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Review

Design and licensing strategies for the fluoride-salt-cooled, high-temperature reactor (FHR) technology

Raluca O. Scarlat [a,*], Michael R. Laufer [b], Edward D. Blandford [c], Nicolas Zweibaum [b], David L. Krumwiede [b], Anselmo T. Cisneros [b], Charalampos Andreades [b], Charles W. Forsberg [d], Ehud Greenspan [b], Lin-Wen Hu [e], Per F. Peterson [b]

[a] *Department of Engineering Physics, University of Wisconsin, Madison, 1500 Engineering Dr, Madison, WI 53711, USA*
[b] *Department of Nuclear Engineering, University of California, Berkeley, 4118 Etcheverry Hall, MC 1730, Berkeley, CA 94720-1730, USA*
[c] *Department of Chemical & Nuclear Engineering, University of New Mexico, 259 Farris Engineering Center, Albuquerque, NM 87131, USA*
[d] *Department of Nuclear Science and Engineering, Massachusetts Institute of Technology, 77 Massachusetts Avenue, 24-107, Cambridge, MA 02139, USA*
[e] *Nuclear Reactor Laboratory, Massachusetts Institute of Technology, 138 Albany Street, NW12-220, Cambridge, MA 02139, USA*

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ABSTRACT

Fluoride-salt-cooled, high-temperature reactor (FHR) technology combines the robust coated-particle fuel of high-temperature, gas-cooled reactors with the single phase, high volumetric heat capacity coolant of molten salt reactors and the low-pressure pool-type reactor configuration of sodium fast reactors. FHRs have the capacity to deliver heat at high average temperature, and thus to achieve higher thermal efficiency than light water reactors. Licensing of the passive safety systems used in FHRs can use the same framework applied successfully to passive advanced light water reactors, and earlier work by the NGNP and PBMR projects provide an appropriate framework to guide the design of safety-relevant FHR systems. This paper provides a historical review of the development of FHR technology, describes ongoing development efforts, and presents design and licensing strategies for FHRs. A companion review article describes the phenomenology, methods and experimental program in support of FHR.

1. Introduction

Fluoride-salt-cooled, high-temperature reactor (FHR) technology uses a novel combination of fluoride salt coolant and high-temperature coated-particle fuel. The low-pressure primary system delivers heat in the temperature range from 600 °C to 700 °C or higher, uses thin-walled reactor vessels as do sodium-cooled fast reactors (SFRs), and enables power densities between 10 and 30 MW/m^3, compared to typical power densities below 5 MW/m^3 for modular helium reactors (Gas Turbine-Modular Helium Reactor, 1996, pp. 4–6), (Matzer and Wallace, 2005). FHRs use natural circulation for emergency decay heat removal, and incorporate a number of other passive and inherently safe features.

Recent studies of FHRs (Forsberg et al., 2003a; Ingersoll et al., 2004; Peterson and Zhao, 2006; Fei et al., 2008) suggest the potential to achieve attractive economic performance while meeting high standards for reactor safety and security. Based on this earlier work, the U.S. Department of Energy (DOE) initiated an Integrated Research Project (IRP) in January 2012 with the Massachusetts Institute of Technology, the University of California, Berkeley, and the University of Wisconsin–Madison, to develop the technical basis to design, develop, and license commercially attractive FHRs.

To initiate this project, the IRP hosted a series of four expert workshops during 2012 to review technical and licensing issues for FHRs. The comments of the experts attending the workshop were integrated into four white papers covering the topics of each of the workshops. These four FHR white papers set the groundwork to identify key technologies and challenges in the development of FHRs (Cisneros et al., 2013a, 2013b; Cao et al., 2013; Carpenter et al., 2013).

This article provides an overview of the FHR white papers, and focuses primarily on the material developed in the first white paper, FHR Subsystems Definition, Functional Requirement Definition, and Licensing Basis Event (LBE) Identification (Cisneros et al., 2013a). The first section of this article reviews the history of the development of FHR technology, summarizes current activities, and describes each of the FHR white papers. The rest of the article discusses the overall strategy for design and licensing of FHRs; how

* Corresponding author. Tel.: +1 5105173685.
E-mail address: roscarlat@wisc.edu (R.O. Scarlat).

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to identify high-level functional requirements of major FHR systems, structures, and components (SSCs); and how to identify a range of LBEs that should be considered in design and in the development of modeling tools and supporting experiments, including a discussion of lessons from the Fukushima Daiichi accident for severe external beyond design basis events (BDBEs). A companion review article focuses on the material developed in the second and third FHR white papers (Zweibaum et al., 2014).

1.1. Historical perspective

The history of molten salts as working fluids for nuclear reactors goes back more than 50 years and begins with Ed Bettis and Ray Briant of Oak Ridge National Laboratory (ORNL) shortly after World War II. They were in charge of designing a nuclear-powered aircraft. They selected molten fluoride salts primarily as a result of the salts' high-temperature performance and overall chemical stability. In 1954, the first small molten-salt reactor, the Aircraft Reactor Experiment, was built and achieved a power of 2.5 MWth. The primary fuel circuit was cooled by sodium, and the circulating fuel comprised a $NaF\text{-}ZrF_4\text{-}UF_4$ mixture. The maximum operating temperature of the fuel was 882 °C (Uhlir, 2007), (Macpherson, 1985).

The military need for nuclear-powered aircraft decreased sharply in the latter half of the 1950s as attention shifted toward ballistic missile technology. Following the closing of the Aircraft Reactor Experiment in 1956, Alvin Weinberg pushed to create the Molten Salt Reactor (MSR) to see whether this technology could be adapted for civilian power reactors. Shortly after, the Molten Salt Reactor Experiment (MSRE) was approved, and design started in the summer of 1960 at ORNL. It was intended to simulate only the fuel stream of a two-fluid breeder reactor. Ultimately, an 8-MWth MSRE was built for just over $8 million (1961 dollars) (Macpherson, 1985); it took approximately 3 years to construct. The initial fuel for the MSRE was $^7LiF\text{-}BeF_2\text{-}ZrF_4\text{-}UF_4$ (Shaffer, 1971), while the intermediate coolant was clean (i.e. fuel-free) $^7LiF\text{-}2BeF_2$ (flibe). In 1968, the original fuel was replaced with ^{233}U, making it the first reactor to run on this fissile fuel. It had a graphite moderator and used Alloy N for its structural material. The MSRE ran from 1965 to 1969 at a typical operating temperature of 600 °C (Shaffer, 1971). During operation, the concentrations of CrF_2 in the fuel salt were observed to rise by a level indicating an average corrosion rate of 0.1 mm (4 mils) per year, and after shutdown it was found that fission products had caused intergranular attack. In contrast, the intermediate loop with clean salt, as would be used in FHRs, experienced no detectable corrosion after over 26,000 h of operation (Rosenthal et al., 1972).

For a variety of reasons, the MSR program in the United States was ultimately shutdown in the middle of the 1970s. At that time, the objectives of the MSR program were shifting toward a thorium breeder technology known as the Molten Salt Breeder Reactor, which competed with the uranium–plutonium Liquid Metal Fast Breeder Reactor program being developed at Argonne National Laboratory (Macpherson, 1985). The fluoride salts were subsequently studied for use as coolants for fusion reactors, but it was not until the early 2000s that research in molten salts as fission reactor coolants was renewed in the United States. The FHR reactor concept with fuel being solid and separate from the coolant represents a significant departure from the liquid fuel MSR technology developed in the 1960s.

Since the 1970s, high-temperature, gas-cooled reactor (HTGR) technology has been studied because of the potential advantages of delivering heat at substantially higher temperatures than are achievable with light water reactors (LWRs). The advantages of higher temperatures include increased efficiency for power conversion; reduced waste heat generation, which can reduce or eliminate the need for cooling water and thus increase siting flexibility; and the capability to provide co-generation and process heat services. It has proven challenging, however, to develop helium-cooled reactor designs with passive decay heat removal capability that have sufficiently low construction costs to compete economically with conventional LWRs. As part of the effort to commercialize HTGRs, a wide experience base with manufacturing and performance of coated-particle fuel has been established in the U.S., U.K., Germany, France, China, Russia, Japan, South Africa, and the Republic of Korea (NGNP Fuel Qualification White Paper, 2010). The FHR also uses coated-particle fuel, and relies on much of the experience base with HTGR fuel.

1.2. FHR development activities

Research on salt-cooled, high-temperature reactors was initiated in 2002 with studies of a Liquid Salt Very High Temperature Reactor (LS-VHTR) aimed at achieving high core outlet temperatures (950–1000 °C), derived from the work at ORNL in the 1960s and 1970s (Forsberg et al., 2003b). The LS-VHTR was essentially a modified helium-cooled VHTR, using liquid salt as the primary coolant, which operated at near atmospheric pressure and substantially greater power density – two to six times higher – than helium-cooled reactors (Ingersoll et al., 2005; Clarno and Gehin, 2006; Casino, 2006). As shown in Table 1, FHR core power densities are in the range of 10–30 MW/m^3; gas cooled reactor core power densities are 4.8 MW/m^3 for the 400 MWth pebble bed modular helium reactor (PBMR), and 6.6 MW/m^3 for the 600 MWth gas turbine modular helium reactor (Gas Turbine-Modular Helium Reactor, 1996, pp. 4–6), (Matzer and Wallace, 2005). While substantially higher than these HTGRs, FHR core power densities are lower than for PWRs (105 MW/m^3) and SFRs (321 MW/m^3). Based upon the metric of primary system volume, given by the specific reactor vessel power (MWe/m^3), FHRs reactor vessels are much more compact than PBMRs and S-PRISM, and less compact than PWR reactor vessels.

As comparisons like these were made, researchers also quickly recognized that liquid salt coolants could achieve the same average primary coolant temperature with a significantly lower maximum outlet coolant temperature compared to helium-cooled reactors. Because thermal efficiency depends primarily on average coolant temperature, rather than peak temperature, the LS-VHTR concept evolved into the Advanced High-Temperature Reactor (AHTR), and then FHR with a core outlet temperature sufficiently low to allow the use of existing American Society of Mechanical Engineers code-certified structural materials for the primary pressure boundary (Forsberg et al., 2003a; Ingersoll et al., 2004; Peterson and Zhao, 2006; Fei et al., 2008), (Forsberg et al., 2012, 2013; Sabharwall et al., 2013).

The most recent conceptual designs classified as FHR technologies include the Pebble Bed FHR (PB-FHR) at UCB (Scarlat and Peterson, 2013), (Krumwiede et al., 2013), the Small Modular AHTR (SmAHTR) at ORNL (Greene et al., 2010b), the large central-station AHTR at ORNL (Holcomb et al., 2011), (Varma et al., 2012), and the solid fuel thorium molten salt reactor (SF-TMSR) at the Shanghai Institute of Applied Physics (SINAP) in China.

SmAHTR is a 125-MWth cartridge-core, integral-primary-system FHR that uses fixed plate-type fuel. The ORNL 2012 AHTR is a large 3400-MWth fixed plate fuel variant of the FHR. This 2012 AHTR design implements novel designs for fuel and refueling, and demonstrates a practical application of supercritical steam for power conversion based upon extensive experience in fossil power plants.

The PB-FHR under development at UCB uses a randomly packed pebble core configuration with capability for online