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RESEARCH METHODOLOGY AND EQUIPMENT TO STUDY PROPERTIES OF IRRADIATED FUEL UPON IN-CELL LOCAL HEATING

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ABSTRACT

The repot is concerned with schematic diagrams of in-cell equipment for study the thermal and corrosion effects occurred in fuel elements and their components on local heating. Described are types and parameters of tests performed at the stands used muffle and induction furnaces. Some technical and methodological aspects of equipment used for local heating are discussed. An illustration of technical ability of the procedure and equipment is in-cell tests of the SM-2, BOR-60 and VVER-1000 irradiated fuel elements. Some qualitative and quantitative distinctions between the thermal and corrosion effects of irradiated and unirradiated fuel elements are presented.

1.INTRODUCTION

In SSC RIAR several hot laboratories have operated for a long time which applied for material science, non-destructive tests of full-size fuel elements and assemblies, production of fuel elements and assemblies, manufacture of radioactive sources. Research methodology and remote handling equipment applied at these laboratories have been described in various prospects, articles and reports in some details.

At the same time the new technical means and research methods of irradiated fuel are continuously being developed. In particular, technical means and methods for study of properties of fuel, fuel element claddings and fuel elements themselves with in-pile and in-cell off-normal heating are under development.

One trend of the new developments developed at RIAR is based on local heating of fuel elements in hot cell [1].

It is this method, its abilities and some results of performed investigations that have been described in the report. The subject of investigations performed by this method is determination of qualitative and quantitative distinction between the thermal and corrosion effects occurred on off-normal heating of irradiated and unirradiated fuel elements. The type and value of these effects may be criterion of fuel element reliability under various off-normal reactor events and basis for the scenarios and calculation codes described the propagation of these events.

2. EQUIPMENT AND RESEARCH METHODOLOGY

2.1. The main features of equipment and method of local heating

The schematic diagram of testing areas of stands for local heating are presented in Fig.1. One can see that either muffle or induction furnace is used for heating of specimens. The testing area of the stand with induction heating is fitted with a glass window for inspection and video recording. The possible medium within the test area may be He, He+H_2O (vapour), He+H_2O (liquid) and others.

Depending on the subject of testing the heaters can be different in size. In the performed tests the inside diameter changed from 20 to 80 mm and from 100 to 1000 mm in length.

In some tests the heater and specimen are in the horisontal arrangement. In case of vertical position of fuel element and overfilling its bottom part with water, three zones specific to one off-normal condition of the VVER core are formed in the volume of the test area which are related to water boiling and evaporation, overheating of fuel element and vapour, condensation of heated vapour and reverse movement of condensate. The vertical arrangement is convenient for tests with the adjustable cooling rate of the heated specimens, their quenching, melting and interaction of melt with water and other materials (steel, concrete, etc.).

A restricted length of heating zone allows for applying the heaters of small size and power as well as limited release of radioactive contamination.

At the same time the restricted length of heating zone does not interfere with testing specimens of the different types ranging from heating a single annular one in inert gas for mechanical tests to melting and runing off the melted fuel element bundle into water.

The technical results are due to carry out off-normal tests by the different type specimens at the small-size stand arranged in the normal hot cell.

In testing the small number of fuel elements, the metholodgical results consist in obtaining a large body of information independent of the non-controlled parameters of manufactured and irradiated fuel elements. These results are specified by possibility of independent tests of a single fuel element at some areas and by realization of different temperatures at one heating area.

2.2 Study of the main thermal and corrosion effects

When testing at the local heating stands, one part of information is obtained in the process of testing and another one - during the subsequent material science study by destructive and non-destructive methods. The main thermal and corrosion effects occurred in the specimens and studied in the process and after heating are as follows:

- cladding deformation under the effect of internal gas pressure;
- type and depth of internal and external corrosion of cladding;
- type and depth of fuel corrosion;
- gaseous and non-gaseous fission products release (Kr, Cs);
- hydrogen release in Zr corrosion;
- helium release from B_4C;
- axial and radial mass-transfer of non-gaseous fission products (Cs,Ru);
- metallurgical fuel-cladding interaction;

- metallurgical and mechanical interaction of fuel assembly components;
- change of metal cladding structure, strength and plasticity as a result of heating, corrosion and quenching.

The axial temperature gradient available at the area of fuel element heating makes problem in obtaining data about temperature dependence on gas release effects (Kr, H_2, He).

At the same time it facilitates obtaining data about temperature dependence on other effects.

3. TYPES AND PARAMETERS OF TESTS AND RESEARCH RESULTS

The main research types and parameters available at the stands with muffle and induction heating designed and manufactured at the RIAR are presented in Table 1,2.

The main data of some types and parameters of specimens and performed tests are given in Table 3.

Some typical results of the performed tests and further material science studies are presented in Fig.2-8.

Taking into account the subject of the present meeting, the report does not include in detail the performed investigations. It is reasonable to note the main technical and methodological aspects to focus attention on some results of the performed tests and investigations.

It should be noted that two-three independent tests have been performed using the heater 220 mm long on the SM-2 reactor full-size fuel element of the total long 420 mm. This has made possible the determination of burn-up influence on the thermal effects appeared in the fuel element having a large burn-up gradient along its full length. To obtain the similar function by the stand of uniform heating, the transportation and dismantling of two-three fuel assemblies as well as testing of two-three fuel elements would be required. Even more tests would be required to obtain the observed effects as a function of temperature and continuous heating.

Fig.2 shows kinetics of fission gas release from the SM-2 reactor full-size irradiated fuel element under test. The peaks of gas release are divided in time. The first peak is due to the cladding damage at the area of maximum temperature. The second peak is due to the cladding damage at the area of less temperature during the more prolonged exposure. The third peak is related to the fuel cracking at cooling up to $T \leq 250°C$.

Fig.3 shows reasons and nature of cladding damage of the SM-2 reactor fuel element. The cladding was failed as a result of fission gas release from the UO_2+Cu dispersive fuel on heating the fuel element. The pressure of gas resulted in deformation of the stainless steel cladding. The intergranular cracks were formed on the internal surface of the cladding in the points suitable for the concentration of bending stress. The propagation of these cracks to a whole depth of cladding resulted in its leakage and release of fission gas.

No other similar thermal effect was observed on heating the unirradiated fuel element. Damage of unirradiated fuel elements was caused by other reasons. In this case the temperature was increased by several hundred degrees. Therefore, it can be said that scenarios of the emergency propagation in the cores contained the similar fuel elements and the codes for calculation of the fuel elements reliability based on the experiments of the unirradiated fuel elements are incorrect.

Three-five independent tests were carried out using the BOR-60 full-size fuel elements of the total length 1100 mm. Figs. 4 and 5 demonstrate a large data file for the rate of cladding corrosion with local heating of the small number of full-size fuel elements. The more number of tests was performed at ANL to obtain the similar function on heating the EBR-II fuel element fragments [2]. There were observed the qualitative similarity in corrosion effects obtained at ANL and RIAR. The difference in the values of the cladding corrosion rates is due to a distinction between the construction of fuel elements.

With local heating of unirradiated and irradiated fuel elements contained metallic fuel the difference was found between the temperature values of intensive corrosion cladding damage. The temperature of irradiated fuel elements was less by 50-100°C because the fission gases retained in the fuel caused swelling and provided a tight fuel-cladding contact. Such contact does not present in the unirradiated fuel elements.

Figs. 6 and 7 demonstrate the technical and and methodical ability of local heating of unsealed fragments which were cut from the VVER -1000 full-size irradiated fuel element. One can see external appearance, micro- and macrostructure cross-section,maximum temperature and ^{85} Kr release as a function of time for the specimen after testing in the heated water vapour. The temperature gradient was 200°C with the specimen 100 mm long. The external appearance of specimen was shown to have the temperature effect on oxidation of zirconium cladding. Five cross-sections of this specimen was studied. Within the range of maximum temperature the cladding was oxidized in the whole depth. Within the range of minimum temperature the depth of corrosion was less by several times.

Some difference between behavior of the irradiated and unirradiated zirconium claddings was found to occur in testing the VVER-1000 fuel elements. In particular, the irradiated claddings were found to be oxidized more intensively compared with the unirradiated ones. The internal surface of irradiated claddings is oxidized more intensively compared with the external one.

At abnormal high temperature reached the temperature of zirconium melting the irradiation effects have not yet been determined. However, the main thermal and corrosion effects occurred in unirradiated zirconium claddings have been determined at temperatures reaching the temperature of melting at the out-cell stand of local induction heating. Fig.8 shows the effects of interaction between the melting zirconium cladding and water.

4. CONCLUSION

The methodology for study of the properties of irradiated fuel by local off-normal heating of full-size fuel elements and their cuts has been developed in RIAR. The equipment has been manufactured to carry out the different types of thermal and corrosion tests in the gas and vapour-gas media including such tests as: "cooling of specimen with the regulated rate", "quenching of heated specimen in water", "thermal cycling of specimen". This equipment is expected to be placed in the normal hot cell.

The different type fuel elements were under tests of various thermal and corrosion effects. It was found that some thermal and corrosion effects of irradiated fuel elements may be different from the similar effects of unirradiated fuel elements. As a result, the scenarios of off-normal reactor event and the calculation codes based on the properties of unirradiated fuel elements may not be correspondent to the reality. For correction of the scenarious and calculated codes the number and type of in-pile and in-cell off-normal tests of irradiated fuel should be increased.

For this purpose it should be used the high effective technique of fuel element local heating and universal in-cell stands similar to those constructed in RIAR.

Equipment for local heatings, methodology and results of performed tests may be considered as the subject for the cooperation.

REFERENCES

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2. A.B.Cohen, H.Tsai and L.A.Neimark, "Fuel/cladding compatibility in U-19Pu-10Zr/HT9 - clad fuel at elevated temperatures".J.Nucl.Mater. 204(1993) 244.

Table 1

TYPE AND PARAMETER OF TESTS IN MUFFLE FURNACE

Parameter	Value	Type	Registered parameter	
			In test	After test
Max. temperature	1100°C	1.Depressurization	$DP = f(T, \tau)$	$\Delta d = f(T)$
Heating rate	0.1 ÷ 5°C/s		$^{85}Kr = f(\tau)$	$^{137}Cs = f(T)$
Length of uniform temperature area	30 ÷ 150 mm		$H_2 = f(\tau)$	
Test time	$10^1 \div 10^4$ s			
Medium	He(Ar);H_2O; He + H_2O	2.Cladding oxidation (one-way, two-way)	$H_2 = f(\tau)$	$\Delta_{corr.} = f(T)$ $\sigma, \delta = f(T)$
		3.Fuel-cladding interaction		— " —
Flow rate: He (Ar)	0 ÷ 200ml/min	4. Fuel oxidation	$^{85}Kr = f(\tau)$	$\Delta_{corr.} = f(T)$
H_2O (stab.)	0 ÷ 0.4ml/min			
H_2O(unstab.)	>0.4 ml/min	5. Flooding	$DP = f(T)$	$\sigma, \delta = f(T)$

Table 2

TYPE AND PARAMETER OF TESTS IN INDUCTION FURNACE

Parameter	Value	Type	Registered parameter	
			In test	After test
Max. temperature	$\geq$ 1900°C	1. Cladding deformation and depressurization	$\Delta d = f(T,\tau)$ $DP = f(T,\tau)$ $^{85}Kr = f(\tau)$ $H_2 = f(\tau)$	
Heating rate	1 ÷ 20°C/s			
Length of uniform temperature area	80 mm	2. Cladding oxidation (one-way, two-way)	$H_2 = f(\tau)$	$\Delta_{corr.} = f(T)$ $\delta, \bar{\delta} = f(T)$
Test time	$10^1 \div 10^4$s	3. Fuel-cladding interaction		— " —
Medium	He(Ar);H_2O; He + H_2O	4. Flooding	$DP = f(T)$	— " —
Flow rate: He(Ar) H_2O	 0 ÷ 200ml/min 0 ÷ 0.4ml/min	5. Fuel oxidation	$^{85}Kr = f(\tau)$	$\Delta_{corr.} = f(T)$
		6. Cladding melting and runing off	Kinetics	
		7. Eutectic formation and runing off	Kinetics	
		8. Interact. of melts with steel, concrete and water interaction		$\Delta_{corr.} = f(T)$

Table 3

TYPE OF SPECIMEN AND PERFORMED TEST

Type	Composition	Specimen state		Furnace type		Type of test	Medium	T^{max}, °C
		irrad.	unirrad.	muf.	induct.			
SM-2 full-size pin	st.steel, (UO_2+Cu)	+		+		1,2,3,4	He; H_2O	800
BOR-60 full-size pin	st.steel, $(UPu)O_2$, U,U-Pu	+		+		1,2,3,4	He	900
VVER pin fragments	Zr, UO_2	+		+		1,2,3,4,5	He; H_2O	960
Fragments of VVER fuel element claddings	Zr	+	+	+		1,2,5	H_2O	960
-"-	Zr		+		+	1,2,4,6,8	He; H_2O	1900
Cladding bundle of VVER pins	Zr		+		+	2,4	Ar; H_2O	1500
VVER fuel assembly combination	Zr, steel, ceramics		+		+	7	Ar	1900
HTGR sphere fuel element	graphite		+		+	1	Ar	1500
VVER absorbing element fragments	st.steel, B_4C, Dy_2TiO_5	+		+		2,3	H_2O	960

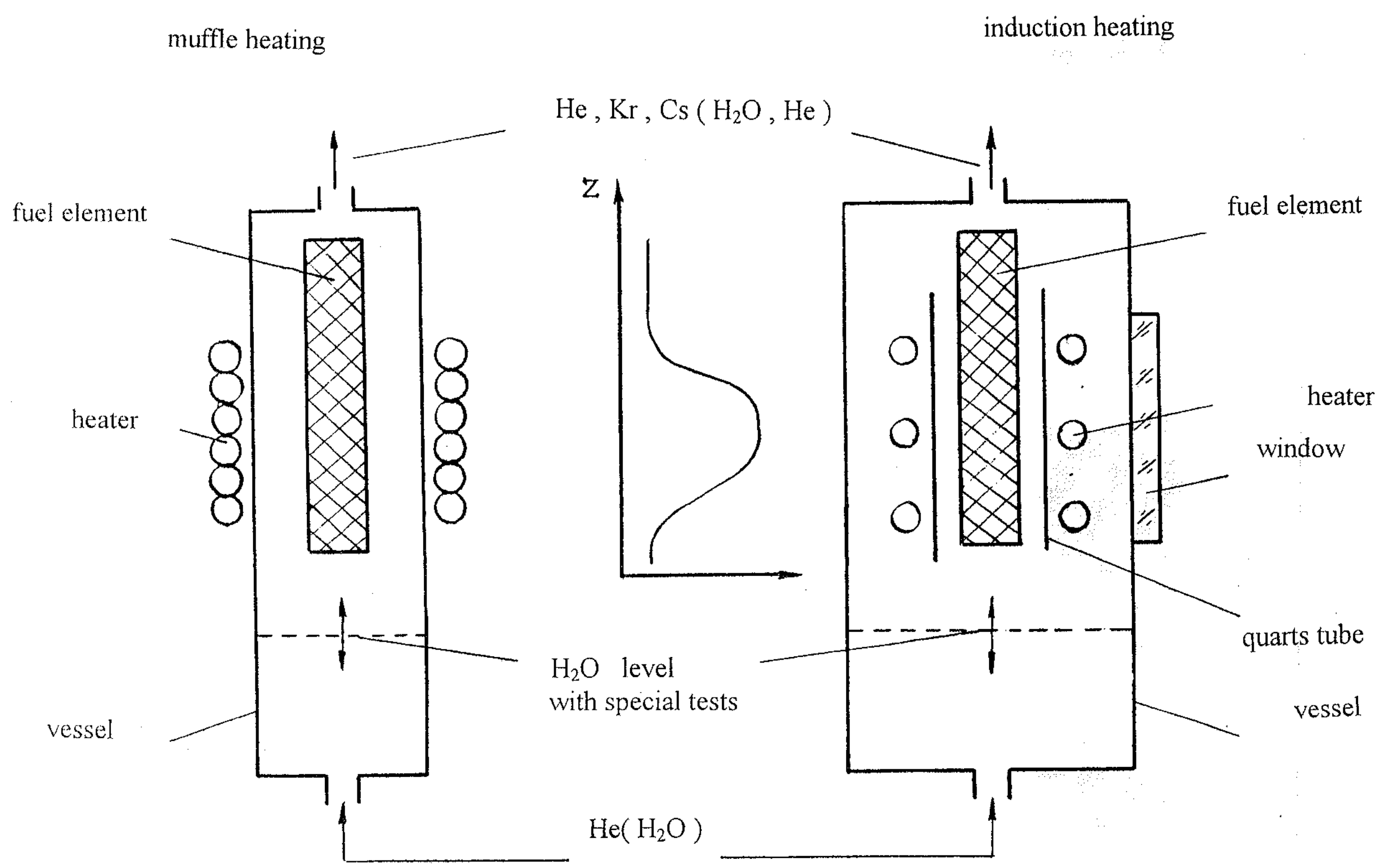


Fig. 1. Shematic diagram of stands for local fuel element heating.

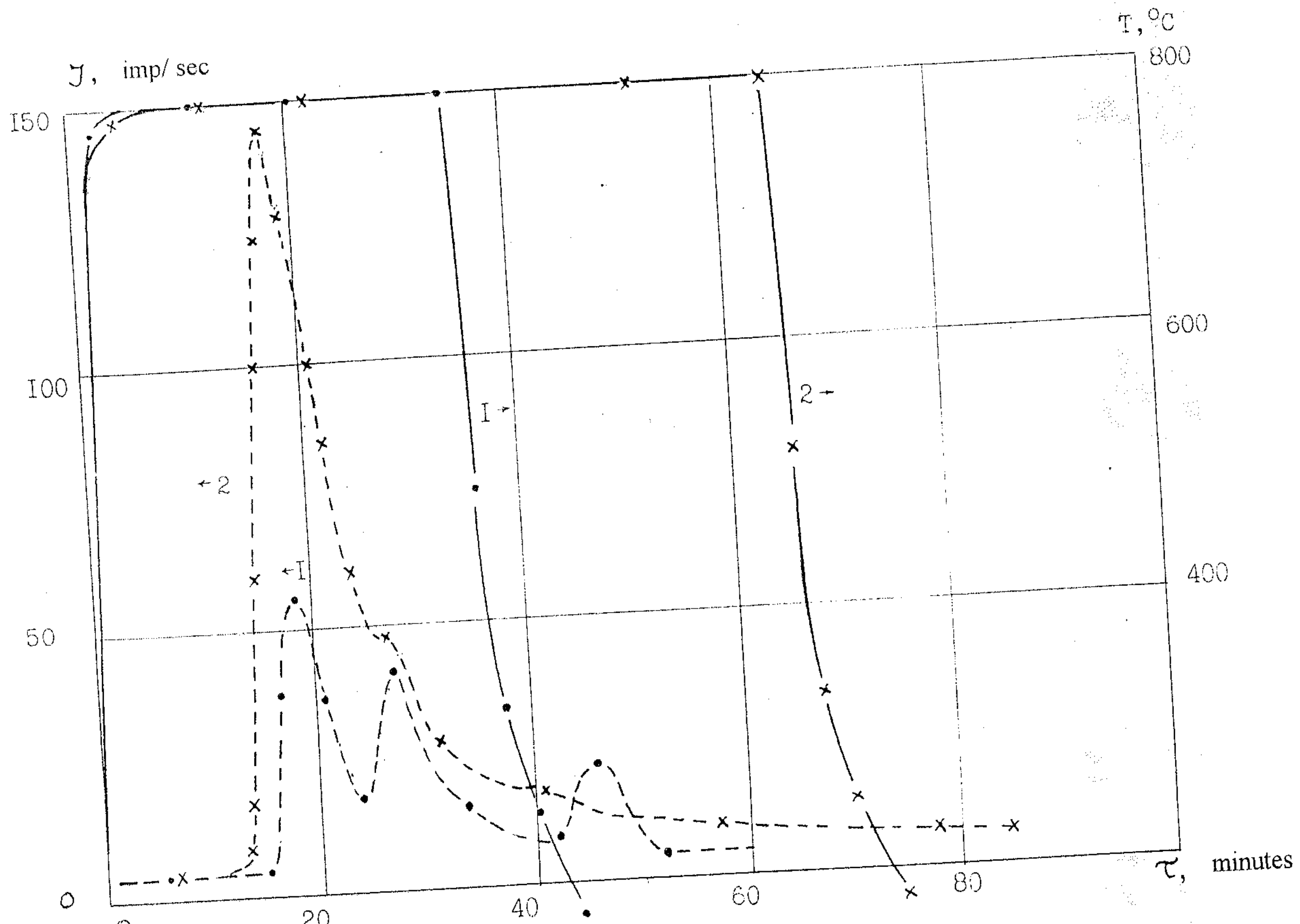
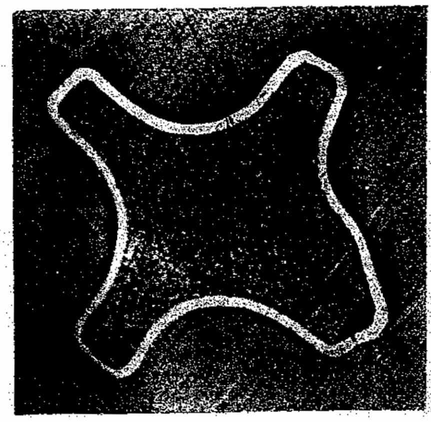


Fig.2 . Variation of temperature and ^{85}Kr release on heating the SM-2 reactor fuel element
1- fuel element № 11/11, He; 2 - fuel element № 9/12, He + H_2O.



x 10

x 100

x 100

x 400, etch.

Fig.3. The SM-2 reactor fuel element № 2/12 fuel assembly №10100186. Cross-section micro- and macrostructures after heating at 690° C x 30 minutes.

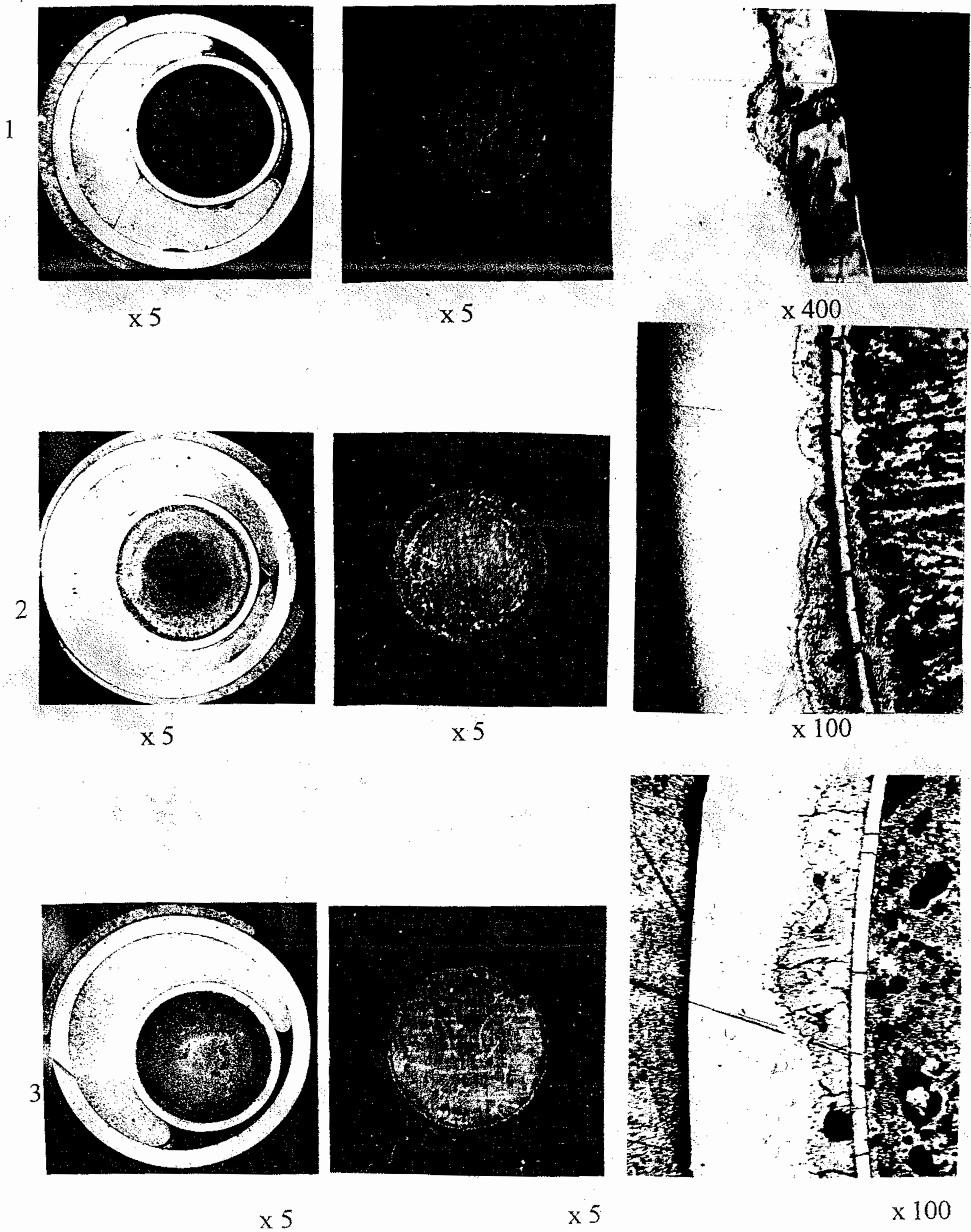


Fig.Y. Cross-section structures of heated fuel element № 22 of fuel assembly A3-14M :
ЭИ-847/W/U-15 wt.%Pu.

1-T_zx τ =760°x 90 min. B_z =6.2% h.a.

2-T_zx τ =800°x 90 min. B_z =6.2% h.a

3-T_zx τ =830°x 90 min. B_z =4.4% h.a.

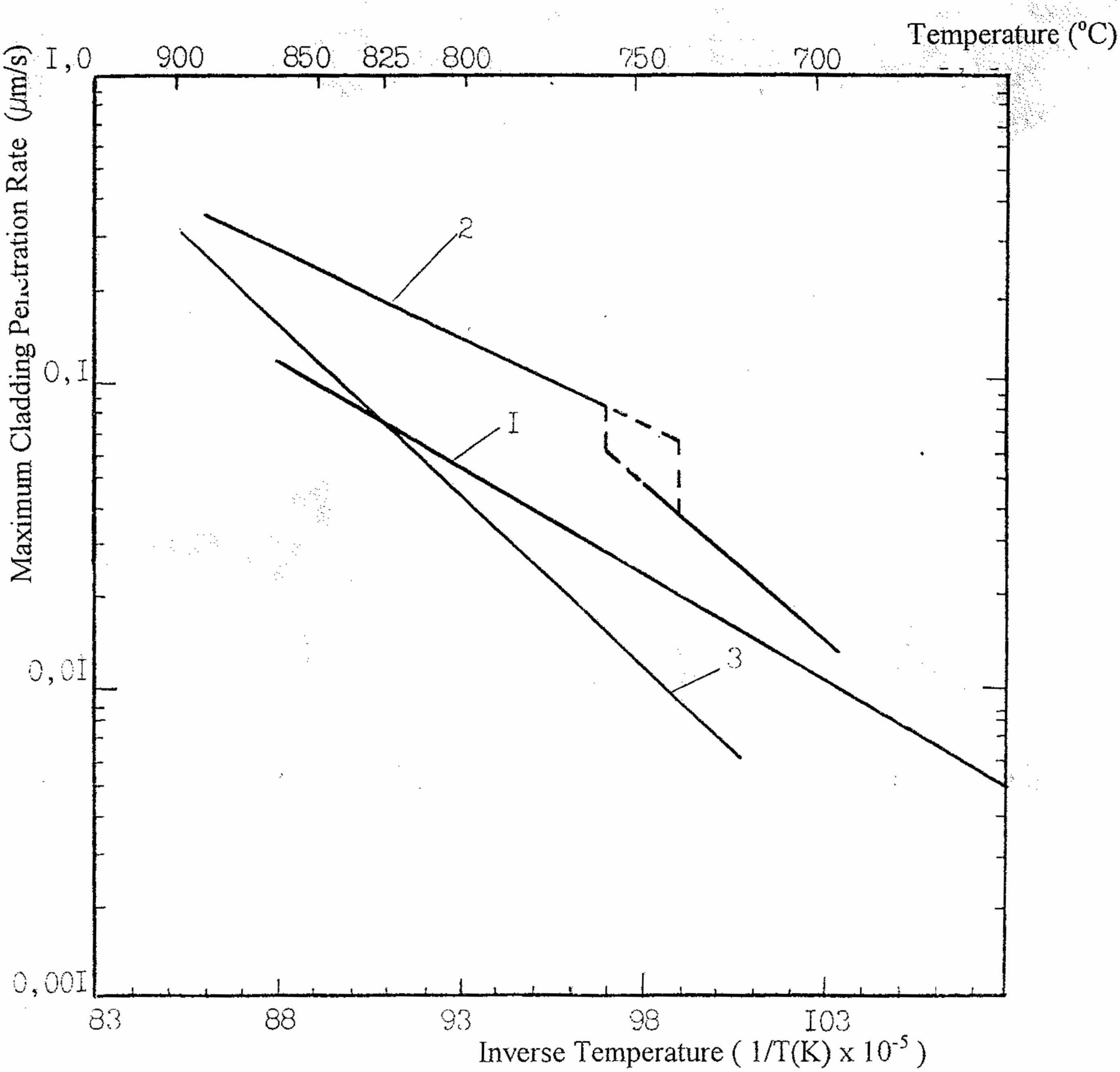
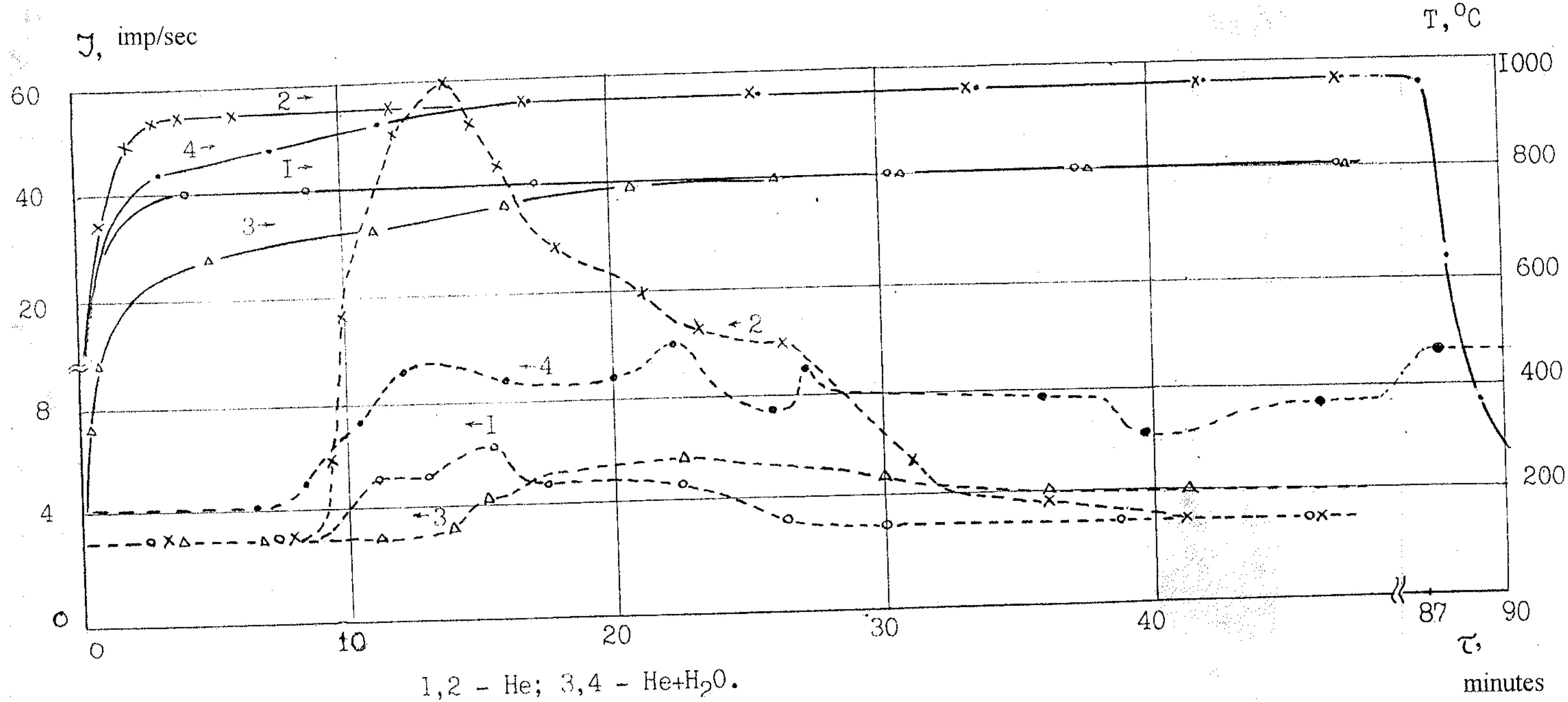


Fig.5. Cladding penetration rate vs temperature for 1-h tests

1- EBR-II reactor fuel elements after burnup B^{max} =5,6-11,1%h.a.
(fuel - U-19Pu-10Zr, cladding-steel HT-9, ANL results);

2- BOR-60 reactor fuel elements after burnup B^{max}=6,8%h.a.
(fuel - U-15Pu, cladding-steel ЭИ-847);

3- BOR-60 reactor fuel elements after burnup B^{max} =6,8% h.a.
(fuel-U-15Pu, cladding -steel ЭИ-847 with W coating)



1,2 - He; 3,4 - He+H_2O.

Fig.6. Variation of temperature and ^{85}Kr release in heating the VVER-1000 irradiated fuel element fragments (fuel assembly № 0329 ZAPS).

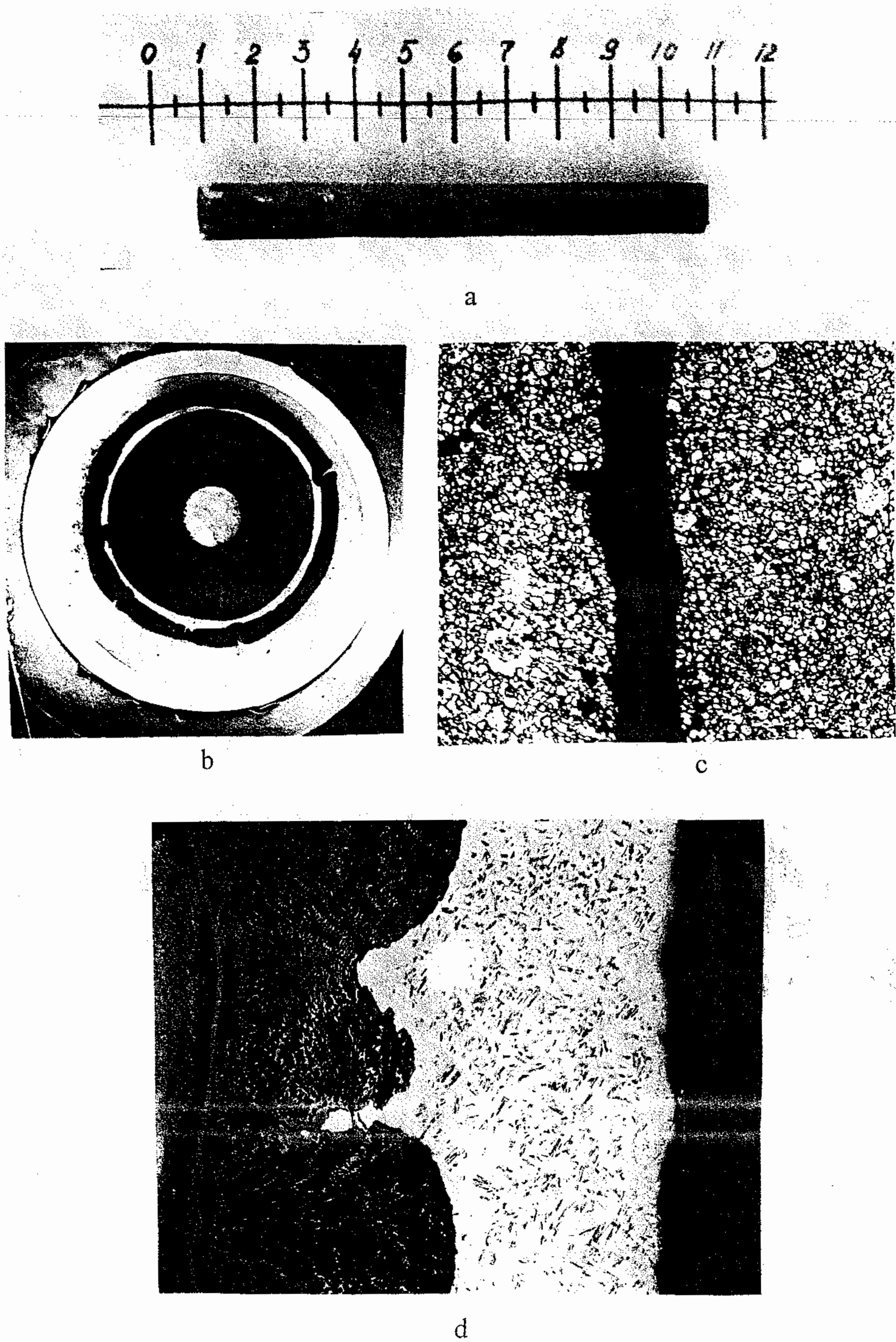
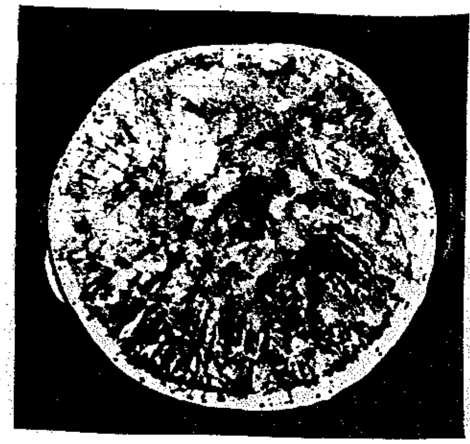
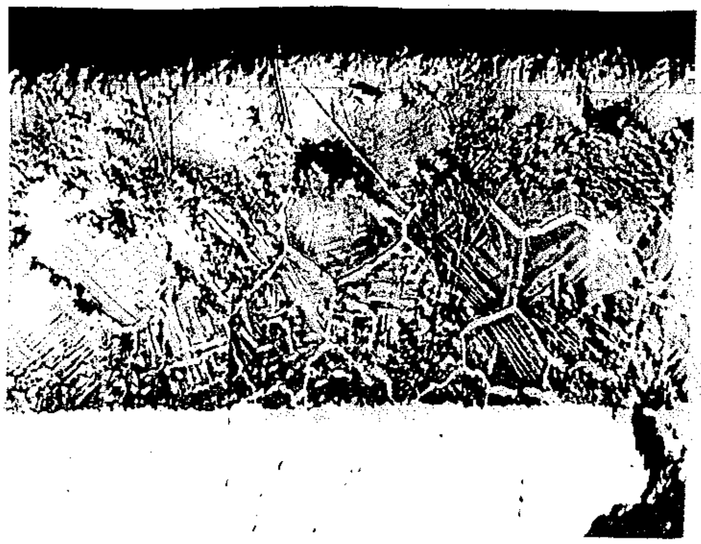


Fig.7. Appearance, cross-section macro- and microstructure of the VVER-1000 fuel element fragment heated in vapour-gas mixture at 950° C x 72 minutes;
a - appearanse, x1; b- macrostructure , x5; c- fuel, x100; d- cladding, x100.



a



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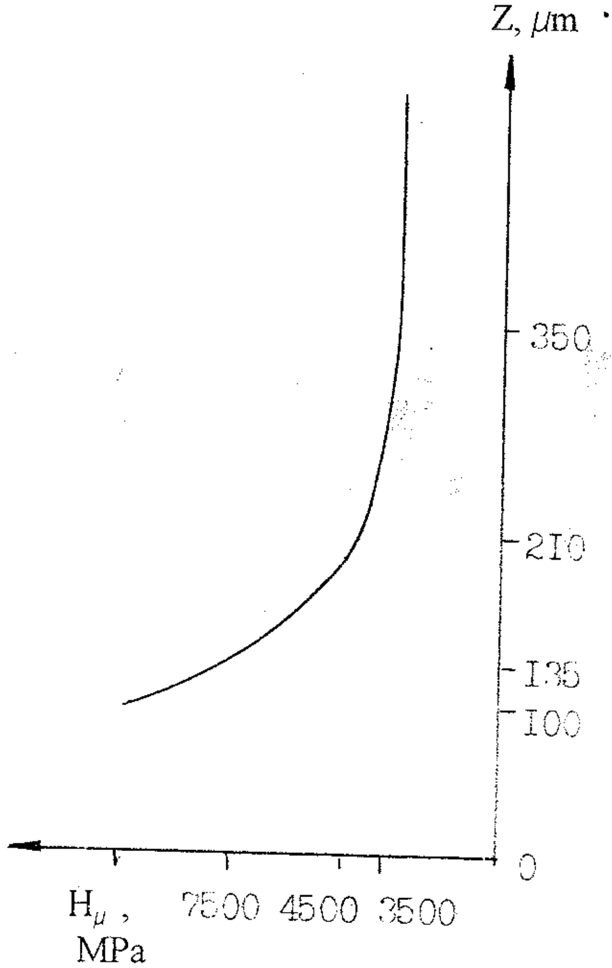
c



d

Fig.8. Results of heating up to melting and water quenching of unirradiated Zr-1 wt.%Nb - cladding.

a - macrostructure of drop , x5;

b - microstructure of drop surfase layer , x500;

c - the same , x200;

d - microhardness along cross-section of drop.