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# SIMULATION OF THE IN-PILE BEHAVIORS EVOLUTION IN NUCLEAR FUEL RODS WITH THE IRRADIATION DAMAGE EFFECTS**

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**ABSTRACT** Based on the commercial computational software, a three-dimensional finite element model to simulate the thermo-mechanical behaviors in a nuclear fuel rod is established; By taking into consideration irradiation-swelling of the pellet and the irradiation damage effects in the cladding together with the coupling effects between the temperature field and the mechanical field, the user subroutines to define the special material performance and boundary conditions have been developed independently and validated. Three-dimensional numerical simulation of the thermo-mechanical coupling behaviors in a nuclear fuel rod is carried out, and the evolution rules of the important thermal and mechanical variables are obtained and analyzed. The research results indicate that: (1) the fuel pellets will be in contact with the cladding at high burnup, which will induce a strong mechanical interaction between them; (2) the irradiation creep effect plays an important role in the mechanical behavior evolution in the nuclear fuel rod.

**KEY WORDS** irradiation hardening, irradiation creep, large-deformation, thermo-mechanical coupling, FEM

## I. INTRODUCTION

A nuclear fuel rod is similar to a thin and long cylinder. It consists of Zircaloy cladding and $UO_2$ fuel pellets. Helium is originally filled in the gap between the pellets and the cladding with a certain pressure. The nuclear fuel rod is the key component of the nuclear reactors and a basic element for power production. As its performance is directly related to the safety, reliability and economy of the whole reactor, it is an important issue for optimal design of the nuclear fuel rods to study their in-pile thermo-mechanical behavior evolution with increasing burnup.

The nuclear fuel rods experience a series of complex in-pile behaviors with increasing burnup. At the initial stage of burnup, the fission heat within the fuel pellets will induce large temperature differences and thermal gradients in the nuclear fuel rod, which will result in thermal stresses due to this thermal effect. With increasing burnup, since the total volume of the gaseous and solid fission products is larger than their original volume before nuclear fission, the volume of the fuel pellets will continuously increase, which is called the irradiation-induced swelling[1]. And the accumulation of fission products will also lead to degradation of the thermal conductivity in the pellets. The width of the gas gap between the fuel

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pellets and the cladding will be narrowed owing to the increasing irradiation swelling in the fuel pellets. At higher burnup, the contact between the pellets and the cladding may occur and cause an intensive mechanical interaction. The above-mentioned effects contribute to the thermo-mechanical coupling behaviors in the whole fuel rod. Specially, the metal cladding material is continuously attacked by the fission fragments and fast neutrons with high energy, which will exchange energy with the lattice atoms until they come to rest. As a result, the atoms of the metal cladding material are displaced from their original lattice positions, and vacancies, interstitials and dislocations appear; on a macroscopic scale the above irradiation damages to the metal materials will lead to different plastic and creep behaviors. The yield strength will be improved for the irradiated metal materials and it will generally become higher for more damaged materials, which is called irradiation hardening[2]. Irradiation creep occurs because of the dislocation climb due to the supersaturation of irradiation-induced vacancies and interstitials[3]. As a result, the mechanical performance of the cladding material will appear to be time-dependent behaviors. Thus, the in-pile behaviors evolution in the nuclear fuel rods is an irradiation-thermal-mechanical coupling problem.

The irradiation experimental research on the thermal-mechanical behaviors evolution is exorbitant, time-consuming and tedious in in-situ examination. The numerical simulation method is playing an increasingly important role in interpreting the damage mechanism and carrying out optimal design.

To improve the fuel modeling precision, a suitable finite element model should be developed. Owing to the geometrical symmetry of the nuclear fuel rod, many researchers choose a two-dimensional axisymmetric model[4,5], a two-dimensional plane strain model[6,7] or a one-dimensional model[8] as the finite element model. Recently, Newman et al.[9] and Michel et al.[10,11] have carried out 3D finite element modeling for the nuclear fuel rods. The numerical simulation using a three-dimensional model shows its advantages in the following respects: firstly, 3D modeling will provide details for intrinsic failure criterion, while the one-dimensional or two-dimensional plane strain results represent mainly the thermal-mechanical behaviors in the pellet mid-plane. Secondly, for further studies taking asymmetry into consideration, the three-dimensional modeling can yield relatively accurate results.

In the simulations, the thermal conductivity variation of the gas between the pellets and the cladding needs to be considered for its influence on the thermo-mechanical behavior evolution. As the heat radiation effect is usually taken into account[4,9], Feltus et al.[6] took the gas as a solid material with the equivalent thermal conductivity and implemented the two-dimensional thermal computation. Marino et al.[12] considered the influences of the pellet positions on the thermal conductivity of the gas.

Several commercial finite element simulation software, such as MATHEMATICA[13], ANSYS[14] and ABAQUS[15], is applied in numerical simulation of the thermo-mechanical behaviors in nuclear fuel elements, while numerical simulations considering the irradiation damage effects of the cladding material are relatively limited.

In our previous study[16], the thermal-mechanical behaviors at the initial stage of burnup together with the effects of the material and structural parameters were studied. The simulation of the in-pile behaviors evolution with increasing burnup should be further performed quantitatively.

In this study, a three-dimensional finite element model is built according to the actual geometrical structure of a single fuel pellet and the related cladding part. In order to implement numerical simulation of their complex irradiation-thermo-mechanical behaviors, the user defined subroutines in ABAQUS are developed according to the proposed algorithm to represent the special thermo-mechanical constitutive relations due to irradiation as well as the specific thermal boundary conditions affected by deformation of the nuclear fuel rod. By using the subroutines, both the temperature-dependent and time-dependent constitutive relations considering the effect of large deformation are obtained conveniently. The evolution results of the thermal and mechanical behaviors with increasing burnup are obtained and analyzed.

## II. THE FINITE ELEMENT MODEL

### 2.1. The Geometrical Model and Material Properties

#### *2.1.1. The finite element geometric model*

The typical shape of a fuel pellet[17] with chamfers and dishes is shown in Fig.1, with pellet outer radius 4.21 mm and full length 10 mm, dish radius 3.08 mm and depth 0.32 mm, and chamfer height 0.2 mm.