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Fission Gas Release Model for the SPACE Code

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1. Introduction

The SPACE code has a static gap pressure model based on the perfect gas law to predict the rod internal pressure (RIP) during a transient [1]. The static gap pressure model of SPACE has the assumption that total mole of gas is always fixed, which is determined by initial RIP specified by user and, the temperature and volume of void region in the fuel at the initialization stage of the code calculation. In addition, a long term transient of fission gas release (FGR) during normal plant operation can be considered by controlling the total moles of gas and the mole fraction of each gap gas according to the result of fuel burnup code calculation such as FRAPCON [2] and ORIGEN [3]. However, when the fuel temperature increases to the very high level above 2000 K (for example, reactivity induced accident, RIA), a certain amount of fission gas trapped in the isolated porous region of the fuel pellet would be released to the open void region such as fuel gap, open pore, fuel crack and pellet dish region. Consequently a FGR will raise the RIP and the early cladding failure can occur due to high RIP. Moreover, released fission gases will degrade gas conductivity in the fuel gap due to their low thermal conductivity. For these reasons, it is required to develop the FGR model to predict the correct behavior of fuel rod during a RIA.

2. Development of FGR Model for SPACE

2.1 Selection of FGR Model

Among the various species of fission gases, SPACE deals with krypton (Kr) and xenon (Xe) for the gap conductance and the RIP model, therefore, candidates for SPACE FGR model should take into consideration both fission gases.

There are two kinds of fission product release model. One is a fractional release rate model of which release rate is proportional to current inventory. For example, CORSOR, CORSOR-M and CORSOR-O models are commonly used in the severe accident analysis codes such as MAAP5 [4], MELCOR [5] and so on. The other is a diffusion-based release model which uses single atom diffusion equation and diffusion coefficient. Diffusion release models are often referred to as 'Booth' models after the Canadian scientist.

Between two models, fractional release rate model and diffusion release model, we selected the former as the FGR model for SPACE from a conservative point of view, despite a weakness of overestimated-release and ignoring the burnup effect.

2.2 Description of FGR Models

Fractional release rate model is described as follows:

$$\frac{dM_i}{dt} = -K_i(T)M_i$$

where M_i is the inventory of fission product and K_i is the release rate coefficient (min^{-1}).

The release rate coefficient of each model is formulated as follows:

$$K_i(T) = A_i exp(B_i T) \qquad \text{for CORSOR [6]}$$

$$K_i(T) = k_{oi} exp(-Q_i/RT) \qquad \text{for CORSOR-M [6]}$$

$$K_i(T) = R_{xi} k_{oi} exp(-Q_i/RT) \qquad \text{for CORSOR-O [7]}$$

where Q_i is the activation energy, R is the universal gas constant, T is the temperature and subscript, i is the type of species.

The constants for Kr and Xe of the equations above are summarized in Table 1 and Table 2.

Table 1. Coefficients of CORSOR

Species / Temperature (°C)	Xe, Kr	
	A_i	B_i
900 < T ≤ 1400	7.02E-09	0.00886
1400 < T ≤ 2200	2.02E-07	0.00667
2200 < T	1.74E-05	0.0046

Table 2. Coefficients of CORSOR-M and CORSOR-O

Models	Species	k_{oi} (min^{-1})	Q_i (kcal/mol)	R_{xi} (-)
CORSOR-M	Xe, Kr	2.00E5	63.8	N/A
CORSOR-O	Xe, Kr	1.20E4	55	1.0

Users should specify FGR model option, the total inventory of Kr and Xe contained in the fuel element and activation trip number in the input card (Hxxx-xx-0607). The total inventory of fission gas is distributed into each fuel region proportional to the power fraction of each region and, FGR model will work only after the trip is activated. Unless the activation trip is specified by users, FGR model will be activated from the beginning of the calculation.

2.3 Total Gas Moles and Mole Fraction

FGR model calculates the amount of released fission gases, therefore, the total moles of gases will be increase and the mole fraction of each gas will be changed. Increase of total mole will raise the RIP (P_g) as described in the equation below.

$$P_g = \frac{MR}{\sum_k V_k/T_k}$$

where M is total moles of gas and, V_k and T_k is the volume and temperature of the region k, respectively.

Moreover, change of total mole will change the mole fraction of each gas species (F_i) as follows:

$$F_i = \frac{M_0 + \Delta M_i}{M} F_{i0}$$

where F_{i0} is the initial mole fraction of the gas i, M_0 and M is the initial and current total moles and, ΔM_i is the increase of mole of the gas i.

3. Validation of FGR Model

3.1 Selection of Validation Problem

ORNL (Oak Ridge National Laboratory) Vertical Induction-heated (VI) test [7] was selected as a validation problem. Among seven VI tests, VI-3, VI-4 and VI-5 test were selected because their experimental data are available.

In the VI test design, a ZrO_2 cylinder (furnace tube) surrounded the fuel rod. A graphite cylinder outside of the furnace tube was heated by an induction coil to heat up the fuel rod. The gas (steam or hydrogen) flowed outside the fuel rod and carried released fission products into the fission product collection systems. The length and outer diameter of the fuel rod is 152 mm and 9.5 mm, respectively and, it was assumed that no power was generated in the fuel rod during the test. Table 3 shows the fuel burnup and fission gas inventory in each test case, estimated by ORIGEN.

Table 3. Burnup and FP inventories estimated by ORIGEN [7]

Test No.	Burnup (MWd/kgU)	FP inventory (mg)	
		Kr	Xe
VI-3	44	37	472.8
VI-4	47	42	503.5
VI-5	42	37	471.0

3.2 SPACE Modeling

In the VI test simulation, only a fuel rod and dummy fluid cells were included in the SPACE modeling because the FGR model of SPACE is a function of temperature and fluid condition is not required to validate the FGR model. The boundary condition at both sides of the cylindrical fuel rod were specified by symmetric/insulated condition (left) and user-specified temperature (right). Dummy fluid cell was connected to right side of the fuel rod. There is no heat exchange between heat structure and fluid cell in the SPACE code when user-specified temperature boundary condition is applied. Therefore, user-specified temperature at the outside of the fuel rod governed the internal temperature distribution during the entire simulation period.

It is assumed that initial gap gas be filled with helium (He) gas only and initial RIP be 40 bar.

3.3 Results of Simulation

Fig. 1 ~ Fig. 3 show the comparison between the simulated and measured temperature in each test case. As shown in the figures, the simulated pellet average temperature agrees well with the measured one. The boundary temperature applied in the simulation was based on the corrected furnace temperature of the event table in each test report [8, 9, 10].

Fig. 4 ~ Fig. 6 show the comparison between the simulated and measured release fraction of Kr in each test case. As shown in Table 1 and Table 2, the release rate coefficients of Kr and Xe are identical to each other, therefore, the releasing fraction of both gases is also identical. In addition, the results of CORSOR and CORSOR-M show almost same behavior because their release rate coefficient (K_i) are very similar to each other below the temperature of 3000 K.

As for the simulation result of VI-3 test, measured FG fraction is slightly lower than simulated value and the result of CORSOR-O is closer to measured data compared with those of CORSOR and CORSOR-M.

The result of VI-4 case shows the early increase of measured data for Kr. Earlier detection of Kr resulted from the high initial inventory of the fission gas and early cladding failure in the test. This early release of Kr is excluded in the comparison with simulated released fraction by considering the measured data as negative value during that period. Final released fraction is smaller than estimated initial inventory because a part of fission gas (~5%) might be released before the fabrication of fuel specimen.

In the VI-5 case, the released fractions of all FGR models show a good agreement with the measured value.

Fig. 7 and Fig. 8 show the simulation results on total moles of gases and mole fractions of He, Kr and Xe in the VI-4 test. As the fission gases are released during the simulation period, total moles of gas increase and the mole fraction of He decreases but those of Kr and Xe increase.

From the results above, it is found that the FGR models were correctly implemented into SPACE as intended.

4. Conclusions

The FGR models such as CORSOR, CORSOR-M and CORSOR-O, which are commonly used in the severe accident analysis codes, have been selected for SPACE and implemented into the code. These models can estimate the release phenomena of Kr and Xe which are considered as fission gases of the fuel gap in SPACE. The selected FGR models were validated against three ORNL VI tests (VI-3, VI-4 and VI-5) and simulation results agreed well with the measured data. The RIP could not be compared directly due to a lack of experimental data but, from the simulation results of the total moles of gases and mole fraction of each gas, it was concluded that SPACE estimated the proper overall behavior of FGR process qualitatively.

ACKNOWLEDGEMENT

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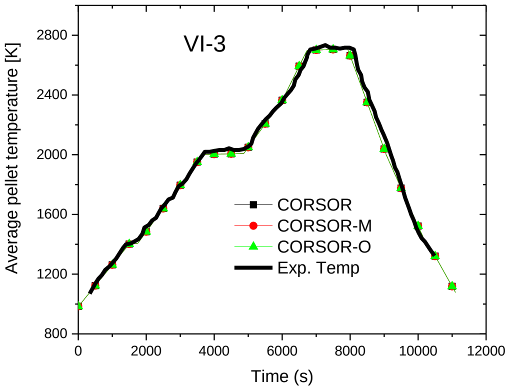

Fig. 1. Fuel temperature (VI-3)

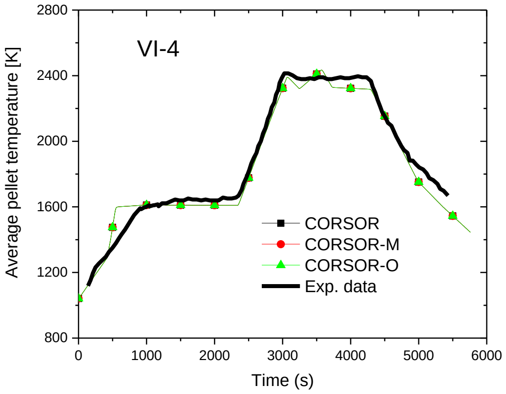

Fig. 2. Fuel temperature (VI-4)

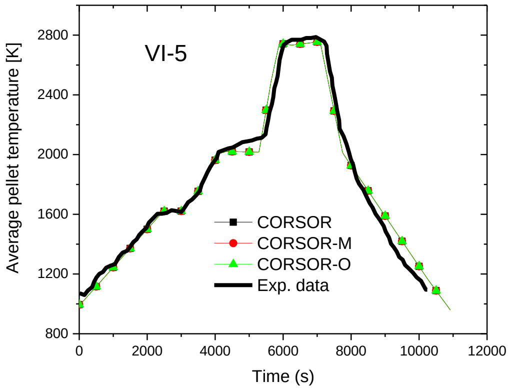

Fig. 3. Fuel temperature (VI-5)

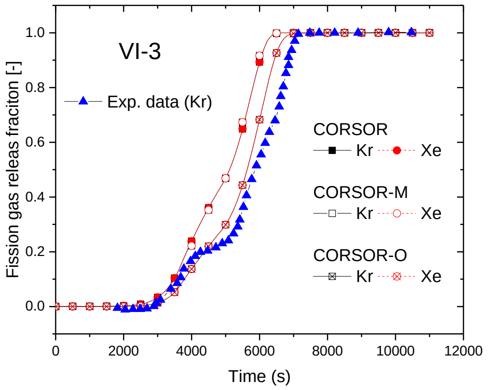

Fig. 4. FGR fraction (VI-3)

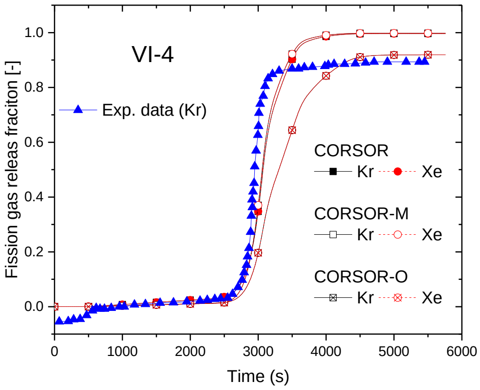

Fig. 5. FGR fraction (VI-4)

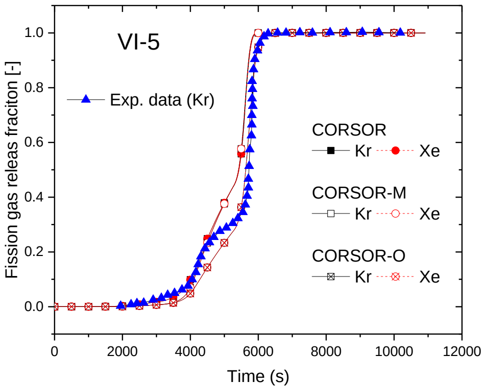

Fig. 6. FGR fraction (VI-5)

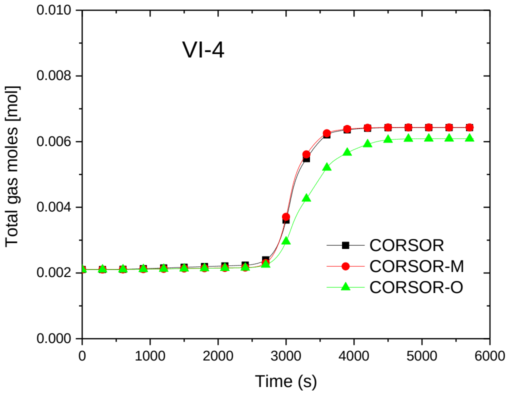

Fig. 7. Total gas moles (VI-4)

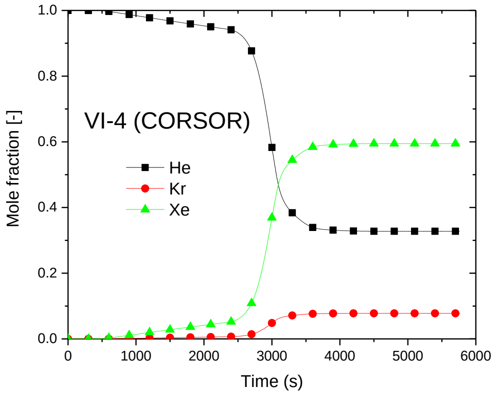

Fig. 8. Mole fraction (VI-4)