Nuclear Engineering and Design 335 (2018) 54–70

Contents lists available at ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

Conceptual design of a freeze-tolerant Direct Reactor Auxiliary Cooling System for Fluoride-salt-cooled High-temperature Reactors

Maolong Liu, Joel Hughes, Amir Ali, Edward Blandford*

The University of New Mexico, 1 University of New Mexico, Albuquerque, NM 87131, USA

ABSTRACT

One of the key potential advantages of the Fluoride-salt-cooled High-temperature Reactor (FHR) is the use of passive safety systems that ensure the safe response of the reactor during anticipated operational occurrences, design basis events, and beyond design basis events. Typically, FHRs use a Direct Reactor Auxiliary Cooling System (DRACS) to remove the decay heat under a variety of accidents when the active reactor shutdown system is unavailable. Thus, it plays a key role in preventing the overheating/overcooling of the reactor in case of the failure of other primary means of heat removal. To enhance the operational reliability of DRACS, two DRACS designs are proposed in this study. The proposed DRACS designs are composed of two natural circulation salt loops and a water tank as the heat sink. This study focused on the transient behavior of DRACS of the FHRs during Loss of Heat Sink (LOHS) accident. Calculations were performed using RELAP5-3D to evaluate the design features of each concept, based on one design concept, the University of California, Berkeley's Mark-1 pebble-bed FHR (PB-FHR). The calculation shows that the Mk-1 PB-FHR with DRACS proposed in this paper can operate for a relatively long time (about 90 h for design A and 430 h for design B) for a LOHS transient without operator involvement.

1. Introduction

The Fluoride-salt-cooled High-temperature Reactor (FHR) is a novel reactor concept using a molten salt coolant and coated-particle tris-tructural isotropic fuel that features a high-temperature, low-pressure liquid fluoride salt working fluid, and fully passive decay heat removal capabilities (Carbajo and Qualls, 2016; Forsberg et al., 2012; Forsberg et al., 2003). It combines the features of the gas-cooled Very High Temperature Reactor (VHTR), sodium factor reactor (SFR), and Molten Salt Reactor (MSR) (Aufiero and Fratoni, 2016; Blandford and Peterson, 2013; Ge et al., 2016), which provides for various potential benefits such as full passive safety, near-atmospheric pressure operation, and high thermal efficiency(Zheng et al., 2015). The objective of FHR development is to improve plant thermal efficiency and to provide a high temperature energy source for commercial electrical power, industrial heat, or hydrogen production (Aaron et al., 2015; Qualls et al., 2016; Yoder et al., 2016). The MSR, with its fuel dissolved in the liquid salt, and the FHR have many research challenges in common (Serp et al., 2014), allowing the FHR concepts to directly benefit from the operating experience of the Molten Salt Reactor Experiment (MSRE), as well as the detailed design efforts for large molten salt reactor concepts (Qualls et al., 2016).

From the early 2000's, research in molten salt as reactor primary fluids was renewed in U.S. (Forsberg et al., 2003), based off the original work done at Oak Ridge National Laboratory (ORNL) on MSR (Blandford and Peterson, 2013). In recent years, the U.S. Department of Energy (DOE) has supported researchers at universities and U.S. national laboratories to study FHRs and to develop the scientific and technical basis to design, license, and construct these reactors (Brown et al., 2017). Several preconceptual and conceptual FHR designs have been proposed by ORNL, the University of California, Berkeley (UCB), and the Massachusetts Institute of Technology (MIT) (Aaron et al., 2015; Qualls et al., 2016). The value of high-temperature MSRs is also recognized internationally (Aaron et al., 2015). In China, the Chinese Academy of Science launched a project aiming to construct a new Thorium Molten Salt Reactor (TMSR) nuclear system in Shanghai Institute of Applied Physics (SINAP) (Ge et al., 2016; Xu, 2016). Several other countries also have salt-cooled reactor development under way (Aaron et al., 2015).

One of the key potential advantages of the FHRs are the passive decay heat removal systems that ensure the safety of the reactor during anticipated operational occurrences, design basis events, and beyond design basis events (Galvez, 2011). In a fully passive implementation, neither electrical power nor operator actions are required to ensure safe

* Corresponding author.
E-mail address: edb@unm.edu (E. Blandford).

https://doi.org/10.1016/j.nucengdes.2018.04.019
Received 13 February 2018; Received in revised form 16 April 2018; Accepted 19 April 2018

system response (Nakata et al., 2013). Typically the FHRs use a Direct Reactor Auxiliary Cooling System (DRACS) to remove the decay heat under a variety of accidents when the active reactor shutdown system is unavailable (Peterson and Blandford, 2011). The DRACS consists of various components designed to remove heat passively by means of pure natural circulation (Galvez, 2011; Lv et al., 2015). Several concepts aim to improve the economics of the design by optimizing the DHX, so that the heat transfer performance under normal operation is degraded and is enhanced during accident conditions (Hughes and Blandford, 2016). Prior research has shown that DRACS is an effective way to remove heat in an accident, enabling large flexibility in FHR design as well as significantly higher power densities (Cisneros, 2013; Sabharwall et al., 2011). Moreover, its performance is also directly related to the overall system efficiency and safety (Sabharwall et al., 2011).

The concept of DRACS was developed by the Sodium Fast Reactor (SFR) community, and then was improved and widely adopted in many advanced liquid–metal reactor designs, such as the Prototype Fast Reactor (PFR) Dounreay, EFR (Farrar et al., 1999), KALIMER-600, Indian Prototype Fast Breeder Reactor (PFBR) (Mathews et al., 2008), ABTR, as well as JSFR (Hughes and Blandford, 2016; Lv et al., 2015; Zhang et al., 2009). With recent increased interest in FHR technology in the advanced reactor community, DRACS design has become a subject of vital importance and is actively studied by a number of researchers (Shin et al., 2016). Interestingly, the potential to overcool the reactor and freeze key equipment of the reactor system is one major issue in adopting a high-melting liquid as the heat-transfer fluid in the DRACS loops (Le Brun et al., 2017; Nakata et al., 2013). Rather paradoxically, this kind of undesirable freeze phenomenon may cause a severe risk to plant safety due to a failure of the passive decay heat removal loop (Eoh et al., 2010). Hence, sufficient design considerations to prevent freezing of the heat transfer fluid are required to enhance the operational reliance of the passive decay heat removal system (Eoh et al., 2010). To reflect on the lessons learned from the Fukushima accident, JSFR improved safety features of DRACS in the preconceptual design so that the time margin of sodium freeze was more than 10 days during a transient (Chikazawa et al., 2015; Kamide et al., 2016). Eoh et al. (2010) also proposed different design options to prevent the sodium freeze for a sodium-cooled fast reactor. Thus, sufficient design considerations to enhance the performance of DRACS as well as to prevent DRACS freeze can be considered a requirement to secure the operational reliance of the DRACS.

In general, pipe blockage caused by freezing may occur during filling of a cold pipe or during a heat transfer process with flowing or stagnant fluids (Gilpin, 1981). Thermal hydraulics models that account for freezing behavior under various operating conditions are required to enhance the operational reliance of the passive decay heat removal system. Experimental studies are currently being conducted to accurately measure thermophysical properties of molten salts near the freezing point, and to develop a model to account for freezing behavior (Chapdelaine and Scarlat, 2017). Since such models are not available yet at the present time, flow channel blockage caused by freezing is assumed to occur in the present study when the bulk fluid temperature of salt reaches its freezing temperature. Table 1 summarizes the freezing temperature and some other thermophysical properties of candidate molten salts for the FHR used in the present study.

Table 2
Mk-1 PB-FHR operating parameters (Andreades et al., 2014; Zweibaum, 2015).

Parameter	Value
Pressure (bar)	1.019
Total thermal power (MW)	236.0
Primary nominal core mass flow (kg/s)	1084.0
Primary coolant inlet temperature (°C)	600.0
Primary coolant outlet temperature (°C)	700.0
Reactor scram time (s)	0.0
Primary coolant pump trip time (s)	0.0
Decay heat	See Fig. 1

The overall objective of the present study is to propose two new DRACS design variations to (1) maintain the ability to cool the reactor even during a severe accident, and (2) to avoid (or delay) the failure of the DRACS caused by freezing of the heat-transfer fluid. The two new DRACS designs are presented in Section 2. RELAP5-3D (The RELAP5-3D Code Development Team, 2012) simulations are carried out in Section 3 to optimize the design parameters of key equipment of the two DRACS designs. Finally, two accident scenarios are simulated to illustrate the performance of two DRACS proposed in the present paper.

2. Concept of passive decay heat removal systems of FHRs

2.1. Mark-1 Pebble-Bed FHR

The DRACS design of this study is based on the Mk-1 PB-FHR (Andreades et al., 2014); however, it is important to note that the design variations presented here have equal applicability to other FHR design concepts that utilize DRACS. It uses three DRACS loops to remove decay heat under emergency conditions when the normal shutdown cooling system is not functional (Andreades et al., 2014). The design parameters of the Mk-1 PB-FHR are summarized in Table 2. Loss of Heat Sink (LOHS) is one of the design basis accidents for FHRs, which employ the DRACS loops for natural circulation decay heat removal (Scarlat, 2012). Each DRACS module consists of a DHX located inside the reactor vessel below the salt pool surface, a DRACS salt loop, and one additional heat exchanger located outside the reactor containment, which transfers heat from the DRACS salt loop to evaporate water or directly to circulating air in a chimney (Andreades et al., 2014). During a LOHS transient, two natural circulation flow loops are formed (one in the primary coolant and one in the DRACS coolant) between the reactor core and the DRACS system to continuously remove the decay heat. The Mk-1 PB-FHR employs three DRACS loops in a two-out-of-three design approach to withstand design basis accident and to avoid vessel or other metallic component failure in the event of complete, permanent station blackout with the loss of a single full DRACS (Flanagan et al., 2012; Greene et al., 2010; Hughes et al., 2016). The decay heat power during the LOHS transient is shown in Fig. 1.

FLiBe is utilized as the primary coolant for several FHR concepts. The relatively high melting point of the fluoride salts makes thermal control of the coolant a challenge (Sabharwall et al., 2011). Potential freezing of DRACS during transient events could increase the core damage frequency due to its vital role in accident mitigation. Various

Table 1
Thermophysical properties of candidate molten salts for FHR (Beneš and Konings, 2009; Davis, 2005; Forsberg et al., 2003; Sohal et al., 2013).

Molten salt coolant	Freezing temperature/Melting point (K)	Boiling point (K)	Density (kg/m^3)*	Specific heat capacity v(J/kgK)	Thermal conductivity (W/m·K)	Viscosity (Pa·s)*
LiF-BeF$_2$ (FLiBe)	733.0		2413.1−0.4884T	2386.0	1.1	$1.16 \times 10^{-4} e^{\frac{3755}{T}}$
LiF-NaF-KF (FLiNaK)	727.0	1843	2729.4−0.73T	1884.0	0.8	$4.0 \times 10^{-5} e^{\frac{4170}{T}}$

* T is salt temperature, K.