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RAPTA-5 CODE: MODELLING BEHAVIOUR OF VVER-TYPE FUEL RODS IN DESIGN BASIS ACCIDENTS VERIFICATION CALCULATIONS

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Abstract

RAPTA-5 code used for licensing calculations to validate the compliance with the requirements for VVER fuel safety in design basis accidents. The characteristic results are given of design modelling experiments simulating thermomechanical and corrosion behaviour of VVER and PWR fuel rods in LOCA. The results corroborate the adequate predictability of both individual design models and the code as a whole.

1. Brief Description of Code

RAPTA-5 code is to be used for calculation of thermomechanical and corrosion behaviour of water cooled power reactor fuel rod in design basis accidents induced by degradation of heat transfer in a core or quick power changes and accompaned by a fuel cladding temperature rise (not higher than 1200 $^\circ$C).

The code has been under development since late 70 [ns] [1,2]. To-day the fifth version of the code has been developed.

The code makes use of the algorithm of the numerical integration of a system of non-steady equations of heat balance of elementary volumes of a multilayer cylindrical area taking account of its geometry changes at each time step. Geometry changes take into consideration thermoelastic strains of fuel and cladding, creep strain of cladding and oxide layer formation at inner and outer surfaces of cladding during oxidation.

To be used in the code a package of independent subprogrammes RAPTA-C (49 modules) has been made up to calculate temperature dependences of properties of the main core materials. They are based on experimental results of investigations of russian material properties and in some cases are supplemented with data taken from literature. The package represents thermophysical properties of UO_2 , Zr1%Nb alloy , ZrO_2 , inert gases, thermomechanical properties of fuel and cladding materials, equation of a cladding material condition in a wide range of stresses and temperatures, conservative and realistic models of Zr1%Nb oxidation kinetics also with the account for the effect produced by steam pressure.

The calculated results contain information on the thermophysical parameters of a fuel rod, strained condition of fuel and cladding, including an analysis of ballooning induced rupture of cladding, corrosion properties of cladding in the design range of time. The results are used to check up the fulfilment of the criteria of the maximum design limit of fuel rod damages in accidents.

The major distinctions of the RAPTA-5 version from the previous one consist in the following:

1) Model of calculation of the local cladding deformation has been introduced with the account for height and azimuthal temperature non-uniformities [3,4];

2) Model has been introduced to calculate local cladding deformation upon symmetrical contact with claddings of adjacent fuel rods;

3) Design model of Zr1%Nb high temperature creep has been improved using experimental results [5,6,7];

4) Based on the supplemented array of experimental data on Zr1%Nb cladding failure effected by excess internal pressure at high temperatures new temperature dependences have been derived for rupture strains to be used in the deformation criterion of rupture;

5) The known conservative dependence used to calculate Zr1%Nb alloy oxidation in steam is supplemented with the model of the transition to the linear oxidation law at high exposure time;

6) A new design model of Zr1%Nb alloy oxidation has been introduced that is based on the realistic dependence of oxygen weight gain at temperatures up to 1600 °C [8];

7) A design model of Zr1%Nb alloy oxidation has been introduced that takes account of a higher steam pressure at temperatures < 1100 °C;

8) A feasibility is envisaged of randomly dividing a fuel rod into axial segments when forming a design array.

2. Main Results of Verification Calculations

The RAPTA-5 code was verified by design modelling a series of experiments. Use was made of the results of the domestic laboratory experiments aimed at studying the deformation behaviour, rupture parameters and oxidation of fuel rod claddings under unsteady temperature - force conditions of loading typical of design basis accidents. Use was also made of the results of foreign integral rig and in-pile experiments with PWR type fuel assemblies; the need material properties and design parameters having been corrected.

2.1. Kinetics of cladding steam oxidation

The most important aspect of a fuel rod behaviour under accident conditions is their high temperature steam oxidation. A large amount` of experimental and theoretical studies deal with corrosion behaviour of Zr1%Nb claddings and influence of oxidation on mechanical properties [8 - 11].

In the specific ranges of temperature and exposure time typical of LOCA there is square law dependence between oxygen weight gain and time that is true for isothermal conditions. Under non-isothermal

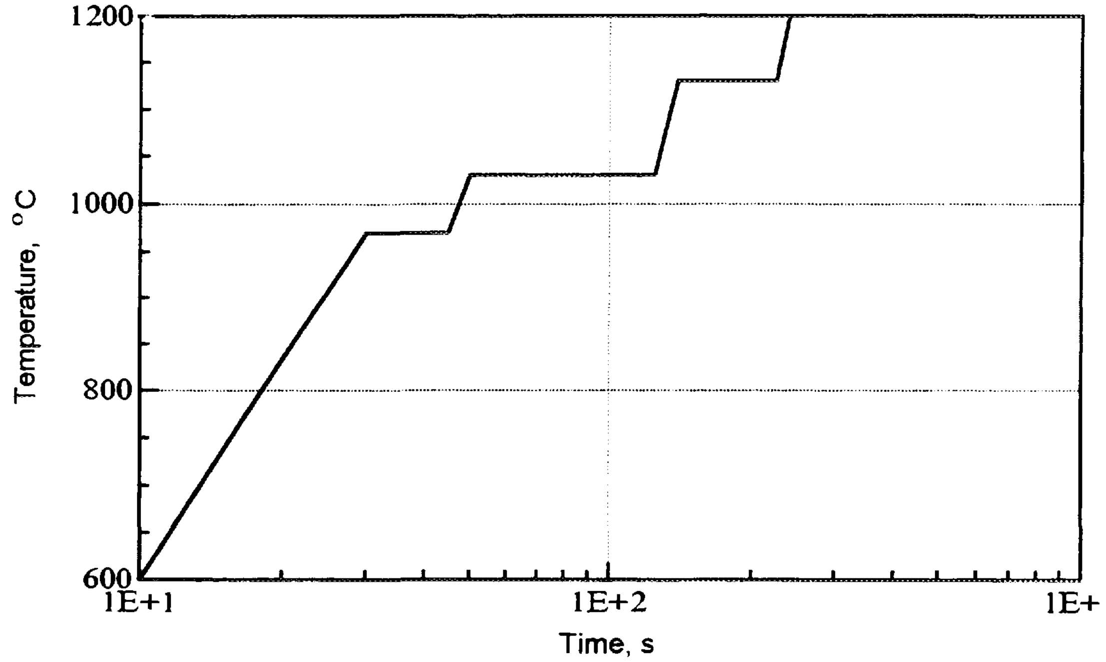

Fig.1 - Temperature evaluation of specimens 1, 2 during experiment

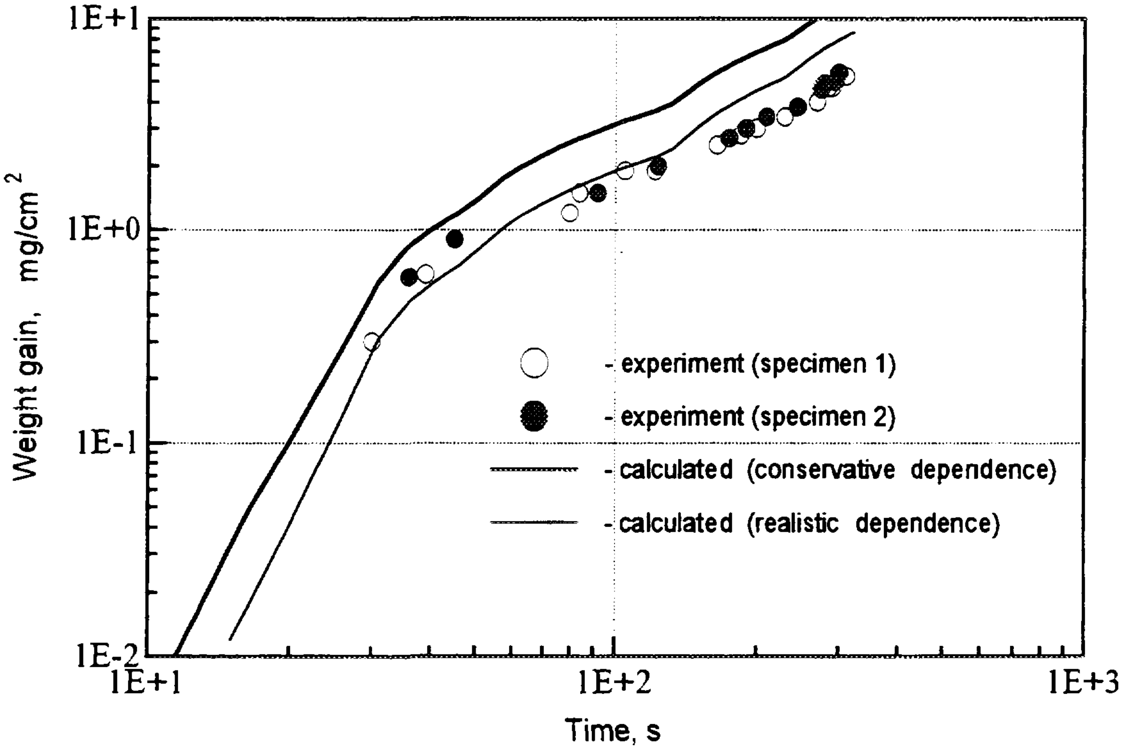

Fig.2 - Weight gain kinetics of specimens 1 and 2

conditions to find a weight gain a reccurent relationship is used taking account of the pre-history of the process

$$W^2 = K_p\ \tau\,,$$
$$K_p = A\ \exp(-Q/T)\,,$$
$$W_i = (W_{i-1}{}^2 + K_{pi}\ (\tau_i - \tau_{i-1}))^{1/2}\,,$$

where W - spesific weight gain of oxygen, mg/cm^2,
τ - time, s,
K_p - is reaction rate parameter, (mg/cm^2)^2 c^{-1},
T - absolute temperature,
A - empiric coefficient,
Q - reduced activation energy, K,
τ_{i-1}, τ_i - are limits of a time range within the temperature T_i is considered constant.

By now a large array of experimental data on Zr1%Nb alloy cladding oxidation has been generated (more then 1000 points); on its base conservative (used for licensing calculations) and realistic kinetic dependences were derived to determine the specific weight gain and release of hydrogen [1 , 8]

conservative $K_p^{1/2} = 920\ \exp(-10410/T)$ at $T < 1773$ K,

realistic $K_p = 1.59 \cdot 10^6\ \exp(-23040/T)$ at $T < 1773$ K,

$K_p = 9.825 \cdot 10^5\ \exp(-20800/T)$ at $T \geq 1773$ K.

The verification of the model describing the interaction between a fuel rod cladding material and steam shows a good agreement of the oxidation kinetics derived using the realistic dependence with the results of non - isothermal experiments with the continuous recording oxygen weight gain in VVER - type fuel rod claddings (fig.1, 2). It was corroborated that the dependence of the kinetics of Zr1%Nb alloy cladding oxidation is conservative.

2.2. Cladding Deformation Behaviour and Loss of Tightness

The equations for Zr1%Nb alloy condition (creep law relating the strain rate to stresses and temperature) [5, 6, 7] were derived using the results of experimental studies in the stress range of 9 - 145 MPa and temperature range of 300 - 1500 K covering the range of the alloy phase transformation

1) for the α - region (temperature < 883 K)
in the stress range of 9 - 32 MPa

$$\varepsilon = 7.1 \cdot 10^5\ \sigma^{2.2} \exp(-28900/T),$$

in the stress range of 32 - 90 MPa

$$\dot{\varepsilon} = 26\,\sigma^{5.1} \exp(-28900 / T),$$

at higher stresses

$$\dot{\varepsilon} = 2{\cdot}10^{9} \exp(0.05\,\sigma)\,\exp(-28900 / T),$$

2) for the β - region (temperature > 1070 K)

$$\dot{\varepsilon} = 0.09\,\sigma^{3.5} \exp(-13200 / T),$$

3) for the $(\alpha + \beta)$ region ($883 < T < 1070$ K) the model of parallel phase joining results in stress additivity:

$$\sigma = f_\alpha \sigma_\alpha + f_\beta \sigma_\beta ,$$

the model of successive phase joining results in strain rate additivity

$$\dot{\varepsilon} = f_\alpha \dot{\varepsilon}_\alpha + f_\beta \dot{\varepsilon}_\beta ,$$

where $\dot{\varepsilon}_\alpha, \dot{\varepsilon}_\beta$ – are straine rates of α– and β–phases,
$\sigma_\alpha, \sigma_\beta$ – are stresses in α– and β– phases,
f_α, f_β – are volume fractions of α– and β– phases.

The cladding failure parameters namely, time to rupture and tangential rupture strain of cladding are determined using the principle of linear summing elementary damages under conditions of isotermal steady loading. The elementary damage is determined as a ratio between a time pitch and time to rupture, the latter in determined from Garofalo criterion or as a ratio of a strain increment at a time pitch to a rupture strain under given isoconditions (deformation criterion)

$$\int_0^{\tau} d\varepsilon_\theta / \varepsilon_{\theta p} = 1 \qquad \text{or} \qquad \int_0^{\tau_\theta} d\tau / \tau_p = 1 .$$

The deformation criterion basis is formed by a large array of experimental data on rupture of Zr1%Nb claddings under the action of excess internal pressure at temperatures 600 - 1300 °C (some 1000 points).

To verify the model of excess internal pressure effected cladding local straining of in the area of a given temperature distribution over height use was made of the results of laboratory experiments with VVER fuel simulators with a 200 mm fuel column length heated by a center tungsten electrode. The heating rate was 20 K/s. The specimens were heated to the specified isothermal state until the cladding lost its integrity. The design of the rig provided the maximum temperature of the specimen central part and the temperature gradient of the 0.5 K/mm. Some results of the design

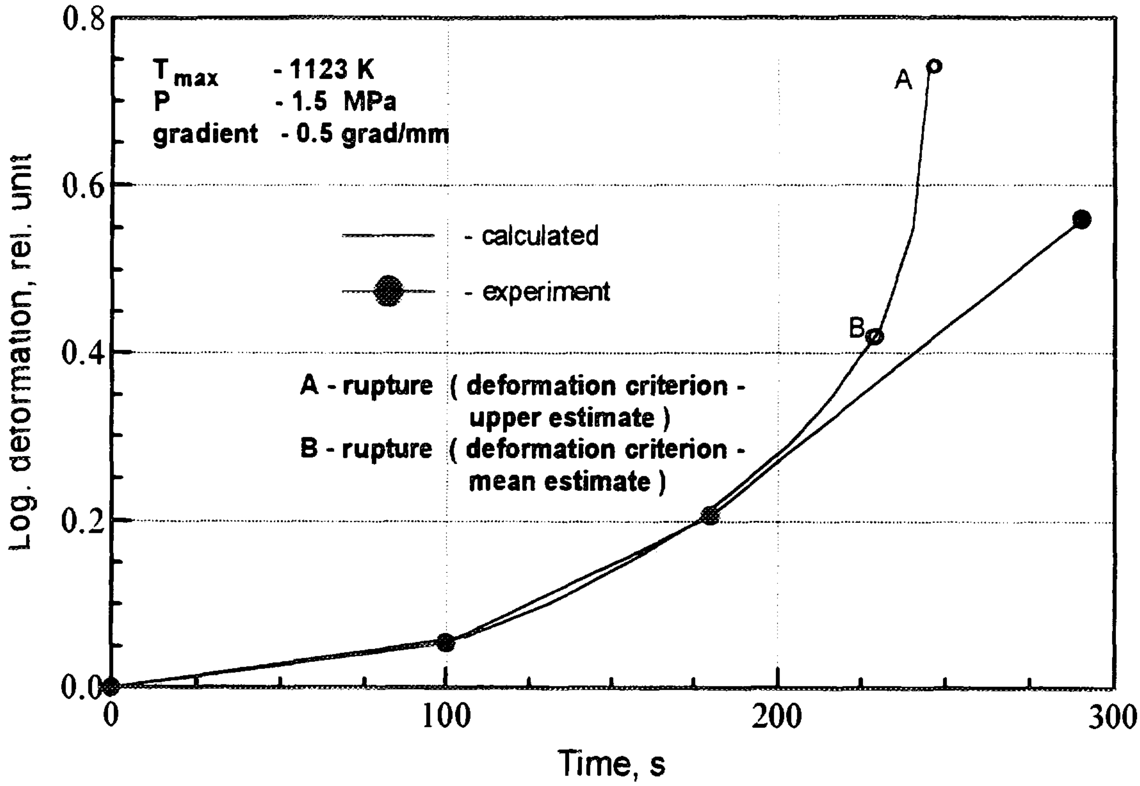

Fig.3 - Hoop strain kinetics (cladding hot cross section)

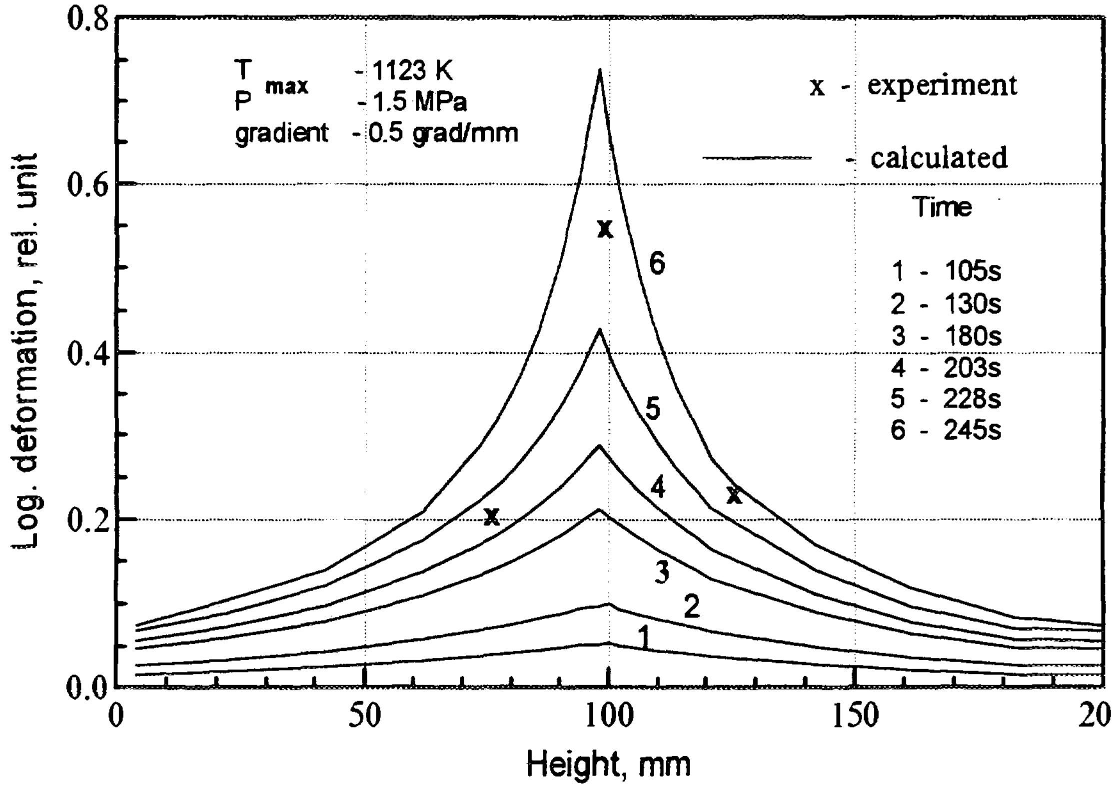

Fig.4 - Height distribution of hoop strain

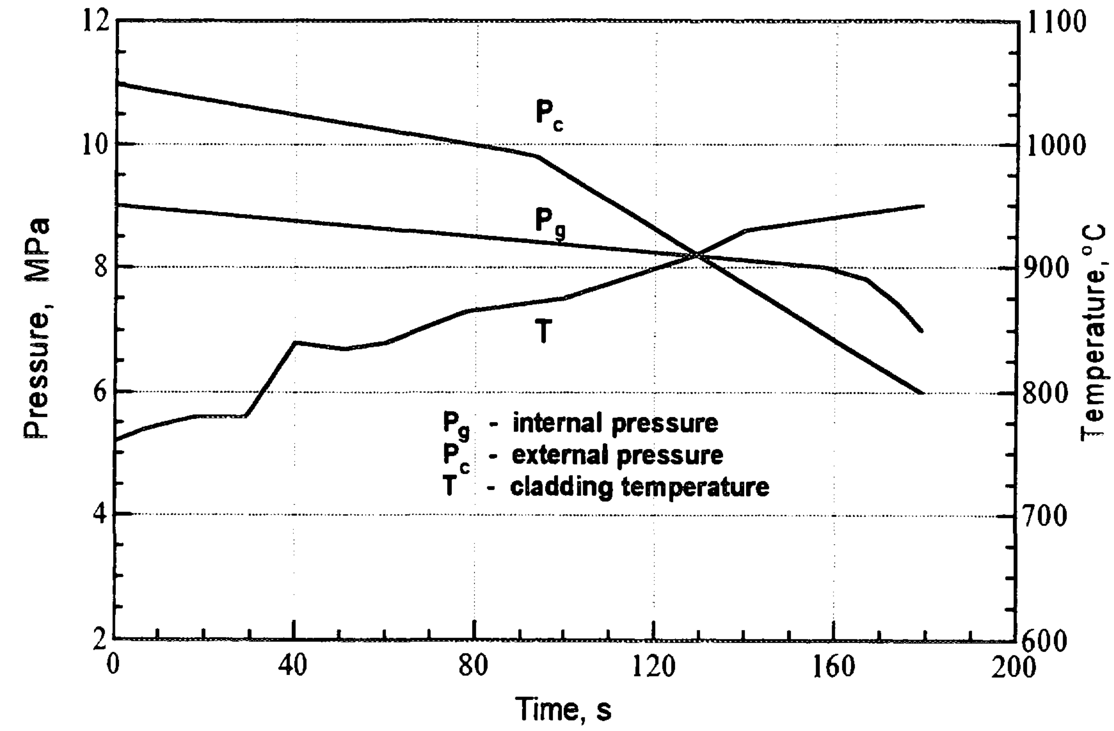

Fig.5 - Looding conditions of simulator (temperature, pressure)

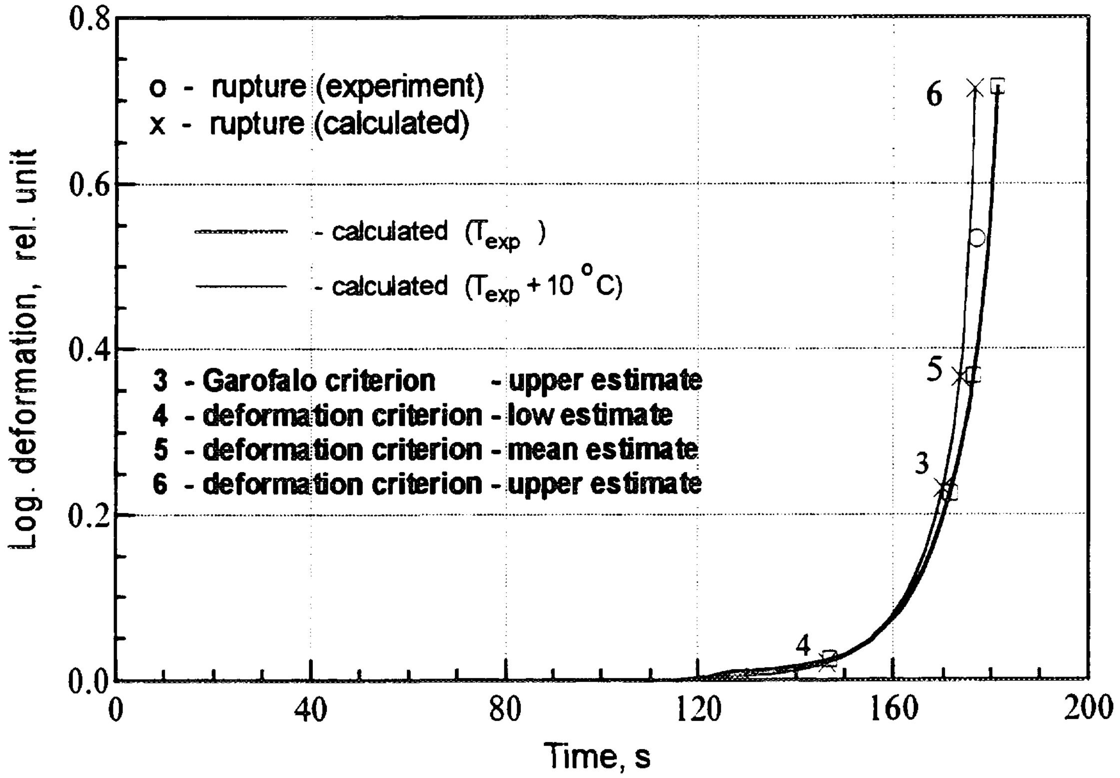

Fig.6 - Comparison of calculated and experimental rupture hoop strain

modelling in comparison to the experimental findings are given in figs. 3, 4. There is an adequate agreement parameters of a fuel cladding rupture and the strain distribution over the height.

The model of cladding rupture due to ballooning was verified using the results of the experiments carried out by OKB "Hydropress" with electrically heated (a molybdenum electrode in the centre) VVER fuel simulators 1.2 m long that had a higher power density zone 0.5 m long. In the experiments the parameters of non-steady loading conditions (cladding temperature, internal and external presssure) were measured. The loading conditions and the results of design modelling are illustrated in figs. 5, 6 for one of the experiments. The calculated cladding rupture parameters (time to rupture and a magnitude of hoop strain during rupture) are in adequate agreement with the experimantally found rupture parameters.

2.3. Blockage of Fuel Assembly Cross - Section

To verify the model of the restrained straining of cladding simmetrically contacting adjacent fuel rod claddings and of a fuel bundle cross-section blockage one of the experiments [12] was taken modelling the thermomechanical behaviour of PWR type fuel simulators in LOCA. In those experiments a (7 × 7) assembly of electrically heated simulators 0.9 m in height was cooled with superheated steam and conditions uniform

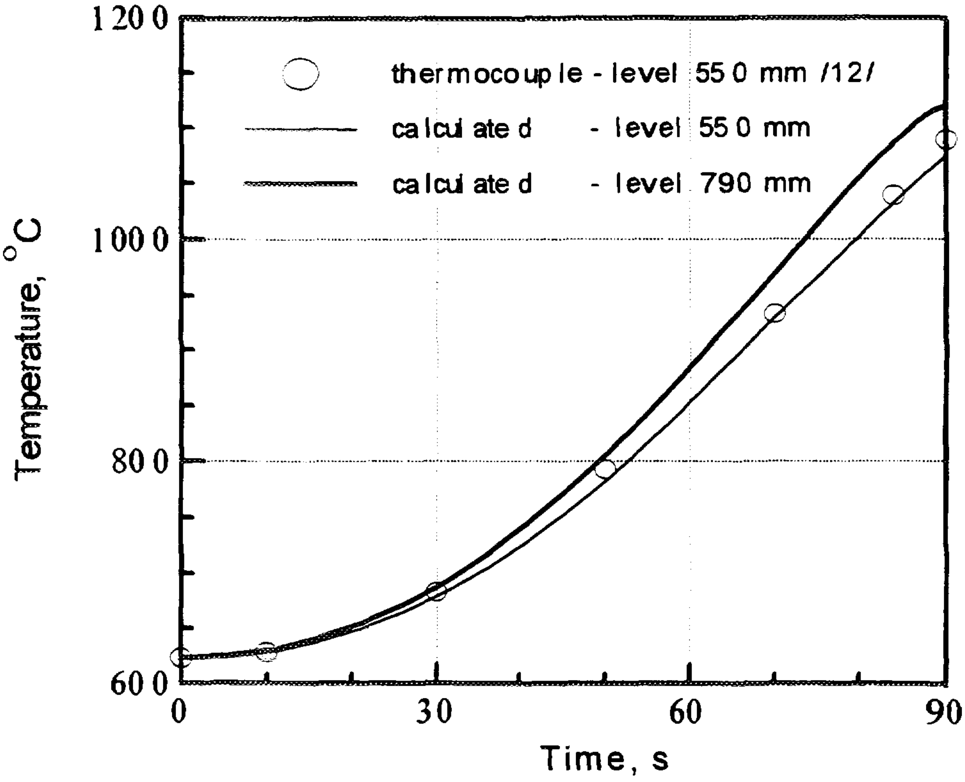

Fig.7 - Temperature during experiment

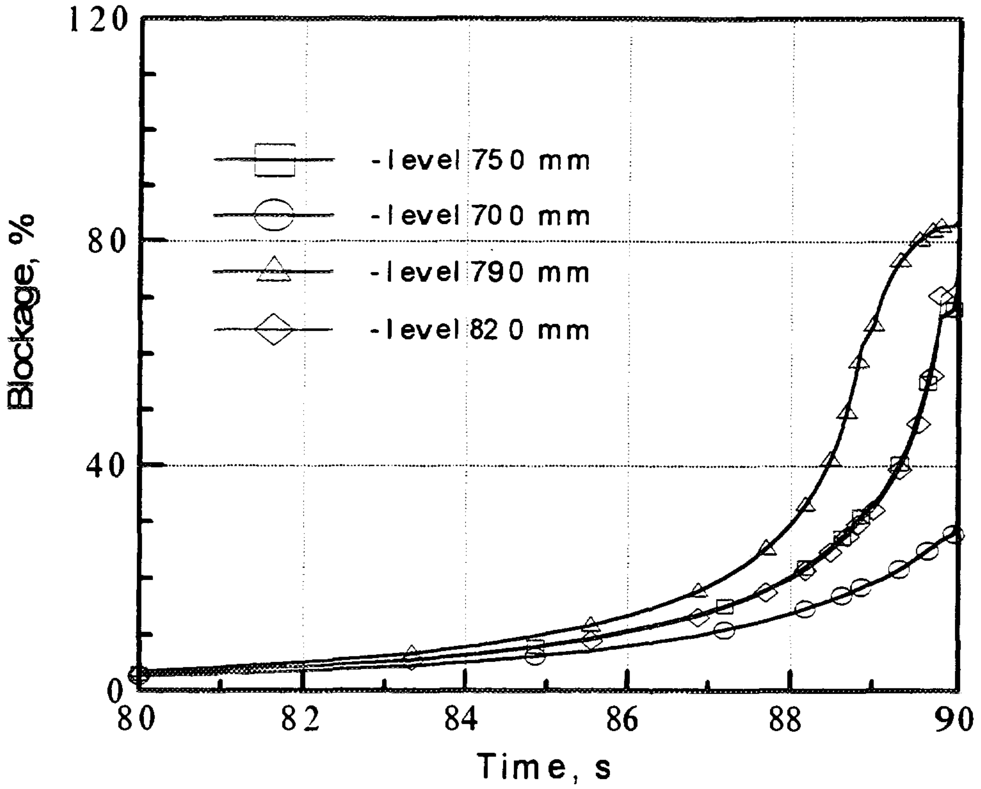

Fig.8 - Predicted blockage

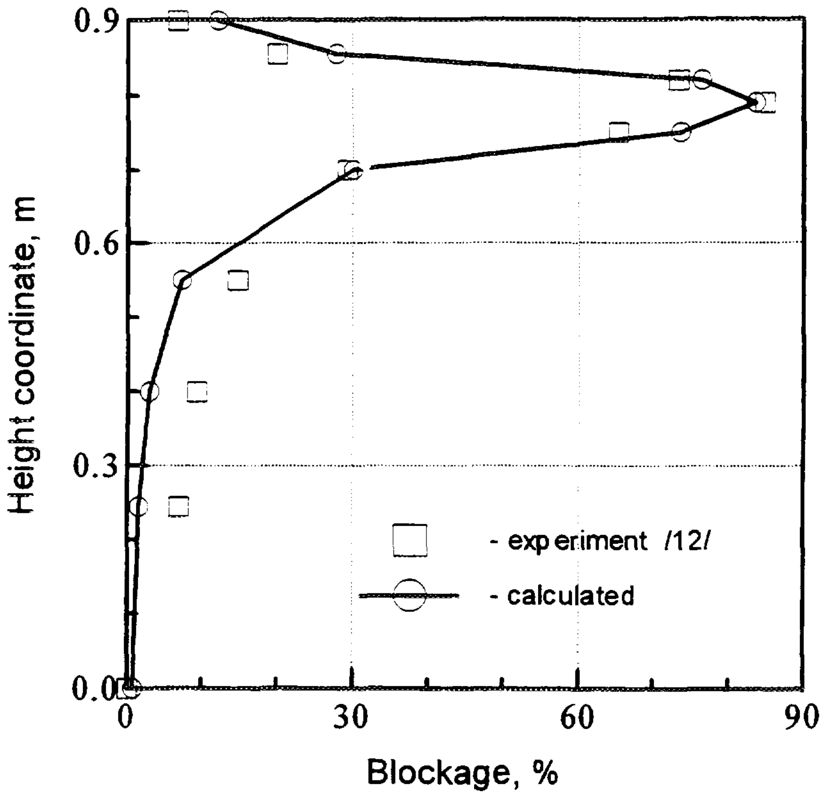

Fig.9 - Height distribution of blockage

across the assembly section were created under which all simulators experienced local ballooning at one and the same level of height. Essentially all claddings came into contact with the adjacent ones and their strain behaviour may be assumed to be similar. The programme was corrected when it was needed as applied to the material properties (the thermophysical properties of Zry-4, the high temperature creep law, the deformation criterion of rupture) and the account for the design feature of the assembly (arrangement of fuel rods in the angles of a square). Besides, also included was a model to calculate the heat transfer to the superheated steam flow. Thus, not only the deformation behaviour of cladding but also the temperature condition of a simulator were modelled. In this sense the modelled experiment is integral. As a result a good agreement was achieved between the calculated and experimental parameters, namely, temperature conditions of simulator claddings, blockage of bundle cross-section (figs. 7 - 9). Blockage was determined as a ratio between the changes in the assembly cross-sectional area and the initial one.

2.4. In - Pile Experiment Modelling

Presently the programme was also tested using the results of the in-pile experiments EOLO, MT-1, FR-2 carried out abroad. In these experiments the thermomechanical behaviour of PWR type fuel rods in LOCA was modelled. As an example, let us discuss the results of

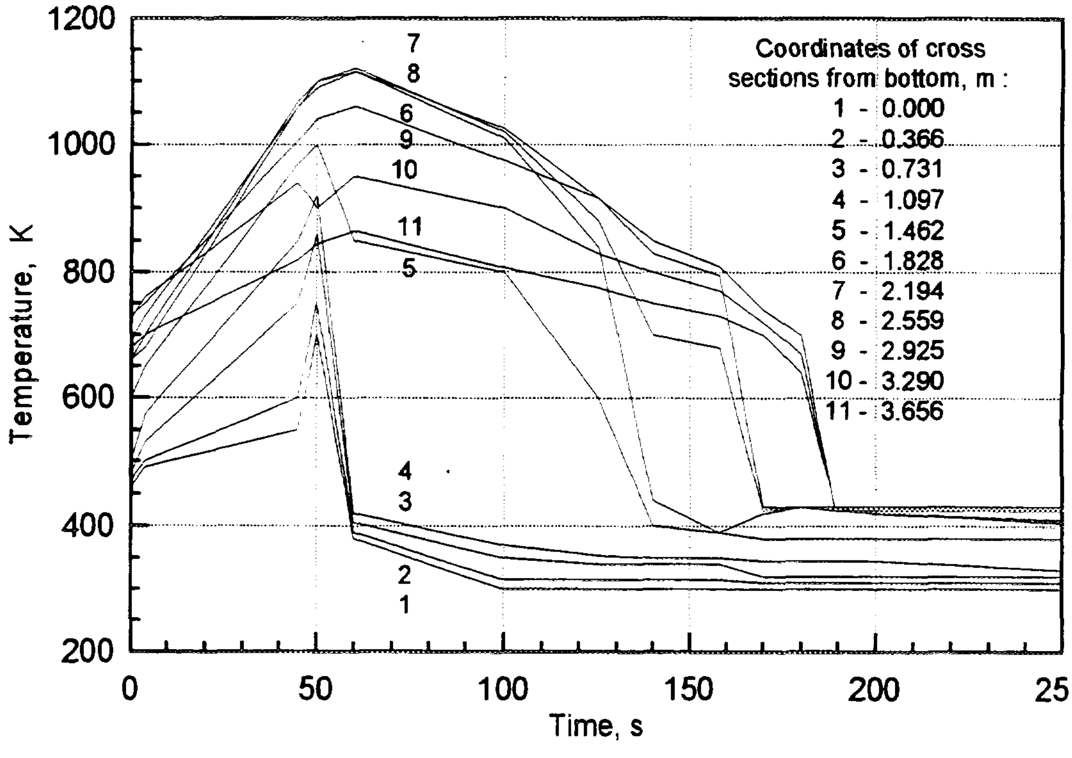

Fig.10 - Temperatures of cladding outer surface during experiment MT-1 (according to expert restore)

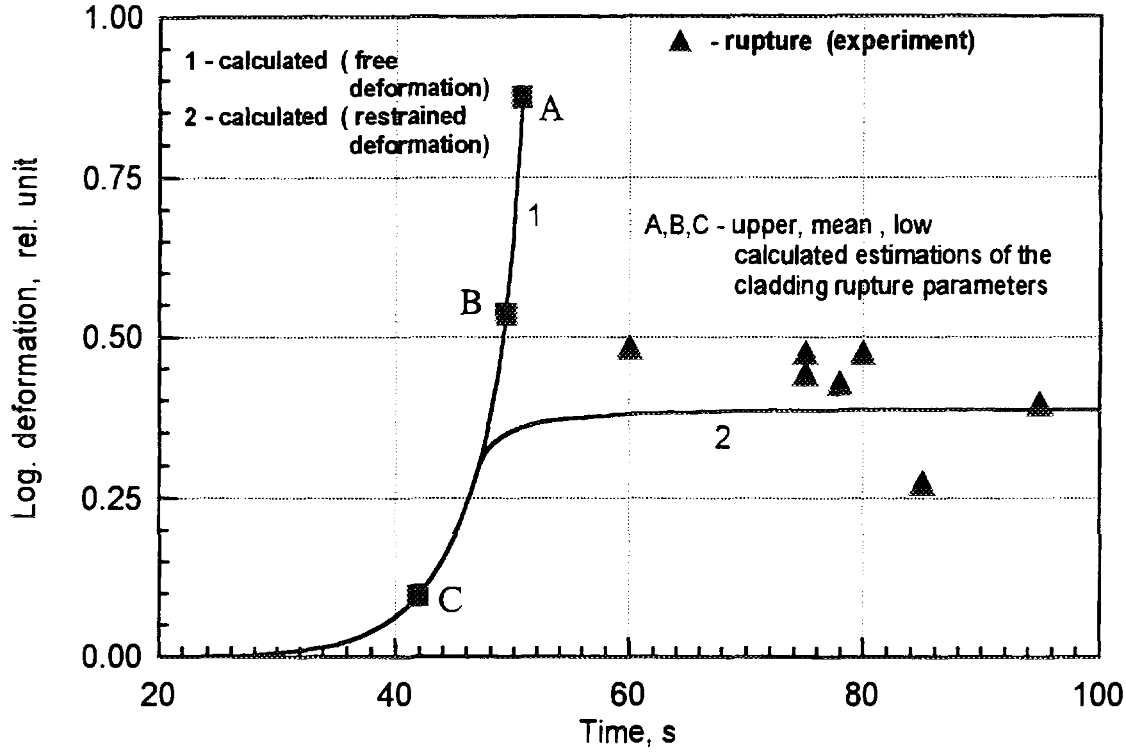

Fig.11 - Maximum hoop strain of cladding versus time

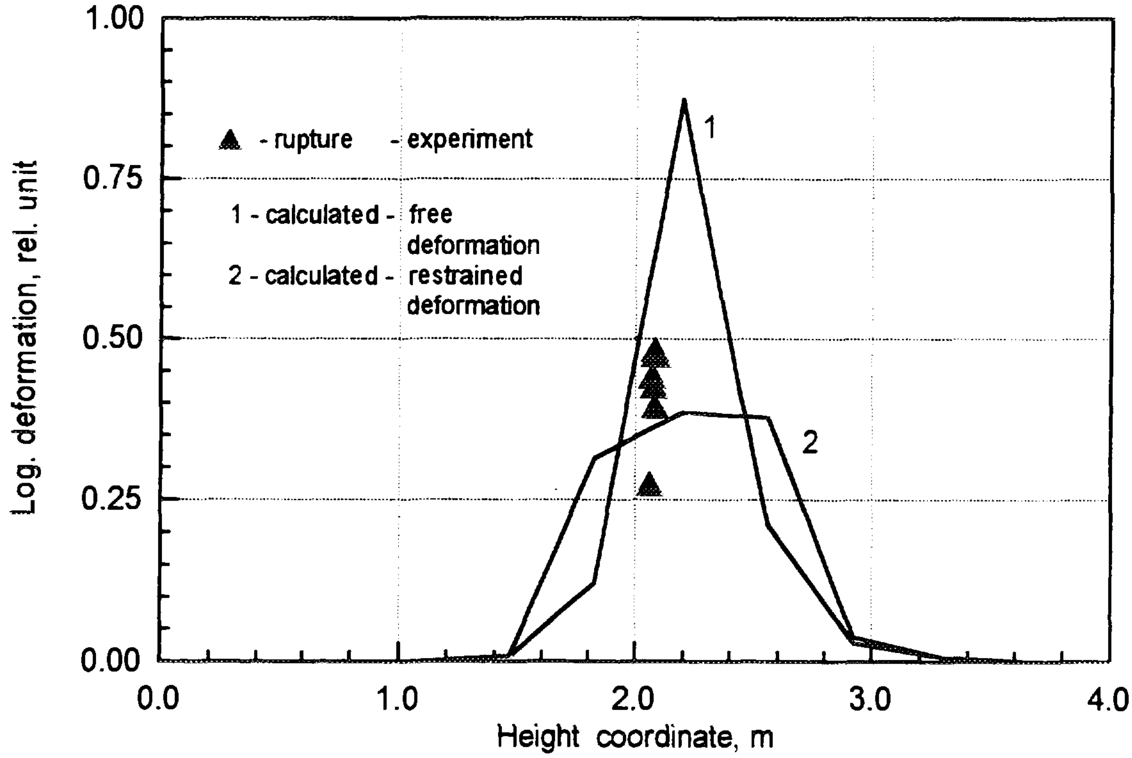

Fig.12 - Height distribution of hoop strain

modelling the experiment MT-1 (the reactor facility NRU, Canada) in which a (6×6) assembly (without fuel rods in the angles) of fuel-scale PWR fuel rods was tested. The experiment consisted of three phases, namely, simulation of a fuel rod operation under steady-state conditions, simulation of steady cooling with a steam flow on residual power rating, simulation of heating up as a result of a deficient heat transfer followed by flooding with water. The design modelling of phase 3 was carried out using the non-steady field of temperatures of an outer cladding surface as a boundary condition of the 1st kind (fig. 10). This field was reconstituted based on the published readings of thermocouples. Modelled were the fuel rod temperature field, kinetics of internal pressure, stress-strained condition and cladding rupture. In this instance as in Section 2.3., the programme was corrected as applied to cladding material properties and design features of assembly. The calculations were performed using two models of cladding deformation, namely free and restrained by symmetrical contact with adjacent claddings. As a result an adequate agreement was achieved between the calculated and experimental data on thermomechanical characteristics of fuel rod cladding failure : time to rupture, rupture location and maximum hoop strains. It can be seen from figs. 11 and 12 almost all experimental points of internally pressurized cladding rupture lie between two calculated curves that correspond to different versions of straining. It can be concluded that the free deformation model and upper estimate of the deformation criterion of rupture are too much conservative. Generally speaking, the maximum rupture strains of individual claddings are unrealistic under fuel rod assembly conditions. On the other hand, the restrained straining model not taking account of local superheating due to a contact gives a somewhat underestimated result.

3. Conclusion

Thus, the RAPTA-5 code was verified using results of laboratory experiments modelling high-temperature processes (oxidation, straining and failure of fuel rod cladding) as well as results of rig and in-pile integral experiments modelling conditions of loading in design basis accidents. The following conclusions can be drawn on the results of verification calculations :

- a good agreement was obtained between the design and experimental parameters of cladding oxidation and straining under specified conditions of temperature and force loading;

- the adequate agreement of cladding strain parameters in integral experiments evidences the adequate modeling of a non-steady temperature field in a fuel rod and of the parameters of the fuel rod filler gas condition;

- the code has conservative models of cladding oxidation, deformation behaviour and rupture that permit licensing calculations to validate the safety of VVER fuel with adequate reliability in design basis accidents.

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