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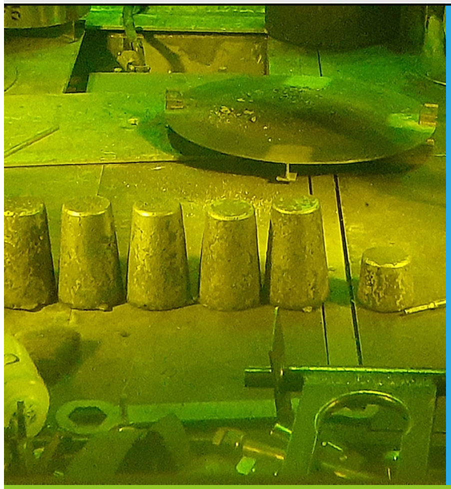
Used Fuel Treatment



Update on EBR-II Used Fuel Treatment

Presentation to the National Academy of Sciences Committee

Merits and Viability of Different Nuclear Fuel Cycles and Technology Options and the Waste Aspects of Advanced Nuclear Reactors

INL/EXT-21-64586

Idaho National Laboratory

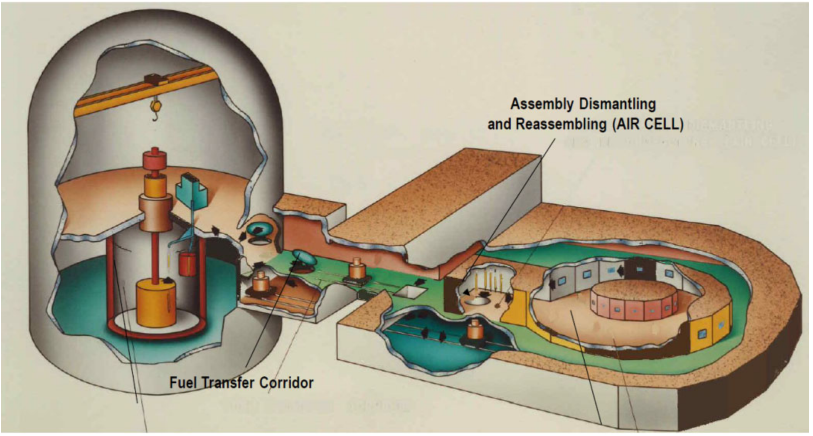
Outline

- Initial Demonstration of the Fast Reactor/Metal Fuel Cycle Concept
- Innovation- Electrometallurgical Treatment
- Driver Fuel Treatment Initiative
- EBR-II SNF – Source of High Assay Low Enriched Uranium
- Damaged Elements and Blanket
- Waste Form Development
- Applications of EBR-II Treatment Technologies in Advanced Fuel Cycles – Lessons Learned

Successful Demonstration

Recovery of uranium from irradiated EBR-II fuel

- Experimental Breeder Reactor II (EBR-II) and the adjacent Fuel Cycle Facility (FCF) were built to demonstrate recycle of metal alloy fuel.
- Recovery and reuse of uranium irradiated in EBR-II was successfully demonstrated from 1964 - 1969
  - Approximately 2.4 metric tons of irradiated fuel was processed in FCF using a pyrometallurgical purification process called “melt refining”



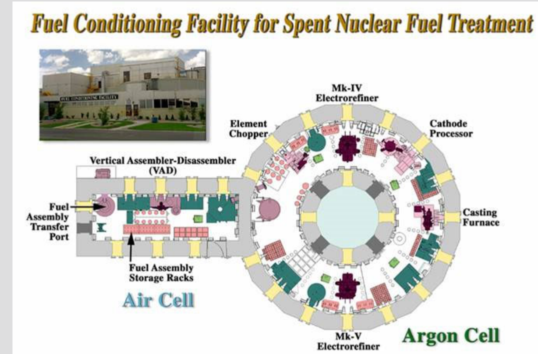
Graphite crucible coated with ZrO_2, similar to what was used in melt refining

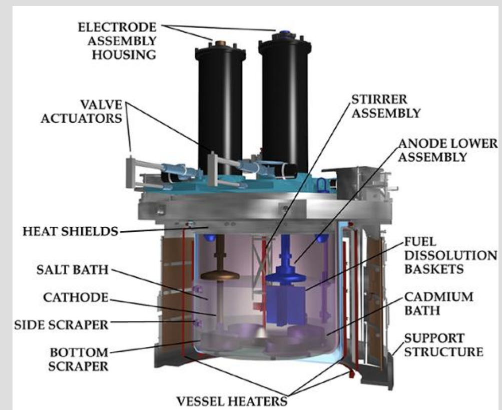
Highly Enriched Uranium pins formed via injection casting

More than 34,000 fuel rods were remotely fabricated and returned to EBR-II for power generation, some up to 4 times

Innovation in Uranium Metal Recovery

- Today's pyroprocess began as a part of the Integral Fast Reactor (IFR) program in the 1980s.
  - Active investigation by multiple nations for advanced fuel cycles
- Melt refining step replaced by molten salt electrorefining
  - Improved separation of fission products (especially noble metals)
  - Capability to recover group U/TRU product
- DOE identifies Electrometallurgical Treatment (EMT) as the preferred alternative
  - 3-year successful feasibility demonstration of the electrorefining concept to deactivate metallic sodium in EBR II driver and blanket elements results in September 2000 Record of Decision for the Treatment and Management of Sodium Bonded Spent Nuclear Fuel





Mk-IV Molten Salt Electrorefiner at INL

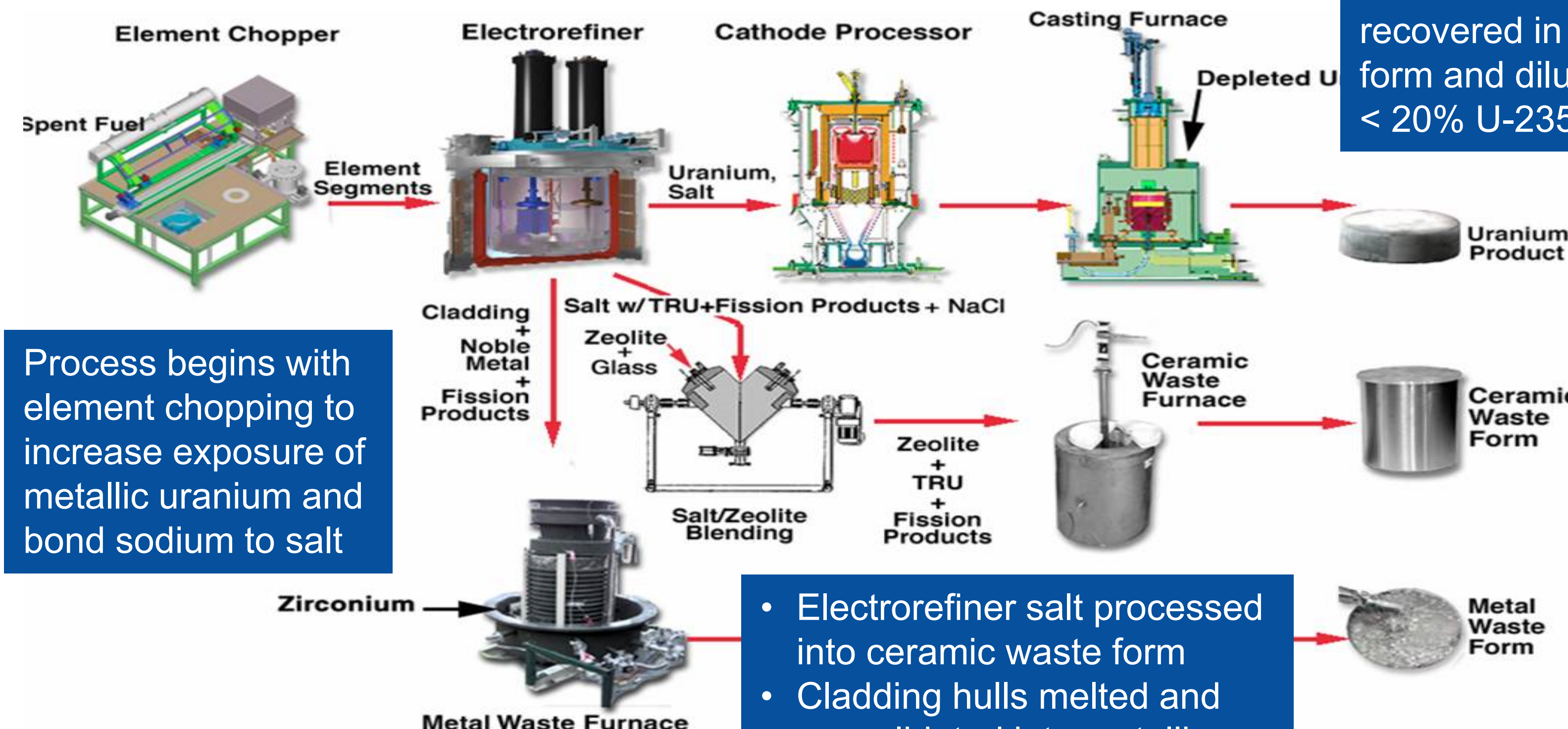
Electrochemical Process Flowsheet

Sodium-Bonded Used Fuel Treatment & Baseline Waste Form Development

Molten salt electrorefiner separates uranium from bond sodium, bulk fission products and Pu

Enriched uranium recovered in metallic form and diluted to < 20% U-235

Process begins with element chopping to increase exposure of metallic uranium and bond sodium to salt



- Electrorefiner salt processed into ceramic waste form
- Cladding hulls melted and consolidated into metallic waste form

Driver Fuel Treatment Initiative

- Closure actions associated with the Fast Flux Test Facility (FFTF) result in sodium bonded metal fuel transferred to INL - 2008
- Building on success of EMT processing of EBR-II irradiated elements, INL called on to treat FFTF metallic fuel
- Processing equipment in FCF configured to accommodate longer length FFTF elements
- Operations schedule expanded to 7 days/week, 12 hrs./day
- Treatment commences in 2011, concludes 13 months later after 24 successful treatment batches amounting to 220 kgs of FFTF HEU fuel demonstrating high throughput capability
- Success of FFTF campaign leads to increased focus on treatment of EBR-II HEU driver fuel
  - Supports progress toward Idaho Settlement Agreement milestones
- Driver Fuel Treatment Initiative commences at end of FFTF campaign facilitating return of early generation EBR-II HEU driver fuel to FCF and subsequent treatment via EMT

FFTF reactor in Hanford, WA

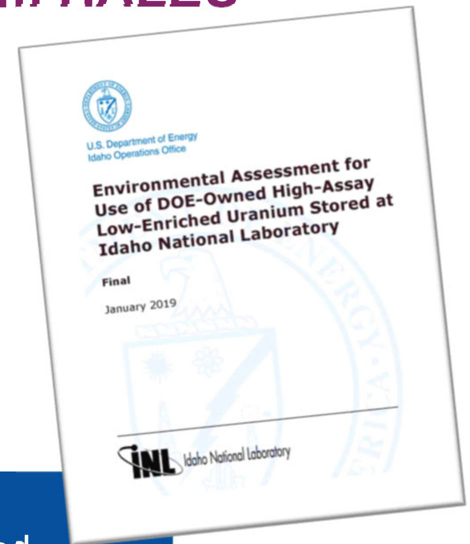
Cask shipment of FFTF fuel

FFTF fuel at FCF awaiting processing

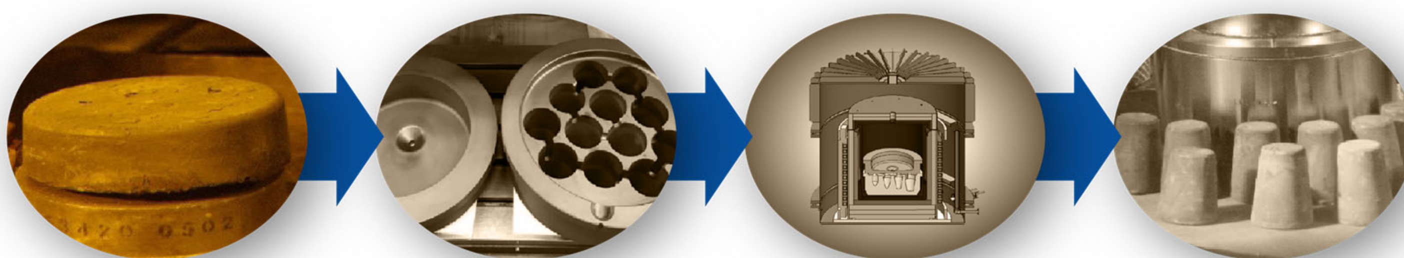
HALEU Influence on EBR-II Driver Treatment

EBR-II Driver Fuel Identified as Potential Near-Term HALEU

- Advanced reactor concepts spur interests in HALEU availability and potential application for recovered EBR-II material
- Environmental assessment (DOE/EA-2087) conducted in January 2019 covering metallic and ceramic fuel fabrication using EBR-II HALEU
- Decontamination investigations conducted to improve handling of EBR-II HALEU in potential fuel fabrication scenarios
- HALEU production process integrated with EBR-II treatment in FCF



- INL has generated more than 4 MT of HALEU metal from used EBR-II fuel.
- Currently 950 kgs is ready to be used as a feedstock for fabricating advanced reactor fuel, with a cumulative quantity approaching 2 MT available by end of 2022.



Large ingot
Diameter = 20 cm
Thickness = 2.5 – 7.5 cm
Weight = 30 – 40 kg

New multi tier crucible system
Converts the large ingot into fuel fabrication-ready reguli

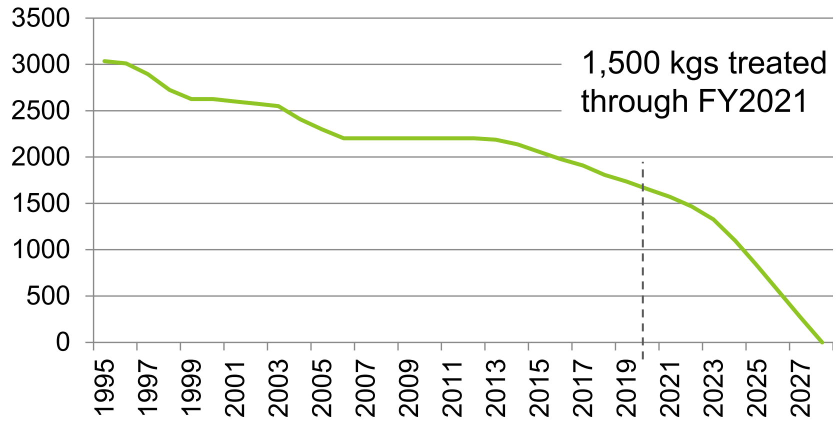
Recast in high temperature furnace
Multi tier crucible used to recast ingot into reguli

Fuel fabrication-ready reguli
Diameter = 6 cm
Height = 9 cm
Weight = 3.3 kg

2019 Supplemental Agreement

Idaho Settlement Agreement

- DOE and the State of Idaho renegotiate the completion deadline for EBR-II driver fuel treatment accelerating end date for treatment by 6 years
- Accelerated end date drives the need for accelerated throughput rate



- Process efficiency increases being pursued through reduction of single point failures and increases in facility availability
- Operations schedule returned to 7 days/week, 12 hrs./day in April 2019
- 24 hour per day operations targeted to commence in FY2024

November 2019 Supplemental Agreement

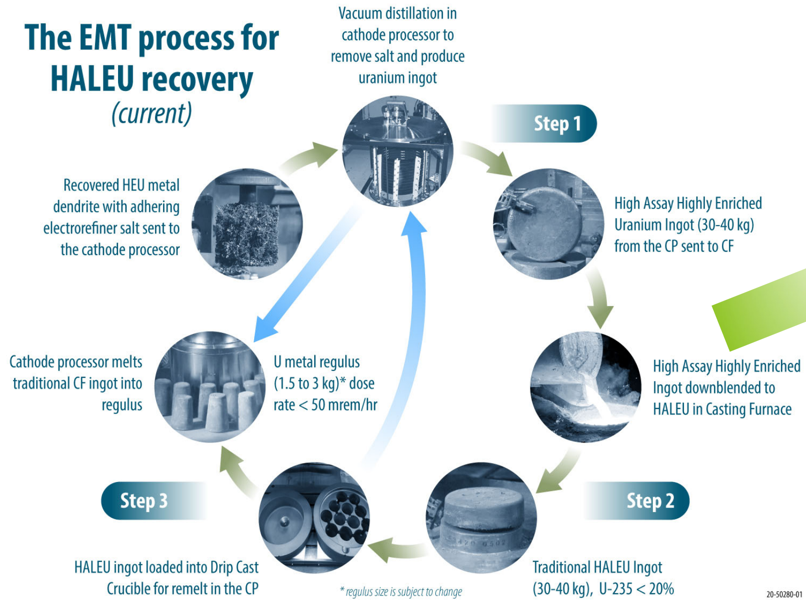
- *DOE shall treat at least 165 pounds (74.8 kg) heavy metal of Sodium Bonded EBR II Driver Fuel pins per year on a three-year rolling average basis; and*
- *DOE shall complete treatment of all Sodium Bonded EBR II Driver Fuel Pins by December 31, 2028; and*
- *Except for HLW, DOE shall dispose of any waste materials, including but not limited to fuel pin cladding material generated during treatment outside of the State of Idaho by not later than January 1, 2035; and*
- *Any HLW generated during treating shall be treated so as to put it into a form suitable for transport to a permanent repository or interim storage facility outside of the State of Idaho by a target date of December 31, 2035; and*
- *If DOE has not put all the treated product material to beneficial use DOE will remove all treated product material from the State of Idaho by January 1, 2035*

Process Efficiency Increases

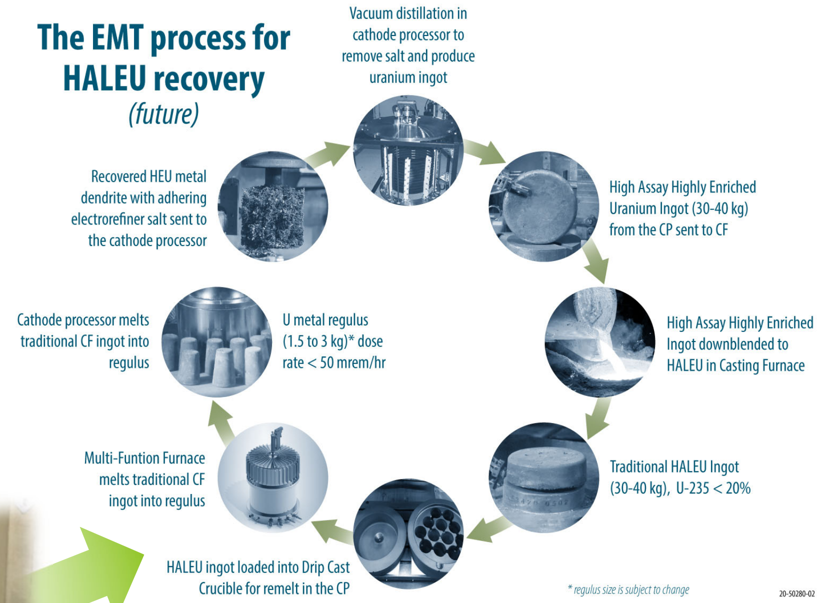
Reduction in Bottlenecks

New high temperature, vacuum atmosphere furnace acquired, installation planned for 2022

- Will increase efficiency of HALEU regulus production, eliminating the current bottleneck
- New furnace functionality will provide redundancy in distillation and casting activities, addressing single point failure risks



New Multi-Function Furnace

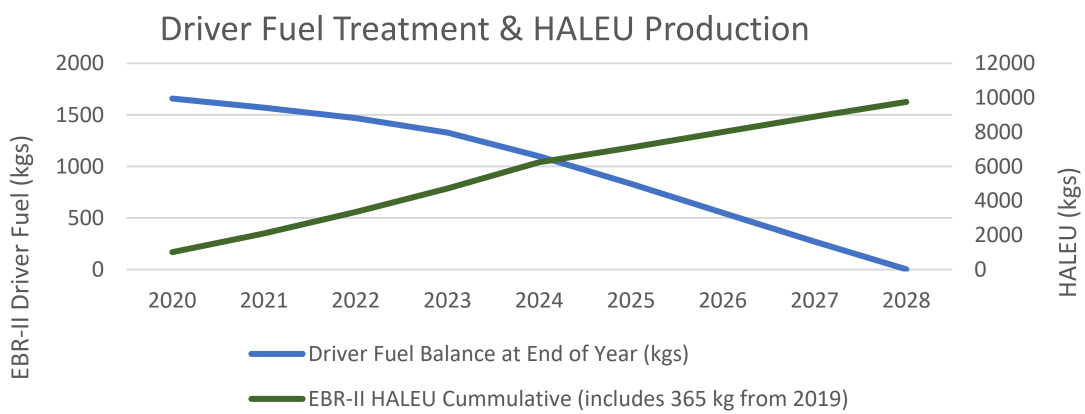


Process Efficiency Increases

Expanded Capability

Reconfiguration and deployment of new technology planned for the Mk-V electrorefiner will enable its use in EBR-II driver fuel treatment

- Mk-V electrorefiner will support testing of new technology intended to reduce handling requirements during electrorefiner treatment
- The Scraped Cathode Rod Assembly Prototype "SCRAPE" will collect and consolidate recovered uranium while in the electrorefiner vessel, reducing frequency and duration of uranium removals during a batch
- SCRAPE technology will also explore incorporation of consumable product collectors manufactured from depleted uranium to further reduce handling steps
- Removal of bottlenecks, increases in redundancy, reduction in handling steps, deployment of new technology are keys to accelerated treatment and HALEU production.

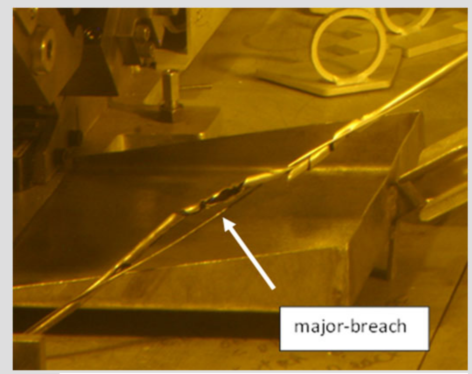


SCRAPE Assembly

Damaged Elements
Non-Candidate Material

- Occasionally irradiated elements are encountered exhibiting signs of significant corrosion as result of cladding breaches exposing the bond sodium and uranium metal to air or water.
- This corrosion typically results in the conversion of the metallic uranium to oxide which is not amenable to treatment via electrorefining. The resultant material is referred to as “non-candidate”
- Advanced pyrochemical techniques such as oxide reduction may be applicable for treatment.
- Research is underway to provide additional characterization and development of potential treatment alternatives that are compatible with baseline EMT process
- Current inventory is less than 25 kgs, projection that inventory may grow as high as 300 kgs as inspection of fuel retrieved from wet storage continues.

Failed elements recovered from wet storage



Example of failed cladding recently inspected element

EBR-II Blanket Element Treatment

- DU ingots recovered from past blanket treatment used in dual anode configuration during recent electrorefining batches treating EBR-II HEU fuels
- New technology development associated with SCRAPE concept anticipated to significantly increase the EMT blanket treatment rate
- Alternative treatment methods are being investigated
  - Several technologies have matured since issuing the ROD/ EIS in 2000
  - Potential to develop more economical treatment approaches
- Melt-Drain-Evaporate (MEDE) technology has been successfully applied to full length element treatment studies
  - Scale up to multiple subassembly studies currently under consideration
- Vitrification concepts also being investigated through application of the GeoMelt® In Container Vitrification (ICV) technology

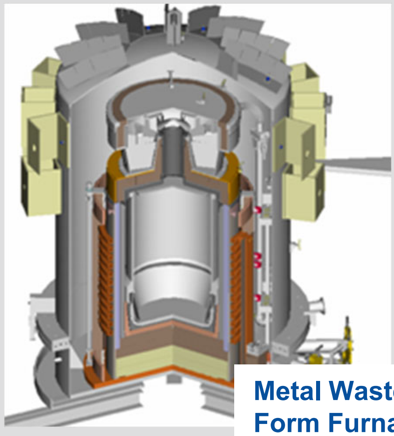
Depleted uranium recovered from blanket treatment successfully used as diluent for downblending EBR-II HEU fuels

GeoMelt® vitrification

EMT Waste Form Update - Metallic

- Baseline planning incorporates formation of durable homogenous ingot produced from stainless steel cladding and transition metal fission products (e.g Mo, Ru, Zr, Tc) remaining after electrorefining of element segments
- Adhering salts are distilled, condensed and returned to the electrorefiner
- Engineering scale process using induction furnace developed to consolidate cladding from multiple electrorefining batches into singular ingots intended to be dispositioned as high-level waste in accordance with 2000 EIS / ROD-0306.
- Ingot characterization confirms:
  - Homogeneity
  - Immobilization of the noble metal fission products
  - Accountancy of any residual actinides remaining in cladding

Cladding hulls remaining after electrorefining

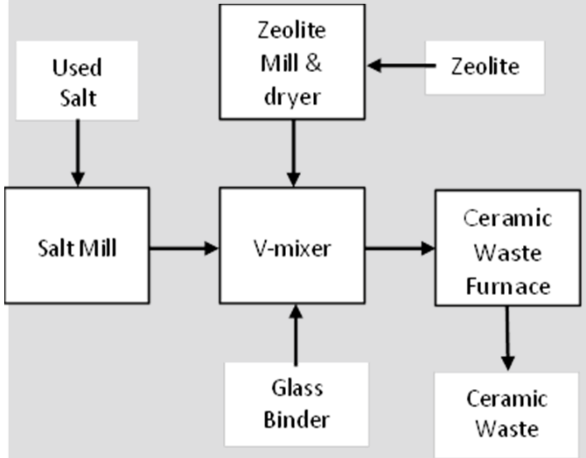


Metal Waste Form Furnace

Ingot produced from melted cladding hulls

EMT Waste Form Update - Ceramic

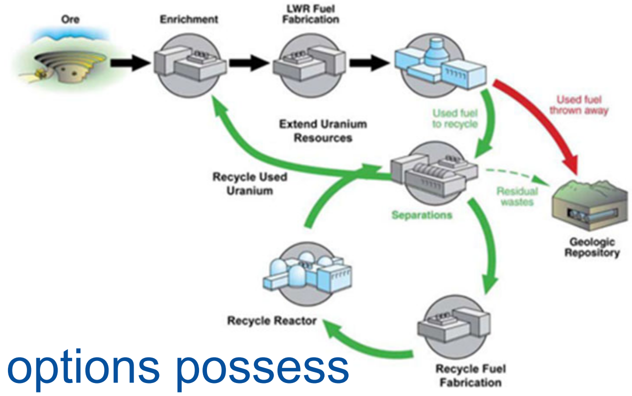
- Baseline planning assumes electrorefiner salt will be removed from treatment processing when sodium, fission products, or Pu accumulate to a point that salt is no longer effective for EMT
- Current modeling suggest driver treatment will complete with no salt replacement required. Just over 1 MT of ER salt used thus far in treatment activities
- Treatment of blanket elements via EMT anticipated to generate additional 4MT of ER salt
- Current planning for disposition of ER salt is based on formation of a durable ceramic waste form (CWF), comparable to borosilicate glass, produced from mixing salt with zeolite and glass powder.
- Near term planning recognizes that repository availability is potentially several decades away, current focus on conditioning salt for interim storage in both inert and non-inert environments
- Alternative disposition pathways for salt involving forms other than the CWF have been researched, for consideration of placement at generic repositories with various geologies.
- ER salt recognized as a potential research asset in on going fuel cycle technology studies, including some advanced reactor concepts utilizing molten chloride fuels



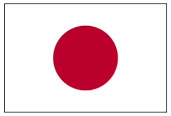
Simplified ceramic waste flow sheet

Prototype salt storage container

Lessons Learned from EMT
Foundational Experience



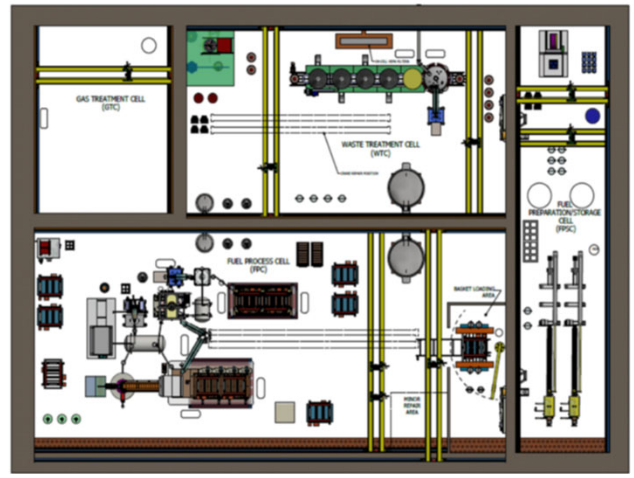
- Pyrochemical-based (“pyroprocessing”) fuel cycle options possess advantages in certain fuel cycle scenarios
  - Ideal for metallic fuels and in some scenarios nitride fuels
  - Generally paired with simple remote fuel fabrication, as is necessary for group TRU and/or multi-recycle
  - Compatible with short cooling times to limit storage inventories
  - Absence of moderator enables comparatively compact processes
  - Pyrochemical processes are generally viewed as more adaptable toward smaller and potentially co-located deployments.
  - There are many varieties of pyrochemical processes (including oxide-based), but most common meaning of “pyroprocessing” is EMT-based processes for metallic fuels
- Advantages for these scenarios also recognized internationally, most often as a component to utilize nuclear energy while limiting burial of transuranium elements
  - South Korean & Japanese studies
  - Russian operated oxide-based pyroprocess



Lessons Learned from EMT
Innovations for Modern Fuel Cycles

Modern pyrochemical fuel cycle options build on the accomplishments of EMT

- Current generation of equipment was designed in the 1980s and installed in a never-repeated facility design from in the 1950s.
- Moderns process designs adapt lessons from EMT and industrial analogues
  - Linear rather than round electrochemical systems to facilitate multiplicity with minimal salt inventory and footprint and staggered-batch continuous operations
  - New paradigm for uranium product management/harvest versus early systems
  - Elimination of unnecessary cadmium layer in electrorefiner
  - Revised engineering approach for more reliable salt vapor management in furnace systems
  - Improved understanding & management of residual contaminants
- The facility has a major role in successful deployment
  - Modern facilities integrate facility, process, and safeguards considerations
  - Processes designed to take advantage of modern facility automation versus manual handling by telemanipulators at shielded windows



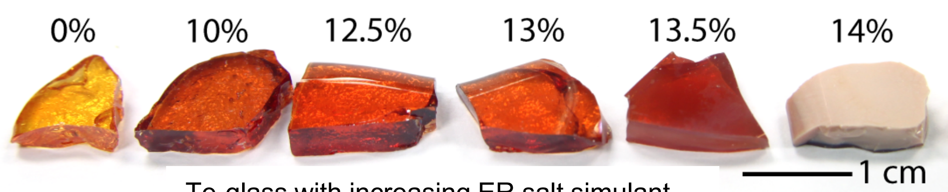
Conceptual layout of advanced pyroprocessing facility

Chang et al., Nuclear Technology
DOI: https://doi.org/10.1080/00295450.2018.1513243

Lessons Learned from EMT

Safeguards and Waste Form Advancements

- Safeguards approaches have significantly improved understanding versus initial deployment of EMT
  - Input accountancy
  - Integrated processing monitoring technologies
  - Inventory modeling
- During EMT development, considerable efforts were placed into development and qualification of the first-generation waste form for salt
  - Viewed today as a reference point between much-improved options
  - Current emphasis is scale up of iron-phosphate glasses from a much simpler process with much higher waste density, and several other waste form options have developed, depending on specifics
  - Other waste-relevant technologies have also been demonstrated, such as salt crystallization to reduce waste salt volumes.

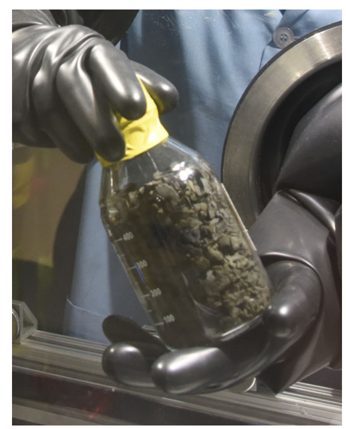


Te-glass with increasing ER salt simulant

Lessons Learned from EMT
Contributions to Advanced Reactors

- HALEU for multiple advanced reactor concepts
  - Direct feedstock for fast reactor applications
  - Polishing step to condition feedstock for expanded applications
- Molten chloride reactor fuel cycles
  - Chloride fission product behaviors
  - Large-scale actinide salt synthesis
  - Chloride salt waste forms
  - Safeguards & process monitoring sensors

Uranium metal in regulus form

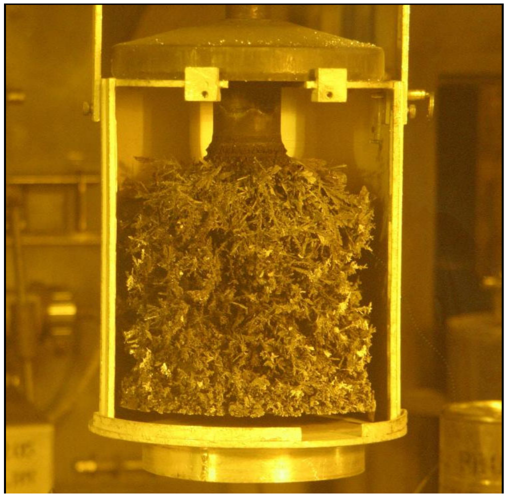


Uranium Oxide

Summary

- Treatment of EBR-II fuel is proceeding in order to achieve Idaho Settlement Agreement.
- Some processing and equipment adjustments are being performed to increase treatment rate and reduce schedule risk.
- Pyrochemical fuel cycles provide advantages in certain fuel cycle scenarios.
- Experience with originally-installed process equipment for EBR-II treatment has established feasibility and groundwork for modern pyrochemical process options.

Wet fuel storage basin housing EBR-II fuel



Uranium metal removed form electrorefiner

Recovered uranium metal in regulus form