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VVER-440 Fuel Rod Performance Analysis with PIN-Micro and TRANSURANUS Codes

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1 Introduction

The reliable prediction of the fuel rod behaviour at normal operational, off-normal and accident conditions is rather important for the safe operation of VVER reactors and for high efficiency of the fuel utilisation.

Since two years activities have been initiated in the Institute for Nuclear Research and Nuclear Energy of the Bulgarian Academy of Sciences to perform thermomechanical calculations and analyses for chosen fuel assemblies (FAs) with different power histories of the Kozloduy NPP VVER-440 units, employing the PIN-micro code [1]. A very important experience has been gained through the participation of the Bulgarian group in the IAEA Coordinated Research Programme FUMEX [2]. This activity has been conducted in co-operation with highly experienced specialists from the Russian Kurchatov's Institute and has been kindly supported by experts from the European Institute for Transuranium Elements. In addition to the analyses made with the PIN-micro code, first analyses were performed utilising the TRANSURANUS VVER version which is under development.

2 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 [4]. It has been improved and verified against VVER fuel rods by introducing specific material property correlations [5].

The models and correlations included in the PIN-micro code describe the radial temperature distribution of fuel and cladding, the radial deformation of 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, the gap size or pellet-to-cladding contact pressure.

The PIN-micro code has been verified by international experiments, as well as on Russian and Czech experiments, specific for VVER. The Russian experiments have been performed in the MR reactor in the Kurchatov's Institute [6]. The behaviour of VVER-440 and VVER-1000 FAs has been investigated by comparing measured and calculated results.

The complexity of the problems which could be solved by PIN-micro was restricted by:

- a simplified mechanistic solution;
- a steady-state solution;
- no cladding failure criteria;
- no model for pellet-cladding interaction (PCI);
- no specific models at extended burnup.

3 The TRANSURANUS Version Used

The original TRANSURANUS code version is described in References [7, 8]. The main features of the code are:

- VVER 1½-D code (superposition of 1-D radial and 1-D axial description), suitable for integral fuel rod thermal and mechanical analysis, taking complicated power histories into account.
- VVER steady-state and transient solutions, accounting for time and burnup dependent processes, such as fuel restructuring and grain growth, densification, creep, swelling, heat transfer coefficient degradation, FGR, etc.
- VVER empirical and semi-empirical modelling, based on experimental observation, as well as physically based description of the fuel rod behaviour.

The present status with emphasis on modelling high burn-up phenomena is given in a contribution to this conference [9]. Although the TRANSURANUS code has been extensively verified using irradiation data from very different sources, the standard version cannot be applied to a VVER fuel rod mainly because of the different cladding material. A first step towards the development of a specific TRANSURANUS-VVER version has been made by introducing VVER cladding data and a specific VVER correlation for the thermal conductivity of the fuel [3]. The most important TRANSURANUS-VVER correlations are the creep rate $\dot{\varepsilon}_{clad}^{creep}$ of the Zr+1%Nb cladding and the thermal conductivity λ_{fuel} for 95% dense fuel:

$$\dot{\varepsilon}_{clad}^{creep} = \left(1 + 7\, e^{-\frac{t}{200}}\right) 36.5\, \sigma_{eff}^{5.4}\, e^{-\frac{25600}{T}} + 1.346 \cdot 10^{-15}\, \Phi\, e^{-\frac{8500}{T}} \sinh\left(3.703 \cdot 10^{-2} \sigma_{eff}\right) \tag{1}$$

$$\lambda_{fuel} = \frac{1}{3.77 + 0.0258T} + 1.1 \cdot 10^{-6}\, T + 1.01 \cdot 10^{-13}\, T^3\, e^{7.2\, T} \tag{2}$$

Both correlations have been published by Strijov et al. in 1988. Evidently, eq. (2) is not burn-up dependent. In view of the well established burn-up dependency of the thermal conductivity of UO_2, the TRANSURANUS standard correlation has been used instead of eq. (2).

It is doubtful whether other TRANSURANUS standard models and correlations apply for VVER fuel rods. Consequently, all predictions should be seen as a first attempt rather then a meaningful prediction. Especially fission gas release should be taken with great caution since local fuel data is not available.

4 Calculated Results

4.1 Input Data

For this comparison the two highest loaded fuel rods of the FAs, which were irradiated in VVER-440 with different power histories, have been selected. The most important operational data, such as power histories, axial power profiles and the primary system parameters, have been taken from Reference [10]. For these two FAs, FA1 and FA2, a set of the most probable average values of all geometrical and technological parameters has been used (see Table 1). The power histories of FA1 and FA2 differ because of the different reloading schemes.

The geometrical representation of the considered fuel rods contains 10 axial segments (in both codes) and 20 or 13 radial segments (in PIN-micro and TRANSURANUS, respectively).

On the basis of the two VVER-440 real cases described, a comparison between PIN-micro and TRANSURANUS codes has been performed, using identical input data.

Table 1 Geometric and technological parameters for the selected variables

Central hole diameter	1.6 *mm*
Fuel outer diameter	7.565 *mm*
Cladding inner diameter	7.76 *mm*
Cladding outer diameter	9.15 *mm*
Diametral gap	0.195 *mm*
Gas inner pressure	0.6 *MPa*
Fuel density	10.6 g/cm^3

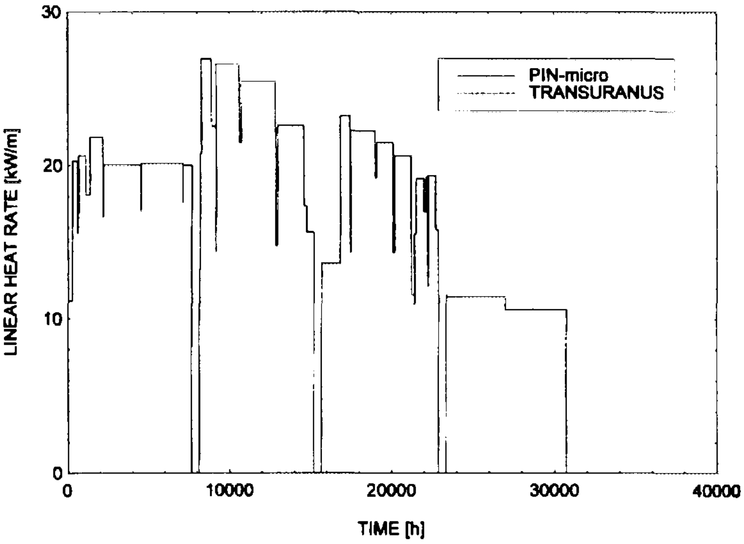

Figure 1 Local linear heat rate, FA1

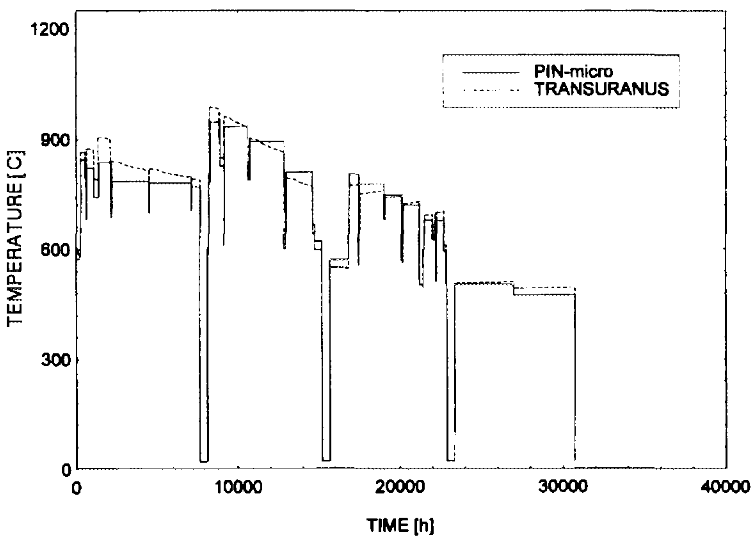

Figure 2 Fuel central temperature, FA1

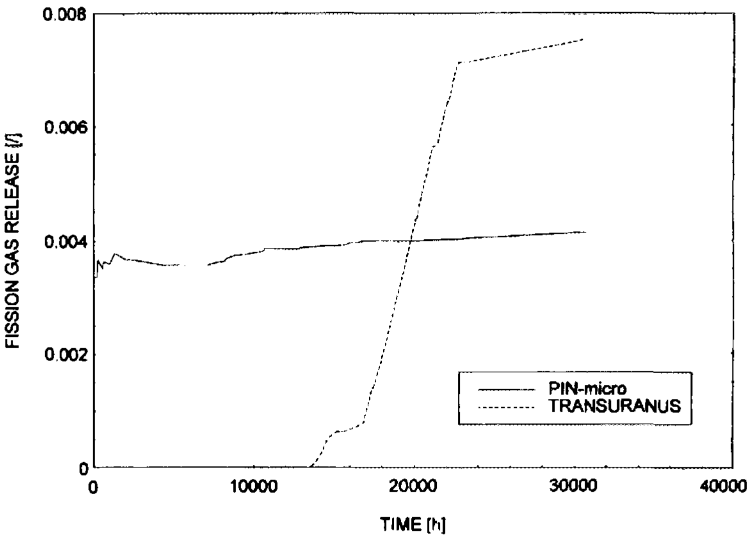

Figure 3 Fission gas release, FA1

4.2 Results and Discussion

The results of the calculations obtained by PIN-micro and TRANSURANUS for the fourth axial segment are compared in Figs. 1 - 5 for FA1 and in Figs. 6 - 10 for FA2.

The complicated power histories are shown in Fig. 1 and Fig. 6 as a function of time. In Fig. 2 - 5, and Figs. 7 - 10, fuel central temperature, FGR, inner gas pressure and gap size, calculated by both codes, are given.

Fig. 2 and Fig. 7 show a satisfactory overall agreement of the fuel centre temperature, except at low burnup, where TRANSURANUS predicts about 100°C higher temperatures. This difference may be due to different densification and relocation models.

The kinetics of fission gas release (FGR) differ mainly in the initialisation threshold of about 10000 hours given by TRANSURANUS for the gas release as well as in the achieved final level being higher of 50% to 80% (Figs. 3 and 8).

It is difficult to understand discrepancy of the inner gas pressure presented in Fig. 4 and Fig. 9. This discrepancy needs further investigation.

The gap size dependences presented in Fig. 5 and Fig. 10 indicate differences of fuel densification, relocation and swelling, especially at low and intermediate burnups, leading to different time of gap closure.

It should be very clearly and strongly emphasised, that all calculations performed by the TRANSURANUS code must be considered only as preliminary. The discrepancies between the TRANSURANUS and PIN-micro can be understood by difference of models and material properties.

The TRANSURANUS code has not yet been verified against VVER fuel rod experimental data and it needs a thoroughly verification. Nevertheless, the results obtained are physically quite reasonable and demonstrate the ability of the code to analyse the VVER fuel rod behaviour. The cases investigated do not yet need the use of the advanced capabilities of TRANSURANUS, compared with PIN-micro, to treat the fuel rod behaviour at fast transients and accidents, which may lead to PCI, cladding ballooning or rod failure.

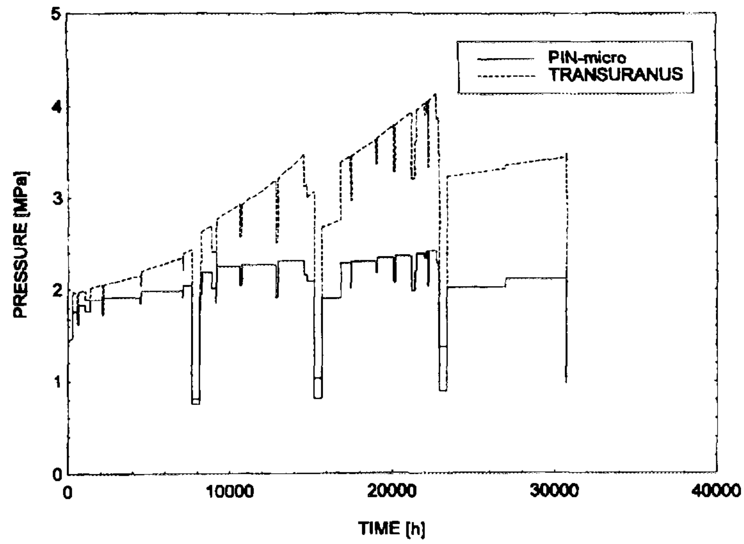

Figure 4 Inner gas pressure, FA1

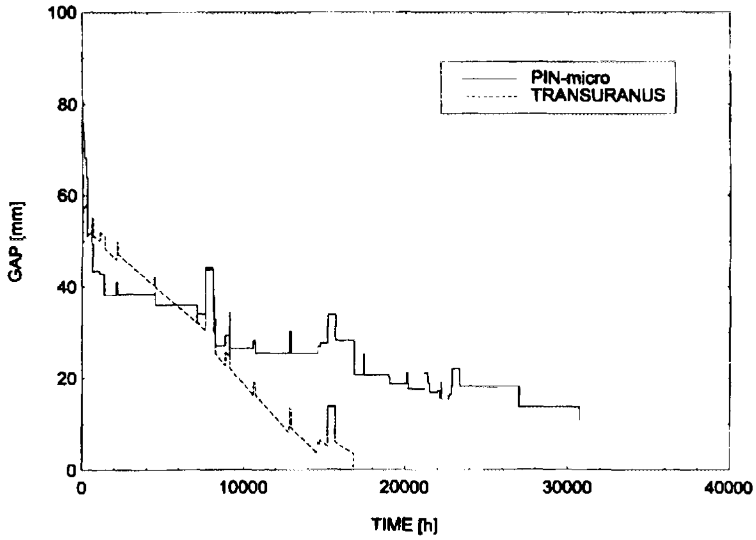

Figure 5 Gap size, FA1

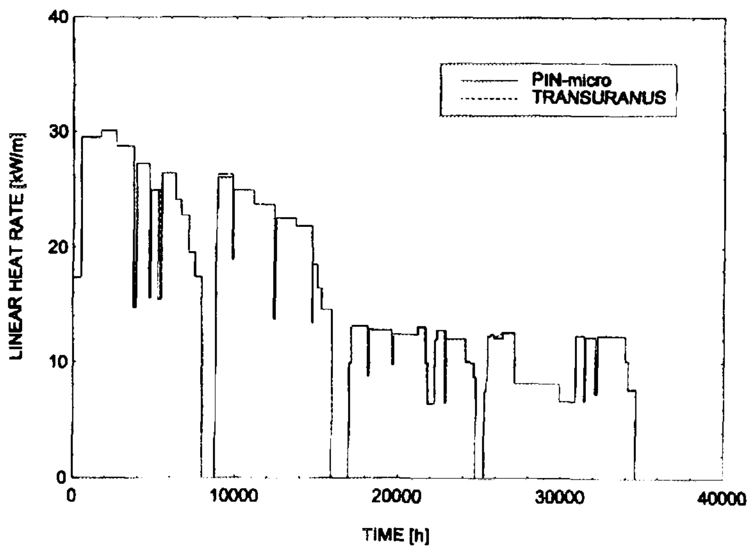

Figure 6 Local linear heat rate, FA2

5 Conclusions

The results presented allow to draw the following conclusions:

1. The PIN-micro code, as an accepted reference code for VVER fuel rod steady-state performance analysis, predicts adequately the thermal and mechanical behaviour of the two considered VVER fuel rods. Moreover, PIN-micro is restricted to be applied to transients and at extended burnups. In this very preliminary comparison between the PIN-micro and TRANSURANUS codes, the results obtained by PIN-micro have to be considered as reference ones.
2. This first and preliminary comparison of the calculated results obtained by PIN-micro and the TRANSURANUS codes shows reasonable agreement and the discrepancies can be explained by the lack of thoroughly VVER oriented verification of TRANSURANUS.
3. It might be expected that the advanced TRANSURANUS code could be successfully applied for VVER fuel rod thermal and mechanical analysis after incorporation of all necessary VVER specific properties and models for the Zr+1%Nb cladding, for the fuel and for the fuel rod as a whole and after validation against VVER experimental and operational data.

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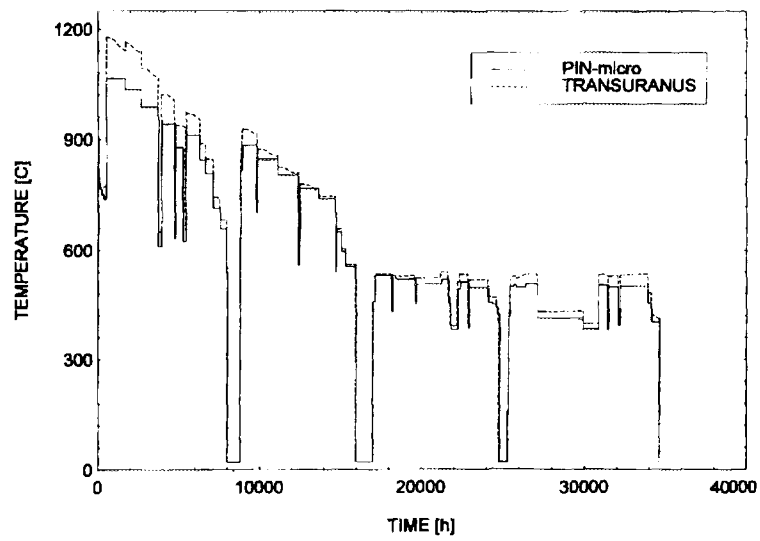

Figure 7 Fuel central temperature, FA2

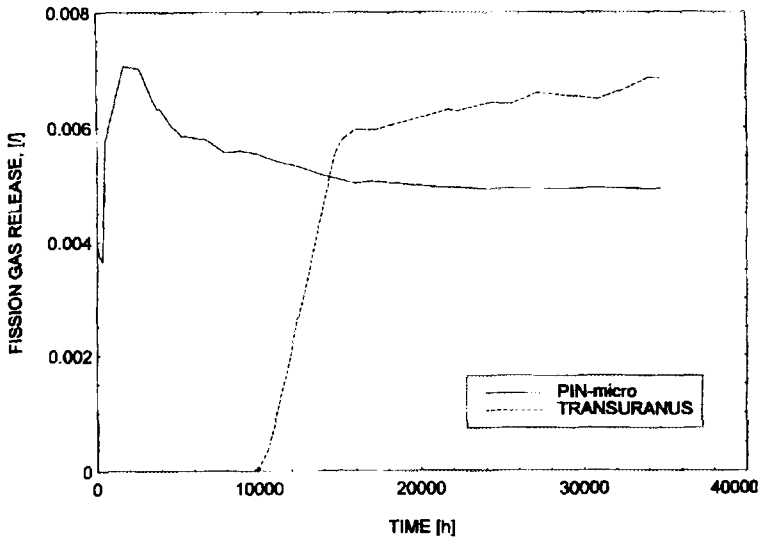

Figure 8 Fission gas release, FA2

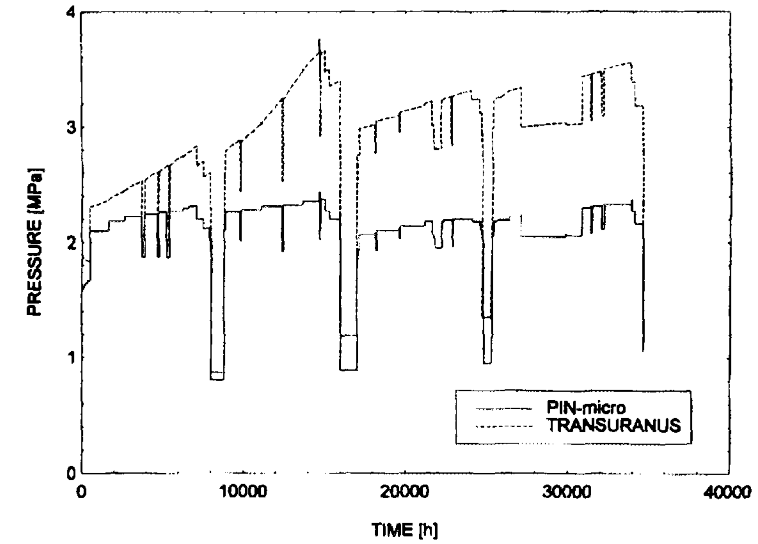

Figure 9 Inner gas pressure, FA2

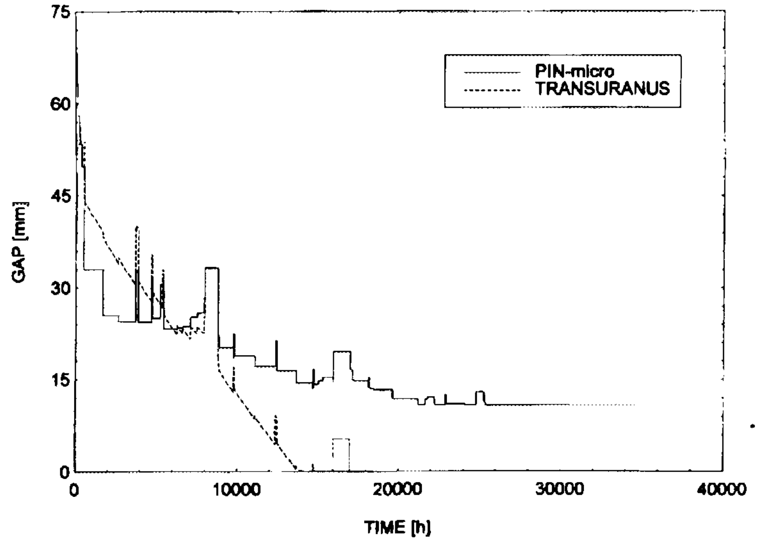

Figure 10 Gap size, FA2

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