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Coupled computer code study on irradiation performance of a fast reactor mixed oxide fuel element with an emphasis on the fission product cesium behavior

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ABSTRACT

A computer code for the analysis of the overall irradiation performance of a fast reactor mixed-oxide (MOX) fuel element was coupled with a specialized code for the analysis of fission product cesium behaviors in a MOX fuel element. The coupled code system allowed for the analysis of the radial and axial Cs migrations, the generation of Cs chemical compounds and fuel swelling due to Cs-fuel-reactions in association with the thermal and mechanical behaviors of the fuel element. The coupled code analysis was applied to the irradiation performance of a fast reactor MOX fuel element attaining high burnup for discussion on the axial distribution of Cs, fuel-to-cladding mechanical interaction owing to the Cs-fuel-reactions and the Cs-Mo-O compound formed in the fuel-to-cladding gap by comparing the calculated results with experimental data obtained from post irradiation examinations.

1. Introduction

When burnup proceeds in fast reactor UO_2-PuO_2 mixed oxide (MOX) fuel elements, mobile and reactive fission product (FP) cesium radially and axially migrates and accumulates at axially lower temperature regions such as the lower and upper ends of the fuel columns to generate low-density Cs-U-O compounds (Cs uranates) on the outer surfaces of the depleted UO_2 blanket fuel pellets. The fuel volume increase (swelling) due to the generation of Cs uranates causes mechanical interaction between the fuel pellet and cladding (FCMI) if the swelling is significant (Johnson and Johnson, 1973; Karnesky et al., 1975). Severe FCMI associated with the Cs uranates induces localized diametral cladding strain (Neimark et al., 1972; Lambert et al., 1973; Karnesky, 1977), which adversely affects the integrity of MOX fuel elements. Thus the Cs behaviors are of great importance to the evaluation of their lifetime when considering fuel burnup extension beyond 100,000 MWd/t.

For the purpose of evaluating Cs behaviors and their effects on FCMI of fuel elements, a computer code MINERVA (Migration Behavior and Reaction of Volatile Cesium Analysis code) was developed by the Japan Atomic Energy Agency (Furuya et al., 1993). This code is capable of calculating axial Cs migration based on the evaporation-condensation process at the pellet-pellet interface as well as the formation of the FP compounds on the basis of chemical thermodynamics. The model of MINERVA was validated through analyses of Cs axial migration behavior of the fast reactor axially heterogeneous MOX fuel elements. In the validation, calculated radial and axial Cs concentration profiles were compared with the measured results obtained from fuel element gamma scanning in post irradiation examinations (PIEs), showing consistency in axial Cs concentration profiles with slight localized Cs concentrations near the interfaces between MOX fuel and blanket columns.

Cs behaviors impact the thermal and mechanical behaviors of the fuel element. This includes change in the gap thermal conductance between fuel pellets and cladding due to the formation of the Cs-Mo-O compound known as JOG (Joint Oxide Gaine), FCMI associated with the Cs uranates and resulting localized cladding strain. These impacts, however, cannot be analyzed by MINERVA alone since the code does not deal with the analyses of thermal and mechanical behaviors of the fuel element.

CEDAR is a finite-element-method computer code designed to analyze the overall irradiation performance of a sodium-cooled fast reactor MOX fuel element: the irradiation performance includes thermal and mechanical behaviors such as fission gas release, fuel pellet restructuring, temperature changes in fuel pellets and cladding, fuel pellet swelling, radial redistributions of Pu and Am, FCMI and diametral cladding strain (Uwaba et al., 2014). The analysis capabilities of CEDAR were validated with PIEs of MOX and MA bearing MOX fuel elements irradiated in fast reactors although Cs behaviors were not taken into

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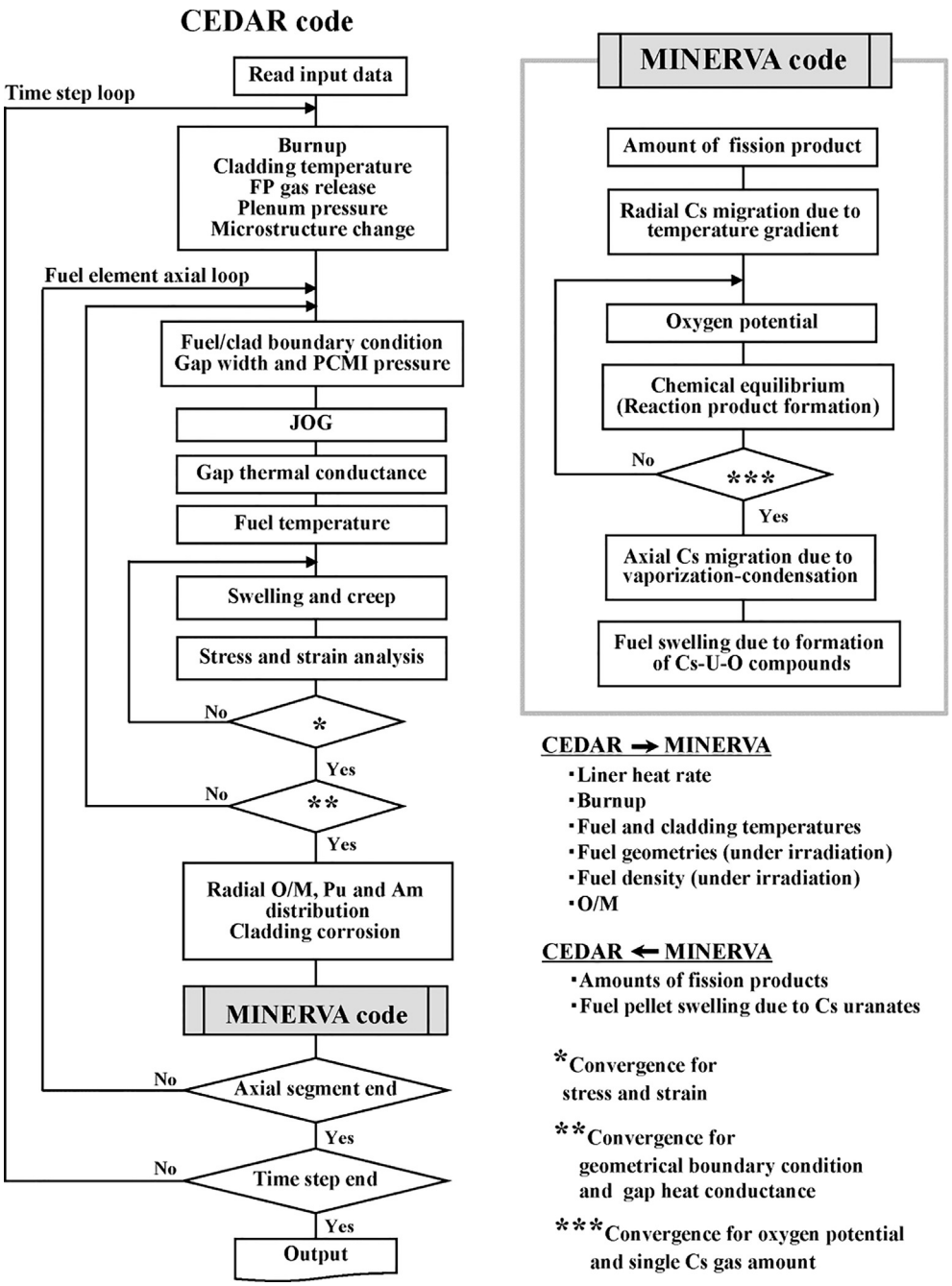

Fig. 1. Calculation flow chart of the coupled code system.

account except for the simplified JOG formation.

Hence, Cs behavior analysis by MINERVA was coupled with the CEDAR analysis to further our understanding of the irradiation performance of MOX fuel elements in fast reactors. Development of the coupled code system and analyses by the system for the irradiation performance of a fuel element are the subject of this paper.

2. Analytical method

2.1. Coupled code system of CEDAR and MINERVA

A calculation flow of the coupled code system is shown in Fig. 1. In the couple code system, the calculation of the Cs behaviors by MINERVA was modularized in CEDAR. Fuel element geometries and fuel pellet chemical composition given as the basic input data for CEDAR are also used in the MINERVA code analysis. MINERVA receives burnup, fuel pellet and cladding temperatures, fuel pellet geometries and fuel O/M ratios from CEDAR while CEDAR receives the amount of Cs_2MoO_4 and fuel pellet swelling associated with the formation of the Cs uranates from MINERVA.

In MINERVA, each axial segment of a fuel element has a length equal to a pellet height and is divided into up to 20 radial meshes to perform radial and axial Cs migration analyses as schematically shown in Fig. 2. The maximum number of the axial segments of a fuel element in CEDAR was increased to up to 100 so that the length of each axial segment could be equal to that of the MINERVA analysis, and the number of radial meshes of the fuel pellet was also adjusted to be consistent in both codes.