Back-End of the Nuclear Fuel Cycle

Used Fuel Management for Advanced Reactors

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National Academy of Sciences, Engineering and Medicine:
Merits and Viability of Different Nuclear Fuel Cycles and Technology Options and the Waste Aspects of Advanced Nuclear Reactors
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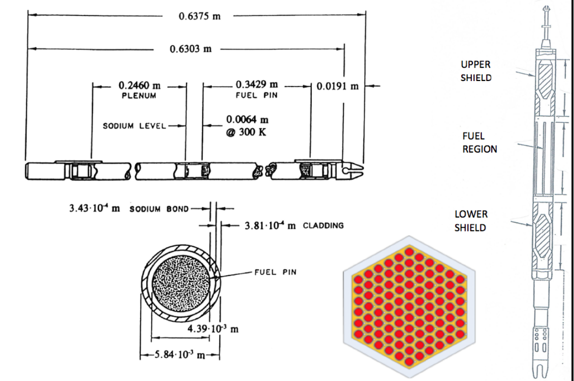
Overview of Presentation

1. Advanced Reactor Fuel Types
2. Generic Fuel Cycle Approach
3. Recycling of Advanced Reactor Fuel Types
4. The U.S DOE’s Standard Contract
5. Current Advanced Reactor Status
6. Takeaways

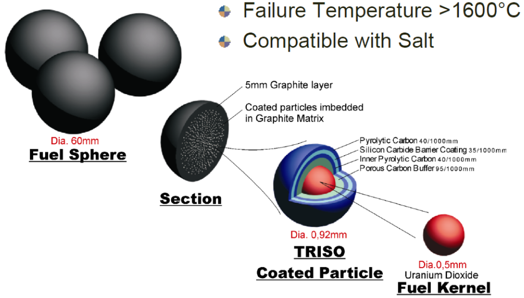
1. Advanced Reactor Fuel Types

1. Primary Fuel Forms
   - Oxide/ceramic fuels
   - Metallic fuels
   - TRISO fuels
   - Liquid fuel salts
   - Thorium fuels (no further discussion)
2. Fuel Enrichments/Content
   - LEU (< 5% enriched U-235)
   - LEU+ (≥ 5% and < 10% enriched U-235)
   - HALEU (≥ 10% and < 20% enriched U-235)
   - HEU (≥ 20% enriched U-235)
   - Mixed U & Pu (oxide, metal, or salt)

Metallic fuel



- Demonstrated in gas-cooled high-temperature reactors
- Failure Temperature >1600°C
- Compatible with Salt



1. Advanced Reactor Fuel Types: Oxide / Ceramic

Some key attributes of ceramic/oxide fuels include:

- Extensive operating, manufacturing, and irradiation experience with UO_2 and MOX fuel
- Sintered pellet UO_2 or MOX fuel similar in design to an existing-LWR oxide fuel pellet
- Fission gas plenum (often helium filled when manufactured)
- **Extensive recycling experience of UO_2 and some experience with MOX**
- **Additional treatment of SNF may be necessary if to be directly disposed of in canisters**

Reactor	Reactor Type	Enrichment
NuScale	Integral PWR (77MWe)	LEU <4.95%, 17x17 6'long
GE Hitachi BWRX-300	ABWR (300MWe)	LEU, 3.40%(avg) /4.95% (max), 10x10
Holtec International SMR-160	Mini-PWR (160MWe)	LEU, 4.95% max, 17x17
Westinghouse SMR	Integral PWR (225MWe)	LEU, <5%, 17 x 17
General Atomics EM^2	High Temp Helium Gas Cooled Fast Reactor (GT-HMR) (265MWe)	LEU, 14.5%, with DU carbide and accident tolerant cladding material

1. Advanced Reactor Fuel Types: Metallic

Some key attributes of metallic fuels include:

- U-Zr or U-Pu-Zr alloy rods (good irradiation stability)
- Often sodium-filled gap between the fuel and cladding (keep fuel temperatures low)
- Fission gas plenum (argon filled when manufactured, accommodate high gas release)
- Injection cast as cylindrical slugs and placed inside the SS or advanced alloy cladding tubes
- **Some recycling experience (pyro-processing/electrochemical and aqueous polishing process)**
- **Conditioning of fuel for removal of internal sodium (bonding Na) needed to prep for disposal**

Reactor	Reactor Type	Enrichment
VTR	Sodium Cooled Fast Reactor (300MWth?)	U-Pu-Zr
TerraPower Natrium	Sodium Cooled Fast Reactor (345MWe)	HALEU/Pu
OKLO AURORA	Liquid Metal Cooled Fast Micro Reactor (1.5MW)	HALEU
GE Hitachi S-PRISM	Sodium Cooled Fast Breeder Reactor (165 & 311 MWe)	U-TRU – 10% Zr, 10.68% Pu
Columbia Basin Consulting Group	Liquid Metal (Lead-Bismuth) Cooled Fast Reactor (SMR)/ (260MWe/100MWe)	LEU

1. Advanced Reactor Fuel Types: TRISO

Some key attributes of TRISO fuels include:

- Tri-structural ISOtropic particle fuel, made up of uranium, carbon, and oxygen fuel kernel, with each kernel encapsulated by three layers of carbon and ceramic based materials
- Arranged in blocks – hexagonal ‘prisms’ of graphite or in billiard ball-sized pebbles of graphite
- For use in either high-temperature gas or molten salt-cooled reactors
- Containment of fission products remain in TRISO particles for temperatures up to 1600C
- **No successful recycling efforts demonstrated <u>yet</u> and will have high waste to fuel ratio**
- **Conditioning of fuel to remove/reduce graphite content potentially needed for disposal**

Reactor	Reactor Type	Enrichment
X-Energy Xe-100	High Temp Helium Gas Cooled Reactor (80MWe)	HALEU Pebble, 15.5%, 220,000 pebbles
Kairos Power KP-FHR	Molten Fluoride Salt-Cooled High Temp (140MWe)	HALEU Pebble, 19.75%
Framatome SC-HTGR	High Temp Helium Gas Cooled Reactor (272MWe)	HALEU (UCO) Prismatic, 14.5% avg, 18.5% max

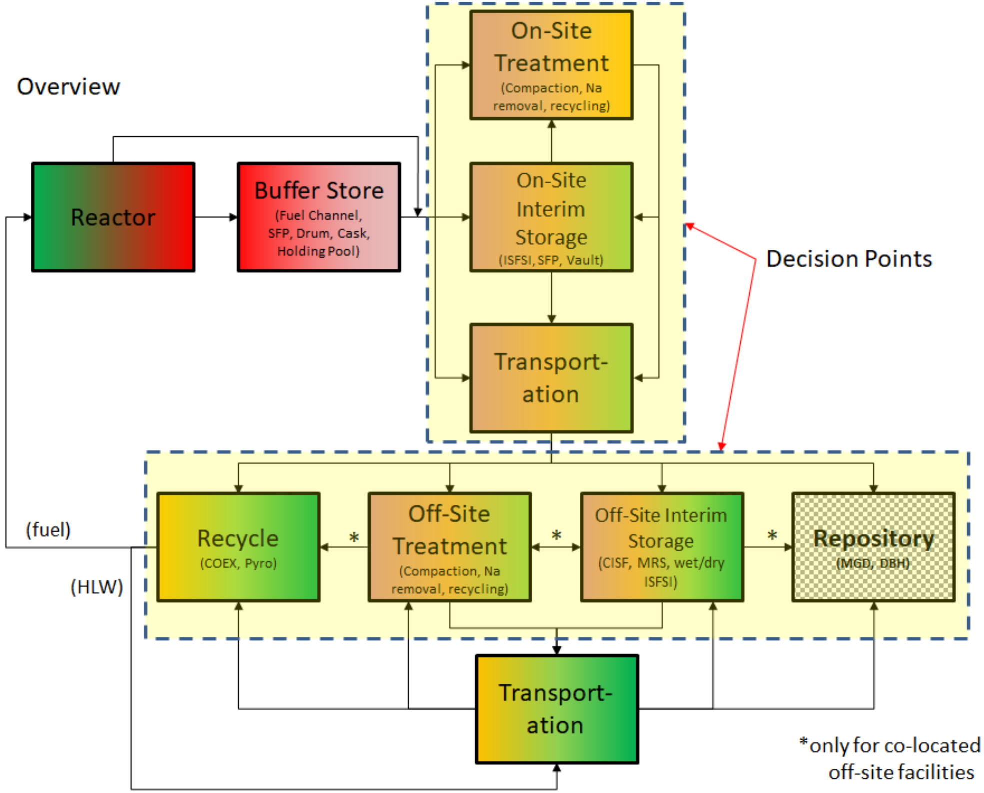
1. Advanced Reactor Fuel Types: Liquid Salts

Some key attributes of liquid salt fuels include:

- Molten fluoride or chloride salt containing fissile material
- No fuel structures like cladding, fuel ducts, grid spacers, etc.
- **Liquid fuel allows for online fueling during operation and real time conditioning/recycling/ waste processing (removal of fission products)**
  - Leads to significant overall UNF volume reduction
  - Transmutation of actinides and minor actinides in reactor
- **Conditioning of fuel (polishing and stabilization) is necessary to avoid fission product buildup in reactor and to produce acceptable waste form for disposal**

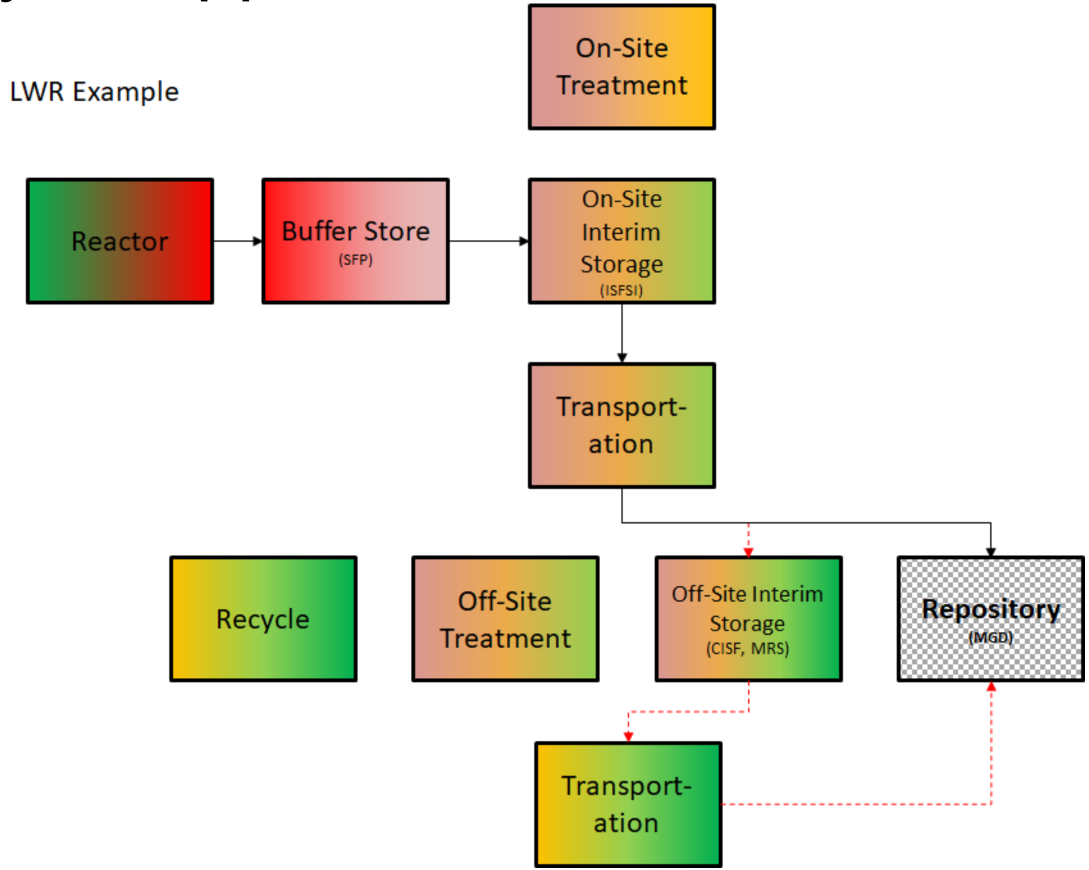
Reactor	Reactor Type	Enrichment
TerraPower MCFR	Molten Chloride Fast Reactor	Molten Chloride Salt 12% HALEU/Pu or mixture of both
Terrestrial Energy ISMR400	Molten Salt Reactor (195MWe)	Eutectic fluoride salt with <5% LEU
Elysium Industries Molten Chloride Salt Fast Reactor MCSFR	MSR – Chloride Reactor (20-2000 MWe)	Molten Chloride Salt 10% Pu fissile/(Pu+U total) or ~15% HALEU
Muons, Inc GEMSTAR	Accelerator Driven Subcritical Molten Salt Reactor (220MWe)	Molten Salt/U, DU, Thorium, SNF, excess W-Pu

2. Generic Fuel Cycle Approach: Overview



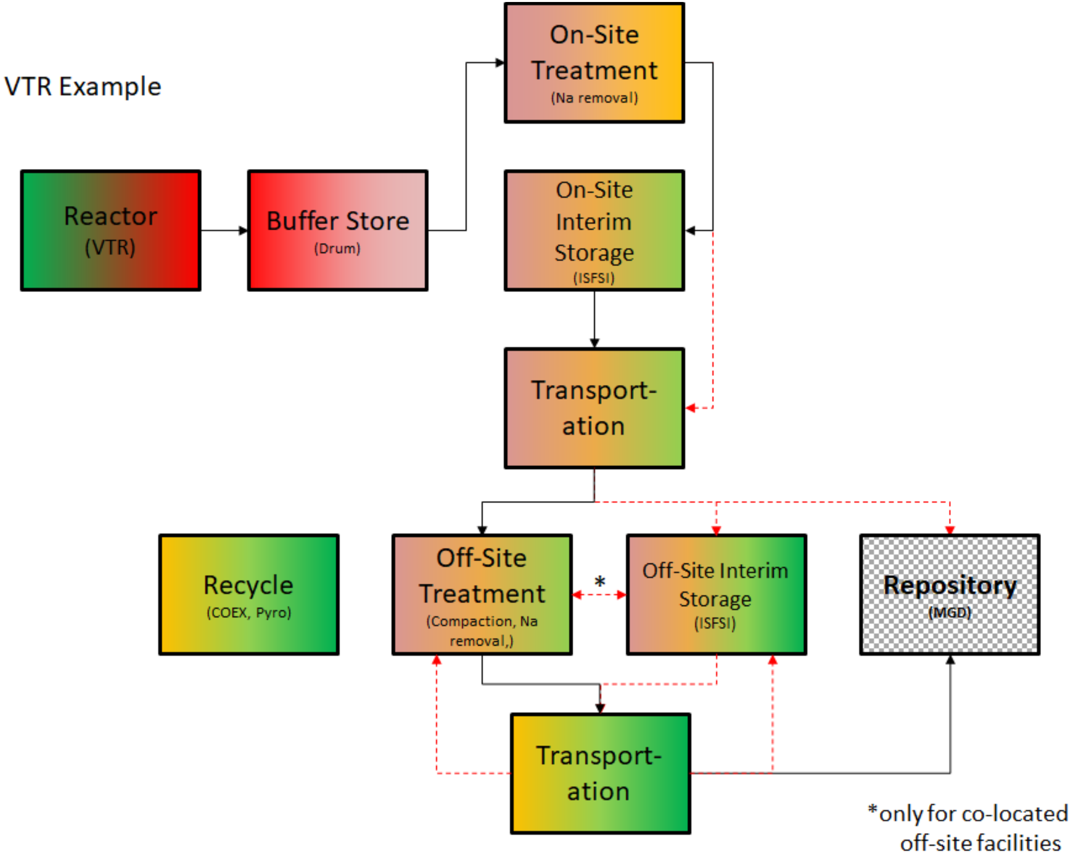
Based on this figure, there are over 600 scenarios the backend of the fuel cycle can contemplate for each reactor type (with numerous additional scenarios possible with recycling and the combining of multiple reactor types).

2. Generic Fuel Cycle Approach: U.S. LWR Plan



The red dashed lines indicate a slightly modified approach going through an off-site consolidated interim storage (CIS) or monitored retrievable storage (MRS) facilities

2. Generic Fuel Cycle Approach: VTR Proposal



The red dashed lines indicate potential alternative approaches being evaluated

2. Generic Fuel Cycle Approach: Challenges

Advanced Reactor **spent** (disposal-bound) or **used** (to be re-used) nuclear fuels can pose **challenges to waste management**, including but not limited to:

- Volume of SNF/UNF produced
- Lack of data supporting wet/dry interim and extended storage
- Protection of Category II material
- Unacceptability for disposal under "current" options and unclear acceptability for disposal under potential "future" options
- Potentially corrosive
- Potentially reactive
- Damaged SNF/UNF
- Criticality hazards
- High dose rates

Safe and secure interim solutions exist for these issues, however the real challenge is the final disposition of the "wastes" (i.e., establishing what the "wastes" are, their disposition path, and aligning and optimizing the interim solutions with the final disposition)

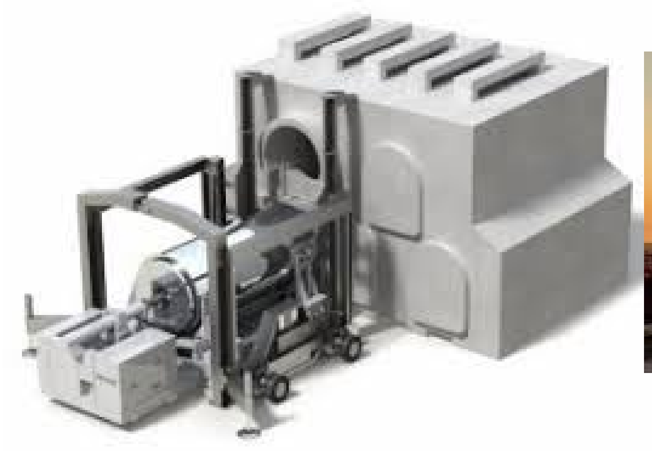
2. Generic Fuel Cycle Approach: Solutions

The backend of the fuel cycle for SNF/UNF must be considered as early in the design process as possible to account for the potential economic, technological, and regulatory challenges that it presents.

Solutions to challenges include but are not limited to:

- Recycling of UNF to reduce potential interim storage issues of UNF and produce waste form suitable for repository disposal
- Double packaging of SNF (inner package acts as cladding equivalent)
- Health monitoring of internal conditions within casks/canisters used for dry interim and potentially extended storage of UNF/SNF
- Conditioning of SNF in preparation for storage, transportation, and/or disposal
- Specifically designed packages for extended interim storage and/or disposal of SNF
- Aging management programs with inspection systems, repair/mitigation, repackaging, etc.
- High density storage systems
- Transportation systems for high burnup fuels
- Damaged fuel cans

2. Generic Fuel Cycle Approach: Example Solutions



Company	SFP Design	Pool to Pad	Dry Storage Systems	ISFSI Design	Transportation Systems	Logistics	Recycling	Treatment Processes	Repository Packaging	Repository WAC
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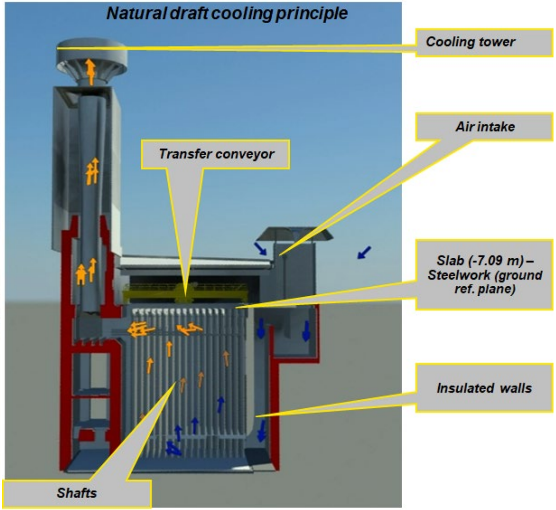
2. Generic Fuel Cycle Approach: Example Solutions



Company	SFP Design	Pool to Pad	Dry Storage Systems	ISFSI Design	Transportation Systems	Logistics	Recycling	Treatment Processes	Repository Packaging	Repository WAC
Orano	X	X	X	X	X	X	X	X	X	X

3. Recycling of Advanced Reactor Fuel Types: Options for UNF

Fuel Type	First Option	Second Option
Oxide/Ceramic UNF	Aqueous Polishing Recycle - Demonstrated mature process	Electrochemical/Pyro-Processing Recycle - Demonstrated at lab-scale - Maturation of final waste forms needed
Metallic UNF	Electrochemical/Pyro-Processing Recycle - Demonstrated process in need of industrialization - Maturation of final waste forms needed	Aqueous Polishing Recycle - Demonstrated process (with UNF from graphite reactors in France, UNGG)
TRISO UNF	Conditioning - Remove/reduce graphite in preparation for direct disposal - Preliminary studies are occurring	Aqueous Polishing Recycle - Challenge to remove outer metals (SiC, PyC) encasing fuel - Conversion of fuel to oxide - Lab-scale demo to be performed first
Liquid Salt UNF	Aqueous Polishing Recycle - Performed on-line for fuel salt - To be demonstrated	Electrochemical/Pyro-Processing Recycle - Potentially performed for bled off wastes

3. Recycling of Advanced Reactor Fuel Types: Options for UNF

Identified Concern	Aqueous Polishing	Electrochemical/ Pyro-Processing	Conditioning	Comments
Economics	Mature	Evolving	Unclear	- Positive when examined on full fuel cycle terms - Benefits may be associated with small modular reprocessing
Proliferation/ Safeguards	Mature	Evolving	Immature	- Improvements associated with implementation of safeguards by design, inclusion of real-time measurement advancements, digital twins, and co-location of facilities
Regulatory (U.S.)	Evolving	Evolving	Unclear	- NRC identified 23 gaps in 10CFR50 for recycling - NEI Working Group in process of examining work around these gaps
Waste Volumes	Mature	Evolving	Unclear	- Optimization of process designs and operations to minimize waste, majority of waste produced is LLW (disposal options exist), HLW in robust and uniform waste form - Multi-recycling in PWRs being examined for spent MOX usage

4. The U.S DOE’s Standard Contract

- The “Standard Contract for Disposal of SNF and/or HLW” establishes the T&Cs under which the DOE will make available nuclear waste disposal services to the owners and generators of SNF and HLW
- DOE will take title to, transport, and dispose of SNF and/or HLW delivered to DOE by those owners or generators who execute the contract
- Establishes the process for allocating the federal government’s finite waste acceptance capacity among those various owners/generators (including the queue)
- Amendment for “New Reactors” was added to all reactors proposed for commercial use after 2008 (Vogtle 3 & 4 first to implement)

4. The U.S DOE's Standard Contract: Findings 1/2

- DOE is under no obligation to sign a Standard Contract with a new reactor
- Without a signed Standard Contract with DOE, a new reactor cannot receive an operating license from the NRC ("Continued Storage of SNF" formerly "Waste Confidence" rule)
- With damages limited to $5 million (2008) per year for non-receipt of SNF/HLW due to DOE-related or controlled issues (no Judicial Fund awards to compensate and only credits to NWF are provided for the $5M/yr)
- No commitment from DOE to accept anything other than (bare) SNF, HLW, and non-fuel components – i.e., no commitment from DOE to accept canisters with these materials

4. The U.S DOE’s Standard Contract: Findings 2/2

- Storage and/or treatment of SNF and HLW produced from at least 20 years of operation of the reactor must be designed and paid for by the operator
- Storage and/or treatment of SNF and HLW produced from the lifetime of operations of the reactor for up to 10 years after shutdown must be designed for by the operator
- If dry storage is to be utilized and DOE willing to accept canisters, then DOE will provide a list of “approved” (by DOE and NRC) canisters

5. Current Advanced Reactor Status in the U.S.

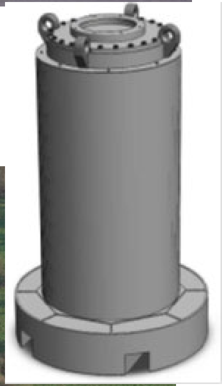
- Several of the advanced reactor vendors are currently following the existing U.S. LWR model:
  - Interim storage of UNF/SNF in wet storage facilities (SFP)
  - Transfer from wet to dry storage facilities (ISFSIs)
  - Transportation by DOE to a disposal site or to consolidated interim storage (MRS)
- In some cases, the expectation is to perform some conditioning of the UNF/SNF before acceptable for disposal, including:
  - Removal of sodium (external and internal)
  - Removal or reduction of graphite volume
  - Solidification/immobilization
- Some advanced reactors are discussing the potential of recycling their UNF as it:
  - Supports a take-back program for overseas clients
  - Allows for recovery of HALEU (and potentially other useful isotopes)
  - Reduces HLW volumes while producing a safe, stable, compact, uniform HLW form devoid of materials requiring safeguarding (simplifying repository safety, design, etc.)

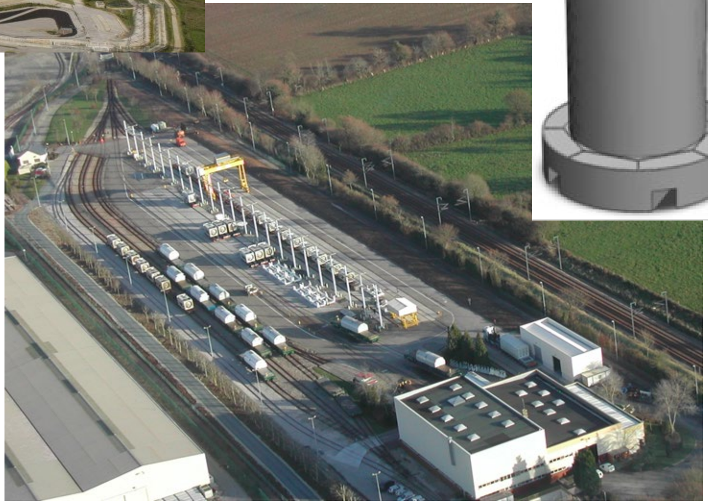
6. Takeaways

Although Used Fuel Management for Advanced Reactors may be challenging (e.g., by DOE's Amended Standard Contract):

- Solutions for the near-term exist, such as:
  - Interim storage systems designed for extended storage with internal health monitoring and application of an aging management program
- Some solutions for the long-term exist, such as:
  - Recycling of UNF to avoid extended interim storage, repackaging, safeguarding disposal, etc.
- Some solutions for the long-term are being developed, such as:
  - Conditioning of TRISO in preparation for recycling and/or disposal
  - Aqueous polishing of UNF combined with MSRs for support of recycling and proliferation goals
- Ultimately, engineering solutions either exist or can be developed to ensure the <u>safe and secure</u> handling, storing, transporting, and treating of the UNF/SNF and HLW potentially produced by the wide variety of proposed advanced reactors

Questions…





Backup Slides

Potential Conditions of Acceptance by DOE of Commercial SNF (repository agnostic?)

- No sodium (or other hazardous materials as defined in the RCRA) permitted in SNF [e.g., sodium-bonded fuels]
- Use of DOE & NRC “approved” welded canisters?
  - If DOE willing to accept canisters
  - Recall Yucca Mountain licensed using DOE Standardized Canister and Transportation, Aging and Disposal (TAD) canister
  - Standardized TAD (STAD) designed for multiple geology types
- Potential requirement for moderator exclusion in SNF package if direct disposal planned?
- Application of physical protection and MCA associated with Category I & II fuels?

An Above Grade Densification Solution for the Interim Storage of UNF

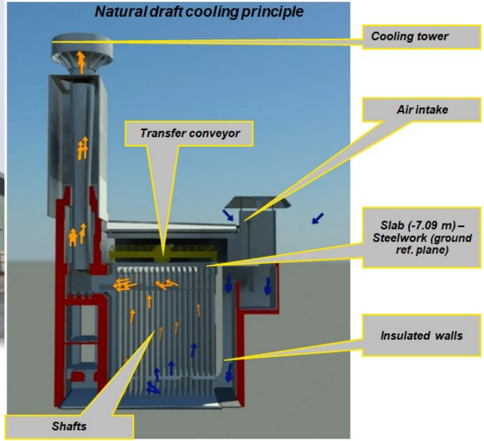
NUHOMS® Matrix System:

- Modular system design (build as needed)
- Developed with high heat rejection system allowing operator to load nearly freshly discharged fuel to dry storage
- Horizontally stacked system to take up significantly less space then current vertical and horizontal storage systems
- Demo built at TN Fabrication facility in NC and 1st unit being built at Wolfe Creek
- **Optimized design to meet requirements of many of the Advanced Reactor UNFs**

An Above or Below Grade Densification Solution for the Interim Storage of UNF

Vault Dry Storage System:

- Modular system design (build as needed)
- Vertical stacked system to take up significantly less space then current vertical and horizontal storage systems (utilized at La Hague for HLW canisters)
- Passive cooling system with natural air circulation or active system with forced air
- **Optimized design to meet requirements of many of the Advanced Reactor UNFs**

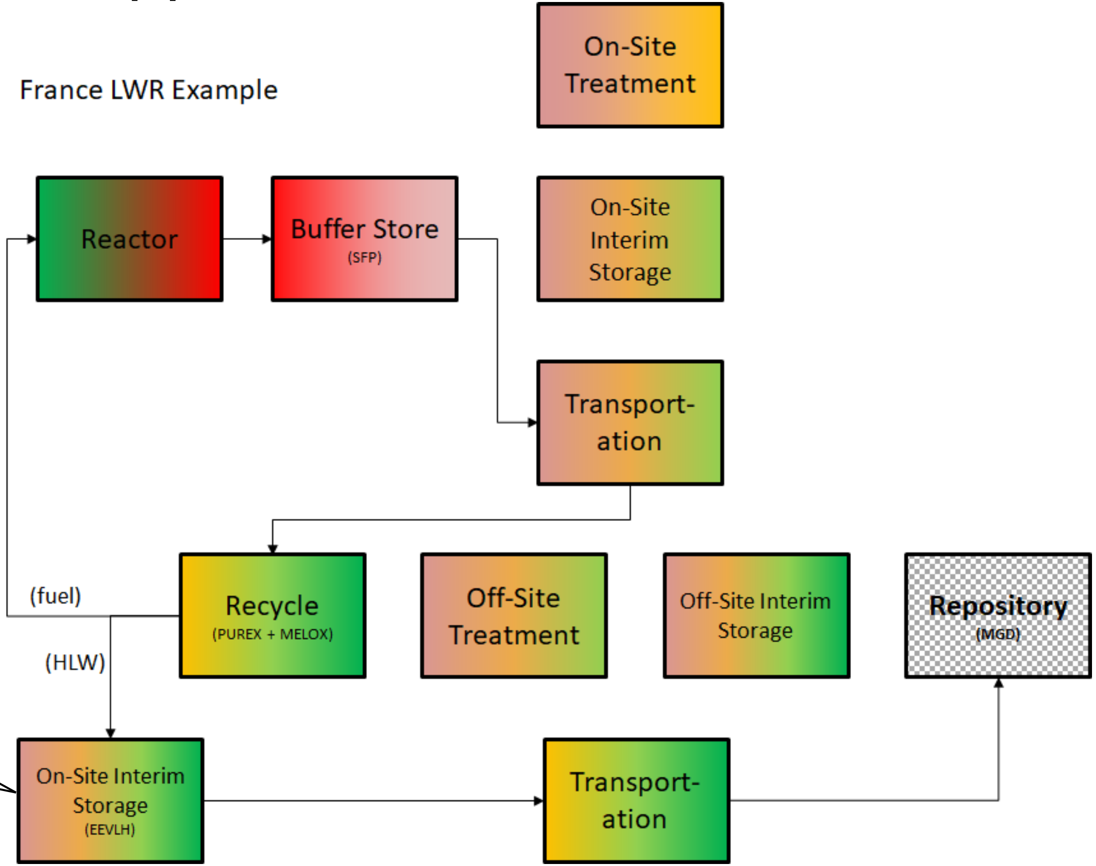


2. Generic Fuel Cycle Approach: France LWR Plan

Added a box for on-site interim storage of HLW

Does not include future recycling plans with advanced reactors

France LWR Example



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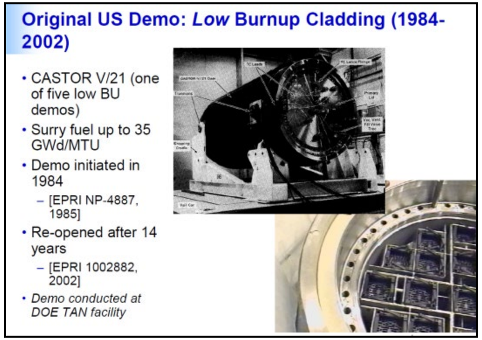
NRC Requirements for UNF Dry Storage

- LWR “low” burn-up fuel original safety basis established with demo project at INL & supported by subsequent safe storage of UNF
- LWR “high” burn-up fuel required a safety basis demonstration
  - Prairie Island & Calvert Cliffs RAIs during renewal (concern DBTT)
  - NRC wanted “industry commitment” to high BU R&D
- Ultimately data is required to demonstrate that UNF in dry storage remains safe (e.g., intact) and retrievable (if repackaging needed)*

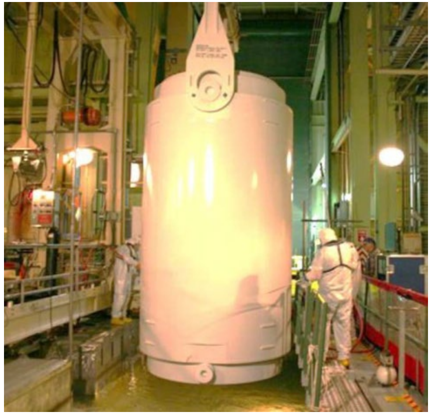
Photo Courtesy INL



* Similar requirements needed for transportation

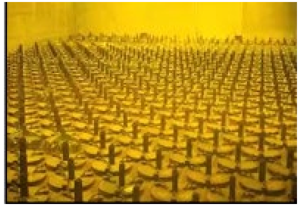
LWR High Burnup Dry Storage Demo Project

- Confirm technical basis with high burnup fuel under real dry storage conditions
- Collect data to support dry storage of HBU UNF for extended storage periods
  - Thermal data collected (63 thermocouples on 7 lances)
  - Gas sampling after vacuum drying and inerting
  - Sibling rods retrieved from UNF assemblies and sent to labs for a myriad set of tests

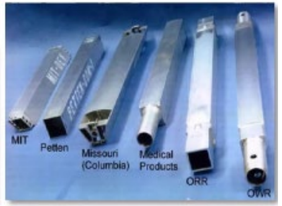


Limited Advanced Reactor UNF Data

- DOE National Labs are currently interim storing (wet and dry) a diverse inventory of SNF
- However data on SNF needed to, for example, credit cladding for maintaining structure and confinement are insufficient, as a result:
  - Significant program for characterizing Al-clad SNF
  - Much of this DOE-owned SNF will be placed into DOE standardized canisters that will provide the needed structural and confinement properties
- DOE is sponsoring programs to treat some of this SNF that is potentially unsuitable for disposal in current form, including:
  - The Melt-Drain-Evaporate (MEDE) process for removal of bonded sodium
  - Electrochemical treatment for EBR-II SNF
- Treatment approaches need to be made economically & commercially viable



CPP-603 Dry Storage
(photo courtesy INL)



Some of variety of SNF stored at National Labs
(photo courtesy INL)

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Giving nuclear energy its full value