Annals of Nuclear Energy 109 (2017) 458–468

Contents lists available at ScienceDirect

Annals of Nuclear Energy

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

# Conceptual design and analysis of heat pipe cooled silo cooling system for the transportable fluoride-salt-cooled high-temperature reactor

Chenglong Wang, Limin Liu, Minghao Liu, Dalin Zhang *, Wenxi Tian, Suizheng Qiu, G.H. Su

*Department of Nuclear Science and Technology, Xi'an Jiaotong University, Xi'an, Shaanxi 710049, China*
*Shaanxi Key Lab. of Advanced Nuclear Energy and Technology, Xi'an Jiaotong University, China*

ARTICLE INFO

*Article history:*
Received 25 September 2016
Received in revised form 6 February 2017
Accepted 9 May 2017

*Keywords:*
TFHR
PRHRS
Heat pipe
Transient analysis

ABSTRACT

After the Fukushima Dai-ichi nuclear power plant severe accident, the advanced facilities that could improve the nuclear safety performance are preferred by the public. This paper discusses the preliminary design and thermal-hydraulic analysis of a heat pipe cooled passive heat removal system for the transportable fluoride-salt-cooled high-temperature reactor of 20 MWth proposed by Massachusetts Institute of Technology in 2014. Under severe accident, the high temperature fuel and fluoride salt sustain at the reactor core, the heat pipes are inserted by gravity to remove the decay heat to the final heat sink of silo cooling system. To illustrate the feasibility of the designed passive heat removal system, the heat pipe startup performance is firstly numerically investigated by self-developed code HPTAC (Heat Pipe Transient Analysis Code). Four heat transfer limits are adopted as criteria for the success of heat pipe operation, 1) Viscous 2) Entrainment 3) Sonic 4) Capillary limits. The benchmark of heat pipe startup compared with experimental data is conducted as well as a sensitivity study for heat pipe inclination angle. Secondly, the transient performance of passive heat removal system based on reasonable assumptions of heat pipe model is analyzed. Results show that the heat pipe reaches the normal operation in 6 min, in good agreement with experimental data with the maximum discrepancy of 16%. Most of fuel decay heat can be removed in 5 h by heat pipe passive heat removal system and all the key temperature are kept below the allowed temperature limits.



## 1. Introduction

After the nuclear disaster at the Fukushima-1 nuclear power plant, the people are very sensitive about nuclear power. More advanced nuclear technologies with higher safety performance are demanded urgently. The Fluoride-salt-cooled High temperature Reactor (FHR), as a technology branch of Gen IV molten salt reactor, combines high-temperature TRISO particles as fuel and high-temperature molten salt as coolant, featured with unique market and safety characteristics. This reactor technology can eliminate large-scale radionuclide releases by avoiding fuel failure during a Beyond Design Basis Accident (BDBA) (Minck, 2013).

No FHR has been built. Currently, the small modular reactor need for remote and isolated sites, such as Antarctic bases, container ships and mining locations, is very strong. It is desirable that the reactor has a compact design and can be easily transported by conventional ways. The reactor could be sized to a much smaller, more transportable, and more economic design by means of FHR technology when compared with other nuclear reactor technologies. As a result, a more compact core configuration with 20 MWth, 18-month one-through fuel cycle, named Transportable Fluoride-salt-cooled High-temperature Reactor (TFHR), is proposed at MIT. Our previous works have conducted the neutronic and thermal-hydraulic design and analysis for the TFHR, preliminary indicating the feasibility of the core design (Wang et al., 2016a; Sun and Hu, 2014).

Little research has been conducted for fluoride-salt-cooled reactor systems, especially for the passive heat removal system (PRHRS). In 1970s, Oak Ridge National Laboratory conducted a series of investigations on the PRHRS of Molten Salt Reactors (MSRs) with liquid fuel; they proposed a conceptual drain tank cooling system using molten salt as the coolant to release the residual decay heat in the scenario of MSR accidents (Robertson, 1971). Following the next 50 years, many MSR conceptual designs are proposed, but the relevant PRHRS kept unchanged despite of few improvements. In 2003, the molten salt reactor with solid fuel, namely FHR, is firstly proposed by Forsberg et al. (2003). The original designed drain tank cooling system could not be adopted

* Corresponding author at: Department of Nuclear Science and Technology, Xi'an Jiaotong University, Xi'an, Shaanxi 710049, China.
*E-mail address:* dlzhang@mail.xjtu.edu.cn (D. Zhang).

http://dx.doi.org/10.1016/j.anucene.2017.05.035
0306-4549/

because that the decay heat retains inside the TRISO particles not the fluoride salt. As a result, the baseline-design Direct Reactor Auxiliary Cooling System (DRACS) or Pool Reactor Auxiliary Cooling System (PRACS) inherited from Sodium Fast Reactor (SFR) is preliminary adopted during the transients (Ingersoll and Forsberg, 2006). In addition, the silo cooling system inherited from High Temperature Gas Reactors (HTGR) is also utilized as shown in Fig. 1. Under the normal conditions, the cooling system prevents heat damage to the concrete and equipment in the silo by circulating air via cooling channels in the wall. When the BDBA occurs, it leads to the startup of the BDBA system and the BDBA buffer salt melts. As temperatures continue to rise, the vessel may fail. If it fails, it contains sufficient molten salt to fill the bottom of the silo with liquid salt while keeping the reactor core covered with molten salt. Heat is transferred between the reactor vessel and the silo by circulating salt (Forsberg et al., 2012).

Above designed PRHRS of fluoride-salt-cooled reactor systems are fully passive actuated, but featured with high system complexity (2 or 3 heat transfer loops) and low economy. They are not suitable for the small modular reactors because smaller reactor sizes often allow for major simplification of systems, especially safety systems. As a result, more advanced heat transfer devices should be considered for the TFHR as simpler configuration as possible. Heat pipes, firstly invented by Gaugle in 1944, are the devices with remarkable heat transfer performance (Gaugle, 1942). They can transfer the huge heat by multi-phase change with a very small temperature drop. Most importantly, heat pipes are fully passive heat transfer elements featured with self-actuating and have a much smaller volume compared with other conventional heat transfer devices. From this point, applying heat pipes to PRHRS of small modular reactor is a better choice without doubt. During the past decades, many researchers focus on the theoretical and experimental investigations of heat transfer characteristics of heat pipes. Cotter firstly focused on the heat pipe startup performance study and developed the transient numerical models for the heat pipe operation (Cotter, 1965). After that, the heat pipe theoretical and experimental studies had a significant increase by a lot of researchers from America, Russia and China et al. As the maturity of heat pipe technology, many researchers from nuclear industry utilized heat pipe into nuclear reactors for temperature range from 370 K to 973 K. China institute of atomic energy employed high temperature sodium heat pipe into radiator of TOPAZ-II space reactor power system (Wang et al., 2016b). Shanghai Jiaotong University proposed a new concept passive cooling system by means of separate-type water heat pipe to remove the residual heat in the spent fuel pool (Ye et al., 2013). For the fluoride-salt-cooled reactors, little research has involved the heat pipe application. Xi'an Jiaotong University firstly proposed a new conceptual design of passive heat removal system for MSR with liquid alkali metal heat pipes and the transient behavior of a single heat pipe was investigated (Wang et al., 2013a,b). University of California at Berkeley takes advantage of thermosiphon mechanism (similar with heat pipe operation) to the DRACS of Mark1 Pebble-Bed Fluoride-salt-cooled High-temperature Reactor (PB-FHR) Andreades et al., 2016.

In the present paper, the high-temperature sodium heat pipe is embedded into the silo cooling system of the small modular TFHR to remove the decay heat during BDBA. Firstly, the heat pipe startup performance is numerically investigated by self-developed code HPTAC (Heat Pipe Transient Analysis Code). Four heat transfer limits are adopted as criteria for the success of heat pipe operation. The benchmark of heat pipe startup compared with experimental data is conducted as well as some key factors sensitivity study. Secondly, the transient performance of passive heat removal system based on reasonable assumptions of heat pipe model is analyzed to show the feasibility of system design. This paper would provide a solid theoretical foundation for the following system experiment benchmark.

## 2. System description

### 2.1. TFHR core configuration

A more compact core configuration can be achieved with the FHR technology to meet potential government missions for ships and remote site (Macdonald and Frosberg, 2013). Our previous works embody the prismatic core designed TFHR from the perspective of neutronic and thermal-hydraulics based on nuclear physics analysis code MCODE and CFD methodology (Wang et al., 2016a; Sun and Hu, 2014). The primary coolant adopts a binary molten salt system of the $^7$LiF-BeF$_2$ (FLiBe, 66.7%–33.3%). Similar with High Temperature Gas Reactor (HTGR), TFHR employs cylindrical fuel compact randomly embedded with TRISO fuel particles and Burnable Poison Particles (BPPs). Stacks of fuel compacts are then inserted into hexagonal graphite matrix to construct a fuel block.

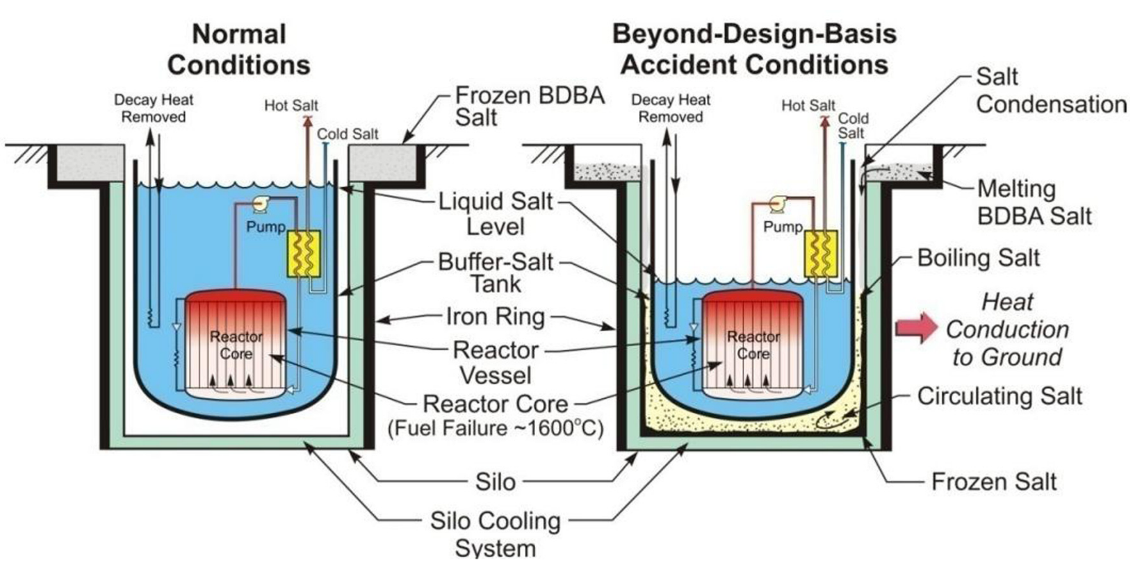


Fig. 1. Schematic of FHR BDBA approach (Forsberg et al., 2012).