Nuclear Engineering and Technology 50 (2018) 268–279

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Original Article

Simulation of reactivity-initiated accident transients on UO_2-M5® fuel rods with ALCYONE V1.4 fuel performance code

Isabelle Guénot-Delahaie [a,*], Jérôme Sercombe [a], Thomas Helfer [a], Patrick Goldbronn [a], Éric Fédérici [a], Thomas Le Jolu [b], Aurore Parrot [c], Christine Delafoy [d], Christian Bernaudat [e]

[a] French Alternative Energies and Atomic Energy Commission (CEA), DEN/Cadarache/DEC, F-13108 Saint-Paul-lez-Durance, France
[b] French Alternative Energies and Atomic Energy Commission (CEA), DEN/Saclay/DMN, F-91191 Gif-sur-Yvette, France
[c] EDF R&D, Materials and Mechanics of Components Department (MMC), F-77818 Moret-sur-Loing Cedex, France
[d] AREVA NP, F-69456 Lyon, France
[e] EDF SEPTEN Nuclear Engineering Division, F-69628 Villeurbanne Cedex, France

ARTICLE INFO

Article history:
Received 14 November 2017
Received in revised form
13 December 2017
Accepted 13 December 2017
Available online 9 January 2018

Keywords:
Pressurized Water Reactor
Nuclear Fuel
UO_2
M5®
Reactivity-initiated Accident
ALCYONE Code

ABSTRACT

The ALCYONE multidimensional fuel performance code codeveloped by the CEA, EDF, and AREVA NP within the PLEIADES software environment models the behavior of fuel rods during irradiation in commercial pressurized water reactors (PWRs), power ramps in experimental reactors, or accidental conditions such as loss of coolant accidents or reactivity-initiated accidents (RIAs). As regards the latter case of transient in particular, ALCYONE is intended to predictively simulate the response of a fuel rod by taking account of mechanisms in a way that models the physics as closely as possible, encompassing all possible stages of the transient as well as various fuel/cladding material types and irradiation conditions of interest. On the way to complying with these objectives, ALCYONE development and validation shall include tests on PWR-UO_2 fuel rods with advanced claddings such as M5® under "low pressure–low temperature" or "high pressure–high temperature" water coolant conditions.

This article first presents ALCYONE V1.4 RIA-related features and modeling. It especially focuses on recent developments dedicated on the one hand to nonsteady water heat and mass transport and on the other hand to the modeling of grain boundary cracking-induced fission gas release and swelling. This article then compares some simulations of RIA transients performed on UO_2-M5® fuel rods in flowing sodium or stagnant water coolant conditions to the relevant experimental results gained from tests performed in either the French CABRI or the Japanese NSRR nuclear transient reactor facilities. It shows in particular to what extent ALCYONE—starting from base irradiation conditions it itself computes—is currently able to handle both the first stage of the transient, namely the pellet-cladding mechanical interaction phase, and the second stage of the transient, should a boiling crisis occur.

Areas of improvement are finally discussed with a view to simulating and analyzing further tests to be performed under prototypical PWR conditions within the CABRI International Program.

M5® is a trademark or a registered trademark of AREVA NP in the USA or other countries.

1. Introduction

ALCYONE is a multidimensional finite element-based nuclear fuel performance code codeveloped within the PLEIADES software environment by the CEA, EDF, and AREVA NP. Dedicated to analysis of pressurized water reactor (PWR) fuel rod behavior, it solves fully-coupled equations of thermomechanics and chemical physics under irradiation for three different schemes: a 1.5D scheme to model the complete fuel rod, a 3D scheme to model the behavior of a pellet fragment with the overlying cladding, and a 2D(r,θ) scheme to model the mid-pellet plane of a pellet fragment [1].

ALCYONE is capable of steady state and transient fuel performance modeling [2]. The simulation of reactivity-initiated accident (RIA) experiments falls in particular within its scope and has seen increasing interest and resources in recent years [2,3]. As regards this case of transient, ALCYONE is intended to predictively simulate

* Corresponding author.
E-mail address: isabelle.guenot-delahaie@cea.fr (I. Guénot-Delahaie).

https://doi.org/10.1016/j.net.2017.12.006
1738-5733/

the response of a fuel rod by taking account of mechanisms in a way that models the physics as closely as possible, encompassing all possible stages of the transient (for details on this aspect and more globally, the reader is referred to the comprehensive NEA state-of-the-art report [4]) as well as various fuel/cladding material types and irradiation conditions of interest. On the way to complying with these objectives, ALCYONE development and validation shall include PWR-UO_2 fuel rods with advanced claddings such as M5® under "low pressure–low temperature" or "high pressure–high temperature" water coolant conditions.

M5® (Zr-1.0%Nb) pertains to zirconium alloys developed with a view to improved resistance to water corrosion and hydriding required in the framework of high-duty reactor operation [5]. The objective of the CABRI REPNa-11 and CIP0-2 as well as the NSRR RH-1 and RH-2 integral tests was in particular to characterize the behavior of high burnup UO_2-M5® fuel rods under RIA conditions. With these CABRI tests performed in the former sodium-loop facility, only the first stage of the transient, namely the pellet-cladding mechanical interaction phase (PCMI), can be grasped. NSRR tests with water coolant conditions will be taken as a basis for addressing the second stage of the transient, should a boiling crisis occur.

Main M5® rodlet features, test characteristics, such as pulse power, coolant, initial temperature and pressure, and test results are shown in Table 1.

In this article, ALCYONE V1.4 RIA-related features and UO_2-M5®–oriented specific modeling are presented first. Selected results of based-on simulations related to the CABRI REPNa-11 and CIP0-2 as well as the NSRR RH-1 and RH-2 integral tests are then shown and compared to relevant available experimental results with a view to the validation of this modeling. Interestingly, this set of four tests allows to study the differences related to the coolant type, its initial temperature, and the pulse width.

2. ALCYONE V1.4 RIA-related features

2.1. Main modeling assumptions and capabilities

As regards material behavior modeling and laws, ALCYONE code modeling incorporates in particular fuel pellet creep and cracking (along with dish filling) and, as regards the cladding, gives the possibility to account for, alternatively or in combination when relevant:

- some temperature and flux-dependent yield stress models such as the one available for irradiated Zy4 [10] derived from the PROMETRA program [11–13] dedicated to the study of zirconium alloys under RIA loading conditions,
- some high temperature creep models such as the one derived from the database of EDGAR tests [14] for M5® under loss of coolant accident conditions, which contribution is activated beyond a limit temperature.

Most models in the ALCYONE code are implemented using the open source MFront code generator, developed by the CEA in the framework of the mechanical behavior and material knowledge management strategy of the PLEIADES platform [15]. MFront provides a set of domain-specific languages handling material properties, mechanical behaviors, and simple material models.

The ALCYONE fission gas model CARACAS [16] deals with fission gas creation and evolution at the grain scale. ALCYONE pulse-irradiation simulations clearly take advantage of starting from the base irradiation conditions that this code itself computes. With no need for any user-dependent specific initialization of the variables before pulse-irradiation simulations—whatever the scheme used (1.5D, 2D, or 3D)—, precise and relevant knowledge of the initial fuel rod state and spatial distribution—intergranular or intragranular, in bubbles or dissolved—of fission gases is automatically ensured. Nevertheless, being not relevant for RIA conditions yet, the fission gas model calculates a negligible fission gas release (FGR), contrary to experimental evidence.

ALCYONE pulse-irradiation simulation capability is based on:

- the solving of the thermal heat balance equation for the pellet-gap cladding system in nonsteady state conditions,
- the solving of the thermal and mass balance equations for sodium coolant in nonsteady state conditions,
- the same for water coolant,
- the incorporation of a material law describing the nonlinear mechanical behavior of irradiated M5® submitted to RIA loading conditions,
- the addition, to fuel pellet creep and cracking modeling, of grain boundary cracking modeling, and
- the use of a specific hypothesis as regards the release of fission gases of the high burnup structure (HBS) zone.

The first two points have been detailed elsewhere [1]. The last four points are discussed hereafter.

2.2. Recent developments

2.2.1. Nonsteady water heat and mass transport

Solving the heat and mass balance equations requires the estimation of the linear heat rate received by the water coolant from the fuel rod, based on the heat exchange between the cladding outer surface and the water, which involves the clad-to-water coolant heat transfer coefficient (HTC) in particular. The HTC is either given together with the coolant bulk temperature or calculated using ALCYONE's built-in thermal hydraulics models [17].

The HTC calculation is based on the water physical properties issued from the CATHARE thermal hydraulics system code [18] developed by the CEA and clad-to-coolant heat flux derived from correlations for different regions of the boiling curve (*i.e.* heat flux *versus* clad temperature) as proposed and described in a study by Bessiron [19] and Bessiron et al. [20] for PWR (150 bar, 280°C, 4 m/s) and NSRR (1 bar, room temperature, stagnant liquid water) conditions, respectively. The influence thereon of the high heating rate involved in RIA is taken into account; this high heating rate renders the heat flux somewhat different from the one in steady-state cases by impacting how boiling can develop and evolve along the clad (as shown in Fig. 1A). The transient boiling curve based on PWR correlations is illustrated in Fig. 1B.

The correlations for stagnant liquid water conditions were derived by Bessiron from inverse analyses of NSRR tests with the SCANAIR code [20]. The transient boiling curve includes four different regimes:

- heat conduction in stagnant liquid water up to the critical temperature (Tsat+20 K),
- vaporization of a 30 μm thick layer of water at constant temperature (Tsat+20 K). This semiempirical model was introduced to account for the impact of the energy deposition rate on the critical heat flux,
- transition and film boiling regime are simulated with a HTC that decreases exponentially with the clad temperature up to Tsat+450 K and then asymptotically tends toward film boiling HTC estimated by Sakurai,