Foreword

Special issue on the Power-to-Melt and Maneuverability (P2M) Simulation Exercise

Guest Editor

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It is my pleasure to introduce this *Nuclear Technology* special issue focused on the Power-to-Melt and Maneuverability (P2M) simulation exercise. P2M is one of the Joint Experimental Programmes (JEEPs) ongoing in the Nuclear Energy Agency (NEA) Framework for IrraDiation ExperimentS[1,2] (FIDES-II). This framework was launched to strengthen international collaboration on key aspects of nuclear fuel behavior by providing access to a network of research reactor facilities with multiple irradiation capabilities (the BR2 reactor of SCK·CEN in Belgium, the TREAT reactor of Idaho National Laboratory in the United States, the NSRR reactor of the Japan Atomic Energy Agency, and the LVR-15 reactor of OACVŘ in the Czech Republic). The JEEPs of the first triennial FIDES-II program (2022–2024) focused on structural materials (stainless steel–based materials), advanced claddings, and high-burnup fuels, submitted to a large range of conditions: in-core mechanical testing (INCREASE), slow transients (P2M), fast transients (HERA), and steady-state irradiation (INCA). The general objectives of FIDES-II are to ensure the future of research reactor facilities by international financing of some key experiments and to strengthen the link between experiments and modeling.

The P2M program was proposed by the Nuclear Research Centre (SCK·CEN, Belgium), the Commissariat à l'énergie atomique et aux énergies alternatives (CEA, France), and Électricité de France (EDF, France). Two staircase power transients on modern fuel designs were planned to be performed in the pressurized water capsule (PWC) of the BR2 reactor at SCK·CEN, aiming at reaching incipient fuel melting without failure of the rodlets. The main objectives of the tests were to estimate the pellet–cladding mechanical interaction resulting from the partial melting of the fuel and the strong fission gas–induced swelling in these particular conditions (slow transient, long holding periods at high power) and to measure online the fission gas release (FGR), thanks to sophisticated instrumentation in the tested rodlets (thermocouples, pressure sensors). Predesigning such power transients where incipient fuel melting is expected without failure of the rodlet is challenging. To help in calibrating the fuel performance codes, two past power ramps with fuel pellet center melting were considered. Following the objectives of FIDES-II, the data of these experiments were gathered, analyzed, compiled, and provided to the FIDES-II participants willing to perform simulations with their fuel performance codes. The simulation results were discussed in several P2M or FIDES-II meetings. Overall, the simulation exercise was joined by 13 organizations (from industry, research institutes, and regulators) from nine countries using 11 different fuel performance codes.

This special issue of *Nuclear Technology* presents in detail the outcome of this data gathering, data analysis, and simulation exercise. The general idea behind this special issue was also to allow participants to give more details on the specific models used in their fuel performance codes. The code-to-code comparisons in this type of simulation exercise are often difficult to analyze because of the limited time available to understand how differences in models in the codes impact the simulation results. This special issue, where more than half of the participants provided details on the models, intends to fill the gaps.

The first experiment selected for the simulation exercise (called HBC-4) was performed on a high-burnup UO_2-Zy-4 fuel rodlet (peak 60 GWd/tU) in the late 1980s in the BR2 reactor during the High Burnup

Chemistry International Program. The ramp terminal level (RTL) reached more than 66 kW/m during a fast transient following a conditioning plateau of several hours at 40 kW/m. Extensive postirradiation examination (PIE) after the sequence showed that the rodlet had failed during the test and that local fuel pellet melting took place at several axial locations. For the second selected experiment (called xM3), melting was not expected but has been suspected from the PIE. This staircase power ramp performed in 2005 on a medium-burnup UO_2-Zirlo fuel rodlet (peak 27 GWd/tU) in the R2 reactor of Studsvik (Sweden) reached an RTL of 70 kW/m without failure of the rodlet. This experiment was already part of a modeling workshop during the second Studsvik Cladding Integrity Program (SCIP II), but fuel melting was not the focus of this simulation exercise.[3]

Reassessment of the experimental and PIE data necessary to provide input for fuel performance simulations proved to be a fruitful exercise. Details on the xM3 base irradiation, power transient, and PIE, never fully published before, are given in two papers in this issue.[4,5] Literature review on fuel melting extends all the way to the early 1960s, when work was first initiated by fuel vendors and utilities to check the behavior of molten fuel in normal operating conditions. Several key questions on the determination of fuel melting from PIE were then discussed: Is a central hole a signature of fuel melting? What relation can be determined between the central hole radius and the melt radius? Does the central hole form prior to or in consequence of melting? What is the origin of the dense fuel rings observed around the central hole—molten fuel, relocated fuel material, pore migration? What relation can be determined between the size of the dense fuel ring and that of the restructured fuel region? Some questions are still unanswered today and show that the planned PIE after the P2M power-to-melt experiments are of great importance and should be analyzed very carefully.

In this issue, a paper[6] by SCK·CEN gives all the details on the HBC-4 experiment carried out at the Belgian nuclear research center. These data on fuel melting, from which the power-to-melt of high-burnup fuel has been estimated, were never fully published. The reassessment led to the suspicion of an early failure of the rodlet by iodine stress corrosion cracking (I-SCC) before the conditioning plateau at 40 kW/m. The consequences of this early failure on fuel melting are discussed in Ref. [6], showing that they are certainly of second order. These results have been confirmed to some extent by advanced 2D simulations of fuel rod failure with incipient melting, presented in another paper in this issue.[7] The reassessment of HBC-4 experimental data in Ref. [6] led to recommendations for the design of the future P2M tests.

The P2M simulation exercise showed that most of the participants could predict melting in the case of the HBC-4 experiment while half could not in the case of the xM3 experiment. Comparison of code-to-code results on thermomechanical measurements (clad and fuel diameters, pellet–clad gap, rod elongation), FGR, and fuel melt radii are detailed in Ref. [4]. This has raised several questions on the level of description in the codes that should be achieved to catch fuel melting, fuel rod failure, fuel rod expansion, and FGR in these experiments: distinction between the solidus and liquidus temperatures for initially stochiometric UO_2 fuel,[8] based on thermodynamic calculations[5]; impact of fuel circumferential cracks on the thermal conductivity of the fuel and on the fuel–clad gap[8]; sliding with friction at the fuel pellet–clad interface[9]; thermal creep of the fuel[5]; mechanistic FGR models for the extremely high temperatures at the pellet center[5,8,10,11]; and modified fuel–clad gap conductance in consequence of the higher-than-usual temperature of the interface.[12] Calculations of fuel rodlet failure/nonfailure during the selected experiments were made by a few participants only.[10,11] All the codes with I-SCC models predicted failure during the HBC-4 experiment, half of them before the conditioning plateau at 40 kW/m, the other half at RTL.

The initial objectives of this simulation exercise in line with FIDES-II were clearly achieved. Past experimental results were reassessed, guaranteeing conservation of knowledge and of the data, usable in the future to design new experiments. This reassessment and the associated literature review showed the complexity of the microstructure observed at the pellet center after incipient melting and the difficulty that may arise when interpreting PIE. The strengthening of the link between modeling and experiments was ascertained by an iterative process that led to numerical results physically consistent with measurements for all the codes and participants. The design of the future P2M experiments will obviously benefit from the process and the experience gained by the code users. The development of new models to better catch the observed microstructure at the pellet center after fuel melting was discussed and may lead to new questions and findings in the future. A detailed analysis of the BR2 PWC thermal hydraulics by computational fluid dynamics simulations was also performed during the simulation exercise to reassess the clad temperature correlations available at SCK·CEN and estimate the rodlet plenum temperature.[13] This information is of great importance for future P2M tests where a pressure sensor will be inserted in the rodlet. It is part of the second simulation exercise currently organized in the P2M program. The FIDES-II second triennial program (2024–2027) is currently on its way. The first planned P2M ramp test with incipient melting should be performed in the BR2 reactor during this second phase.

Acknowledgments

Michelle Bales and Tatiana Ivanova from the NEA are gratefully acknowledged for their support in the preparation of this special issue.

References

1. M. BALES, "The NEA Framework for Irradiation Experiments (FIDES): A New Future for International Collaboration on Nuclear Fuel Research," *Proc. TopFuel 2022 Conf.*, Raleigh, North Carolina, October 9–13, 2022, American Nuclear Society (2022); https://doi.org/10.13182/TopFuel22-39084.
2. "Second Framework for Irradiation Experiments (FIDES-II)," OECD Nuclear Energy Agency; https://www.oecd-nea.org/jcms/pl_70867/.
3. V. ARIMESCU et al., "Third SCIP Modeling Workshop: Beneficial Impact of Slow Power Ramp on PCI Performance," *Proc. WRFPM 2014*, Sendai, Japan, September 14–17, Paper No. 100045 (2014).
4. V. D'AMBROSI et al., "P2M Simulation Exercise on Past Fuel Melting Irradiation Experiments," *Nucl. Technol.*, **210**, *2*, 189 (2024); https://doi.org/10.1080/00295450.2023.2194270.
5. V. D'AMBROSI et al., "Presentation of the xM3 Test Case of the P2M Simulation Exercise and Modeling with the Fuel Performance Code ALCYONE," *Nucl. Technol.*, **210**, *2*, 285 (2024); https://doi.org/10.1080/00295450.2023.2253660.
6. G. BONNY et al., "The UO_2 Power-to-Melt Experiment Performed in the High Burnup Chemistry International Program," *Nucl. Technol.*, **210**, *2*, 216 (2024); https://doi.org/10.1080/00295450.2023.2264505.
7. J. SERCOMBE et al., "2D(r,θ) Simulations of the HBC-4 Power-to-Melt Experiment with the Fuel Performance Code ALCYONE," *Nucl. Technol.*, **210**, *2*, 269 (2024); https://doi.org/10.1080/00295450.2023.2188138.
8. A. MOHAMAD and Y. UDAGAWA, "Modeling of the P2M Past Fuel Melting Experiments with the FEMAXI-8 Code," *Nucl. Technol.*, **210**, *2*, 245 (2024); https://doi.org/10.1080/00295450.2023.2185061.
9. J. CORSON, A. CHUNG, and S. MULLER, "Modeling of the P2M Past Fuel Melting Experiments with the Fuel Performance Code FAST-1.0.1," *Nucl. Technol.*, **210**, *2*, 261 (2024); https://doi.org/10.1080/00295450.2023.2181042.
10. A. CHAIEB et al., "Modeling of the P2M Past Fuel Melting Experiments with the Fuel Performance Code CYRANO3," *Nucl. Technol.*, **210**, *2*, 232 (2024); https://doi.org/10.1080/00295450.2023.2232664.
11. D. ROZZIA et al., "Modeling of OECD/NEA P2M Benchmark Cases by Means of TRANSURANUS Code," *Nucl. Technol.*, **210**, *2*, 324 (2024); https://doi.org/10.1080/00295450.2023.2229186.
12. K. INAGAKI, "Fuel Melting Simulation with FRAPCON/FRAPTRAN Codes for the Power-to-Melt-and-Maneuverability Simulation Exercise and Consideration of Model Modifications," *Nucl. Technol.*, **210**, *2*, 308 (2024); https://doi.org/10.1080/00295450.2023.2239041.
13. A. FAYET et al., "Determination of the Gas Plenum Temperature of the P2M Instrumented Fuel Rodlets on the Basis of a Thermal-Hydraulic Study of the Belgian Reactor 2 Pressurized Water Capsule," *Nucl. Technol.*, **210**, *2*, 354 (2024); https://doi.org/10.1080/00295450.2023.2271222.