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Sensitivity/uncertainty analyses comparing LR-0 reactor experiments containing FLiBe salt with models for molten-salt-cooled and molten-salt-fueled reactors ☆

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ABSTRACT

Critical experiments using an insertion zone with FLiBe salt performed at the LR-0 reactor at Research Centre Řež (RC Řež) have been compared to application models for solid-fueled, fluoride-salt-cooled high-temperature reactor (FHR) and liquid-fueled molten salt reactor (MSR) concepts using sensitivity and uncertainty (S/U) analysis techniques. These experiments support FHR and MSR advanced reactor concepts by informing on neutron spectral effects and nuclear data uncertainties related to fluoride salts. The FLiBe salt in the LR-0 experiments is from the Oak Ridge National Laboratory Molten Salt Reactor Experiment and is enriched to greater than 99.99% ^{7}Li. This work is part of a broader collaboration between the United States and the Czech Republic on MSR and FHR technology. Results from the S/U analyses for FHR and MSR models indicated the most significant potential source of eigenvalue bias due to nuclear data within the FLiBe salt is radiative capture in ^{7}Li. Other smaller but potentially significant contributions come from ^{19}F, ^{6}Li, and other ^{7}Li reactions. Similarity comparisons of the RC Řež LR-0 experiments and FHR and MSR application models indicate that the LR-0 FLiBe experiments could be useful as candidate benchmarks for low-enriched uranium–fueled application models. However, sensitivity differences observed included both spectral effects, due to the LR-0 reactor being moderated by water instead of graphite and fluoride salt, and sensitivity magnitude effects driven by the amount of FLiBe inserted and its location. New experiments with refined designs to increase the volume and importance of salt in the system could provide improved data. Results also demonstrate that salt systems using thorium and/or ^{233}U fuel will require additional experiments with relevant driver fuels. Increased contributions from the graphite moderator and ^{19}F and covariance between reactions such as ^{233}U fission and ^{233}U radiative capture indicate higher uncertainty contributions from the salt and significant differences in contributions from the fuel species due to underlying uncertainties in their nuclear data.

1. Introduction

Recent experiments conducted at Research Centre Řež (RC Řež) using the LR-0 low power nuclear reactor investigated the neutronic impacts and uncertainties of FLiNa (60 mol% LiF and 40 mol% NaF) and FLiBe (2 LiF + BeF_2) salt insertion zones (Losa et al, 2017a,b; Košťál et al., 2015; Losa et al., 2015). The experiments, which included using FLiBe salt originally from the Molten Salt Reactor Experiment (MSRE) at Oak Ridge National Laboratory (ORNL) that contained enriched lithium (99.994 mol% ^{7}Li), were intended to provide information on neutron spectral effects and nuclear data uncertainties for advanced reactor systems using FLiBe salt in a thermal neutron energy spectrum.

Molten salt reactors are a class of advanced nuclear reactors that uses liquid salts either as (1) a coolant with solid fuel, as in fluoride-salt-cooled high-temperature reactors (FHRs), or (2) a fuel and coolant, with fuel dissolved into a carrier liquid salt that also serves as the coolant, as in liquid-fueled molten salt reactor (MSRs) (Gehin and Powers, 2016). For the purposes of this paper, the term MSR will refer specifically to liquid-fueled reactors (or concepts),

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not the general class of reactors that also includes FHRs. Liquid fluoride or chloride salts can be used in MSRs; however, MSRs designed to operate using a thermal neutron energy spectrum typically use fluoride salts. The LR-0 critical experiments with salt insertion zones are intended to provide benchmark data to aide validation of neutronics calculations for FHR and MSR concepts (Uhlir, 2015). They may also provide insight into relevant nuclear cross section data, identifying nuclides and energy ranges that would benefit from new measurements or evaluations.

As part of an ongoing collaboration on civilian nuclear energy research between the United States and the Czech Republic (Uhlir, 2015; United States Department of Energy and Czech Republic Ministry of Industry and Trade, 2014), ORNL worked with RC Řež to perform sensitivity/uncertainty (S/U) analyses of these LR-0 experiments with salt insertion zones to (1) identify potential sources of bias due to nuclear data uncertainties in FHR and MSR simulations and (2) produce energy-dependent, nuclide-specific sensitivities of neutron multiplication to cross section data. Establishing high-quality models for the LR-0 critical experiments with FLiBe salt, including assessing the sensitivities and uncertainties in the neutronics models, is an essential part of establishing critical benchmarks that may help validate reactor physics calculations for fluoride salt reactor concepts. These S/U analyses may also help assess the adequacy of ENDF/B-VII.1 cross sections for analysis of fluoride salt reactor concepts. Earlier experiments using FLiNa salt and other materials are not considered in this paper.

The results from S/U analyses in this paper were used to assess whether desired nuclear data sensitivities (e.g., sensitivity to ^{7}Li reaction rates in the thermal neutron energy region) appear in the LR-0 experiments. In addition, S/U analyses using models of representative FHR and MSR designs were used to identify potential nuclear data deficiencies with regard to improvements needed to support modeling and simulation for these reactors. Future work could use S/U analyses to support development of a benchmark evaluation for the LR-0 critical experiments that were conducted, design new experiments with improved sensitivities to nuclides and neutron energy regions of interest, or develop a roadmap of data needs and recommendations for future experiments and collaborations. Previous LR-0 experiments with FLiNa salt and Teflon (C_2F_4) could also undergo S/U analysis to assess their relevance to FHRs and MSRs using FLiBe or other salts.

This paper documents the key methods, models, calculations, results, and findings of a collaborative project between ORNL and RC Řež. In this paper, Section 2 ("Methods") provides an overview of the methods used during this project, including the general approach and specific computational codes. Section 3 ("LR-0 Reactor Modeling and Analysis") focuses on LR-0 experiments by describing the physical reactor, LR-0 models created during this work, and results from calculations. Sections 4 and 5 respectively describe the models and results for S/U analyses of the FHR and MSR application cases, including MSR models for two different fuel types. Section 6 compares the results from the LR-0 experiments with those from the FHR and MSR application models using both a numerical similarity assessment and qualitative discussions. Finally, Section 7 summarizes key conclusions of this work and identifies possible future work. Further details of some of the experimental and computational methods and results may be found elsewhere in the literature (Losa et al., 2017a; Košťál et al., 2015; Losa et al., 2015; Losa et al., 2017b; Brown et al., 2016).

2. Methods

S/U analysis can be used to identify potential sources of bias due to nuclear data uncertainties. The effectiveness of an experiment in obtaining data relevant to reducing the uncertainty of nuclear data for nuclides and reactions of interest can be assessed by calculating the sensitivity to specific nuclear reactions in an energy regime of interest and comparing experimental sensitivities against the sensitivities of interest in the target application model. In S/U analysis, the eigenvalue sensitivity coefficient is defined as

$$S_{k,\Sigma} = \frac{\delta k/k}{\delta\Sigma/\Sigma},$$

where Σ is the system parameter (e.g., cross section) with a given uncertainty. An experiment should be highly sensitive to the nuclide of interest in the energy region of interest to be most relevant to other problems sensitive to that condition. Improved experimental configurations can also be identified by examining sensitivity profiles as a function of energy and using these profiles to inform design changes that accentuate the potential sources of bias of interest. Fig. 1 illustrates a general approach to using S/U analysis to inform experimental design.

The work described in this paper focused on S/U analysis of the LR-0 reactor with and without FLiBe insertion zones in the system. Calculations were performed using the SCALE software package (Rearden and Jessee, 2016), primarily using KENO-VI and TSUNAMI-3D (Perfetti et al., 2016) with continuous energy (CE) cross sections and physics. Simplified two-dimensional (2D) and detailed three-dimensional (3D) models of the LR-0 reactor were developed during this work. Results from the detailed 3D models agreed very well with draft results intended for the benchmark handbook of the International Reactor Physics Experiment Evaluation (IRPhE) Project (Košťál et al., 2016) and with references elsewhere in the literature (Košťál et al., 2015; Losa et al., 2015).

Several configurations of the LR-0 underwent scoping S/U analyses. In addition, application models for S/U analysis of FHR and MSR concepts were adapted from the literature for relevant representative concepts. The Advanced High Temperature Reactor (AHTR) (Varma et al., 2012) was chosen as representative of FHR concepts, and the Molten Salt Breeder Reactor (MSBR) (Gehin and Powers, 2016) was chosen as representative of MSRs. First, the FHR and MSR application models were used to identify potential sources of uncertainty due to underlying nuclear data. Following this, results from S/U calculations of the LR-0 experiment models and the FHR and MSR application models were compared to assess their similarity for the sources of uncertainty of interest. The S/U analyses of the LR-0 experiments were used to investigate the adequacy of nuclear data for FLiBe constituents by comparing computational models against integral reactivity experiments. Analyses of the LR-0 FLiBe experiments also included assessments of the ability of the experimental configurations used, as well as

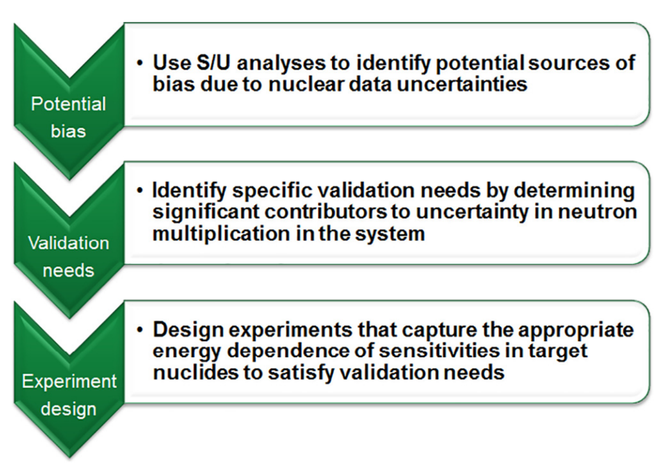

Fig. 1. General approach to using S/U analysis to enhance experiments.