Transactions of the **13th International Conference on Structural Mechanics in Reactor Technology** (SMiRT 13), Escola de Engenharia - Universidade Federal do Rio Grande do Sul, Porto Alegre, Brazil, August 13-18, 1995

Simulation of accident and normal fuel rod work with Zr-cladding

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ABSTRACT: The technique of simulation of heat-physics, strength and safety characteristics of reactor RBMK and WWER rods under steady-state, transient and accident conditions is presented. That technique is used in mechanic and heat physics codes "PULSAR-2" and "STALACTITE".

Simulation in both full scale and the most stress-loading part of cladding statement under accident conditions are considered. In this zone local swelling and cladding failure are possible. The accident simulation is based on the mechanical creep-plasticity problem solution in three-dimensional approach. The local cladding swelling is initiated with determining of little hot spot on the clad with several degrees temperature departure from average value. Mechanical problem is solved by finite elements method. Interaction of Zr with steam is taken in to account. Fuel and cladding melting, shortness and dispersion formation processes are simulated under subsequent rods warming up.

1 DISCUSSION AND OBSERVATIONS

This paper is sequel of paper devoted to power plants rods behavior simulation. The first part of the paper is devoted to discussion of experimental data comparison with calculational ones, obtained with help of calculational code "PULSAR-2" [1]. Results of code verification with experimental data for rods of WWER-440 and research reactor MR (in Russia) fuel assemblies. Reactors were working under steady-state conditions. Calculation results of rods lengthening, rod claddings diameters changing, fuel temperature and fission gas release from fuel to cladding were compared with experimental data.

In the second part of paper rods accidental behavior models are discussed. Mathematical simulation of local swelling and rod cladding depressurization method, melting and molten fuel and cladding interaction criterion, cladding and fuel fragments shortness and crumbling, fuel and rod claddings criterion are presented.

Technique of molten materials moving and their consolidation in the colder axial layers is considered. These processes are important from point of view of coolant section and coolant volume correction, under joint solution of heat hydraulics and reactor core cavity destroy problems under accident conditions. Presented models are used in the calculation code "STALACTITE" devoted to core geometry change simulation under accident conditions.

2 CALCULATION CODE "PULSAR-2" VERIFICATION

2.1 *WWER-440 reactor rods normal work simulation*

Experimental data for fuel rods assembly, which has worked in WWER-440 during 3 years have been used for verification. Fuel pellets with rather high density (10,55-10,63 g/sm^3) have been used in the rods. Pellets have had faces and central holes. Average burnup along the assembly has reached 43,7 MW·days/kg. Maximum value of average of irradiation first year and was equal to 195 W/sm.

Axial distributions of two rods diameters residual change after assembly unloading from reactor are presented on fig.1,2. Experimental data have been obtained at 10 points along rod high. They are joined by broken line on fig.1,2. Mathematical simulation results are depicted by continuous line. Its obvious that numerical and experimental results are in good coincidence. Average rods lengthening is equal to 8 mm. Difference between accounted and measured values is not more than 1mm.

2.2 *RBMK reactor rods behavior simulation*

Assemblies with four rods equipped with thermocouples have been tested in the research reactor.

Test has been conducted in the base of work condition. That corresponded to RBMK work conditions. Fuel burnup for that period of time average 8,8 MW·days/kg.

Calculation and experimental time-dependence of fuel maximum temperature are presented on fig. 3,4. Good coincidence between experimental and calculation data testifies to adequateness of using physical and mathematical models.

In order to know a quantity of fission products escaped from fuel under the cladding perforate of rods had been conducted after assembly unloading from reactor. Comparative gas release values measured and calculated are presented below. Good coincidence between experimental and calculated results is clear.

3 Rods behavior simulation under NPP accidents

3.1 *Deformation and depressurization of rod cladding*

Accident modes are characterized by sharp worsening of heat-transfer from rods. Residual energy release leads to prompt rod claddings warming up and fuel clad material fluidity limit decreasing. Claddings destroy is accompanied by local swelling or crumpling on the destroy place, and shape changing could be both asymmetrically or no. Using in program "STALACTITE" model imitates raptures epicenter in the hot spot form several millimeters size with clad temperature departure from average value in several degrees. Local swelling (crumpling) simulation are conducted on the base of nonlinear elastic-plastic problem solution using finite elements method.

For calculation simplification thin-walled claddings approximation has been used. For plastic strains determination theory of unisotermic anisotropic flow has been used. Plastic deformation curve has been used in the form of quasi-linear function determining plastic characteristics of cladding alloy Zr+1%Nb.

Under cladding thermal creep process description under accidental situation Zr+1%Nb alloy creep rate of temperature dependence has been used in form: $\dot{\varepsilon}_{ef}=c\sigma^{\nu}\exp(-T_o/T)$, where σ_{ef}- effective stress, ν,c,T_o-constants. At high temperatures interaction between Zr and water steam has been simulated. Oxide layer thickness has been determinated from kinetic equation solution:

$$\frac{\partial}{\partial\tau}(\delta^2) = A\exp(-B/T),$$

where T-temperature, δ-oxide layer thickness, A,B-constants. Two criteria have been used for determination of rod cladding depressurization:

1. Plastic and creep deformation reach up the limit value. These limit values depend on temperature.
2. Cladding oxidation on 98% on its thickness.

Results of comparison between experimental and calculation data about WWER-440 rod claddings depressurization temperature depending on inside and outside pressure overfall are presented on fig.5.

Experimental data have been obtained on plant with rods imitators, which warming up has been conducted by electric currant in laboratory conditions.

3.2 *Fuel and rod claddings destroy*

Using mathematical model considers rod melting. In particular, molten substance break of cladding oxide film; drops of molten substance folling down along the outside rod surface and determination of position at which the mixture become solid. For which axial layer in the rod we determinate whether surface oxide layer had been destroyed at this time-step or not. If not, then calculation of molten substance moving is not conducted. If destroy take place, then molten fuel and cladding flow through break, and position where molten substance becomes solid are calculated.

Program "STALACTITE" contains the model simulating formation of porous fuel and claddings fragments. They are formatted in a result of thermoshock, appearing under cold water pouring of core cavity and shortness in result of oxidation. In accordance with [2] shortness and fragmentation of oxide rods occur under $\Delta r<0,1$ mm, where Δr- thickness of unoxide cladding. It is assumed that shortness rods crumble to pieces under cladding cooling to value $T_{clad} \leq T_{sat}+T_x$, where T_{sat}- coolant saturation temperature, $T_x \cong 500 \div 700^{\circ}$.

The third mechanism of rods destruction is fuel and cladding dispersion formation under sharp power increase. In the case dispersion formation from great number of rods explosion takes place in reactor.

Program contains models, determining character sizes of dispersion and heat irradiations coefficient from dispersion to the coolant.

Fragments of rod destruction, obtained with help of program "STALACTITE" are presented on fig 6.

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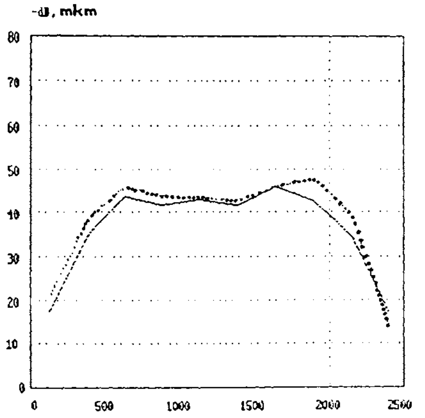

Fig.1. Axial distribution of rod diameter change for 1-st rod

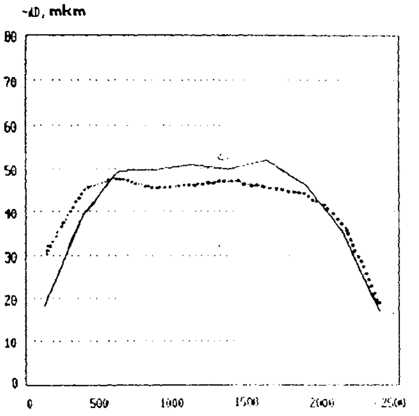

Fig.2. Axial distribution of rod diameter change for 2-nd rod

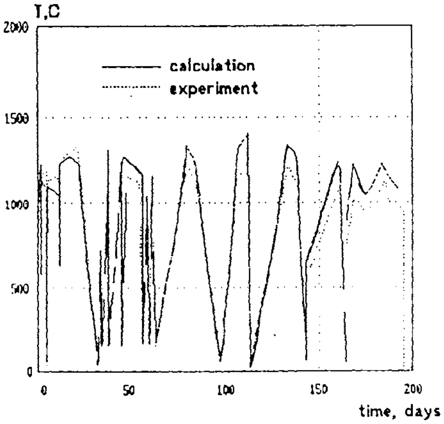

Fig.3. Time-dependence of fuel temperature

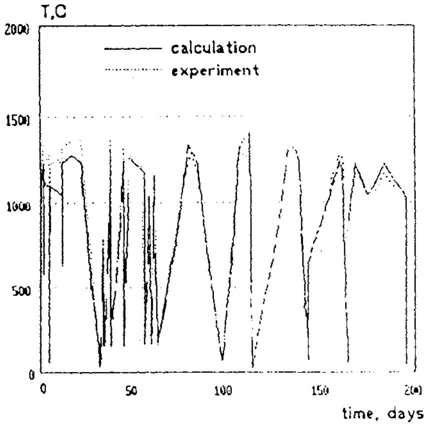

Fig.4. Time-dependence of fuel temperature

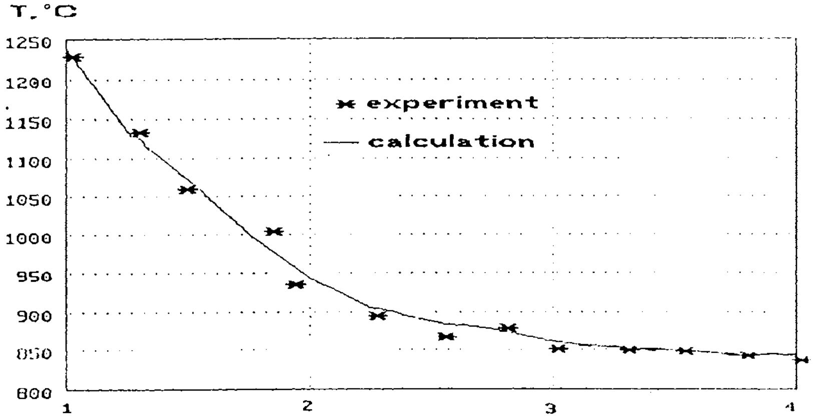

Fig.5. Depressurization temperature dependence on pressure overfall

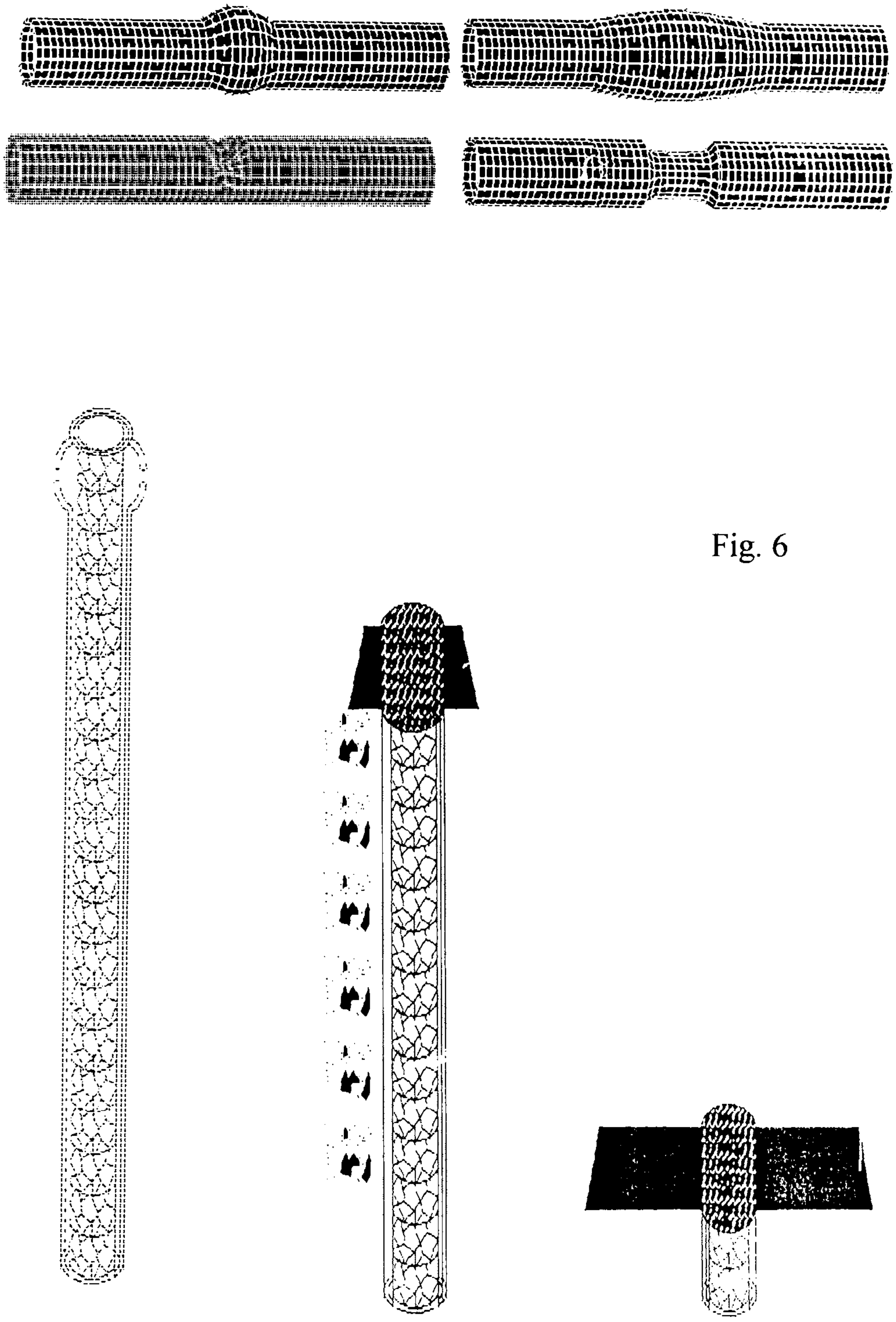

Fig. 6