National Nuclear Security Administration

MATERIAL MANAGEMENT AND MINIMIZATION

CONVERT, REMOVE, DISPOSE

Office of Nuclear Material Removal and Elimination

Lessons Learned in Technology Development and Management of Non-Standard Research Reactor Spent Nuclear Fuel

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IAEA Technical Meeting on Operating Experience and Lessons Learned on Managing Non-Standard Legacy Spent Fuels from Power and Research Reactors

Presentation Overview

- NNSA's Role & Relevance
  - U.S. Highly Enriched Uranium (HEU) Minimization Activities and Accomplishments
  - Relevance for Exotic Spent Nuclear Fuel (SNF) Management
- SNF Treatment and Conditioning Considerations
- DOE's "Traditional" SNF Management Practices
- Emerging U.S. Treatment and Conditioning Technologies for Non-standard Fuels
- Conclusions and Summary

NNSA's Role and Relevance

Detect Proliferation and Verify Compliance
Nuclear Explosions
Materials and Warheads
Material Production
Weapons Development
Pu/U Verification teams
Eliminate/Minimize Nuclear and Radiological Materials No Longer In Use
Convert
Remove
Dispose
NON-STATE ACTORS
NUCLEAR ARMED STATES
STATES SEEKING NUCLEAR WEAPONS
DNN FOCUS: NUCLEAR AND RADIOLOGICAL THREATS
Control Further Spread of Nuclear Materials/ Technology/Expertise
Export Controls
Counter Nuclear Smuggling
Treaties, Agreements, Policy
Safeguard Nuclear Materials and Secure Nuclear Facilities and Radiological Materials In Use
Safeguards tools/training/expertise
Secure sites/materials

Program Mission

Office of Reactor Conversion and Uranium Supply	Office of Nuclear Material Removal and Elimination	Office of Plutonium Disposition
(NA-231)	(NA-232)	(NA-233)
• Eliminate the need for, and production of, weapons-usable materials in civilian applications • Provide a sustainable supply of high-assay low-enriched uranium (HALEU) for research reactors and isotope production so that highly enriched uranium (HEU) minimization successes endure • Support establishment of domestic commercial production of molybdenum-99	• Identify excess nuclear material and implement solutions for its removal and/or in-country elimination to reduce the risk a terrorist or malevolent actor could acquire it • Maintain capabilities to expeditiously characterize, stabilize, and package at-risk nuclear materials globally • Identify and eliminate sensitive nuclear infrastructure at research reactors' end-of-life	• Dispose of surplus plutonium (Pu), in support of U.S. nonproliferation and disarmament commitments. • Remove material from the State of South Carolina, in accordance with the 2020 Settlement. • Engage partner-states to support responsible plutonium management and disposition.

Program Mission

Identify excess nuclear material and implement solutions for its removal and/or in-country elimination to reduce the risk a terrorist or malevolent actor could acquire it

Removal is the transportation of material to its country of origin or an appropriate third country for elimination

In-country activities involve eliminating material in the country in which it is currently located

Elimination is a process which renders material significantly less attractive for terrorist/malevolent actor acquisition

Acquisition for use in an improvised nuclear device*

What's the Scope?

Identify excess nuclear material and implement solutions for its removal and/or in-country elimination to reduce the risk a terrorist or malevolent actor could acquire it

- *Aluminum-based fuels – UAl_x, $Al\text{-}UO_2$, $Al\text{-}U_3O_8$*
- *TRIGA Fuel – U-ZrH*
- *"Common" bulk/feedstock materials – U metal, oxides, silicides, nitrate, UF_4*
- *Graphite-based fuels – TRISO, U-SiC-Graphite pebbles, U-Th oxide kernels*
- *Thorium-based fuels - $UO_2\text{-}ThO_2$*
- *Exotic/"uncommon" fuels and feedstocks – Nitrides, carbides, Pu, UF_6*

Significant experience and expertise in packaging and transport of SNF from around the world

Availability of technologies to treat and condition these materials has been key to U.S. minimization activities and a critical driver for technology development activities

Convergence of Fuel Types

Traditional Power Reactor Fuels

- *Zircaloy-clad UO_2*
- *Zircaloy clad Mixed Oxide (U-Pu)*

Current and Legacy Research, Test and Demonstration Reactors

- *Aluminum-based fuels – UAl_x, Al-UO_2, Al-U_3O_8*
- *TRIGA Fuel – U-ZrH*
- *"Common" bulk/feedstock materials – U metal, oxides, silicides, nitrate*
- *Graphite-based fuels – TRISO, U-SiC-Graphite pebbles, U-Th oxide kernels*
- *Thorium-based fuels - UO_2-ThO_2*
- *Nitrides, carbides, Pu*

Advanced Reactors including SMRs, Microreactors Fuels for Power and RTRs

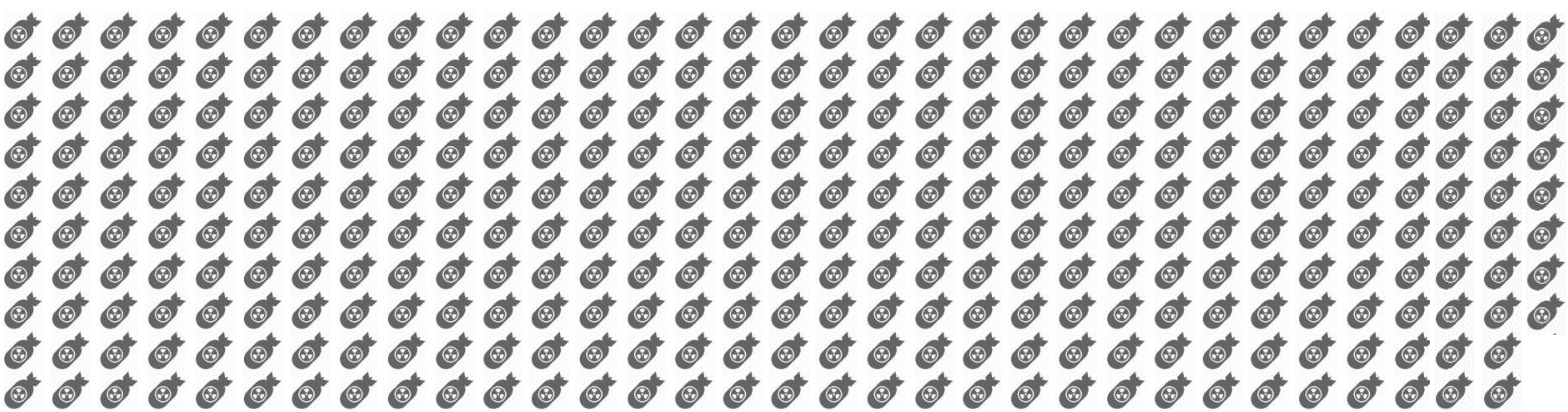
- *Zircaloy clad UO_2*
- *Graphite-based fuels – TRISO, U-SiC-Graphite pebbles*
- *Thorium-based fuels – UO_2-ThO_2*
- *Molten Salt Fuel based reactors*
- *Nitrides, carbides, Pu*

Many of the power reactor fuel systems being considered are same as those used in RTRs

Accomplishments to Date

As of February 2025, M3's Office of Nuclear Material Removal and its international partners have eliminated more than 7,340 kilograms of weapons-usable nuclear materials from 48 countries and Taiwan—enough for approximately 328 nuclear weapons.

Over 410 kilograms of plutonium removed to date—enough for approximately 51 nuclear weapons



Over 6,930 kilograms of HEU removed to date—enough for approximately 277 nuclear weapons

Research Reactor Spent Fuel Wet Storage

U.S.-origin HEU SNF has been primarily stored in spent fuel basins pending treatment and conditioning

- Significant lessons learned through this process.
  - Water quality, including conductivity, pH and basin materials of construction are key to extended basin (wet) storage
  - DOE's Savannah River Site L-basin holds many non-standard fuels, many of which have been in storage for over 60 years
  - See, e.g., *Good Practices for Water Quality Management in Research Reactors and Spent Fuel Storage Facilities,* IAEA Nuclear Energy Series No. NP-T-5.2
- Defensible scientific basis for extended wet storage of research reactor SNF
- Extensive experience in wet storage of RTR (standard and non-standard) exists globally

Photo source: SRNS

SNF Treatment & Conditioning Considerations

Defining Terms

Treatment

Minimizing the volume of material to be disposed

Driven by logistical, practical, or economic considerations

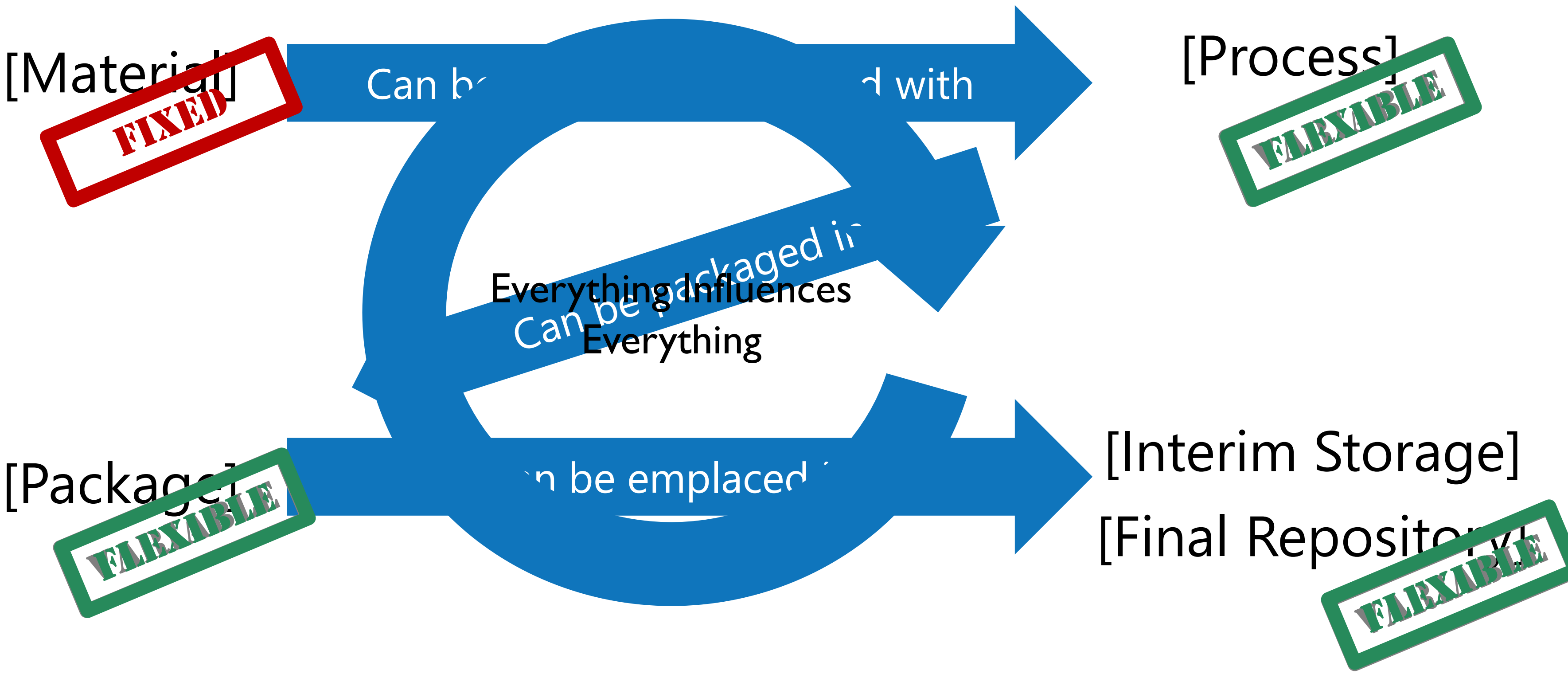
Conditioning

Transforming material to a stable state to reduce potential hazards of material being disposed

Driven by safety considerations

Can include the downblending of HEU to low-enriched uranium (LEU)

A Guiding Framework



Why Treat & Condition?

- Enhance security and safety particularly for weapons-usable materials
- Reduce costs for future storage/disposal
- Tailor products to meet waste acceptance criteria
- Manage infrastructure footprint
- Establish lifecycle certainty

Key Considerations for T&C

Front-end

Defining the materials to be treated/conditioned

Characterizing the materials to be treated/conditioned

Documentation (material provenance, operating/use history, support future [unknown] needs)

Back-end

Material end-point (storage/disposition)

Waste acceptance criteria & product form

Synthesis

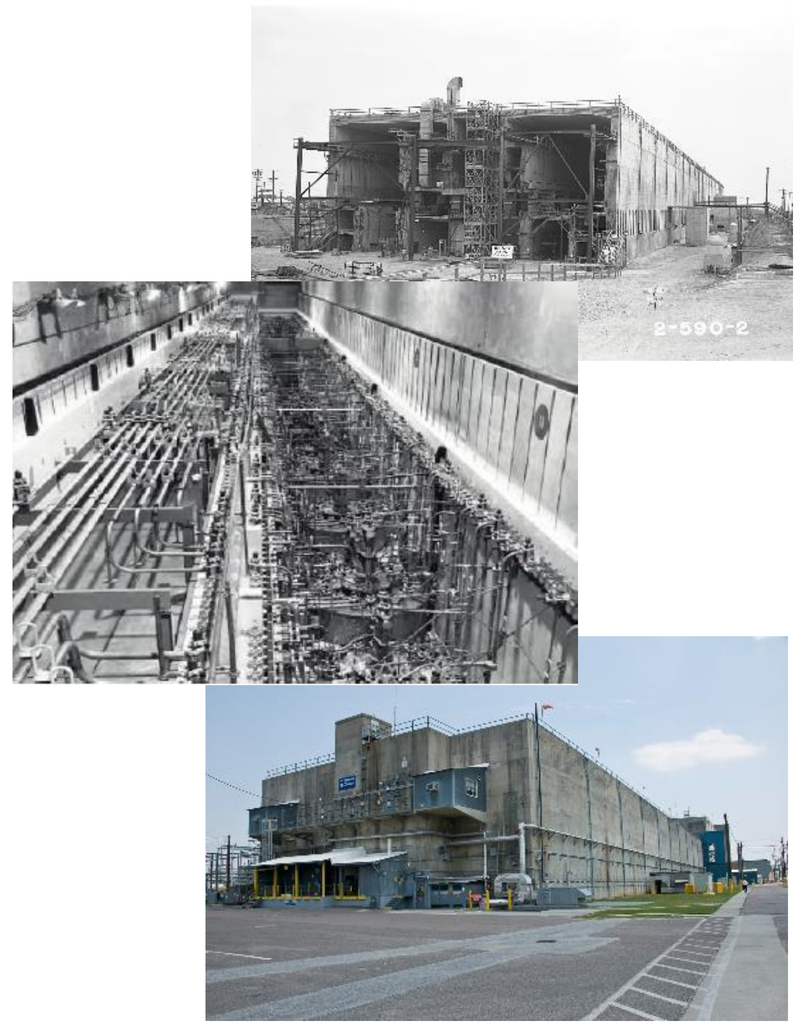
Given these: what options are technically, economically, and politically feasible?

DOE's "Traditional" SNF Management Practices

Traditional Approaches: Conventional Processing

H-Canyon is the only operating, production-scale, shielded separations facility in the United States

- Has operated since 1955
- Although primarily used for aluminum clad MTR fuel, it has also been applied to non-standard SNF such as U-Th metal fuel
- Early application included separation of fissile material but this approach has now fully transitioned to the "ABD mission" which is primarily a downblending and vitrification operation

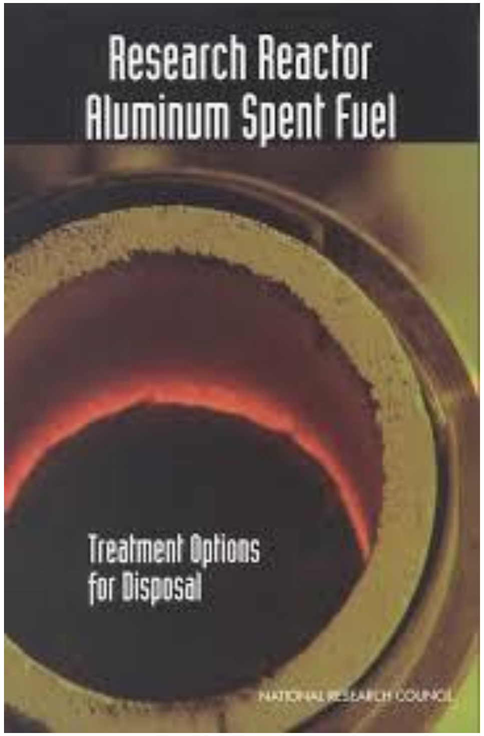


Photos source: DOE

Traditional Approaches: Other T&C Options

1998 National Academies report summarizing possible "treatment" options for ASNF

- Examined 11 "treatment" technologies for ASNF relative to conventional processing, including two DD options and MD
- Other options examined included:
  - "Press-and-dilute" (two variants)
  - Electrometallurgical processing
  - Dissolve and vitrify
  - Glass material oxidation and dissolution
  - Plasma arc
- The two final options were screened out before further analysis
  - "Canister-in-canister"
  - "Chop-and-dilute"



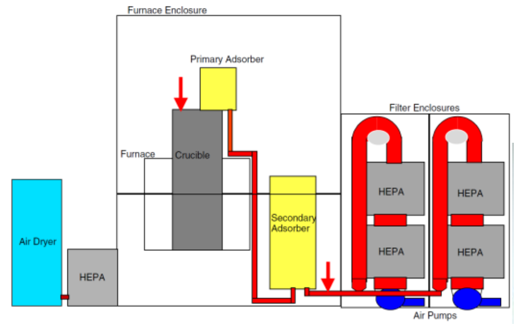
Source: National Academies, 1998

Although primarily focused on Al-Ualx and Al-UO2, it has subsequently been explored for non-standard SNF

Traditional Approaches: Alternative Technologies

Melt-dilute process for HEU ASNF

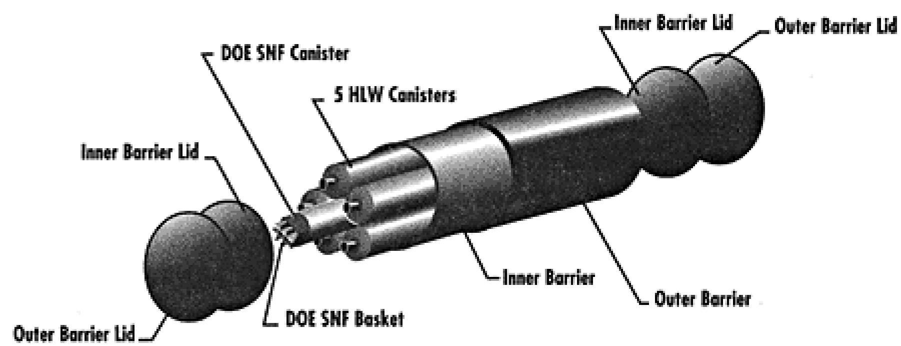
- Involves melting HEU ASNF with depleted uranium to reduce enrichment to LEU



Source: Melt Dilute Treatment of Spent Nuclear Fuel Assemblies from Research and Test Reactors, H.B. Peacock et al. , RERTR Conference, Budapest 1999

Direct (Co-)Disposal

- Fuel would be conditioned, packaged, and emplaced in a repository



These technologies have not been implemented due to funding limitations and lack of a suitable repository

Traditional Approaches: TRIGA (UZrH fuel)

TRIGA (and other non-aluminum SNF) are transported to Idaho National Laboratory (INL) for storage pending disposition

- Triga fuels are drip dried and placed in vented storage at the Irradiated Fuel Storage Facility in the Idaho Nuclear Technology and Engineering Center
- Fuel is not currently being sent to INL per DOE agreement with the State of Idaho

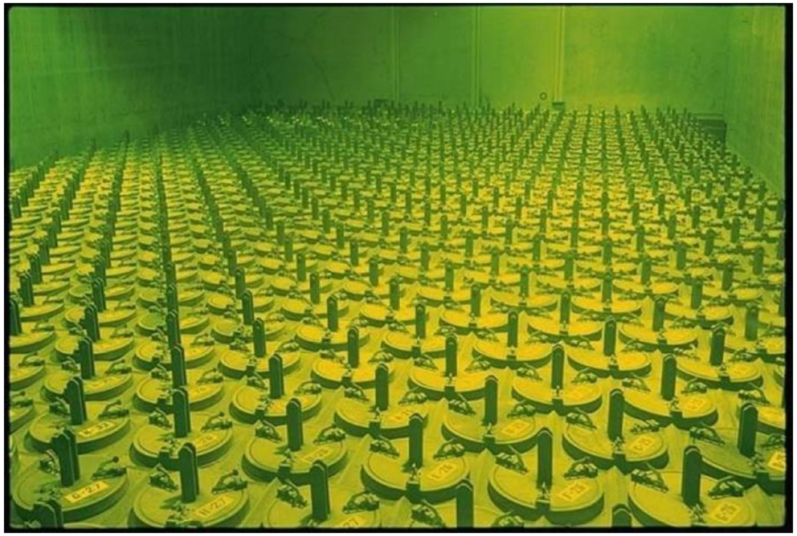


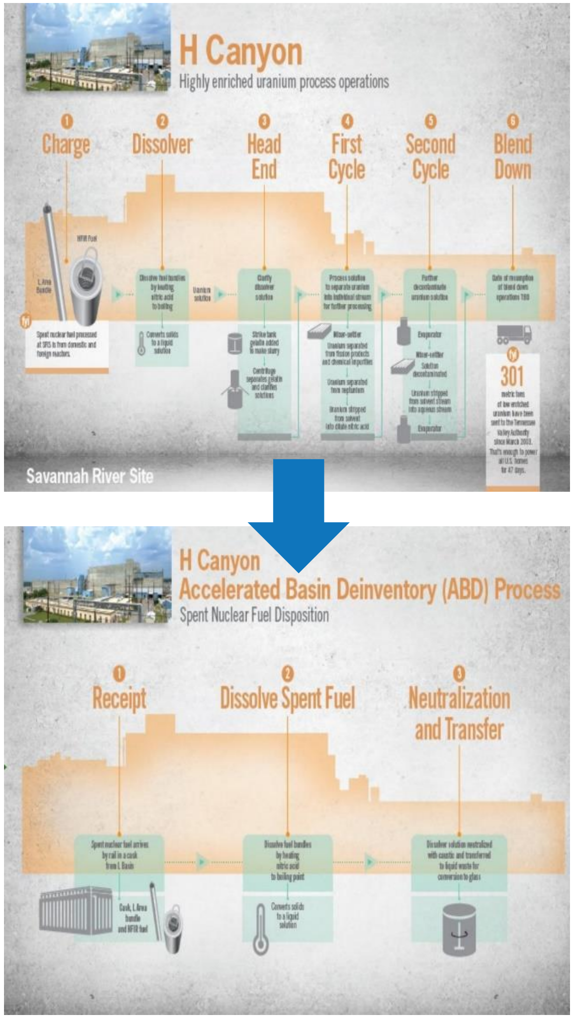
Photo source: DOE-EM

"Emerging" U.S. Treatment & Conditioning Approaches for Non-standard Fuels

Emerging Approaches: ABD

The Accelerated Basin De-inventory (ABD) mission is similar to conventional processing in H-Canyon; however, actinide materials are not separated: they are sent to the liquid waste system for vitrification

- Enables significantly faster processing of ASNF at lower risk and cost
- Downblended uranium solution is vitrified with fission products, limiting the practical recoverability of the material
- This approach was also adopted for a small inventory of U-Th metal non-standard fuel



Source: SRS Presentation to South Carolina Governor's Nuclear Advisory Council, October 2022

Emerging Approaches: Mobile Melt-Consolidate (MMC)

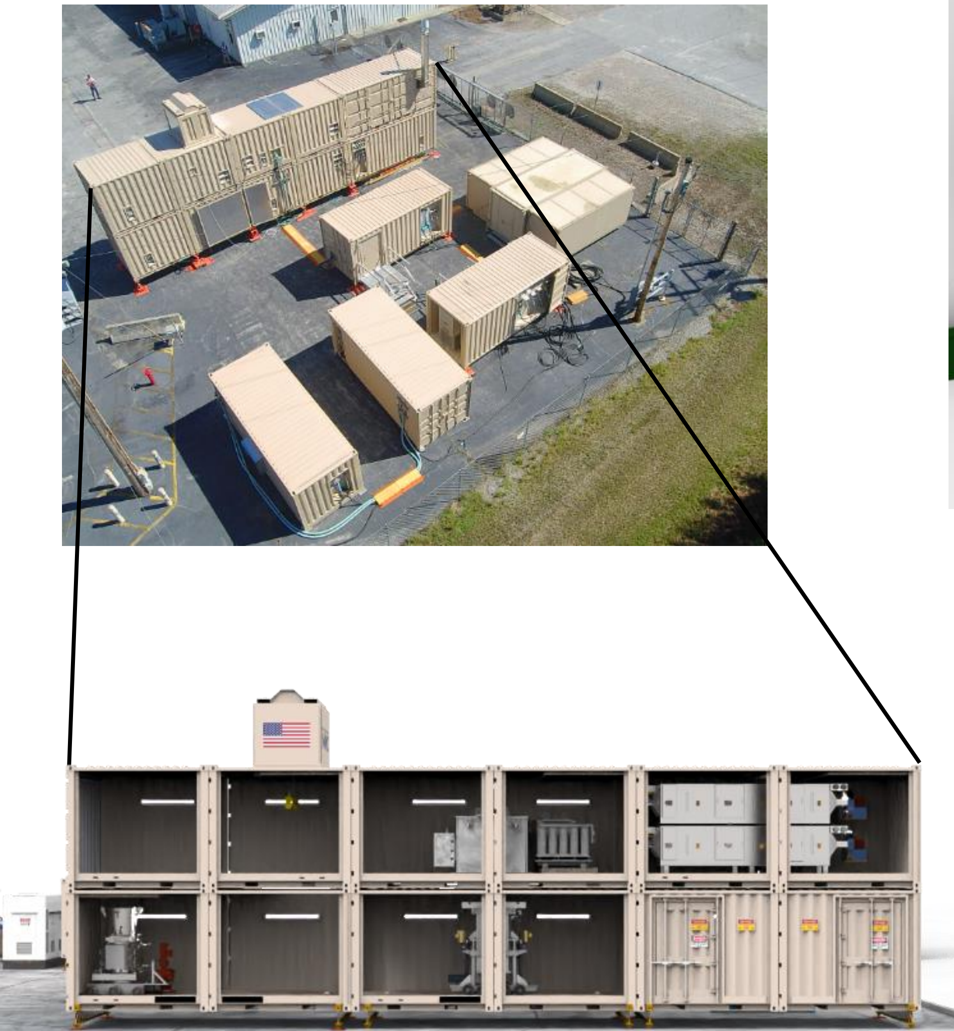
Builds on the lessons learned from melt-dilute, broadens the gamut of processable materials, and does so in a deployable footprint

- Enables treatment and conditioning (including downblending) at a partner's existing facility
- Significant U.S.-Norway cooperation on this project, targeting shipment of the system to Norway in 2025

Material Type	Research reactor fuel elements or bulk materials containing HEU
Chemical Form	Metal, alloy, oxide, silicide, carbide, graphite
Primary* Heavy Metals	Uranium, thorium
Cladding	Aluminum, stainless steel, magnesium, zirconium alloys
Irradiation	Unirradiated or irradiated
Product Mass (Per Batch)†	Up to 100-200 kg
Typical Inventories	10s to <100 kg fissile; 5-10 countries

*Small amounts of other actinides (e.g., capture products) are compatible
† Includes total mass of targeted material and additives

Emerging Approaches: Mobile Melt-Consolidate



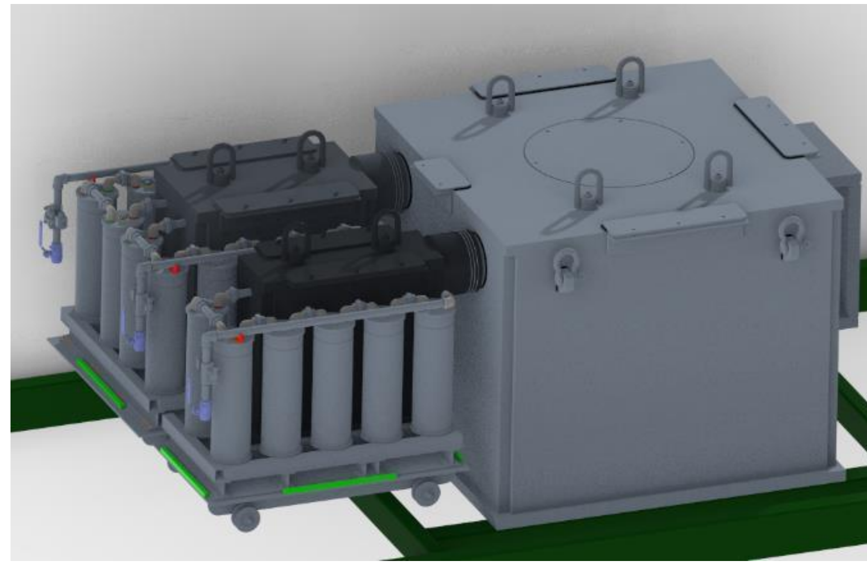
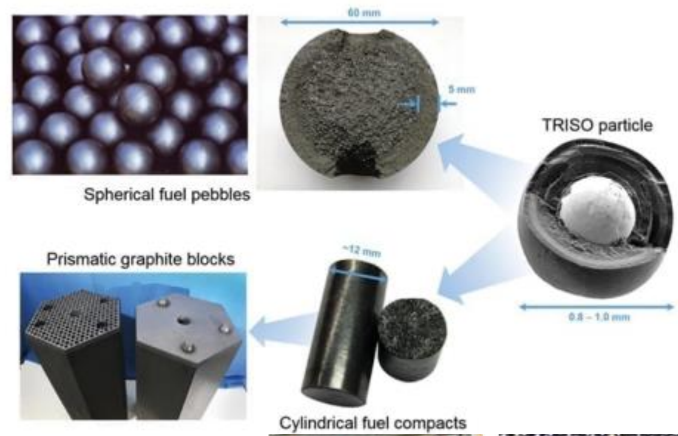


Photo Source: SRNL, DOE/NNSA, M3 program documents

Emerging Approaches: Managing Graphite

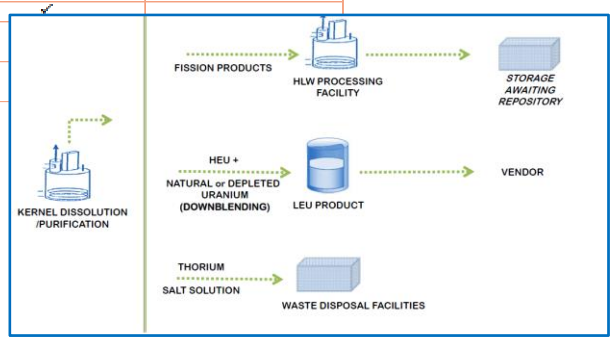
Significant interest (past and present) in graphite fuels

- Many different approaches to removing graphite
- Multiple U.S. National Labs exploring

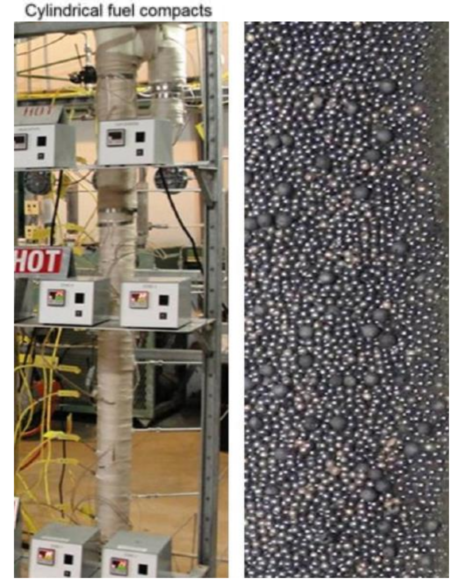


	Block and compact deconsolidation	Pyrolytic carbon breach	Silicon carbide breach
Acid Intercalation	✓		
Thermal Shock	✓	✓	✓
Acoustical		✓	✓
Hot Chlorine Gas		✓	✓
Pyrometallurgical		✓	✓
Combustion		✓	
Electrolytic – Constant Current	✓		
Electrolytic – Pulsed Current	✓		

Source: PNNL Report PNNL-32969, June 2022



Source: DOE-EM presentation to S.C. Governor's Advisory Council, July 2014



Chemical Digestion of Graphite

Source: SRNL Instagram, 2024

Emerging Approaches: Dry Downblending

NNSA has supported the National Nuclear Center of Kazakhstan in the development of a dry downblending system

- Designed to downblend graphite fuel from the IGR reactor
- Close coordination with IAEA
- Will involve crushing, grinding, mixing, cementation and then storage/disposal

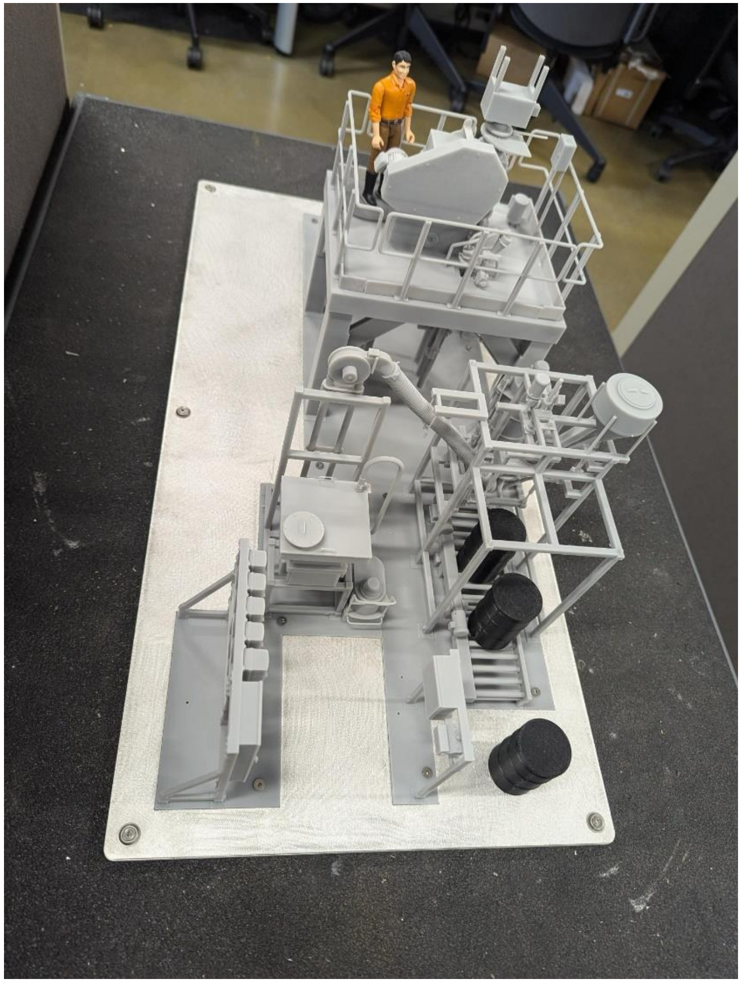


Photo Source: INL, DOE/NNSA, M3 program documents

Emerging Approaches: Next Gen Modular Downblending

As current approaches are refined and deployed, NNSA continues to explore next generation systems

- Leveraging six National Labs
- Focused on flexibility and significantly enhanced modularity, to include:
  - plug-and-play process modules
  - “mounting” in existing host facilities
  - varied waste forms
- NNSA welcomes feedback and potential applications!

Image Source: Canva

In Summary

The United States is a significant user of and has a strong interest in the development and deployment of treatment and conditioning approaches for HEU materials. These include standard and non-standard fuel materials used in research and test reactors

- Beyond the myriad economic, environmental, and safety benefits these techniques produce, they also facilitate the elimination of weapons-usable nuclear materials (WUNM)
- Ensuring HEU minimization is factored into waste management plans is a critical step in reducing the amount of excess WUNM globally
- NNSA/M3 continues to make investments in HEU downblending technologies and other approaches to eliminate WUNM in support of its partners and international nonproliferation efforts
- These technologies can be leveraged for application to LEU/HALEU based spent fuel – standard and non-standard