INL/CON-24-76928-Revision-0

Criticality Analysis of Fort St. Vrain Spent Nuclear Fuel in the DOE Standard Canister

March 2024

Changing the World's Energy Future

Benjamin Luis Estrada, Evans Damenortey Kitcher, Daniel Albert Thomas, Kristy Diane Yancey Spencer

INL/CON-24-76928-Revision-0

Criticality Analysis of Fort St. Vrain Spent Nuclear Fuel in the DOE Standard Canister

Benjamin Luis Estrada, Evans Damenortey Kitcher, Daniel Albert Thomas, Kristy Diane Yancey Spencer

March 2024

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

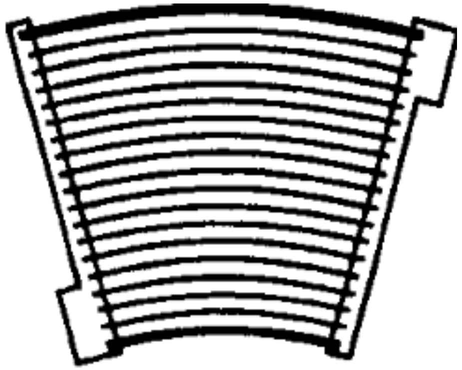
March 12, 2024

Benjamin Estrada

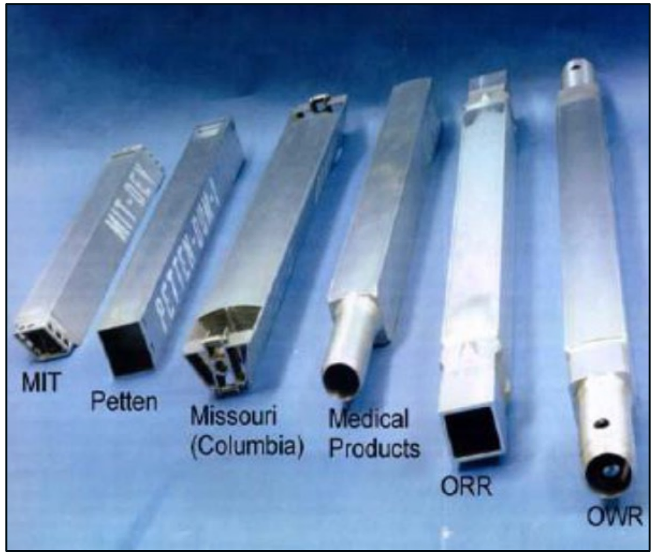
Criticality Analysis of Fort St. Vrain Spent Nuclear Fuel in the DOE Standard Canister

DOE manages a broad array of SNF

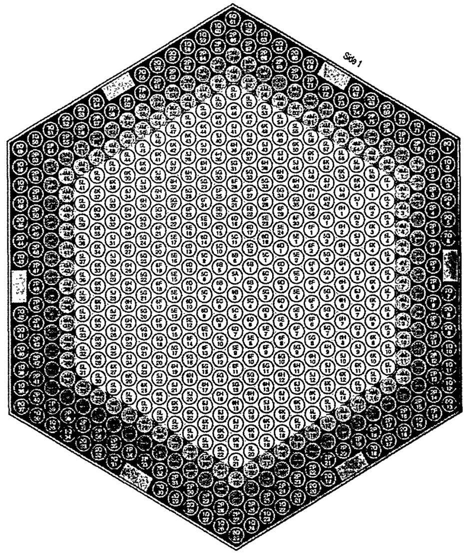
- Over 300+ types of DOE-managed SNF across the DOE complex
  - Fuels (oxides, metals, carbides, etc.)
  - Different enrichments, geometries, and sizes



ATR Fuel Element



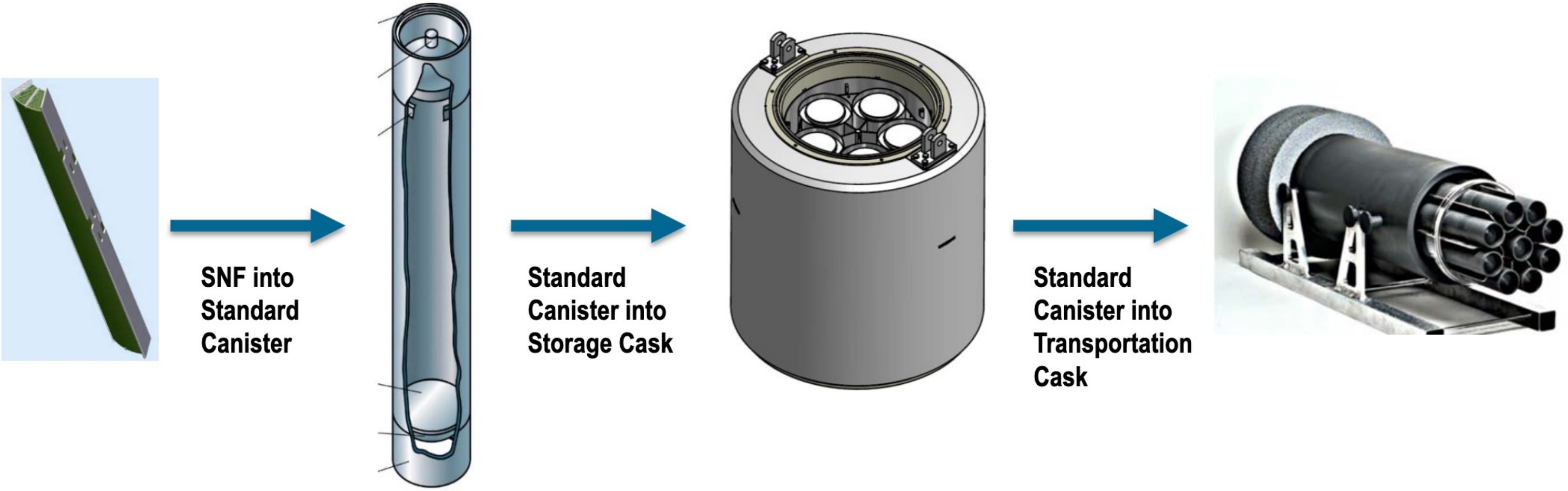
Fuels from Research Reactors



Shippingport Fuel Element

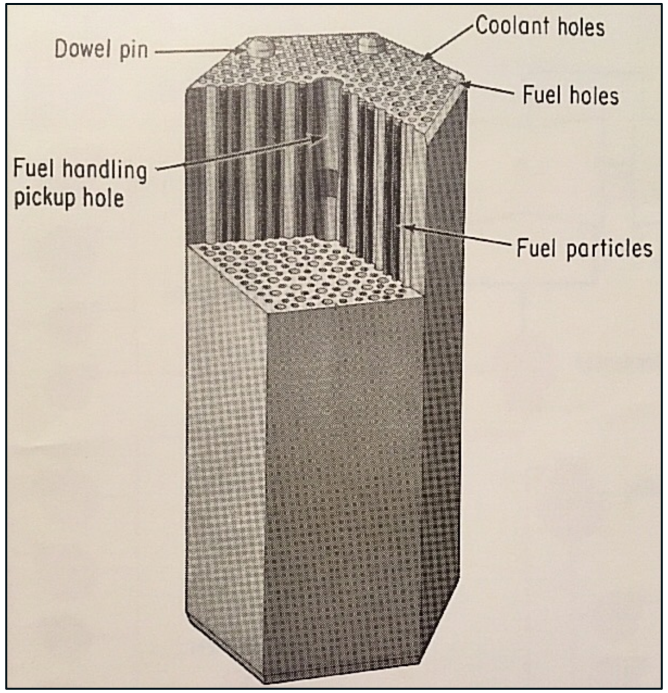
DOE-managed SNF can be packaged in standardized canisters

- The National Spent Nuclear Fuel Program designed the DOE Standard Canister in the 1990s.
  - Minimizes dependence on fuel type and characterization
  - Based on the reliability of systems, structures, and components
  - Can be used to transport and store SNF

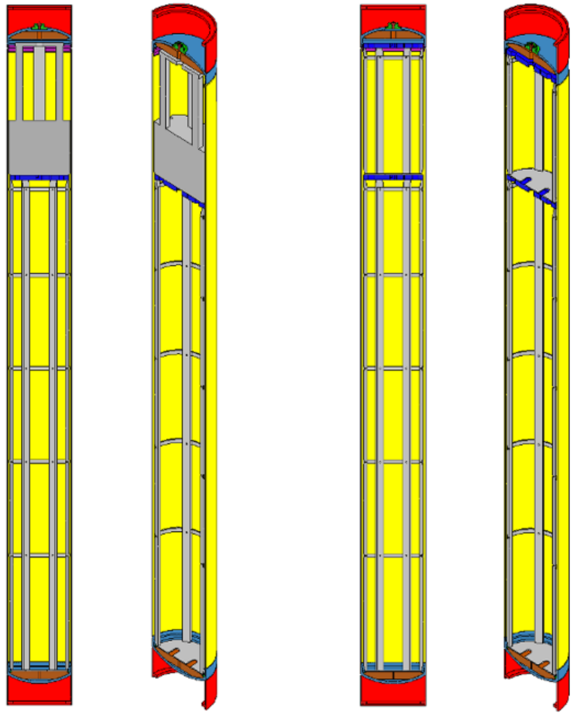


DOE is funding a packaging demonstration at INL

- The goal is to load 4 or 5 FSV fuel elements into the DOE Standard Canister.



FSV Fuel Element



Cross-Sectional 3-D Model of the DOE Standard Canister

Criticality Analysis

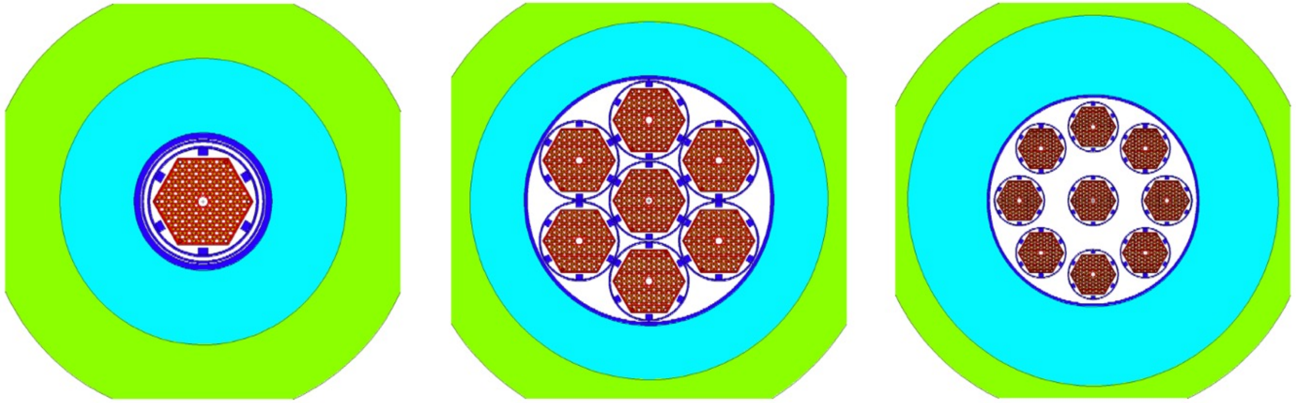
- The neutron multiplication factor (k_{eff}) is found via Monte Carlo N-Particle Transport (MCNP) 6.2.
- Upper subcritical limits (USLs) are calculated using Whisper 1.1.
- One, seven, or nine canisters are loaded into a concrete overpack.
- The cases are derived from credible abnormal conditions.
  - Moderator ingress
  - Geometry changes
  - Concentration
  - Reflection

$$k_{calc} + 2\sigma < \text{USL}$$

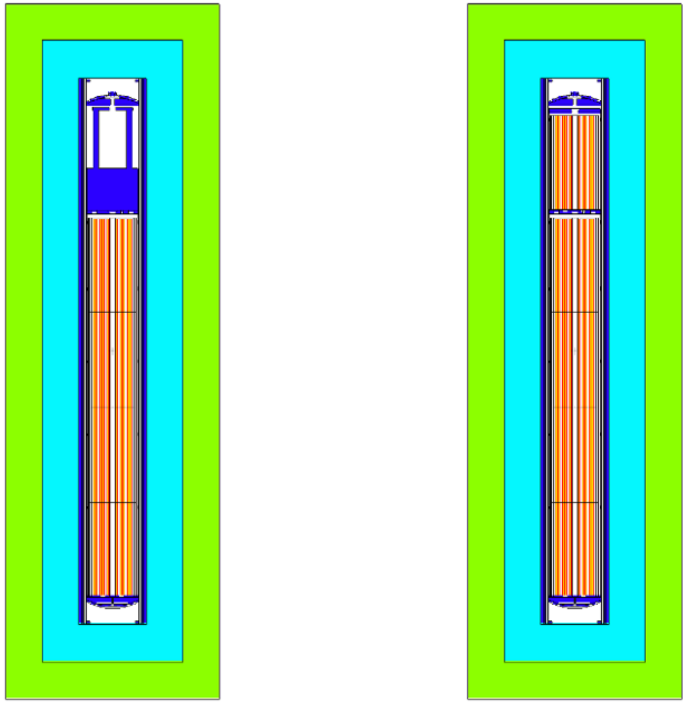
$$\begin{aligned}\text{USL} = 1 \\ &+ \text{(Bias)} \\ &- \text{(Bias Uncertainty)} \\ &- \text{(Margin of Subcriticality)}\end{aligned}$$

Normal Conditions

- Dry fuel, canister, and overpack
- The fuel is assumed fresh and intact
- Full water reflection



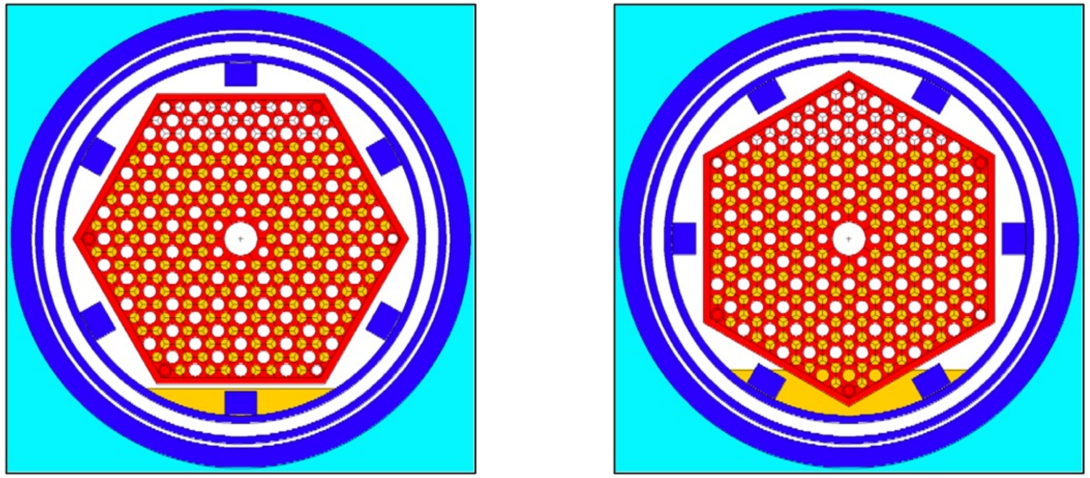
Single-, Seven-, and Nine-Canister Arrangements



Four vs. Five FSV Fuel Assemblies Loaded

Transport Scenarios

- USL of 0.92171 for transport
- Scenario 1: degraded fuel collects at the bottom of a canister

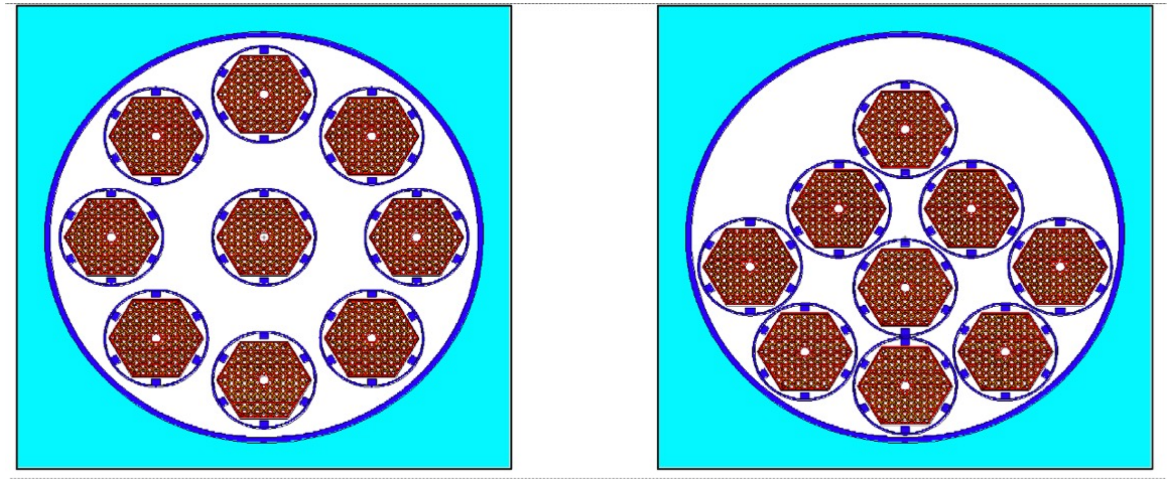


Two Different Orientations

Configuration		$k_{eff} + 2\sigma$		
		1 SC	7 SCs	9 SCs
4 FSV assemblies	Dry overpack	0.12827	**0.38794**	0.31711
	Flooded overpack	0.18078	0.38071	0.24284
5 FSV assemblies	Dry overpack	0.12852	0.36116	0.29969
	Flooded overpack	0.18046	0.35565	0.22289

Transport Scenarios

- Scenario 2: nine-canister drop event



Configuration		$k_{eff} + 2\sigma$
4 FSV assemblies	Dry overpack	0.3252
	Wet overpack	0.26418
5 FSV assemblies	Dry overpack	**0.3296**
	Wet overpack	0.26438

Storage Scenarios

- USL of 0.95171 for storage
- Moderator ingress through fuel saturation, canister flooding, and overpack flooding

Seven-Canister Overpack

Configuration		**$k_{eff} + 2\sigma$**	
		Unsaturated	Saturated
4 FSV assemblies	Dry canister in a dry overpack	0.34092	0.93005
	Dry canister in a fully flooded overpack	0.33145	0.80986
	Fully flooded canister in a dry overpack	0.83726	0.94594
	Fully flooded canister in a fully flooded overpack	0.78439	0.91848
5 FSV assemblies	Dry canister in a dry overpack	0.34233	0.93036
	Dry canister in a fully flooded overpack	0.33244	0.8108
	Fully flooded canister in a dry overpack	0.83726	**0.94626**
	Fully flooded canister in a fully flooded overpack	0.7845	0.91794

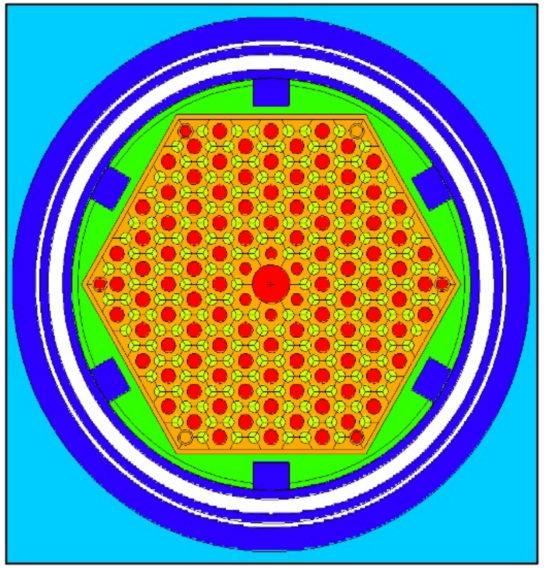
Storage Scenarios

Nine-Canister Overpack

Configuration		$k_{eff} + 2\sigma$	
		Unsaturated	Saturated
4 FSV assemblies	Dry canister in a dry overpack	0.27689	0.88459
	Dry canister in a fully flooded overpack	0.20416	0.68488
	Fully flooded canister in a dry overpack	0.82348	0.93884
	Fully flooded canister in a fully flooded overpack	0.72593	0.88651
5 FSV assemblies	Dry canister in a dry overpack	0.28441	0.88774
	Dry canister in a fully flooded overpack	0.20445	0.68504
	Fully flooded canister in a dry overpack	0.82387	**0.93907**
	Fully flooded canister in a fully flooded overpack	0.72591	0.8866

Disposal Scenarios

- USL of 0.95171 for disposal
- Formation of a water-uranium slurry



Configuration		**k_{eff} + 2σ**		
		1 SC	7 SCs	9 SCs
4 FSV assemblies	Fully flooded canister in a dry overpack	0.90397	**0.94989**	0.94281
	Fully flooded canister in a fully flooded overpack	0.89331	0.92315	0.8921
5 FSV assemblies	Fully flooded canister in a dry overpack	0.90403	0.94988	0.94289
	Fully flooded canister in a fully flooded overpack	0.89324	0.923	0.89202

Disposal Scenarios

- Degradation of stainless steel into hematite or goethite

Degradation into hematite

Configuration		$k_{eff} + 2\sigma$		
		1 SC	7 SCs	9 SCs
4 FSV assemblies	Fully flooded canister in a dry overpack	0.89984	**0.95033**	0.94249
	Fully flooded canister in a fully flooded overpack	0.89016	0.92212	0.88926
5 FSV assemblies	Fully flooded canister in a dry overpack	0.90009	0.95026	0.94233
	Fully flooded canister in a fully flooded overpack	0.88965	0.92268	0.8898

Degradation into goethite

Configuration		$k_{eff} + 2\sigma$		
		1 SC	7 SCs	9 SCs
4 FSV assemblies	Fully flooded canister in a dry overpack	0.88937	0.93593	0.92923
	Fully flooded canister in a fully flooded overpack	0.88414	0.91419	0.88655
5 FSV assemblies	Fully flooded canister in a dry overpack	0.88894	**0.93682**	0.92905
	Fully flooded canister in a fully flooded overpack	0.88504	0.91464	0.88651

Summary of Results

- No scenario exceeded the application-specific USL (i.e., 0.92171 for transport; 0.95171 for storage/disposal).
- The highest k_{eff} (i.e., 0.95033) stemmed from stainless steel degradation into hematite.
- Saturated fuel, flooded canister, and dry overpack were the most reactive conditions.
- k_{eff} showed minimal variation when comparing four vs five fuel elements.

Questions?

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.