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Progress on Considering the Back End of the Fuel Cycle for Small Modular Reactors

IAEA Technical Meeting on Back End of the Fuel Cycle Considerations for Small Modular Reactors

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To the extent discussions or recommendations in this report conflict with the provisions of the Standard Contract, the Standard Contract governs the obligations of the parties, and this report in no manner supersedes, overrides, or amends the Standard Contract.

This report reflects technical work which could support future decision making by DOE. No inferences should be drawn from this report regarding future actions by DOE, which are limited both by the terms of the Standard Contract and Congressional appropriations for the Department to fulfill its obligations under the Nuclear Waste Policy Act including licensing and construction of a spent nuclear fuel repository.

Contributors and Acknowledgments

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Outline

- **Small Modular Reactor Fuel Cycle**
  - LWR Small-Modular Reactors (SMRs), Molten-Salt Reactors (MSRs), Sodium-Cooled Fast Reactors (SFRs), Lead-Cooled Fast Reactors (LFRs), Gas-Cooled Reactors
- **Regulatory Requirements**
  - Storage and Transportation
- **Spent Nuclear Fuel Conditioning and Treatment**
- **Strategic Recommendations**
- **Conclusions**

Light Water Reactor (SMRs)

- Examples: GE-Hitachi BWRX-300, Westinghouse SMR, Holtec SMR-160, NuScale SMR
- LWR SMRs use existing BWR/PWR fuel characteristics
- Changes to fuels are small enough that LWR SMRs can use current infrastructure with minimal, if any, changes

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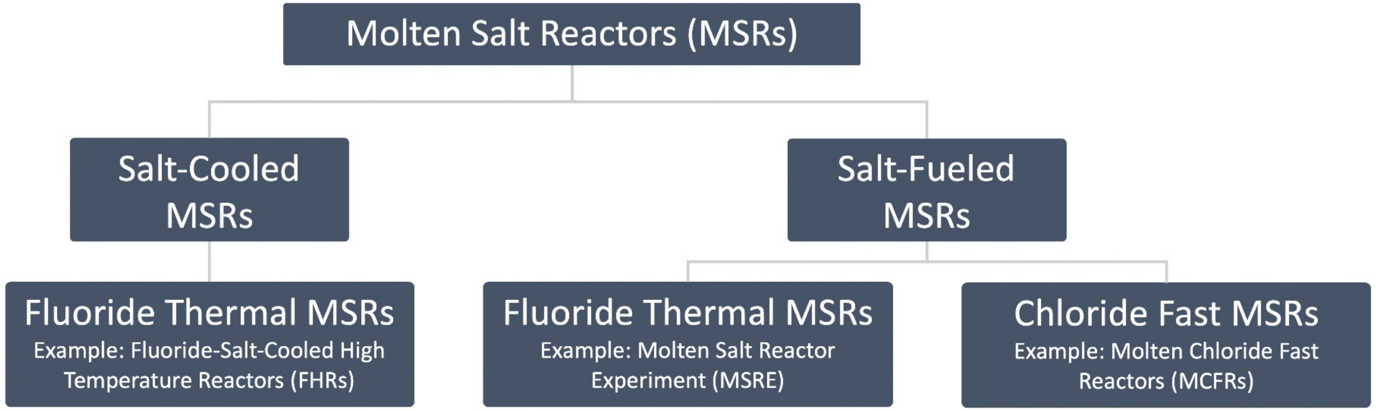
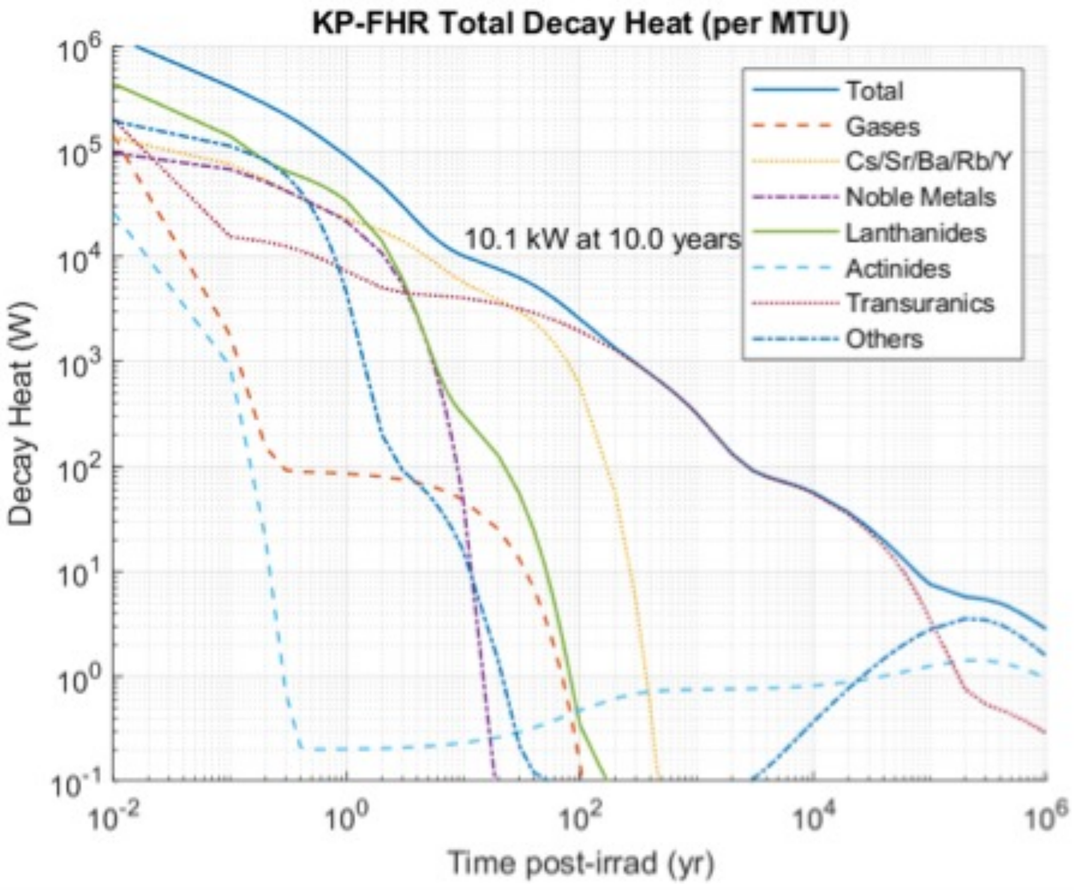
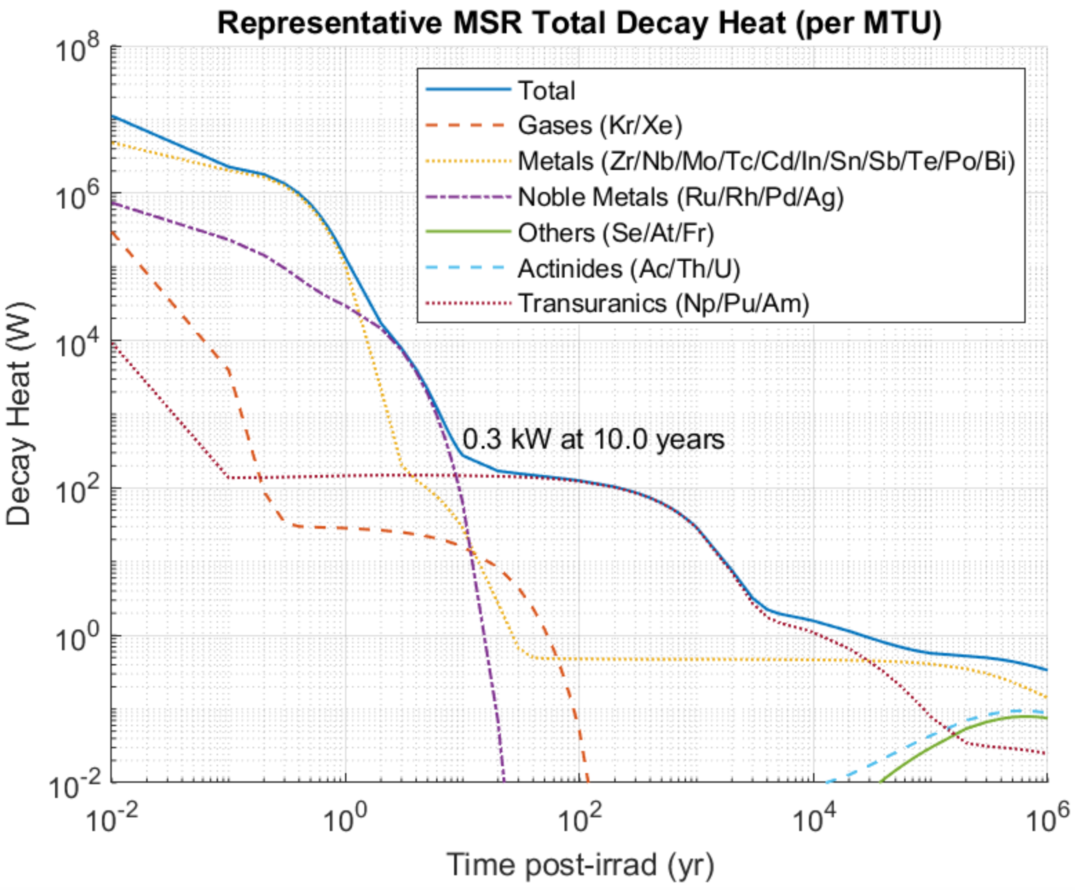
Molten Salt Reactors

- Use molten salt as coolant, can also use molten salt as fuel
- Molten-salt coolant: Kairos FHR
- Molten-salt fuel: TerraPower MCFR, Elysium MCSFR, Flibe LFTR, Terrestrial Energy IMSR
- Novel fuel form will require significant modifications to certain infrastructure



Molten Salt Reactors



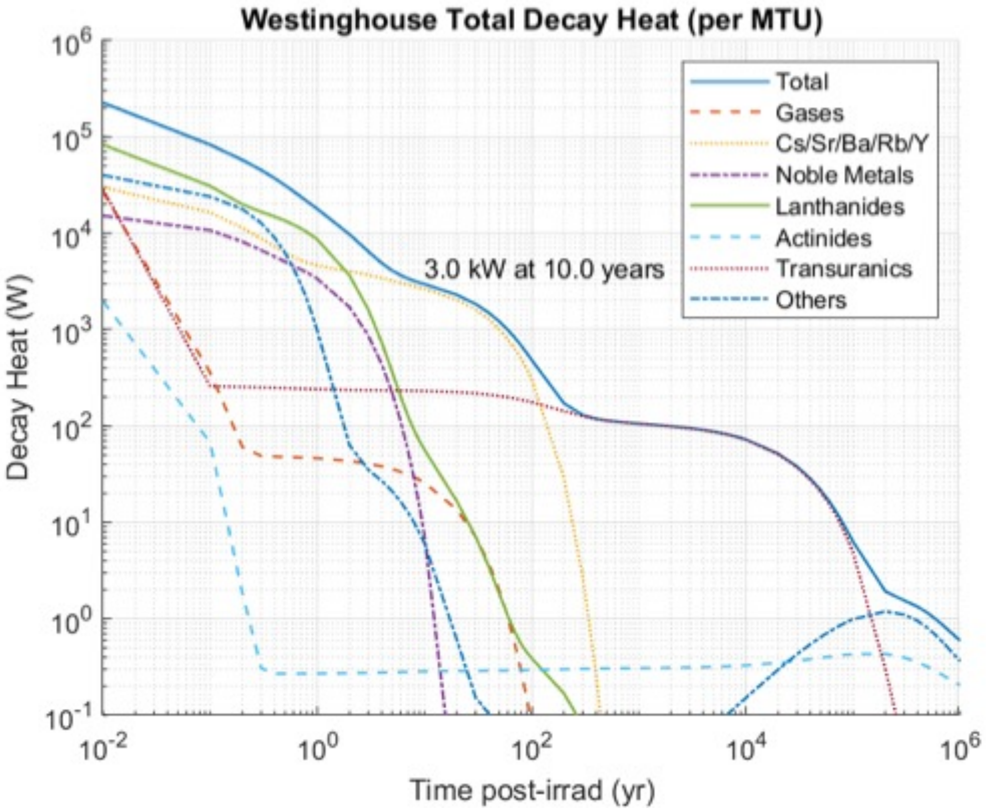


Sodium Cooled Fast Reactors

- **Examples: TerraPower TWR and Natrium Reactors, GE-Hitachi PRISM, Holtec ARC-100**
- **3 of 4 technologies will employ sodium bonded fuel;**
  - i.e., no gap between fuel pellet and cladding
    - Better for thermal performance, may cause issues with disposal
- **Natrium-U plans to forgo sodium bond, other material**

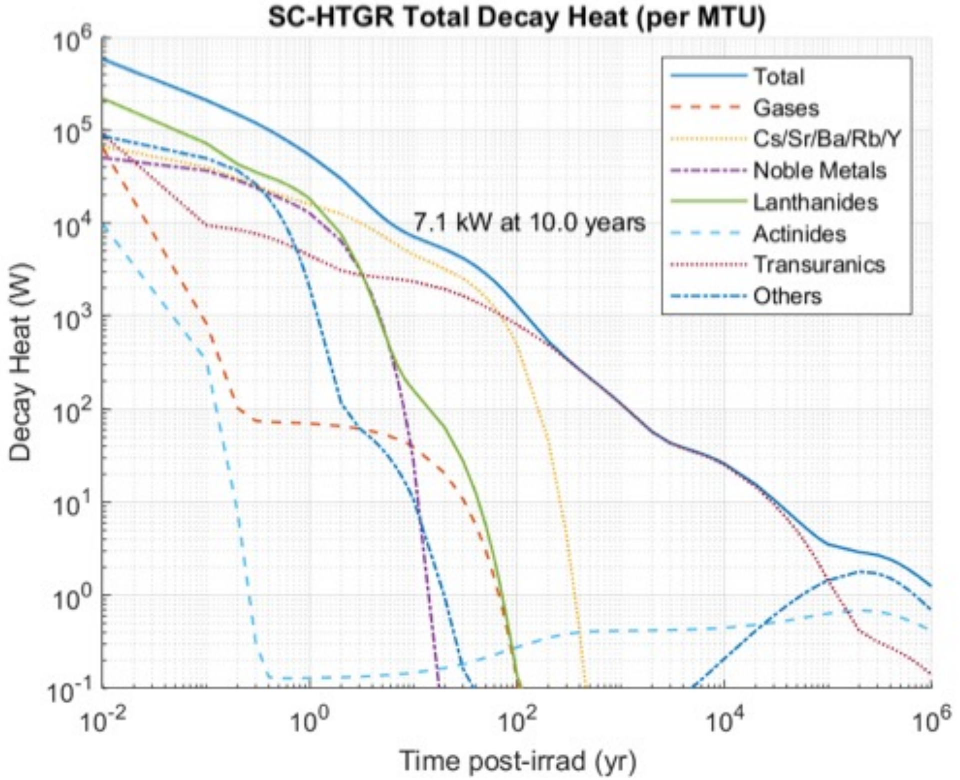
Lead Cooled Fast Reactors

- Examples: Westinghouse LFR, Newcleo Small LFR
- Fuel is structurally similar to LWR fuel
- Biggest challenge is disposal of lead coolant



High Temperature Gas-cooled Reactor (HTGR)

- Examples: Framatome SC-HTGR, HolosGen Holos Quad, X-energy Xe-100, GA EM2, Ultra Safe MMR, StarCore
- Kairos FHR uses TRISO fuel
- All technologies use some form of TRISO: Pebble or Prismatic
- TRISO provides own containment of fission products, but fuel does take up much more volume (graphite)



Storage and Transport Regulations

- Storage requirements contained in Title 10 of the Code of Federal Regulations Part 72 (10 CFR 72) – spent fuel storage in ISFSI

- Transportation requirements contained in 10 CFR 71
- Overall, current definitions appear broad enough that they can be applied to SMR SNF with careful consideration

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Spent Nuclear Fuel Conditioning & Treatment

- May be necessary to ensure that spent fuel meets transportation, storage, or disposal requirements
  - Are there materials that are hazardous or reactive?
  - Is physical form suitable for management/disposal?
- May be elective if it simplifies or streamlines spent fuel management operations
  - SNF volume reduction
- May be precursor to reprocessing, but SNF conditioning & treatment is conceptually distinct as it does not intentionally separate actinides or fission products

SNF Conditioning & Treatment

- LWR SMR: Few changes since fuels based on current LWRs
- MSR – Salt-Fueled: SNF salts likely unsuitable for disposal, need treatment
  - Potentially direct disposal in salt-repository
- MSR – Salt-Cooled: Only Kairos FHR reviewed in this report, essentially same treatment as HTGRs (except cleaning to remove coolant)

SNF Conditioning & Treatment

- SFR – Sodium-Bonded: Sodium bond should likely be removed
- SFR – Sodium-free bond: No fuel treatment foreseen
- LFR: Likely acceptable for management without treatment (lead disposal is a concern)
- HTGR – Prismatic: Only elective treatment for volume reduction
- HTGR – Pebble: Elective treatment not anticipated

Damaged SNF Treatment

- Damaged SNF is “any fuel rod or fuel assembly that cannot fulfill its fuel-specific or system-related functions” [SFST ISG-1]
- Other solid fuel types resembling LWR SNF, such as sodium-cooled and lead-cooled fuel, might potentially use existing guidance

Damaged SNF Treatment

- Other fuel types will need more consideration, especially breached fuel
  - “Spent fuel rod with cladding defects that permit the release of gas from the interior of the fuel rod” and “a breached spent fuel rod may also have cladding defects sufficient to permit release of fuel particulate”
  - What happens when no pellet/cladding system?
- MSRs – Is “fuel” structure salt and tank?
- TRISO – Challenging to access breached particles, so gross counts?

Strategic Recommendations

- Regulator and vendor work closely to facilitate compliance to evolving standards
  - Design of spent fuel pools or fuel cooling areas
  - Siting and design of onsite SNF storage installations (if applicable)
  - Updated Normal Conditions of Transport characteristics for a respective fuel type
  - Assessment of off-normal and accident conditions applicable for each fuel type
  - Assessment of bounding and nominal repository conditions for each fuel type

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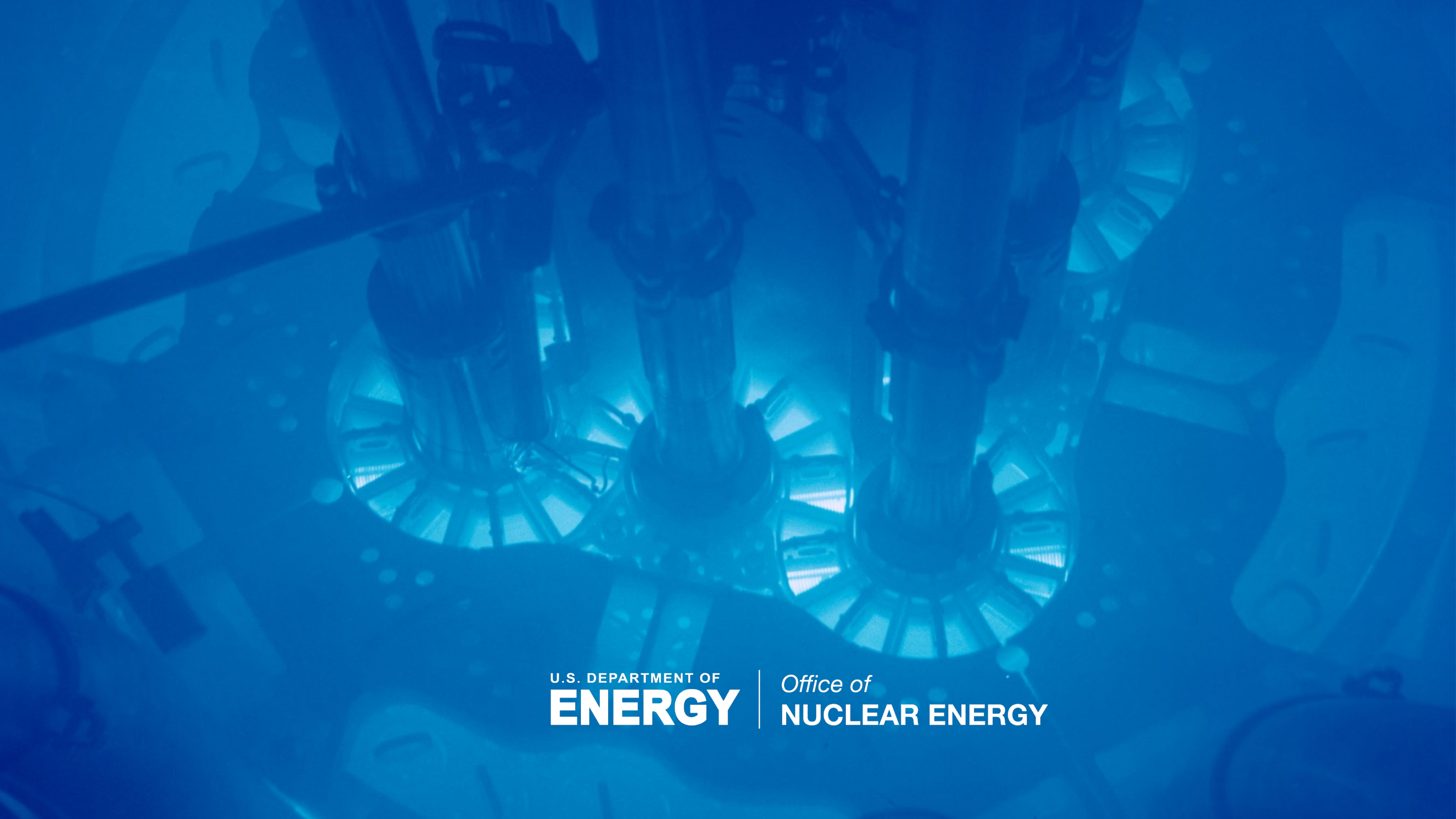
Strategic Recommendations

- Ongoing studies of the regulatory and industrial environment of SMRs and SNF management
  - Initiate R&D as-needed as technical and regulatory gaps become evident
- Collaboration with SMR vendors will facilitate fuel cycle back end impacts are understood and acted upon in advance of deployment

Conclusion

- Types of fuel to be used in these rector designs are different than the fuel used in current LWR fleet
- May require modification of regulations for SNF management
  - Damaged fuel seems to be biggest gap yet to be closed
- Conditioning and treatment likely required or desired for several designs
- Ongoing collaboration with reactor vendors to understand fuel cycle back end impacts recommended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