RESULTS OF EXPERIMENTAL INVESTIGATIONS FOR SUBSTANTIATION OF WWER CERMET FUEL PIN PERFORMANCE

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Abstract

The out-of-pile experiment results on interaction of the cladding and matrix materials and uranium dioxide at cermet fuel temperature for normal operating conditions of the WWER-440 reactor are analysed. Cermet fuel element behaviour under the maximum designed damage of the WWER-440 reactor is considered. In the AM reactor loop a fission product output from the unsealed cermet fuel elements have been studied.

Introduction

The cermet fuel pin shown in fig. 1 has a monolithic type design that is as follows: a fuel core consisting of uranium dioxide particles ("middlings") surrounded by metallic matrix with good physical, thermophysical and corrosion-resistant properties is rigidly bonded with a Zr + 1 % Nb clad in a metallurgical or diffusional way.

Thermal resistance at a "cermet fuel - clad" boundary is to be minimized, and a cermet fuel core must have good thermal conductivity, so that the maximum fuel temperature should not exceed the matrix melting point as well as the temperature at which strong interaction of fuel pin components begins. The cermet fuel composition must have good corrosion and erosion resistance in the coolant to ensure safe reactor operation even if some unsealed fuel pins are available.

In the present paper consideration is given to results of pre-reactor and post-reactor tests of pins with cermet fuel consisting of uranium dioxide particles in the silumin matrix.

1. Investigations of thenrnophysical properties of cenmd fuel pins

1. 1. Measurement of fuel thermal conductivity

Cermet fuel specimens 7,8 mm in diameter and 20 mm in height consisting of 60% vol. $U0_2$ + 40% vol. silumin have been investigated. Cermet thermal conductivity measurements have been carried out in the experimental unit "KS" in steady state by the plate method using as a primary standard an Armco-iron specimen having known thermal conductive. The measurements have been carried out in a vacuum of $\sim 10^{-3}$ Pa in a temperature range 100 - 500°C.

The measurement relative error was 12% at the 100°C temperature level and 7% at higher temperatures.

Average values of cermet fuel thermal conductivity are given in Table. 1.

1.2 Measurements of the resistance of clad-fuel bonding

Testing of "fuel composition-clad" bonding degree has been carried out by the active thermal method with moving of a fuel pin through the central hole of a tubular furnace. Evaluation of the bonding degree was carried out by the time of heating a external surface is less fuel pin external surface up to a specified temperature. If there exists a thermal resistance in a zone of contact, the heating up time of the than if an ideal thermal contact takes place. For temperature registration the thermal indicator of melting (TI-85) was used that was applied on entire surface of a fuel pin. By increasing the heating time and locating the thermal indicator melting zones, one can reveal zones with still lower and lower thermal resistance at the clad-fuel boundary.

Table 1.

Values of cermet fuel composition thermal conductivity (λ)

Type of composition	λ, W/m·°C								
60% vol. UO_2 +	100	150	200	250	300	350	400	450	500
40% vol. Silumin	39,0	38,1	37,4	36,6	35,9	35,1	34,3	33,7	32

For quantitative evaluation of thermal resistance a program "SKOPO 3" has been developed that was intended for calculation of temperature field in a fuel pin. According to this program relationships of time, during which the fuel pin surface attains the thermal indicator melting point, to a value of the contact thermal resistance (Fig. 2) were obtained; taking them as a basis, by the intervals of times, found experimentally, heat transfer conditions were being determined.

Analysis of test results showed that in investigated fuel pins thermal resistance at the fuel-clad boundary is less than $1 \cdot 10^{-5}$ m^2·oC/W (the limit of this method's sensitivity).

Calculations of temperature fields in cermet fuel pins with use of received thermophysical characteristics shawed that a ma)dmum temperature in the centre of a cermet fuel pin (60% vol. $U0_2$ + 40% vol. silumin) is: $(T_{fuel})_{max}$= 442°C - in the WWER reactor.

Pre-reactor isothermal tests were carried out at temperatures close to this one.

2. Investigations of compatibility of fuel pin materials in the process of a prolonged isothermic exposure

For this purpose simulators of cermet fuel pins (60% vol. $U0_2$ + 40% vol. silumin) have been subjected.

Fuel pin simulators were placed into argon-filled containers filled with argon and tested in the process of a prolonged isothermic exposure (τ =2700 hours) at the temperature 500°C.

After the test no cracks, bowings, distortions or other defects have been discovered in the fuel pin simulators.

The simulators have retained their geometric stability. The clad diameter changes were within the limits of measurement error.

Autoradiographic investigations have showed that at T = 500°C in the time τ = 2700 hours the diffusional penetration of uranium into the silumin matrix does not exceed 10 μm.

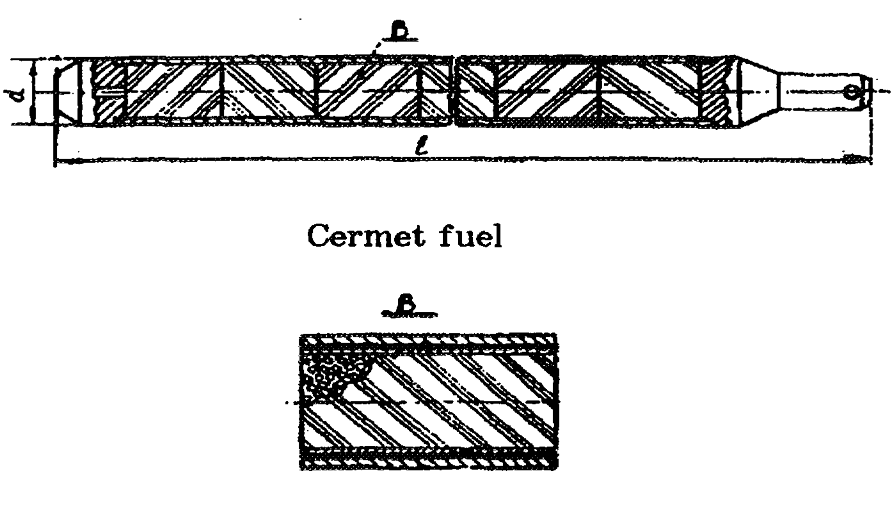

Fig. 1. Cermet fuel rod for WWER-440 reactor.

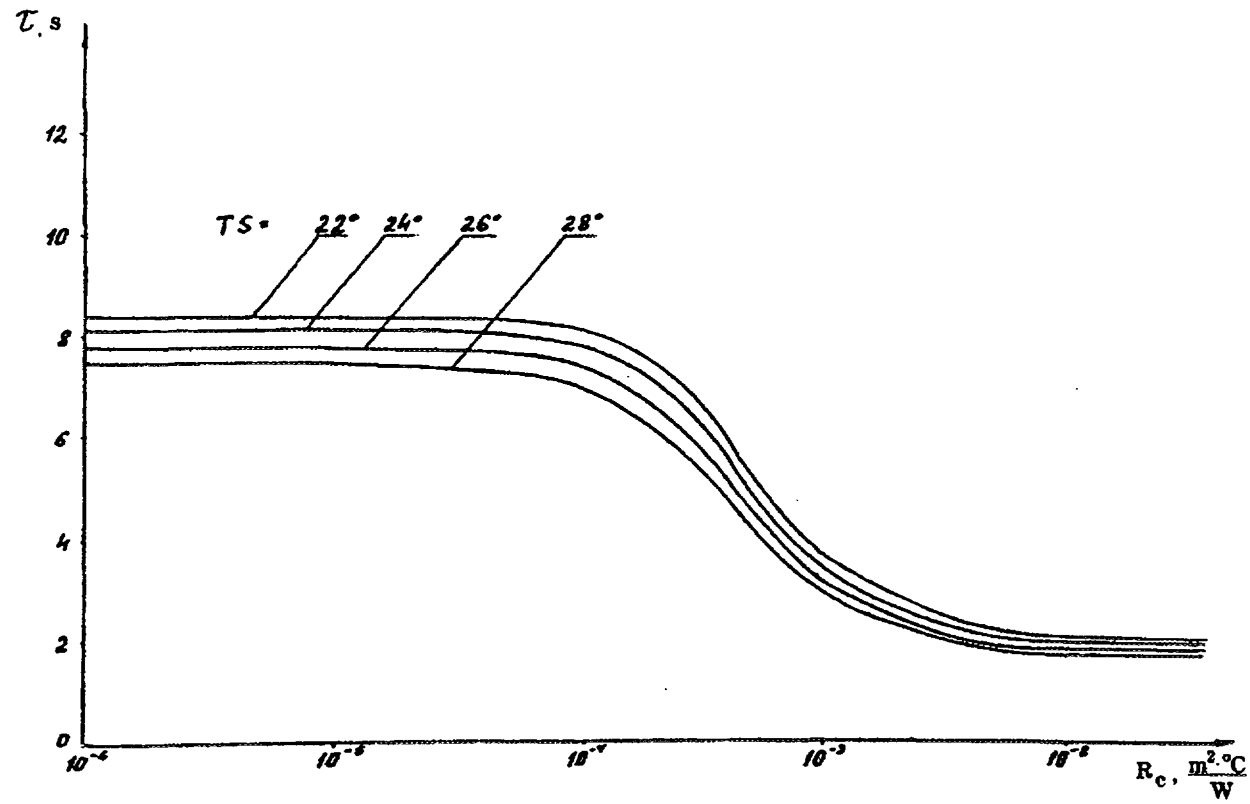

Fig. 2 Dependence of heating time (to 80 °C) of a fuel pin with 60% vol. UO_2 + 40% vol. silumin on contact thermal resistance

Metallographic anabpis of the fuel composftion has shown that the exposure of fuel pins under isothermal conditons does not lead to crack and void formation in the fuel composftion. No difference in fuel structure has been revealed in comparison with initial structure. lsothermic exposure of fuel pin simulators at the temperature 500°C causes no rise of the silumin microhardness both in the matrix base and immediately near the dioxide particles, and it remains comparable with microhardness of silumin in initial state (Table 2).

The distribution of main elements of fuel compositions after tests is presented in Fig. 3. One can see that uranium concentration at the $U0_2$ particles - matrix boundary reduces practically to zero values in areas having extent of no more than 10-15 μm.

Concentration of aluminium and silicium at the matrix-$U0_2$ particles boundary reduces to zero values in areas having extent of no more than 10-12 μm. Diffusional penetration of aluminium and silicium into $U0_2$ particles at the temperature 500°C does not take place.

X-ray phase analysis of cermet fuel has shown that main phases of the fuel compositions tested at the temperature 500°C are the initial components of the cermet fuel: $U0_2$, AI, Si. Exposure of fuel pin simulators under the temperature 500°C leads to appearance of such phases as UAI_3 and $USiO_4$. But their quantity is insignificant and they can be registered not in all zones of the cermet fuel.

Table 2

Microhardness of areas of fuel composition.

Matrix material	Particles	Matrix microhardness, kg/mm² close to particle	base
Initial silumin	-	-	50-90

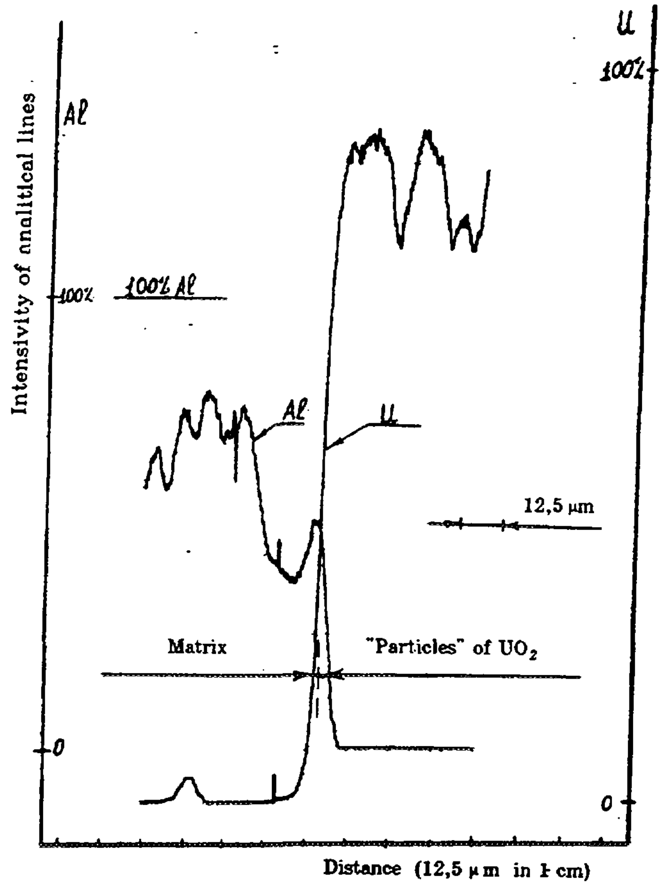

Fig. 3. Distribution of Al and U at the boundary "particle UO_2-matrix" after tests at temperature 500°C (a model)

3. Tests of fuel pin simulators with cermet fuel under conditions of design-basis accidents

Calculation investigations carried out previously showed that in the process of a maximum design-basis accident (MDBA) cermet fuel pins can attain the temperature up to 400-500°C (Fig. 4, 5).

Tests with fuel pin simulators have been carried out in the atmosphere of superheated water steam under the pressure of 0.15-0.25 MPa and at the temperature 500°C during 6 hours.

Exposure of fuel pins to superheated steam at the temperature 500°C during 6 hours leads to formation of dense dark-coloured oxide films on the surface of clad of Zr + 1 % Nb alloy. Received experimental results concerning the weight gain of fuel pin simulators investigated and of reference fuel pin simulator have shawn that corrosion resistance of fuel pin clads is on the level of corrosion resistance of a reference pin (wfth clad of fuel pin of standard design).

Fuel pin simulators have not changed their dimensions in the resuft of tests.

4. Tests of unsealed cermet fuel pins

4.1. Autoclave tests

With the purpose of determining of cermet fuel composition resistance in the coolant the autoclave tests with unsealed clads of fuel pin simulators and fuel composition specimens have been carried out in the following conditions: temperature 310°C, coolant pressure 10.6 MPa.

Autoclave tests of fuel pin simulators with artificial defects have been carried out during 72 hours. After autoclave testing the fuel pin clads have acquired the even black colour. Changes of fuel pin external diameter have not taken place. Dimensions of slots in specimens practically have not changed.

Analysis of water in which these fuel pin simulators has been tested showed absence of uranium in it (the sensitivity of method is 0.3 mg/m).

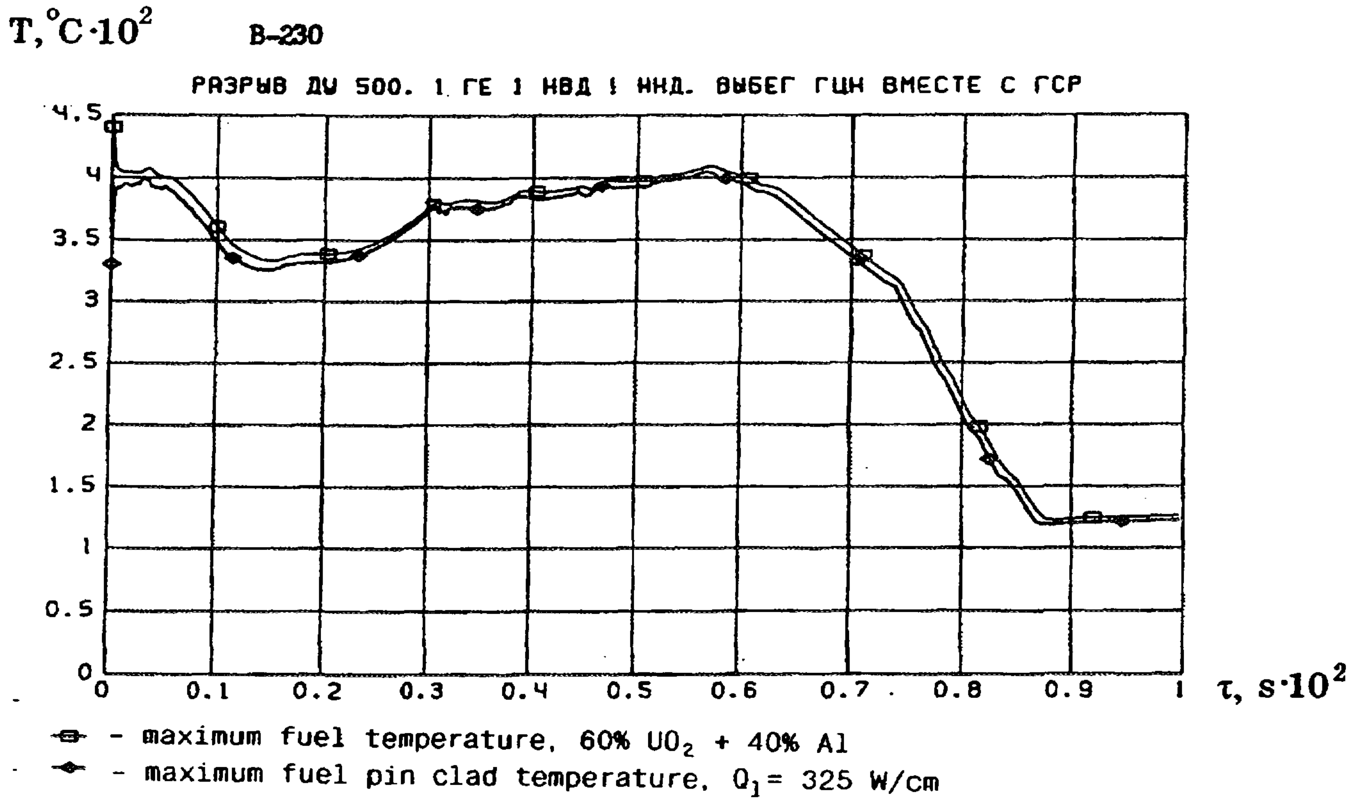

Fig. 4. Fuel rod temperature in the process of a maximum design-basis accident.

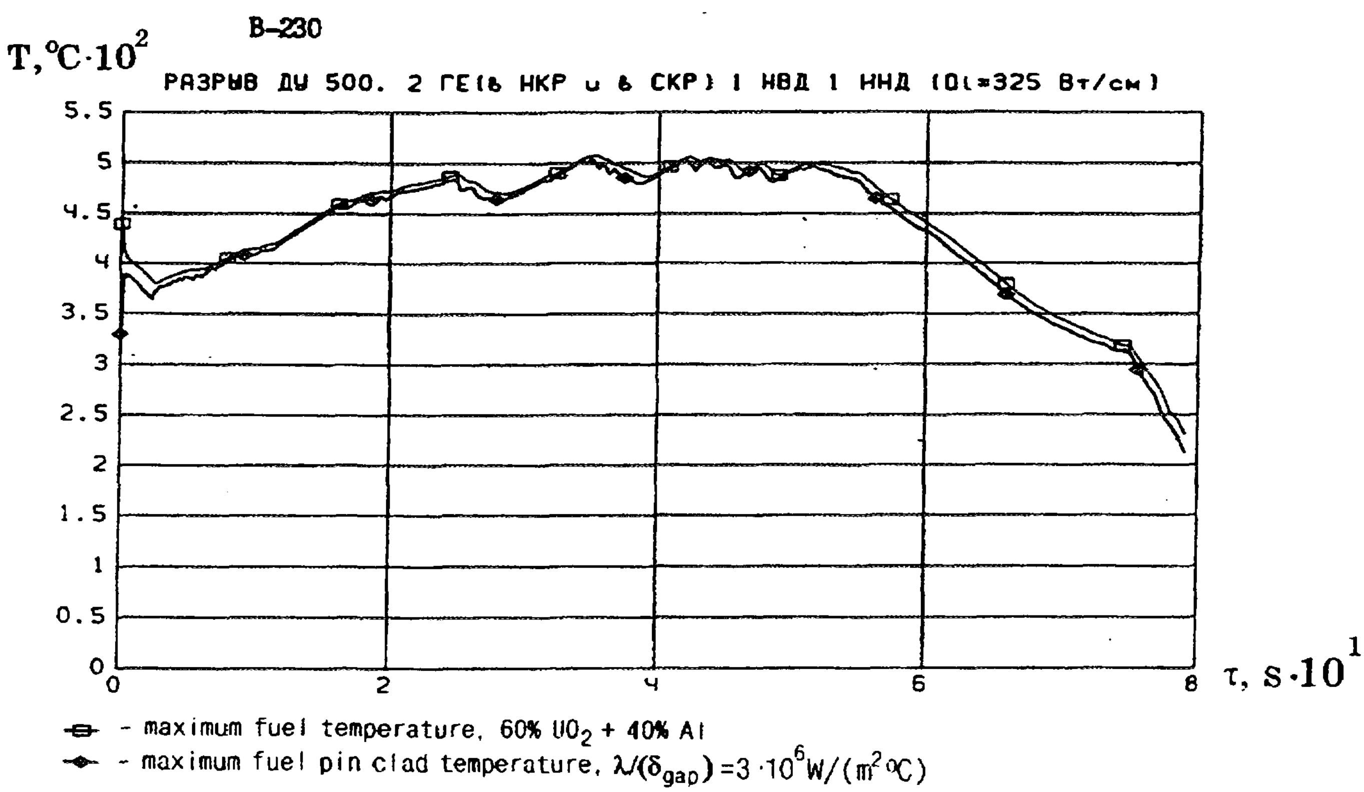

Fig. 5. Fuel rod temperature in the process of a maximum design-basis accident.

Autoclave tests have been carried out as well with a cermet fuel composition (60% vol. UO_2 + 40% vol. silumin) without cladding during 10 hours. After autoclave tests specimens have not changed their weight, they retained their form and microstructure. With these specimens more prolonged tests (τ = 50-200 hours) were also carried out. Investigations of tested specimens have shown that with the increase of contact time of specimens and coolant a non-significant increase of oxides in matrix takes place.

4.2. In-pile tests

A good corrosion resistance of cermet fuel composition (60% vol. UO_2 + 40% vol. silumin) in the coolant having operating parameters had been revealed in autoclave tests and made a basis for realization of unsealed fuel pins in-pile testing. For this purpose a special channel-loop has been created in the AM research reactor. The channel contained 3 fuel pins. Every fuel pin consisted along its length of three parts fully isolated one from another (Fig. 6), a summary length of a fuel pin being 930 mm. Dimensions of its clad were 9.15 mm x 0.7 mm. Its middle part 60 mm long had in its clad a through slot imitating a crack. Its dimensions were 0.45 x 9.0 mm.

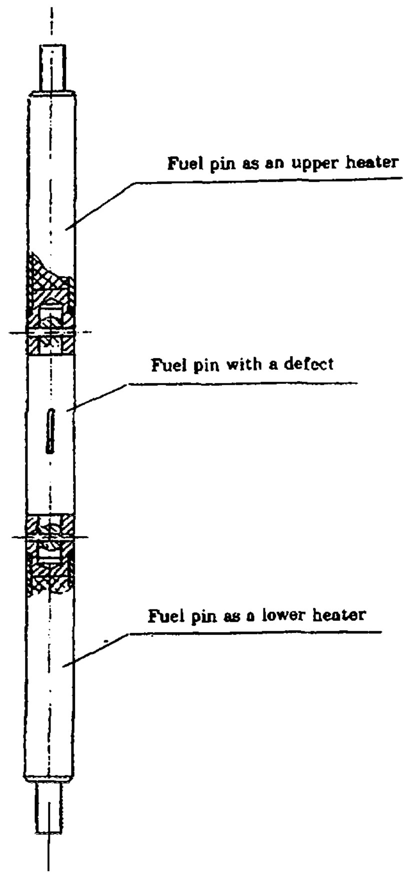

Fig. 6. A sectional fuel rod with an artificial defect.

Table 3

Temperature distribution along the radius of a cermet fuel pin

q_l, W/cm	T_{clad}, °C	$T^{fuel}_{surface}$, °C	T^{fuel}_{centre}, °C
138	296.0	314.0	344.0

When the reactor operated with power N = 28% of nominal, the linear thermal load of a fuel pin was q_l = 138 W/cm.

The outlet coolant temperature was 227-230°C.

The temperature distribution along the fuel pin radius in the process of a test is given in the table 3.

For investigation of release of fission products from a cermet fuel the following methods have been used:

- A gamma-spectrometer method (without sampling) for analysis of radionuclides that release out of a fuel composition and enter into the coolant. For this purpose a microcircuit to the channel-loop, a detector and a sensor of the exposition dose rate have been created. Pulses from the detector output were fed to the input of a multichannel pulse analyzer connected with a control and information processing unit;

- Sample-taking with subsequent gamma-spectroscopic analysis of radionuclides;

- Continuous measurement of exposition dose rate on the operational section (a standard method). In-pile tests were being carried out during two months.

5. Conclusions

The analysis of fission products release into the coolant allowed to make following conclusions:

a) During two-month fuel pin operation most fission products were retained by the cermet fuel rather firmly. The main mechanism of the fission products release is a direct emission.

b) A strong influence of acidity of the coolant medium on "washing-away' and "healing" of the fuel composition through clad cracks is noted to exist. During the operation in a stationary regime the operation).