INL/CON-24-76902-Revision-0

Preliminary Analysis of Advanced Reactor Spent Nuclear Fuel Storage, Transportation, and Disposal

March 2024

Changing the World's Energy Future

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Idaho National Laboratory

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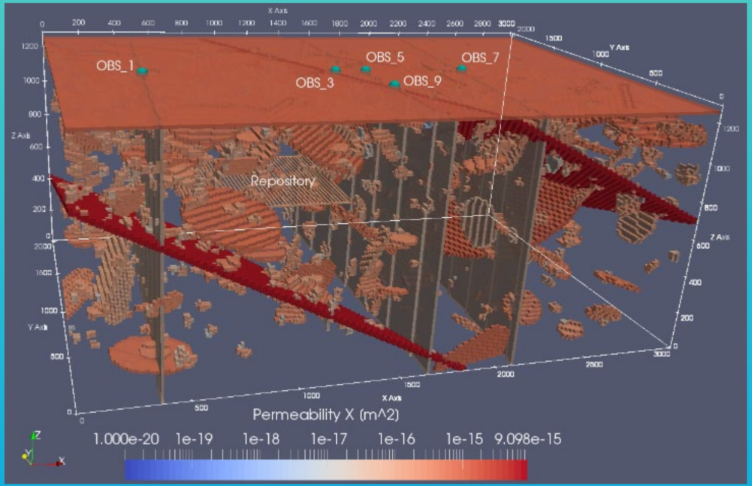
U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

Clean. Reliable. Nuclear.

Spent Fuel and Waste Science and Technology (SFWST)



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Department of Energy (DOE) is Heavily Investing in Advanced Reactors

- Advanced Reactor Demonstration Project (ARDP) (~$3.2B)
  - Advanced Reactor Demonstrations (Demos)
  - Risk Reduction for Future Demonstrations (Risk Reduction)
  - Advanced Reactor Concepts-20 (Arc-20)
- Gateway for Accelerated Innovation in Nuclear (GAIN)
- National Reactor Innovation Center (NRIC)

ARDP

NRIC National Reactor Innovation Center

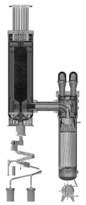
GAIN Gateway for Accelerated Innovation in Nuclear

WM SYMPOSIA

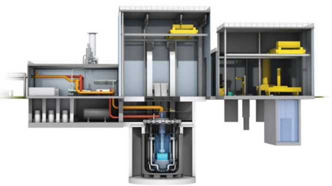
ARDP Award Winners Encompass Many Different Designs

DEMONSTRATION

Test license and build reactor in **5-7 years**



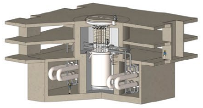
Xe-100
High-temperature gas reactor
X-ENERGY



Natrium Reactor
Sodium-cooled fast reactor + molten salt energy storage system
TERRAPOWER

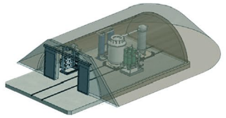
RISK REDUCTION

Solve technical, operational, and regulatory challenges to support demonstration within **10-14 years**



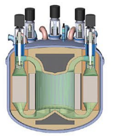
KP-FHR
Flouride salt-cooled high-temperature reactor
KAIROS POWER

eVinci
Heat pipe-cooled microreactor
WESTINGHOUSE NUCLEAR



BWXT Advanced Nuclear Reactor (BANR)
High-temperature gas-cooled microreactor
BWX TECHNOLOGIES

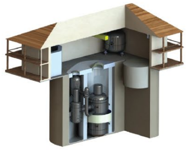
SMR-160
Advanced light-water small modular reactor
HOLTEC INTERNATIONAL



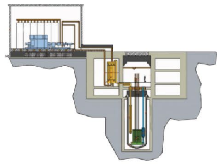
Molten Chloride Fast Reactor
SOUTHERN COMPANY

CONCEPT DEVELOPMENT

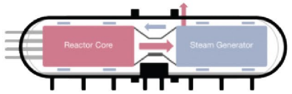
Solidify concept to mature technology for potential demonstration by **mid-2030s**



Fast Modular Reactor
GENERAL ATOMICS



Fast Modular Reactor
GENERAL ATOMICS



Horizontal Compact High-Temperature Gas Reactor
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

23-50560

Examples of Different Advanced Reactor Concepts

Water-cooled SMR		Sodium-cooled Fast Reactors		High Temperature Gas-cooled Reactors		Molten Salt Reactors		Lead-cooled Reactors		Micro Reactors	
Existing LWR characteristics		Metal fuel		TRISO fuel		Molten salt fuel		Metal fuel		Variety of fuel types	
Example: Reactor Vendor | Reactor Name											
NuScale	VOYGR	**Terra Power/GE-Hitachi**	**Natrium**	**X-energy**	**XE-100**	Terra Power	MCFR	Westing-house	Westing-house LFR	Westing-house	eVinci
Holtec	SMR-160	GE-Hitachi	PRISM	Framatome	Steam-Cycle HTGR	Terrestrial Energy	IMSR	Hydro-mine	Amphora LFR	Oklo	Aurora

SMR: small modular reactor; LWR: light water reactor; TRISO: tristructural isotropic; HTGR: High-Temperature Gas Reactor; MCFR: Molten Chloride Fast Reactor; IMSR: Integral Molten Salt Reactor; LFR: lead-cooled fast reactor

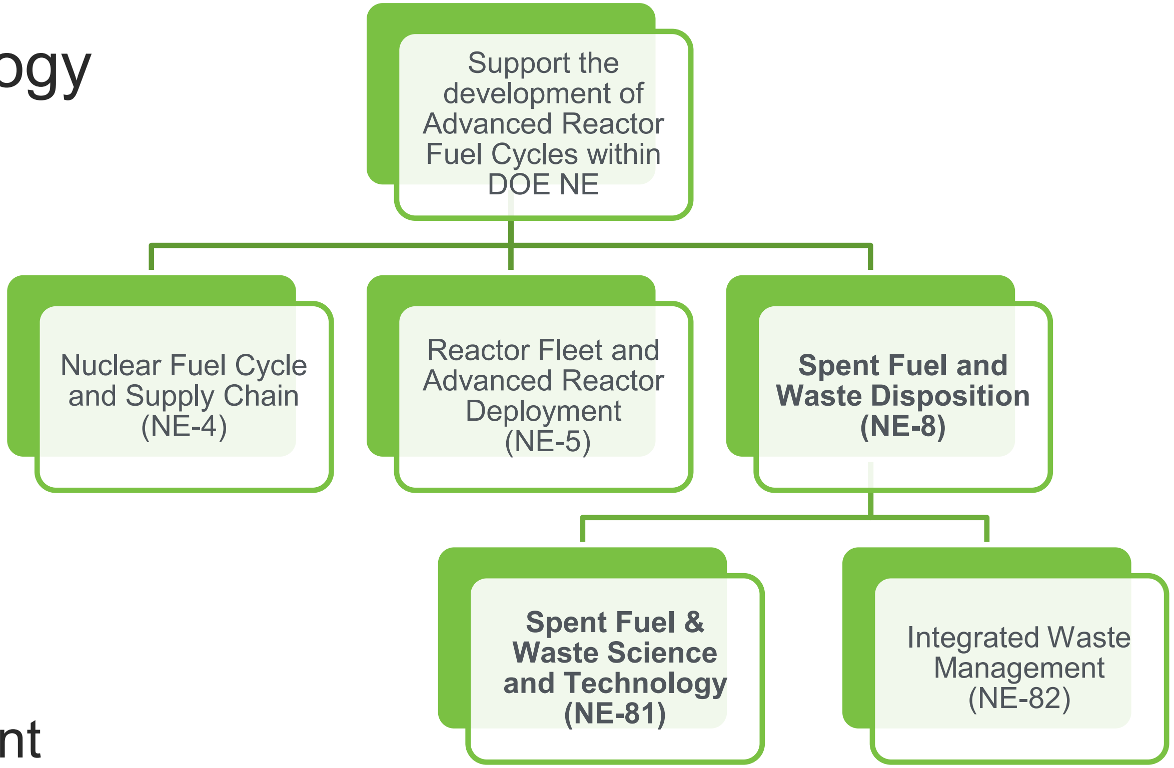
How will the Spent Nuclear Fuel (SNF) from advanced reactors be managed?

Spent Fuel and Waste Science and Technology

- Advanced Reactor SNF and Waste Streams: Strategies for the back-end of the nuclear fuel cycle
- Characterization and Packaging Options for Advanced Reactor SNF[1]
- Back-End Management of Advanced Reactors (BEMAR)

▪ Integrated Waste Management

- Advanced Fuel Cycle Waste Form Management and Planning
- BEMAR

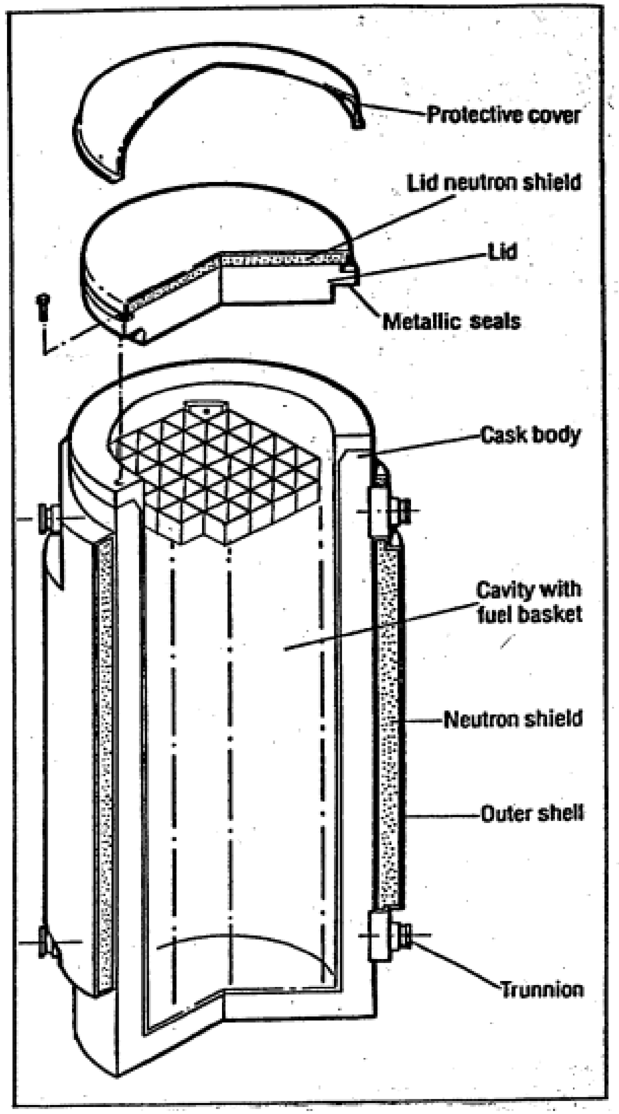


Characteristics and Packaging Options for Advanced Reactor SNF

- Examined advanced reactor fuel forms
  - TRISO
  - Metallic
  - Fuel Salt
- Characteristics
  - SNF volume and mass
  - Radiation levels over time
  - Thermal conditions over time
  - Potential radionuclide source terms
  - Chemical interactions and evolutions
- Packaging Options
  - Geometric
  - Known operational approaches and loading procedures
  - Physical and chemical considerations and conditions for the storage environments
  - As-loaded radiation, thermal, and criticality constraints

Packaging Options Focused on Existing Canister Designs

- General 37
  - Large diameter (~2 m in diameter)
  - Contains up to 37 pressurized-water reactor assemblies
- DOE Standard Canister
  - Small diameter (~45–60 cm)
  - Varying lengths (~250–400 cm)



Example of a commercial spent nuclear fuel cask

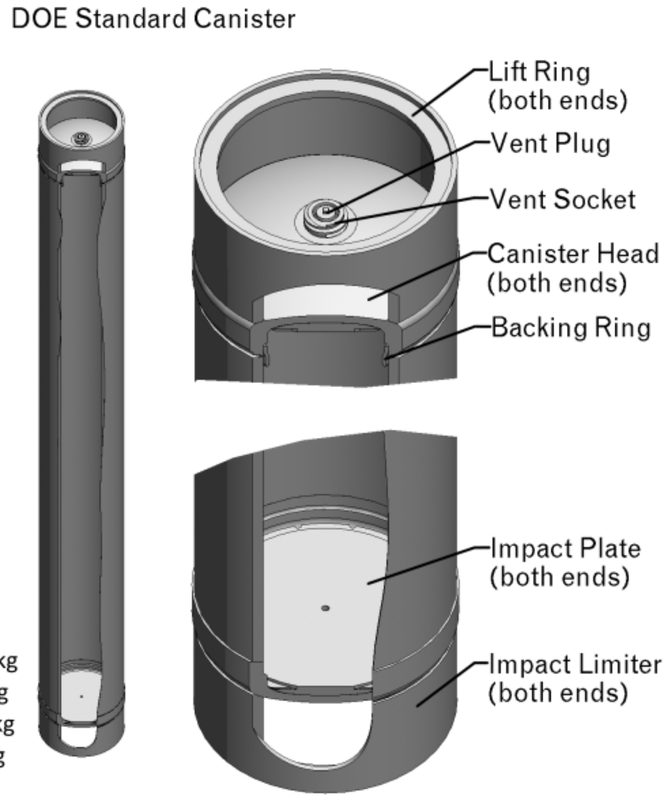
Material:
316L stainless steel

Nominal Outside Diameters:
45.7 cm ("small") or
61.0 cm ("large")

Overall Length:
3.0 m ("short") or
4.6 m ("long")

Wall Thickness:
0.95 cm for small canister
1.27 cm for large canister

Maximum Gross Weight:
small - short canister: 2,270 kg
small - long canister: 2,720 kg
large - short canister: 4,080 kg
large - long canister: 4,540 kg



Management of TRISO-based SNF in the United States

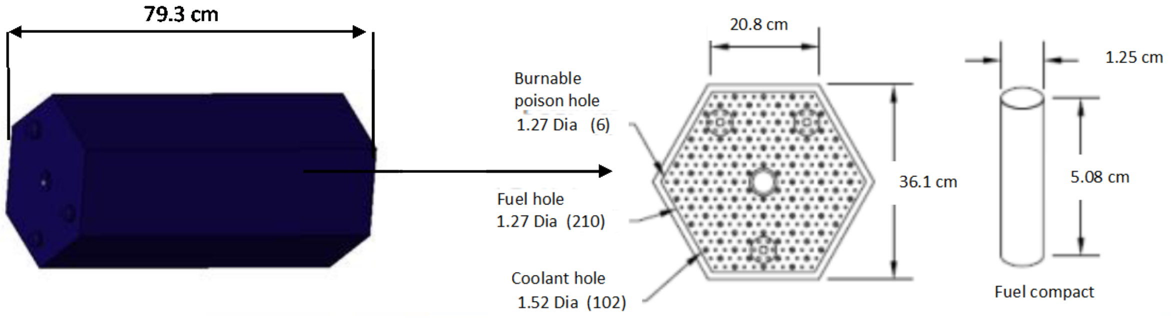
DOE manages TRISO-based SNF from Peach Bottom Unit 1* and Fort St. Vrain

- Storage: TRISO SNF is stored in vented dry vaults at INL and Fort St. Vrain**
- Transportation: TRISO SNF was transported to INL
- Potential Disposal: TRISO SNF has been analyzed for geologic disposal in the past

Differences between advanced reactor concepts and legacy TRISO fuels:

- Potential pebbles vs. prismatic blocks
- Uranium vs. uranium/thorium
- Enrichment (10–20% vs. >20%)

FSV fuel element, cross section, and fuel compact



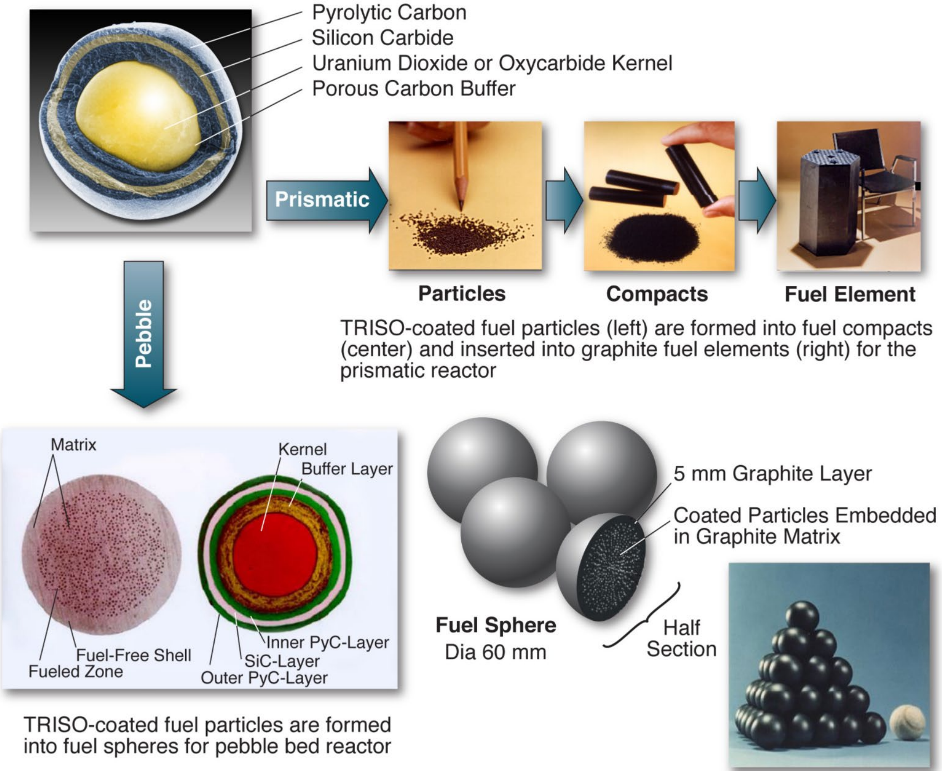
Peach Bottom Unit 1 Core 2 element with handling mechanism removed

*Peach Bottom Unit 1 fuel is a predecessor to TRISO fuel

**Some Peach Bottom Unit 1 SNF is stored in sealed canisters at INL

Characteristics of TRISO SNF from Advanced Reactors

- High burnup (60–193 GWd/MTU)
- High-assay low-enriched uranium (HALEU)
- Defects in TRISO particles dominated by manufacturing defects
  - 1/100,000 TRISO particles
- High melting temperature (3103 K) due to SiC coating
- Fission product diffusion can occur through the SiC layer
  - Most fission products are still expected to remain in matrix material



TRISO-coated fuel particles are formed into fuel spheres for pebble bed reactor

Packaging Analyses for TRISO SNF

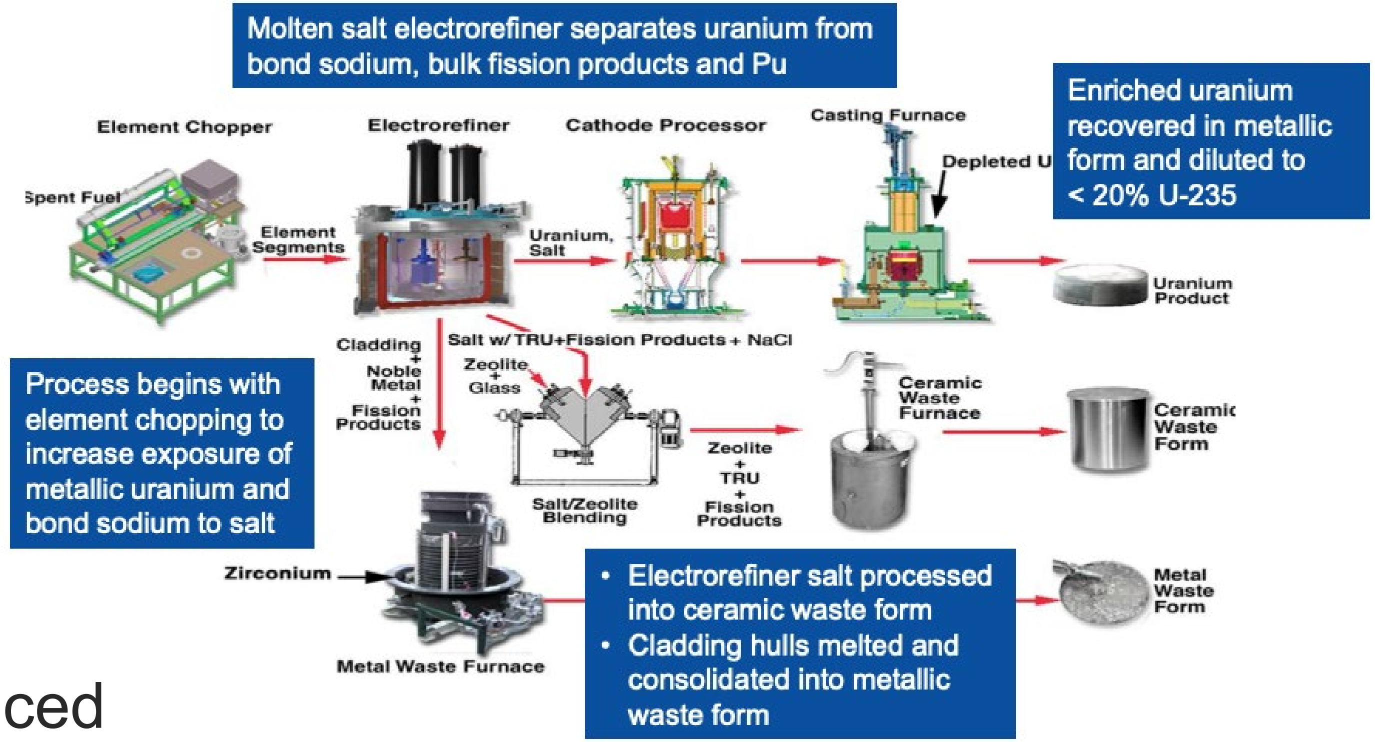
- No significant issues related to the structural performance of dry storage systems or transportation packages.
- Subcriticality of single-canister contents can be maintained in both dry storage and transportation conditions although the diameter of the canister may need to be limited for transportation.
- Thermal challenges for storing or transporting TRISO SNF within the existing LWR dry storage system or package size envelope are not anticipated.
- No significant issues related to shielding and radiation dose control are expected due to the lower dose rates of TRISO SNF relative to LWR SNF.
- TRISO SNF has been stored and transferred for decades at INL and Fort St. Vrain (FSV).

Reactor	Burnup (GWd/MTU)	Enrichment (wt.%)	Specific Power (MW/MTU)
X-energy Xe-100	165	15.5	129.6
Kairos Power KP-X	193	19.55	335

Assumptions based on publicly available data to perform analyses [1].

Management of Metallic SNF in the United States

- DOE manages metallic-based SNF from FERMI 1, Experimental Breeder Reactor-II, N-Reactor, and Fast Flux Test Facility (FFTF)
  - Storage: Metallic SNF is stored in vented and sealed canisters
  - Transportation: Metallic SNF was transported to INL
  - Potential Disposal: some types of metallic SNF have been analyzed for geologic disposal
  - Treatment: Sodium-bonded metallic SNF is being treated to remove sodium bond
- Primary differences between advanced reactor concepts and legacy metallic SNF:
  - Enrichment (10–20% vs. >20%)
  - Possibility of sodium-free fuel

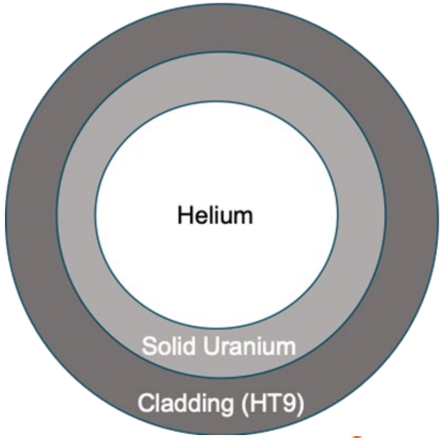


EBR-II Used Fuel Treatment using Electrometallurgical Processing (EMT) [2]

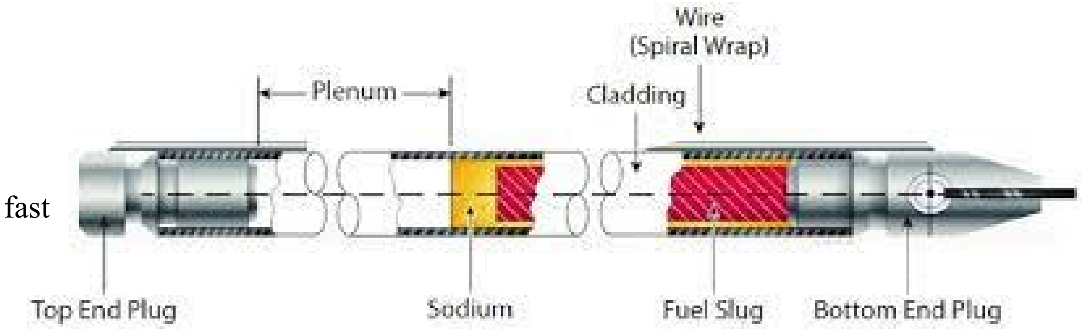
Characteristics of Metallic SNF

- High burnup (up to 150 Gwd/MTU)
- HALEU
- Utilizes internal sodium to prevent fuel-cladding chemical interaction (FCCI)
  - Some new metallic designs focus on eliminating internal sodium
- FCCI occurs when the slug interdiffuses with the cladding
- Fuel slug increases in porosity at higher burnups
  - Sodium migrates into the fuel slug

Experimental Breeder Reactor (EBR-II) assembly



Schematic of Annular Metallic Fuel



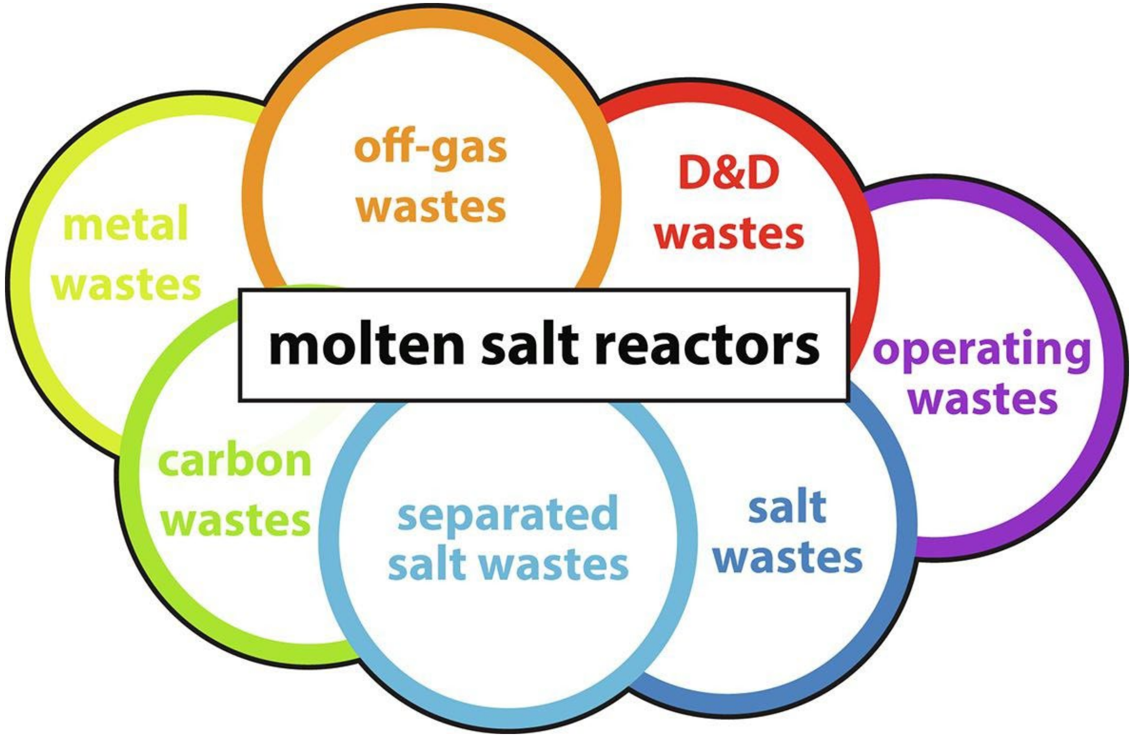
Simplified sketch of a sodium fast reactor fuel rod [3].

Packaging Options for Metallic SNF

- No significant issues related to the structural performance of dry storage systems or transportation packages.
- Subcriticality of single-canister contents can be maintained in both dry storage and transportation conditions.
  - Reconfiguration of SNF or basket could challenge upper criticality limits.
- No significant issues related to shielding and radiation dose control are expected due to criticality loading constraints.
  - If utilizing neutron absorbers, this conclusion needs to be re-evaluated.

Molten-salt was utilized in the molten salt reactor experiment at Oak Ridge National Laboratory (ORNL)

- Residual fuel salt remains stored in fuel drain tanks
  - In solid state
- The Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA) decision documents were updated and completed in 1990s
  - Uranium deposit removal [4]
  - Treatment and removal of fuel and flush salts [5]
- Transportation and disposal strategies of MSRE legacy waste have not been definitively established
- Primary differences in advanced reactor concepts and legacy MSRE salts:
  - Additional salts



Examples of different wastes produced in MSRs [6]

Packaging Options for Irradiated Fuel Salts

- No significant issues related to the structural performance of dry storage systems or transportation packages.
- Subcriticality of single-canister contents can be maintained in both dry storage and transportation conditions.
- No significant issues related to shielding and radiation dose control are expected due to the lower dose rates of MSR salts relative to LWR SNF.
- Fuel salt is expected to off-gas, which presents challenges related to transportation.
- Fuel salt has been stored at ORNL in the Molten Salt Reactor Experiment fuel tanks.
  - Never been transported
  - Never been stored under NRC or DOE storage regulations
- Large uncertainties exist due to concepts using different fuel salt and spectrums.

Disposal Challenges and Considerations

TRISO

- TRISO SNF was included in the previous repository disposal plan.
- A larger volume of TRISO SNF is generated compared to other SNF categories.
- TRISO SNF has favorable chemical characteristics for disposal.

Metallic

- Sodium-bonded metallic fuel can not be directly disposed of due to its pyrophoric nature.
- Treating sodium-bonded SNF using the EMT or another technique should be assessed.
- Sodium reaction with water causes hydrogen gas generation and the formation of a caustic solution.
- Degradation rate of metallic SNF is faster than other SNF categories.

MSR

- SNF generated from MSRs presents uncertainties compared to other advanced reactor SNF.
- Spent fuel salts can easily dissolve in water, increasing radionuclide availability for transport.
- Challenges arise from the high temperature of salt fuel and the need for shielding during fuel salt injection into disposal wells.
- Gas generation is a concern.
- Salts may also pose a respirable fraction issue for certain events.

Back End Advanced Reactor Analyses: Future Considerations

- Identify feature, events, and processes and perform gap analysis for different SNF and any associated waste streams
- Identify potential standardization issues in advanced reactor packages

TRISO

- Continue to examine effects of radiolysis
- Examine the possibility of over-pressurizing the SiC containment layer from alpha decay
- Examine the distribution and escape of fission products from the TRISO particles and graphite matrix
- How will material and accountability be performed for SNF pebbles?

Metallic

- Feasibility of direct disposal
  - Sodium-bonded
  - Non-Sodium-bonded
- Feasibility of doing large scale treatment
- Best practices for handling failed fuel assemblies
- Evaluate the drying aspects for metallic fuels and the potential to create uranium-hydrides

MSR

- SNF generated from MSRs presents uncertainties compared to other advanced reactor SNF
- Waste form development
- Develop open model for molten chloride fast reactor
- Continue to narrow down characteristics of different types of MSRs
- Evaluate regulatory framework to examine applicability to salt-waste form

References

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6. Riley, B. et al., “Molten Salt Reactor Waste And Effluent Management Strategies: A Review” Nuclear Engineering and Design, Vol. 345 pg. 94-109, 2019.

Thank you for your attention