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3D fuel cracking modelling in pellet cladding mechanical interaction

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Abstract

This study is concerned with the modelling of fuel behaviour and of pellet–cladding interaction (PCI). A new fuel software (PLEIADES) is currently co-developed by the Atomic Energy Commission (CEA) and Electricité de France (EDF). This software includes a multi-dimensional FE program (ALCYONE) devoted to Pressure Water Reactors (PWR) fuel rods. PCI studies are mainly undertaken with the 3D model of ALCYONE. The objectives of this work are twofold: first, to propose a constitutive model for the fuel pellet which accounts for the stress relaxation of the material resulting from cracking and creep, second, to estimate the impact of the pellet cracking on PCI.

In this paper, a mathematical formulation which couples a viscoplastic law for creep with a multi-surface plastic softening law for cracking is detailed, leading a two inelastic strains model. Mesh dependency is overcome thanks to a material parameter related to the finite element size. The 3D calculations of PCI presented in this paper show that the considered modelling of fuel cracking is consistent with the experimental knowledge available on crack development under irradiation. A parametric study is then presented which leads to the conclusion that the tangential stresses at the pellet cladding interface and hence the risk of PCI failure are significantly reduced when the fuel tensile strength is divided by two.

Keywords: PWR; Pellet–cladding interaction (PCI); Failure behaviour

1. Introduction

Failures due to pellet–cladding interaction (PCI), as discovered in the early 1970's, can be avoided in pressurized water reactors (PWRs) thanks to optimised plant operational procedures and fuel management schemes. However, research and development programs on this item are still undertaken worldwide in order to improve the understanding of the mechanisms possibly leading to PCI failure, as well as to qualify a PCI resistant rod design. In this purpose, several fuel performance applications aiming at simulating the behaviour of PWR rods subjected to "Class 2" transient loading conditions have been developed at the CEA.

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To model PCI in PWRs, it is necessary to account for various non-linear physical phenomena which take place in the fuel pellet and the cladding, furthermore on a wide range of scales. At the CEA, two separate applications called METEOR [1] and TOUTATIS [2] have been developed during the last two decades. METEOR is based on a one-dimensional axi-symmetric description of the radial dimension of the fuel element, associated to a discrete axial decomposition of the fuel rod in stacked independent fuel "slices". An overview of the METEOR code and of its physical sub-models can be found in the description of the TRANSURANUS fuel performance application [3] from which it originates. The main advantage of the METEOR application is its potential for a precise description of most of the phenomena taking place in the fuel pellets under irradiation via the use of complex chemo-physico-mechanical models. The one-dimensional METEOR code is used to assess the global geometrical changes of the fuel rod during irradiation and to estimate the quantity of fission gases generated by irradiation, up to high burn-up levels. To describe fuel pellet cracking in the METEOR application, a finite element mechanical model [4], based on an axi-symmetric stress distribution, has been developed. It gives an assessment of the stress redistribution taking place in fuel pellets due to fragmentation. However, it is not sufficient to estimate precisely the local stresses in the cladding resulting from PCI. Only a more detailed description of the thermo-mechanical behaviour of the fuel pellet and of the cladding, based on 2D or 3D FE analyses can provide detailed informations on this point. This has prompted, in parallel to the development of the METEOR application , the development of the fuel application TOUTATIS [2] which is based on the finite element code CAST3M. The main aspects of the 3D model, i.e., the geometry of the meshed fuel pellet fragment, the boundary conditions, the loading applied to the pellet and the cladding, the thermo-mechanical coupling, the friction at the pellet–cladding interface are detailed in reference [5].

Recently, in order to enable one to use simultaneously the chemo-physical models available in the METEOR application and the detailed thermo-mechanical description of the fuel pellet proposed in the TOUTATIS code, the multi-dimensional PWR fuel application ALCYONE [6] has been developed in the framework of the PLEIADES [7] environment. This study focuses on the modelling of cracking processes in the fuel pellet fragment, as implemented in the new fuel application ALCYONE. The objectives of this work are first, to model the development of cracking in the fuel pellet fragment due to irradiation, second, to quantify the impact of pellet cracking on PCI.

In the first part of this paper, the main aspects of the 3D finite element model of ALCYONE are detailed. In a second part, the development of cracks in fuel pellets during irradiation is described. In a third part, the constitutive equations of the continuum formulation coupling viscoplasticity and damage due to cracking are presented. The mesh dependency of the formulation is discussed via theoretical and numerical analyses. Finally, the impact of the pellet tensile strength on PCI is assessed by performing 3D simulations of a fuel rod submitted to a base irradiation and a power ramp test.

2. Modelling of the fuel and cladding behaviour

2.1. Description of the main phenomena

The main phenomena involved in the modelling of fuel behaviour under irradiation, according to references [1–5], are summarized in Fig. 1. They can be classified in two distinct categories: the first one includes nuclear power deposition and structural material changes due to fission products, the second one side power evacuation and mechanical stresses and strains induced by local volume variations. While the former are mainly linked to mechanisms occurring at the atomistic scale (micro-pore evolutions resulting in densification, solid swelling due to fission products, gas generation induced by the behaviour of fission products in the fuel pellet,...), the latter are usually described at the macroscopic scale and hence commonly used for the integrity assessment of structures submitted to thermo-mechanical loads. The numerical scheme used in the 3D FE model of ALCYONE is based on a weak coupling between the thermal, physical (irradiation) and mechanical problems, as illustrated in Fig. 2. Weak stands here because the gas-induced swelling is not included in the convergence loop used to solve at each time step the mechanical (displacements) and thermal problems. In fact, on a practical point of view, gaseous swelling is estimated at each time step from one-dimensional