MODELLING OF WWER-440 FUEL ROD BEHAVIOUR UNDER OPERATIONAL CONDITIONS WITH THE PIN-MICRO CODE

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Abstract

The report summarizes the first practical experience obtained by fuel rod performance modelling at the Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences. The results of application of the PIN-micro code and the code modification PINB1 for thermomechanical analysis of WWER-440 fuel assemblies (FAs) are presented. The aim of this analysis is to study the fuel rod behaviour of the operating WWER reactors. The performance of two FAs with maximal linear power and varying geometrical and technological parameters is analysed. On the basis of recent publications on WWER fuel performance modelling at extended burnup, a modified PINB1 version of the standard PIN-micro code is shortly described and applied for the selected FAs. Comparison of the calculated results is performed. The PINB1 version predicts higher fuel temperatures and more adequate FGR rate, accounting for the extended burnup. The results presented in this paper prove the existence of sufficient safety margins for the fuel performance limiting parameters during the whole considered period of core operation.

1. INTRODUCTION

Fuel performance modelling and analysis in Bulgaria began less than two years ago. Calculated results and analysis of the thermomechanical behaviour of selected WWER-440 fuel assemblies (FAs) are presented in this paper. These results must be considered as preliminary, because of the insufficient experience of the Bulgarian authors in this field.

The calculations for the fuel rods (FRs) with highest power in the chosen FAs, are performed with the PIN-micro code [1] and with a modification of the code PINB1. The aim of these calculations and analyses is to determine the extreme values of the limiting parameters accepted for the normal reactor operation and to prove the existence of sufficient safety margins.

2. SHORT DESCRIPTION OF THE PIN-MICRO CODE

The PIN-micro code is a steady-state, quasi-two-dimensional code, developed on the base of the GAPCON-THERMAL-2 code [2]. It has been improved and verified against WWER FRs by introduction of specific correlations [3]. The consideration of the calculated results such as linear power, fuel burnup, fuel and cladding temperatures, gap gas composition and pressure, fuel and cladding deformations, caused by irradiation and depending on burnup, allows the FR behaviour to be analysed during its whole core-life.

The PIN-micro code cannot be applied to predict behaviour of the FR at fast transient and accident conditions.

2.1 INCORPORATED MODELS

The models and correlations included in the PIN-micro code describe: the radial temperature distribution in fuel and cladding, the gap size or pellet-to-cladding contact pressure, the radial deformation of the fuel pellets due to thermal expansion, relocation, densification and swelling, fuel grain growth and restructuring, the radial deformation of cladding due to thermal expansion, creep and irradiation growth, the axial elongation of fuel and cladding, the fission gas release (FGR), the gas composition and pressure.

2.2 CODE VERIFICATION

The PIN-micro code is verified in the framework of international experiments, as well as on Russian and Czech experiments, specific for WWER. The Russian experiments are performed in the MR reactor in the Kurchatov's Institute [3]. The behaviour of WWER-440 and WWER-1000 FAs has been investigated through comparison of measured and calculated results.

At present some Russian, Czech and Bulgarian specialists are applying their own PIN versions to improve and verify them in the framework of the IAEA CRP "FUMEX -- Fuel Modelling at Extended Burnup" against the Halden reactor extended burnup irradiation data.

3. THE MODIFIED PINB1 VERSION

Aiming to improve the user's convenience and partly to overcome some little lacks, a modification PINB1 of the PIN-micro code has been prepared on the basis of recent Russian publications and local considerations [4, 5, 6].

Compared to PIN-micro, the PINB1 includes the following modifications: FGR model for very low and extended burnup [4]; relocation and swelling models to account for fuel creep, which is not modeled; open gap and contact heat conductivity model [5, 6] and fuel thermal conductivity correlation [7]. The approach to the burnup determination is modified in accordance with the possible pellet chamfering, dishing etc., on the base of measured results for initial fuel debris [5, 6]. The burnup accumulation between two time steps in PINB1 does not depend on power during the next, but during the previous time step. The radial flux depression correlation is also modified [5]. The fast neutron flux determination dependent on burnup is based on the correlations from [4].

4. INPUT DATA PREPARATION

The most important input data, such as power history, power axial and radial distributions and peaking factors have been taken from [8]. The geometrical representation of the FR is performed through 10 axial and 20 radial segments.

4.1 GEOMETRICAL AND TECHNOLOGICAL PARAMETERS

For the calculations of the chosen two FAs, three variants of characteristic sets are defined: the case AVER representing the set of the most probable average values of all parameters; the case MAX, representing the most conservative from the central temperature point of view, conjunction of the fuel lowest density and maximal initial radial fuel to cladding gap; and the case MIN with maximal fuel density and minimal gap size, representing also a conservative conjunction of parameters leading to the earliest

Table I. Geometrical and technological parameters for the selected variants

Parameter		Variants		
		AVER	MIN	MAX
Central hole diameter,	mm	1.6	2.0	1.2
Fuel outer diameter,	mm	7.565	7.54	7.59
Cladding inner diameter,	mm	7.76	7.72	7.80
Cladding outer diameter,	mm	9.15	9.10	9.20
Gap,	mm	0.195	0.180	0.210
Gas inner pressure,	MPa	0.6	0.75	0.45
Fuel density,	g/cm^3	10.6	10.8	10.4

PCI. For the cases MAX, MIN it must be kept in mind that they are to be considered only as of very low probability to occur only locally within few FRs. The most important geometrical and technological parameters for the selected variants are given in Table 1.

5. CALCULATED RESULTS

The calculations for the chosen FAs are performed with the standard version of the PIN-micro code.

All presented graphical results are for the AVER case except for Fig. 6 and Fig. 12, where results obtained and compared for the MAX and MIN variants are given.

5.1 FUEL ASSEMBLY 1

The calculated results for the FA 1 performance, variant AVER, during a three-year operational period in core and for a prognosed fourth cycle are presented in Fig. 1 -- 6. Its reshuffling positions are "out-in-out". This FA has the highest power (25 kW/m) during the second year of operation, compared with the first and the third year (about 20 kW/m).

The maximum fuel temperature during the whole period remains lower than 1000 C. The FGR and the gas pressure are very low, less than 0.4% and 25 bar at the end of the predicted fourth cycle respectively, because of the low temperatures typical for the WWER-440 reactors.

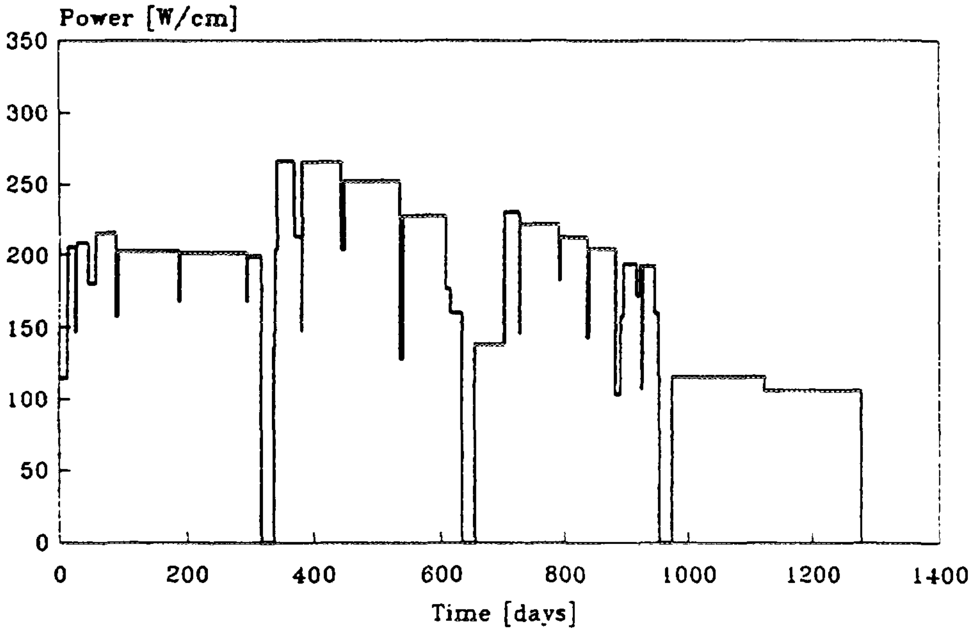

FIG. 1. Power History WWER-440, Assembly 1

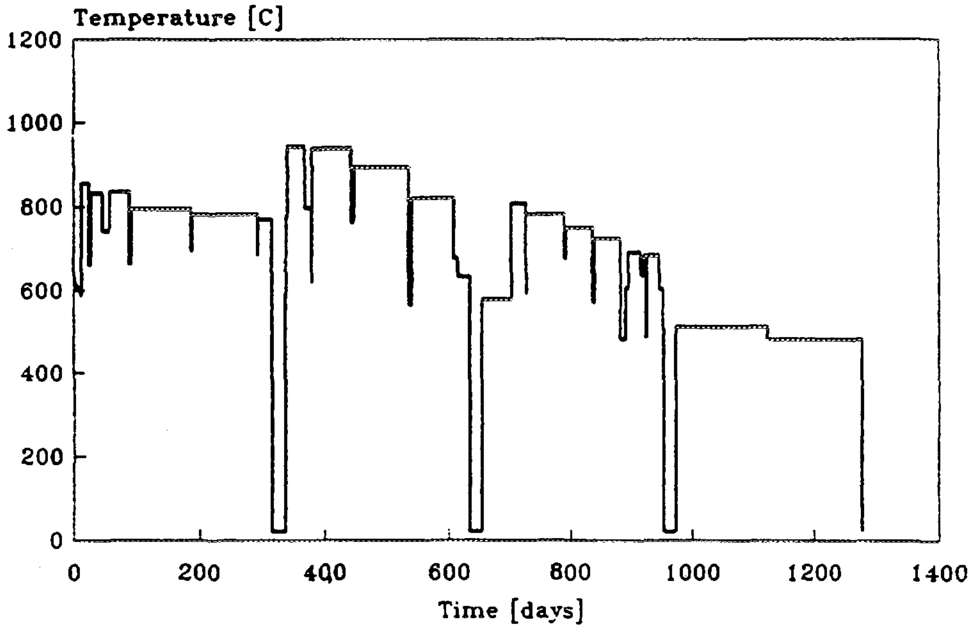

FIG. 2. Fuel Central Temperature WWER-440, Assembly 1

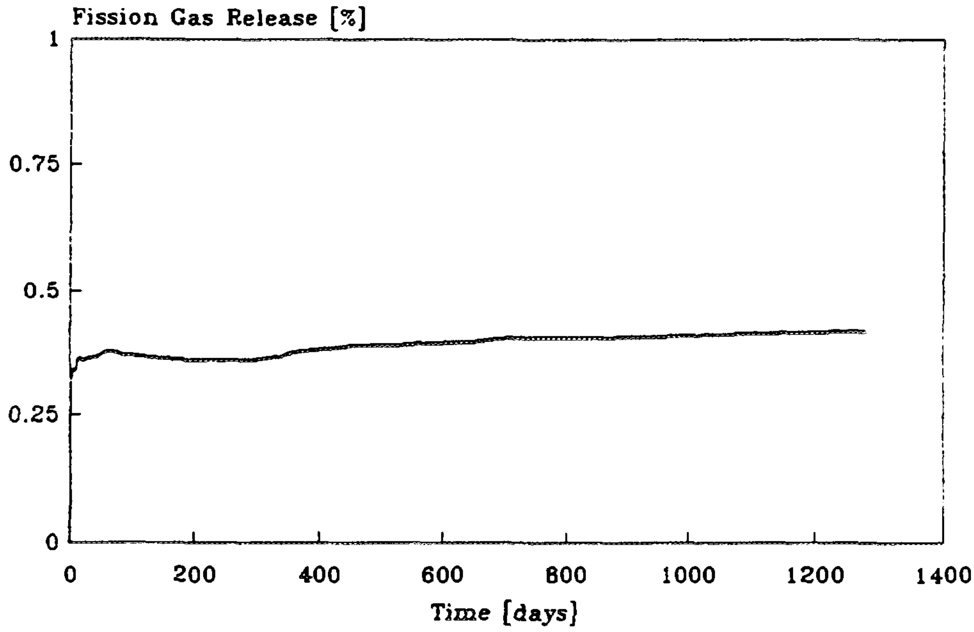

FIG. 3. Fission Gas Release WWER-440, Assembly 1

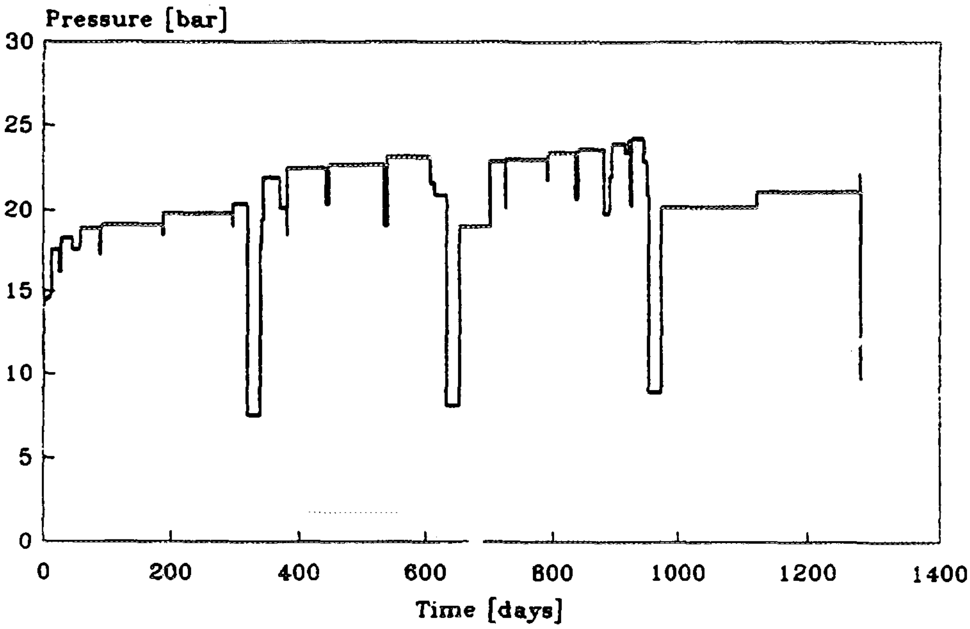

FIG. 4. Gas Pressure WWER-440, Assembly 1

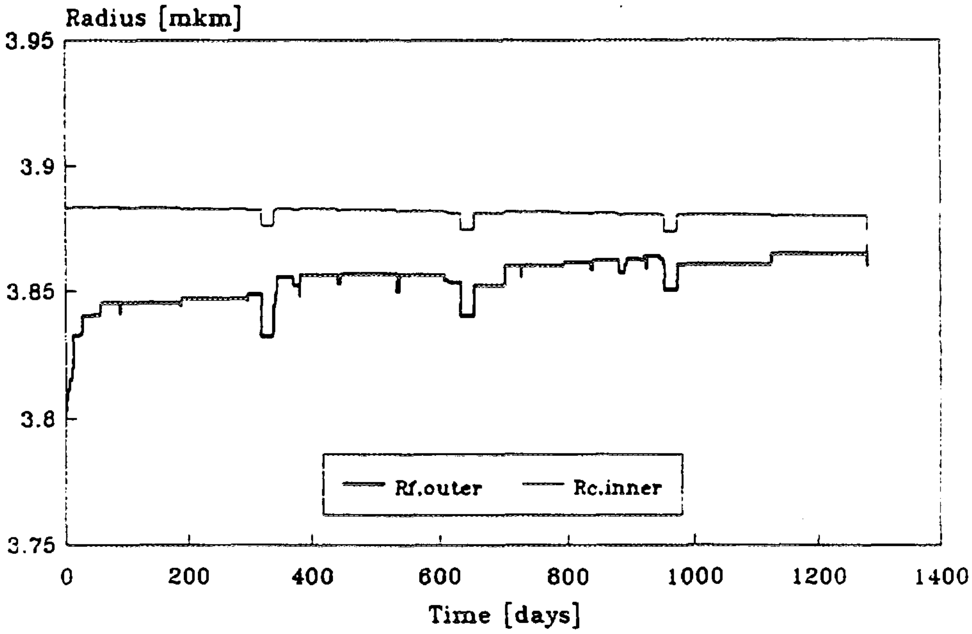

FIG. 5. Fuel & Cladding Radii WWER-440, Assembly 1

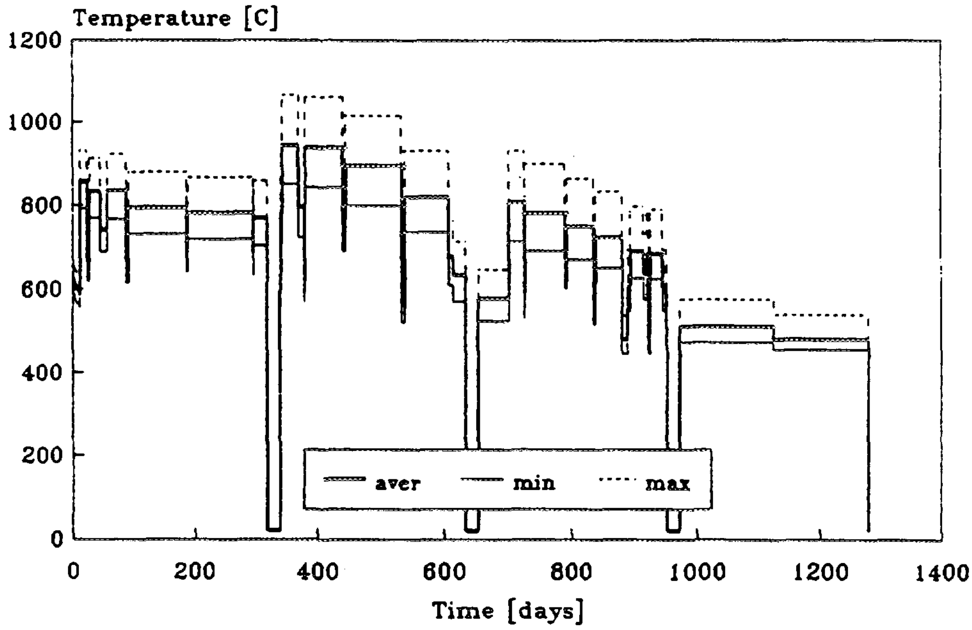

FIG. 6. Fuel Central Temperatures WWER-440, Assembly 1

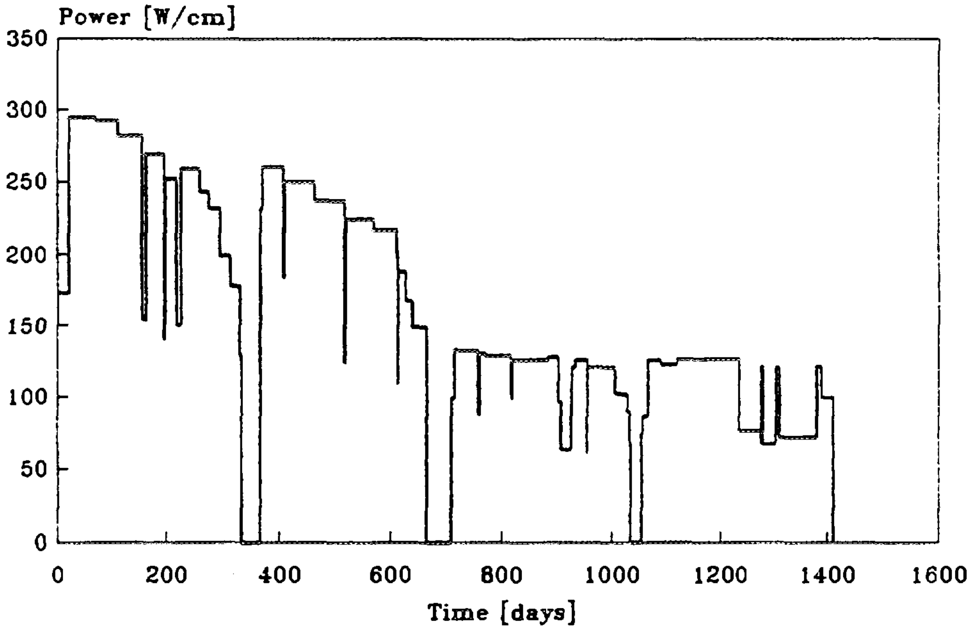

FIG. 7. Power History WWER-440, Assembly 2

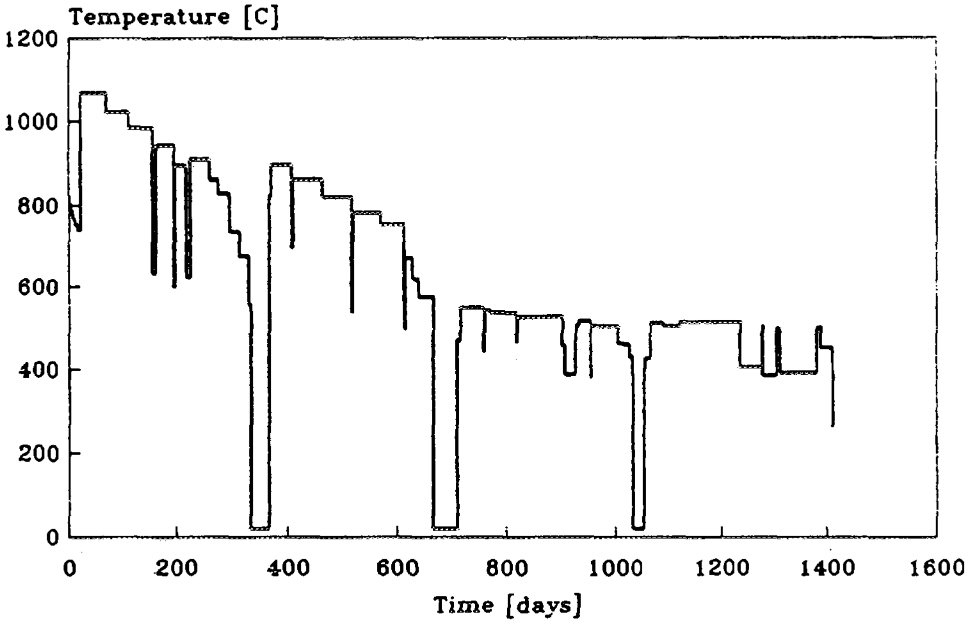

FIG. 8. Fuel Central Temperature WWER-440, Assembly 2

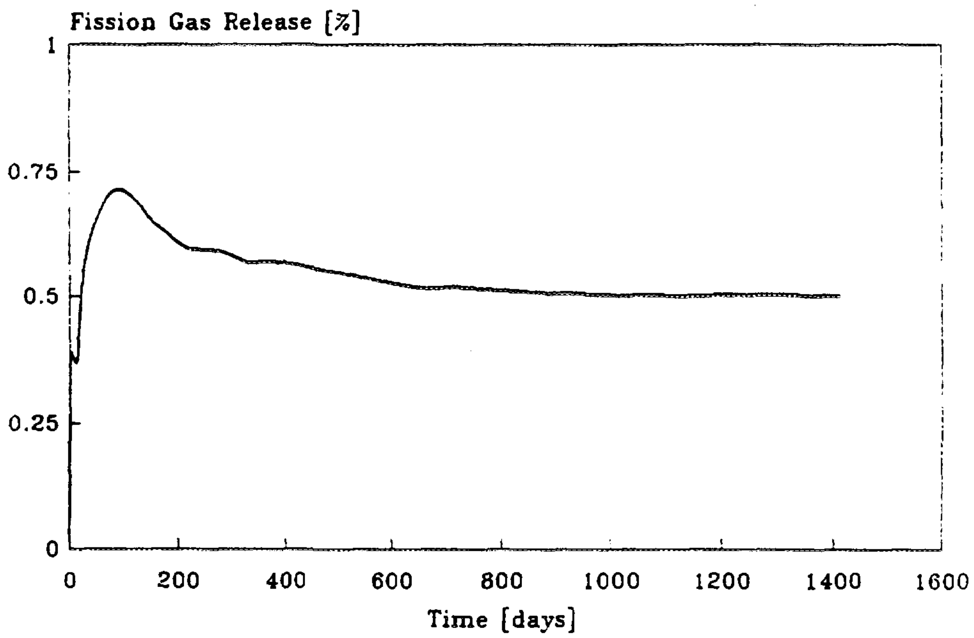

FIG. 9. *Fission Gas Release WWER-440, Assembly 2*

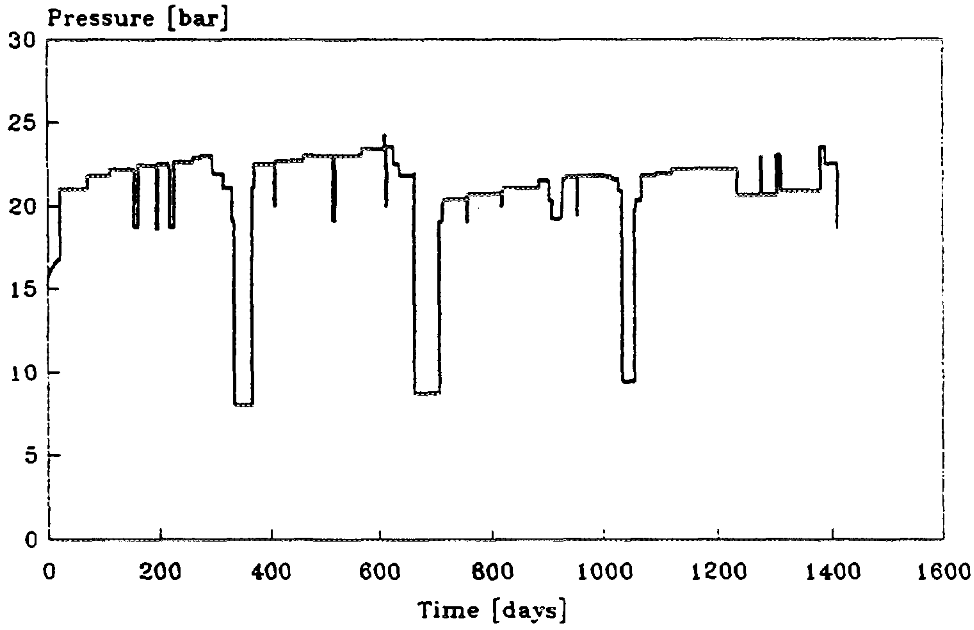

FIG. 10. *Gas Pressure WWER-440, Assembly 2*

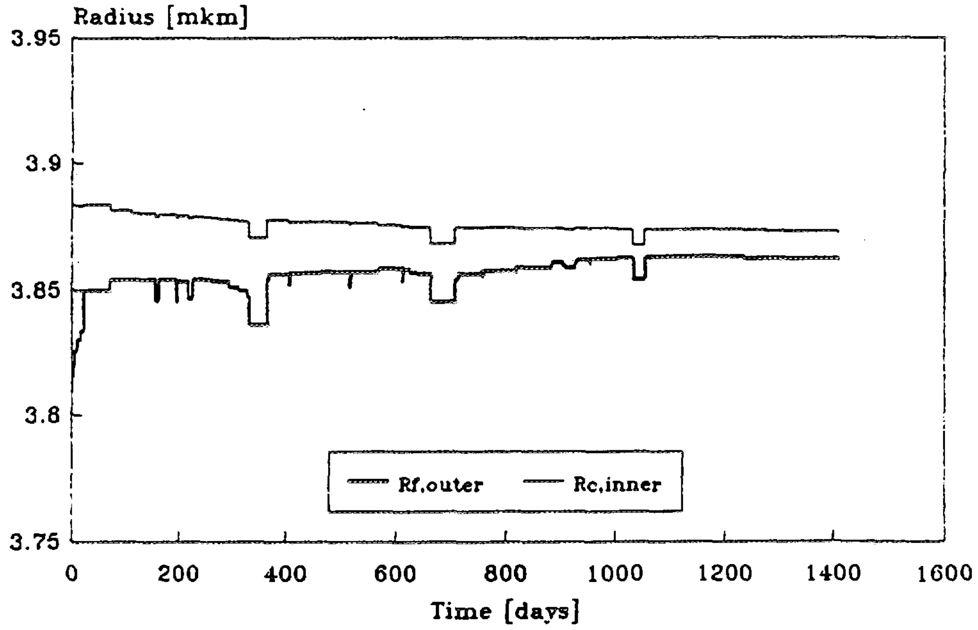

FIG. 11. *Fuel & Cladding Radii WWER-440, Assembly 2*

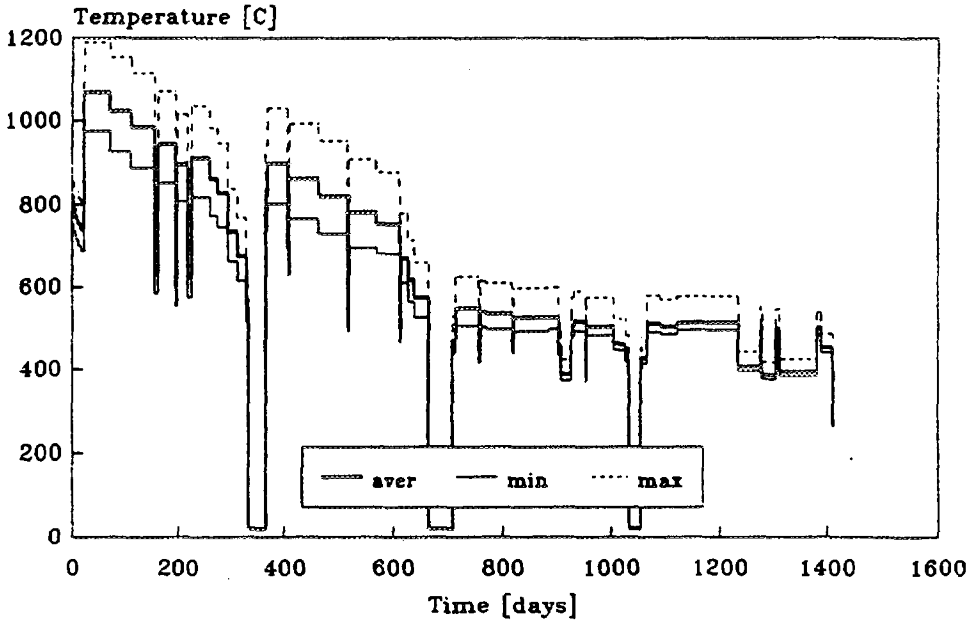

FIG. 12. *Fuel Central Temperatures WWER-440, Assembly 2*

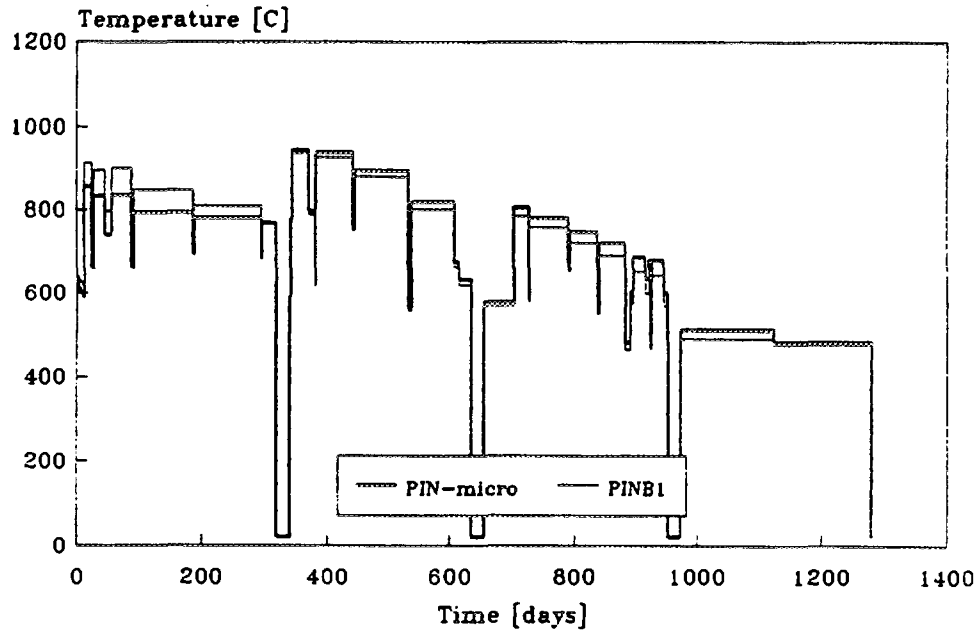

FIG. 13. Fuel Central Temperatures WWER-440, Assembly 1

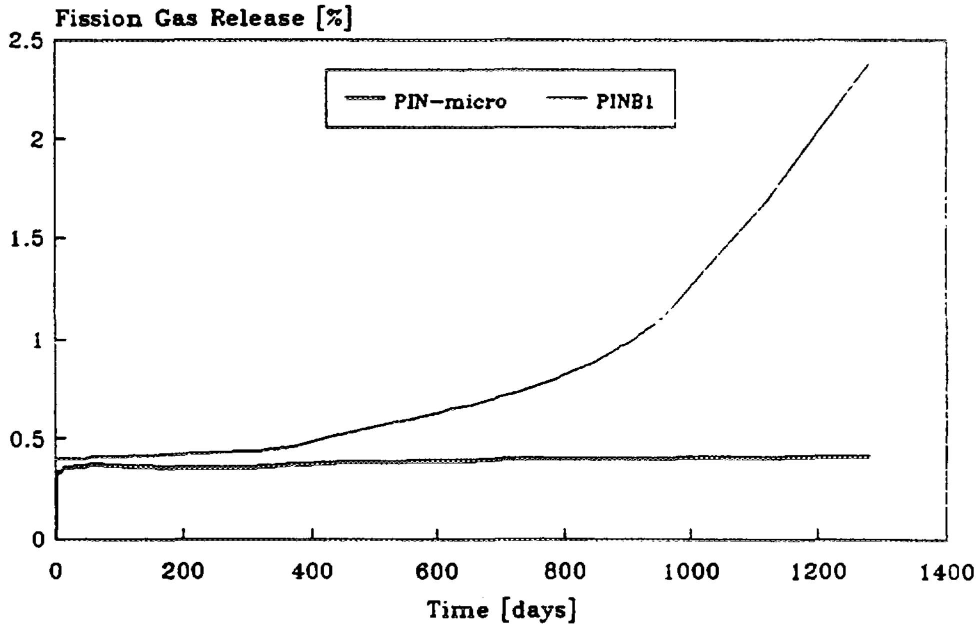

FIG. 14. Fission Gas Release WWER-440, Assembly 1

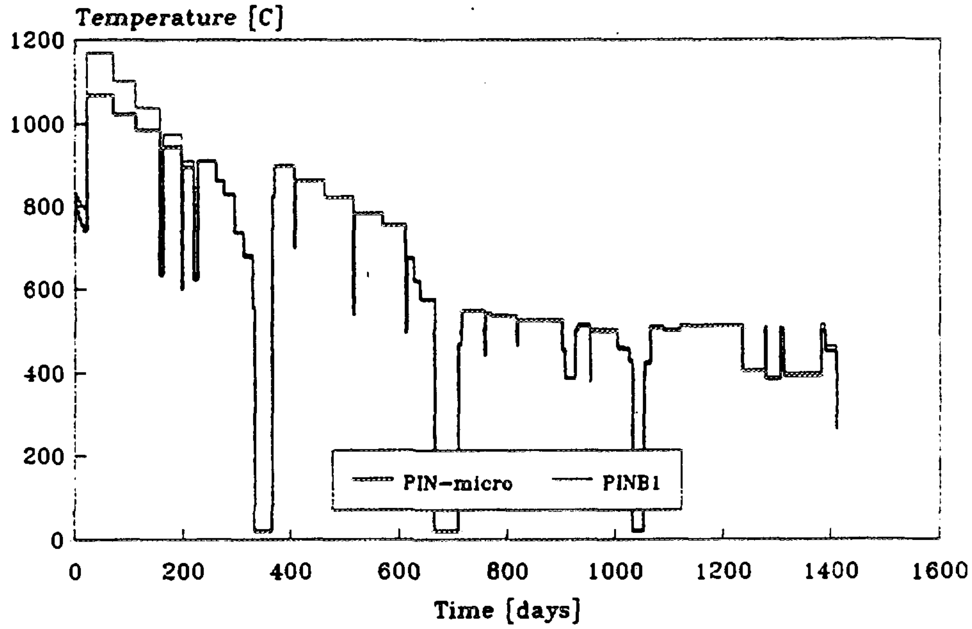

FIG. 15. *Fuel Central Temperatures WWER-440, Assembly 2*

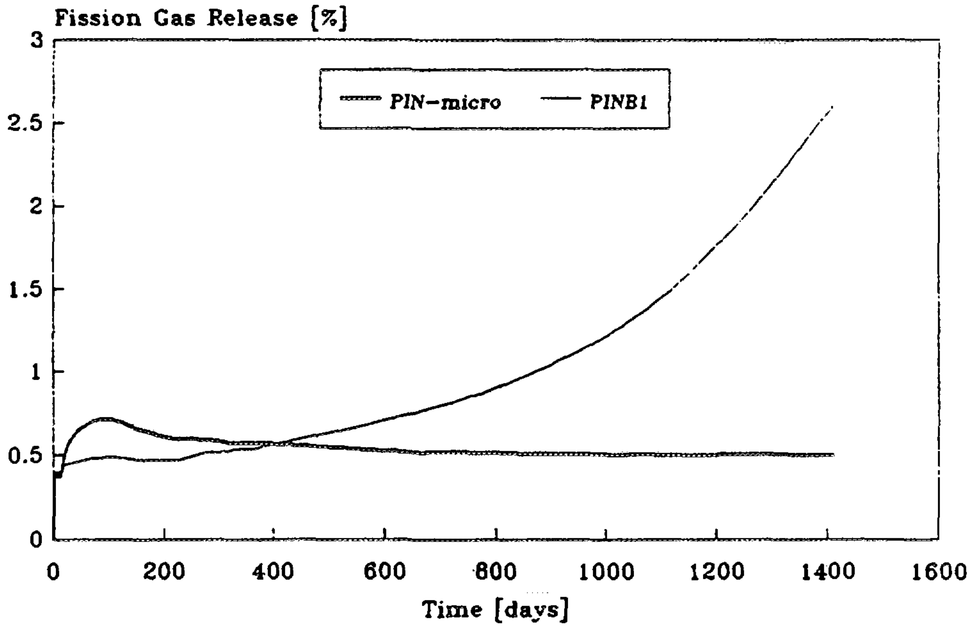

FIG. 16. *Fission Gas Release WWER-440, Assembly 2*

The results for the fuel and cladding radii are given in Fig. 5 and 6. For the cases AVER and MAX the gap closes gradually due to fuel swelling and fuel and cladding creep and comes to thermal contact during the third cycle. For the case MIN the gap closes at the beginning of the third cycle, but no mechanical contact occurs. The results for the fuel central temperatures for the formulated three variants of input data are given in Fig.6.

The analysis of the FA 1 predicted results show, that the FA has significant safety margins to operate for a fourth cycle in the reactor core.

5.2 FUEL ASSEMBLY 2

The calculated results for FA 2, variant AVER, are shown in fig.7 -- 12. This FA has worked successfully during 1177 effective days and the cladding tightness measurements have given very good results. The reshuffling positions for this FA have been "in-in-out". The linear power during the first and the second cycles is relatively high for WWER-440, about 30 kW/cm and 25 kW/cm, respectively. The maximum fuel temperature is 1050 C for the first year and about 800 C for the second. Because of the low temperatures, the FGR rate remains lower than 0.5% and the gas pressure is less than 23 bar at the end of core life. The results for the fuel and cladding radii and for the gap size show fuel-to-cladding thermal contact occurrence at the middle of the third cycle. For the MAX variant no mechanical contact occurs as well as for the MIN variant up to the end of the core life. The results for the fuel central temperatures for the formulated three variants of input data are given in Fig.12. The threshold temperature for intensive FGR has been reached only for the MAX variant during the first year.

The analysis of the FA 1 results proves its successful and reliable performance and the existence of significant safety margins during the whole core life.

5.3 COMPARISON OF THE PIN-MICRO AND THE PINB1 CALCULATED RESULTS

Some results obtained with the standard PIN-micro and the modified version PINB1 are compared in Figs.13 -- 16. Differences mainly in central fuel temperature and FGR values can be observed. The higher fuel temperatures correspond to the FGR, fuel thermal conductivity and other model modifications, leading to more adequate description of the processes within the fuel rod, accounting for burnup extension.

6. CONCLUSIONS

The presented results allow us to draw the following conclusions:

1. The PIN-micro code predicts adequately the thermal and mechanical behaviour of the WWER fuel rods at the steady-state operational conditions. The original code and its modification have been successfully applied to analyse regimes with extended burnup.
2. The comparison of the calculated results obtained by PIN-micro and the modified version PINB1 show higher fuel temperatures, particularly at low burnups, higher burnups due to the correction of the calculation approach, more adequate FGR, accounting for the first power ramp and for the regimes with extended burnup. The PINB1 version has to be verified against WWER experimental data.
3. The main thermomechanical characteristics predicted by the PIN-micro code prove successful performance of the selected WWER-440 FA 1 and FA 2 for. Sufficient safety margins for the accepted limiting parameters are present during the whole considered period of core operation.

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