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

Spent Fuel and Waste Science and Technology (SFWST)

Clean. Reliable. Nuclear.

Advanced Reactor Fuel Gap and FEP Analyses

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PNNL-SA-189354

NWTRB Summer Meeting

August 30, 2023

Idaho Falls, ID

Disclaimer

This is a technical presentation that does not take into account the contractual limitations or obligations under the Standard Contract for Disposal of Spent Nuclear Fuel and/or High-Level Radioactive Waste (Standard Contract) (10 CFR Part 961). For example, under the provisions of the Standard Contract, spent nuclear fuel in multi-assembly canisters is not an acceptable waste form, absent a mutually agreed to contract amendment.

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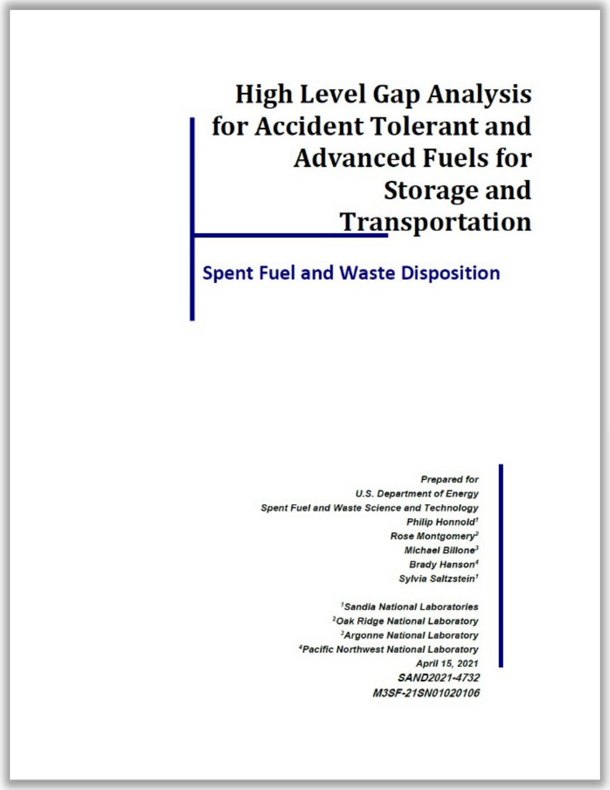
FY2021-2023 Activities


High Level Gap Analysis for Accident Tolerant and Advanced Fuels for Storage and Transportation

Spent Fuel and Waste Disposition

Prepared for
U.S. Department of Energy
Spent Fuel and Waste Science and Technology
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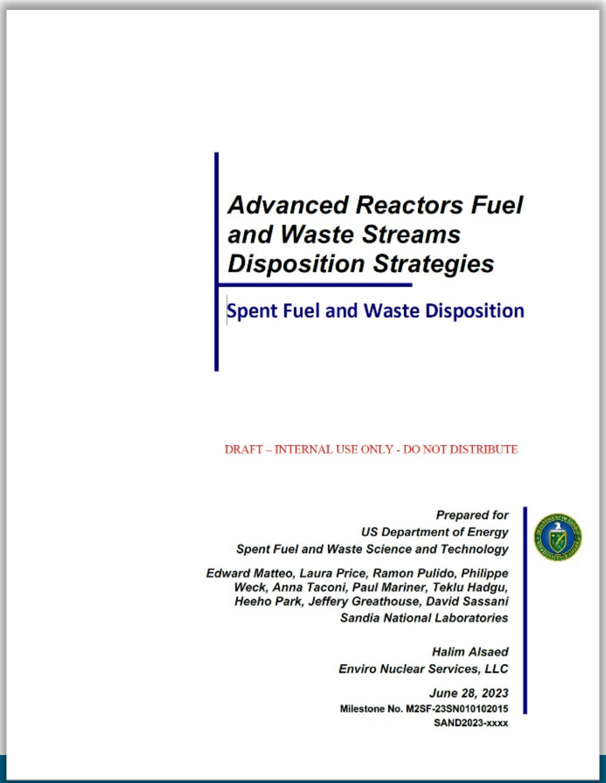
April 15, 2021
SAND2021-4732
M3SF-21SN01020106


Advanced Reactors Fuel and Waste Streams Disposition Strategies

Spent Fuel and Waste Disposition

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Prepared for
US Department of Energy
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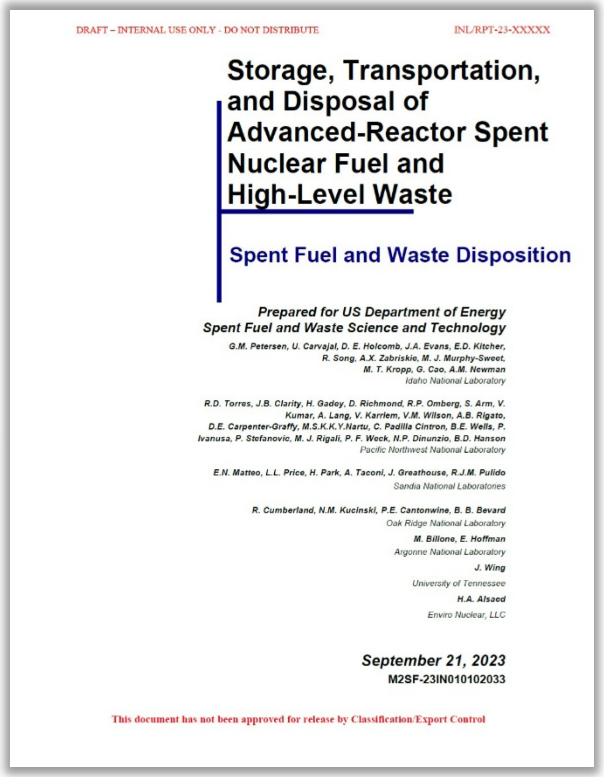
June 28, 2023
Milestone No. M2SF-23SN010102015
SAND2023-xxxx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Storage, Transportation, and Disposal of Advanced-Reactor Spent Nuclear Fuel and High-Level Waste

Spent Fuel and Waste Disposition

Prepared for US Department of Energy
Spent Fuel and Waste Science and Technology

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September 21, 2023
M2SF-23IN010102033

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- High level gap analysis
  - Testing similar to Sibling Pins is needed
- Disposition Strategies
  - Regulatory guidance may need updating
    - Peak cladding temperature e.g.
  - High assay low enriched uranium (HALEU) and post-closure criticality
- Program direction advanced reactor report
  - TRISO
  - Metallic
  - Molten salt

Planned FY2024 and Beyond

Accident Tolerant Fuels (ATF)
High Burnup/High Enrichment (HBHE)
Advanced Reactor Spent Fuel and Waste Forms

Storage and Transportation Detailed Gap Analysis

- Cross-cutting gaps
- Structures, systems, and components (SSC) gaps
  - Fuel
  - Cladding

Disposal Features, Events, and Processes (FEP)

- Spent fuel and waste form
  - Waste form lifetime
  - In-package criticality
- Waste package materials
- Self protection

Lack of publicly available data is a significant hindrance

Waste Characteristics – Radionuclide Inventory

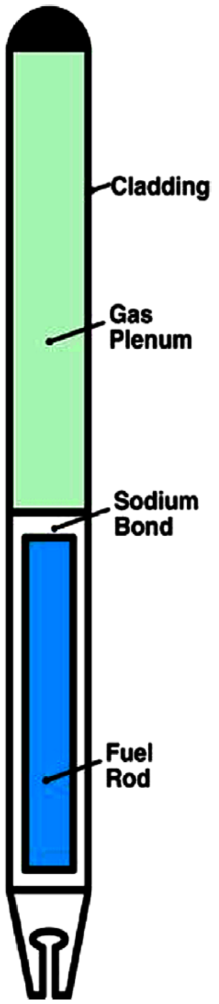
- Higher burnup results in higher radionuclide inventory
  - Current LWR limit ~62 GWd/MTU on a fuel rod average basis
    - Average assembly burnup ~45 (BWR) and ~47 (PWR) GWd/MTU
  - HBHE/ATF seeks initial increases to 75 GWd/MTU
  - Xe-100 ~168.5 GWd/MTU
  - Natrium Type 1B ~150 GWd/MTU
    - Hanford N-Reactor ~1 – 2.7 GWd/MTU
- Higher enrichment of ^{235}U
  - Differences in cumulative fission yields → more ^{90}Sr, less ^{129}I and higher actinides
  - LWR <5%; HBHE/ATF 8-10%; Xe-100 15.5%; Natrium Type 1 18.5%, Type 1B 16.5%
- Fast vs. thermal
  - Fission higher actinides

Waste Characteristics - Thermal

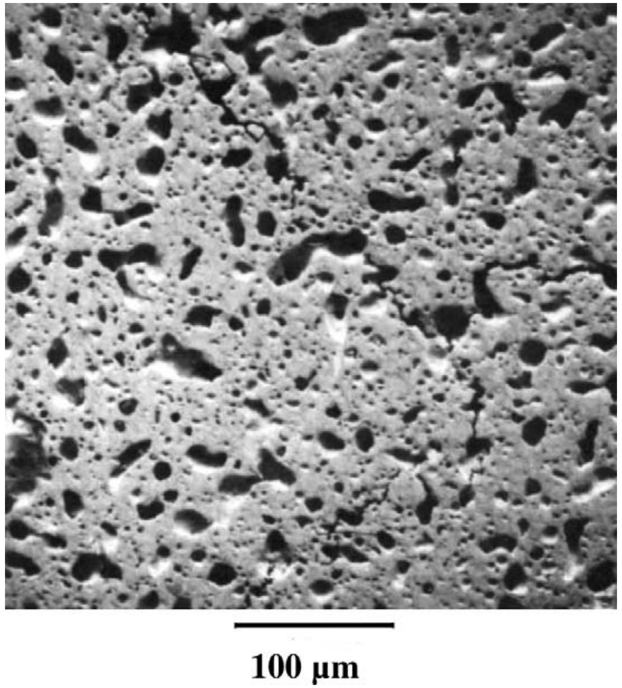
- Higher temperatures → faster degradation rates
- To a first approximation, the size of a repository footprint is affected by the thermal density of the waste and repository-specific temperature limits
- Temperature limits
  - Host rock
  - Waste package surface
  - Peak cladding/structure, system, and component temperature
  - 10 CFR 71.43 (g) For transportation, no accessible surface of a package can have a temperature exceeding 50˚C (122˚F) in a nonexclusive shipment, or 85˚C (185˚F) in an exclusive use shipment
- TRISO ~7 g U/pebble (6×10^{-2} g U/cc); LWR ~9 g U/cc; U metal ~ 19 g/cc
- Coolant temperatures
  - BWR ~288˚C, PWR ~ 290- 325˚C; TRISO 260 - 750˚C; Natrium 390 - 540˚C
- LWR cladding may exceed reactor temperatures during drying and initial dry storage

Waste Characteristics - Chemical

- Metallic sodium is pyrophoric with a strong exothermic reaction with moisture/water
  - Infuse into open pores of fuel
- Metallic uranium reacts rapidly with water
  - $k = 5.03 \times 10^9 \exp[-66.4/RT]$
  - 2.5 $mg/cm^2/h$ @ 100° C
  - N-Reactor fuel assumed to react instantaneously in Yucca Mountain
- U-20Zr reacts much slower
  - $k = 1.13 \times 10^3 \exp[-51.9/RT]$
  - 6×10^{-5} $mg/cm^2/h$ @ 100° C
- Effects of irradiation?



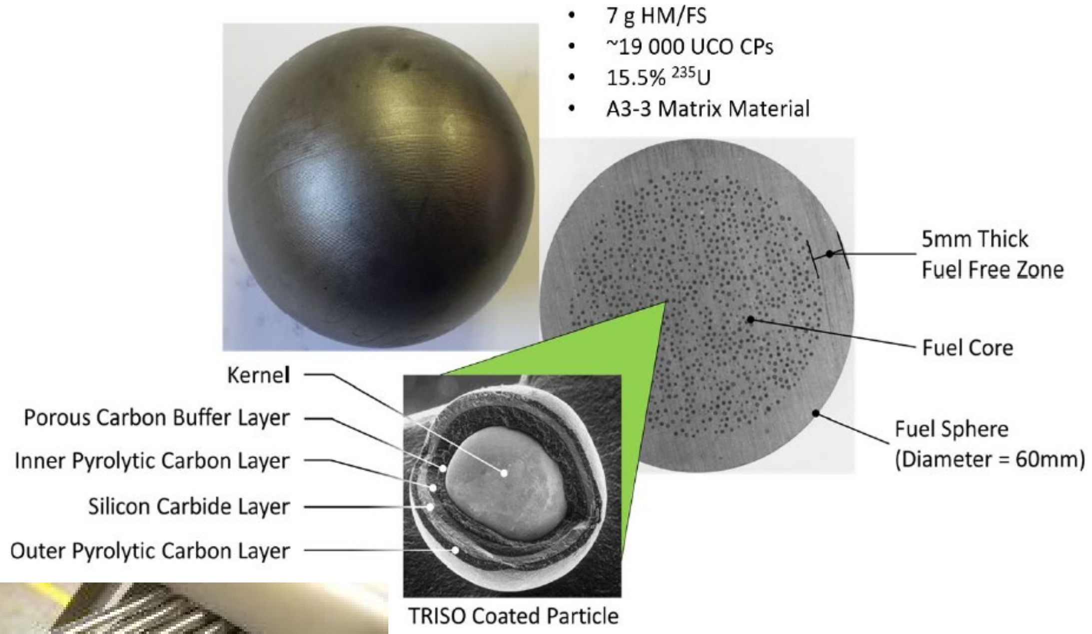
Schematic of a metallic, sodium-bonded fast reactor fuel element



Fission gas pore morphology in U-10Zr fuel

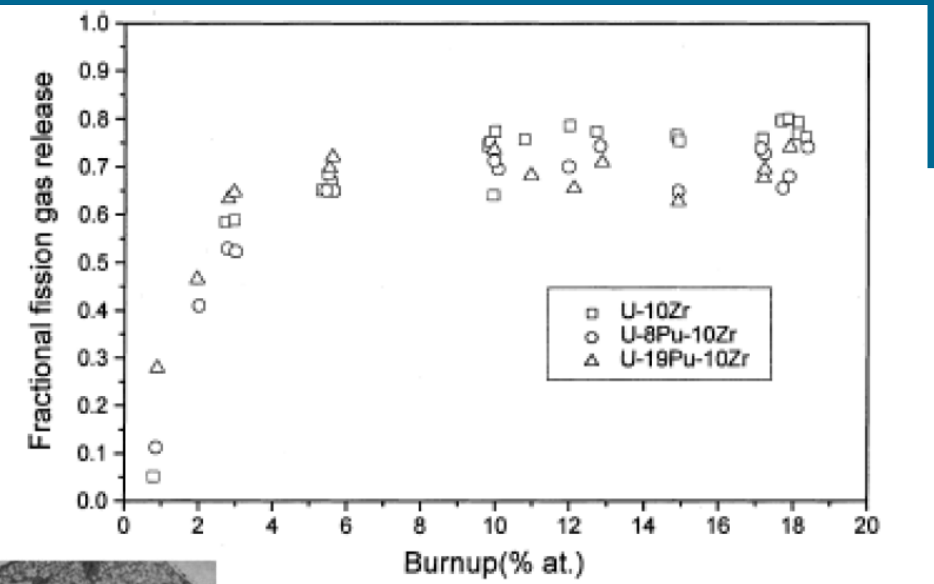
Cross-cutting Gaps

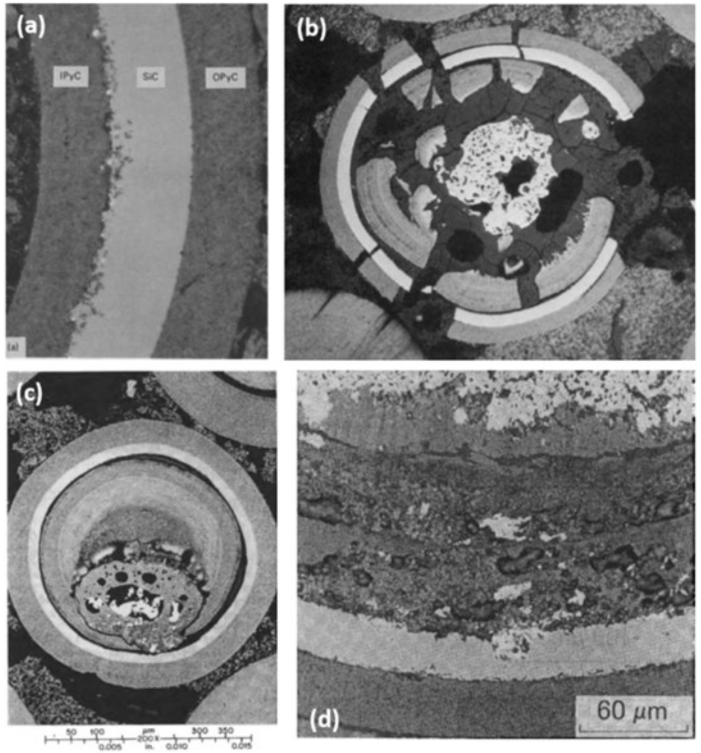
- Thermal Profiles
- Stress Profiles
  - Vibrations during normal conditions of transport
    - Generation of graphite/carbon dust (^{14}C, ^{3}H)
    - Fretting from wire wrap
    - Fretting through Cr-coating
  - 30 cm drop analysis
    - Fracture of SiC layer or cracking of pyrolytic carbon (PyC) layers
    - Large plenum/wire wrap
- Drying Issues/Fuel Transfer Options
  - Xe-100 TRISO is always dry
  - Rewetting of potentially failed Na-bonded fuel
- Subcriticality/Burnup Credit
  - HALEU; higher actinides



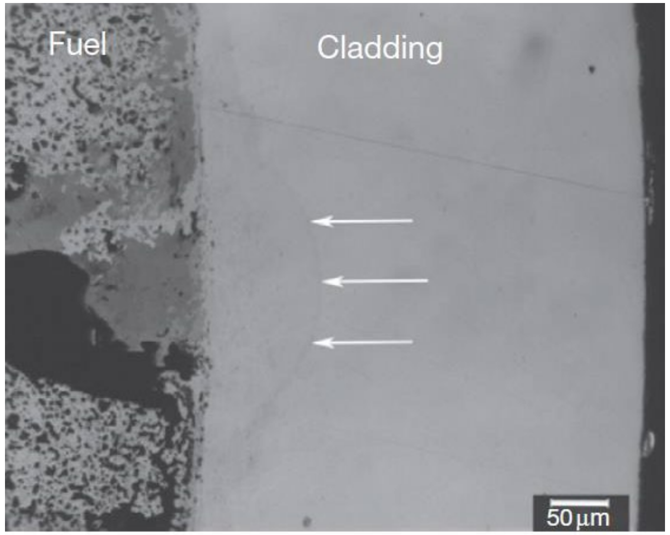
Fuel Gaps

- Fuel fragmentation
  - High burnup structure
- Restructuring/swelling
  - Cr-doped pellets retain more fission gas
  - Long-term alpha decay pressurization
  - Secondary swelling of uranium metal
- Fission product attack on cladding
  - Fuel cladding chemical interaction with metallic fuels
  - Long-term attack on IPyC and SiC
- Fuel oxidation
  - Metal
  - UCO
  - Very high burnup





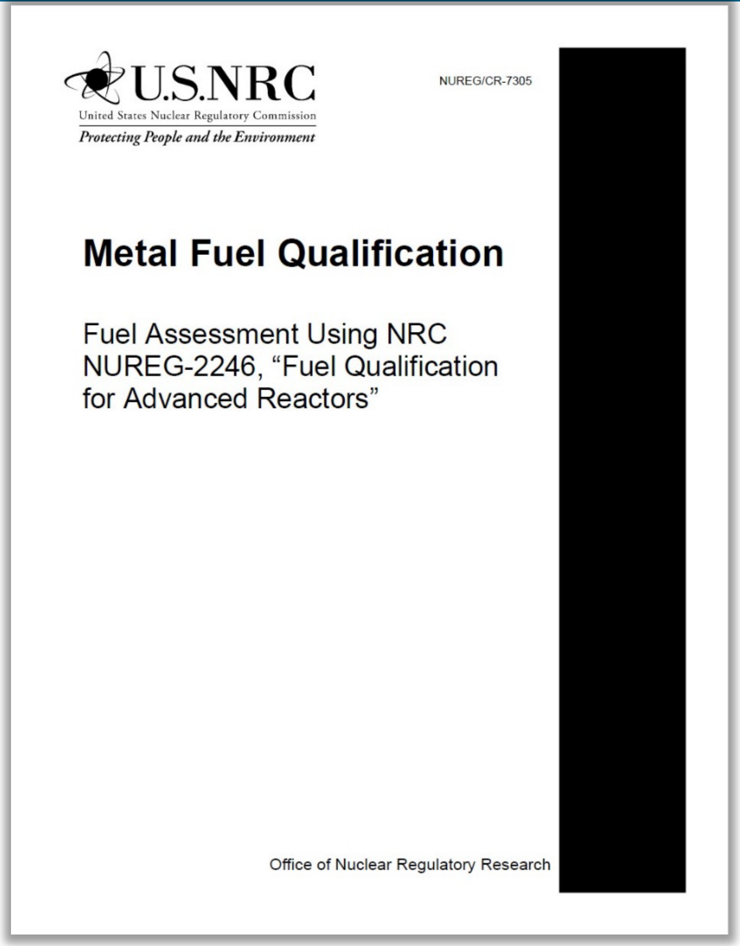
a) Pd attack on SiC
b) SiC pressure vessel failure
c) Kernel migration
d) Rare earth corrosion of SiC



Fuel-cladding interaction adjacent to large deposit of lanthanide fission products

Cladding Gaps

- Radiation damage/annealing of damage
  - Other than for ATF and HBHE,
    storage temperatures < in-core temperatures
- Metal fatigue caused by temperature fluctuations
  - Large axial temperature gradient with metallic fuels
- Embrittlement
  - Cr/Zr diffusion
- Potential new mechanisms
  - HT9 cladding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NUREG/CR-7305

Metal Fuel Qualification

Fuel Assessment Using NRC NUREG-2246, "Fuel Qualification for Advanced Reactors"

Office of Nuclear Regulatory Research

This initial qualification (for U-10Zr in HT9 cladding), while containing other conditions to be discussed, hereby extends to 10 at% burnup (BU). U-Zr system applications exceeding this BU limit will require additional monitoring, surveillance, and testing.

FEP

- General corrosion (uniform thinning, temperature dependence, patches)
- Stress corrosion cracking (initiation, propagation, stresses, patches)
- Localized corrosion (initiation, propagation, defect sites)
- Microbially influenced corrosion (humidity)
- Early failure (undetected defects, handling)
- Package physical form (strength, chemical behavior, dimensions, cladding, outer barrier)
- Radionuclide mass fractions in waste form and toxicity (radiation, chemical)
- Interaction between codisposed materials
- Waste form degradation processes (alteration, dissolution, radionuclide release)
- Chemical interaction with groundwater, package degradation products

FEP (cont)

- Radionuclide solubility and sorption (chemical environment)
- Colloids (intrinsic, pseudocolloids)
- Radioactive decay and ingrowth

- Some FEP excluded from Yucca Mountain but may need to be added
  - Alpha recoil
  - Pyrophoricity
  - Cladding corrosion and degradation
  - Hydride cracking
  - Internal corrosion of waste package materials prior to waste package breach
  - Mechanical impact
  - In-package and external criticality FEP

Summary

- SFWST is initiating a detailed gap analysis for ATF, HBHE, and advanced reactor spent fuel and waste forms for storage and transportation and FEP analyses for disposal
- This is a very complex undertaking because of the large number of proposed variations in advanced reactor fuels and the limited publicly available data on fuel and reactor designs
  - Multi-year effort
- If we assume direct disposal of storage packages will occur, then post-closure criticality, especially with HALEU and higher actinide inventories, becomes important
- Working with EPRI ESCP Advanced Fuel Subcommittee

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