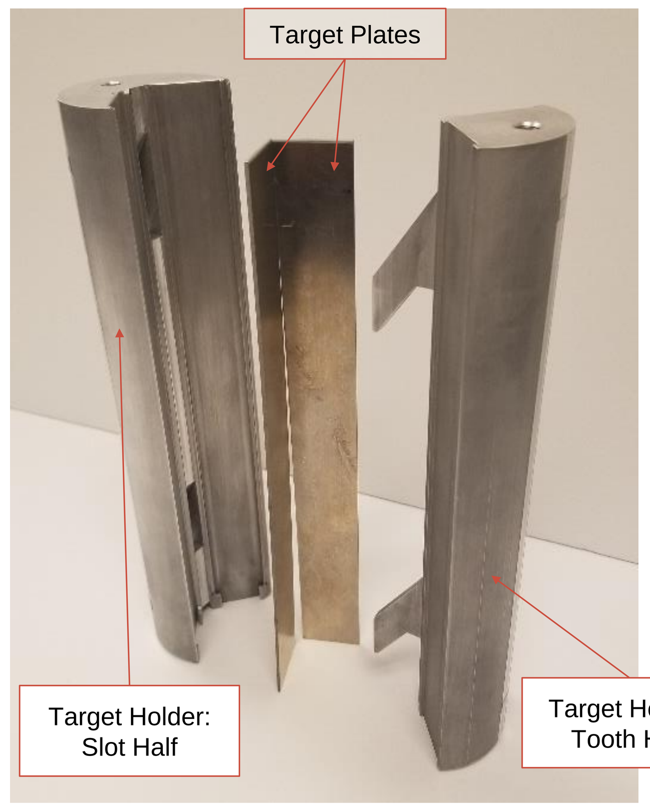


- A set of bounding analyses were made to quantify the maximum plate enrichment and target configuration that could be sufficient cooled within a large vertical ex-core experimental facility.
- It was determined that an enrichment of 19.75% ^{235}U, the HALEU threshold, would generate 127 kW of power and could be cooled during normal operation and all abnormal events using less than 2.2 L/s of reactor coolant water.
- The primary initial thermal concern was cladding surface temperatures in excess of the fluid saturation temperature, but these were never reached due to narrow coolant channels with high local coolant velocities of 15 m/s.
- Aluminum oxide spallation of the cladding was the limiting factor, as the spallation limit would be reached before the completion of one HFIR irradiation cycle
- A novel two-piece target holder was designed to simplify retrieval and disassembly. It allows the plate to be free with no weld or pinned condition, but instead simply supported while under flow.



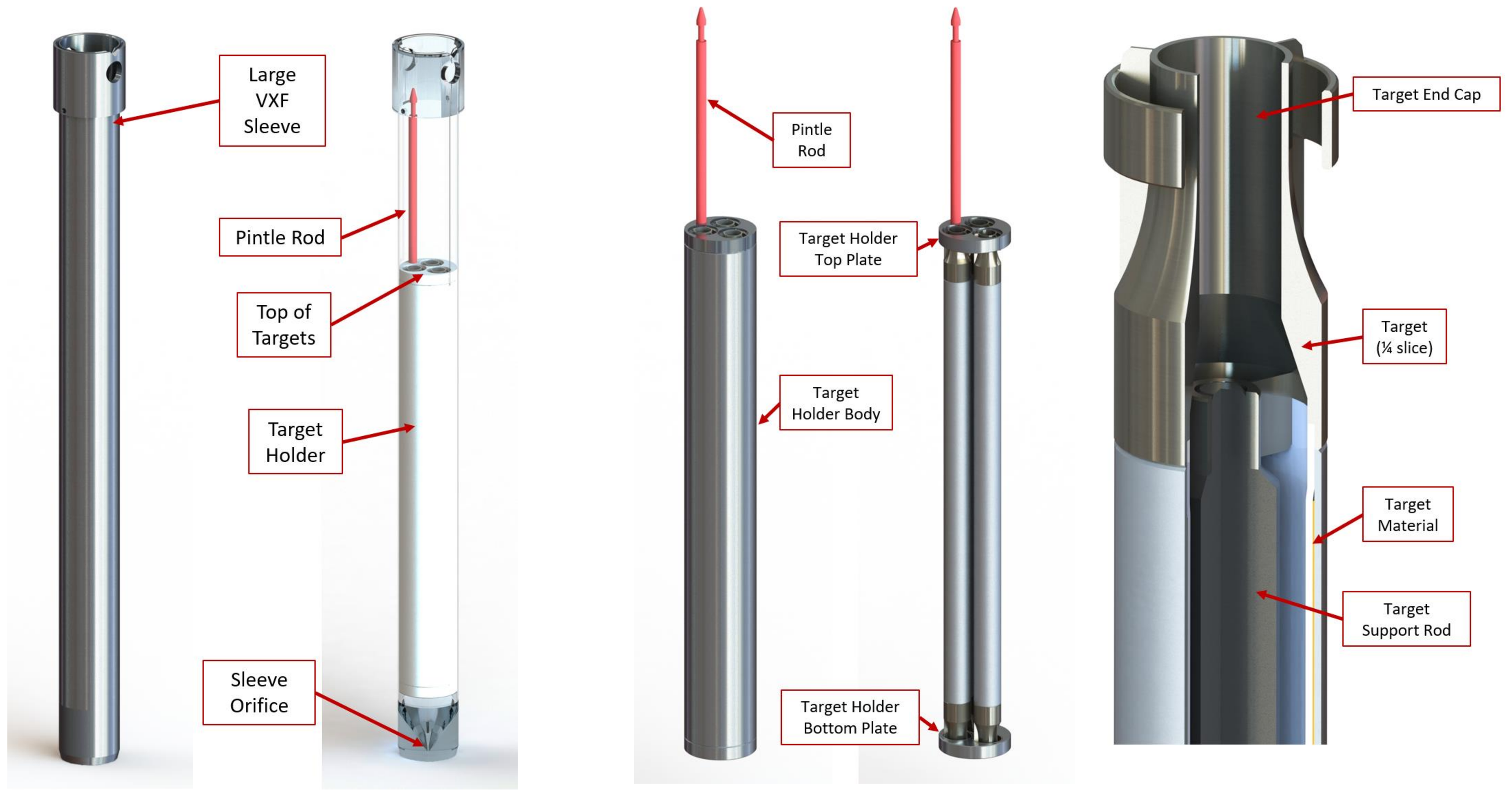




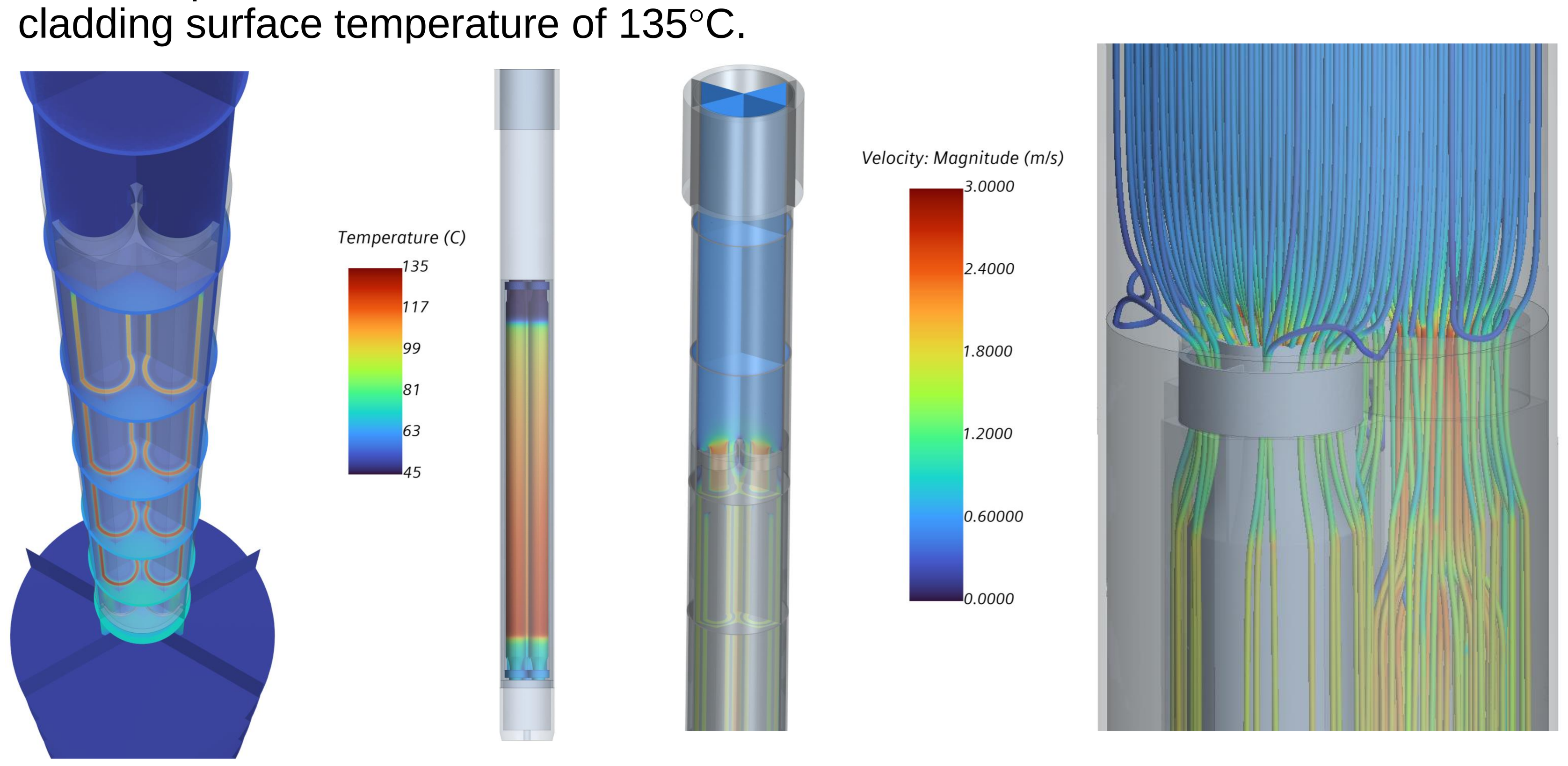


Annular-Type Targets

- Others are considering an annular-type target design. A HFIR irradiation position can support up to three of these annular targets within a single sleeve.



- Thermal and flow fields for a three-target configuration producing 90 kW of power with a required 2.1 L/s of reactor coolant water to maintain a maximum wetted cladding surface temperature of 135°C.



- Thermal and flow fields for a single-target configuration producing 30 kW of power with a required 0.7 L/s of reactor coolant water. A simpler experimental design for first-of-a-kind fuel forms can often yield increased safety margins and reduce the source term.