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Assessment of fuel rod performance codes under ramp scenarios investigated within the SCIP project

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ABSTRACT

The behavior of advanced cladding materials under challenging conditions needs to be fully characterized, understood and modeled. This paper assesses the current predictability of fuel performance codes under loadings expected from pellet–clad mechanical interactions. A set of scenarios experimentally characterized within the SCIP project, were chosen so that a variety of materials and ramp power sequences could be examined.

Four codes have been used in this study: ALCYONE V1.1, FALCON-PSI, FRAPCON-3 v3.3 and STAV7.3. Their predictions have been compared to data in terms of cladding oxidation, diameters and elongation. Predictability of clad oxidation was certainly scattered and while some codes showed reasonable accuracy, other results were notably deviated. As for diameters, most of the codes were capable of qualitatively capturing the axial profile, and showed consistency between diameters and hoop stress and strain predictions. Elongation estimates were generally poor, and were rather far from measurements in most cases (even the trends observed just vaguely followed by the codes).

The results reported have been discussed in the light of the set of individual hypotheses and approximations made by modelers and codes regarding both boundary conditions (i.e., power histories, inlet coolant temperature, refabrication, etc.) and fuel and clad characterization (i.e., densification, rim porosity, materials properties, etc.). Additionally, code-to-code comparisons of some key variables (i.e., fuel temperature, contact pressure, hoop and axial stresses, etc.) highlighted systematic tendencies of the codes and supported the observations made.

1. Introduction

The industry trend towards achieving high burn-up in nuclear fuel did immediately result in the launch of a good number of investigation projects. They have been aimed at gaining a better knowledge of nuclear fuel evolution during both steady state and transient operation and design basis accidents. A key issue in most of them has been the characterization and response of the advanced cladding materials under any expected and unexpected conditions. A good example is the international SCIP project (Alvarez-Holston et al., 2007).

The generic objective of the SCIP project has been to improve the fundamental understanding of the dominant failure mechanism for LWR fuel cladding under PCMI loadings during normal operation and transients at high burn-up. Particular attention has been paid to specific failure mechanisms: PCMI driving force, PCI, hydride embrittlement and DHC. This information will complement that coming from the CABRI and ALPS international projects on fuel behavior during RIAs.

A total of ten power ramp tests have been carried out in the R2 reactor of Studsvik. The test samples were rodlets taken from a set of fuel rods irradiated in different nuclear power plants. Several advanced cladding materials have been tested. Further than knowledge gain, the resulting database has the additional value to serve as a benchmark against which to validate the existing analytical tools.

Abbreviations: BI, base irradiation; BWR, boiling water reactor; DHC, delayed hydride cracking; EPRI, Electric Power Research Institute; FGR, fission gas release; HE, hydrogen embrittlement; KKL, Kernkraftwerk Leibstadt; LOCA, loss of coolant accident; LWR, light water reactor; NRC, Nuclear Regulatory Commission; PCI, pellet cladding interaction; PCMI, pellet cladding mechanical interaction; PNNL, Pacific Northwest National Laboratory; PWR, pressurized water reactor; RIAs, reactivity initiated accidents; RT, room temperature; RTL, ramp terminal level; SCC, stress corrosion cracking; SCIP, Studsvik Cladding Integrity Project.

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Nomenclature

D_{pre}^{exp}	experimental data before ramp test
D_{post}^{exp}	experimental data after ramp test
D_{post}	post-ramp diameter predicted
D_{pre}	pre-ramp diameter predicted

A code benchmark was organized within the frame of the SCIP project to assess the current capability of fuel performance codes to simulate power ramps, with particular emphasis on the cladding response to these challenging conditions. Respective base irradiations were also modeled as a preparatory step to set the initial of test samples. Once validated, code simulations could assist in SCIP test interpretation and specific phenomena understanding.

The benchmark was structured in two phases in which a total of 8 SCIP tests were chosen as a validation matrix. Through a preparatory phase the codes addressed a set of tests (KKL-4, M5-H1, Z2 and Z3) involving all the cladding materials to be considered in the next phase, so that they were adapted to the peculiarities and features of the experimental device. In other words, a set of hypotheses and approximations were derived and tested to achieve a better code response when modeling the benchmark phase test scenarios. Then, the properly called benchmark phase, was devised in such a way that a sound and deep insight into code capabilities to simulate different fuels (KKL-1, M5-H2, O2 and Z4) submitted to several types of power ramps (i.e., short- and long-holding time ramps and stair-like ramps) could be got.

A comprehensive set of specifications included test sample design characteristics, coolant conditions, power histories (base irradiation and ramps), axial power profiles and outer cladding temperatures during ramps. The main requested variables were related to rodlet mechanical responses to ramps, like diameters and elongations. In addition, other variables characterizing rodlet behavior, like fuel temperature or FGR, were also useful in the code-to-code comparisons.

This paper summarizes the main outcomes from the benchmark phase of this comparison exercise. Consistently with the benchmark purpose, the paper is focused on providing a global insight of present modeling capabilities of power ramps and possible ways to enhance it. Thus, an individual assessment of participating codes is out of its scope. From the results obtained and their discussion a set of lessons learned have been gathered in terms of model needs and recommendations for further experimentation.

2. Modeling approaches

The ramp tests used in the benchmark phase (Table 1) of the comparison exercise entailed recrystallized zircaloy-2, with (KKL-1) and without (O2) clad inner liner, recrystallized M5 (M5-H2) and stress-relieved ZIRLO (Z4). The KKL-1 rodlet (62.5 GWd/tU) was conditioned for 14 h at 12 kW/m and then followed by a six-step sequence with power increases of 5 kW/m. The O2 test (55 GWd/tU), conditioned for 18 h at 25 kW/m, reached a RTL of 45 kW/m with a short holding time of 30 s. The M5-H2 (68 GWd/tU) was submitted to a ramp till getting to 40 kW/m from a conditioning period in which it underwent a 16 kW/m for 18 h; the holding time was 12 h. Finally, the Z4 rodlet (76 GWd/tU), conditioned for 18 h at 15 kW/m, consisted of two long ramps of 6 h after which it got to 33 kW/m and 38 kW/m, respectively. The only rodlet failed during the experiments was the KKL-1 one (after 40 min held at 42.5 kW/m). A more detailed description of these and the preparatory phase tests may be found in SCIP (Källström, 2005).

Several codes were used by different organizations to simulate the above scenarios: FRAPCON-3 v3.3 (Lanning et al., 1997, 2005), CIEMAT; FALCON-PSI (Rashid et al., 2004), PSI; ALCYONE V1.1 (Thouvenin et al., 2007), CEA; STAV7.3, Westinghouse. Given the nature of the analyses conducted, next a few remarks concerning their mechanical models are given. Further details could be found in the respective code references.

FRAPCON-3 is being developed by PNNL and is sponsored by the U.S. NRC. The code was qualified to deal with long irradiation cycles at steady conditions and slow power ramps (Lanning et al., 1997) up to rod average burn-ups of 65 GWd/tU. The TUBRNP model (Lassmann et al., 1994) included within the code for power and burnup radial calculations can be applied up to 80 GWd/tU for pellet average burnup. The thermal models of the code are based on steady state equations and the heat flow is calculated only in the radial direction. The gas release models do not reflect release rates expected for fast power changes. Then, the maximum change in power should not exceed 1.5 kW/ft between time steps and the time steps should be in the range [0.1–50] days (only for thermal response time steps up to 0.001 days). The code has been extensively validated and partially extended to a larger database (Vallejo and Herranz, 2008). The geometry for the pellets that can be simulated by the code includes, dished, no dished, solid and annular pellets, but chamfers are not modeled.

Its deformation model is based on the rigid pellet approximation (FRACAS-I). In this model when fuel and cladding are in contact, only the fuel deformation model applies a driving force to the cladding one, but no reverse. In the closed gap regime, the model assumes a thin cylindrical shell with prescribed external pressure and radial displacement of the cladding inside surface obtained with the fuel expansion models. The gap is open or closed considering the relative movement of the fuel cladding inside surface and the fuel outside surface.

The FRACAS-I model includes the relocated fuel–cladding gap size for thermal and mechanical calculations, although the latter considers only 50% of the total relocation. Other assumptions included in the model are: thin wall cladding; isotropic work-hardening; no axial fuel–cladding slippage; axis-symmetric loading and strain of cladding; the Prandtl–Reuss Flow rule is applied for elastic–plastic analysis; and cladding creep consideration (the model is based on old Zy-2 data, though). The predictions of cladding strains as result of PCMI have not been assessed (Lanning et al., 1997), then no accurate predictions of strain relaxation effects are expected. The solid–solid contact conductance model has a range of application for contact pressures up to 4000 psia, for higher values the model is expected to yield low results.

Corrosion of advanced cladding materials (ZIRLO and M5) is approximated by reducing both the corrosion rate and the hydrogen pick-up fraction of the cladding with respect to Zry-4 (Lanning et al., 2005). The oxide thickness changes in the circumferential direction are not considered in the code.

The boundary conditions at the cladding coolant-interface are maintained constant during each time step; specifically the coolant inlet temperature, rod pitch and outside cladding diameter are supplied from the input-deck. The axial cladding surface temperature profile can be optionally supplied too from the code input-deck (this is the case for SCIP simulation tests with FRAPCON-3 code).

FALCON-PSI is an explicit coupling of the standard FALCON code (Rashid et al., 2004) and the GRSW-A model (Khvostov, 2009) for gaseous swelling and FGR, presently being used by PSI for the analysis of LWR fuel behavior. The code assessment (Lyon et al., 2004), included analysis of steady-state irradiation, RIA tests – with a strong emphasis on PCMI, – as well as fuel behavior under LOCA. The emphasis was placed on high burn-up (rod average burn-up up to or exceeding ~70 GWd/tU). Some separate-effect models, such as ones included into the GRSW-A model for FGR, fuel swelling