Impact of Advanced Nuclear on the Fuel Cycle

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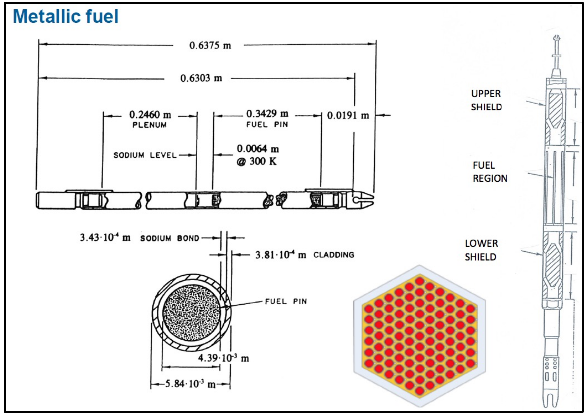
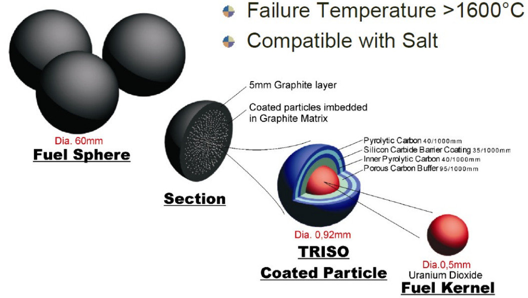
Advanced Reactor Fuel Types

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)



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



Advanced Reactor Fuels: 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
- Amended Standard Contract for receipt of UNF does not permit suing DOE, requires reactors to provide interim storage up to 10 years after shutdown of the plant, etc.

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)

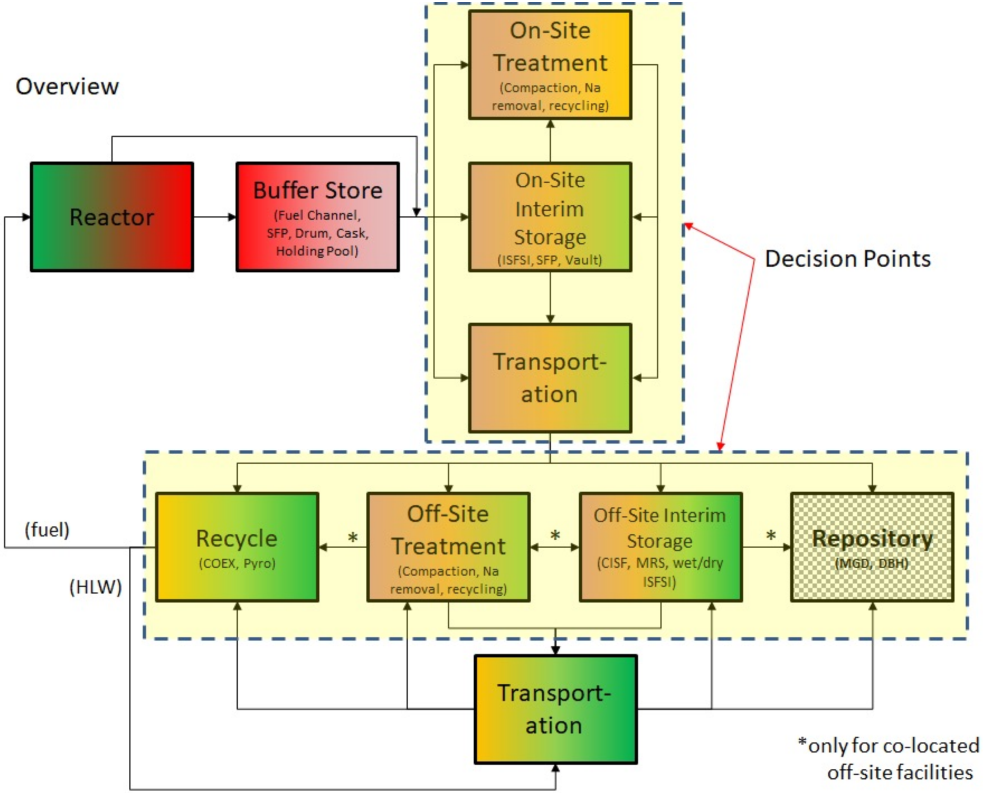
Advanced Reactor Fuels: Solutions

Solutions to these 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 exist for advanced fuels

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.

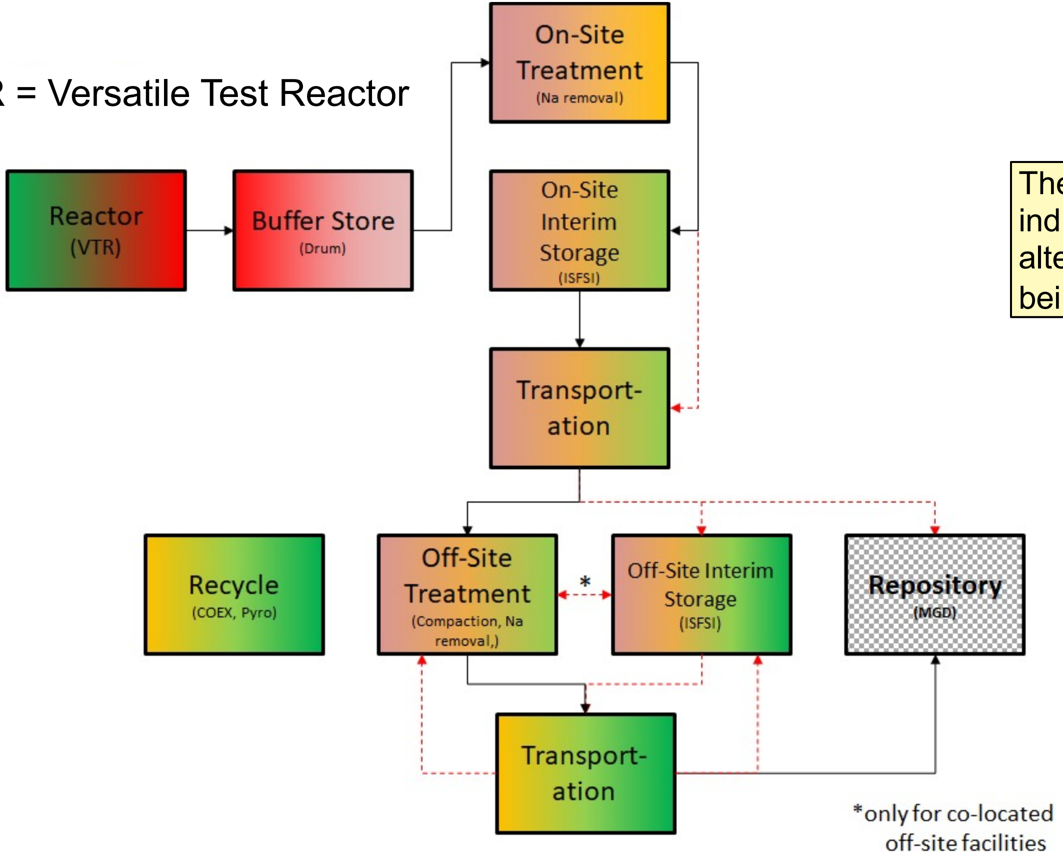
Generic Fuel Cycle Approach: Overview



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).

Example Fuel Cycle Approach: VTR Proposal

VTR = Versatile Test Reactor



The red dashed lines indicate potential alternative approaches being evaluated

Treatment of Advanced Reactor Fuel Types: Options

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	In-Line Recycling - Performed while reactor is in operation to remove FPs detrimental to operation - To be demonstrated	Electrochemical/Pyro-Processing Recycle - Potentially performed for bled off wastes

Current Advanced Reactor Status in the U.S.

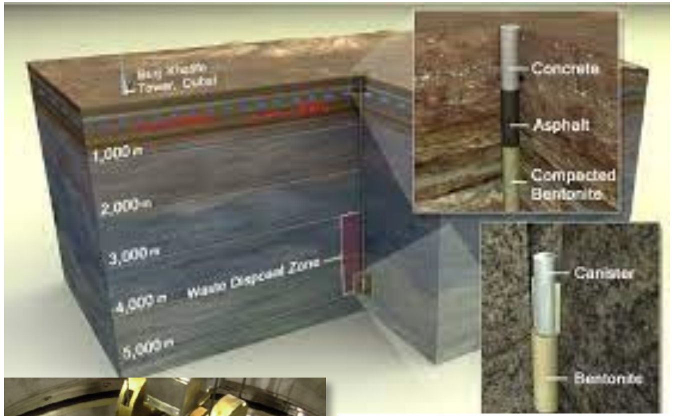
- Many of the advanced reactor vendors are currently following the existing U.S. LWR model:
  - Interim storage of UNF/SNF in wet storage facilities (SFP)
  - Transfer from wet to dry storage facilities (ISFSIs)
  - Transportation by DOE to a disposal site or to consolidated interim storage (MRS)
- In 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.)

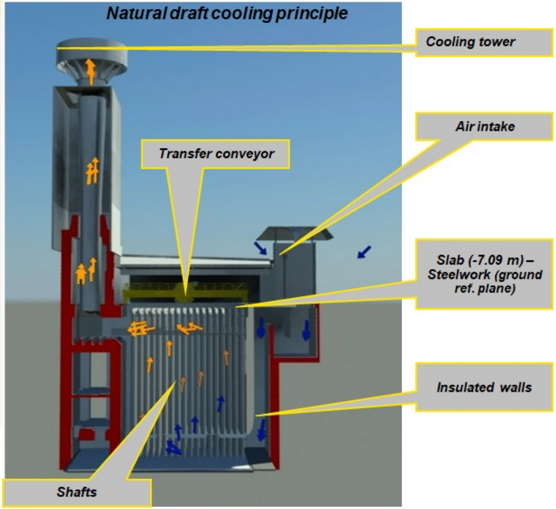
6. Takeaways

Although Used Fuel Management for Advanced Reactors may be challenging:

- 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 safe and secure handling, storing, transporting, and treating of the UNF/SNF and HLW potentially produced by the wide variety of proposed advanced reactors

Questions…


1,000 m
2,000 m
3,000 m
4,000 m
5,000 m
Waste Disposal Zone
Concrete
Asphalt
Compacted Bentonite
Canister
Bentonite


Natural draft cooling principle
Cooling tower
Air intake
Transfer conveyor
Slab (-7.09 m) – Steelwork (ground ref. plane)
Insulated walls
Shafts

Backup Slides

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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

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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

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 yet 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

Advanced Reactor Fuel Types: Liquid Salts

Some key attributes of liquid salt fuels include:

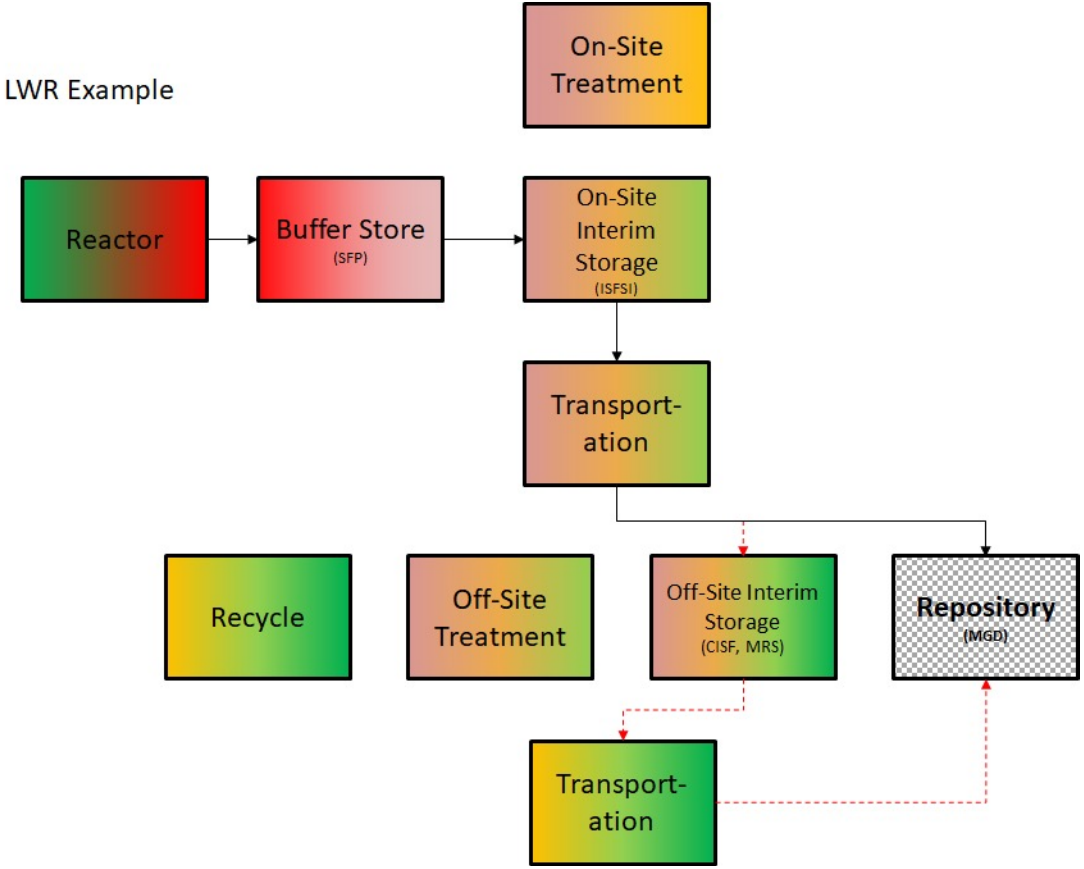
- Molten fluoride or chloride salt containing fissile material
- No fuel structures like cladding, fuel ducts, grid spacers, etc.
- **Liquid fuel allows for online fueling during operation and real time conditioning/recycling/ waste processing (removal of fission products)**
  - Leads to significant 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

The U.S DOE's Standard Contract (briefly)

- The "Standard Contract for Disposal of SNF and/or HLW" establishes the terms & conditions under which the DOE will make available nuclear waste disposal services to the owners and generators of SNF and HLW
- Amendment for "New Reactors" was added to all reactors proposed for commercial use after 2008 (Vogtle 3 & 4 first to implement)
- Without a signed Standard Contract with DOE, a new reactor cannot receive an operating license from the NRC
- 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)
- Storage and/or treatment of SNF and HLW produced from at least 20 years of operation of the reactor and up to 10 years after shutdown must be designed and paid 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

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

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Giving nuclear energy its full value