IMPLEMENTATION OF FECRAL CLADDING MODELS IN FUEL ROD CODE TESPA-ROD

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ABSTRACT

Accident-tolerant Fuels (ATF) became an evolutionary step in the development of light water reactor (LWR) fuel. One strong candidate is the concept of ferritic steel-based claddings (FeCrAl alloys), now with lead test rods already in use in commercial NPP [1]. Hence, it becomes mandatory to upgrade simulation programs to predict the behaviour of this kind of fuel rods. The mechanical models of the GRS fuel rod simulation code TESPA-ROD [2] were extended with thermo-mechanical models such as deformation, creep, burst and oxidation models, and are based on experimental work from ORNL, INL and models developed at GRS [3],[4]. To verify the enhanced code, the new FeCrAl model was applied to an operational cycle of the ACTOF benchmark [5].

INTRODUCTION

After the Fukushima Daiichi Nuclear Power Plant accident in 2011, several developments started to strengthen LWR (light water reactor) capabilities to withstand design extension conditions. Only one year after the accident, the US Department of Energy (DOE) implemented a 10-year program to develop different concepts for ATF (Accident-tolerant Fuels), with the eager plan to have a lead test assembly installed in a commercial reactor by the year 2022. With several fuel vendor companies working on that goal, it becomes mandatory to upgrade fuel rod simulation codes to stay relevant for upcoming questions. Strong candidates, with outstanding oxidation resistance in steam, are ferritic steel-based claddings (FeCrAl alloys). Since they are considered as a cladding material for almost a decade, many feasibility studies were performed. Due to this major interest in FeCrAl materials many material properties, needed for simulation, are free accessible such as in the Handbook of FeCrAl material by Nuclear Technology Research and Development [3]. Despite the disadvantage of parasitic absorption of thermal neutrons, FeCrAl lead test rods already in use [1]. Beside the fact, that not all necessary data for simulation are publicly available today, especially irradiation data, it is still sufficient for creation of a simplified model.

The GRS fuel rod simulation code TESPA-ROD is used for the thermo-mechanical modelling of LWR fuel rod behaviour during normal operation, power ramps, design basis accidents (DBA) and long-term storage. TESPA-ROD's mechanical models were extended with thermo-mechanical models, such as deformation and creep model, burst and oxidation models, based on FeCrAl material data.

The recently released ACTOF Benchmark [6] is a good opportunity to compare the TESPA-ROD code to other simulation codes. The Benchmark includes two modelling cases, a normal operating and a LOCA (Loss-of-Coolant Accident) case. The following work is only focused on the normal operating case, which consists of continuos power generation for approximately four years run-time. As FeCrAl material, the optimised alloy C35M, developed at the Oak Ridge National Laboratory (ORNL), was used.

MODEL DESCRIPTION

Used Models

Up to now TESPA-ROD was applied to various Zircaloy-based claddings. Before calculating the ACTOF Benchmark [5] with TESPA-ROD, new models had to be integrated. We mainly focused on equations presented in the Handbook of FeCrAl material by Nuclear Technology Research and Development [2] and by Gamble et al. [7]. Furthermore, we focused on the FeCrAl material C35M, which is an important candidate for the use in commercial LWR. In Table 1 an overview of the used models and their source is presented. Some equations required modification to allow implementation in the TESPA-ROD code.

Table 1: Models and references of the material specific models used for the integration of FeCrAl claddings in TESPA-ROD.

Model	modified	Reference
Young's modulus	No	Handbook [3]
Ultimate tensile strength	Yes	Pastore et al [5]
Creep	No	Handbook [3]
Irradiation creep	No	Gamble et al [7]
Thermal conductivity	No	Handbook [3]
Specific heat	No	Handbook [3]
Thermal expansion	No	Handbook [3]
Burst criteria	Yes	Gamble et al [7]
Poisson's ratio	No	Gamble et al (C35M) [7] Handbook (other) [3]
Oxidation model	Yes	Handbook [3]
Heat capacity Al_2O_3	No	McMillan et al [8]
Thermal conductivity Al_2O_3	-	Model by GRS

The models mentioned in Table 1 were used to extend the application range of TESPA-ROD, while the main calculation routine remains unchanged. This approach means, the calculation still follows the same parent code structure and was only extended by a new set of data for the FeCrAl material. The cladding failure criteria, as suggested by Gamble et al., was implemented with some adaptation [7]. We used a combination of UTS (Ultimate Tensile Strength) and an exponential fit for the burst criteria and extended it with the melting point of FeCrAl. The current oxidation model includes the oxidation of Aluminium for a build-up of Alumina (Al_2O_3) at accident conditions ($T > 1323$ K) [3]. In contrast, the operational oxidation exhibits completely different processes leading to iron and iron-chromium oxides, which is not implemented in the code yet.

Stress and Strain

The ACTOF benchmark [5] final report includes results obtained with the simulation programs BISON, FEMAXI-7 and TRANSURANUS. To gain a better understanding of the quantitative deviation between the different FeCrAl predictions by these codes, the same scenario was calculated additionally with Zircaloy-4 cladding material. We calculated the stress and strain for Zry-4 and FeCrAl based on the parameters given by the ACTOF Benchmark [5] and compared them with the results of the participants [6]. The applied parameters are presented in Table 2. Both cases include a UO_2 pellet. The power history was adopted from the ACTOF Benchmark [5] which comprises a linear increase from 0 kW/m to 25 kW/m in 3 h, constant heat rate over 3,5037 h (i.e., approx. 4 years) and linear power decrease to 0 h in 3 h. The operational cladding oxidation of Zry-4 and FeCrAl is not considered here.

Table 2: Input parameters used for ACTOF Benchmark.

Input	**Zircaloy**	**FeCrAl**
Cladding Material	Zry-4	C35M
Outer Diameter of Fuel Pellet (mm)	8.19	8.57
Outer Diameter of Cladding (mm)	9.5	9.5
Thickness of Cladding (mm)	0.575	0.385
Density of Fuel (kg/m^3)	10431	10431
Active Length of Fuel Rod (m)	0.1186	0.1186
Inactive Length of Fuel Rod (m)	0.027	0.027

RESULTS AND DISCUSSION

The simulation results are shown in Figure 1 and Figure 2. In Figure 1 the hoop stress of FeCrAl (C35M) and Zry-4 is displayed. Both materials show a rapid stress increase within the first hours, which is caused by the pellet's thermal expansion due to the power increase. Negative stress indicates the higher coolant pressure compared to the fuel rod's inner gas pressure. Densification processes of the fuel pellet leads to a diameter reduction and therefore a stress relief in the cladding. The FeCrAl cladding experiences an almost three times higher hoop stress than Zry-4, which can be explained by the lower Young's modulus of Zircaloys compared to ferritic stainless steels. Due to outer over pressure, the Zry-4 cladding creeps until the pellet-cladding gap is closed. For FeCrAl, creep deformation is much lower. Between 1,000, the fission gas release is the cause of a small stress increase, followed by a strong increase due to gap closure.

In all four graphs, between 25,000 h and 30,000 h a kink can be observed, resulting in a lower increase of stress or strain, respectively. This is based on the empirical model for pellet swelling, where the fuel's crystal lattice swelling rate decreases for any further burn up increment. The time for reaching the threshold differs little between Zry-4 and FeCrAl. This cannot be attributed to the cladding material, but due to the difference in pellet diameter. The creep rate in Zry-4 is much higher, leading to a faster gap closure in the zircaloy material. The stress values of Zry-4 in the second half can be compared to the value of the other codes. For FeCrAl we received a much higher value after the gap closure than the other participants. Also, the gap closure occurs 6,000 h later as the latest gap closure of the other codes, here TRANSURANUS. Whereas the time of the gap closure of Zry-4 is comparable to the other participants. This could be based on the lower creep deformation of FeCrAl, leading to delayed gap closure. All in all, the stress simulated with TESPA-ROD differs strongly in the beginning of the calculation of Zry-4 and at the end of FeCrAl. The calculated stress at around 33,500 h is sufficiently large for plastic deformation, which leads to a kind of plateau with very low increase at the end of the FeCrAl stress diagram.

The simulated strain depicted in Figure 2 shows a similar trend with few differences. The decrease of strain is much faster compared to the other codes, but is in the same range, despite for the Zircaloy calculation. In this case we have negative strain which is more than half the positive strain (-0.45 %; 0.78 %). No other code shows negative strain. The reason could be a higher densification value calculated by TESPA-ROD, which results in a smaller pellet diameter. Thus, the cladding is negatively deformed, based on the higher coolant pressure.

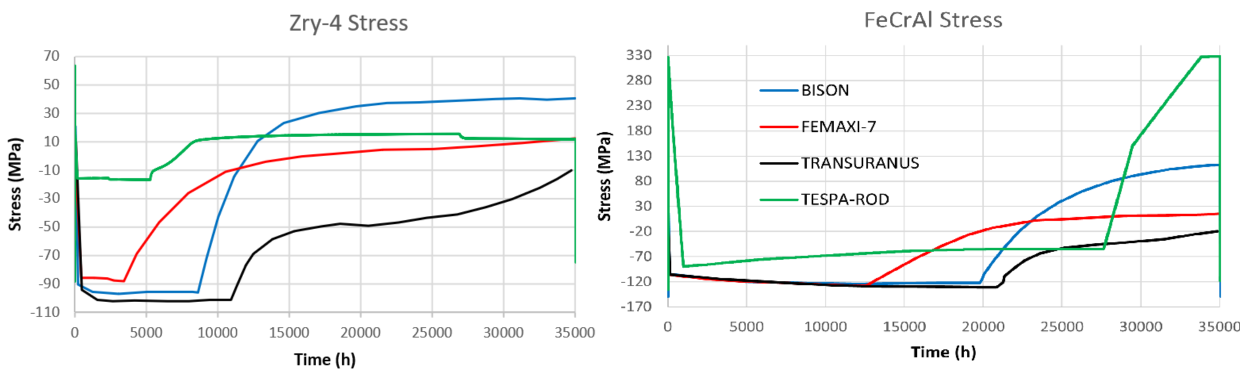

Figure 1: Cladding hoop stress evolution over time for FeCrAl (left) and Zry-4 (right) (Results of the other participants taken from ACTOF report [6])

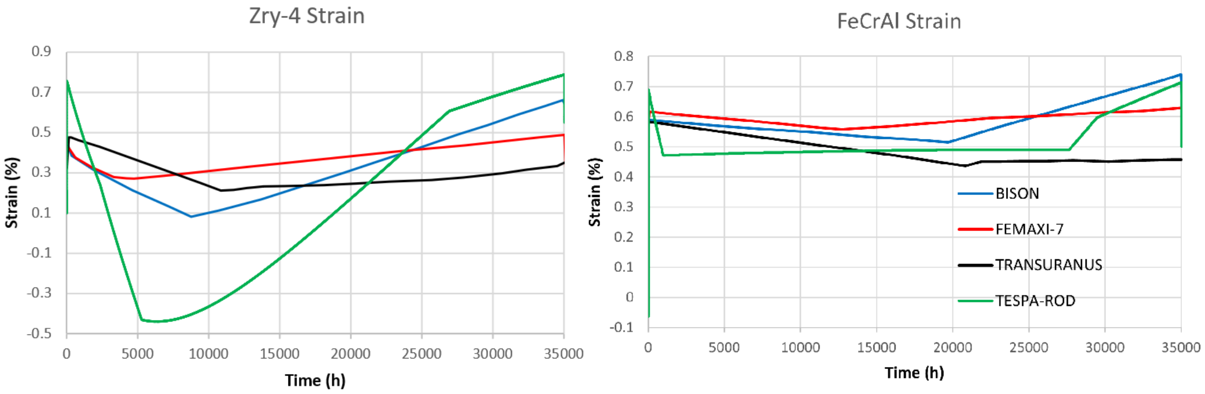

Figure 2: Cladding hoop strain evolution over time for FeCrAl (left) and Zry-4 (right) (Results of the other participants taken from ACTOF report [6])

CONCLUSION

For verification purposes, the new FeCrAl model in TESPA-ROD was applied the first task of the ACTOF benchmark, which includes a normal operating case as well as a LOCA transient [5]. The LOCA case was not simulated, because it is based on forced pressurised tubes, which currently cannot be realized in TESPA-ROD. The normal operating case includes a power ramp followed by approximately 30,000 h of constant power operation and a subsequent shut-down. In contrast to Zircaloy, the TESPA-ROD predictions for FeCrAl cladding does not exhibit a typical creep down due to a constant over-pressure of the coolant towards the fuel rod inner pressure. Pellet-cladding gap closure occurs twice: during heat-up ramp as well as due to the fuel swelling. A cladding relaxation due to creep does not appear, while the fuel swelling applies stronger hoop stresses to the cladding up to plastic deformation.

With these first promising results, TESPA-ROD will continue further validation processes on FeCrAl and other ATF models. Therefore, an oxidation model will be added, which does not only contain the formation of Al_2O_3, which does mainly appear above 1323 K, but also the formation of mixed oxides, during operational temperatures. The code for fuel swelling is a simple approach, which leads to high stress in the FeCrAl material. A more complex approach is already in progress and may lead to lower stress values more in the range of the other participants.

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