Overview of of Advanced Reactor Spent Nuclear Fuel

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Abstract

There is considerable international interest to develop and deploy advanced nuclear reactor technologies, both as part of a strategy to meet zero emissions climate goals, and for applications to generate heat and energy in remote areas away from industrial infrastructure. While there are many design concepts being proposed for Advanced Reactors (ARs), there are essentially three main categories of AR SNF that currently need to be considered for Back-end Nuclear Fuel Cycle (BENFC) management – TRi-structural ISOtopic (TRISO), metallic, and Molten Salt Reactor (MSR) SNF. This paper will provide an overview of the characteristics and attributes of these AR SNF types, with particular emphasis on aspects relevant to BENFC considerations. This will include preliminary analysis of potential AR SNF types, and a discussion of previously analysed fuels from the US DOE-managed SNF inventory that have similar characteristics to AR SNF.

TRSIO SNF is utilized in high temperature gas reactors (HGTRs) or MSRs, where the fuel may be arrayed either in prismatic block or pebble bed configurations in an HGTR, or as pebbles in an MSR. Metallic fuel is used in Sodium Fast Reactors (SFRs), and sometimes has a sodium bond between the fuel and cladding that can accommodate fuel swelling during SFR reactor operation. MSRs typically use a fluoride or chloride based molten salt coolant with uranium or thorium fuel, which is typically interspersed within the molten salt coolant during reactor operation.

TRISO fuel was included in the disposal plan for Yucca Mountain (DOE, 2008), as were of some types of metallic fuels. TRISO SNF is suitable for disposal, although there are several ways in which it differs from typical LWR SNF (e.g., potential gas generation from radiolysis of graphite and graphite impurities). Metallic fuel without sodium was included for disposal, while metallic fuel that included a sodium bond between the fuel and the cladding was not considered for disposal. Salt waste generated by a molten salt reactor was not included in the disposal plan for Yucca Mountain (DOE, 2008). Disposal in other types of repositories could present challenges because the salt waste form will dissolve easily in water and has the potential for gas generation.

Introduction

There are over one-hundred advanced reactor design concepts that are in various stages of development and/or demonstration internationally (Price, 2021), with over thirty designs being proposed in the US (GAIN, 2023). Many of these designs implement operational features, e.g. fuels and coolants, that differ from the Light-Water Reactor (LWR) designs that form the basis of the currently deployed commercial nuclear fleet. The AR SNF, and in some cases other waste streams associated with AR fuel cycles, may need permanent disposal in a deep geologic repository. Disposal of LWR fuel has been well-studied and the Features, Events, and Processes (FEPs) associated with LWR SNF disposal have been identified and analyzed (DOE, 2008; SNL, 2008; Faybishenko, et al., 2016; OECD/NEA 2019; Swfit and Sassani, 2020). This paper broadly describes the major categories of AR SNF (TRISO, Metallic, and MSR fuels/waste) and briefly describes previous experience with similar fuel types.

Description of AR Fuel Types

TRISO Fuel

TRISO pellet fuels were designed for high temperature gas reactors and are tolerant to very high temperature operation and transient conditions. TRISO fuel particles are the smallest subunit of the TRISO fuel and consist of a fuel kernel surrounded by carbon-based layers (Sassani et al. 2018; Sassani and Gelbard, 2019). The fuel kernel is typically UO_2 or a mixture of UO_2 and UC_2, referred to as UCO. A UO_2-based kernel is the more typical design, and the uranium may be enriched in U-235 to less than 5% (low enriched uranium, LEU) or may be enriched in U-235 to between 5% and 20%, known as high-assay low-enriched uranium (HALEU). The kernel has a diameter of around 500 microns for both pebble-bed-type fuels and fertile prismatic fuel. It is roughly 350 microns for fissile prismatic kernels. The layer covering the kernel is the Inner PyroCarbon (IPyC) layer. This is followed by the silicon carbide (SiC) layer and the Outer PyroCarbon layer (OPyC). When arranged for use in a prismatic block reactor, the coated particles are encapsulated in graphitic fuel compacts that are tens of mm in diameter and ~10 cm in length. When arranged for a use in a pebble bed reactor, the coated TRISO particles are embedded in a graphite matrix and formed into pebbles about 60 mm in diameter.

In a prismatic block reactor, the fuel is handled on a compact-by-compact basis, whereas in a pebble bed reactor, the pebbles move freely through the reactor. Pebble bed reactors using TRISO fuel could be cooled by gas or by molten salt. The TRISO fuels were originally designed for once-through operation, so reprocessing is possible but challenging given the effort to remove the fuel from each pellet.

In the U.S., two reactors using TRISO fuel in a prismatic block configuration were licensed by the Atomic Energy Commission, the predecessor of the Nuclear Regulatory Commission: the Peach Bottom Reactor, which operated near Delta, Pennsylvania, and the Fort St.Vrain reactor, which operated near Denver, Colorado. Disposal of TRISO SNF from these reactors was included in the disposal plan for the proposed repository at Yucca Mountain (DOE, 2008).

Metallic Fuels

Most metallic fuels are being developed for sodium-cooled fast reactors, generally have uranium or plutonium metal alloy as the fuel and have excellent heat-transfer properties. Fast reactors allow for higher-Z actinides to fission, thus preventing a buildup of higher-Z actinides in the fuel cycle. As such, reprocessing was originally envisioned for fast reactor fuel to recycle all Pu and minor actinides.

A typical metallic fuel contains sodium between the fuel and the cladding to facilitate heat transport and accommodate fuel swelling. However, disposal options for this type of fuel will likely entail treatment for removal or deactivation of the sodium (INL, 2007) because metallic sodium is highly reactive in both air and water. In 2000, the DOE determined that direct disposal of sodium-bonded SNF would not meet DOE or NRC repository acceptance criteria, mainly due to the potential for pyrophoric reaction of metallic sodium with water with which it may come into contact (DOE, 2000). The National Academy of Sciences also asserts that sodium-bonded spent fuel is not suitable for direct disposal because of the highly reactive and pyrophoric characteristics of sodium (NAS, 2022). Advanced metallic fuels that do not contain sodium internal to the fuel rod have been proposed and are being developed (NAS, 2022). These fuels would use helium in the core as a heat-transfer fluid, rather than metallic sodium (TerraPower, 2022). Further evaluations of FEPs related to disposal of metallic fuels will include assessment of its reactivity and pyrophoricity in generic disposal systems.

As implied above, the U.S. has experience with several different types of metallic fuels, both with and without internal sodium. An example of metallic fuel without internal sodium is a low enriched (~1% enrichment) uranium fuel with zirconium cladding that was used for both production of nuclear material and energy production in the N Reactor at Hanford, a graphite block reactor. The N Reactor fuel consisted of two concentric tubes of uranium metal, about 6 cm in diameter and about 60 cm long (SNL, 2014). An example of metallic fuel with internal metallic sodium is that used in the Experimental Breeder Reactor-II at Idaho, a fast spectrum reactor. That fuel was composed of uranium alloys with stainless steel cladding and had metallic sodium between the fuel and the cladding to facilitate heat transfer (DOE, 2000). As noted above, the DOE decided not to dispose of this type of spent fuel (and others like it) because of the reactivity and ignitability of the sodium, which had bonded with the fuel in the driver rods (DOE, 2000). Rather, the DOE decided to treat the sodium-bonded metallic fuel using electrometallurgical treatment (EMT), in which the metal sodium reacts chemically to become a sodium salt, which is no longer reactive or ignitable (DOE, 2000).

Molten Salt Fuels

In a molten salt reactor, the fuel can be dissolved in the salt itself or it can be contained in TRISO pebbles. The salt may be fluoride-based or chloride-based, the fuel can typically be thorium or uranium, and the spectrum can be fast or thermal. Some designs are fueled by cores that are replaced every 7-8 years with very limited on-site treatment, while other designs have a molten salt core with continuous fission product removal. Regardless of the design options chosen, molten salt reactors will likely generate a salt waste that will require disposal or treatment. It is not clear what or how much material might be removed during the treatment process. The material resulting from treatment may be classified as high-level waste and may be subject to evaluation for deep geologic disposal.

Previous experience with molten salt reactors that had fuel dissolved in the salt itself is limited to the Molten Salt Reactor Experiment at Oak Ridge and the Aircraft Reactor Experiment. The Molten Salt Reactor Experiment was shut down in 1970; the DOE continues to manage the spent salt fuel that remains in the reactor tanks. There is no known previous experience with molten salt reactors in which the fuel is contained in TRISO pebbles.

Conclusions

Multiple vendors have proposed AR concepts that are significantly different from typical LWRs currently in use. The SNF produced by ARs will eventually need to be disposed of, either directly or after appropriate treatment. This paper briefly discusses some FEPs that might need to be considered prior to disposal of three broad categories of AR SNF (TRISO, Metallic, and MSR).

For TRISO SNF, the following might need to be considered prior to disposal include: 1) gas generation from H-3, C-14, flammable gases generated upon exposure of carbide to water, and off-gassing of salt residue for TRISO used in a molten salt reactor; 2) whether any salt residue for TRISO used in a molten salt reactor makes the SNF subject to RCRA; 3) postclosure criticality potential because of higher enrichment; 4) determining the isotopic content of spent TRISO pebbles, and 5) disposal of irradiated graphite blocks and other graphite materials.

For metallic SNF, sodium-bonded metallic SNF is not suitable for disposal as-is but must be treated prior to disposal. The waste forms produced by EMT were included in the disposal plan for the proposed Yucca Mountain repository and thus were studied. Different waste forms produced by a different treatment process would presumably be engineered to have desirable properties with respect to disposal. Disposal of non-sodium bonded metallic fuel would require further study of its degradation rate under repository conditions and of the effects of pyrophoricity on repository performance.

Salt SNF would likely require treatment prior to disposal in anything but a salt repository or a deep borehole. If salt SNF were to be disposed of as-is, the following might need to be considered: 1) gas generation (H-3, F_2), 2) generation of Cl-36, and 3) the thermal load.

References

DOE, 2000. "Final Environmental Impact Statement for the Treatment and Management of Sodium-Bonded Spent Nuclear Fuel, Volumes 1 and 2," DOE/EIS-0306, U.S. Department of Energy Office of Nuclear Energy, Science, and Technology, Washington, D.C.

DOE, 2008. "Yucca Mountain Repository License Application, Safety Analysis Report," DOE/RW-0573, Update No. 1, November 2008, U.S. Department of Energy, Office of Civilian Radioactive Waste Management, Las Vegas, NV.

Faybishenko, B., Birkholzer, J., Sassani, D., and Swift, P., 2016. International Approaches for Deep Geological Disposal of Nuclear Waste: Geological Challenges in Radioactive Waste Isolation, Fifth Worldwide Review, LBNL-1006984, Lawrence Berkeley National Laboratory.

INL, 2007. "Idaho National Laboratory Preferred Disposition Plan for Sodium-Bonded Spent Nuclear Fuel," Idaho National Laboratory, Idaho Falls, ID.

Matteo, E. N., L. Price, R. Pulido, P. Weck, A. Taconi, P. Mariner, T. Hadgu, H. Park, J. Greathouse, D. Sassani, and H. Alsaed (2023). "Advanced Reactors Fuel and Waste Streams Disposition Strategies," SAND2023-08602R, Sandia National Laboratories, Albuquerque, NM.

NAS, 2022. "Merits and Viability of Different Nuclear Fuel Cycles and Technology Options and the Waste Aspects of Advanced Nuclear Reactors." Washington, DC: The National Academies Press. https://doi.org/10.17226/26500.

OECD/NEA, 2019. "International Features, Events and Processes (IFEP) List for the Deep Geological Disposal of Radioactive Waste, Version 3.0" Organization for Economic Co-operation and Development, Nuclear Energy Agency. https://inis.iaea.org/collection/NCLCollectionStore/_Public/50/061/50061148.pdf

Price, R. (2021). "Bringing the Back-End to the Forefront: Spent Fuel Management and Safeguards Considerations for Emerging Reactors," Stimson Center, Washington DC.

Sassani, D., P. Brady, F. Gelbard, L. Price, J. Prouty, R. Rechard, M. Rigali, R. Rogers, A. Sanchez, W. Walkow, and P. Weck, (2018). "Inventory and Waste Characterization Status Report and OWL Update," SAND2018-12352R, Sandia National Laboratories, Albuquerque, NM.

Sassani, D., and F. Gelbard, 2019. "Performance assessment model for degradation of tristructuralisotropic (TRISO) coated particle spent fuel," Proceedings of the American Nuclear Society International High-Level Radioactive Waste Management Conference, April 14-18, 2019, SAND2019-1906 C, Sandia National Laboratories, Albuquerque, NM.

SNL, 2008. "Features, Events, and Processes for the Total System Performance Assessment: Analyses." ANL-WIS-MD-000027 REV00, Albuquerque, NM: Sandia National Laboratories.

SNL, 2014. "Evaluation of Options for Permanent Geologic Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste in Support of a Comprehensive National Nuclear Fuel Cycle Strategy,", Rev. 1, Volume I, SAND2014-0187P, Volume II: Appendices," SAND 2014-0189P, Sandia National Laboratories, Albuquerque, NM.

Swift, P.N., and Sassani, D. C., 2020. "Impacts of Nuclear Fuel Cycle Choices on Permanent Disposal of High-Activity Radioactive Wastes," SAND2019-5941 C, 2019 IAEA Spent Fuel Management Conference, Paris, France, June 2019, Proceedings 2020.

TerraPower, 2022. Natrium Advanced Reactor Fuel Cycle Management, NEA: Management of Spent Fuel, Radioactive Waste, and Decommissioning in SMRs or Advanced Reactor Technologies, Ottawa, Canada, November 7, 2022.

ACRONYMS

AR: Advanced Reactor

BENFC: Back-End Nuclear Fuel Cycle

DOE: US Department of Energy

FEP: Features, Events, and Processes

HALEU: High-Assay Low-Enriched Uranium

HGTR: High-Temperature Gas Reactor

IPyC: Inner Pyrolitic Carbon

LWR: Light-Water Reactor

MSR: Molten Salt reactor

OPyC: Outer Pyrolitic Carbon

SFR: Sodium Fast Reactor

SiC: Silicon Carbide

SNF: Spent Nuclear Fuel

SNL: Sandia National Laboratories

TRISO: TRi-structural ISOtopic

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