Capabilities of TRANSURANUS code in simulating BWR Super-Ramp Project

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Abstract – *After one-two years of normal operation in a LWR, the fuel–cladding gap may close, as a result of as a result of several phenomena and processes, including the different thermal expansion and swelling of both the fuel and the cladding (Pellet Cladding Interaction). In this equilibrium state, a significant increase of local power (like a transient power ramp, i.e. power increase in the order of 100kW/m-h), induces circumferential stresses in the cladding. In presence of corrosive fission products (i.e. iodine) and beyond specific stress threshold, material dependent, cracks typical of stress corrosion may appear and grow-up: this phenomenon is called stress corrosion cracking (SCC). The cracks of the cladding may spread out from the internal surface, causing the fuel failure. The objective of the activity (performed in the framework of the IAEA CRP FUMEX III), is to validate the TRANSURANUS models relevant in predicting the fuel failures due to PCI/SCC during power ramps. Focus is given on the main phenomena, which are involved or may influence the cladding failure behavior. The database selected is the Studsvik BWR Super-Ramp Project, which belongs to the "public domain database on nuclear fuel performance experiments for the purpose of code development and validation – International Fuel Performance Experiments (IFPE) database" by OECD/NEA. It comprises the data of sixteen BWR fuel rods, that have been modeled and simulated with suitable input decks. The burn-up values range between 28 and 37 MWd/kgU. Eight rods, of KWU standard type, are subjected to fast ramps, the remaining rods experience slow ramps and are of standard GE type.*

I. INTRODUCTION

The present activity is focused on the behavior of the fuel component. The aim is to study the PCI/SCC phenomenon during power ramp in water nuclear reactor, i.e. BWR. The relevance of PCI in nuclear technology is connected with the prevention of fuel failures due to stress corrosion cracking (SCC), involving the lost of integrity of the first and second barriers (defense in depth concepts), during normal, off normal and accident conditions.

The objective is the assessment of TRANSURANUS[1] [2] [3] code performance in predicting fuel and cladding behavior under pellet cladding interaction using one experimental database based on BWR rods at burn-up ranging from 28 to 37 MWd/kgU: the BWR Super-Ramp Project [4]. The datasets of the Super-Ramp Project, are part of the International Fuel Performance Experiments (IFPE) [5] [6].

II. BWR SUPER RAMP PROJECT

The main technical objectives of the BWR Super-Ramp were the following [4]:

- "Establish through experiments the PCI failure threshold of standard design BWR test fuel rods on fast power ramping at burn-up levels exceeding about 30MWd/kgU";
- "Establish safe reduced ramp rates for passing through the failure threshold using high burn-up rods".

The BWR-SR power ramped 16 individual test fuel rods of standard as well as modified designs. Kraftwerk Union AG/Combustion Engineering (KWU/CE), as fuel suppliers, delivered 8 rods that have been base irradiated in the Wurgassen nuclear power reactor, Germany up to an average burn-up of 32-37 MWd/kgU. The rods were all identical in design. They formed the group BK7.

General Electric Company (GE), as a fuel supplier, delivered 8 rods following base irradiation in the Monticello reactor, USA (burn-up 28-37MWd/kgU).

These rods formed the two groups, BG8 and BG9. The main difference between BG8 and BG9 rods is the fuel-cladding gap dimension. The power ramping of the experimental fuel rods (BK7, BG8 and BG9 groups), was performed in the R-2 Reactor at Studsvik [7] (Sweden), in the pressurized loop n°1 with forced circulation cooling simulating BWR conditions. Further details about ramping are available in TABLE I.

TABLE I

BWR Super-Ramp Project: ramping phase main data.

Rod group	Rod Label	CL [1] [kW/m]	HT [2] at CL [h]	RTL [3]1 [kW/m]	RR [4] 1 [Kw/mh]	HT at RTL1 [min]	Exp F/NF	RR2 [kW/mh]	RTL2 [kW/m	HT at RTL2 [min]	Exp F/NF
BK7	BK7-1	25.5	24	37.5	540	154	F	--	--	--	--
	BK7-2	25.0	24	36.0	510	720	F	--	--	--	--
	BK7-3	25.0	24	32.5	540	720	NF	--	--	--	--
	BK7-4	18.0	24	30.0	540	720	NF	--	--	--	--
	BK7-8	18.0	24	33.0	540	160	F	--	--	--	--
	BK7-5	25.0	24	32.0	540	1440	NF	540	37.5	720	NF
	BK7-6	25.0	24	32.0	540	1440	NF	540	40.5	720	NF
	BK7-7	25.0	24	32.5	600	720	NF	540	40.5	390	F
BG8	BG8-1	21.5	1	34.0	0.264	--	F	--	--	--	--
	BG8-2	21.5	1	32.0	0.264	--	NF	0.198	38.0	720	NF
	BG8-3	21.5	1	41.5	0.198	--	NF	0.198	40.0[$]	--	F
	BG8-4	21.5	1	32.0	0.264	--	NF	0.198	38.0	720	NF
BG9	BG9-1	27.5	1	44.0	0.336	720	NF	--	--	--	--
	BG9-2	27.5	1	42.0	0.318	--	F	--	--	--	--
	BG9-3	21.5	1	41.8	0.330	--	F	--	--	--	--
	BG9-4	21.5	1	43.3	0.294	160	F	--	--	--	--

[$] Interrupted at 41.5 kW/m due to reactor scram, re-ramped from 38.5 kW/m failed at 40.0 kW/m.

[1] CL: Conditioning Level
[2] HT: Holding Time
[3] RTL: Ramp Terminal Level
[4] RR: Ramping Rate

II.A. KWU Rods Ramping Details

The ramp phase was performed as follow:

- Conditioning with a rather slow increase of the LHR from an initial value to a selected value and holding at this level for 24 hours.
- Ramping with a rapid increase of about 100W/(cm-min) from the CL to a pre-selected RTL.
- Holding at this last terminal power level for 12 hours (or until failure).

The first three rods (BK7-1, BK7-2, BK7-3) were conditioned at 25 kW/m (Fig. 1 (a)), two other rods (BK7-4, BK7-8) were conditioned at 18 kW/m. A different approach was applied to the remaining last three rods (BK7-5, BK7-6, BK7-7), a double step ramp was executed (Fig. 1 (b)):

- Conditioning at 25 kW/m of power and holding 24 hours at this value.
- Ramping to 32.5 kW/m with a RR of 100W/(cm-min).
- Holding at 32.5 kW/m 12 or 24 hours
- Ramping again to a pre-selected RTL (at 100W/(cm-min)).
- Holding 12 hours or until failure

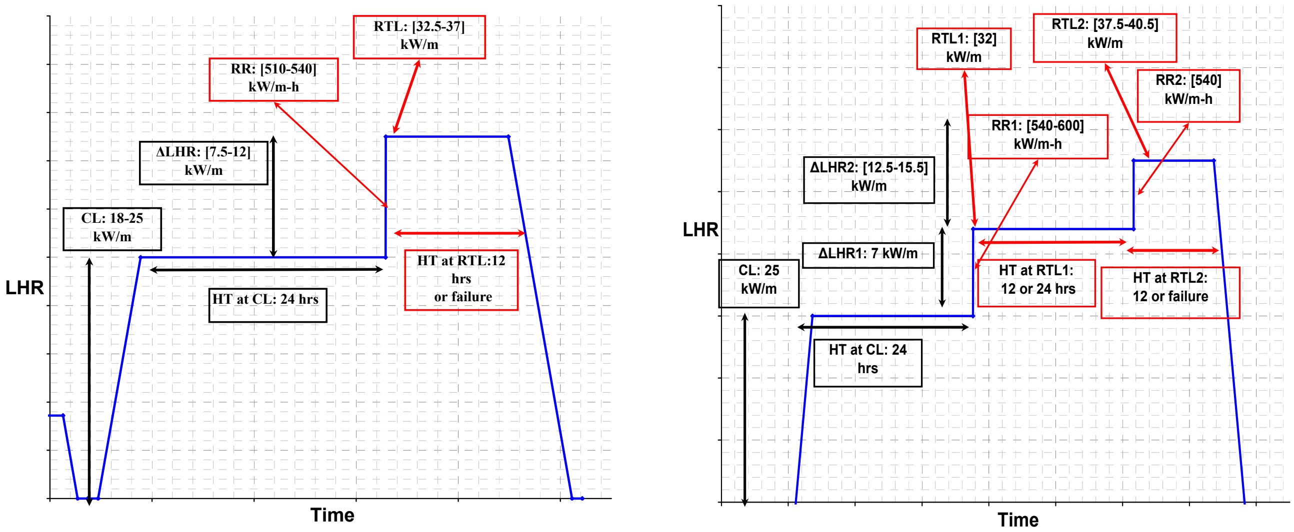
II.B. GE Rods Ramping Details

The ramp phase was performed as follow:

- Conditioning at 27.5 or 21.5 kW/m and holding for 1 hour at the conditioning power.
- Ramping with a selected RR (from 0.033 to 0.056W/(cm-min)) to a RTL of 44 kW/m or until failure.
- Holding at 44 kW/m for 12 hours or until failure (Fig. 2 (a)).

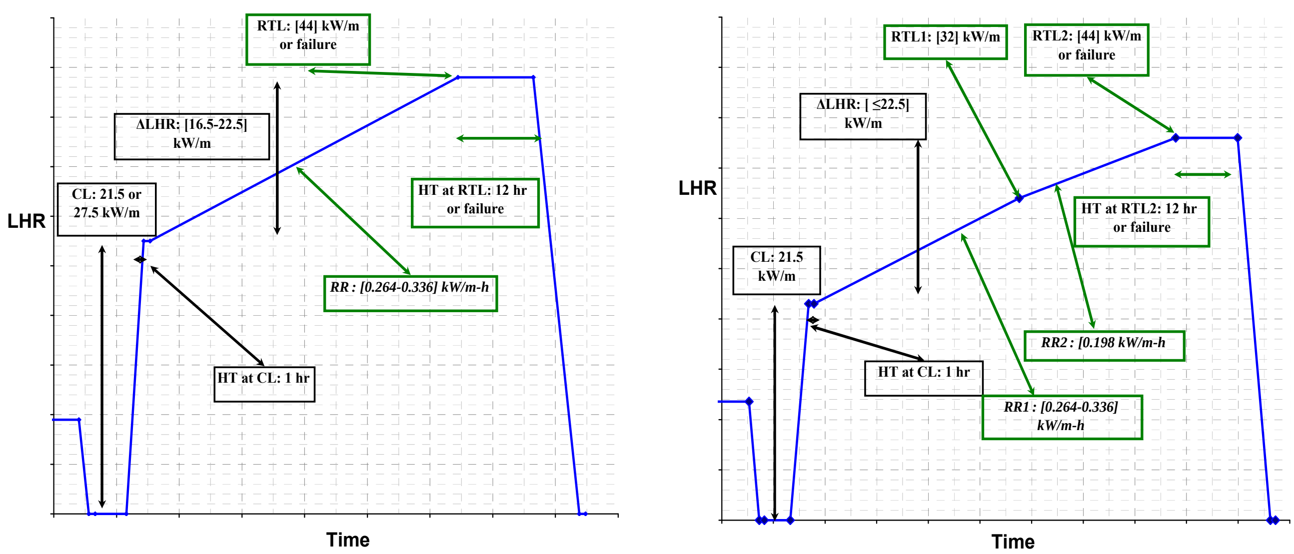
Rods BG8-2 and BG8-4 were ramped with the following approach (taking the BG8-3 behavior as reference, Fig. 2 (b)):

- Ramping at 32kW/m (instead of 44kW/m) at a selected RR.
- Continuing the ramp with a lower RR (the same of rod BG8-3), until 44 kW/m or 38 kW/m.



a) BK7-1, BK7-2, BK7-3, BK7-4 and BK7-8 ramping scheme. *b) BK7-5, BK7-6, BK7-7 double step ramping scheme.*

Fig. 1. BWR S-R: KWU rods, very fast ramp schemes.



a) BK8-1, BK8-3, BG9 ramping scheme. *b) BG8-2, BG8-4 ramping scheme.*

Fig. 2. BWR S-R: GE rods, very slow ramp schemes.

III. MODELING

The input deck has been prepared respecting the information available in the code manual [3]. The models selected are generally the ones standard for the transient to be simulated. Only the active part of the fuel is accounted for the simulation. The active part has been divided into 3 or 5 axial slices, according to the experimental data available [5].

For the reference calculations, the nominal geometrical values were assumed (when available). The main differences among the groups are listed in TABLE II.

The boundary conditions implemented for the analysis are: 1) linear heat rate (LHR) at the axial position according to the ASCII files; 2) cladding temperature histories (same position of LHR); 3) fast neutron flux (same positions of LHR) and 4) pressure. Details on the input decks are reported in Ref. [8].

IV. VALIDATION OF TU CODE AGAINST BWR-SR

The present section provides a summary of the main results achieved from the reference simulation as well as the sensitivity analyses (see Ref. [8] for more details). The code version is TRANSURANUS 2009 (v1m1j09).

TABLE II

BWR S-R: KWU and GE rods main features.

Group	N° of rods	Type	Grain size [µm]	Active length [mm]	Gap width [µm]	Avg LHR [kW/m]	Nominal burn-up [MWd/kgU]
BK7	8	Standard **KWU**	7.6	314	100	12-23	32-37
BG8	4	Standard **GE**	18	753	67	11-13	27-33
BG9	4	Standard **GE**	18	753	115	12	28-31

IV.A. Reference Case: FGR Analysis

More details about measurement techniques are available in Refs. [4] and [8]. The reference simulation shows a good agreement between measured and calculated values of FGR (Fig. 3 and TABLE III). The error is within +/-35%. In the figure is reported also the experimental accuracy (+/-8%).

In TABLE III are summarized the achieved results and are outlined some parameters (they are not exhaustive), that affect the predictions as the maximum centerline temperatures both in base irradiation (BI) and ramp phases. The possible explanation for the underestimation of BG8 group is related to their initial gap. These rods (only) experience gap closure during the BI, this causes enhancement of the gap conductivity and reduction of the fuel centerline temperature (that is responsible of gas diffusion and release from the grain boundaries).

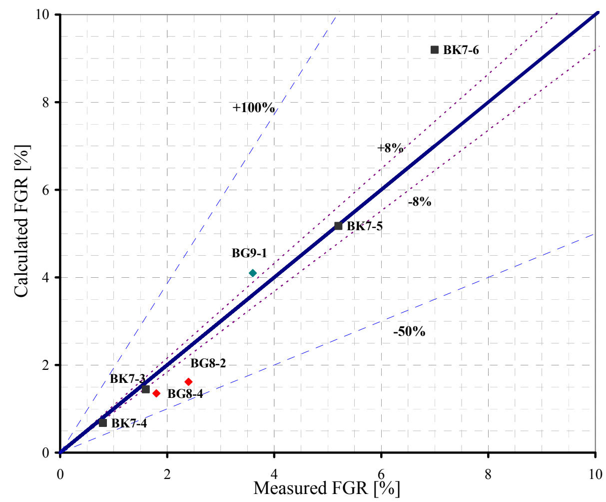


Fig. 3. BWR S-R Exp. vs. TU v1m1j09 results: FGR analysis.

TABLE III

BWR S-R Exp. vs. TU v1m1j09 results: FGR analysis.

Rod group	Rod Label	EXP FGR [%]	TU Calc. FGR	Err.	Parameters that can affect TU predictions			
Accuracy		+/-8 [%]	[%]	[%]	Initial gap [µm]	Avg LHR in BI [kW/m]	TU calc. Max centerline T in BI [°C]	TU calc. Max centerline T in ramp [°C]
BK7	**BK7-3**	1.6	1.4	***-9.7***	100	18.2	1080	1300
	BK7-4	0.8	0.7	***-15.2***	100	16.9	1090	1200
	BK7-5	5.2	5.2	***-0.5***	100	20.2	1130	1530
	BK7-6	7.0	9.2	***31.4***	100	19.6	1110	1650
BG8	**BG8-2**	2.4	1.6	***-32.5***	65	12.2	730	1560
	BG8-4	1.8	1.4	***-24.7***	65	11.3	650	1530
BG9	**BG9-1**	3.6	4.1	***13.9***	115	10.9	740	1770

IV.B. Reference Case: Grain Size Analysis

The experimental data [4] are expressed as Mean Intercept Length (MIL), the grain size (G) is obtained from the following expression according to Ref. [9]:

$$G = MIL*Fs*Fd \quad (1)$$

Where *Fs* is dependent from grain shape, it is equal to 1.50 for sphere shape (our case). The constant *Fd* is usually equal to 1 when the grains are uniform in the size. No experimental data are available to calculate *Fd*. In order to check the degree to the grain uniformity, the initial grain size is compared with the measured MIL After Ramp (AR) at pellet periphery. The approach assumes that no major deviations have to be observed between initial grain size and grain size at pellet periphery AR. The acceptability band, based on conservative judgment, is fixed to 25%.

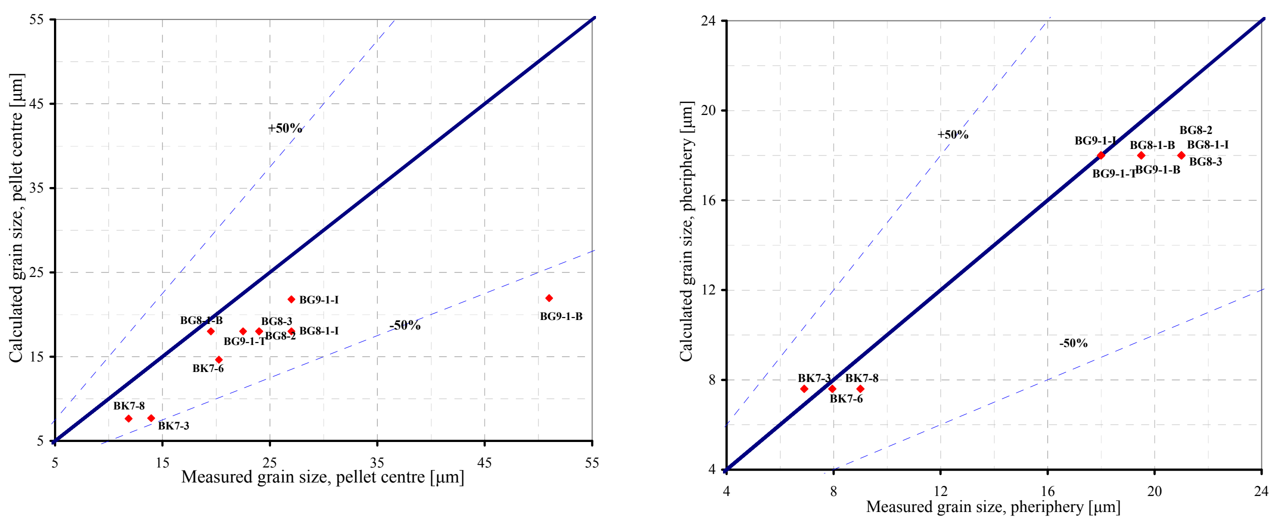
The comparisons at the pellet periphery (Fig. 4 b, TABLE IV) highlight a general accordance between measured and calculated values. The errors are within 15%, therefore, the previous hypothesis are fulfilled.

The analysis of the results (Fig. 4 a, TABLE IV) reveals that the code generally underestimates the grain size at the centre of the pellet. The maximum error is 57% (rod BG9-1B). The restructuring effects predicted by TU code are clearly visible only for rods BK7-6, BG9-1-I and BG9-1-B, in all the other cases the grain size remains close to the initial value. The experimental measures reveal restructuring effects for rods BK7-3, BK7-6 and BG9-1-B. The indexes B, I and T indicate the axial position of measures: bottom, intermediate and top elevations respectively.

TABLE IV

BWR S-R Exp. vs. TU v1m1j09 results: summary of grain size analysis.

Rod group	Rod label	EXP grain size PC [µm]	TU Calc. grain size PC [µm]	Err [%]	EXP grain size at PP [µm]	TU Calc. grain size at PP [µm]	Err. %	TU calc. Max central T [°C]	Max local ramp power [kW/m]	Hold time [min]
BK7	**BK7-3**	14.0	7.7	-44.8	8.0	7.6	-4.4	1300	32.5	720
	BK7-8	11.9	7.7	-35.5	6.9	7.6	10.1	1300	32	160
	BK7-6	20.3	14.6	-27.7	9.0	7.6	-15.6	1650	40.5	1440+720
BG8	**BG81I**	22.5	18.0	-20.0	21.0	18	-14.3	1370	33..5	720
	BG81B	27.0	18	-33.3	19.5	18	-7.7	1350	33.5	720
	BG8-2	24.0	18.0	-25.0	21.0	18.0	-14.3	1560	38	720
	BG8-3	24.0	18.0	-25.0	21.0	18.0	-14.3	1635	39.5	0
BG9	**BG91B**	51.0	22.0	-57.0	19.5	22.0	0.0	1770	44	720
	BG91I	27.0	21.8	-19.3	18.0	18.0	0.0	1600	38-	720
	BG91T	19.5	18.0	-7.7	18.0	18.0	-7.7	600	4	720



a) Pellet centerline *b) Pellet periphery*

Fig. 4. BWR S-R Exp. vs. TU v1m1j09 results, grain size analysis.

IV.C. Reference Case: Clad Outer Corrosion Analysis

The experimental results, described in Ref. [4], are largely different: the corrosion layer of GE rods ranges from 6 to up to 14 µm, while the corrosion layer of KWU (BK7) ranges from 6 to up to 100 µm.

TU calculations (**Error! Reference source not found.**) show an under-estimation of the outer oxidation layer in the case of KWU rods (BK7). Contrary results are obtained in the case of GE rods (BG8 and BG9). The GE rods absolute values are larger then the predictions achieved for KWU rods. The reason for this difference is related to the base irradiation conditions reported in **Error!**

Reference source not found. that are representative for the two groups. The duration of the BI plays the most important role: BG and BK7 rods are irradiated at similar avg. temperature conditions but, due to a lesser average LHR of BG rods, the duration of the irradiation is larger in order to reach similar burn-up. This causes the higher prediction achieved for BG rods.

TU simulations show that oxidation thickness is axially uniform. In TABLE V the results are summarized, some parameters that can influence the simulations are also given as the average coolant temperature and the average clad surface temperature.

Must be mentioned that the water chemistry plays a role in the cladding corrosion. A possible explanation of the general difference between calculated and measured values may be connected with the different reactor in which the rods are base irradiated.

TABLE V

BWR S-R Exp. vs. TU v1m1j09 results: oxidation analysis.

Rod group	Rod label	EXP clad oxi [µm]	TU calc. clad oxi [µm]	Parameters that can affect TU predictions			
				Reactor	Avg. burn-up [MWd/kgU]	Avg. coolant T. in BI [°C]	Avg. clad surface T. in BI [°C]
BK7	BK7-3	6-90	17	Wurgassen	34.8	290.8	292.8
	BK7-8	8-100	17		38.4	290.4	292.2
	BK7-6	8-100	17		35.4	291.3	293.4
BG8	BG8-1	6-12	25	Monticello	30.3	290.5	292.4
	BG8-2	10-14	25		32.7	290.8	292.8
	BG8-3	8	24		27.3	289.8	291.5
BG9	BG9-1	7-8	26		28.4	290.1	291.8

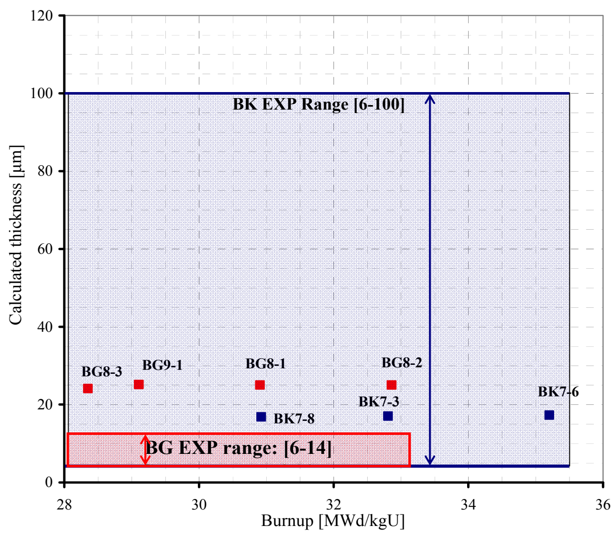


Fig. 5. BWR S-R Exp. vs. TU v1m1j09 results: analysis of corrosion.

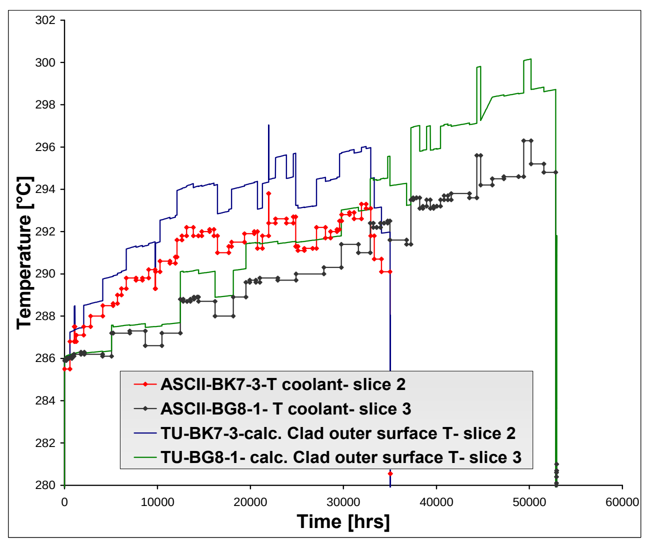


Fig. 6. BWR S-R Exp., groups BK and BG; comparison of the time trends in peak axial position.

IV.D. Reference Case: Failures Analysis

In TABLE VI and TABLE VII the cladding failure by PCI/SCC is analyzed, some parameters, are also reported. TU predictions are compared with experimental results [4] in TABLE VIII. The reference calculation predicts 4/8 KWU rods correctly, the errors are all of not conservative type. From the simulations, no one KWU rod experiences failure and PCI in BI. Three out of eight GE rods are correctly simulated; three errors are of not conservative type.

BG8 group results conservatively predicted, it differs from the other groups in the initial gap size. Due to the lowest gap, the rods belonging to this group experience PCI during the base irradiation (TABLE VII).

The failure thresholds obtained with TU of each sub-group are reported in TABLE VIII in terms of ramp terminal level for BK7 group only. These thresholds are also identified experimentally. Due to the purpose of the experiment, BG8 and BG9 failure thresholds are not analyzed. The analysis of the experimental data and of the code results brought to the observations reported hereafter.

BK7, one step, conditioned at 25 kW/m: in the experiment, a failure threshold due to PCI/SCC mechanism was established in the power range of 32.5 and 36.0 kW/m, and the delta power range of 7.5 to 11.0 kW/m. In the TU simulations (TABLE VIII), two different thresholds are evidenced: 48 kW/m for the rods held 720 min (BK7-2 and BK7-3) and 68 kW/m for the rod BK7-1 that was ramped 154 min only (due to experimental failure).

BK7, one step, conditioned at 18 kW/m: the ramp power change was in the range 12.0 to 15.0 kW/m and the power level for failure 33 kW/m. Thus, any influence of the conditioning level (comparison between 18 and 25 kW/m) could not be ascertained from the experiment. In the TU simulations (TABLE VIII), an increase of SCC resistance up to 73 kW/m (BK7-8), was revealed with a holding time similar to rod BK7-1.

BK7, two steps: performing the ramp in two steps with holding 12 or 24 hrs (after the first step), it was possible to exceed the level of 36 kW/m and 11 kW/m of delta power without experiencing failure. Thus, an influence of this conditioning was evidenced. In particular, comparing the non-failed rod BK7-6 (held 24 hours at 32 kW/m and ramped at 40 kW/m) with BK7-7 rod (same conditions of BK7-6 exception for the holding: 12 hrs only), can be observed an increase in SCC resistance increasing the holding time between the first and the second steps. In the TU simulations (TABLE VIII), opposite results are obtained: the SCC resistance is reduced in comparison to one step ramping (44kW/m is the new threshold for the rods conditioned at 25 kW/m and held 720 min in the second step). In addition, the SCC resistance of rod BK7-7 increases up to 48 kW/m. This may be connected with the increase of PCI duration compared to the one step ramp. This last conditions is essential to initiate the chemical crack creation model contained in the subroutine that treat failures (REF). In order to check the influence of the holding time 720 minutes were applied to rods: BK7-1, BK7-7 and BK7-8, the results are reported in brackets in TABLE VIII.

IV.E. Sensitivity Analysis

The sensitivity analysis is a fundamental step for the assessment of the code capabilities. Different objectives shall be fulfilled such as to demonstrate the robustness of the calculation, to characterize the reasons for possible discrepancies between measured and calculated trends or values observed in the reference calculation, to optimize code results and user option choices, to improve the knowledge of the code by the user. Several sensitivity analyses were performed and documented in Ref. [8]. Here after are presented the results of main interest.

TABLE VI

BWR S-R Exp. vs. TU v1m1j09 results: F/ NF against ramp parameters.

Rod group	Rod label	CL [1] [kW/m]	HT [2] at CL [h]	RTL [3] 1 [kW/m]	RR [4] 1 [kW/mh]	HT at RTL1 [min]	Exp F/NF	RR2 [kW/mh]	RTL2 [kW/m]	HT at RTL2 [min]	Exp F/NF	TU F/NF
BK7	BK7-1	25.5	24	37.5	540	154	F	--	--	--		NF[5]
	BK7-2	25.0	24	36.0	510	720	F	--	--	--		NF
	BK7-3	25.0	24	32.5	540	720	NF	--	--	--		NF
	BK7-4	18.0	24	30.0	540	720	NF	--	--	--		NF
	BK7-8	18.0	24	33.0	540	160	F	--	--	--		NF
	BK7-5	25.0	24	32.0	540	1440	NF	540	37.5	720	NF	NF
	BK7-6	25.0	24	32.0	540	1440	NF	540	40.5	720	NF	NF
	BK7-7	25.0	24	32.5	600	720	NF	540	40.5	390	F	NF
BG8	BG8-1	21.5	1	34.0	0.264	--	F	--	--	--		F
	BG8-2	21.5	1	32.0	0.264	--	NF	0.198	38.0	720	NF	F[6]
	BG8-3	21.5	1	41.5	0.198	--	NF	0.198	40.0 $	--	F	F
	BG8-4	21.5	1	32.0	0.264	--	NF	0.198	38.0	720	NF	F
BG9	BG9-1	27.5	1	44.0	0.336	720	NF	--	--	--		NF
	BG9-2	27.5	1	42.0	0.318	--	F	--	--	--		NF
	BG9-3	21.5	1	41.8	0.330	--	F	--	--	--		NF
	BG9-4	21.5	1	43.3	0.294	160	F	--	--	--		NF

$ Interruped at 41.5 kW/m due to reactor scram, re-ramped from 38.5 Kw/m failed at 40.0 kW/m.

[1] CL: Conditioning Level [3] RTL: Ramp Terminal Level [5] Red colour indicates not conservative prediction

[2] HT: Holding Time	[4] RR: Ramping Rate	[6] Blue colour inicates conservative prediction

TABLE VII

BWR S-R Exp. vs. TU v1m1j09 results: F/NF against BI parameters.

Rod group	Rod label	Initial gap width [µm]	Initial grain size [µm]	Avg. LHR in BI-(1) [kW/m]	Avg. neutron fast flux (2) [n/cm²s]	Meas. burn-up [MWd/kgU]	TU PCI in BI [hrs]	Reactor	Exp F/NF	TU F/NF
BK7	BK7-1	100	7.6	19.9	6.4*1E13	37.7	0	Wurgassen	F	NF[5]
	BK7-2	100	7.6	19.2	6.7*1E13	36.5	0		F	NF
	BK7-3	100	7.6	18.2	6.8*1E13	34.8	0		NF	NF
	BK7-4	100	7.6	16.9	6.4*1E13	31.8	0		NF	NF
	BK7-8	100	7.6	17.2	6.5*1E13	32.6	0		F	NF
	BK7-5	100	7.6	20.2	6.4*1E13	38.4	0		NF	NF
	BK7-6	100	7.6	19.6	6.8*1E13	37.2	0		NF	NF
	BK7-7	100	7.6	18.6	6.8*1E13	35.4	0		F	NF
BG8	BG8-1	65	18.0	11.5	2.8*1E13	30.3	20000	Monticello	F	F
	BG8-2	65	18.0	12.2	2.6*1E13	32.7	20000		NF	F[6]
	BG8-3	65	18.0	10.6	2.5*1E13	27.3	20000		F	F
	BG8-4	65	18.0	11.3	2.4*1E13	29.6	20000		NF	F
BG9	BG9-1	115	18.0	10.9	2.5*1E13	28.4	0		NF	NF
	BG9-2	115	18.0	11.6	2.4*1E13	31.1	0		F	NF
	BG9-3	115	18.0	10.9	2.5*1E13	28.5	0		F	NF
	BG9-4	115	18.0	11.6	2.4*1E13	30.9	0		F	NF

1 Calculated from ASCII flies	3 Red colour indicates not conservative prediction
2 Calculated from ASCII flies	4 Blue colour inicates conservative prediction

TABLE VIII

BWR S-R Exp vs. TU v1m1j09 results: failure thresholds.

Rod group	Rod label	CL [kW/m]	HT at CL [h]	RTL1 [kW/m]	HT at RTL1 [min]	RTL2 [kW/m]	HT at RTL2 [min]	Burn-up [MWd/kgU] EXP	Burn-up [MWd/kgU] TU calc.	Exp RTL threshold [kW/m]	TU RTL threshold [kW/m]	Notes
BK7	BK7-1	25.5	24	37.5	**154**	--	--	37.7	35.8	36.0	68.0 (55)	Similar hold time, different CL
	BK7-8	**18.0**	24	33.0	**160**	--	--	32.6	30.9	33.0	74.0 (56)	
	BK7-2	25.0	24	36.0	**720**	--	--	36.5	34.5	36.0	48.0	Similar hold time, different CL
	BK7-3	25.0	24	32.5	**720**	--	--	34.8	32.8	36.0	48.0	
	BK7-4	**18.0**	24	30.0	**720**	--	--	31.8	30.3	33.0	50.0	
	BK7-5	25.0	24	32.0	1440	37.5	720	38.4	36.3	>40.5	44.0	Double step ramps, different hold times
	BK7-6	25.0	24	32.0	1440	40.5	720	37.2	35.2	>40.5	44.0	
	BK7-7	25.0	24	32.5	**720**	40.5	**390**	35.4	33.5	40.5	47.0 (47)	

Gap Dimension

This sensitivity is based on the following consideration: BG8 group is the once that is conservatively predicted (4/4 failed rods in the simulation, 2/4 in the experiment). The main difference among the three groups is the gap initial dimension: BK7 and BG9 groups have large gap (100 and 110µm respectively), while BG8 has the smallest gap (65 µm). The gap impact is also confirmed by the post-processing analysis, in fact, BG8 group, is the once that experiences about 2000 hours of PCI in the reference simulation during the base irradiation. With the aim to reveal the influence of the as fabricated gap, the gap geometrical design of BG8 group is applied to BK7 and BG9 groups.

The results are showed in TABLE IX. All the rods experience cladding failure. This analysis reveals a strong influence of the gap initial dimension in the failure criterion. The existence of gap ranges at fixed burn-up at which the code is conservative or non-conservative has to be investigated.

Corrosion Models

The objectives of the selected sensitivities are to verify which code models are able to improve the accuracy of the results, and to address the relevance of the outer oxidation layer on the prediction of the failures / not failures due to PCI/SCC.

The "Reference" option to simulate waterside corrosion is ICORRO 3, a MATPRO model for BWR conditions [3] that considers thermal and mechanical effects. Three different sets of sensitivities are carried out assessing:

- BWR conditions, one MATPRO model investigated (ICORRO 1);
- LWR conditions, five MATPRO models investigated (ICORRO 40, 41, 42, 43, 48)
- LWR condition, four EPRI models investigated (ICORRO 21, 22, 23, 24).

The analysis pointed out that the clad outer corrosion does not affect the prediction of failures. Nevertheless, among the models investigated, the MATPRO models for LWR conditions resulted of interest to improve the simulation of corrosion.

ICORRO 40: MATPRO corrosion model for T ≤ 673 K. Thinning of the cladding wall is not considered. ICORRO 41: MATPRO corrosion model for T ≤ 673 K. Thinning of the cladding wall is considered.

ICORRO 42, 43, 48 apply the same MATPRO models previous mentioned in the temperature range [0,673K], they differentiate over 673 K..

The GE rods are predicted within the range of measurements (Fig. 7). Therefore, the simulations of these rods result enhanced with respect to the reference calculation.

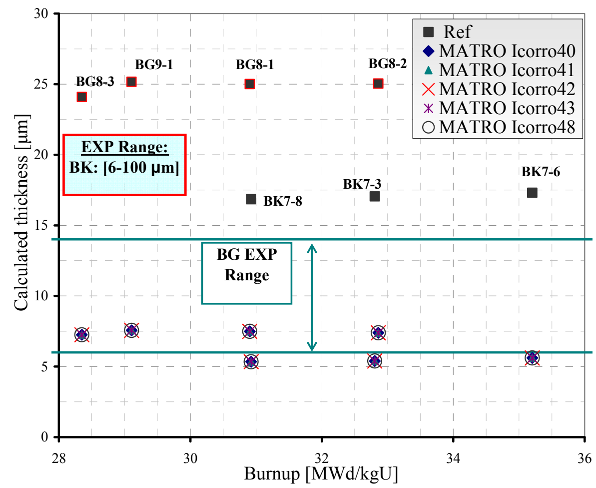


Fig. 7. BWR S-R Exp. versus TU v1m1j09 results: sensitivity analysis addressing the influence of the LWR MATPRO cladding outer corrosion models.

TABLE IX

BWR S-R Exp. vs. TUv1m1j09: sensitivity analysis addressed to the gap dimension.

Rod group	Rod label	Initial design gap [µm]	Exp F/NF	TU Ref F/NF	TU Gap of BG8 F/NF
BK7	BK7-1	100	F	NF	F
	BK7-2		F	NF	F
	BK7-3		NF	NF	F
	BK7-4		NF	NF	F
	BK7-8		F	NF	F
	BK7-5		NF	NF	F
	BK7-6		NF	NF	F
	BK7-7		F	NF	F
BG8	BG8-1	65	F	F	F
	BG8-2		NF	F	F
	BG8-3		F	F	F
	BG8-4		NF	F	F
BG9	BG9-1	110	NF	NF	F
	BG9-2		F	NF	F
	BG9-3		F	NF	F
	BG9-4		F	NF	F

V. CONCLUSIONS

The capability of TRANSURANUS (version “v1m1j09) code in predicting the phenomenon of the pellet cladding interaction is assessed against BWR Super-Ramp Project. The experiment addresses the behavior of 16 BWR fuel rods (Zr-2 cladding), including preceding base irradiation, during the over-power ramping. The burn-up values range between 28 and 37 MWd/kgU.

The prediction of the failures of KWU rods is correct for 4 out of 8 rods in the “Reference” simulation. The analysis of the results demonstrates that the code resulted non-conservative, under predicting the fuel failures. On the contrary, the 8 GE rods reveal two different trends: 4 BG8 rods are conservatively predicted (4/4 failures in the simulation, 2/4 in the experiment), while, 4 BG9 rods are non conservatively predicted (0/4 failures in the simulation, 3/4 in the experiment). The main difference between BG8 group and BG9 group is the initial gap dimension (BG8 has the lowest gap).

The initial gap influences the behavior of the following models, which are relevant to PCI: the gap conductance model, the relocation model and indirectly, by means of the temperature the fuel swelling model. On the basis of the code results, a direct connection between the gap width (analyzed ranges from 65 to 110 µm), and type of failure prediction (conservative or not) is detected. This should be connected with the failure threshold implemented in TU, which might be calibrated/validated for specific ranges of the gap and cladding materials. Further investigations are necessary to confirm this hypothesis and identify the ranges.

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NOMENCLATURE

AR	After Ramp
BI	Base Irradiation
BWR	Boiling Water Reactor
CE	Combustion Energy
CL	Conditioning Level
Exp	Experiment
F/NF	Failure / Non Failure
FGR	Fission Gas Release
FP	Fission Product
FUMEX	FUel Modeling at Extended Burn-up
GE	General Electric company
GRNSP	Gruppo di Ricerca Nucleare San Piero a Grado
HT	Holding Time
IAEA	International Atomic Energy Agency
IFPE	International Fuel Performance Experiment
ITU	Institute for TransUranium Elements
KWU	KraftWerk Union
LHR	Linear Heat Rate
LWR	Light Water Reactor
MIL	Mean Intercept Length
NEA	Nuclear Energy Agency
NSC	Nuclear Science Committee
OECD	Org. for Econom. Co-operation and Develop.
Oxi	Oxidation layer thickness
PC	Pellet Centre
PCI	Pellet Cladding Interaction
PTI	Prior To Irradiation
PTR	Prior To Ramping
PP	Pellet Periphery
RR	Ramp Rate
RTL	Ramp Terminal Level
SCC	Stress Corrosion Cracking
S-R	Super-Ramp
T	Temperature
TU	TransUranus code
UNIPI	UNIversity of PIsa

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