Incorporation of Mechanistic Based Fission Gas Release Model to the Metal Fuel Performance Code

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1. Introduction

U-Pu-Zr metallic fuels, particularly U-19Pu-10Zr alloys, have garnered significant attention for use as sodium-cooled fast reactor fuel due to their good thermal conductivity, and favorable compatibility with cladding materials. These attributes enable efficient neutron economy, high breeding ratios, and enhanced heat transfer performance, making them strong candidates for sodium-cooled fast reactor designs.

Despite these advantages, a major challenge for U-Pu-Zr fuels lies in their behavior under irradiation—most notably, the generation of solid fission products and fission gases, leading to fuel swelling. Fission gases are continuously generated during irradiation, resulting in bubble formation, growth, and interconnection, which ultimately cause volumetric expansion of the fuel. To decrease the swelling of fuel slugs, metallic fuels were designed to enable fission gas release, thereby reducing pressure within the fuel slugs. Swelling leads to fuel-cladding chemical interaction (FCCI) and fuel-cladding mechanical interaction (FCMI), decreasing cladding integrity and increasing cladding stress, ultimately limiting fuel lifetime. Therefore, an accurate understanding and prediction of fission gas behavior and release mechanisms are essential for reliable fuel design and safe reactor operation.

To address these phenomena, fission gas release models have been developed to capture the complex processes involved in fission gas behavior. Most models are semi-empirical equations derived from metallic fuel irradiation experiments. However, fission gas release is so complex that semi-empirical equations can be applied only within a limited range of temperature, flux, and other factors. To overcome this issue, a mechanistic fission gas release model, GRSIS (Gas Release and Swelling in ISotropic fuel matrix), was developed [1]. In GRSIS, fission gas bubbles are assumed to nucleate isotropically within the metallic fuel matrix—at both grain boundaries and phase boundaries—followed by growth through gas diffusion and coalescence. Once the bubble swelling or density reaches a critical threshold, bubbles interconnect to form open channels, allowing internal gas to be released. The GRSIS model was incorporated into the metallic fuel performance analysis code (MACSIS), and its validity was evaluated by comparing fissions gas release predictions with EBR-II irradiation results.

2. GRSIS Model Incorporation

2.1 GRSIS Model

The GRSIS model [1] is based on the description in Fig. 1, where fission gases are released into the outside environment due to the growth of bubbles caused by diffusion. The model divides bubbles into four stages depending on the size of bubbles. Specifically, fission gas atoms form the smallest-sized bubble-1 and can transform into bubble-2 through bubble growth. Fission gases can be absorbed into all stages of bubbles through diffusion, thereby contributing to bubble growth. When a bubble grows to the final stage, bubble-4, it becomes a pore and connects with the outside, allowing fission gases to be released externally.

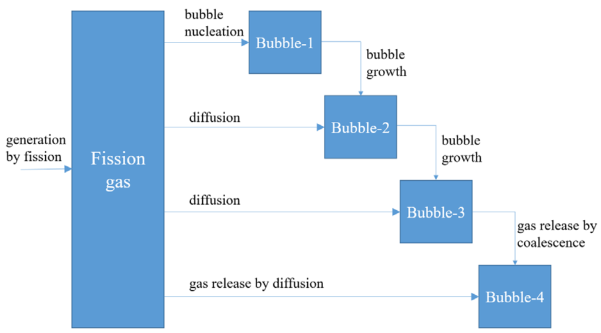

Fig. 1. Fission gas and bubble movement in the GRSIS model [1].

2.2 Comparison with PIE Data

The GRSIS model was incorporated into the fuel performance analysis code (MACSIS), and its validity was evaluated by comparing prediction results with the irradiation test results of the X425 fuel [2], which was irradiated in the EBR-II reactor. The irradiation test description is shown in Table I, and the peak linear heat generation rate and peak coolant temperature, as depicted in Fig. 2 and Fig. 3, respectively, were reflected in the fuel performance analysis code. The comparison of fission gas release behavior between the prediction from the fuel performance analysis code and the post-irradiation examination (PIE) data is shown in Fig. 4. The term "fission gas release" refers to the proportion of fission gases produced by nuclear fission that are released outside the fuel slug. The fission gas release predicted by the GRSIS model exhibited similar results to the PIE data, indicating that the mechanistic fission gas release model can be successfully applied to predict fission gas release behavior.

Table I: X425 fuel irradiation data [2]

Parameter	Value
Fuel composition	U-19Pu-10Zr
Clad material	HT9
Fuel slug radius (mm)	2.16
Clad inner radius (mm)	2.54
Clad outer radius (mm)	2.92
Fuel smear density	72.4
Fuel active length	34.3
Plenum to fuel ratio	1.0
Peak linear heat rate (kW/m)	40
Peak clad temperature (℃)	590

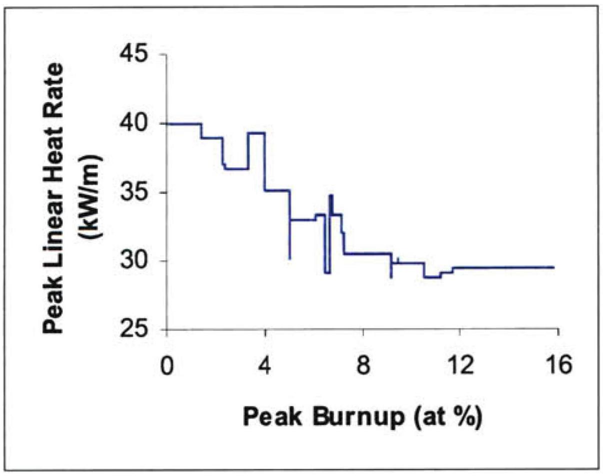

Fig. 2. Peak linear heat rate of X425 fuel during irradiation at EBR-II [2].

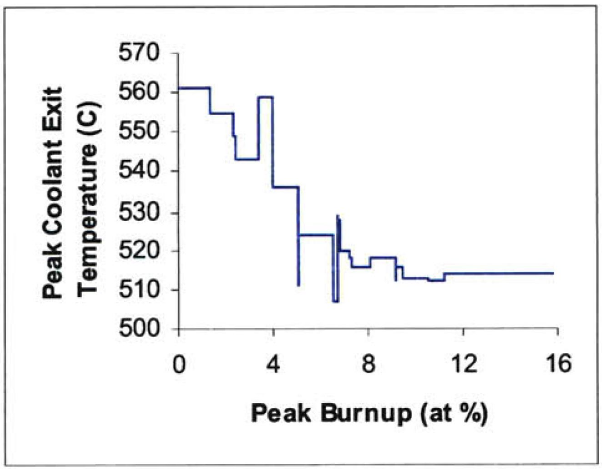

Fig. 3. Peak coolant temperature of X425 fuel during irradiation at EBR-II [2].

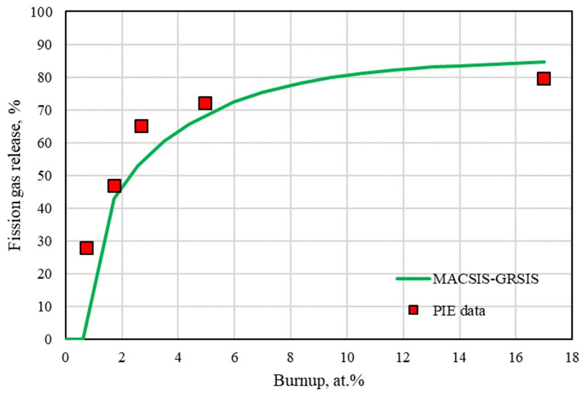

Fig. 4. Comparison of fission gas release behavior between fuel performance analysis codes and PIE data.

3. Conclusions

The GRSIS model, a mechanistic-based fission gas release model, was incorporated into the fuel performance analysis code (MACSIS). The validity was evaluated by comparing fission gas release predictions with the irradiation test results of the X425 fuel [2], which was irradiated in the EBR-II reactor. The fission gas release predicted by the GRSIS model exhibited similar results to the post-irradiation examination (PIE) data, indicating that the mechanistic fission gas release model can be successfully applied to predict fission gas release behavior.

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