NUKLEONIKA 2007;52(3):93–95

ORIGINAL PAPER

A study of the effects of changing burn-up and gap gaseous compound on the gap convection coefficient (in a hot fuel pin) in VVER-1000 reactor

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Abstract. In this article we worked on the result and process of calculation of the gap heat transfer coefficient for a hot fuel pin in accordance with burn-up changes in the VVER-1000 reactor at the Bushehr nuclear power plant (Iran). With regard to the fact that in calculating the fuel gap heat transfer coefficient, various parameters are effective and the need for designing a model is being felt, therefore, in this article we used Ross and Stoute gap model to study impacts of different effective parameters such as thermal expansion and gaseous fission products on the h_{gap} change rate. Over time and with changes in fuel burn-up some gaseous fission products such as xenon, argon and krypton gases are released to the gas mixture in the gap, which originally contained helium. In this study, the composition of gaseous elements in the gap volume during different times of reactor operation was found using ORIGEN code [3]. Considering that the thermal conduction of these gases is lower than that of helium, and by using the Ross and Stoute gap model, we find first that the changes in gaseous compounds in the gap reduce the values of gap thermal conductivity coefficient, but considering thermal expansion (due to burn-up alterations) of fuel and clad resulting in the reduction of gap thickness we find that the gap heat transfer coefficient will augment in a broad range of burn-up changes. These changes result in a higher rate of gap thickness reduction than the low rate of decrease of heat conduction coefficient of the gas in the gap during burn-up. Once these changes have been defined, we can proceed with the analysis of the results of calculations based on the Ross and Stoute model and compare the results obtained with the experimental results for a hot fuel pin as presented in the final safety analysis report of the VVER-1000 reactor at Bushehr [2]. It is noteworthy that the results of accomplished calculations based on the Ross and Stoute model correspond well with the existing experimental results for this reactor.

Key words: VVER-1000 • nuclear reactor • burn-up • Ross and Stoute model • gap convection • hot fuel pin • thermal expansion

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Received: 6 March 2007
Accepted: 31 May 2007

Introduction

Considering the fact that gap heat transfer coefficient depends on the type and gaseous compounds in gap space and a given value of gap thickness (between fuel and clad) corresponding to thermal expansion and that of efficiency of radiation heat transfer with consideration of existing cracks on fuel surface, while these cracks have a tendency to bring about direct fuel connection with clad, we can find that gap heat transfer coefficient is a function of various parameters dependent on one another. This paper aims to study the changes in the value of gap convection coefficient and parameters influencing it due to changed burn-up in a hot fuel pin of the VVER-1000 reactor. According to the calculation results, the rate of these changes corresponds well with the experimental results as reflected in an FSAR report issued for the Bushehr reactor.

Procedure

Given the computational Ross and Stoute gap heat transfer coefficient model in no contact status, the heat transfer coefficient can be computed from the following equation [4]:

$$h_{\text{gap-open}} = \frac{K_{\text{gas}}}{\delta_{\text{eff}}} + \frac{\sigma}{\frac{1}{\varepsilon_f} + \frac{1}{\varepsilon_c} - 1} \cdot \frac{T_{fo}^4 - T_{ci}^4}{T_{fo} - T_{ci}} \tag{1}$$

where: $h_{\text{gap-open}}$ – heat transfer coefficient for an open gap; δ_{eff} – effective gap width; T_{fo} – temperature of the fuel outer surface; T_{ci} – temperature of the clad inner surface; ε_f, ε_c – surface emissivities of the fuel and cladding [1]; σ – Stefan-Boltzmann constant.

Therefore, the effective gap width is larger than its real width. One can compute the effective gap thickness from the following equation

$$\sigma_{\text{eff}} = \delta_{\text{gap}} + \delta_{\text{jumpl}} + \delta_{\text{jump2}} \tag{2}$$

In atmospheric conditions, the numerical value of ($\delta_{\text{jumpl}} + \delta_{\text{jump2}}$) for helium would be 10 μm and 1 μm for xenon gas, where this parameter is calculated and changing according to gas compound. Total gas heat conduction coefficient (K_{gas}) is defined for a mixture of four gases as follows:

$$K_{\text{gas}} = (K_{\text{He}})^{X_{\text{He}}}(K_{\text{He}})^{X_{\text{Xe}}}(K_{\text{Kr}})^{X_{\text{Kr}}}(K_{\text{Ar}})^{X_{\text{Ar}}} \tag{3}$$

where $X_{\text{Ar}}, X_{\text{Xe}}, X_{\text{Kr}}, X_{\text{He}}$ is the mole fraction of the above gases.

The heat conduction coefficient of any gas is calculated from the following formula:

$$K_{(\text{pure gas})} = A \times 10^{-4} T^{0.79} \text{ (W/m·K)} \tag{4}$$

$$T_{\text{gap}} = \frac{T_{fo} + T_{ci}}{2} \text{ (K)} \tag{5}$$

where: T_{gap} – gap gas temperature (K).

Given the fuel cracks effect (due to radiation), the fuel swelling or heterogeneous thermal expansion in fuel and clad produces a decreased gap thickness and results in probable direct contact of the fuel with the clad in some gap regions.

These effects in the gap can be modeled in calculations by using the following equation [4]:

$$h_{\text{contact}} = C \frac{2K_f K_c}{K_f + K_c} \cdot \frac{P_i}{H\sqrt{\delta_g}} \tag{6}$$

where: K_c – clad thermal conductivity (W/m·K); C – constant = 18.1130 $\text{m}^{-1/2}$pi; K_f – fuel thermal conductivity (W/m·K); P_i – surface constant pressure (Pa); H – Meyer's hardness number; δ_g – mean thickness of the gas space.

Based on these accounts, the total gap heat transfer value is defined by:

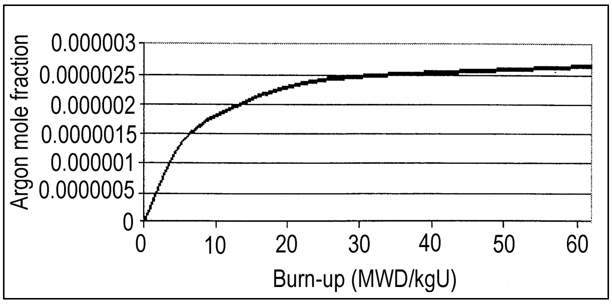

Fig. 1. Total mole fraction of argon in a gaseous mixture of the gap vs. burn-up.

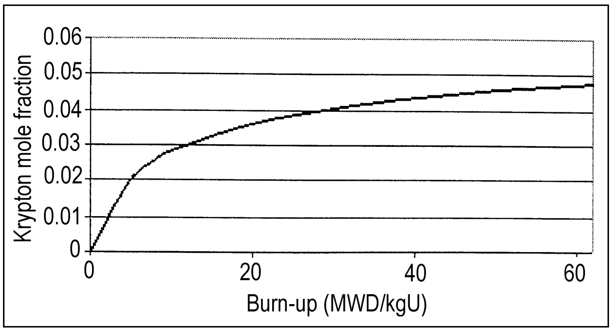

Fig. 2. Total mole fraction of krypton in a gaseous mixture of the gap vs. burn-up.

$$h_{\text{gap}} = (h_{\text{gap-open}}) + (h_{\text{contact}}) \tag{7}$$

Now, developing the input file suited to the operational conditions in the reactor and executing calculations with ORIGEN code [3] we can obtain the concentrations of gas components in the gap space (between fuel and clad) based on burn-up changes and compute their mole fraction in the gap space.

In Figs. 1, 2, 3 and 4 we have shown the rate of changes and mole fraction of helium, argon, krypton and xenon based on burn-up changes.

As the results in the FSAR report for the VVER-1000 BUSHEHR reactor have been obtained for the heat transfer coefficient changes in a hot fuel pin in function of burn-up, we base the computations on linear power equal to 44.8 KW/m and deal with necessary temperature calculations in Ross and Stoute gap model according to the following procedure.

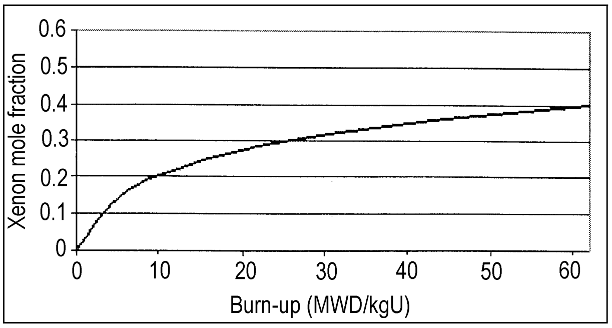

Fig. 3. Total mole fraction of xenon in a gaseous mixture of the gap vs. burn-up.

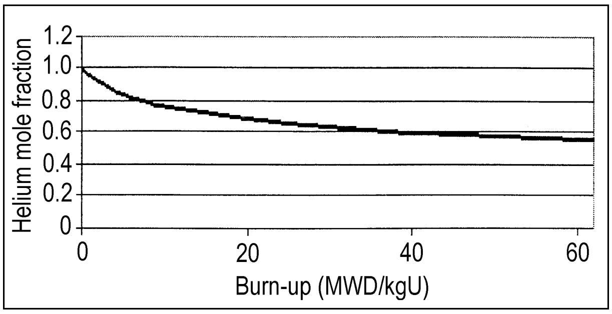

Fig. 4. Total mole fraction of helium in a gaseous mixture of the gap vs. burn-up.

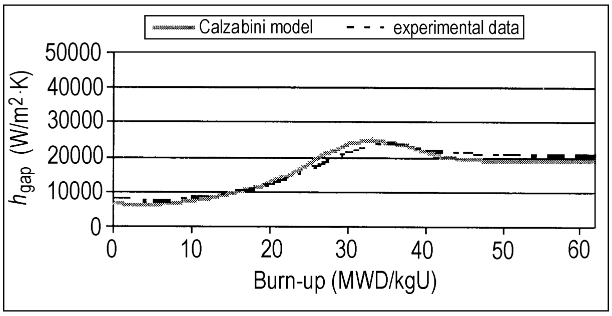

Fig. 5. Comparison of the gap heat transfer coefficient changes vs. burn-up (calculated by Ross and Stoute model) with a final safety analysis report of experimental data for VVER-1000 BUSHEHR reactor [2].

Thus, when the initial temperature is known and the finite differential computational method is used, we will be able to calculate the effects of thermal expansion in fuel and clad as well as the effects of changes in gaseous compounds mixture, and calculate gap model parameters by a continued recurrent computational process. Now, by calculating and using ORIGEN code results, we can define the changes of gap heat transfer coefficient for a fixed linear power of 44.8 kW/m as dictated by changed burn-up in a hot fuel pin as shown in Fig. 5.

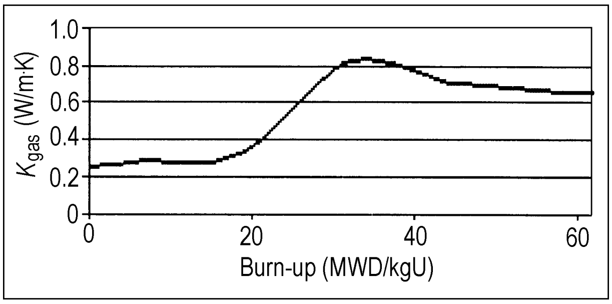

Fig. 6. Changes of the gaseous mixture thermal conductivity vs. burn-up.

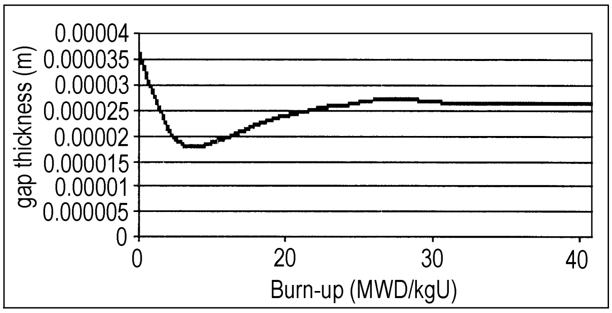

Fig. 7. Changes of the gap thickness vs. burn-up.

Conclusion

Observing Fig. 5 and reviewing the changes of h_{gap}, we will see that in spite of increasing the summary content of xenon, krypton and argon vs. burn-up, which results in a decreased value of gap heat conduction, the effective gap heat transfer begins to rise. Observing the rate of changes in K gas parameters (as shown in Fig. 6) and effective thickness of clad-fuel gap in hot fuel pin (as shown in Fig. 7) as expected due to increasing burn-up, we shall see that the heat transfer in the gap increases with increasing burn-up. Due to the lowered gap effective thickness, the process of h_{gap} increase will begin to slow down after reaching a maximum, and finally the decreasing rate of changes of in h_{gap} results in very little changes of effective overall gap heat transfer.

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