Flowing salt loop for the MIT Reactor, TRISO Fuel Safeguards and Irradiated Graphite Disposal

C. W. Forsberg

Massachusetts Institute of Technology

Molten Salt Reactor Campaign Annual Review
Pacific Northwest National Laboratory
Discovery Hall 650 Horn Rapids Rd,
Richland, WA 99354
2:25-2:50 PM, April 23, 2025

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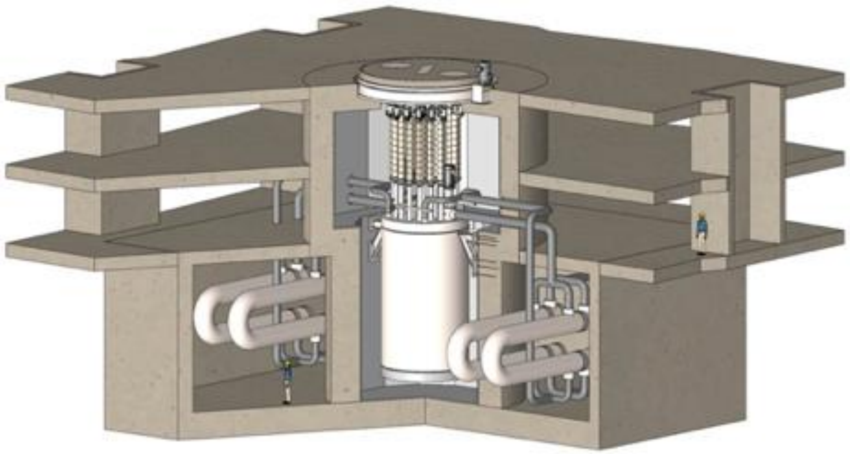
Customers: 3 Salt Reactors within the Next Several Years

Fluoride salt cooled Triso Solid Fuel

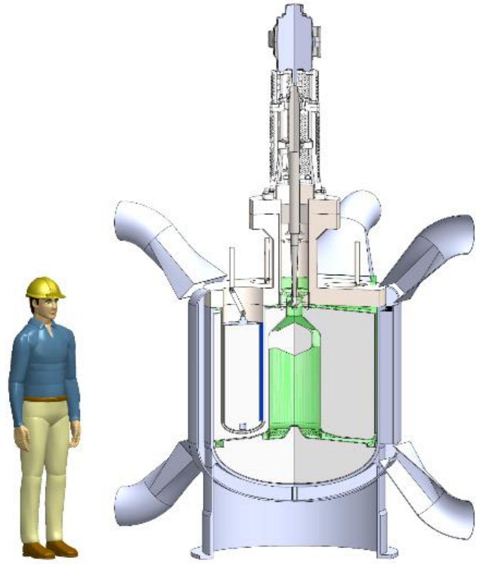


Kairos Power
35 MWt FHR, 2027
Hermes, Oak Ridge

Fluoride salt with Dissolved Fuel

Abilene Christian University / Natura Resources 1-MWt Molten Salt Research Reactor

Chloride salt with Dissolved Fuel



TerraPower/Southern
200 kW Molten Chloride Reactor Experiment, INL

C. W. Forsberg. Market Basis for Salt-Cooled Dispatchable Heat, Hydrogen, and Electricity with Assured Peak Power Capacity, *Nuclear Technology*, 206 (11), 1659-1685, November 2020. https://doi.org/10.1080/00295450.2020.1743628

MIT Reactor Flowing Salt Loop (IRP)

Why need flowing salt loops with neutron irradiation

MIT reactor salt loop

Lessons learned to accelerate future salt loops at other universities and National Laboratories

Massachusetts Institute of Technology

NC STATE UNIVERSITY

Berkeley UNIVERSITY OF CALIFORNIA

OAK RIDGE National Laboratory

Why Build Flowing Salt Test Loops?

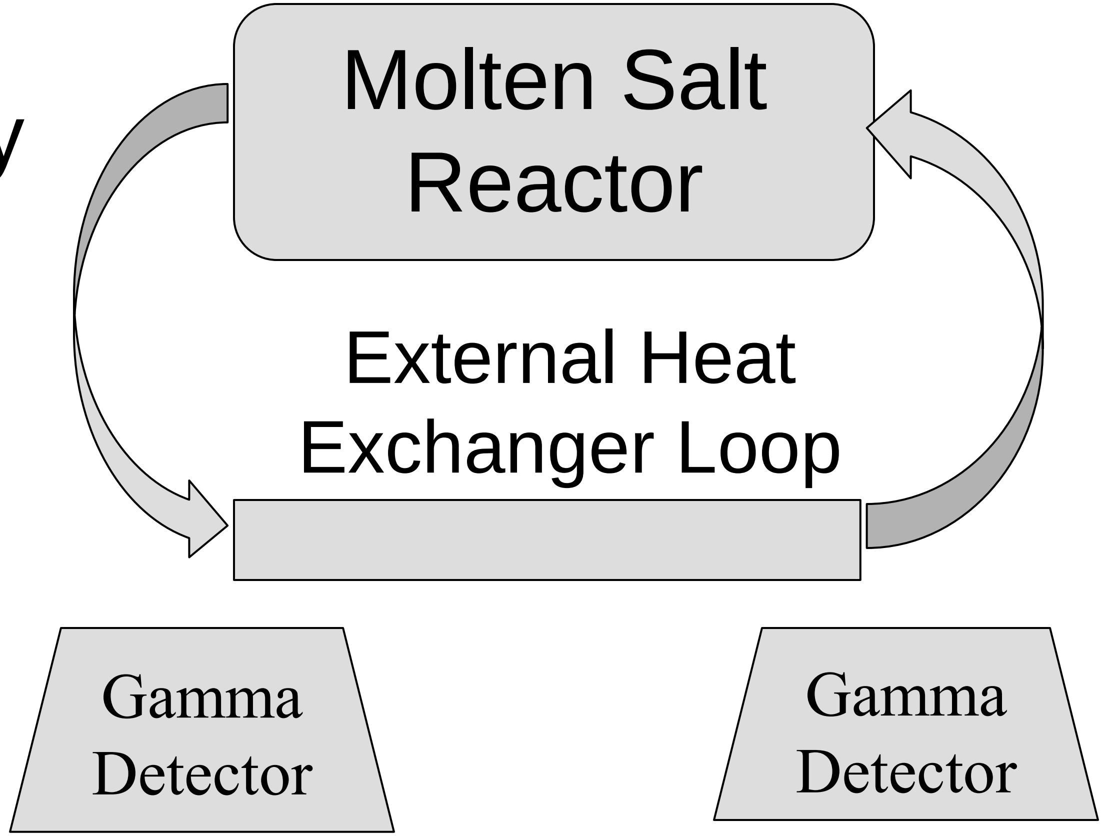
Require Development and Testing with Irradiated Flowing Salt to Provide Short-lived Radionuclides

- Testing instrumentation
- Understanding fission product transport and plate out
- Test tritium control systems
- Understand / Test fission gas removal
- Corrosion testing
- Measuring fissile materials production
- Safeguards

C. Forsberg, D. Carpenter, A. I. Hawari, R. O. Scarlat and K. Robb, Applications of Flowing Molten Salt Loops with Neutron Irradiation, *Transactions American Nuclear Society Winter Meeting*, Orlando, Florida, November 17-21, 2024.

Salt Reactors May Enable a Revolution in Instrumentation Using Gamma Rays to Measure Many Radionuclides

- Velocity and mass flow by decay of short-lived radionuclides
- Total burnup (^{137}Cs)
- Fissile materials production rate
  - U-238 + neutron → Np-239
  - Np-239 decays to Pu-239
- Measure Xenon in salt—efficiency of off-gas removal system



Can Measure Flow with 11 Second F-20, 1633 KeV

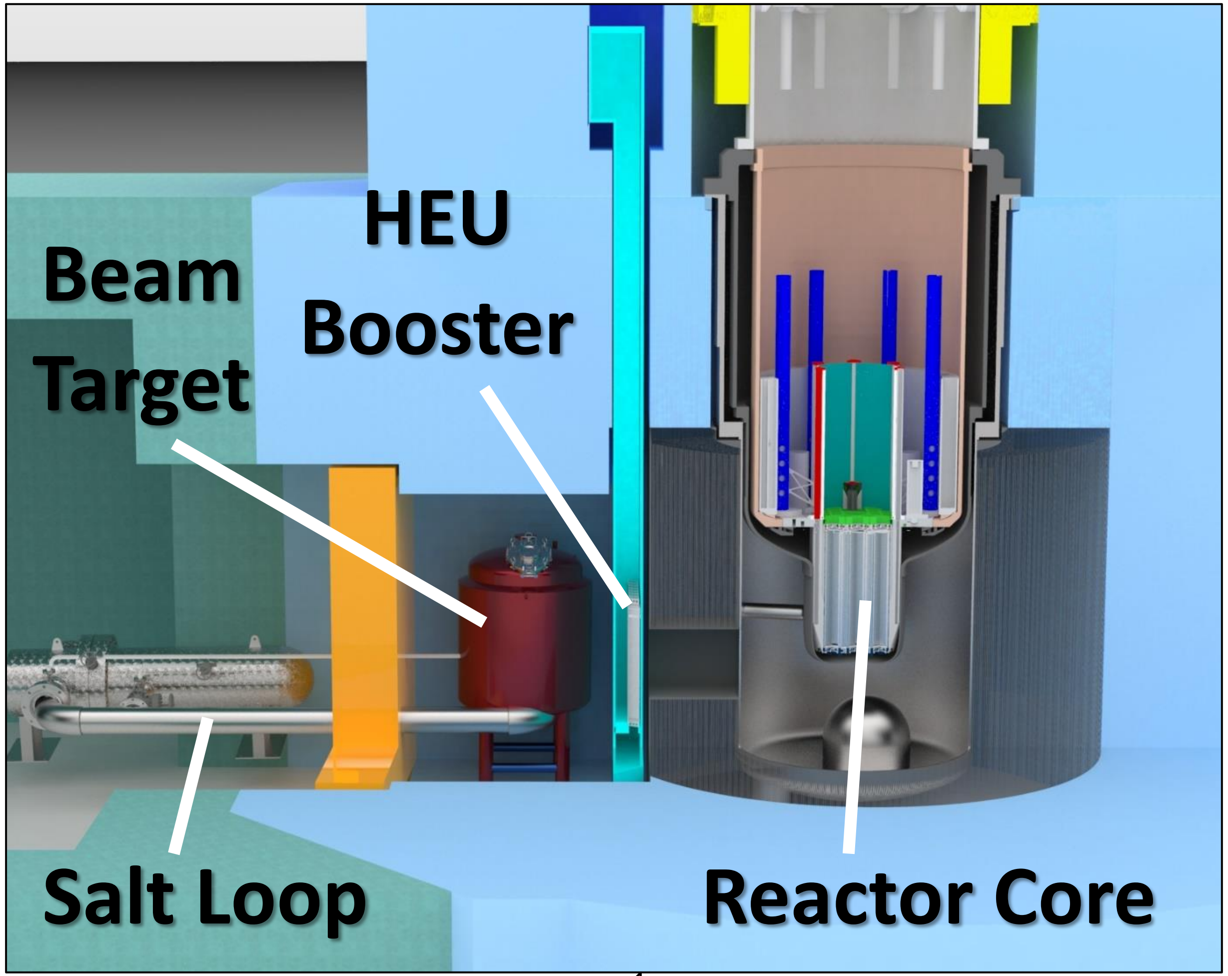
C. Forsberg et. al. Measuring Flow Rates and Compositions in Salt Reactors with Gamma Spectroscopy, *Transactions of the American Nuclear Society*, American Nuclear Society Annual Meeting, Las Vegas, June 16-19, 2024

MIT Has Initiated the Design and Construction of a Flowing Salt Loop at MIT Reactor: Operational 2025

- **Goal I is <u>forced circulation salt loop</u> for the MIT reactor (6 MWt)**
  - Neutron & gamma irradiation
  - Heated and cooled
  - Fully instrumented
- **Goal II is to transfer lessons learned to accelerate loop construction at other university and DOE reactors**
- **Partners: U.C. Berkeley, North Carolina State University and Oak Ridge National Laboratory**

MIT Reactor Design Enables Loop with Fissile Material

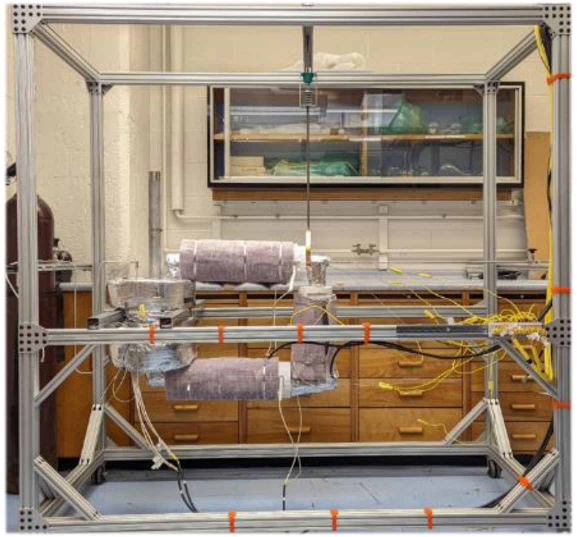
- 6 MWt reactor, 24/7 operation, 70 day cycle
- **Loop outside the reactor tank that partly decouples reactor neutronics from loop**
- Avoids large neutronic feedback effects and enables use of fissile materials in loop
- Can adjust fissile and lithium-6 content of salt to obtain desired salt behavior



Neutrons

Much Work Required Before Operating Loops

Lowering CVD SiC-coated graphite crucible into the furnace



High temperature dry test facility for Insulation, Heaters and Flanges

Salt Pump System Testing

Modifying Interior of Hot Cell Next to Reactor for Salt Flow Loop

Two Loops Have Been Designed and Procured

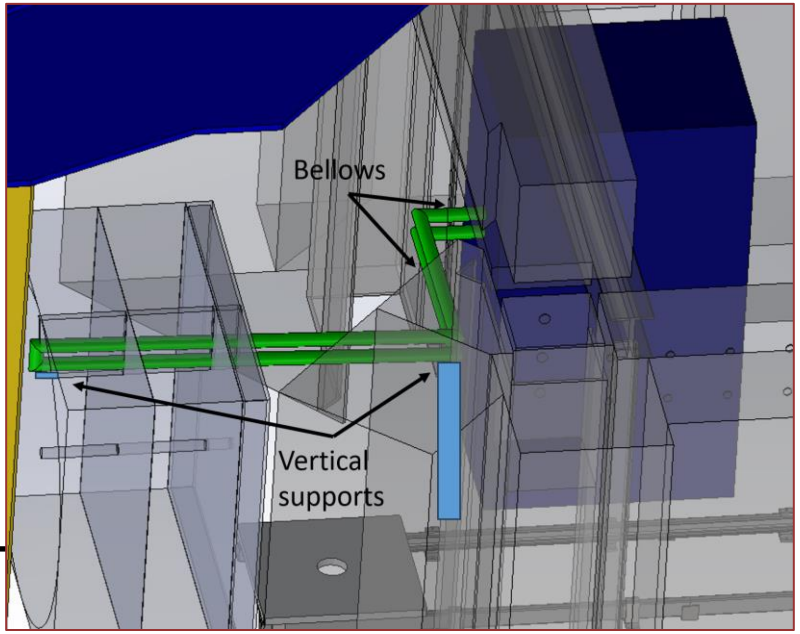
Non-radioactive full loop with:

- variable temperatures
- forced circulation using flinak salt
- gain practical O&M experience
- integrate UCB sensors

Second reactor-coupled loop with:

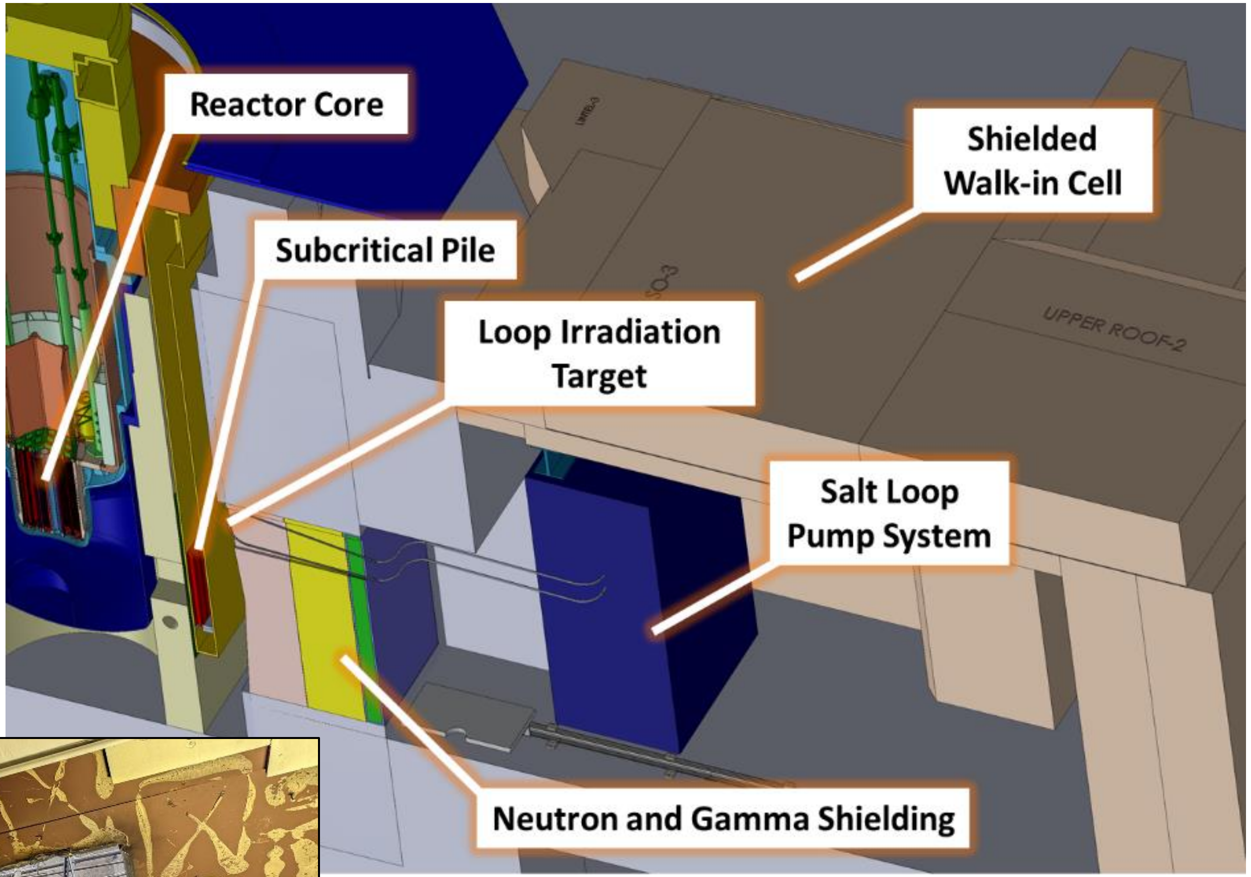
- flibe salt
- off-gas monitoring
- activity monitoring

Use this to progress to successful irradiation loop



Expect Loop Operation in June-July Timeframe

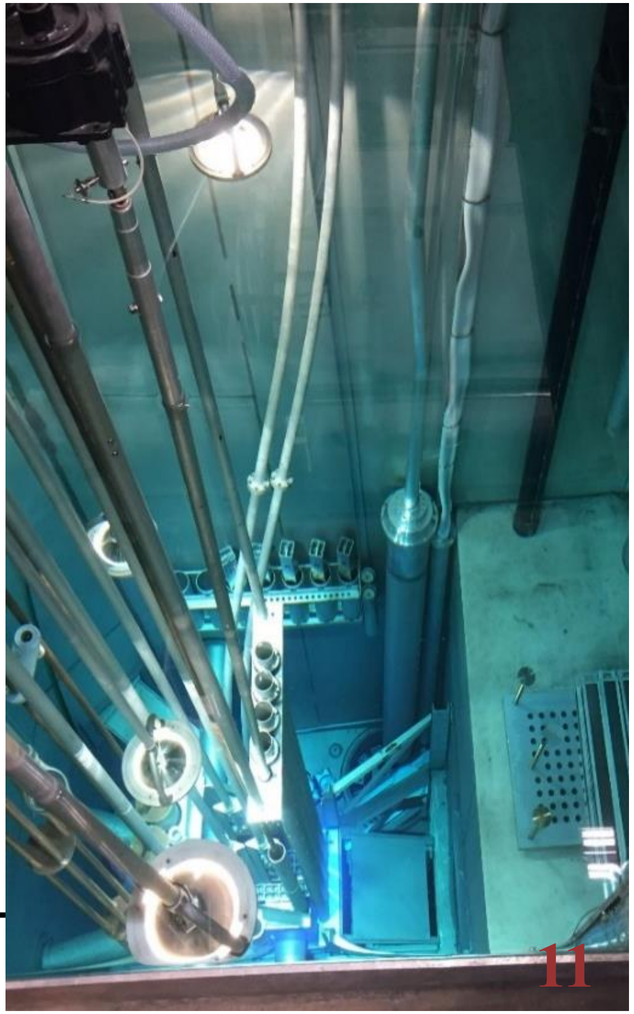
- MIT Reactor had an 18 month unplanned outage
  - Delayed all experiments
  - Same staff involved in restart as with experiments
- Remaining work to fully remodel hot cell next to the reactor that will contain the loop



Hot Cell Roof Hatch

North Caroline State University Built Off-Gas Measuring System with Off-Gas from Pot of Molten Salt with Uranium Irradiated at NCSU Pulstar Reactor

- MSRs generate gaseous fission products and noble metal aerosols that go to the off gas system—many very short lived
- Noble metals may plate out on heat exchangers / graphite or into off-gas system
- Need real off gas for realistic measurement and modeling of system behavior



Two Lessons Learned Workshops Were Conducted

Transfer Experience Between Research Groups: Agenda 2024 Workshop

1. MIT Lessons Learned in Salt Irradiations (D. Carpenter, MIT)
2. U.C. Berkeley Lessons Learned (R. Scarlat (UCB)
3. Lessons Learned From Building and Running a Thermal Convection Loop, including Purifying the Salt to Fill It (S. Raiman and C. Shamberger, U. of Michigan)
4. Lessons Learned from Operating the Pilot-Scale Fluoride Molten Salt Facility FLUSTFA (A. Burak and X. Sun (U. of Michigan)
5. Chloride salt loop experience (J. Zhang, Virginia Tech)
6. Operation of Brazed Silicon Carbide Natural Convection Loop with Sodium Magnesium Chloride (T. Kooyman (NAAREA)
7. Lessons Learned During UCl_3-NaC Fuel Salt Capsule Irradiations (T. Karlsson and M. Kropp, INL)
8. ORNL Recent Lessons Learned (K. Robb, ORNL)
9. Lessons learned on molten salt chemistry and pyro processing at INL (G. Cao, INL)

10, Lessons Learned at ACU developing a MSR (T. Head & K. Pamplin, ACU)

C. Forsberg, D. M. Carpenter, R. O. Scarlat, R. Kevin, and A. I. Hawari. Lessons Learned In How to Conduct Loop and Irradiated Salt Experiments: Workshop II, *Transactions American Nuclear Society Summer Meeting*, Chicago, Illinois, June 15-18, 2025.

Examples of Lessons Learned

- **Keep salt hot until it is out of the irradiation zone**. Frozen salt under irradiation enables radiolysis of free fluorine and other species that will not form at higher temperatures.
- **Temperature is not just a number**. Care must be taken to assure no freezing of salt. Test systems in non-radioactive environment
- **Beryllium safety requires planning in advance to avoid major impacts on schedule and costs**. Require fast efficient methods to monitor beryllium contamination.

1. C. Forsberg, D. M. Carpenter, R. O. Scarlat, R. Kevin, and A. I. Hawari. Lessons Learned In How to Conduct Loop and Irradiated Salt Experiments: Workshop II, *Transactions American Nuclear Society Summer Meeting*, Chicago, Illinois, June 15-18, 2025.
2. C. W. Forsberg, D. M. Carpenter, R. O. Scarlat, R. Kevin and A. I. Hawari, Lessons Learned In How to Conduct Irradiated Salt Experiments, *Transactions of the American Nuclear Society Annual Meeting*, Indianapolis, June 11-14, 2023.

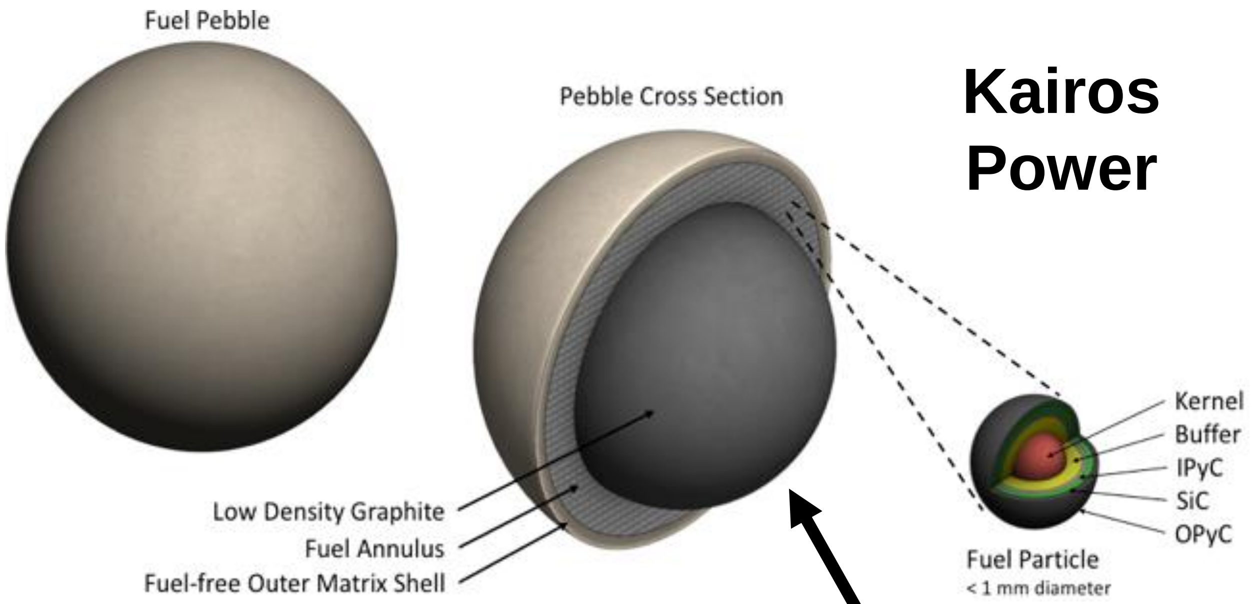
Management of Irradiated Graphite

Some Options Enable Using Graphite to Clean-up Salt or Recover Valuable Components from Salt

1. C. W. Forsberg, Roadmap of Nuclear Graphite Management Options. *24th International Nuclear Graphite Specialists Meeting (INGSM)*, Berkeley, California, September 8-12, 2024.
2. H. M. Wainright, L. Hines, K. Shirvan, C. W Forsberg, L. Snead and P. F. Peterson, Irradiated Graphite Disposal Regulations: Path Forward for Advanced Reactor Graphite. *24th International Nuclear Graphite Specialists Meeting (INGSM)*, Berkeley, California, September 8-12, 2024.
3. C. Forsberg, Roadmap of Graphite Moderator and Graphite-Matrix TRISO-Fuel Management Options, *Nuclear Technology*, **210**, 1623-1638, September 2024. https://www.tandfonline.com/doi/full/10.1080/00295450.2024.2337311

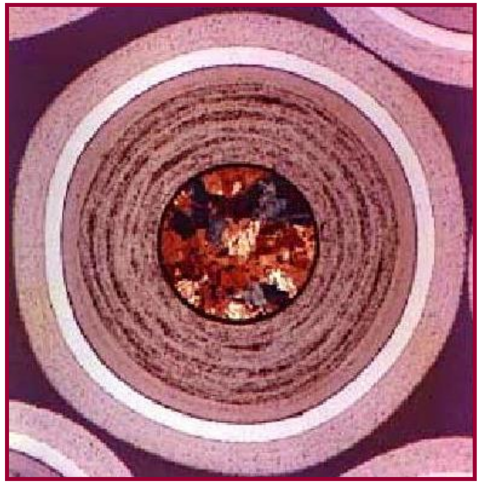
Large Incentives to Remove Graphite from Graphite-Matrix TRISO Coated-Particle Fuels for Disposal or Reprocessing

- Graphite-matrix fuels may be the largest volume of wastes to the repository
- Large economic incentives to reduce volume (eliminate graphite) to reduce cost of disposal (waste packages, repository size, etc.)



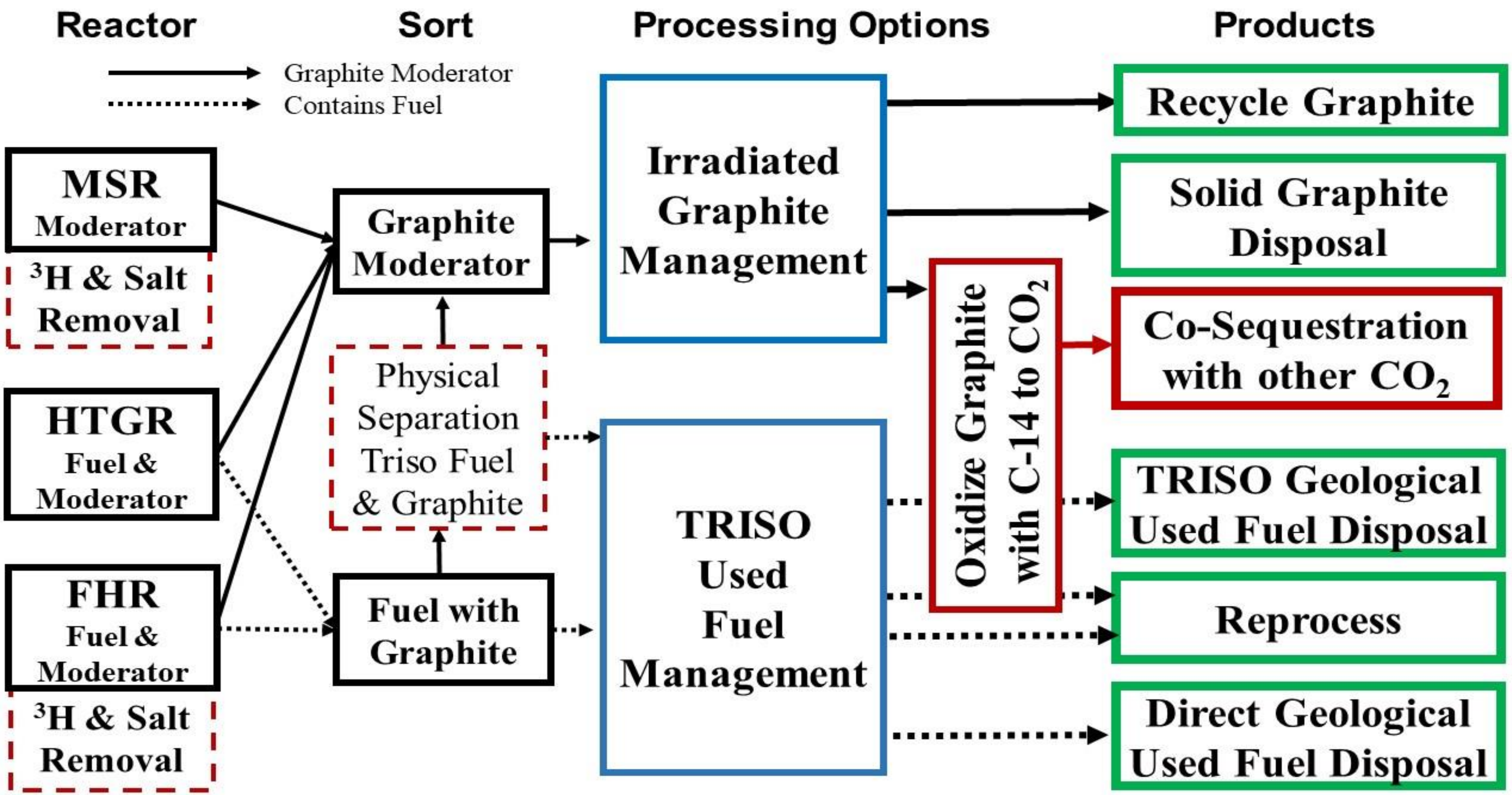
Kairos Power

Graphite



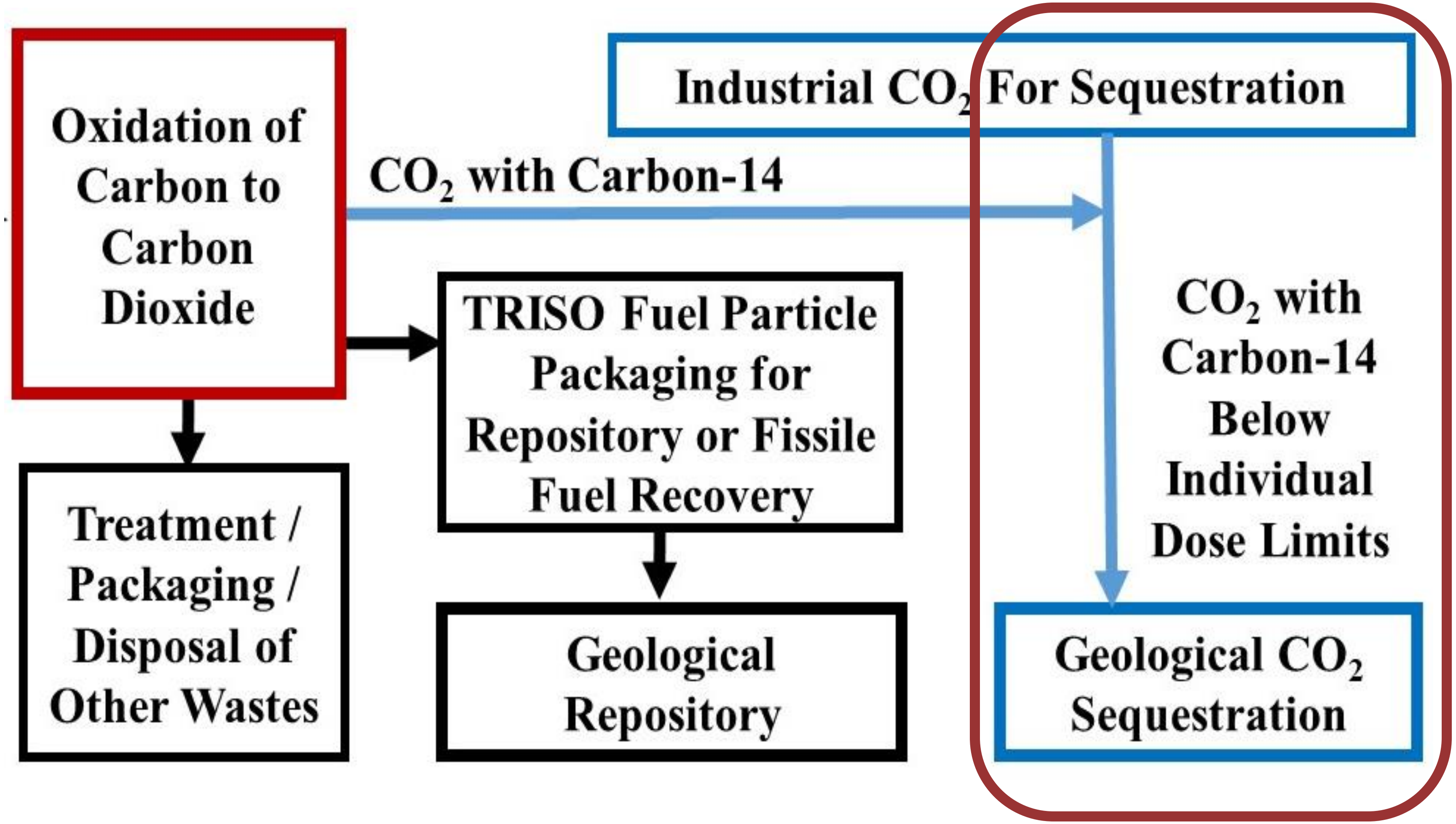
TRISO Fuel Particle

Roadmap of Major Options for Irradiated Graphite and Fuel



Low-Cost Option: Disposal By Oxidation and Co-Sequestration CO_2 with Industrial Carbon Dioxide

- Cost an order of magnitude less than alternatives
- Dilute carbon-14 to below individual radiation dose limits



Creates Option to Recover Li-7 and Other Valuable Elements or Use Graphite to as Part of In-Situ Salt Cleanup System

Safeguards for HALEU TRISO

Fresh and High-Burnup Used Nuclear Fuel

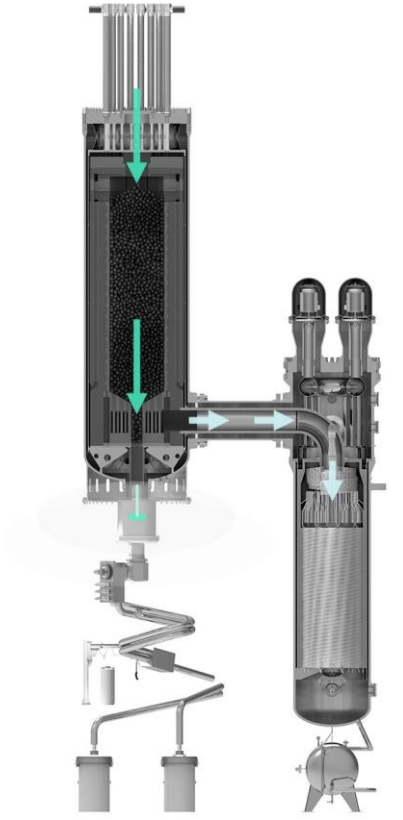
Are TRISO-Fueled Reactors the Preferred Option to Export With Minimum Safeguards (Diversion of Fissile Materials to Weapons) Concerns?

1. C. Forsberg and A. Kadak, Safeguards and Security for High-Burnup TRISO Pebble-Bed Spent Fuel and Reactors, *Nuclear Technology*, 210 (8), August 2024. https://doi.org/10.1080/00295450.2023.2298157

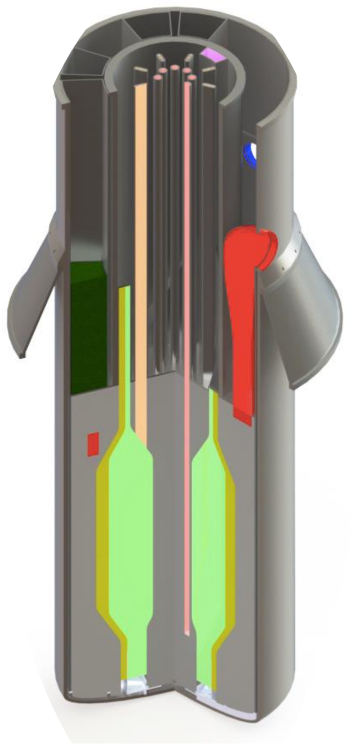
2. C. Forsberg and A. Kadak, Reducing Proliferation Risks with High-Assay Low-Enriched Uranium (HALEU) Fuels in Reactors with Coated-Particle (TRISO) Fuels, *Nuclear Technology*, April 2025. https://doi.org/10.1080/00295450.2025.2462378

Examined Safeguards for HALEU TRISO Fuel

- HALEU enables high burnups exceeding 150,000 MWd per ton
- X-Energy (HTGR) and Kairos Power (FHR) are developing pebble bed reactors with these extreme burnups in thermal-neutron spectrum reactors
- Fresh and used nuclear fuel characteristics radically different than other fuels



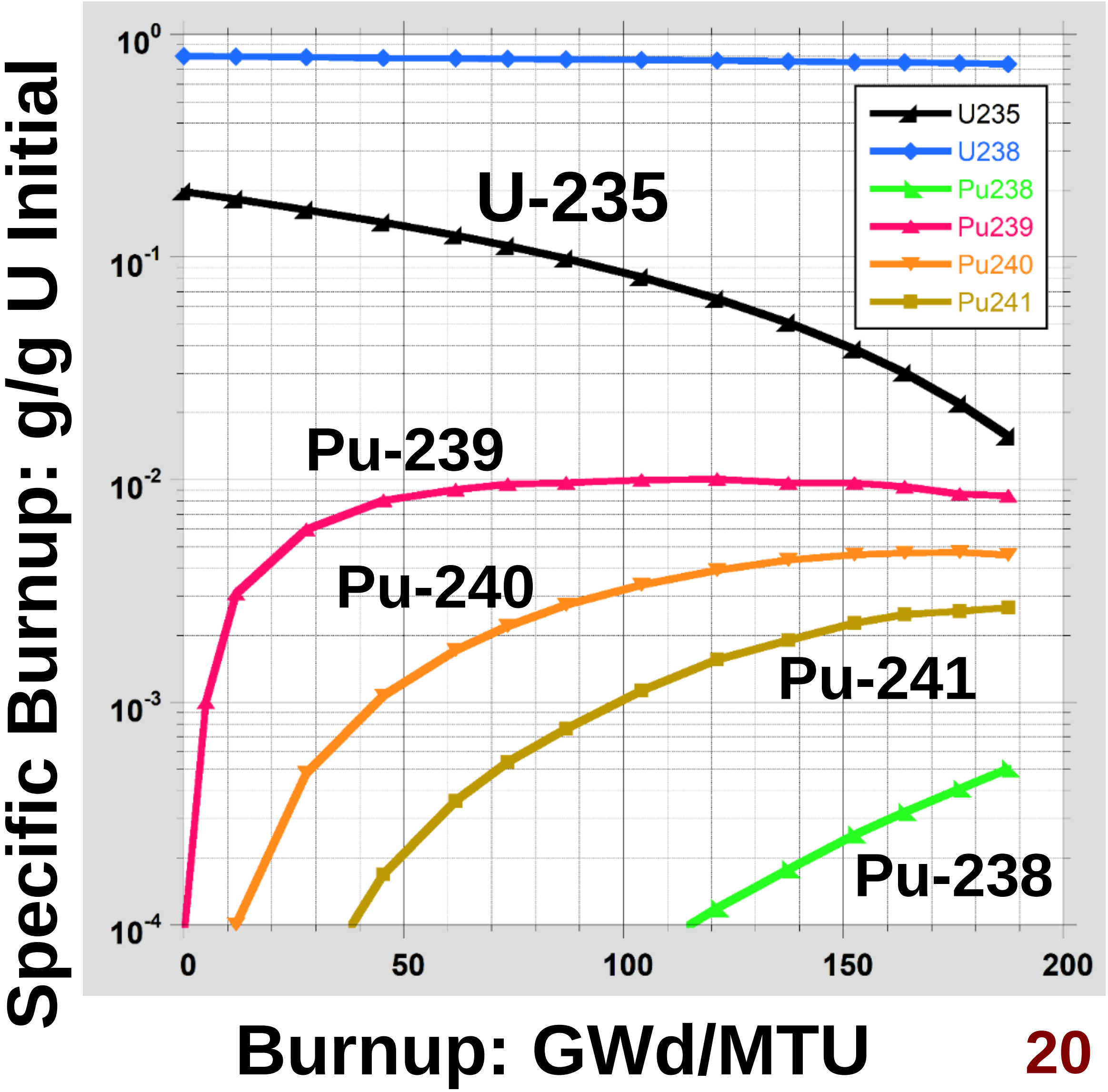
X-Energy



Kairos Power

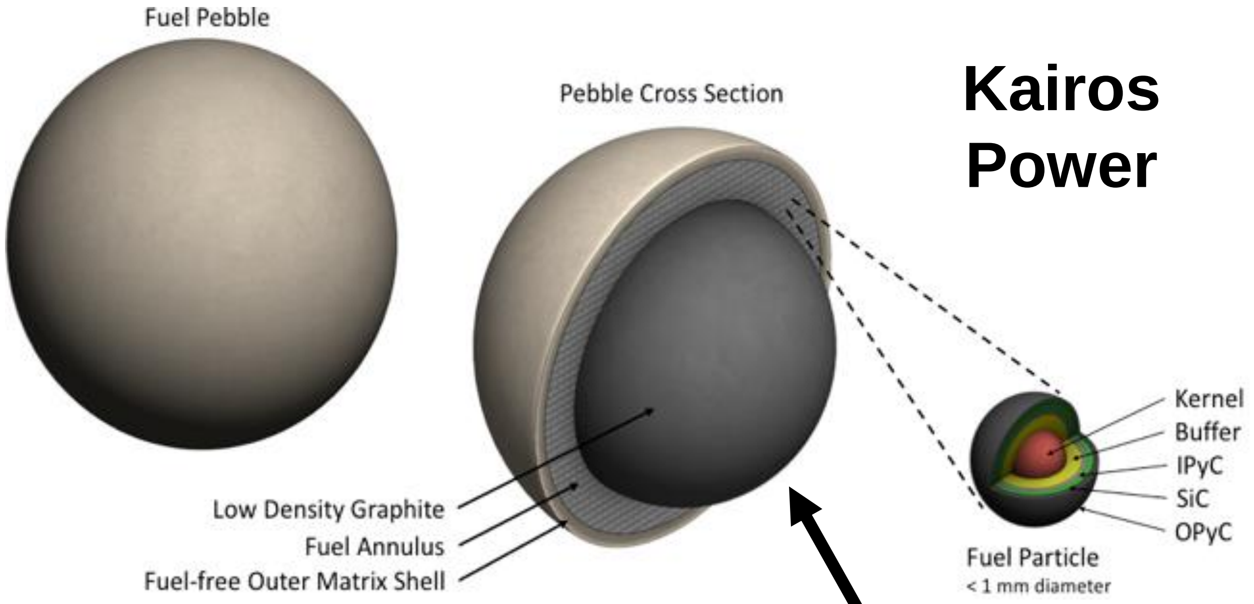
We Can Reduce Safeguards and Security for HALEU High Burnup (>150,000 MWd/T) Used TRISO Fuel Relative to LWR UNF

- Plutonium critical mass increases with buildup of other Pu isotopes
- High heat generation from Pu-238 making fabrication very difficult with requirement to cool weapon after Pu fabrication
- Very high spontaneous neutron generation
- High U-236 content, poor feed for re-enrichment U-235 to HEU
- Low fissile content UNF



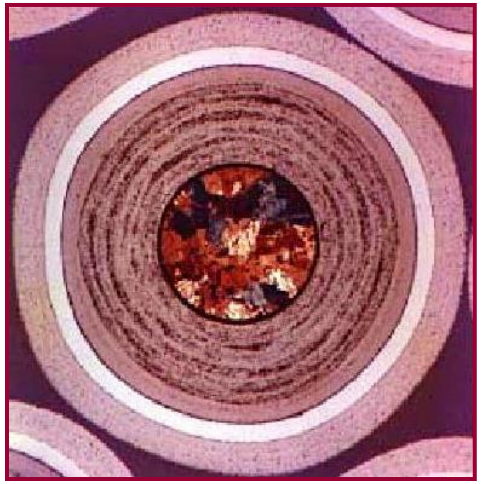
We Conclude that LWR Safeguards May be Sufficient for Fresh TRISO HALEU Fuel at the Reactor

- Uranium content extremely dilute in fuel versus LWR fuel
- 150,000 pebbles must be stolen—2 years fuel for these modular reactors
- Complex chemical processing required to recover uranium



Kairos Power

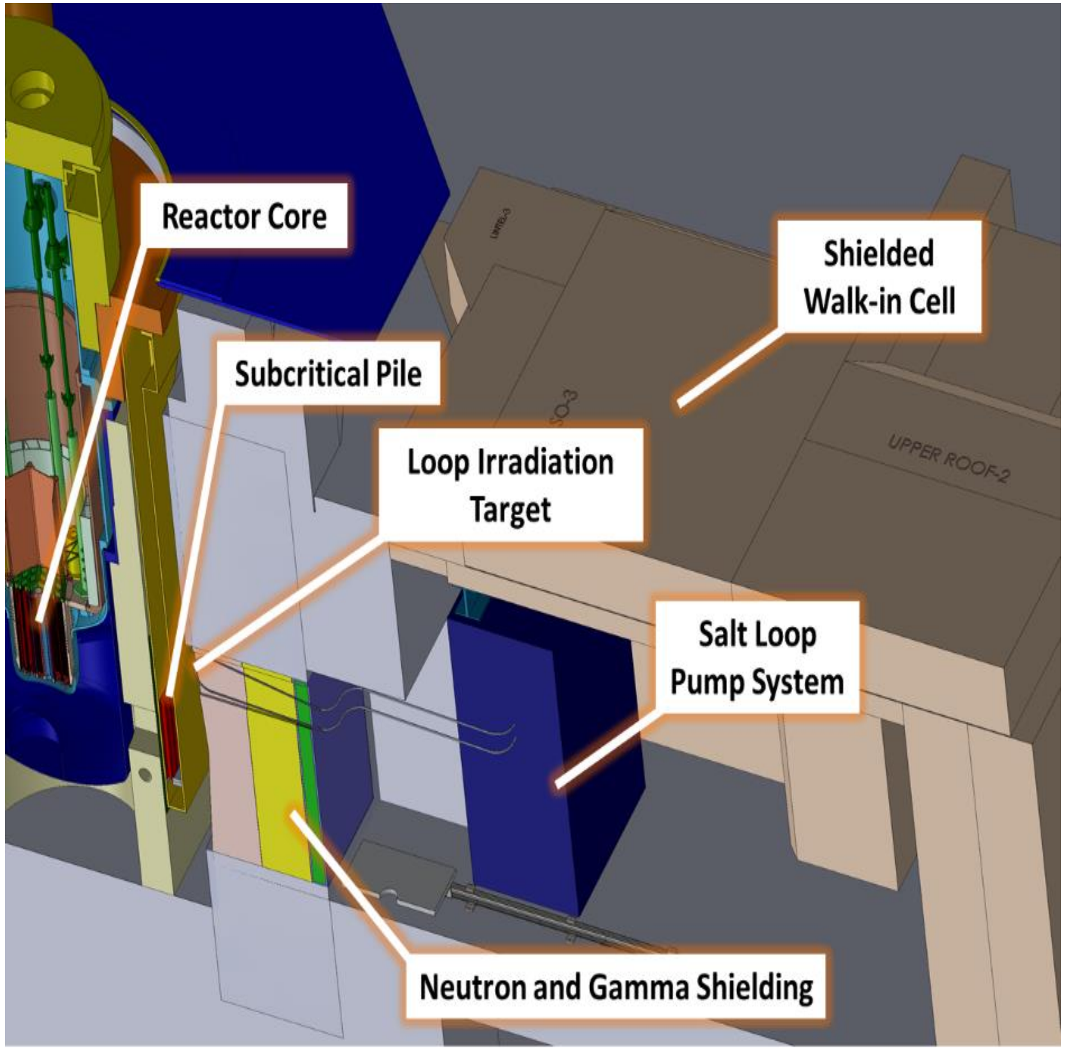
Graphite



TRISO Fuel Particle

Conclusions Going Forward

- We need multiple flowing salt loops in research and test reactors to support salt reactor development
  - Building loop at MIT, startup 2025
  - Accelerate deployment of other loops
- Potential low-cost disposal of irradiated graphite by oxidation and sequestering CO_2 underground
- Can reduce safeguards for high-burnup HALEU TRISO used fuels relative to LWR UNF



Biography: Charles Forsberg

Dr. Charles Forsberg is a principal research scientist at MIT. His current research areas include Fluoride-salt-cooled High-Temperature Reactors (FHRs), hybrid energy systems, utility-scale 100 GWh heat storage systems and nuclear biofuels systems. He is one of the three inventors of the FHR. He teaches the fuel cycle and energy systems classes. Before joining MIT, he was a Corporate Fellow at Oak Ridge National Laboratory. Earlier he worked for Bechtel Corporation and Exxon.

He is a Fellow of the American Nuclear Society (ANS), a Fellow of the American Association for the Advancement of Science, and recipient of the 2005 Robert E. Wilson Award from the American Institute of Chemical Engineers for outstanding chemical engineering contributions to nuclear energy, including his work in waste management, hydrogen production and nuclear-renewable energy futures. He received the American Nuclear Society special award for innovative nuclear reactor design and is a former Director of the ANS. Dr. Forsberg earned his bachelor's degree in chemical engineering from the University of Minnesota and his doctorate in Nuclear Engineering from MIT. He has been awarded 13 patents and published over 300 papers. . Dr. Forsberg is one of the co-inventors of electrically-conductive firebrick—an enabling technology for nuclear thermodynamic power topping cycles