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Preconceptual design of a fluoride high temperature salt-cooled engineering demonstration reactor: Motivation and overview ☆

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ABSTRACT

Engineering demonstration reactors are nuclear reactors built to establish proof of concept for technology options that have never been built. Examples of engineering demonstration reactors include Peach Bottom 1 for high temperature gas-cooled reactors and the Experimental Breeder Reactor-II for sodium-cooled fast reactors. Engineering demonstrations have historically played a vital role in advancing the technology readiness level of reactor concepts. This paper details a preconceptual design for a fluoride salt-cooled engineering demonstration reactor. The fluoride salt-cooled high-temperature reactor (FHR) demonstration reactor (DR) is a concept for a salt-cooled reactor with 100 megawatts of thermal output. It would use tristructural-isotropic (TRISO) particle fuel in compacts within prismatic graphite blocks. FLiBe (2 $^{7}LiF-BeF_2$) is the reference primary coolant. The FHR DR is designed to be small, simple, and affordable. Development of the FHR DR is an intermediate step to enable near-term commercial FHRs. The design philosophy of the FHR DR was focused on safety, near-term deployment, and flexibility. Lower risk technologies are purposely included in the initial FHR DR design to ensure that the reactor can be built, licensed, and operated as an engineering demonstration with minimal risk and cost. These technologies include TRISO particle fuel, replaceable core structures, and consistent structural material selection for core structures and the primary and intermediate loops, and tube-and-shell primary-to-intermediate heat exchangers.

Important capabilities to be demonstrated by building and operating the FHR DR include:

- core design methodologies,
- heat exchanger performance (including passive decay heat removal),
- pump performance,
- reactivity control,
- salt chemistry control to maximize plant life,
- salt procurement, handling, maintenance and ultimate disposal, and
- tritium management.

Non-nuclear separate and integral test efforts (e.g., heated salt loops or loops using simulant fluids) are necessary to develop the technologies that will be demonstrated in the FHR DR.

1. Introduction

This paper describes a high-level overview of a preconceptual design for a fluoride salt-cooled engineering demonstration reactor. This paper is a companion paper to Brown et al. (2016), which presents details of the reactor core design and preliminary safety analysis for that engineering demonstration reactor.

In 2015, the U.S. Congress authorized the U.S. Department of Energy Office of Nuclear Energy (DOE-NE) to initiate the Advanced

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Demonstration and Test Reactor (ADTR) study (Petti et al., 2016). The ADTR study evaluated advanced reactor technology options, capabilities, and requirements within the context of national needs and public policy to support innovation in nuclear energy (Petti et al., 2016). National laboratories, industry, and other relevant stakeholders of an advanced nuclear reactor conducted the ADTR study.

The ADTR study team identified several diverse and important missions for advanced reactor technologies based on recent DOE-NE and international studies. Based on these technology needs, the ADTR study identified several potential strategic objectives for reactor technology *demonstration* and for *testing*. The strategic objectives for reactor technology demonstration include: (1) process heat applications to reduce the carbon footprint of U.S. industry, (2) closing the nuclear fuel cycle and extending natural resource utilization, and (3) increasing the overall system technology readiness level (TRL). An additional strategic objective was identified for a test reactor: provide an irradiation test reactor to support development and qualification of fuels, materials, and other important components/items (e.g., control rods, instrumentation) of both thermal and fast neutron-based Generation-IV (Gen-IV) advanced reactor systems.

The results of a TRL assessment (Gougar et al., 2015) were used to identify potential technology options to be considered against each strategic objective. These options included high temperature gas-cooled reactors (HTGR), sodium-cooled fast reactors (SFR), fluoride salt-cooled high-temperature reactors (FHRs), and lead-cooled fast reactors (LFR). Although they are potentially promising technologies, the gas-cooled fast reactor (GFR), supercritical water reactor (SCWR), and liquid-fueled molten salt reactor (MSR) were determined to be insufficiently mature (low TRL) to be considered for near-term deployment, and therefore they were not assessed against the strategic objectives of the ADTR study. For the FHR and LFR concepts, engineering demonstration reactor point designs were commissioned for evaluation in the study. For the more mature HTGR and SFR concepts, both test reactor and commercial demonstration point designs were commissioned for evaluation in the study.

FHRs hold promise for providing high-temperature heat from a low-pressure, high-power-density system, but the technology is relatively immature. Significant knowledge gaps to implementation may be addressed using a small-scale engineering demonstration reactor (DR) to increase the TRL of the system. This paper outlines the FHR DR preconceptual design and associated philosophy. In addition, the paper addresses how the FHR DR would advance the TRL of FHR concepts.

FHRs comprise a class of reactor concepts that use fluoride salts as low-pressure coolants to produce high-temperature heat with a high degree of passive safety. The objective of FHR development is to improve on the economics and potential applications of a light water reactor. This is accomplished by using a high reactor outlet temperature and attractive coolant thermal properties in a low-pressure system. The high outlet temperature enables high efficiency generation of electricity and the potential for diverse process heat missions. FHRs can replace other thermal reactor technologies in a once-through fuel cycle.

Several preconceptual FHR design efforts have been conducted. Specific designs include the Oak Ridge National Laboratory (ORNL) Advanced High Temperature Reactor (AHTR) with 3400 megawatts of thermal output (MWt) (Holcomb et al., 2011), as well as a 125 MWt small modular AHTR (SmAHTR) from ORNL (Greene et al., 2010). Other important examples are the Mark 1 (Mk1) pebble bed FHR (PB-FHR) concept from the University of California, Berkeley (UCB) (Andreades et al., 2016; Forsberg et al., 2014a) and an FHR test reactor (TR) design developed at the Massachusetts Institute of Technology (MIT) (Forsberg et al., 2014b). Additionally, a small FHR demonstration reactor design is under development by the Shanghai Institute of Applied Physics (Xiao et al., 2014). These FHR concepts are based on reasonable assumptions for their intended objectives and include a large commercial plant (ORNL AHTR), a small modular reactor (SmAHTR), a commercial demonstration plant (PB-FHR), and a test reactor (MIT FHR TR).

It is notable that FHR concepts, though solid-fueled, directly benefit from the operating experience of the liquid-fueled Molten Salt Reactor Experiment (MSRE), as well as the detailed design efforts for a large molten salt reactor concept and its breeder variant, the Molten Salt Breeder Reactor.

The FHR Technology Development and Demonstration Roadmap (Holcomb et al., 2013) identified several "remaining technology challenges and the research, development, and demonstration (RD&D) needed to address the challenges." Successfully designing, licensing, building, and operating an engineering demonstration FHR is necessary to address key technology gaps. These include design performance prediction, infrastructure and regulatory maturation, and development and demonstration of systems and components at capacities that can be confidently scaled to commercial deployment. Infrastructure and regulatory maturation goals include:

(1) generating the data and validating the models needed to eventually license an FHR as a power reactor,
(2) providing validation data for computational modeling and simulation capabilities in areas including reactor analysis, safety performance and salt chemistry modeling,
(3) demonstrating key fabrication techniques for FHR reactor components, and
(4) developing a supply chain for FHR-specific components and materials, including fuels and salts.

System and component technology goals include:

(1) developing and demonstrating FHR-specific instrumentation and control systems,
(2) fuel performance demonstration and qualification, and
(3) using refueling technologies needed to support commercial FHR operation.

Each of these technology needs can and will be developed to some maturity level using separate effects testing facilities and integral effects testing capability, but an operating FHR DR will enable engineering demonstration of these technology solutions. Thus, the FHR DR is the keystone of a broader set of FHR technology development and demonstration efforts and fulfills a crucial role in FHR technology development by advancing the technological maturity and readiness level of salt systems as a whole.

The FHR DR mission is not a performance demonstration or a commercial demonstration, but rather an engineering demonstration to support reducing and mitigating risk for a later commercial demonstration. Therefore, it could be licensed as a test or research reactor as defined by the US Nuclear Regulatory Commission (NRC) (see U.S. 10CFR Part 50 Section 22), and it is expected to have a limited operational lifetime compared to a commercial plant, at smaller scale and lower cost. It is expected that some systems will be less mature than what is needed for commercial applications, and it is acknowledged that there will be large uncertainties when estimating the costs of some of these systems.

The objective of the FHR DR is rapid advancement of the TRL of FHRs (although other molten salt technologies would also benefit). Construction and operation of the FHR DR will enable commercial FHR deployment through disruptive and rapid technology development and demonstration, closing gaps to commercial viability. Incorporating lower-risk technologies into the initial design is