# GAMMA Air Ingress Analysis for a Pebble-Bed Gas-Cooled Reactor

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## 1. Introduction

The GAMMA (multi-dimensional Gas Multi-component Mixture Analysis) code [1] developed to analyze the thermo-fluid transients in an High-Temperature Gas-Cooled Reactor is applied to the analysis of the air ingress accident following a double-ended break of the coaxial pipe for a pebble-bed gas-cooled reactor. We selected PBMR 268MWt [2] as a reference reactor and performed the sensitivity analyses on air volumes in a vault.

## 2. GAMMA Simulation Models

### *2.1 Chemical Reaction Models*

In order to simulate the chemical reactions during air ingress process, the following chemical reaction models were selected and well tested with the pebble oxidation experiment conducted in the VELUNA test facility [3] as shown at Fig. 1:

A. CO-$O_2$ exothermic bulk reaction: [4]

$$R_{CO}\left(kg/m^3-s\right)=-2.24\times10^{12}\exp\left(-167400/\bar{R}T\right)$$

$$*\,\rho\left(\rho/W_{O_2}\right)^{1/4}\left(\rho/W\right)^{1/2}Y_{CO}Y_{O_2}^{1/4}X_{H_2O}^{1/2}$$

B. C-$O_2$ exothermic surface reaction: [3]

$$R_C^{\,w}\left(kg/m^2-hr\right)=720\exp\left(-16140/T\right)P_{O_2}$$

C. $CO_2$-C endothermic surface reaction: [5]

$$R_C^{\,w}\left(kg/m^2-s\right)=\frac{0.145\exp\left(-25000/T\right)P_{CO_2}}{1+3.4\times10^{-5}\exp\left(7000/T\right)P_{CO_2}^{\,0.5}}$$

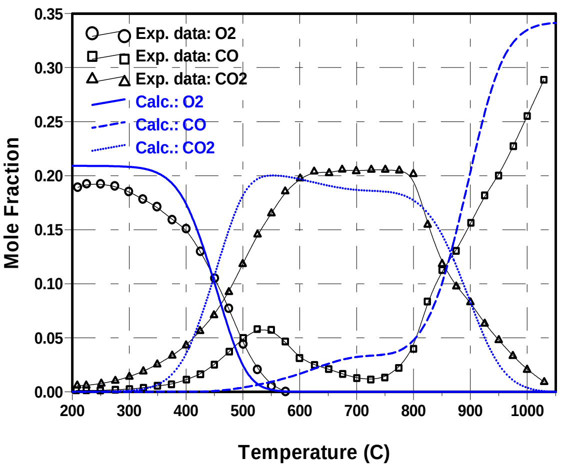


Fig. 1. Graphite oxidation test for the VELUNA pebble-bed experiment

As pebble temperature increases, more oxygen is consumed, producing the heavy gases, CO and $CO_2$. At middle temperature, the produced $CO_2$ is balanced with the depleted $CO_2$ due to the depletion reaction (C). At high temperature larger than 800$^o$C, the CO production reactions (A, C) become dominant.

### *2.2 System Nodalization*

In PBMR 268MWt, helium at 500$^o$C enters the pebble core through the riser holes and exits at 900$^o$C, at a flow rate of 129 kg/s. Fig. 2 show the GAMMA modeling of PBMR and the helium flow paths at the right figure. The pebble core and reactor cavity are modeled by 2-D geometry, and all the solid structures are modeled by 2-D geometry. For all the cavities or plenums, the radiation heat exchanges are considered.

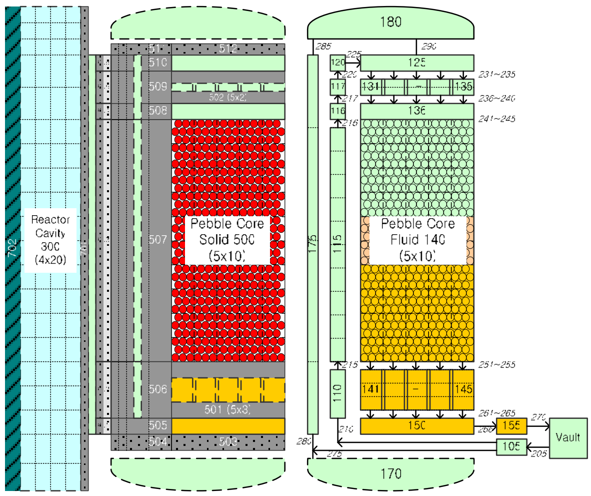


Fig. 2. GAMMA nodalization for PBMR 268MWt

## 3. Analysis Results and Discussions

Following the accident, the event sequences are categorized as three phases. During the blowdown phase, the reactor vessel is rapidly depressurized and immediately a reactor trips. The system pressure equalizes to the cavity pressure within a few minutes. During the molecular diffusion phase, the oxygen in air begins to enter into the reactor vessel by molecular diffusion and a very weak natural convection. Although the graphite/oxygen reaction takes place, its reaction rate is too low due to slow air supply. Therefore, heat generated by chemical reactions is very small. The first peak in fuel temperature during this phase is due to the power mismatch between decay heat and heat removal to RCCS. As heavy gases continue to be produced, the density of the gas mixture gradually increases. When the density difference is enough to overcome the gravitational force, global natural convection initiates, resulting in large air inflow. During the natural convection phase, the graphite oxidation becomes very active, generating a large amount of heat. Fuel is re-heated and then reaches the second peak temperature. As the oxygen is depleted by chemical reactions, the graphite oxidation stops and eventually, fuel continues to cool by heat removal to RCCS.

As shown at Fig. 3, the air ingress rate rapidly increases when the natural convection occurs at about 230 hrs. From that time, the oxygen in a vault begins to decrease due to continuous consumption in the core and the CO and $CO_2$ transported from the reactor inside begins to accumulate in a vault. Due to the large air ingress at about 230 hrs, the graphite oxidation becomes active, producing the additional heat. Therefore, the bottom reflector and the pebbles at the core bottom undergo rapid increase in temperature as shown at Fig. 4. As air is depleted by chemical reactions, heat generation stops and then temperature continues to decrease by the conduction cooling and thermal radiation to RCCS.

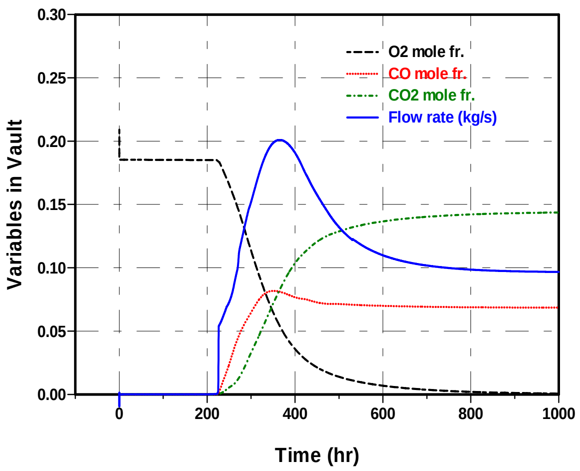


Fig. 3. Predicted mole fractions of species in a vault and air flow rate into the core ($V_{air}$=50,000 $m^3$)

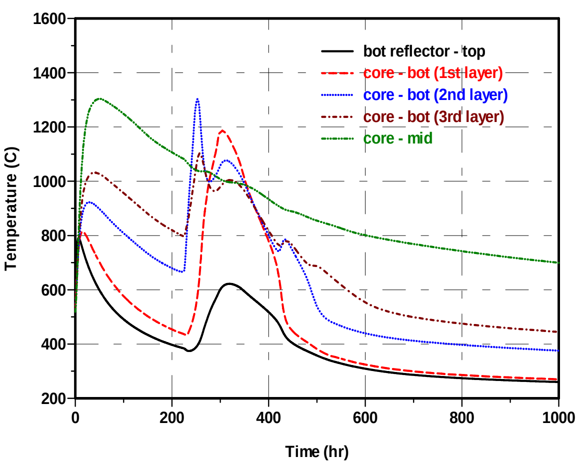


Fig. 4. Predicted axial temperatures at the center ring ($V_{air}$=50,000 $m^3$)

The sensitivity analyses on air volumes, as shown at Fig. 5, show that, as air volume decreases, the onset time of natural convection is delayed gradually. However, the peak fuel temperature is not a simple function of air volume but depends on the combination of the bottom reflector temperature and air ingress flow. When the bottom reflector temperature is low, more oxygen survives through the bottom reflector.

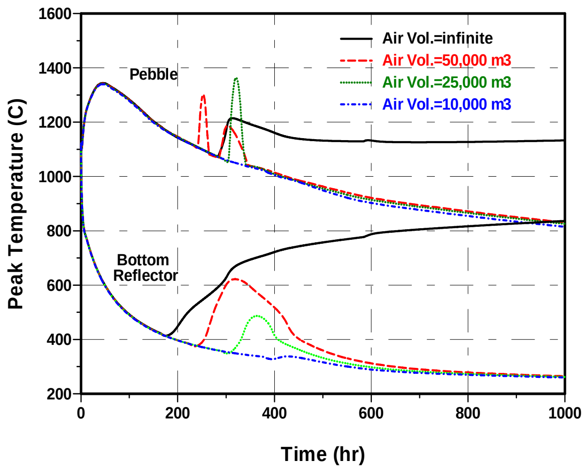


Fig. 5. Predicted peak fuel temperatures for various air volumes in a vault

### 4. Conclusion

In the analysis of the air ingress accident for a pebble bed gas cooled reactor, significant rise in pebble temperature was observed at the bottom of the core due to graphite oxidation. Since the air ingress process depends on the vault conditions, further analysis coupled with more detailed vault or containment modeling would be performed as a next study.

### REFERENCES

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