Decay Heat Removal of a Seismically Isolated Reactor Silo

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ABSTRACT

This paper describes the effect of seismic isolation on the passive decay heat removal capacity of a High Temperature Gas Cooled Reactor (HTGR) design. A non-linear finite element model is developed for the numerical simulation of the heat transfer phenomenon. Two reactor silo configurations are analyzed, namely, the conventional design and the design incorporating seismic isolation. A comparison of the temperature profiles for the two configurations provides a quantitative measure of the effects of seismic isolation on the heat removal capabilities. The effects of the temperature increase on the base isolation system design are discussed.

1 INTRODUCTION

The HTGR design considered here encloses the reactor vessel and the steam generator in a concrete silo located below grade. The silo is about 60 feet in diameter and 100 feet deep and is connected to containment tunnels, also located below grade, provided for the retention of a postulated accidental release of gas/steam. The concept is illustrated on Figure 1.

Forced convection core cooling system extracts heat from the core. The system includes a main circulator and heat exchanger and a shutdown circulator and heat exchanger. In addition, heat is dissipated by thermal conduction through the core material, radiation from the vessel to the reactor cavity, conduction through the concrete walls, eventually to the geologic medium surrounding the silo.

Emergency decay heat is removed by an active/passive water cooled Reactor Cavity Cooling System (RCCS). The RCCS is expected to maintain concrete temperatures to 66°C during normal operations and 150°C during off-normal events. For the standard HTGR design, cavity temperatures between 100° and 200°C are predicted during normal operations and between 200° and 400°C during conduction cooldown events. If conduction cooldown occurs in conjunction with RCCS failure cavity temperatures in excess of 600°C are predicted.

As conceived for the study reported here a full seismic isolation of the containment system places the reactor cavity and other cells of the standard silo inside a concentric outer silo. The concept is illustrated on Figure 2. The seismic isolation thus introduces an air gap and an additional concrete wall which add to the thermal resistance in the path of the decay heat removal. The study reported here quantifies the difference in the cavity temperatures for operating and off-normal conditions between the standard design and the seismically isolated design.

2 TECHNICAL APPROACH

This study considers the following three conditions to evaluate the decay heat removal of the isolated HTGR design:

- Steady-state operating condition;
- A conduction cooldown event; and
- A conduction cooldown event with RCCS failure.

The steady-state and transient heat flow from the reactor to the RCCS and surrounding medium is computed on the basis of nonlinear heat transfer theory (e.g. Chapman, 1987).

The technical approach is based on steady-state and decay heat flow to the reactor vessel boundary calculated from the RCCS performance data for the conventional design and constant ambient soil temperatures at the outside boundary of the model. The conduction cooldown event is similarly represented by time-dependent decay heat flow to the reactor vessel boundary. Failure of the RCCS during a conduction cooldown event affects both the temperature distribution as well as the transient heat flow to the reactor vessel boundary, this heat flow is approximated as the difference between the calculated heat flow to the reactor vessel during a conduction cooldown event and the attendant heat rejection in the RCCS.

3 ANALYTICAL MODEL

A planar 2-dimensional model represents a symmetric half of a plane horizontal section through the reactor vessel, silo, concrete walls, air gaps, and the surrounding geologic medium. The model is presented in Figure 3. The finite element model uses three different element types, namely, conduction elements for air, concrete and soil, radiation elements for the air surrounding the reactor vessel, the silo, and the air gap, and convection elements representing the Reactor Cavity Cooling System (RCCS) distributed on the inside of the silo wall. The various elements are assigned temperature-dependent heat transfer properties (Cheremisinoff, 1985; Rohsenow, 1985; Thakur, 1985; Zangle et al., 1989).

Although the 2-D representation approximates the 3-D heat flow, this analysis is expected to provide representative differences in the thermal response of the two configurations.

4 HEAT TRANSFER ANALYSIS

4.1 Operating Condition

Using a constant residual heat flow to the reactor vessel boundary the steady-state temperatures are calculated on the basis of heat loss through conduction, convection and radiation. The reactor cavity temperature in the presence of the seismic gap is about 3 deg.F higher or about 5 percent above the temperature without the air gap. The analysis concludes that the influence of the air gap during operating conditions is minimum. Heat rejection in the RCCS in advance of the seismic isolation gap decreases its impact during normal operating conditions.

4.2 Off Normal Condition

The off-normal condition is defined as the conduction cooldown event in which the decay heat is primarily removed in the RCCS. Thermal response of the reactor silo is examined using transient heat transfer analysis. A comparison of the resulting temperature distribution in the silo with and without seismic isolation showed very small differences (less than 5 percent) concluding that, as in the stead-state case the seismic gap does not influence the reactor cavity temperature and that the RCCS is adequate to remove decay heat in both configurations.

4.3 Accident Condition

The accident condition is defined as a conduction cooldown event accompanied by failure of the RCCS. Figure 4 presents the resultant time-dependent heat flow to the reactor vessel boundary for the two configurations. The analysis for the accident condition predicts significant increase in the reactor cavity temperature over the off-normal event when the RCCS is operational. This is true for both configurations. The maximum temperatures of 1234 °F and 1360 °F are predicted for the conventional and isolated cases, respectively. The maximum temperature occurs at node 110 along a centerline of symmetry. Figure 5 presents the time-dependent temperature at node 110 with and without the seismic isolation. As seen from this figure, the presence of the seismic gap results in an increase in the cavity wall temperature by about 120° F. This is predicted to be the maximum temperature difference and occurs at an exposure time of about 290 hours.

Figure 6 presents the temperatures in the reactor silo along a radial line through node 110 for the two configurations analyzed. This figure shows that the maximum temperature difference occurs at the location of the outside silo wall. This difference is about 172°. The seismic air gap temperature is about 900 deg. F. Although this occurs at about mid-height it is representative of the temperature environment that the isolation system need to sustain. Also shown in this figure is the predicted temperature increment along a radial line through the silo when seismic isolation is used. The seismic air gap results in increase in the reactor vessel and the silo temperatures.

5 SUMMARY AND CONCLUSIONS

This paper has briefly described a heat transfer analysis performed to assess the impact of seismically isolating the HTGR on its decay heat removal capacity. The analysis is based on the thermal characteristics of the commercial HTGR and its Reactor Cavity Cooling System design. During normal operation and off-normal conditions, the presence of the seismic gap does not impose any significant additional load on the RCCS system. If conduction cooldown event occurs in conjunction with RCCS failure, the presence of the seismic gap is predicted to increase the reactor cavity temperatures by a maximum of about 20 percent. This maximum occurs at exposure times in excess of 250 hours. Consistent with the assumptions, it is concluded that seismic isolation of the HTGR does not significantly affect its decay heat removal capabilities.

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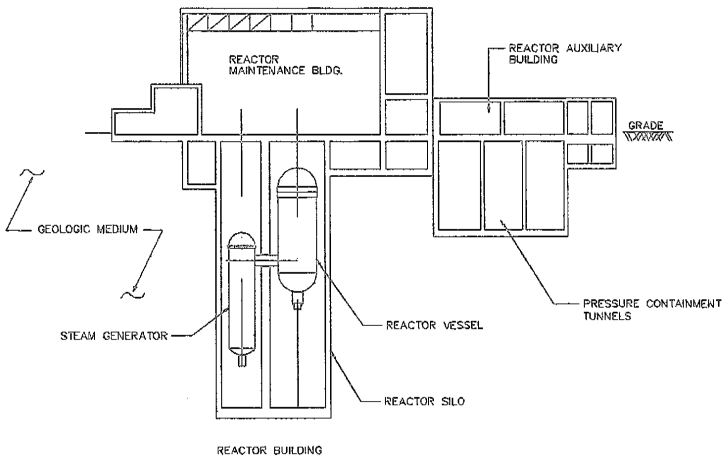

FIGURE 1 – HTGR CONFIGURATION, CONVENTIONAL DESIGN

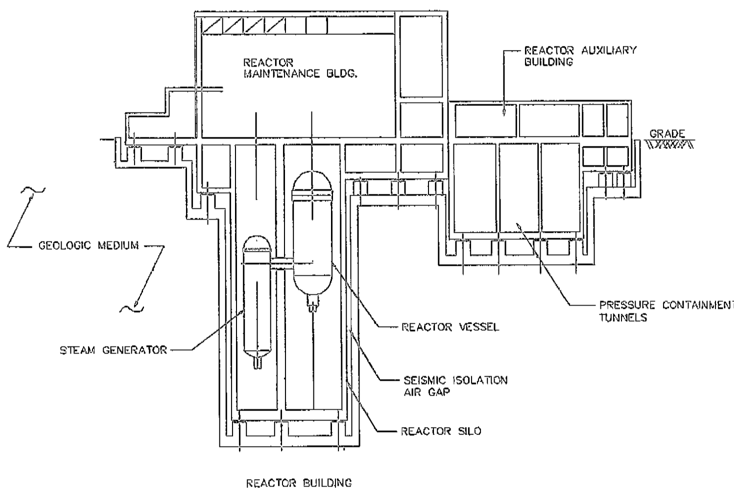

FIGURE 2 – HTGR CONFIGURATION, SEISMICALLY ISOLATED DESIGN

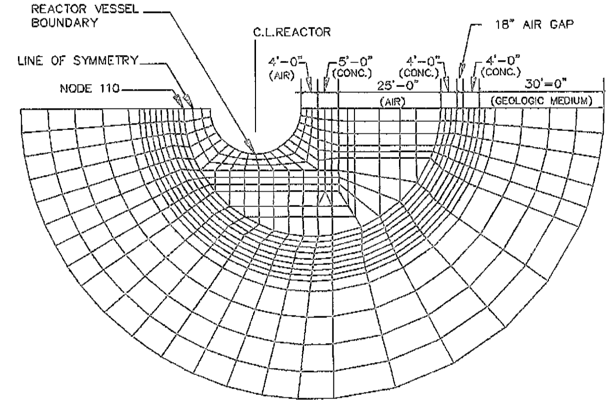

FIGURE 3 – FINITE ELEMENT MESH

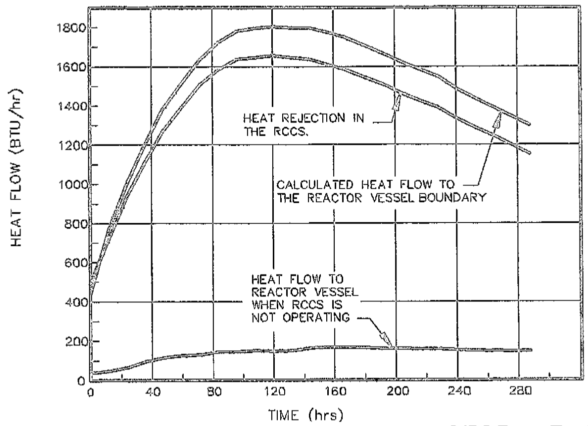

FIGURE 4 – HEAT FLOW TO REACTOR VESSEL DURING CONDUCTION COOLDOWN EVENT

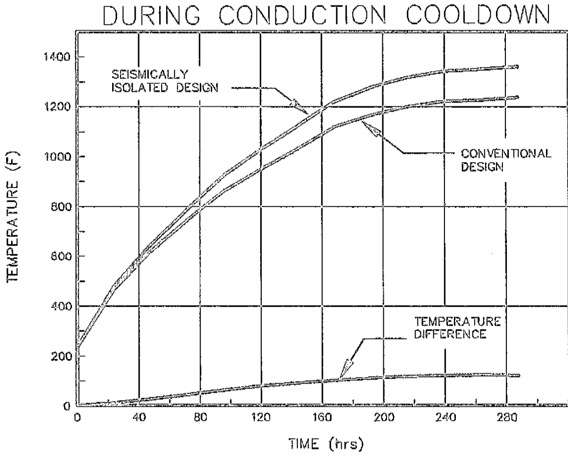

FIGURE 5 – REACTOR CAVITY WALL TEMPERATURES ACCIDENT CONDITIONS, CONVENTIONAL AND ISOLATED DESIGN

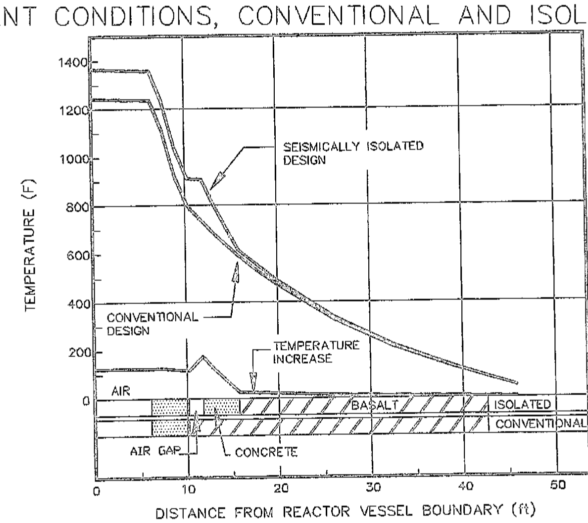

FIGURE 6 – REACTOR SILO TEMPERATURES CONVENTIONAL AND ISOLATED DESIGN, ACCIDENT CONDITION