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Modelling of VVER-1000 Fuel: State and Prospects

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1 Introduction

Significant experience of the VVER-1000 fuel operation indicative about high reliability of fuel elements is at present accumulated. In the last years the level of fuel failures on Russian NPP units does not exceed $(1.5 - 2.0)\cdot 10^{-5}$. Post irradiation examination of the fuel pins operated up to design burnup have confirmed their good condition without any attributes, capable to limit their further operation.

This result permits to consider a question on further increase of fuel burnup.

The fuel reliability is provided with the project of an active core, perfection of a design and fabrication technology of fuel pin. The important role in maintenance of necessary reliability of fuel belongs to computer methods of modeling of fuel pin behavior in real conditions of operation.

Code START-3, with application of which fuel pin VVER-1000 are developed is based on representative volume of experimental data on study of material properties, processes, post irradiation examination of experimental and standard fuel pins.

At the stage of verification and correction in accounts are used characterized parameters of experiments. In design work the reasonable conservative approach, assuring the satisfaction to design limits with necessary margins is applied.

2 VVER-1000 Fuel Pin

The main features of a design of a fuel pin VVER-1000 are stipulated by application of alloy Zr-1%Nb for cladding, pellets with a central hole and flat end faces, availability sufficiently large plenum.

The fuel is operated in 3-year cycle with average burnup of unloaded assemblies of 43 *MWd/kgU.*

Post irradiation examination have shown following results on a condition of fuel pins.

Corrosion of cladding

The oxide film thickness on the external surface does not exceed 4 - 8 μm and does not grow with burnup. It weakly changes on a length of a fuel pin (gain on 1 - 2 μm from a bottom to a top).

On an internal surface there are only local sites with thickness not more than 10 μm.

Cladding hydriding

There are insignificant quantity of hydrides with random or tangential orientation. The content of hydrogen does not exceed $(5 - 6)\cdot 10^{-3}$%.

Mechanical properties of a cladding

It is observed an usual radiating hardening, which does not hereinafter depend on burnup. Uniform and general lengthening is not less than 4 and 15 % accordingly.

Cladding deformation

The elongation of fuel pin linearly depends on burnup and does not exceed 0.37%.

The reduction of a diameter depends on burnup and at ~ 45 *MWd/kgU* approaches ~ 1%.

Fuel pellets

The axial gaps in a fuel column are away. The fuel structure corresponds to initial one. It is observed a usual cracking pellet picture. Swelling is less than 3%.

Fission gas release

Fission gas release as an average one in assembly makes 0.7 - 3% up to burnup of ~ 47 *MWd/kgU.*

The examination results testify to a good condition of fuel pins down to maximum design burnup, that is confirmed by experience of operation. The level of refusals of fuel pins does not at present exceed $(1.5 - 2)\cdot 10^{-5}$.

Characteristics of VVER-1000 fuel pin

Cladding	
Material	Alloy Zr-1%Nb
Outside diameter, *mm*	9.1
Internal diameter, *mm*	7.72
Fuel pellet	
Outside diameter, *mm*	7.57
Internal diameter, *mm*	2.4
Enrichment, %	3.6 - 4.4
Density, g/cm^3	10.4-10.7
Fuel pin	
Length, *mm*	3837
Length of a fuel column, *mm*	3530
Helium pressure, *MPa*	2

3 Code START-3

The models, used in the code, are based on experimental study of material properties, processes, post irradiation researches of experimental and standard fuel pins. They include such labor-consuming works, as in-pile research:

- non-steady creep of zirconium claddings,
- fuel creep,
- irradiation fuel densification.

The code includes following main selections:

- thermo-hydraulic account,
- thermo-physical account,
- mechanical account.

Table 1 Parameters of experimental VVER-1000 fuel pins and measured gas release levels

Pin No.	Irradiation time	Gap size	Average fuel density	Burnup, *MWd/kgU*		Gas release	Maximum of heat rate
	h	*mm*	*g/cm³*	Average	Max	%	*W/cm*
1 2	9091	0.19 - 0.32	10.55 10.60	27.32 28.53	32.57 36.23	30 46	400/250 450/280
3 4	10799	0.19 - 0.32	10.53 10.53	33.5 28.6	45.3 40.0	58 45	460/397 407/350
5 6	18288	0.19 - 0.32	10.65 10.64	37.6 52.76	49.63 71.23	16 54	300/210 435/305

The results of thermo-hydraulic calculations are temperatures of an outside surface of a cladding, which are boundary conditions for determination of temperature fields in a fuel pin.

In thermo-physical accounts are defined:

- non-stationery temperature fields in sections of a fuel pin,
- gas composition and pressure inside a fuel pin,
- swelling and irradiation densification of a fuel.

Taking into account:

- cracking and radial moving of pellet fragments,
- pellet restructure (growth of columnar and equiaxial grains),
- fuel conductivity degradation in dependence on burnup,
- non-uniformity of burnup and heat rating on pellet radius, owing to Pu building and availability of an integrated absorber,
- zirconium cladding oxidation.

As a result of mechanical account the fields of stresses and deformations in a fuel and cladding are defined. Also the degree of cladding damage is estimated in the form of an accumulated depth of stress corrosion crack.

Taking into account:

- thermal, elastic, plastic, creep deformations, volume changes, irradiation growth;
- pellet cracking and healing.

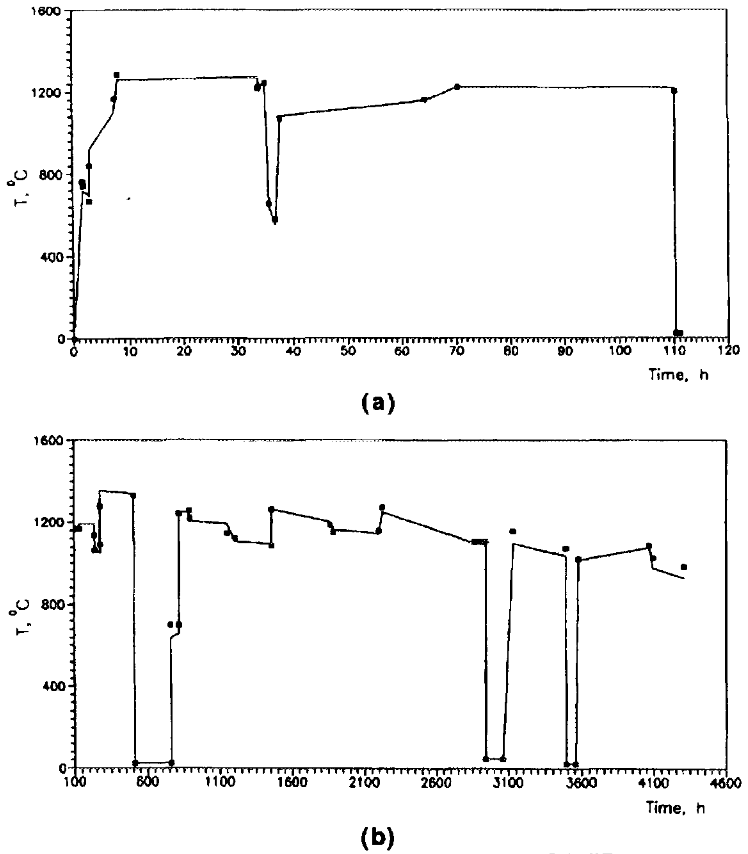
Whole fuel pin is divided into sites in a longitudinal direction (up to 30 and more). The load history is described by parameters in a given set of basic points, between which parameters linearly approximated. The quantity of basic points is not limited and in practice is limited only to acceptable time of the account. The code is used on computers PC 385, 486, 586 and includes ~ 5600 lines.

4 Accounts of Standard and Experimental Fuel Pins

The code capability was checked up by comparison with experimental evidence on standard and experimental fuel pins. Some results of check on a domestic data are here indicated.

For check and updating of temperature accounts were used. In particular, results of Russia-Finland experiment SOFIT on test rods of type VVER, equipped with thermocouples.

The accounts have confirmed a possibility of good enough forecasting with the help of a code START-3 of temperature fields in a fuel pin. As an example on Fig. 1 the comparison of calculated and measured fuel center temperatures in the rod No. 3 irradiated up to the average burnup of 8.8 *MWd/kgU*.



(a)

(b)

Figure 1 Fuel center temperature (fuel rod 3 SOFIT): calculation (cont. line) and experimental data

Fission gas release was considered in a wide range of magnitudes: from low sizes, characterized for a standard fuel VVER-1000 up to high significance's, achieved in experimental fuel pins, irradiated in reactor MR.

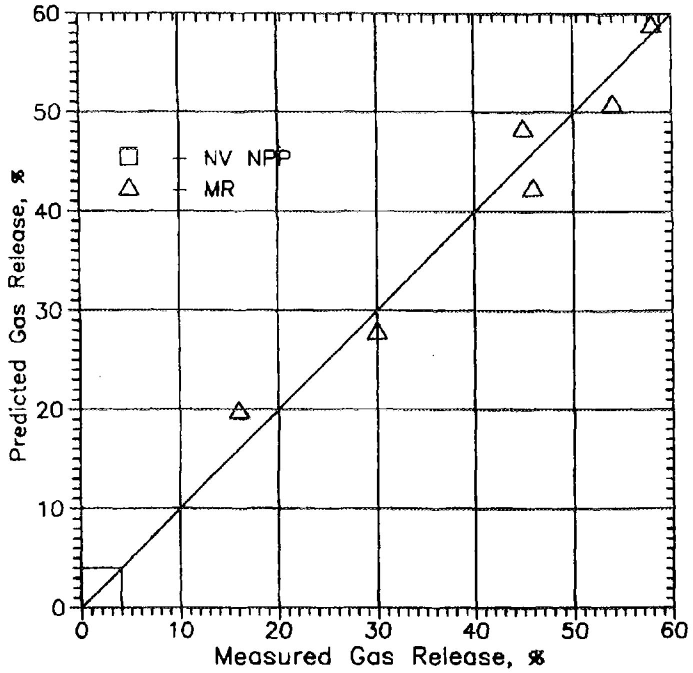


Figure 2 Comparison of predicted and measured gas release

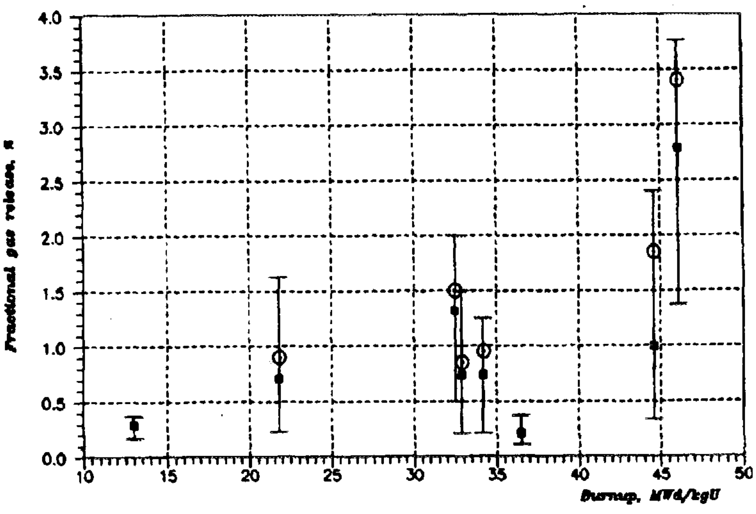


Figure 3 Gas release vs. burnup for VVER-1000 fuel

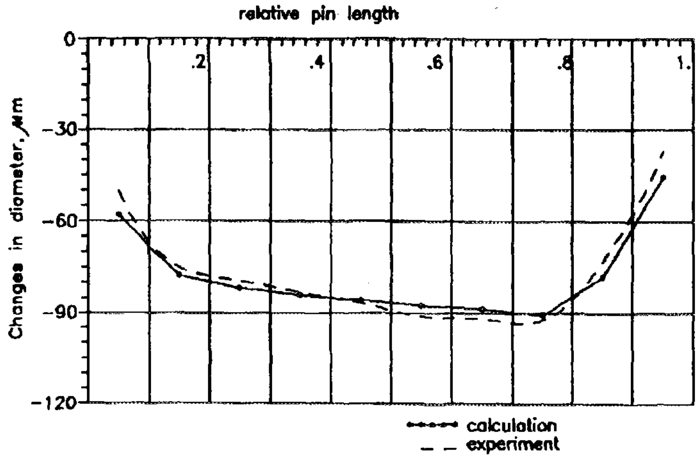


Figure 4 Changes in fuel pin outer diameter at the end of campaing

In Table 1 the characteristics of experiment in MR are indicated and on Fig. 2 the comparison of calculated and measured FGR is shown.

The fuel VVER-1000 is characterized relatively small FGR as it is shown on Fig. 3. Appreciable spread given for fuel pins within the assembly is thus observed.

On this picture the accounted significance's are shown two. As it is visible, the calculated significance's are within the limits of natural spread of the data.

In design works, that VNIINM conducts on development and substantiation of fuel VVER-1000 with the use of code START-3 the calculations are carried out for parameters, ensuring forecasted FGR at a level not below maximally observable significance's. It guarantees unconditional fulfillment of the requirements on design limits and margins.

For maximum accounted design parameters given with certain margins the calculated evaluations show that FGR in a fuel pin during 3 year campaign does not exceed 12%, gas pressure less than 1.1 *MPa*.

As it is visible for a design of a fuel pin VVER-1000 fission gas release is not the restrictive factor for achievement extended burnup.

On Fig. 4 the estimated and measured change of fuel pin diameter for standard assembly VVER-1000 after burnup of 44.7 *MWd/kgU* is shown.

Over the set of accounted and experimental data it is possible confidently to conclude that the fuel pin has sufficient margins of serviceability, capable to provide the further increase of design burnup of fuel VVER-1000.

As it is shown the code START-3 reasonably good forecasts behavior of fuel pins VVER-1000 in normal operation conditions. Certain confirmation of capability of the code are also results of accounts of the experiments within the framework of the program FUMEX (see Table 2).

Conducted at the first stage of our work the accounts of cases 1, 2 and 5 have shown reasonable conformity with experimental data and results of other codes. At the same time the analysis of results has shown that at preparation of a code for given

Table 2 Participants in FUMEX Blind Problem

N	Country	Organization	Code
	Norway/OECD	Halden	Experiment
1	Argentina	CNEN	BACO
2	Bulgaria	INRNE	PIN Micro
3	Canada	AECL	ELESIM.MOD11
4	Finland	VTT	Enigma 5.8f
5	France	EdF	TRANSURANUS EdF 1.01
6	France	CEA/DRN	METEOR - TRANSURANUS
7	CEC	ITU	TRANSURANUS
8	India	BARC	PROFESS
9	India	NPC	FUDA
10	India	BARC	FAIR
11	Japan	NNFD	TRUST 1b
12	Japan	CRIEPI	EIMUS
13	China	CIAE	FRAPCON-2
14	Romania	INR	ROFEM-1B
15	Swiss	PSI	TRANSURANUS -PSI
16	Czech Rep.	NRI Rez	PIN/W
17	UK	BNFL	ENIGMA 5.2
18	UK	NE	ENIGMA 5.8D
19	Russia	IIM	START 3

accounts some discrepancies were allowed. After corresponding corrections the more precise results for specified cases were received and the calculation of other rods were fulfilled.

Number of these results are presented on Figures 5 - 17 in comparison with experimental data and results of other codes.

It is possible to note their reasonable conformity. At the same time, submitted by Halden project the very detailed experimental data present the good basis for further improvement of a code. Such work is scheduled within the framework of the program FUMEX.

5 Prospects of VVER-1000 Fuel Modelling

The majority of codes created at present reasonably simulate a fuel behavior at design burnup, that is confirmed by results of accounts, executed by the participants in the program FUMEX.

At the same time, the planned increase of fuel design burnup puts additional problems before the developers of the codes. The decision then is connected with calculating and experimental researchers on such directions, as:

- refinement of FGR models under extended burnup;
- fuel pin behavior in maneuver mode of operation at increased burnup;
- fuel conductivity degradation under burnup taking into account the complex enough nature of this phenomenon;
- the features of fuel pin behavior in conditions of dense contact between pellet and cladding, including heat transfer and mechanical interaction;
- development of secondary defects in leak fuel pin;
- study of formation process and properties of external porous pellet rim concerning to its influence on fuel temperatures and FGR.

This rim occurs in a zone increased local burnup on pellet external edge, which is stipulated by plutonium formation there. On Fig. 18 the calculating radial distributions in the pellet of fuel pin VVER-1000 are shown at various average burnups. As it is visible the non-uniformity is increased with burnup growth and together with them a layer with increased local burnup is enlarged. The structure changes and the possible significance's of thickness of this layer are that the necessity of the account of this phenomenon at fuel modeling is obvious.

The results of mentioned above works will be used for further improvement of code START.

6 Conclusion

The comparison of calculated and experimental data shows ability enough of the code START-3 to simulate a fuel pin behavior in normal operation conditions.

The calculations confirm the experimentally observed evidence of an essential margin on serviceability of fuel pin VVER-1000 with three year operation cycle, that permits to increase a design fuel burnup in the nearest future.

The main directions of work on further development of modeling methods consists of the calculated and experimental researches of features of a fuel behavior at extended burnup.

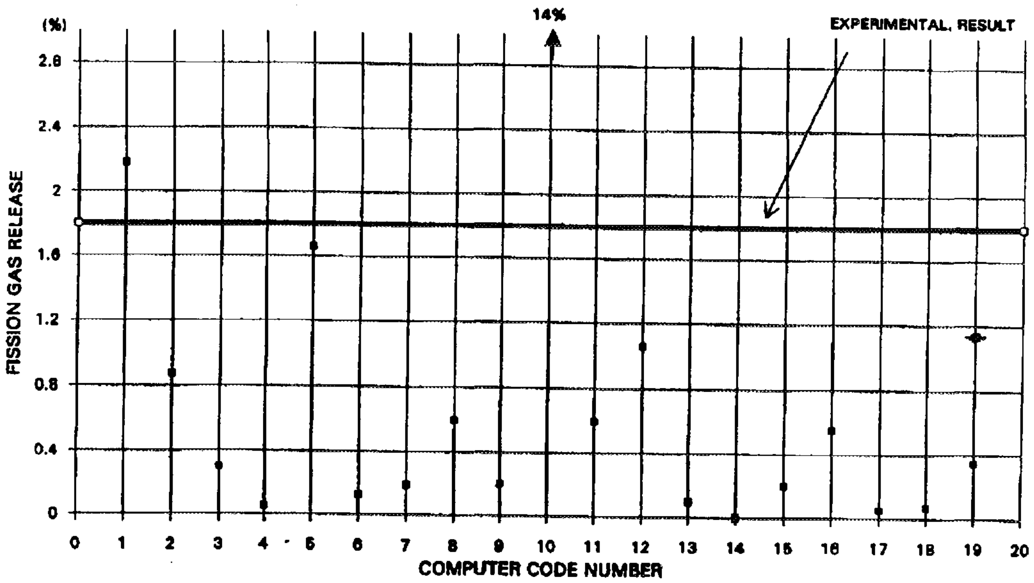


Figure 5 FUMEX 1: E.O.L fission gas release

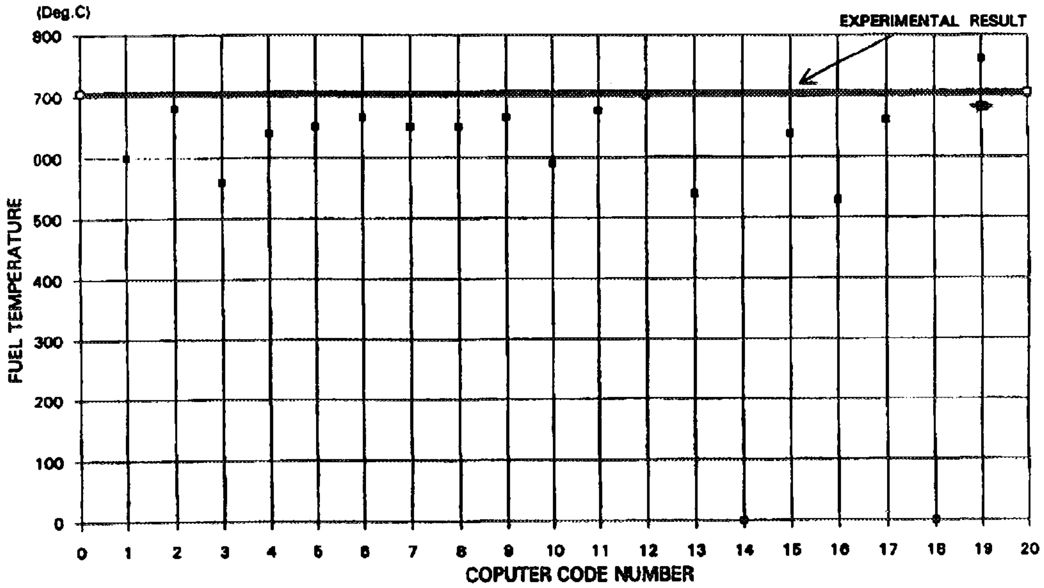


Figure 6 FUMEX 1: Fuel central temperature at 5 MWd/kg and 15 kW/m

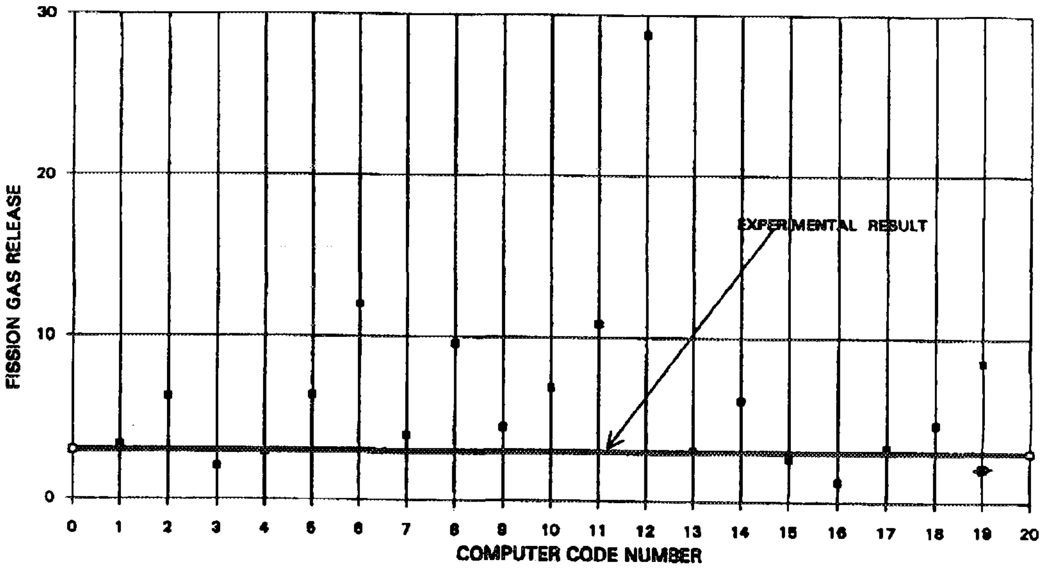


Figure 7 FUMEX 2: E.O.L fission gas release

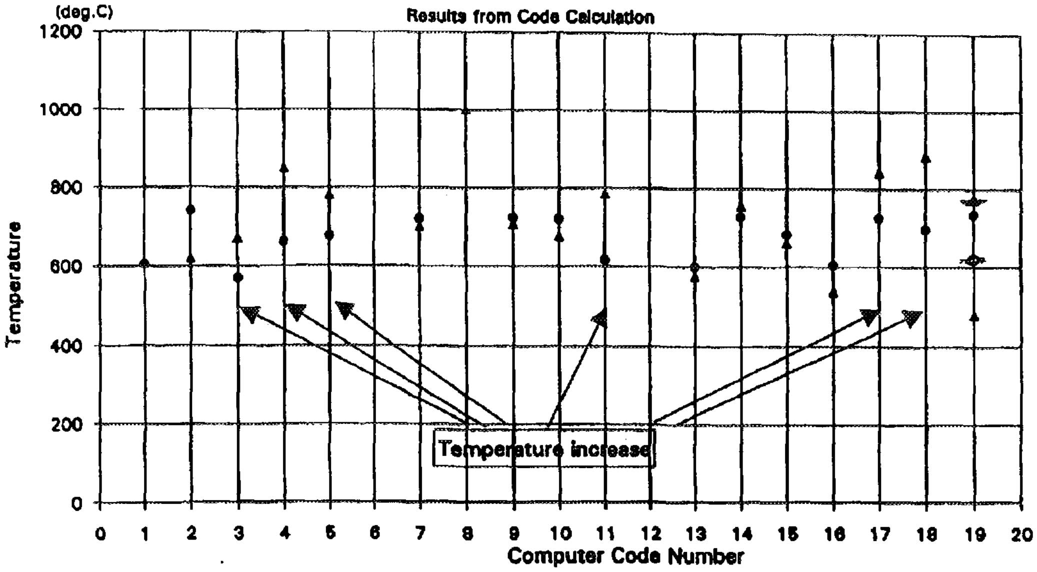


Figure 8 FUMEX 2: Fuel central temperature at 5 MWd/kg, 15 kW/m (●) and E.O.L (Δ)

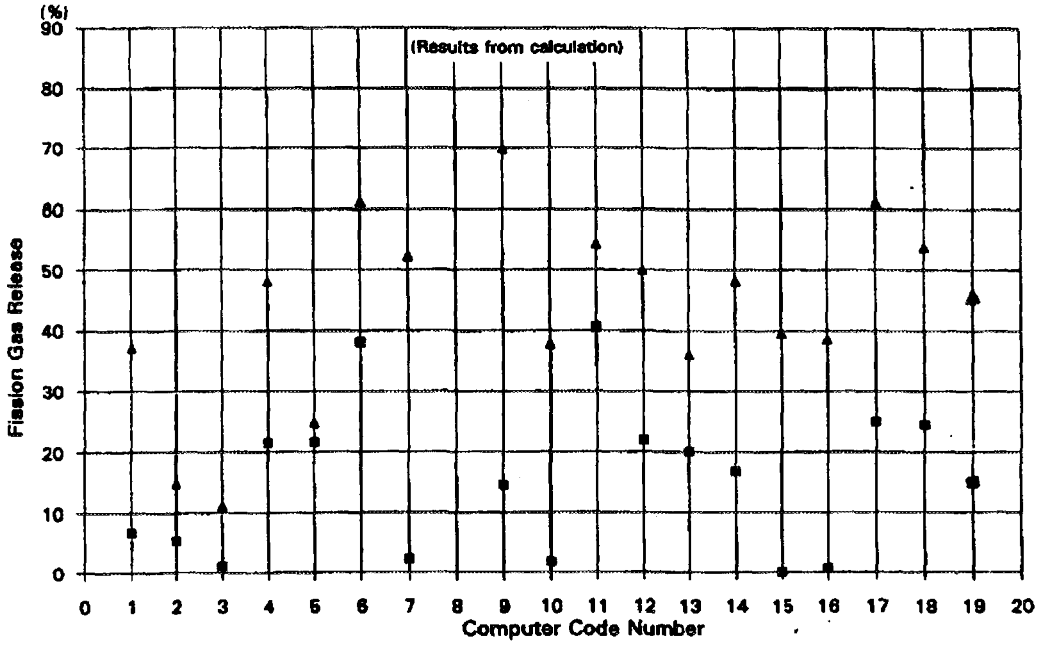


Figure 9 FUMEX 3.1: Fission gas release just before (■) and after (Δ) ramp

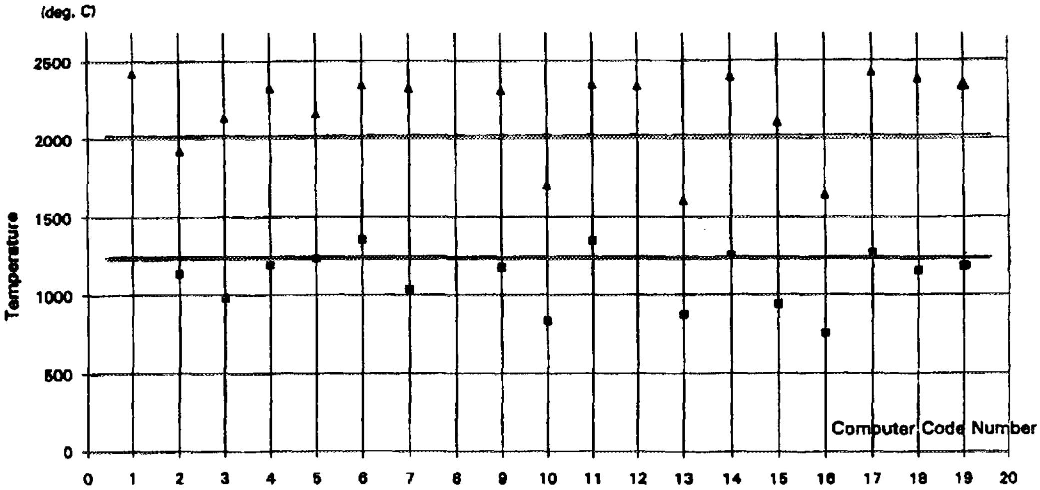


Figure 10 FUMEX 2: Fuel central temperature just before (■) and at top (Δ) of the ramp; experimental data: ▬ before and — after ramp.

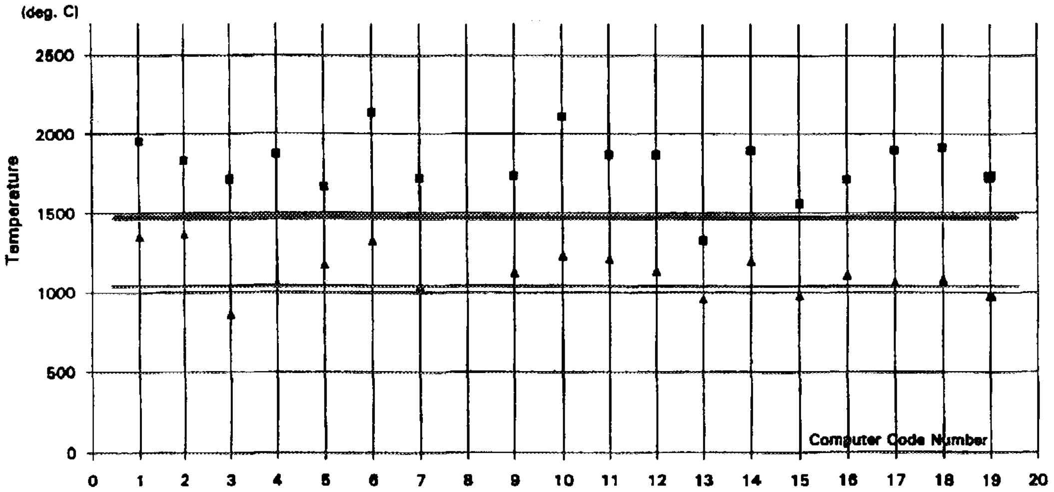


Figure 11 FUMEX 3.2: Fuel central temperature at 25 kW/m, before (Δ) and at the top (■) of the ramp; experimental data: — before and ▬ at top of the ramp.

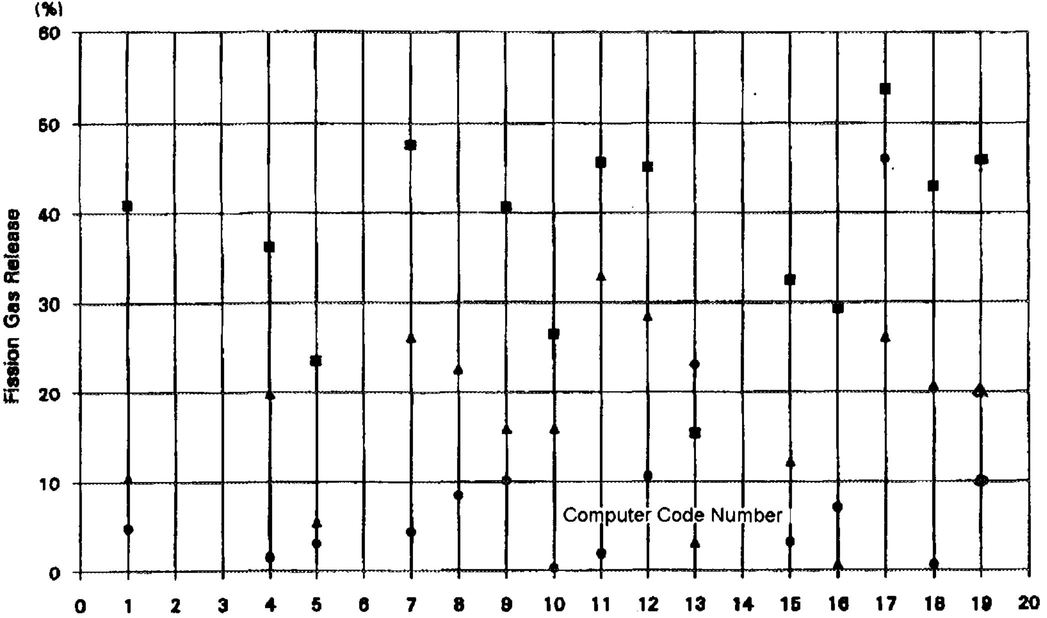


Figure 12 FUMEX 4A: Fission gas release before (●), after (Δ) ramp and E.O.L (■)

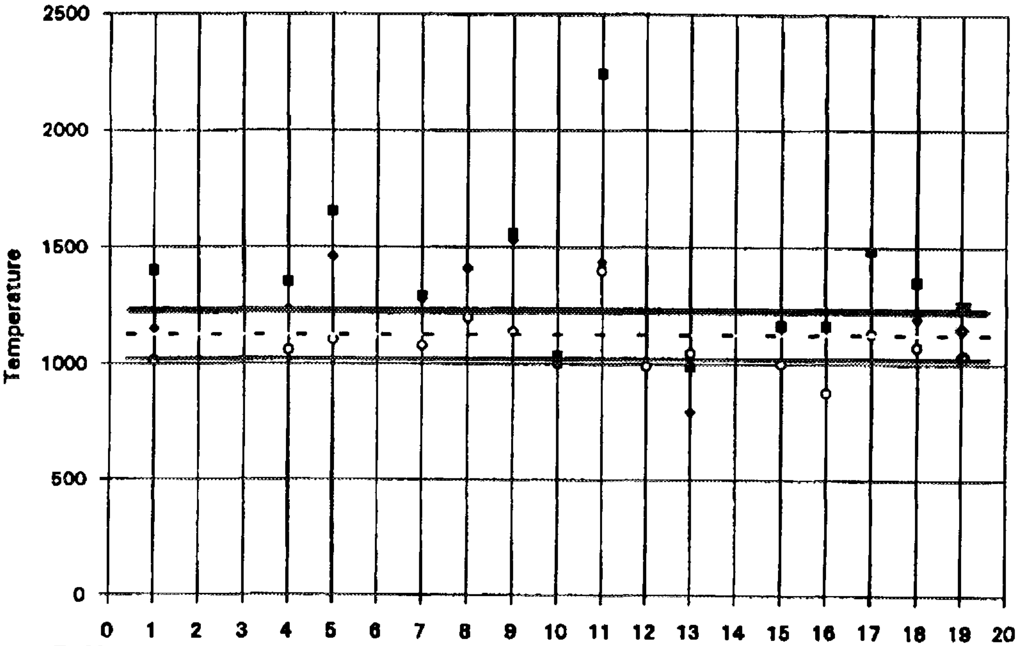


Figure 13 FUMEX 4A: Fuel central temperature at 30 kW/m, start-up (○), ramp (◆) and E.O.L (■); experimental data: — start-up, – – ramp and ▬ E.O.L.

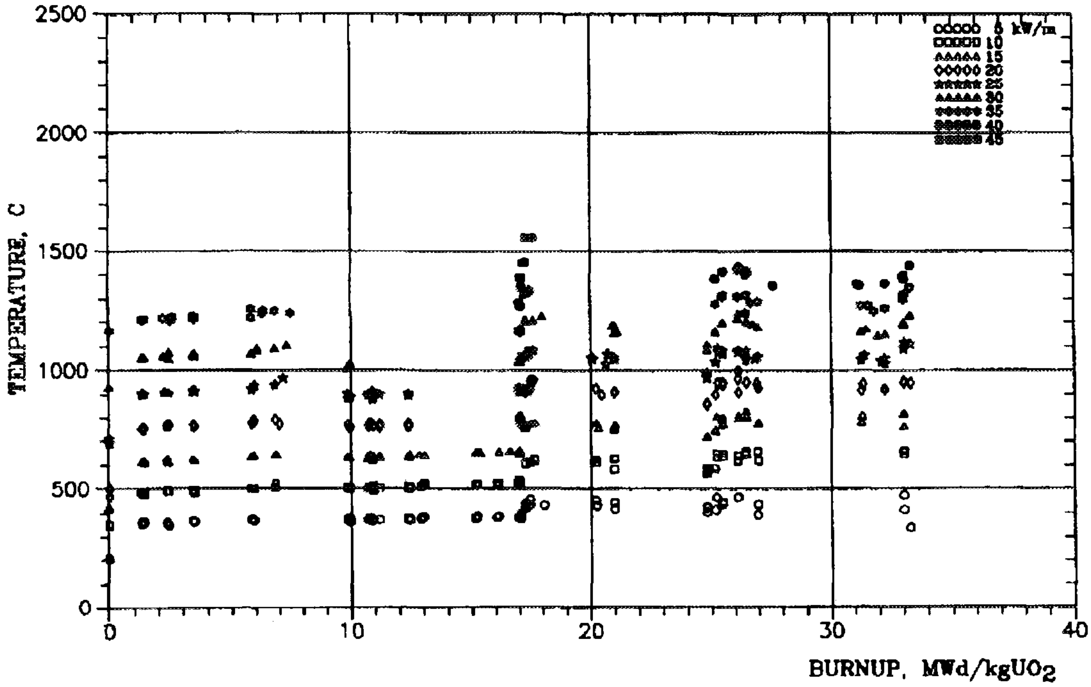


Figure 14 FUMEX 4A: Fuel central temperature vs. burnup

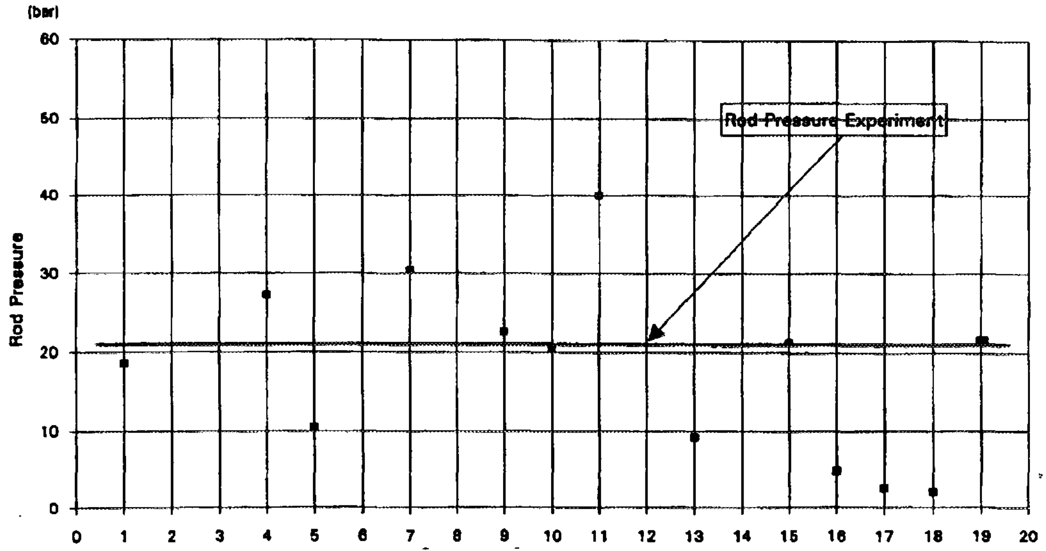


Figure 15 FUMEX 4A: Rod pressure after ramp (hot conditions)

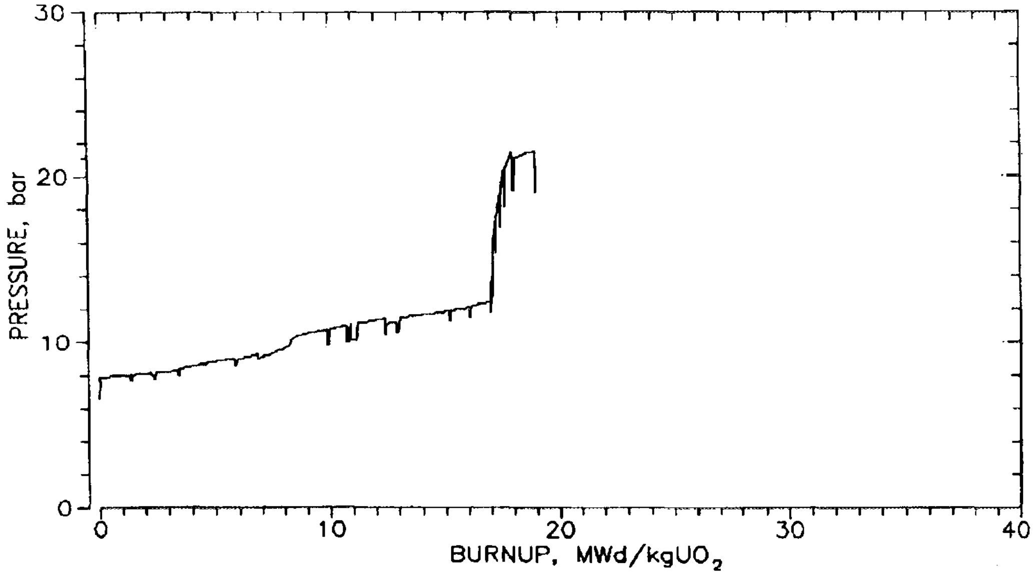


Figure 16 FUMEX 4A: Pressure vs. burnup

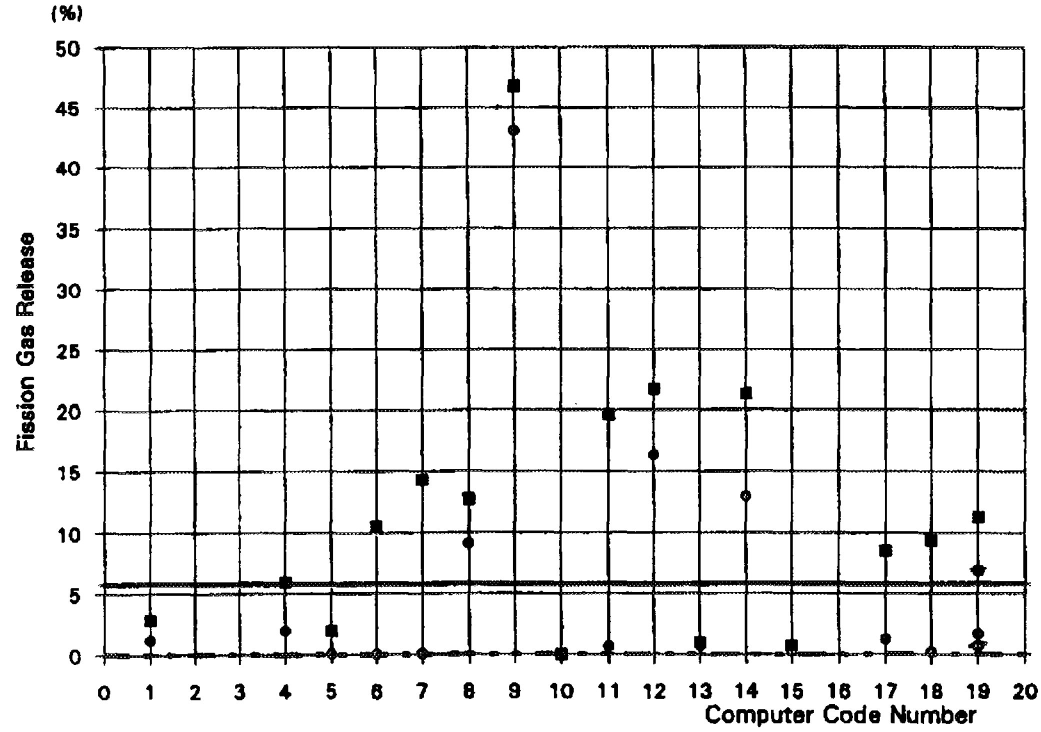


Figure 17 FUMEX 5: Fission gas release at start of ramp (O) and E.O.L (■); experimental data: – – start of ramp and ▬ E.O.L.

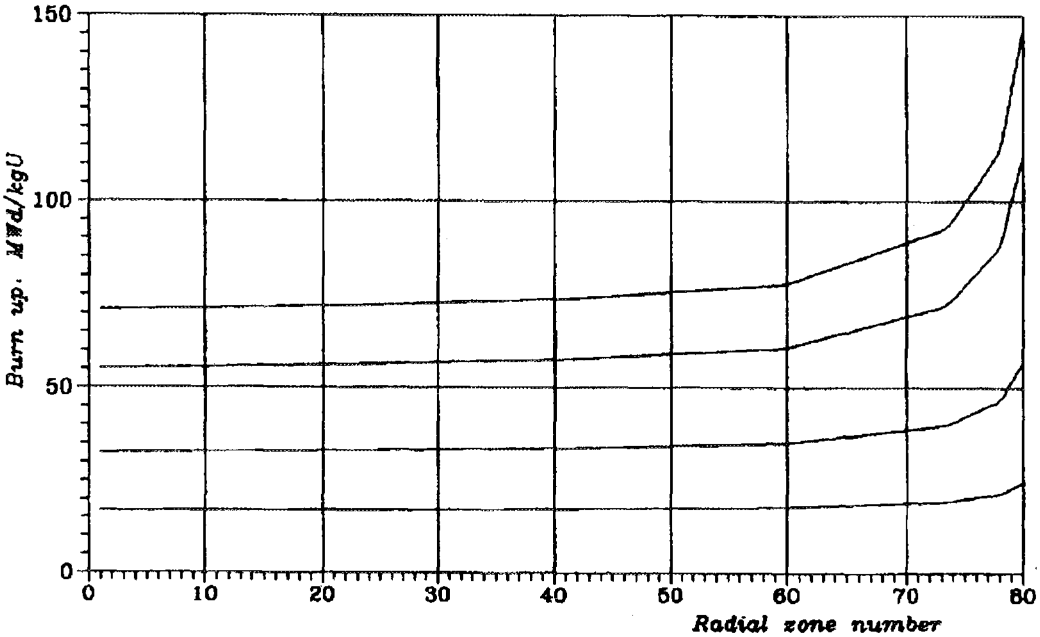


Figure 18 Radial burnup distribution for several average fuel pellet burnup levels

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