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Fuel cycle and neutronic performance of a spectral shift molten salt reactor design ☆

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ABSTRACT

The fuel cycle performance and core design of the Transatomic Power liquid-fueled molten salt reactor concept is analyzed. This advanced reactor concept uses configurable zirconium hydride moderator rod assemblies to shift the neutron spectrum in the core from intermediate at beginning of life to thermal at end of life. With a harder spectrum during the early years of reactor operation, this spectral shift design drives captures in fertile ^{238}U. The converted fissile plutonium makes up over 50% of the fissile material in the fuel salt over the last half (~15 years) of reactor operation. A softer spectrum late in reactor life helps drive the fuel to a burnup of 90 GWd/MTU. Continuously changing physics necessitates time-dependent analyses resolved over long timescales (i.e., months to years), as this concept does not meet an equilibrium condition. The spectral shift and molten salt reactor material feeds and removals enable this concept to perform better in fuel cycle metrics, increasing resource utilization by more than 50% compared with a typical light water reactor (i.e., from ~0.6% to ~1%). These metrics are compared to similar fuel cycles using alternate technologies. Additional core design and analysis challenges associated with the spectral shift and use of molten salt reactor technology are identified and discussed.

1. Introduction

Liquid-fueled molten salt reactor (MSR) systems have the potential to yield safety, economic, and fuel cycle benefits, depending on the reactor design. The very broad design space for liquid-fueled MSRs encompasses various carrier salt compositions (fluoride and chloride salt mixtures), fertile and fissile materials (thorium, uranium, and plutonium), neutron spectra (fast, thermal, and intermediate), fuel cycle scenarios (full recycle, partial recycle, and once-through), and fuel salt processing choices (fission gas sparging and rare earth element separations). Along with additional reactor characteristics, these design choices define the performance of the system and its benefits with respect to current light water reactor (LWR) technologies and other advanced reactor technologies.

Due to this large design space, there are several MSR developers with varied concepts that target different societal, technical, or economic impacts (e.g., reducing actinide waste or consuming LWR spent nuclear fuel). These potential impacts stimulate the growing private investment in advanced reactor technology (Brinton, 2015), which drives the resurgent interest in liquid-fueled MSRs and encourages regulators and the US Department of Energy (DOE) to seriously consider and support the deployment of these technologies (US Department of Energy, 2015).

Transatomic Power develops one of these concepts: a 1250 MWt MSR with an LiF-based uranium fuel salt (Transatomic Power Corporation, 2016a). This concept is notable for its use of configurable zirconium hydride metal rod assemblies as a moderator. These assemblies are deployed so that the moderator-to-fuel ratio is increased during operation over the lifetime of the reactor. This steady increase causes the neutron spectrum to change from intermediate to thermal during operation. The resulting spectral shift core design benefits from having a harder spectrum early in core life, resulting in increased breeding of fissile material, and a

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softer spectrum towards the end of core life, resulting in efficient burning of available fissile material.

Spectral shift core designs using solid-fuel water-cooled reactor technology were initially proposed in the 1960s (Mars and Gans, 1961) as a more efficient form of reactivity control (i.e., control of long-term excess reactivity in lieu of burnable absorbers) and have been studied sporadically since. Several implementation methods for achieving the spectral shift have been identified: (1) mixing D_2O and H_2O to change neutron slowing down physics (Mars and Gans, 1961), (2) incorporating tubes containing variable density H_2O to change moderator mass (Ronen and Galperin, 1980; Galperin and Ronen, 1983), (3) using non-absorbing control rods to displace water in the fuel lattice (Martin et al., 1991), (4) controlling the coolant density during operation to yield an intended spectral shift in a boiling water reactor (BWR) (Ronen and Galperin, 1980), or (5) a combination of these methods (Ronen and Fahima, 1984). Recent work on using hardened neutron spectra in BWRs is relevant for spectral shift design, and recent applications of these designs have extended to small modular reactors (SMRs) (Lindley and Parks, 2016). Spectral shift designs are generally noted for increasing burnup of the fuel; the amount of this increase is highly dependent on the reactor, fuel, and method used to obtain the spectral shift. Implementation methods that specifically change the moderator-to-fuel ratio directly result in the highest increase to burnup (Ronen and Galperin, 1980). Few efforts have been made to deploy spectral shift MSRs (Robertson, 1971), even though the implementation methods may be simple for some designs.[1]

This article discusses the analysis of the neutronic and fuel cycle performance of the Transatomic Power spectral shift MSR concept using modeling and simulation tools developed at Oak Ridge National Laboratory (ORNL) (Betzler et al., 2017a). While MSR systems present challenges to current nuclear analysis tools, many meaningful performance metrics may be generated with some additional effort and with extensions to existing capabilities (e.g., modeling continuous processing of fuel salt with semicontinuous methods). For comparison, the fuel cycle of this concept is categorized within the context of the DOE Office of Nuclear Energy (DOE-NE) Fuel Cycles Options (FCO) campaign Evaluation and Screening (E&S) Study (Wigeland et al., 2014). This study provides information about the potential benefits and challenges of nuclear fuel cycle options (i.e., the complete nuclear energy system from mining to disposal). Classifying the Transatomic Power MSR concept in the FCO E&S Study provides worthwhile context and means for comparison to other promising fuel cycle options. The detailed physics-based analyses required for this categorization yield meaningful fuel cycle metrics, such as resource utilization and waste generated per unit thermal energy. These metrics identify the benefits of a given technology. This article only discusses liquid-fueled MSRs. Discussions of MSRs herein refer only to the liquid-fueled variants.

2. The TRANSATOMIC POWER molten salt reactor concept

Initial details of the Transatomic Power concept (Transatomic Power Corporation, 2014; Massie and Dewan, 2011) were updated in July 2016 in a technical white paper (Transatomic Power Corporation, 2016a) and a neutronics overview (Transatomic Power Corporation, 2016b). All analyses and comparisons herein are based on the information available in the most recent open literature and additional information on the most recent iteration of this concept.

2.1. Design description

The 1250 MWt Transatomic Power concept is adapted from the original design of the Molten Salt Reactor Experiment (Haubenreich and Engel, 1970) (MSRE) by modifying two fundamental design features: the fuel salt and the moderator. Substitution of LiF-UF_4 for the MSRE's LiF–BeF_2-ZrF_4-UF_4 fuel salt provides for an increase in the uranium concentration within the fuel salt (from 0.9 to 27.5%) while maintaining a relatively low melting point (490°C compared with 434°C). Although graphite has a low capture cross section (resulting in a high moderating ratio) and performs well with molten salts (which have low corrosion potentials), the low lethargy gain per collision requires that large volumes of graphite be present to achieve criticality, making the core large, and limiting the core power density. To resolve this issue, the Transatomic Power concept uses zirconium hydride, allowing for a significant increase in power density, as the zirconium hydride offers a higher neutron moderating density than graphite. The combination of these two choices allows for a more compact reactor than the original graphite-moderated design, facilitating the potential deployment of this technology using uranium enrichment facilities that are currently commercially available, providing up to 5% low-enriched uranium (LEU).

In currently operating light-water reactors (LWRs), beginning of life (BOL) excess reactivity is controlled via soluble boron in the coolant, burnable absorbers, and/or control elements, which are gradually removed and/or depleted during irradiation, until they are almost completely removed toward the end of life (EOL). This inefficient method of reactivity control sacrifices neutrons in absorbers and control elements that could otherwise be used for fission and conversion; this is the primary motivation for studying spectral shift control water-cooled reactors (Mars and Gans, 1961). Through the use of continual feeds, removal of fission products, and configurable moderator rod assemblies, the Transatomic Power concept compensates for the buildup of negative reactivity via increased moderation, as well as material addition and removal. The concept includes several control rods moving continuously through drive mechanisms to provide short time scale reactivity control (on the order of days to weeks), maintaining reactivity in the long term by periodic replacement of stationary zirconium hydride rod assemblies with those containing more rods (e.g., replacement of a five-rod assembly with a nine-rod assembly).

In the cylindrical Transatomic Power core, fuel salt flows through rectangular moderator assemblies consisting of arrays of small-diameter zirconium hydride rods clad in a corrosion-resistant material. The core moderator-to-fuel salt ratio, or the salt volume fraction (SVF), is varied during operation to shift the spectrum from intermediate[2] to thermal energies (from BOL to EOL, respectively) to maximize the fuel burnup. Note the inverse relationship between the moderator-to-fuel ratio (V_M/V_F) and SVF,

$$\mathrm{SVF} = \frac{V_F}{V_F + V_M}, \tag{1}$$

where V_F and V_M are the fuel and moderator volumes, respectively. For the Transatomic Power concept, EOL of the reactor (i.e., fuel salt and components) occurs when the maximum number of moderator rods are inserted into the core, and further fueling does not result in a critical configuration.

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[1] Some MSR designs incorporate replaceable moderators due to material fluence limits.

[2] An intermediate spectrum is defined as one in which a relative majority of fissions are induced by incident neutrons between 1 eV and 100 keV. At BOL, approximately 10%, 48%, and 42% of the fissions in the TAP core occur at fast, intermediate, and thermal neutron energies, respectively.