CONCEPTUAL DESIGN OF A PASSIVE, INHERENTLY SAFE EMERGENCY SHUTDOWN ROD FOR HIGH-TEMPERATURE REACTOR APPLICATIONS

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ABSTRACT

The concept of a passive, inherently safe, and fail-safe design for an emergency control rod is presented. The functioning of the rod is based solely on inexorable physical laws. The operation of the rod in its emergency function does not require the intervention of a human operator, nor does it rely on any signal from a monitoring or safety system. Although the concept could be applicable to a variety of reactors (provided a normal temperature range is specified), in this paper, the concept is applied to the emergency shutdown of a pebble-bed reactor. The preliminary study presented here demonstrates that the proposed Electro-Magnetic Optimally Scramming Control Rod (EM-OSCR) naturally operates *when needed*. The rod is held out of the core region by the force of an electromagnet. The force is generated by a current carried by a conductor, a portion of which passes near or through the reactor core region. When the temperature in the conductor increases because of an increase in temperature in the reactor, the conductor resistivity increases. This, in turn, leads to a current decrease. When the current decreases below the level necessary to hold the rod up, the rod is released and it falls into the core under the effect of gravity.

1. Introduction

Recently, the pebble-bed reactor (PBR) concept has been receiving a great deal of renewed interest. For example, a consortium led by the South African Utility Eskom is studying the possibility of development and deployment of reactors of this type [1]. This renewed interest is motivated, in part, by the pebble-bed promise of safety features superior to those of the current generation of light water reactors (LWRs). Such passive safety features have been demonstrated experimentally in the German AVR project [2]. In particular, the PBR was shown to be safe against a loss of forced cooling (LOFC) without scram but without depressurization [3] and against depressurization with the simultaneous loss of forced cooling (DLOCF) but with scram [4]. The most severe scenario of the same type would be a depressurized loss of forced cooling without scram. Such a scenario has not been tested experimentally but has been modeled for a prismatic High Temperature Gas-Cooled Reactor (HTGR) [5]. In all cases, these HTGRs are shown to be safe. Yet, in all cases redundant safety systems for emergency shutdown and for maintaining the shutdown state are expected to be required. Passive (i.e., not requiring any intervention by a mechanism or by an operator) or inherent (i.e., relying on inexorable physical laws) systems will probably be preferred. Since in the PBR concept strong negative temperature feedback is expected to be the most likely shutdown mechanism in the LOCA events, control rods would be required only for maintaining sub-criticality following the eventual cooling down of the core. Since in a PBR the reactor core cooling process would take considerably longer than the time of descent of a rod into the core, the redundant shutdown rods would be effective even if they dropped into the core relatively slowly, as discussed later.

In this paper, a passive and inherently actuated control rod concept for emergency shutdown and for redundant, post-cooling reactivity hold-down is presented. Although the emergency shutdown concept is illustrated for a PBR, it is applicable to other types of reactors, provided a “normal” operating temperature range is specified. Preliminary analysis shows that the design can be made to be fail-safe, as the rod or rods would drop into the core under all failure conditions.

In the next section, a synopsis of the EM-OSCR is presented. The following section discusses the mechanism that holds the rod out of the core during normal operations and the means available for fine-tuning and adjusting the holding force. The evaluation of the neutronic performance of a set of EM-OSCR rods is then presented. The falling time, or time to descent into the core, is modeled and evaluated in the following section. The last section is a discussion of the paper is a discussion of the concept, its fail-safe features, and a summary of the principal findings.

This preliminary study shows that the EM-OSCR concept is feasible and that OSCR rods can be an effective passive and inherent system for the scramming of gas-cooled reactors and for the prevention of re-criticality following drops in temperature. In the analyses presented here, it is assumed that the reactor under consideration is similar in thermal design and other physical features to the Pebble-Bed Modular Reactor (PBMR) currently undergoing design in South Africa [1].

2. Synopsis of the EM-OSCR Concept

The EM-OSCR concept is illustrated in Figure 1. The EM-OSCR control rod is intended to remain outside the core region during normal operations and to drop into the core under the influence of inexorable natural laws when the temperature in (or near) the core exceeds a pre-set value. The control rod is held out of the core region by an electromagnet (E-M). The electrical supply line to the E-M includes a portion that passes in or near the core. That portion is made of a material of known temperature-dependent resistivity. As the temperature in the core rises above a prescribed set point, the temperature in the in-core conductor rises, and hence the resistance. This in turn decreases the current that powers the E-M, and therefore the E-M lift force. When the lifting force drops below the weight of the control rod assembly, the rods drop into the core by gravity. No switch, no signal, and no operator intervention are needed to actuate the control rod. Fuses within the circuit limit or interrupt the current, as needed. Failure modes such as loss of power to the E-M or disruption of the continuity of the conductor line are fail-safe as they result in the rod being dropped into the core.

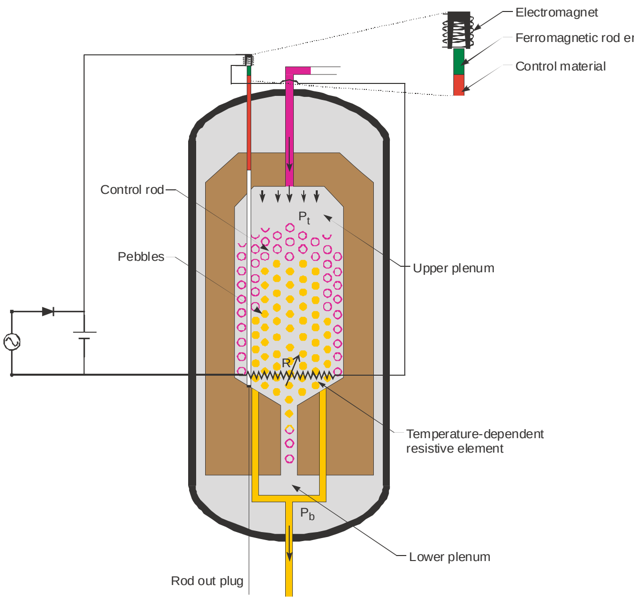

Figure 1. EM-OSCR Concept

3. Lifting Force Evaluation

The concept described in the previous section has been modeled for a steel in/near-core conductor segment. In the model it is assumed that the bulk of the conductor line from the electricity source to the core region and then from the core region to the E-M does not undergo temperature changes. In contrast, the portion of conductor within the core region changes temperature in response to changes in the core temperature, and in proportion to those changes. This assumption is plausible, since changes within the core region are expected to be prompt, whereas outside they would not be. Outside the core region, temperature changes would also occur, but the scramming response would be needed before such changes arise from the effect of heat conduction to the outside electrical conductors. With these assumptions, the electrical resistance, R(T), of the E-M circuit can be written as

$$R(T) = R_0 + R_c(T) \quad , \tag{1}$$

where R_0 is the resistance of the balance of the circuit (outside core region) at normal operating temperature and R_c is the resistance of the portion of circuit within the core region as a function of the temperature T. The temperature dependence of R_c is given by

$$R_c(T) = \rho_o \left[1 + \alpha(T - T_0)\right] \frac{L}{A} \quad , \tag{2}$$

where it has been assumed that in the range of interest (within 50 °C of the nominal operating temperature) the conductor resistivity is a linear function of temperature. In equation 2, the resistivity at normal operating temperature is denoted by ρ_0, the normal operating temperature is T_0, and the temperature coefficient of resistivity is α. L is the length of conductor wire and A is its cross sectional area. Using equations 1 and 2 and Ohm's law, one determines the current flow in the E-M circuit for any given temperature. From the current I (expressed in amperes), the E-M force is obtained. It is given by [6]

$$F = s\left(\frac{NI}{\ell_a c}\right)^2 + \frac{CsNI}{\ell} \quad , \tag{3}$$

where c is the leakage factor, C is the E-M pull in pounds per square inch per ampere-turn per inch, ℓ_a is the air gap in inches, s is the cross section area of the core or plunger of the E-M in square inches, N is the number of coil turns in the solenoid, and ℓ is the length of the solenoid. It is assumed that the wiring is made of cooper everywhere, except in the core region, where it is assumed that soft steel is used. The values assumed for the various parameters are shown in Table 1. For simplicity, it is assumed that all parameters remain valid and unchanged throughout the applicable temperature range. With these values, the pull force is found to be about 8.11 lbf at 900 ºC. At 950 ºC, the pull force drops to 7.70 lbf, and at 1000 ºC, it is 7.33 lbf. Thus, as temperature increases from 900 ºC to 950 ºC or to 1000 ºC, the E-M no longer develops the force necessary to hold an 8-lb rod in place and the rod falls under the influence of gravity. At the maximum value of the pull, the current is about 1 ampere. In that situation, the power dissipation in the entire circuit is under 5 watts, a negligible contributor to heating.

Table 1. Parameter values for EM pull model.

Symbol	**Property**	**Value**
c	EM leakage factor	2600
C	Pull factor	0.01 (lbf/in^2-Amp-turn-in)
l_a	Air gap	0.9 mm
s	Area of plunger cross section	2 in^2
N	Number of turns in solenoid (one layer)	200
ℓ	Length of solenoid	14.4 in
V	Voltage	5.5 V
D	Coil diameter	4.79 in
d_{Cu}	Diameter of Cu wire (excluding insulation)	1.434 mm
d_{Fe}	Diameter of soft steel wire (excluding insulation)	1 mm
L	Length of Cu wire in E-M	76.8 m
L'	Length of Cu wire outside E-M	30.5 m
L''	Length of soft steel conductor in/near core (non active coil)	10 m
ρ_{Cu}	Resistivity of Cu at 20 °C	1.76E-6 Ω-cm
α_{Cu}	Cu temperature coefficient of resistivity	0.004
ρ_{Fe}	Resistivity of soft steel at 20 °C	1.59E-5 Ω-cm
α_{Fe}	Soft steel temperature coefficient of resistivity	0.0016

4. Neutronics Performance

In this section, the results of a preliminary assessment of the scramming effectiveness of the EM-OSCR are presented. From the results of the previous section, it is clear that either a single control rod or a set of control rods of mass up to 8 pounds each could be held outside the core with a small current and little energy dissipation. The rod or rods would fall into the core when the temperature exceeds the nominal operating conditions by 50 °C. The effectiveness of one such rod or of a set of rods is evaluated for a hypothetical, though realistic, PBR. For this demonstration, an MCNP model of this PBR was constructed. The PBR is of a size suitable for power plant use. Parameters characterizing the reactor and shutdown system are given in Table 2. The reactor model is identical to one recently used to study a similar concept [7] that relies on the presence or absence of flow and/or pressure for its operation.

Table 2. Model reactor and shutdown system design parameters.

Reactor and Shutdown System Design Parameters	
Core height	10 m
Core diameter	3 m
Fuel material	UO2
Reflector thickness (all around)	1 m
Reflector material	graphite
Control element material	boron carbide (B4C)
Control element diameter	1 cm or 2.5 cm
Control element cladding material	Stainless steel
Control element cladding thickness	1 mm
Control rod guide tube material	Stainless steel
Control rod guide tube thickness	5 mm
Number of control rods	4
Radius of control-rod circle	75 cm
Length of control elements	1 m or 2 m
Packing fraction of pebbles in core	61%

The core was assumed to be uniform in composition, based on pebbles in which "TRISO" coated UO2 microspheres are embedded in a spherical graphite matrix inside a shell of pure graphite. The pebbles are assumed to be packed in the core with a packing fraction of 0.61, which is a typically observed value. The fuel concentration is adjusted to produce a critical core when the control rods are suspended above the reflector. In this study, the four control rods were arbitrarily located at 90-degree intervals on a circle 75 cm in diameter, centered on the core axis. The model assumes a uniform core. This assumption introduces two sources of inaccuracy (ignoring the actual axial composition distribution of the asymptotic core loading pattern and ignoring the heterogeneity of the core). The extent of the effects of these inaccuracies is discussed in that work and in a previous study [7, 8], and it is shown that the model is sufficient for assessing changes in multiplication factor resulting from rod insertion. In Table 3, the effect of insertion of four control rods (off-centered, as described above) is shown for three different cases. The largest rod mass shown is 3.64 kg (or about 8 pounds). It is clear from these results that four such EM-OSCR rods are sufficient to scram the reactor, as the corresponding reactivity insertion would be of the order of -3.6$. A set of four of the smallest rod shown would insert merely -0.76$. Although this would be insufficient for a secure scram, it would be enough to maintain subcriticality after cooling of the core, which is the principal function of the OSCR rods. A higher reactivity hold-down variant of the EM-OSCR rod, for a more secure scram, could easily be devised, merely by increasing the voltage of the power supply to the E-M and hence increasing the E-M pull. These results show that the proposed emergency shutdown system can be devised to provide ample shutdown negative reactivity with control rods that can be supported easily by E-M pull corresponding to low currents and hence low energy dissipation, as discussed in the previous section.

Table 3. MCNP k_{eff} results and control rod masses

k_{eff} and EM-OSCR Rods Worth			
Control element length (m)	1.0	1.0	2.0
Control element diameter (cm)	1.0	2.5	2.5
k-effective (rods withdrawn)	1.00441	0.98793	0.98793
k-effective (rods inserted)	0.99940	0.97252	0.96452
Reactivity worth of 4 rods ($)	0.76	1.8	3.6
Mass of one control rod (kg)	0.244	1.82	3.64

5. Rod Time of Descent

The EM-OSCR is expected to drop into the core during any abnormal occurrence in which the temperature in or near the core region exceeds its nominal normal range by more than 50 °C. Assuming that gaseous coolant is present in the guide tube and, conservatively, that no flow takes place, the law governing the fall of the rod is given by

$$M\frac{d^2x}{dt^2} = Mg - \frac{1}{2}C_d A_s \rho v^2 \ , \tag{4}$$

where M is the mass of the rod, x is its displacement from its initial position, t is time, g the acceleration of gravity, C_d the coefficient of friction between the rod and the ambient gas, ρ the gas density, A_s the cross section area of the rod (projection), and v the relative velocity of the rod and the ambient coolant. If the normally downward coolant flow were present in the guide tube, the descent of the rod into the core region would be even faster. At the initiation of abnormal occurrences, the flow would still be downward, thus it is conservative to assume absence of flow. Another conservative assumption is to consider that no depressurization has taken place and that the rod must fall through the tube at full operational coolant pressure. It is noteworthy, however, that in the event of a breach of the pressure boundary, depressurization (the equivalent of the loss-of-coolant accident for a PBR) would be complete in less than 3 seconds [9]. With these assumptions, v reduces to the time derivative of x. Then equation (4) can be solved analytically. The solution,

$$x(t) = \sqrt{\frac{g}{\alpha}}t - \frac{1}{\alpha}\ln\left(\frac{2}{1+\exp\left(-\sqrt{\alpha g}t\right)}\right) \ , \tag{5}$$

where

$$\alpha = \frac{C_d A_s \rho}{2M} \ , \tag{6}$$

is used to determine the time of descent to any desired final position. For circumstances typical of PBR designs under consideration, such as an operating pressure of 6.99 MPa, the density of helium coolant would be about 3.42 kg/m^3. Further, a friction coefficient of 1.0 is arbitrarily assumed (sensitivity calculations show that the results depend negligibly on this parameter). The rod cross section area is taken as 4.91 cm^2, corresponding to a 2.5-cm diameter. Then, for a mass of 1.8 kg, the descent time for a distance of 10 m is about 1.43 second. This time is hardly distinguishable from the time for free fall in vacuum. Drop times of roughly the same magnitude should be expected for more massive rods. It is clear from these results that the EM-OSCR would drop into the core well in advance of the times when it would be needed for reactivity hold-down.

6. Discussion and Conclusions

This paper has presented the concept and preliminary performance study of a passive, inherently safe, and fail-safe design for an emergency control rod. The functioning of the rod is based solely on inexorable physical laws. The operation of the rod in its emergency function does not require the intervention of a human operator, nor does it rely on any signal from a monitoring or safety system. Although the concept could be applicable to a variety of reactor types, in this paper it is applied to the emergency shutdown of a PBR. It is clear from this study that the EM-OSCR will drop into the core fast enough provide the required scram. It will also be within the core well in advance of the times at which it would be needed to prevent re-criticality following core cooling. Even if the rod were dropped into the core much slower than the above study shows, it would be effective for this function. In all case, the EM-OSCR would constitute an effective backup system.

The neutronic effectiveness of the OSCR concept has also been demonstrated with a range of rod sizes. It is clear from the examples shown and from the discussion of larger rod masses (via larger currents or EM design modification) that large scramming reactivities can be achieved. Further optimization of the EM-OSCR are of course possible, including via better positioning of the rods at location of larger neutronic importance or via more massive rods. All of these possible improvements warrant further study.

7. Acknowledgements

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