COMPUTER MODELLING OF THE VVER FUEL ELEMENTS UNDER HIGH BURNUP CONDITIONS BY THE COMPUTER CODES PIN-W AND RODQ2D

M. VALACH, J. ZYMÁK, R. SVOBODA
Nuclear Research Institute Řež plc,
Řež, Czech Republic

Abstract

This paper presents the development status of the computer codes for the VVER fuel elements thermomechanical behaviour modelling under high burnup conditions at the Nuclear Research Institute Řež. The accent is given on the analysis of the results from the parametric calculations, performed by the programmes PIN-W and RODQ2D, rather than on their detailed theoretical description. Several new optional correlations for the UO2 thermal conductivity with degradation effect caused by burnup were implemented into the both codes. Examples of performed calculations document differences between previous and new versions of the both programmes. Some recommendations for the further development of the codes are given in conclusion.

1. INTRODUCTION

Development of the modernized computer codes, describing the thermomechanical behaviour of fuel elements during steady-state and transient operation of the VVER-440 type reactors, is supported by the ČEZ utility, NPP Dukovany and the Czech Nuclear Safety State Office. Process of safety upgrading and modernization of the originally designed Russian reactors and nuclear cores brings with also some important questions related to the fuel performance under higher burnup conditions. Discussion about introducing the 4 and 5 year reloading cycles for the VVER-440 reactors postulated also requirements connected with the fuel safety parameters (fuel centerline temperatures, fission gases release and inner pressure at EOL, etc.). The process of fuel vendors diversification for the Dukovany NPP (VVER-440) as well as for the Temelin NPP (VVER-1000) became a reality in the Czech Republic. Main reason for the innovation of the computer code PIN and development of a new code RODQ2D is the necessity to preserve the gained experience and to establish a national capacity for the independent safety assessments and evaluations of nuclear fuel behaviour.

2. BRIEF CHARACTERIZATION OF THE CODES

PIN computer code is based on the Gapcon-Thermal-2 methodology (Fig. 1). Physical models are based on semi-empirical approach and verified on the Russian experimental data. The code is able to predict the fuel temperature field, pellet-cladding gap thermal conductivity, fission gases release and internal rod pressure under steady-state conditions. The programme does not include any fuel cladding failure criterion. Main goal of its innovation is to expand the code capabilities for the standard PWR-type fuel rods. The PIN-W version includes the interactive screen graphic output of the main modelled parameters.

RODQ2D is originally based on the STOFFEL code, written by Reinfried (ZfK Rossendorf, Germany) in PLI language. The code was reprogrammed into Microsoft FORTRAN by B. Golomysov (IAE Moscow, Russia). In the frame of the NRI Řež and Kurchatov Institute cooperation the following changes were incorporated: the iteration scheme for the gap conductance calculation was changed to allow arbitrary gas composition, more time-effective method was used to compute fuel and cladding creep, the material properties library for the cladding material ZrlNb was included (Fig.2).

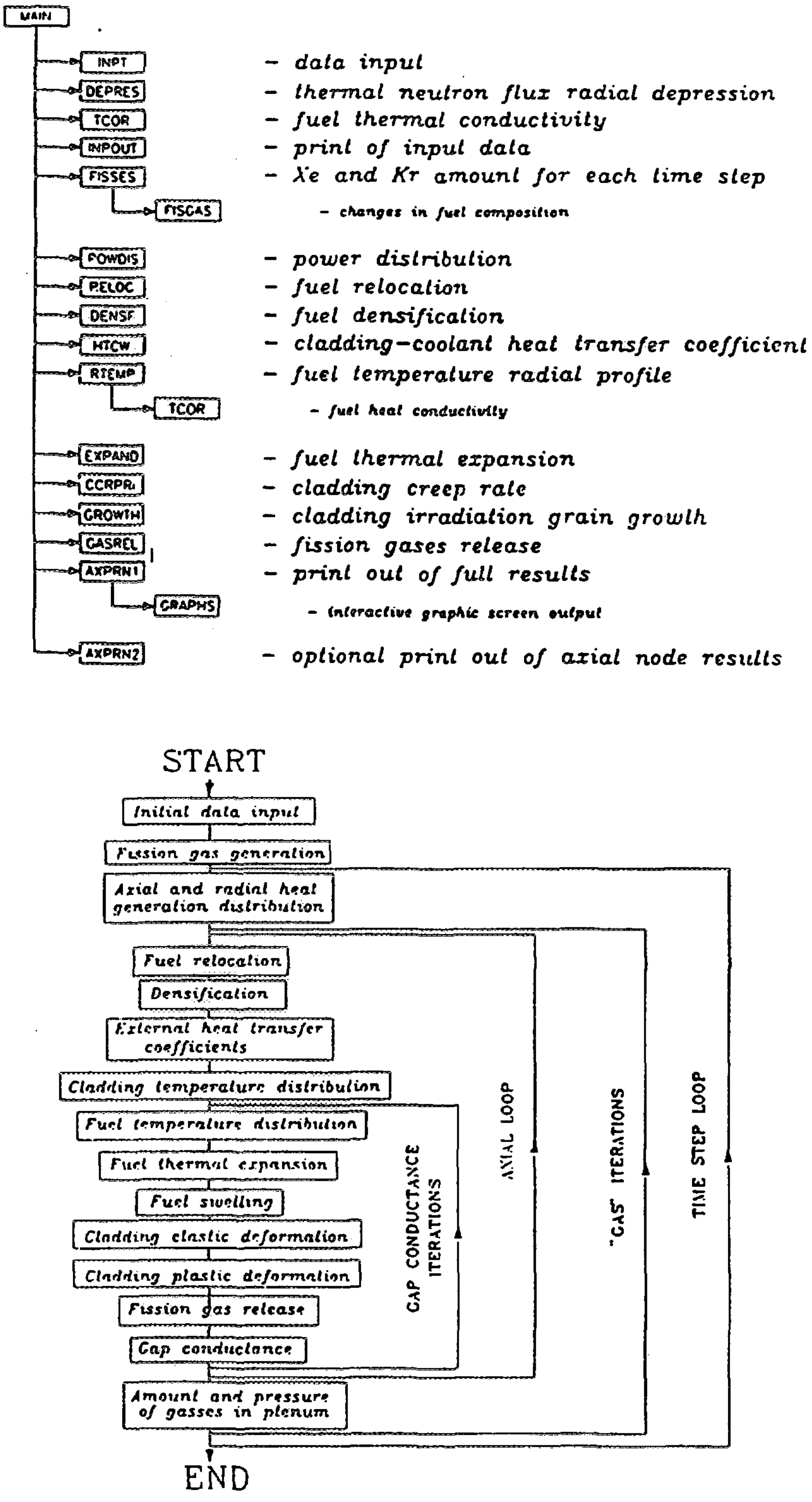
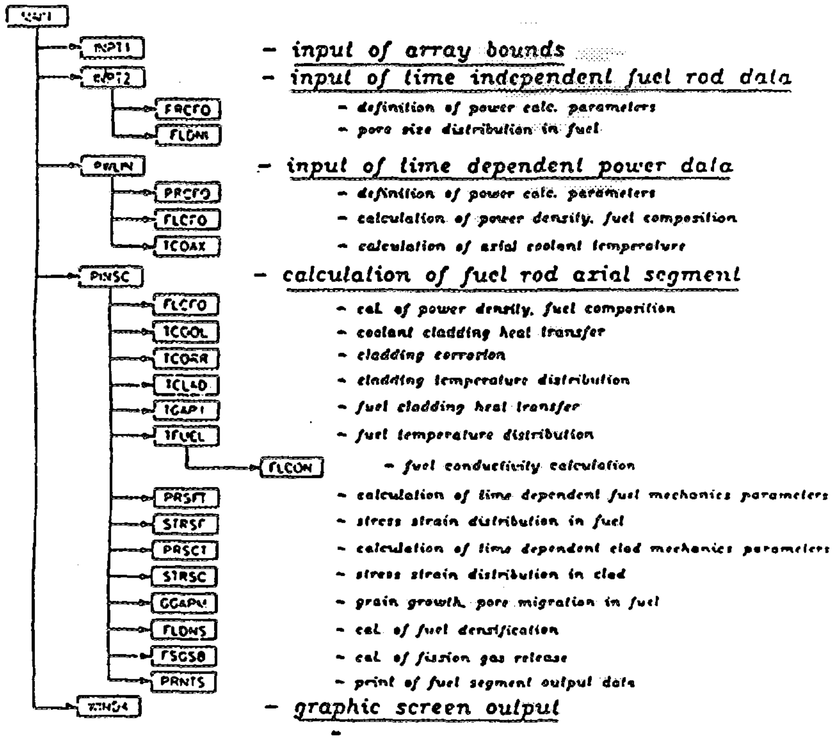


FIG. 1 *Structure of the code PIN-MICRO*
Flow chart of the code PIN-MICRO



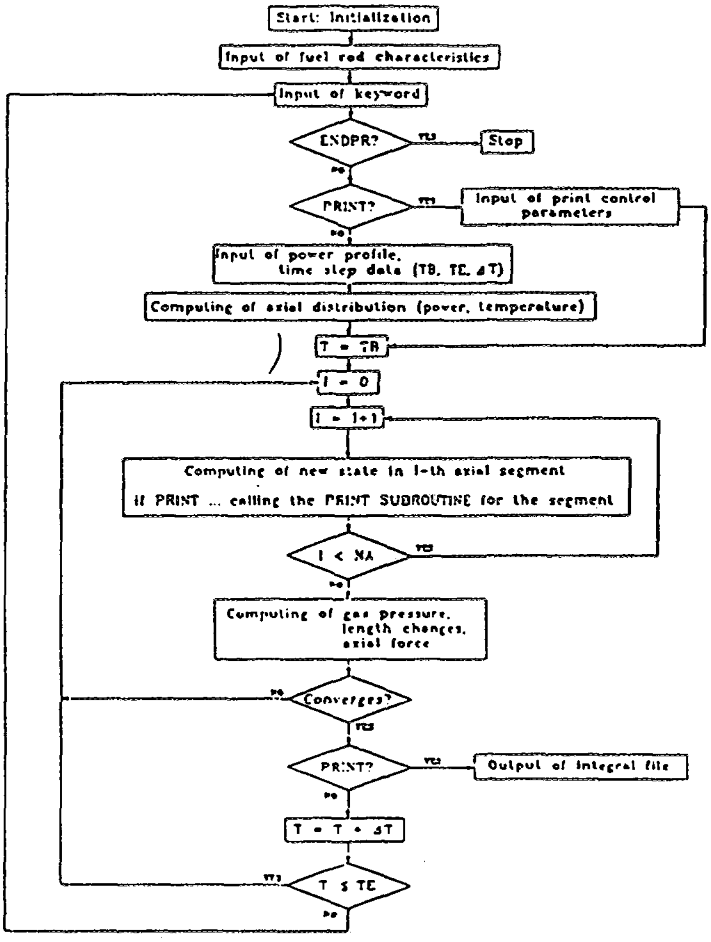


FIG. 2 *Structure of the code RODQ2D*
Flow chart of the code RODQ2D

The code belongs among the quasi two-dimensional integral codes. It is designed to predict the in-pile behaviour of a cylindrical water-cooled oxide fuel rod during quasistationary operation. The code enables also the calculation of power ramps with various ramp rates. Models for fission gas behaviour, densification and power density distribution are based on simplified mechanistic approach.

The numerical solution comprises geometrical nodalization into the axial and radial segments for using of finite differences method. The one-dimensional equation for radial heat conduction and Lame's equation for the strain-stress distribution are solved at each axial node. The coupled effects of the response parameters are treated by iterating to convergence at each power-time step. There are no restriction in the number of nodes or power-time steps.

During the last period of development the code was completely rewritten from the numerical, programming and physical point of view as well. In contradiction to the PIN-W, the RODQ2D is based on more "analytical approach", above all in the mechanical part. After finalization of this first version, more realistic modelling of gap changes during transients have to be the main attribute and advantage of the RODQ2D in comparison to the PIN-W possibilities.

The inner structure of the code is designed very flexibly (Fig. 2). The modern programming approach, based on Lahey FORTRAN, was used with some FORTRAN 90 features. The restart option and interactive graphic output is the standard feature of this version. The RODQ2D code was developed as a computer platform independent software. The transfer from the Lahey development environment (IBM-PC) to workstations with the UNIX and Windows NT was tested.

3. BASIS FOR THE PARAMETRIC CALCULATION

Participation of the NRI Řež plc in the OECD-HRP and in the IAEA FUMEX Blind problem strongly supports the process of the codes testing and validation. Open access to the unique experimental data-base of the OECD-HRP enabled preparation of the input data packages consistent for both codes.

3.1 DESCRIPTION OF THE EXPERIMENTAL DATA

The OECD-HRP Test Case (experiment IFA-432) and IAEA FUMEX exercise were found as a suitable data basis for the parametric simulations [1], [4], [5]. The IFA-432 can be characterized as a "high temperature experiment" with pronounced FGR (high level of linear power) and the FUMEX 1 exercise as a "low temperature experiment" with very long irradiation time and burnup related degradation effects. Calculations were performed by both codes from the beginning of this year. The submodels of relocation and fuel conductivity were modified for the codes tuning. The centerline fuel temperatures were used for the code to code and codes to the experiment comparison.

3.2 RELOCATION MODEL

The PIN-W empirical relocation model [6]:

$$\delta R = (A*(B/(1 + B) + C*P + 3)*G/100$$

where:

δR [inch] - fuel radius change, P [kW/ft] - linear power
G [inch] - fuel-cladding gap, $B = \exp(-4*Bu^{0.25})$
Bu - burnup, A and C - parameters.

Model can be used in the conservative or best-estimate version.

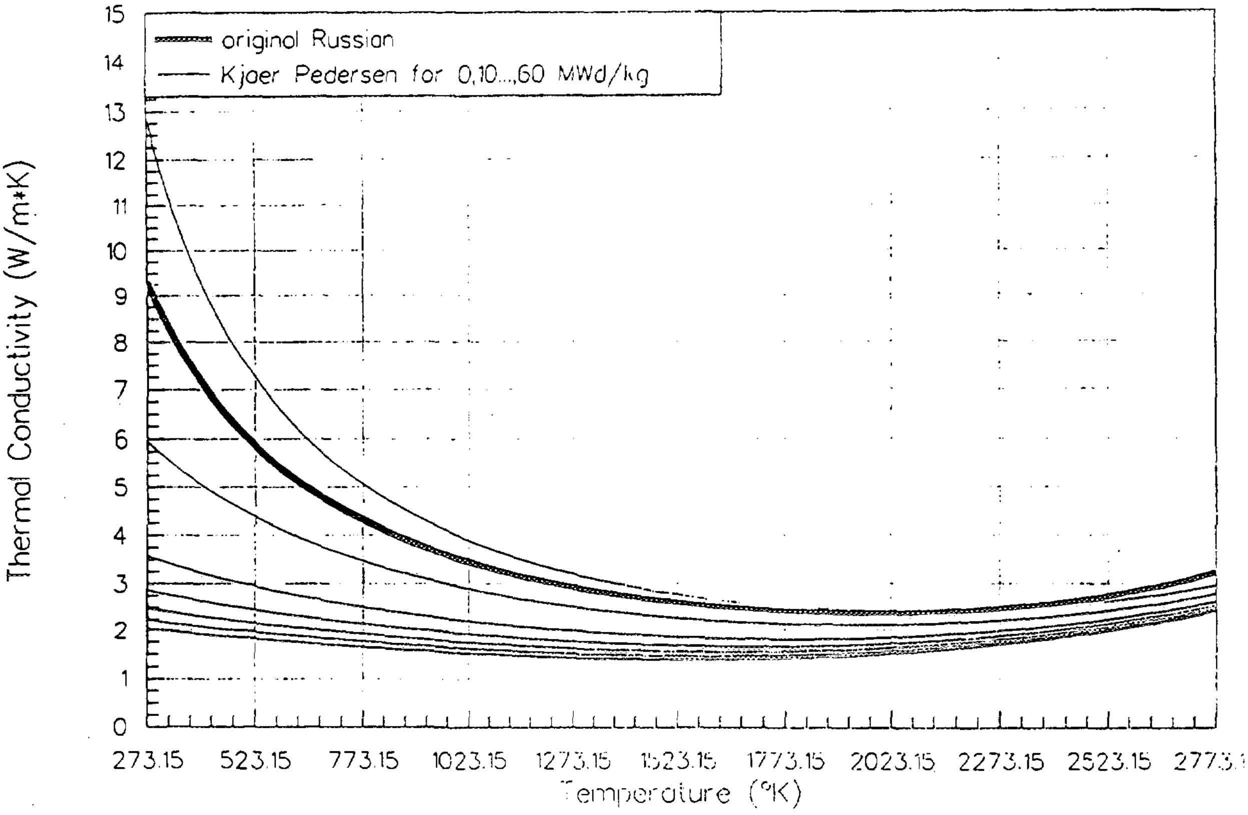


FIG. 3 *Thermal conductivity* UO_2

3.3 FUEL THERMAL CONDUCTIVITY MODELS (FIG.3)

Original Russian model [6]:

K = 1./(A*T+B) + C*T + D*T^3 *exp(E*T)

where:

K [W/cm/K] - thermal conductivity
T [K] - fuel temperature, A, B, C, D, E - parameters.

HRP Vitanza-Kosaka model [3]:

K = 1 / (A + B*T + (C*Bu - D*B^2)) + E*T^3

where:

K [kW/m/°C] - thermal conductivity
T [°C] - fuel temperature, Bu [MWd/kg] - fuel burnup
A, B, C, D, E - parameters.

Kjaer-Pedersen model [2]:

$$K = 93 / (0.0224*T + 1.1 + 56*P + 3*F(Bu)) + 2.5*10^{-14}*T^4$$

where:

K [W/m/K] - thermal conductivity, T [K] - fuel temperature
Bu [MWd/kg] - fuel burnup, P [1] - fuel porosity
for $Bu <= 10$ MWd/kg $F(Bu) = (Bu/10)^2$
for $Bu > 10$ MWd/kg $F(Bu) = ((Bu - 7.5) / 10)^{0.5}$

4. CALCULATIONS

Calculations were performed at the NRI on the PC-486/66 MHz computers. Both codes used the same geometry nodalization. IFA-432 experiments were modelled by 10 axial and 20 radial segments. The CPU time for the PIN-W code was around 55 s and for the RODQ2D code up to 240 s. The FUMEX test cases were modelled by 8 axial and 20 radial segments. The PIN-W code consumed 1100 s of CPU time and RODQ2D 1300 s for one test run.

4.1 MATRIX OF CALCULATIONS

conductivity		relocation
Russian	PIN-W	original Russian conservative
Russian		hrp '93, coefficient C changed
Kjaer Pedersen		hrp '94, coefficient A changed
Russian	ROD-Q2D	no relocation
Russian		original Russian conservative
Russian		hrp '93, coefficient C changed
Kjaer Pedersen		no relocation
Kjaer Pedersen		original Russian conservative
Kjaer Pedersen		hrp '93, coefficient C changed

4.2 SUMMARY OF THE RESULTS

The calculation variants A2 and Al represent the IFA-432 rod No_1 and No_3 respectively. Fuel centerline temperature measurements for both rods and internal pressure for the A2 case were available [1], [6].

Fig. 4 shows IFA-432.1 recalculation by the PIN-W, Fig. 5 shows comparison against experimental data, Fig. 6 and 7 show results of the RODQ2D.

Fig. 8 and Fig. 9 include results of both codes for FUMEX-1. Two representative cases with the combination of the relocation and fuel conductivity models are presented. Both codes were relatively stable during calculations with different models.

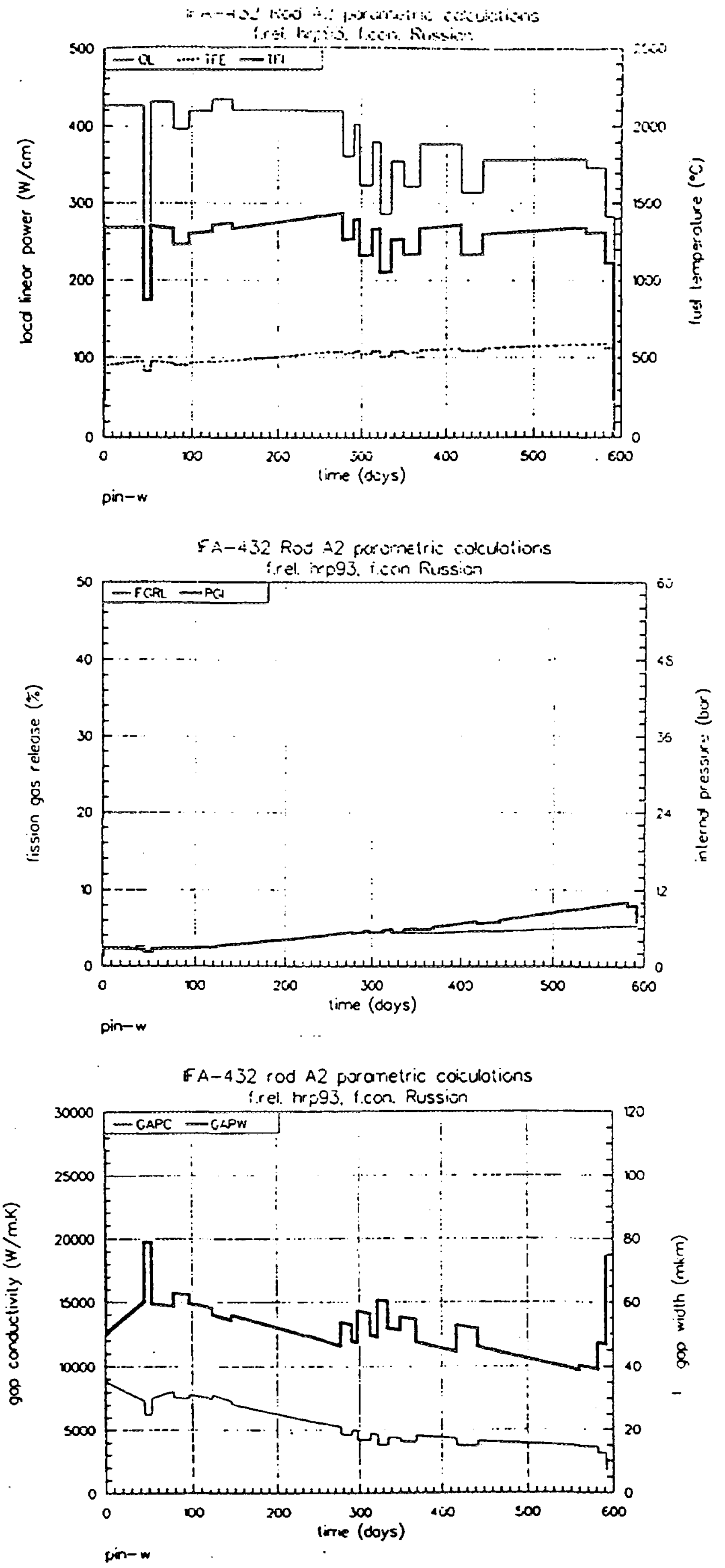
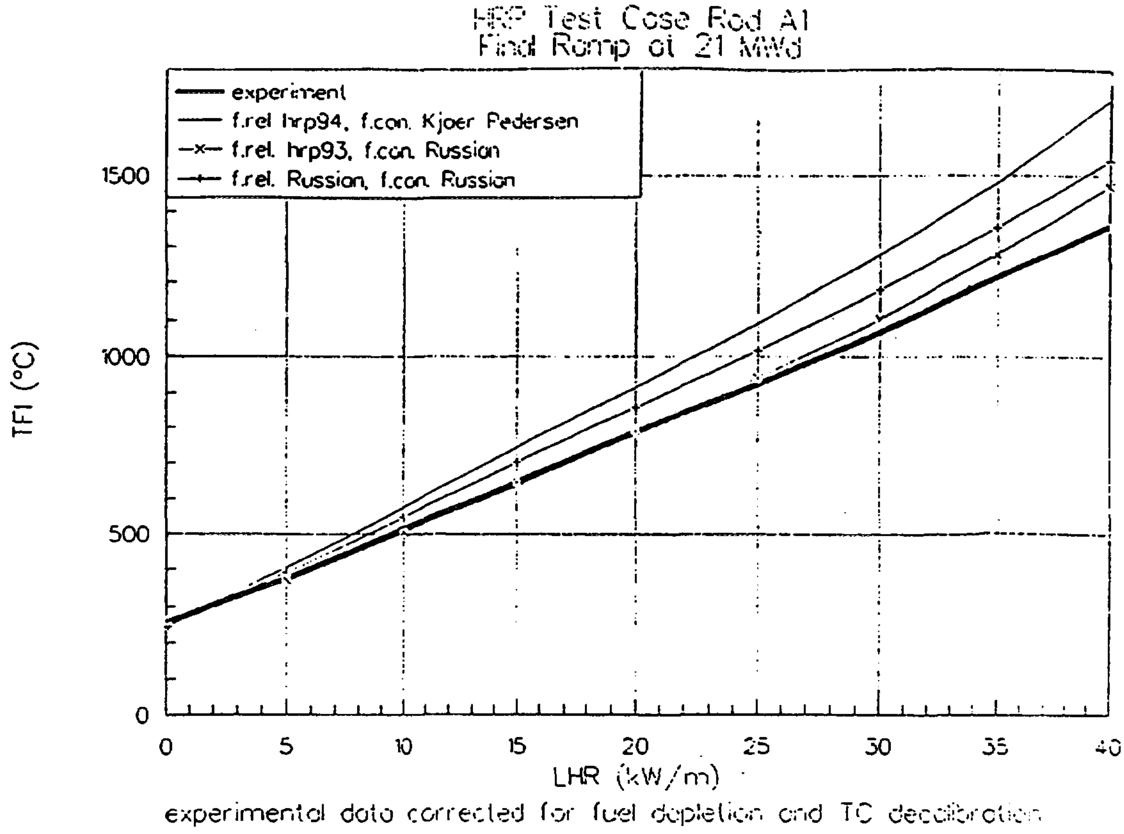


FIG. 4 *IF-432 rod A2 parametric calculations*


HRP Test Case Rod A1
Final Ramp at 21 MWd

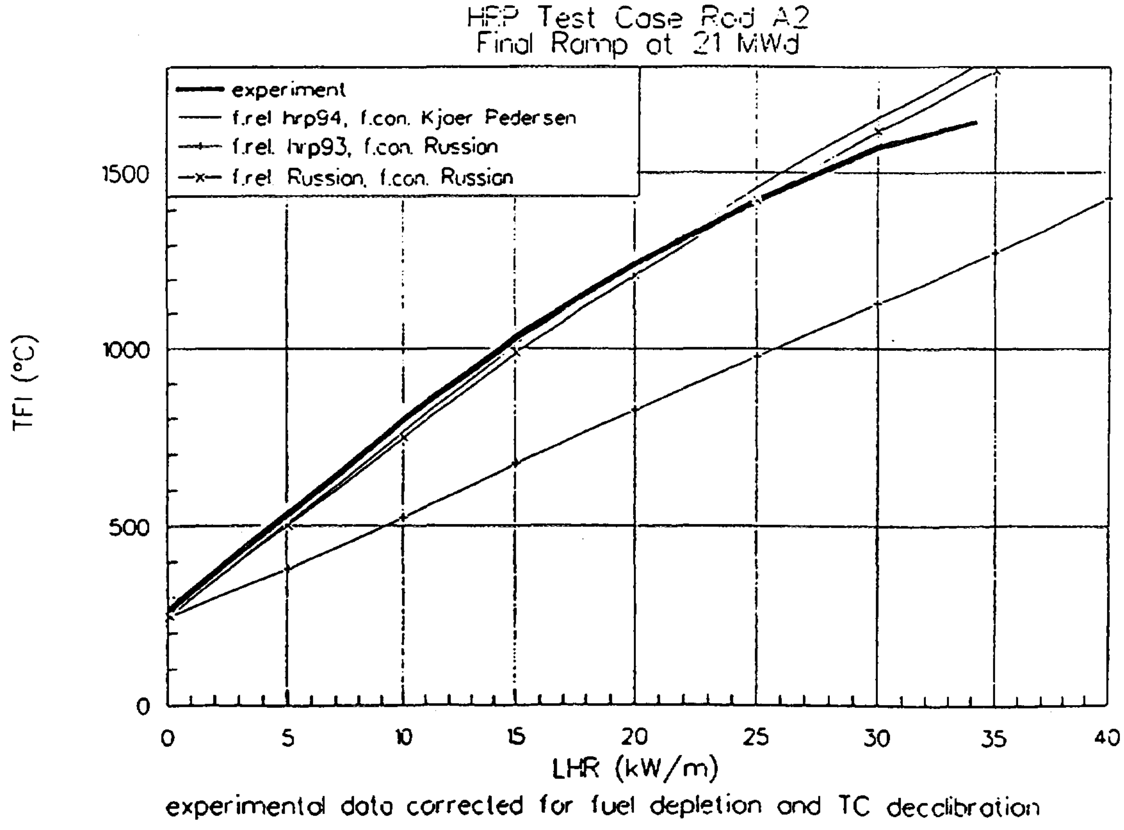

HRP Test Case Rod A2
Final Ramp at 21 MWd

FIG. 5 HRP Test Case Rod A2 - Final ramp at 21 MWd

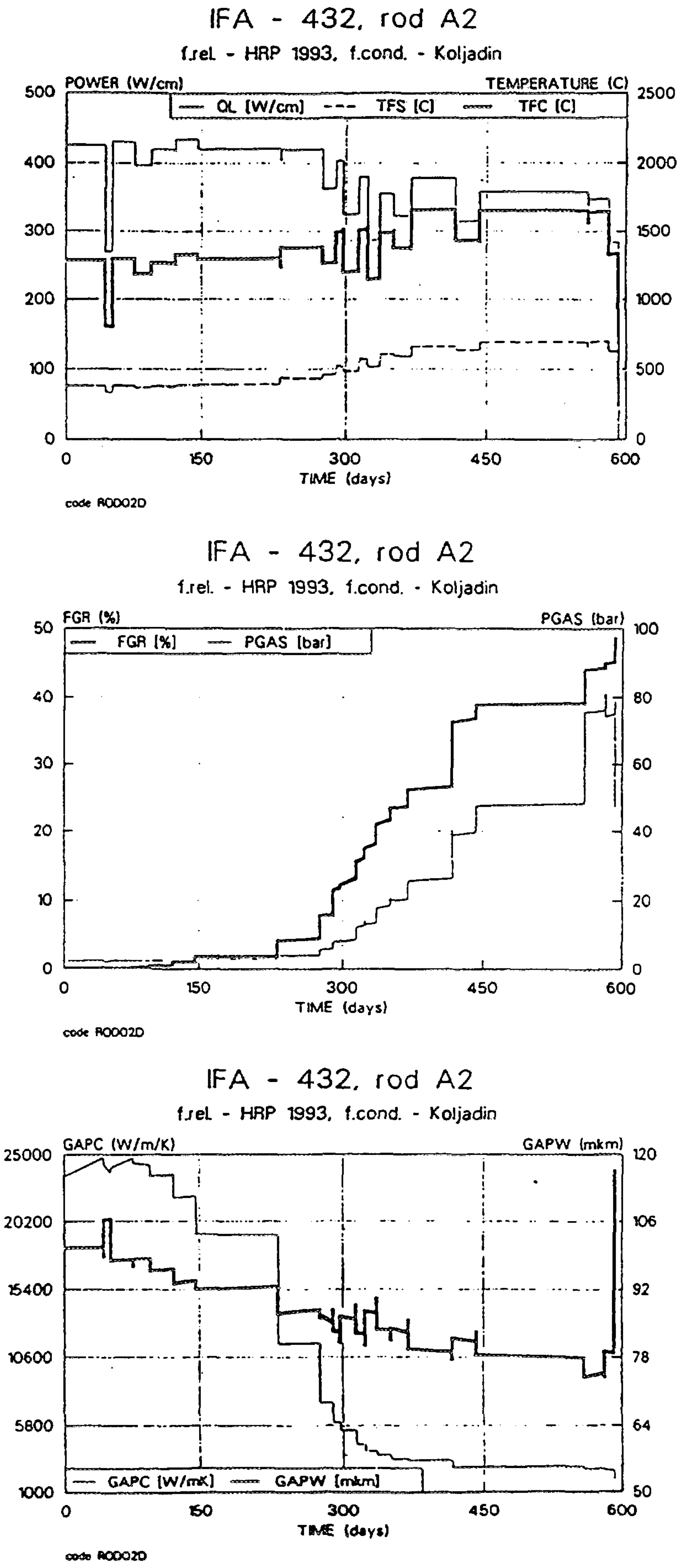


FIG. 6 IFA-432 rod A2

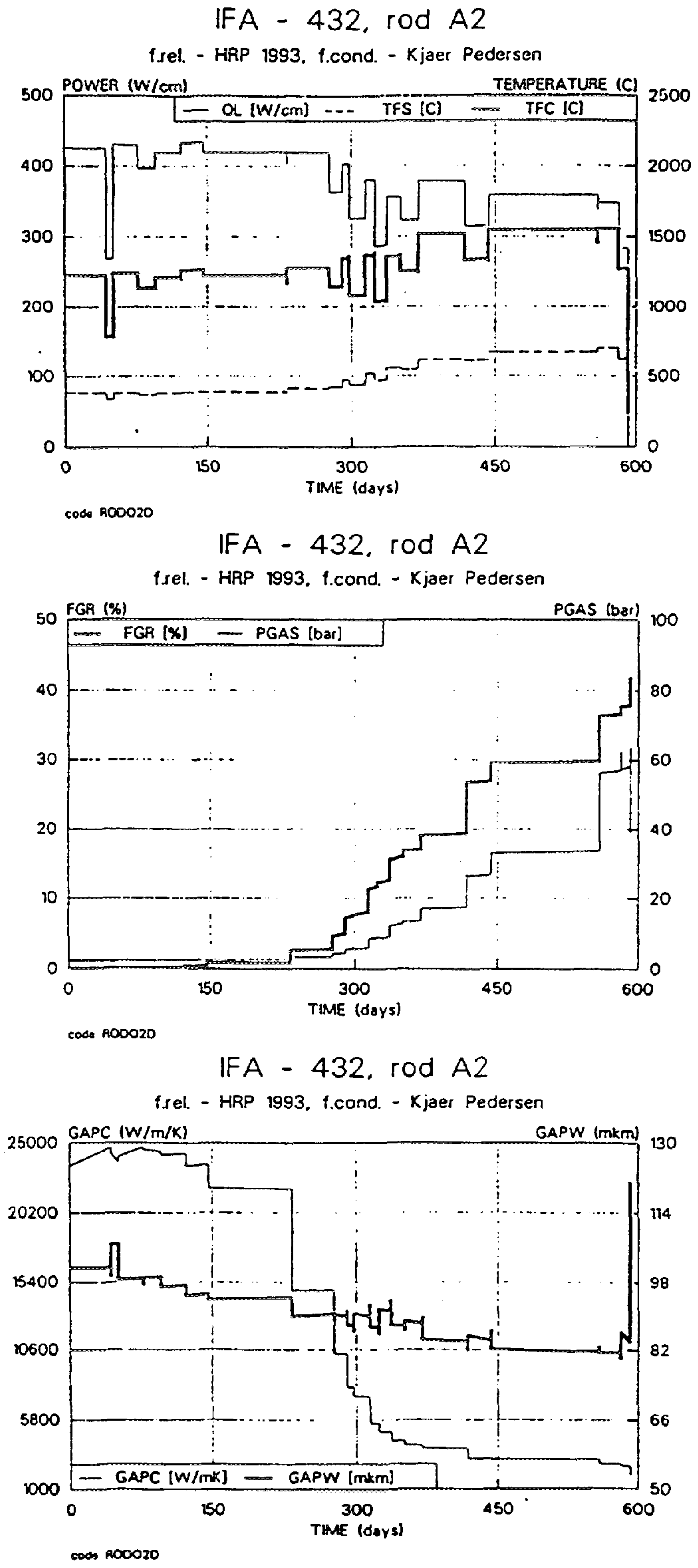


FIG. 7 *IFA-432 rod A2*

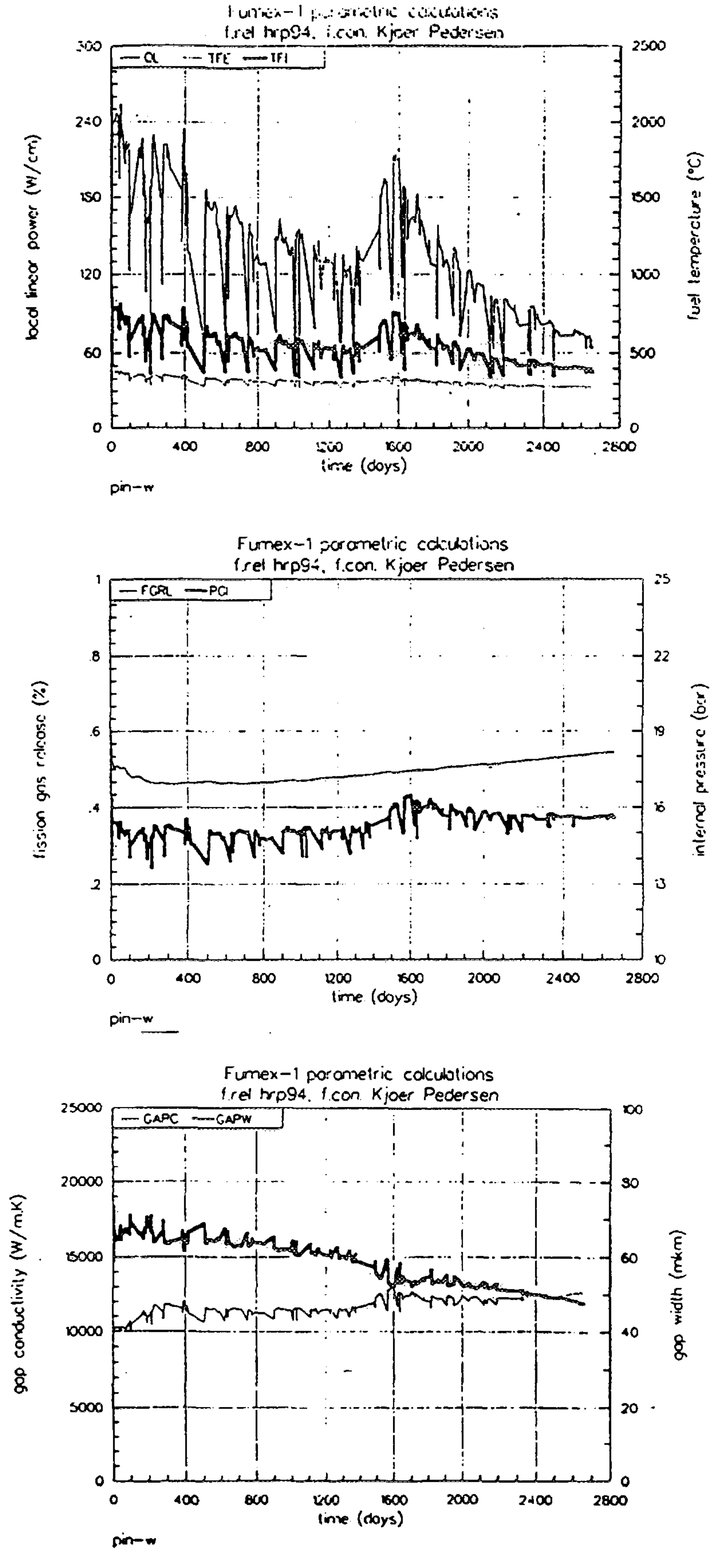


FIG. 8 Fumex-1 Parametric calculations

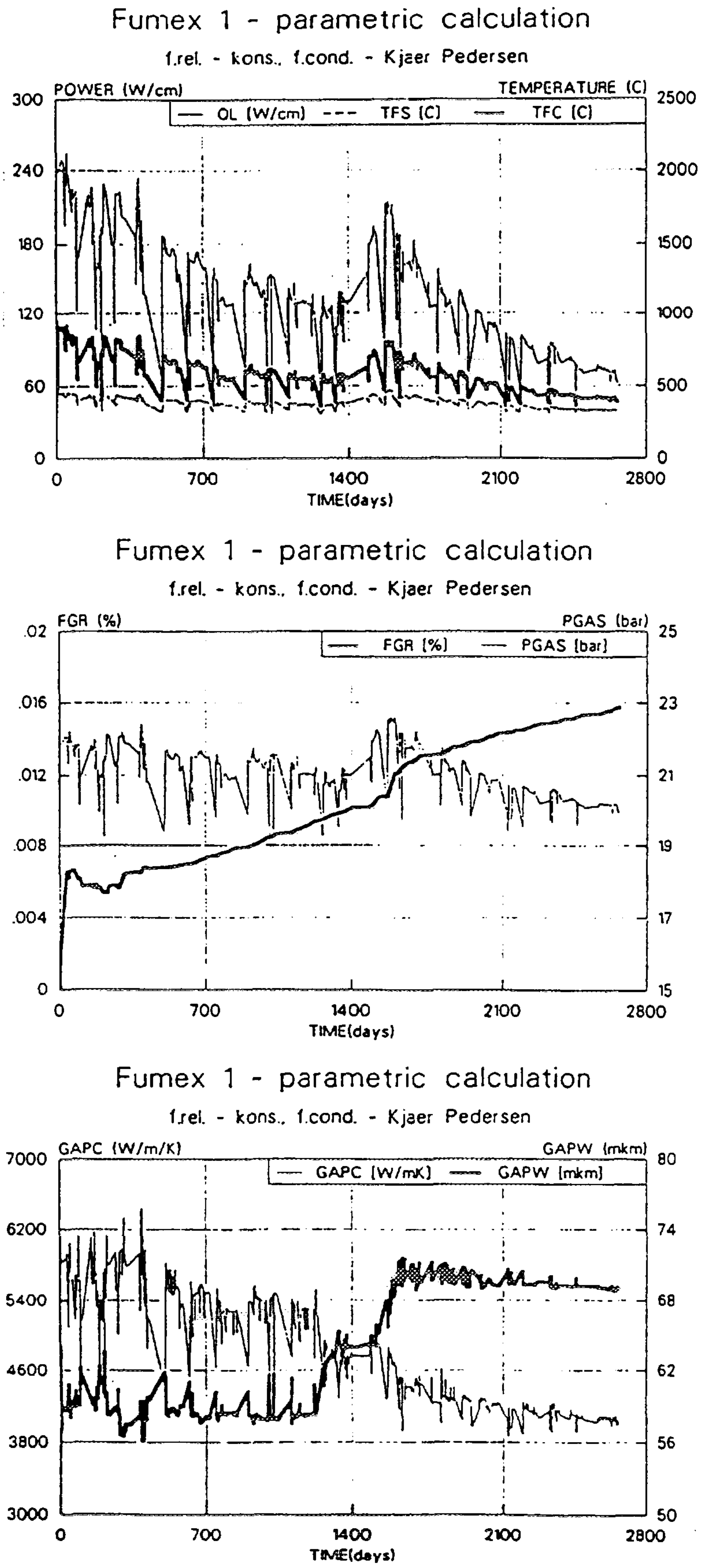


FIG. 9 *Fumex-1 Parametric calculations*

5. DISCUSSION

During the tuning of the relocation model on the IFA-432 rod A1 (small gap) and A2 (large gap) better confidence level for A2 case was obtained (Fig.5). Differences between PIN-W and RODQ2D in centerline temperature are probably caused by the extensive fission gas release in RODQ2D. Fig. 6 and 7 document small influence of the conductivity degradation during this low burnup and high power experiment.

The FUMEX-1 has relatively low measured temperatures. There are no significant differences between codes predictions, except much smaller fission gas release in the RODQ2D (Fig.8 and 9). The FGR predicted in this case by both codes were strongly underpredicted against the experimental value. This is probably caused by the inadequacy of the low-temperature FGR model or by the specific HBWR irradiation history.

6. CONCLUSION

The results of performed parametric calculations indicate, that the innovation of the fuel conductivity and fuel relocation models is not sufficient to reach satisfactory predictions of the codes. Nevertheless the centerline temperatures in best-estimate variants agrees with experimental results, the fission gases release is underpredicted. Correct prediction of the high burnup experiments by the codes PIN-W and RODQ2D (e.g. FUMEX 1) needs more realistic modelling of the fission gas release in the low temperature region, taking into the account other coupled effects (swelling, rim effect, fuel cracking, etc).

REFERENCES

[1] Reactor Fuel Performance Modelling Workshop, Vaaksy, Finland 14-19 June, 1982. OECD-HRP, January 1983, HWR 81.

[2] KJAER-PEDERSEN, N: Rim Effect Observations from the Third Ris Fission Gas Project. Fission Gas Release and Fuel Rod Chemistry Related to Extended Burnup. IAEA, April 1993, IAEA-TECDOC-697.

[3] KOSAKA, Y.: Thermal Conductivity Degradation Analysis of the Ultra High Burnup Experiment (IFA-562). OECD-HRP, February 1993, HWR-341.

[4] VALACH,M., SVOBODA, R., ZYMÁK, J.: Presentation of work performed in the frame of research agreement No.7344/CF between IAEA and NRI Řež plc. as a part of IAEA FUMEX coordinated programme. ÚJV-9990 T, 1st RCM on FUMEX, Halden, Norway, 28th June to 1st July 1993.

[5] VALACH,M., SVOBODA, R., ZYMÁK, J.: The first year's experience of the NRI cooperation with the OECD-HRP in the High Burn-up Fuel Performance, ÚJV-9884 T,M, March 1993.

[6] PAZDERA,F.,STRIJOV, P.,VALACH, M., et al.: User's Guide for the Computer Code PIN-micro, ÚJV 9517-T, Řež, November 1991.