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An Overview of the xM3 Slow Power Ramp Transient Staircase Exercise

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1. Introduction

The xM3 power ramp exercise is the subject of this investigation. The Power to Melt and Maneuverability (P2M) plan includes this power ramp test. The Joint Experimental Programmers (JEEP) enclosed the other four plans, including P2M, to form the Framework for Irradiation Experiments (FIDES). The FIDES framework allows advanced experiments in nuclear material science. The Organization for Economic Cooperation and Development (OECD) and the Nuclear Energy Agency (NEA) are intergovernmental agencies that promote and support the FIDES, JEEP, and P2M projects.
Under OECD/NEA support, FIDES, JEEP, and P2M plans have assisted member countries in developing nuclear technology. Initially, the P2M plan focused on thermal and mechanical fuel cladding behavior during a slow transient. A core group is to support several tasks comprising SCK, CEN (Belgium), CEA, and EDF (France). Core group support facilities enclose the BR2 materials testing reactor (Belgium), the CEA hot cells in France, and the Studsvik reactor (Sweden).
The xM3 case is a staircase power ramp transient after a low irradiation cycle. During the P2M, participants use several performance codes of their choice. In the P2M exercise, participants from nine countries used 11 different fuel performance codes. Between these codes were TRANSURANUS [1], FRAPCON/FRAPTRAN [2], FAST [3], ALCYONE [4], FEMAXI [5], TESPA-ROD, FINIX, and BISON, all of which showed similar results.
The P2M analyzes the light water reactor's (LWR) fuel response under slow and high-power transients. In XM3 fuel, there is partial melting on the fuel pellet but no cladding failure. The exercise worked with two power ramp cases: xM3 and HBC4. While the HBC4 case worked on a high-burnup UO2/Zircaloy-4 fuel rodlet (peak 48 GWd/tU) in the late 1980s in the BR2 reactor, in sequence, it suffered a slow power ramp of around 45 hours.

2. Methodology

The P2M focused on the structural safety material by studying the partial melt formed under the power ramp. Regardless, the fuel codes must simulate the rods, identifying potential factors affecting cladding failure. The Pacific Northwest National Laboratory developed the FRAPCON and FRAPTRAN fuel performance codes, which the United States Nuclear Regulatory Commission (US NRC) adopted in the 1970s to license civilian reactors [6]. The xM3 test represents a fuel response transient for medium-burning UO_2-Zirlo. On Vandellos-II, a pressurized water reactor (PWR) in Spain achieved 27 GWd/tU fabricated by Mitsubishi Heavy Industries UO_2 and Zirlo cladding.
Following initial irradiation, the xM3 rod underwent a staircase ramp protocol composed of 10 consecutive steps increasing 5 kW/m, achieving 70 kW/m in sequence. Under the transient phase, the xM3 fuel rod showed recrystallization in the pellet center region of around 15% without failure.

The xM3 experiment used UO_2 as fuel and Zirlo as cladding, with an outer diameter of 9.5 mm. Following irradiation, the Studsvik R2 reactor was subjected to a staircase ramp for 10 hours, reaching a ramp terminal level (RTL) of 70 kW/m applied in ten successive steps with an increase of 5 kW/m. The fuel centerline temperature is around 1050 °C, and the pellet border region is about 480 °C. The results of the neutron transport calculations depend on neutron cross-sections and define fuel temperature gradients. Table I displays the mechanical characteristics of the fuel rod used in input files in the FRAPCON and FRAPTRAN simulations.

Table I: Rod parameters of xM3 case used with fuel codes.

Rod parameters	xM3	Pellet parameters	xM3
Rod length (mm)	522	Outer diameter (mm)	8.2
Stack length (mm)	441	Height (mm)	10
Plenum length (mm)	44	Enrichment (U-235%)	4.5
Gap (µm)	170	Grain size(µm)	30

An essential parameter of the xM3 rod is a central hole with a radius of 0.15 mm. During pre-irradiation, the burnup was 27 (GWd/tU) average and peak, and fuel centerline temperature varied between 300 ºC and 762 ºC. The fission gas release achieved 0.2%, and fuel hydride achieved 84 ppm. The FRAPCON code accurately estimated the fuel stack length to within ± 1 cm since pellet-clad does not exhibit a solid contact delay if the predicted gap is still wide open. Following results from the base irradiation, several codes showed convergence in the open gap. Figure 1 depicts the linear heat rate (LHR) applied to xM3 during pre-irradiation and a staircase ramp test.

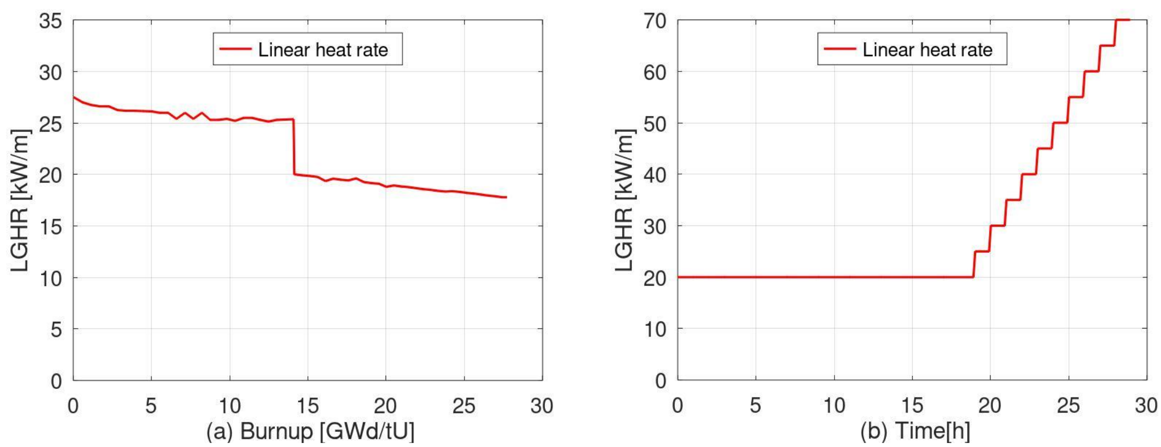

Figure 1: The linear heat rate used (a) for pre-irradiation and (b) during the staircase power ramp.

UO_2 has been the primary fuel for commercial nuclear reactors. It has a fluorite-type cubic structure and incorporates excess oxygen, forming a series of hyperstoichiometric oxides. Thus, the determination of the physical properties of the $UO_{2\pm x}$ phase becomes a matter of great importance. However, the melting of UO2+x depends on its stoichiometric composition, such as UO_2.12. When the U/O rate decreases, the melting point temperature should also slightly increase. MatLib, the material properties library for UO_2 fuel, shows two subroutines for the melting temperature in the FRAPCON and FRAPTRAN codes.
Though fuel codes show slight differences in the melting temperature for steady-state and transients, that way, the MELCOR code for severe accidents assumed 2850 °C, and FRAPCON adopted 2840 °C. The melting temperature of UO_2 is given as a function of burnup, where the melting point decreases linearly from 2840 °C to around 3.2 °C for each increase of one GWd/tU. The calculated curves determined the change between the solidus and liquidus phases as a function of temperature and burnup dependence.

Figure 2 depicts the melting temperature of UO_2 as a function of burnup and Schottky defect percent.

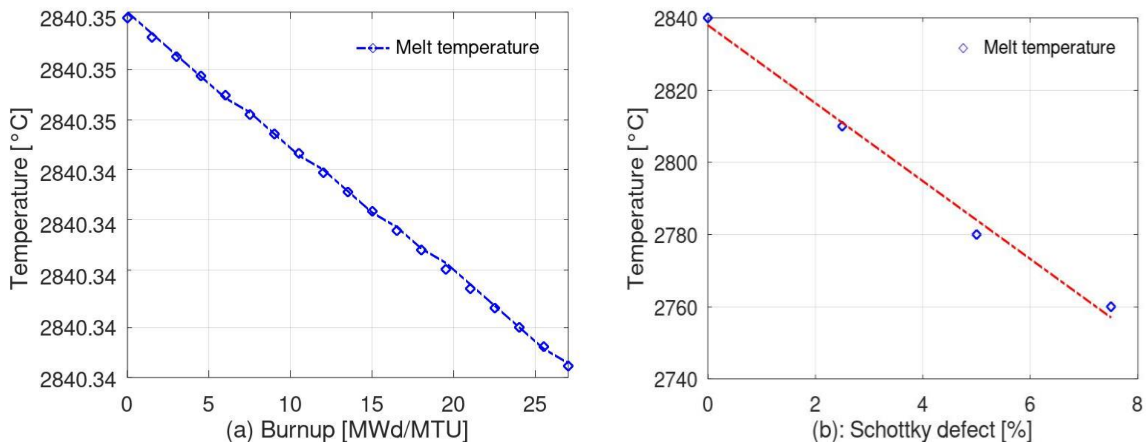

Figure 2: Melting temperature of UO_2: (a) as a function of burnup, and (b) in the function of Schottky defect percents.

3. Results and Discussion

In sequence, xM3 suffered a staircase power ramp with a ramp step of 5 kW/m, maintaining a ramp step rate of 10 kW/m min. Each ramp step holding time was 1 hour, and RTL reached up to 70 kW/m with an uncertainty of ±5%. The temperature at which the liquid fuel fraction of the solidus becomes non-zero for the liquidus. Figure 3 displays two distinct normalized axial power profiles, one for pre-irradiation and the other for the staircase ramp transient.

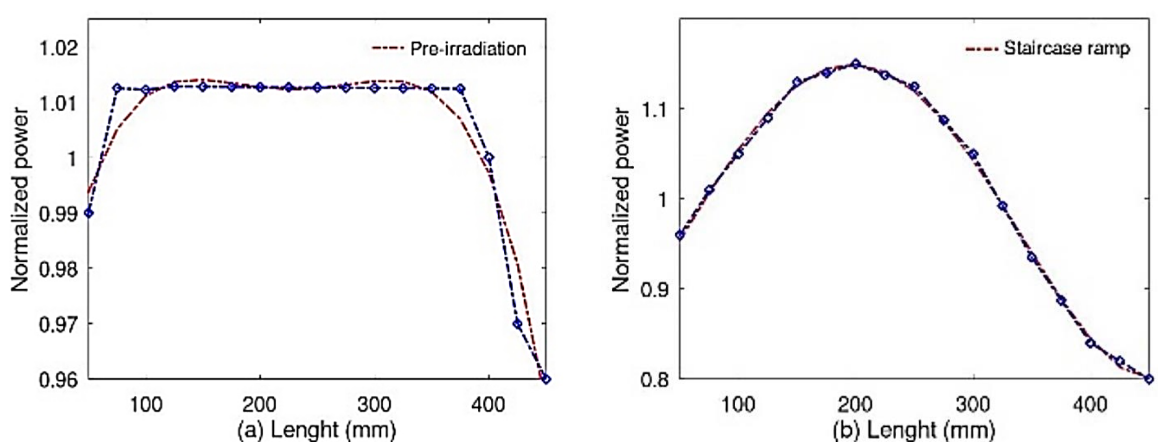

Figure 3: Power profile: (a) pre-irradiation, and (b) under staircase power ramp.

The test uses two axial power profiles that differ between regular irradiation and power transients. The P2M plan goals should help calibration advances against high-temperature fuel behavior and improve melting modeling developed under the power ramps. Figure 4 depicts fuel pellet temperatures.

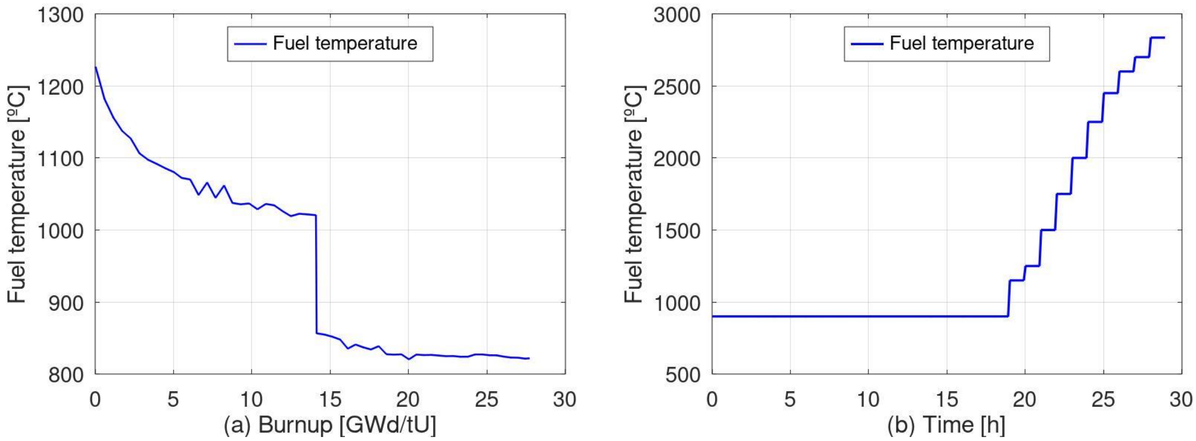

Figure 4: xM3 temperature: (a) during pre-irradiation fuel temperature and (b) in staircase ramp test.

4. Conclusions

Under the FIDES framework, executing the P2M target to review the xM3 exercise leads to partial fuel melting, becoming a challenge for licensing fuel performance codes. The near-centerline pellet partially melted around a 0.4- to 1.2-mm radius. In the MatLib used in the FRAPCON and FRAPTRAN codes to simulate the staircase ramp, the fuel centerline temperature between 21 and 22 hours was around 1500 °C, achieving a 28 to 29-hour value of 2840 °C, corresponding to the calculated melt radius of 0.4 mm.

Acknowledgments

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