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A buoyantly-driven shutdown rod concept for passive reactivity control of a Fluoride salt-cooled High-temperature Reactor

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HIGHLIGHTS

- We develop a novel buoyantly-driven shutdown rod concept for a FHR.
- Shutdown rod system can be actively or passively activated during transients.
- Response of the rod was computationally simulated and experimentally validated.
- Initial results indicate rod could provide effective transient reactivity control.

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ABSTRACT

This paper presents a novel buoyantly-driven shutdown rod concept for use in Fluoride salt-cooled High-temperature Reactors (FHRs). The baseline design considered here is a 900 MWth modular version of the FHR class called the Pebble Bed Advanced High-Temperature Reactor (PB-AHTR) that uses pebble fuel. Due to the high volumetric heat capacity of the primary coolant, the FHRs operate with a high power density core with a similar average coolant temperature as in modular helium reactors. The reactivity control system for the baseline PB-AHTR uses a novel buoyantly-driven shutdown rod system that can be actively or passively activated during reactor transients. In addition to a traditional active insertion mechanism, the new shutdown rod system is designed to also operate passively, fulfilling the role of a reserve shutdown system. The physical response of the shutdown rod was simulated both computationally and experimentally, using scaling arguments where applicable, with an emphasis on key phenomena identified by a preliminary Phenomena Identification and Ranking Table (PIRT) study. This paper presents results from both the pre-predicted simulation and experimental validation efforts.

1. Introduction

It was not until the early 2000s with the introduction of the Liquid Salt Very High Temperature Reactor (LS-VHTR) (Forsberg et al., 2003), that research in molten salts as reactor primary fluids was renewed in the United States from the work done at Oak Ridge National Laboratory (ORNL) on molten salt fueled reactors from the 1950s through the early 1970s. The LS-VHTR was essentially a modified helium-cooled VHTR using liquid salt as the primary coolant, which operates at near atmospheric pressure and substantially greater power density than helium-cooled reactors. This reactor configuration with the fuel being separated from the coolant represented a significant departure from the earlier liquid fuel Molten Salt Reactor (MSR) technology. In the Gen IV roadmap (DOE, 2002), the term AHTR has been used to describe fluoride salt cooled, high temperature reactor technology that uses solid fuel. More recently, the term Fluoride Salt-Cooled High Temperature Reactor (FHR) has been used to describe a class of fluoride salt cooled, high temperature reactor technology that uses solid fuel.

UC Berkeley has studied Fluoride salt-cooled High-temperature Reactors (FHRs) in collaboration with Oak Ridge National Laboratory. The FHR is the based on the original AHTR concept to use liquid fluoride salt to cool coated particle high temperature reactor fuels (Ingersoll et al., 2004), which has undergone several transformations over nearly a decade years (Peterson et al., 2008). FHRs take advantage of technologies developed for gas-cooled high temperature thermal/fast reactors, sodium fast reactors, and liquid salt reactors. The modular 900-MWth Pebble Bed Advanced High-Temperature Reactor (PB-AHTR) is the reference design for this paper.

An important element of developing advanced reactor technology is ensuring robust and reliable reactivity control across the design basis envelope. Due to the unique thermophysical properties of liquid fluoride salts, there exists a unique possibility

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Nomenclature

A_{ch}	cross-sectional area of the channel
A_{cs}	cross-sectional area of the rod
A_r	corrected cross-sectional area of the rod
A_s	corrected surface area of the rod
C_D	drag coefficient
D	diameter of the rod
F_B	buoyancy force on the rod
F_D	profile drag force on the rod
g	gravitational acceleration
k_{eff}	*k* effective
L	length of the rod
m_r	mass of the rod
t	time
$T_{c,in}$	core inlet temperature
u_{co}	coolant flow velocity
u_r	insertion velocity of the rod
V_r	rod volume
Greek	
μ	dynamic viscosity
υ	kinematic viscosity
ρ	fluid density
$\Delta\rho$	density difference between fluid and rod
Dimensionless groups	
N_F	Froude number
N_R	Reynolds number
Subscripts	
m	model
p	prototype
r	ratio

of using buoyancy forces to provide reserve shutdown insertion of shutdown rods. In order to demonstrate the viability of the buoyantly-driven shutdown rod concept, both computer simulation and experimental validation are required. This work included separate effects testing in order to measure the rod drag coefficient using isodensity drop testing to compare measured values with theoretical estimates. Additionally, integral effects testing was performed to demonstrate buoyantly-driven insertion where rod position was prepredicted using the empirically measured drag coefficient.

2. Fluoride salt cooled High-temperature Reactor (FHR)

2.1. System description

In Fig. 1, the primary loop of a representative FHR is represented by the blue line connecting the core and the intermediate heat exchanger (IHX) modules. During a loss of forced circulation (LOFC) transient (i.e. after a primary pump trip), a natural circulation flow loop is formed between the core and a set of Direct Reactor Auxiliary Cooling System (DRACS) heat exchangers (DHX modules). The DRACS heat exchangers transfer heat by natural circulation flow of a DRACS salt from the DHX modules to heat rejection exchangers cooled by outside ambient air, as indicated by the purple flow path. Under forced circulation the reverse bypass flow through the DHX is reduced by a fluidic diode.

One of the more challenging events for the FHR is a loss of heat sink (LOHS) transient without scram, where the IHX heat removal is interrupted but the primary pumps continue to operate and transfer fission power from the core to primary loop structures. This would also be a very severe transient for a MHR, since if forced circulation of the primary coolant continues without scram after loss of heat removal, the shutdown of an MHR on negative fuel temperature feedback would drive primary loop components and the pressure boundary to very high temperatures. The FHR reaches a lower peak coolant outlet temperature than a MHR because it also has negative coolant temperature feedback. The goal in the design of the buoyant shutdown rod system is to further reduce this peak temperature under a LOHS transient without scram, as well as for LOFC without scram. Therefore the figure of merit for a LOHS is the same as the LOFC where the peak coolant outlet temperature, which determines the temperature reached by metallic structures, is the main parameter of interest. However, one key difference is overcooling transients are not of concern for a LOHS.

The annular space between the reactor vessel and the guard vessel may filled with a low-cost buffer salt, such as a mixture of sodium and potassium fluoroborate, which minimizes primary salt inventory loss if the reactor vessel is faulted. The red flow path represents the IHX's intermediate loop which can be used to deliver thermal power to a variety of applications such as process heat for hydrogen generation or electricity generation. It should be noted that the design of FHRs, like all liquid salt technologies, must consider the potential for overcooling transients where after a substantial time period the salt could freeze in the primary loop.

2.2. FHR reactivity control

In FHRs, reactivity is controlled by the reactor control system (RCS) during normal or expected operation. As required by general design criterion 26 in Appendix A in 10CFR Part 50, FHRs are required to have two independent reactivity control systems with different design principles. The FHR may have the following reactivity control methods which are illustrated in Fig. 2, (1) normal shutdown by forced insertion of multiple shutdown rods; (2) reserve shutdown by insertion of multiple control rods; (3) reserve shutdown by passively driven buoyancy-activated insertion of multiple shutdown rods; and (4) shutdown by core negative temperature feedback.

Fig. 3 shows plan and elevation views of a Pebble Bed Advanced High-Temperature Reactor (PB-AHTR) (Caron et al., 2008), one of the reference designs for the FHR, depicting the locations of the control and shutdown safety rods. Following a scram signal or other shutdown signal, the shutdown rods and control rods are inserted via gravity by a heavy control rod actuator located above the rod, when the power is cut to the magnetic latches holding the actuators. For reserve shutdown, the shutdown rods will also insert passively due to negative buoyancy resulting from the rise of coolant temperature.

2.3. Shutdown rod system

The baseline PB-AHTR design shown in Fig. 3 has six buoyant shutdown rods that sink into the reactor core if the coolant temperature exceeds normal levels. The shutdown rods are located in 19.8-cm diameter channels in six of the seven hexagonal Pebble Channel Assemblies (PCA) that comprise the reference PB-AHTR reactor core. Each of the shutdown rods is designed to be neutrally buoyant at a flibe salt density corresponding to a flibe temperature of 615 °C ± 5 °C, taking into account all sources of uncertainty in the safety rod buoyancy (mass of the rod, volume of the rod, entrained gas bubbles on rod surfaces, flibe density, and other phenomena that would be identified in a detailed safety rod Phenomena Identification and Ranking Table (PIRT)).