

EXPERIENCE AND OPPORTUNITIES OF JSC "INM" REACTOR AND EXPERIMENTAL FACILITIES FOR FUEL MATERIALS TESTING

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Abstract

The paper presents methodology to carry out irradiation testing of advanced fuel compositions and mock-up or full-size fuel elements to justify their operating capacity in conditions reflecting technical operation requirements. The main technical characteristics of IVV-2M research reactor are given. The development and manufacturing level of different types of experimental facilities and irradiation rigs providing examination of fuel compositions in gas and liquid metal coolants is given. It is noted that during the above-mentioned tests steady-state, transient and emergency modes along with online control of radioactive gaseous, volatile and solid fission product release are simulated.

Based on achieved technical level the paper gives the main experimental data on:

- tested objects (samples based on UO_2 , Er-doped UO_2 , HTGR coated particles and pebbles),
- irradiation time (up to 2 years),
- temperature modes (700 to 2000 °C),
- fast neutron fluence ($E > 0.1$ MeV),
- kinetics of gaseous fission product release ($R/B = 10^{-7}$ to 10^{-1}).

1. Introduction

IVV-2M water-moderated research reactor is located at the Joint Stock Company "Institute of Nuclear Materials" site, about 50 km from Yekaterinburg, an industrial and research centre of the Urals. IVV-2M started up in April 1966. In May 2018 the equipment modernization has been completed providing reactor service life extension till 2025.

The main scientific and production activities at IVV-2M reactor are as follows:

- investigation in the field of materials science,
- testing of fuel element mock-ups of different nuclear power facilities,
- production of a range of radioactive isotopes.

As for the announced topic, the paper briefly describes three types of the main equipment (Fig.1), used in irradiation experiments on fuel compositions, and mock-up and full-size fuel elements.

Irradiation testing aims at:

- experimental studies of the behaviour of fuel materials individually and as a part of fuel element mock-ups (or full-size fuel elements wherever possible) in conditions close to operation for nuclear power facilities (nominal, transient, and accident conditions),
- acquisition of the experimental data on temperature, fluence, burn-up, gaseous fission product (GFP) activity to verify computational codes,
- replenishment and update of the fuel irradiation database.

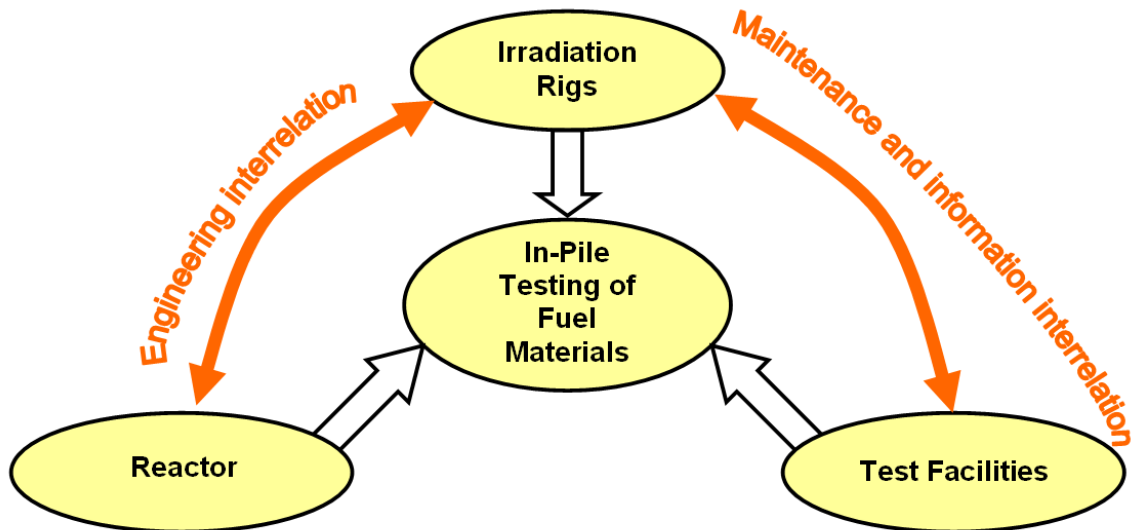


Fig.1. Maintenance of the fuel materials irradiation tests

Acquired irradiation testing data, along with post-irradiation examination (dimensional, physical and mechanical, microstructural and other types of examination), provided determination of operation capacity of HTGR and LWR-fuel materials (Fig.2).

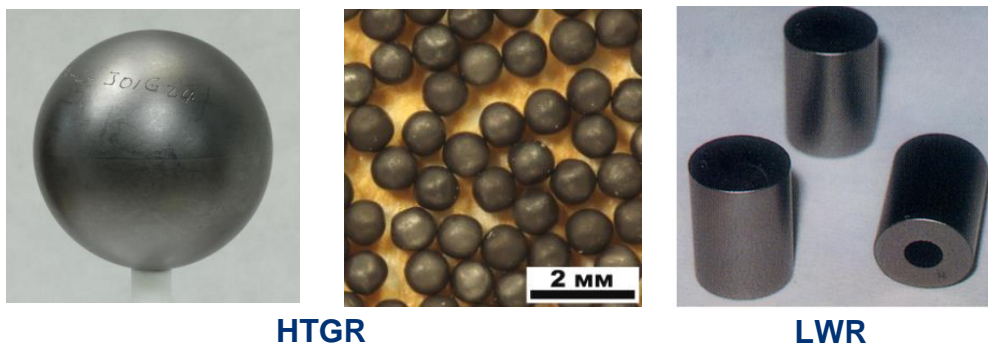


Fig.2. HTGR and LWR fuel

2. MAINTENANCE OF THE IRRADIATION TESTS

2.1 IVV-2M Reactor [1]

IVV-2M research reactor is a water-moderated pool-type reactor with the nominal power of 15 MW. The reactor core consists of hexagonal fuel assemblies; the reflector is formed of hexagonal beryllium units (Fig.3). Modular structure of the core and reflector provides formation of the cavity for irradiation rigs (IRs):

- inside the core – 6 pcs, 60 mm in diameter each, or 1 pc, 120 mm in diameter,
- in the inner fuel assembly cavity – 24 pcs, 27 mm in diameter each,
- in the beryllium reflector – 40 pcs, 60 mm in diameter each, and 1 pc, 120 mm in diameter.

Maximum flux density

- 5×10^{14} n/(cm²·s) for thermal ($E < 0.625$ eV) neutrons,
- 2×10^{14} n/(cm²·s) for fast ($E > 0.1$ MeV) neutrons.

The core height is 500 mm.

2.2 Irradiation Rigs [2]

JSC "INM" has experience in development and manufacture of irradiation rigs (IRs) of different sizes (27, 60 and 120 mm in diameter) for HTGR and LWR-fuel testing.

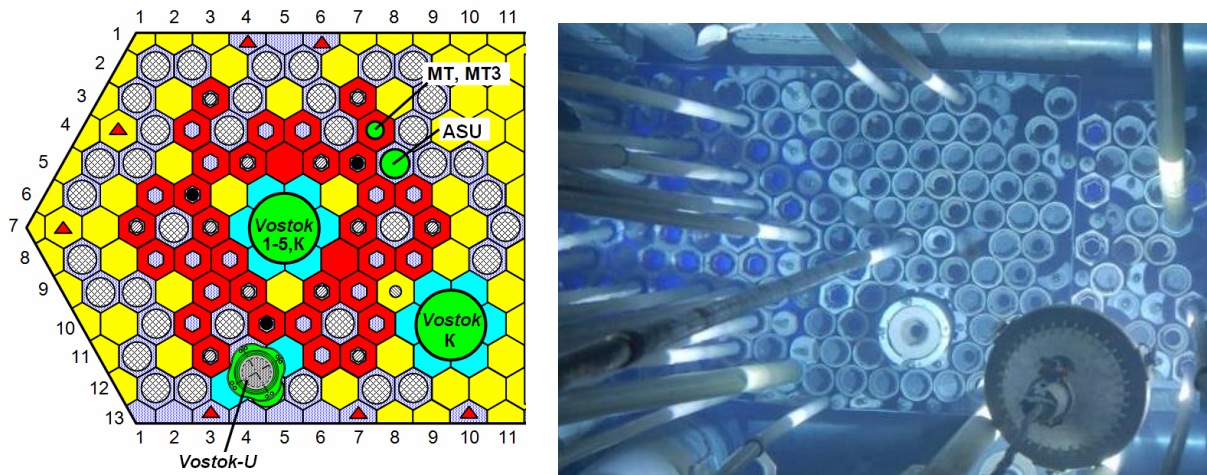


Fig.3. IVV-2M reactor core

MT-type IR, 27 mm in diameter, is designed for irradiation testing of 6 to 8 capsules, with upper two equipped with gas lines to control gaseous (GFP) and volatile (VFP, mainly caesium) fission product release. Each capsule contains one sample in the form of a compact (Fig.4,a, version 1) or a cylinder (Fig.4,a, version 2). In order to investigate VFP release the cavity between the samples and the capsule vessel is filled with highly pure carbon microspheres, which are a good VFP absorber. GFP sampling is performed during reactor operation by intermittent capsule purging with inert gas at flow rate, insufficient to transport carbon microspheres. VFP sampling is performed during reactor shutdown by intense capsule purging with inert gas at flow rate, sufficient to transport carbon microspheres to the analysis site. Testing is carried out at fuel temperature up to 1500 °C and thermal neutron flux density about 5×10^{13} n/(cm²·s).

Vostok-type IR, 120 mm in diameter (Fig.4,b), is designed to test four full-size fuel spheres (FS) in self-contained capsules (Fig.5). Each FS is placed in a graphite capsule unit with 1-2 mm gas gap. Moreover, there is a self-contained thermostatic gas gap in each capsule. FS temperature is settled in the range between 1000 and 1800 °C by gas concentration in capsule gas gaps and their movement along the core with the motor drive. Maximum thermal neutron flux density in FS is 1.2×10^{14} n/(cm²·s).

ASU-18 IR, 60 mm in diameter (Fig.6), is designed for comparative testing of three LWR-fuel types under similar conditions and analysis of GFP released activity. Inside the steel capsule an aluminium displacer is placed with three holes for three steel vials with fuel samples. Each vial is equipped with two thermocouples (tungsten-rhenium one in the middle of the socketed fuel sample, while chromium-aluminium one is in the part of vial, which is under lower temperature) and gas lines for vial purging with inert gas and regular GFP sampling. The motor drive provides capsule movement along the core. Fuel temperature is in the range between 800 and 1500 °C, specific energy release from 400 to 1000 W/cm³.

2.3 RISK Test Facility [3]

RISK reactor test facility (Fig.7) is used to provide irradiation testing of fuel samples and investigation of GFP release kinetics under irradiation. The facility consists of four parts:

- system of inert gas (helium, neon, helium-neon mixture) supply to the capsule and vials with excess pressure up to 1 bar and controlled flow rate of inert purging gases through vials with fuel samples from 1 to 10 cm³/s,
- system of gas coolant clean-up from moisture (using silica gel at temperature –196 °C) and oxygen (using titanium-based trap),
- system of taking GFP-containing gas samples, along with gamma spectroscopy of krypton and xenon isotope activity,

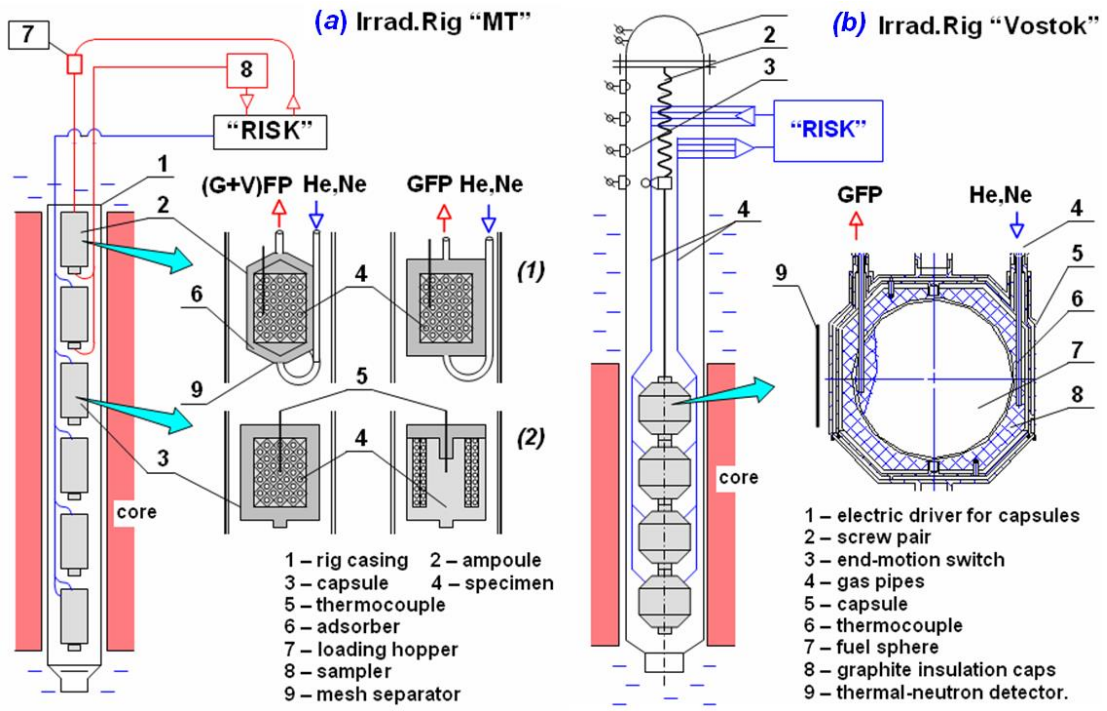


Fig.4. Irradiation rigs for HTGR-fuel testing

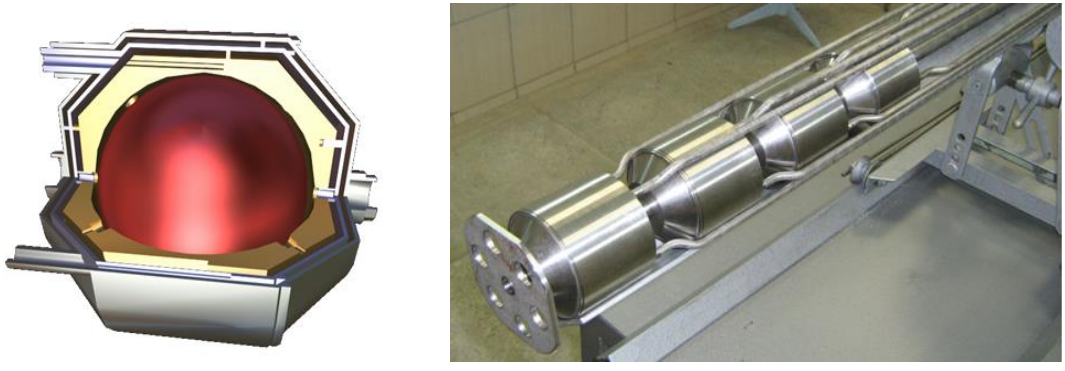


Fig.5. Capsule and irradiation rig assembly for HTGR FS testing

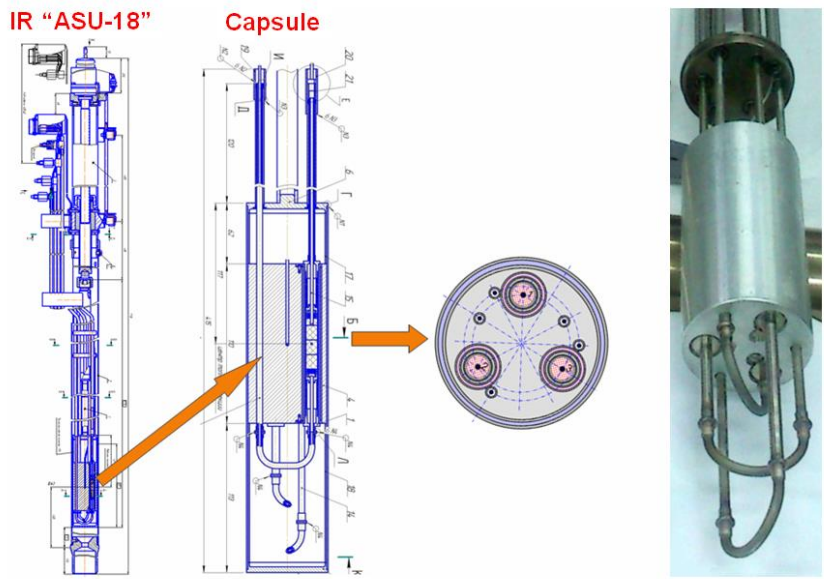
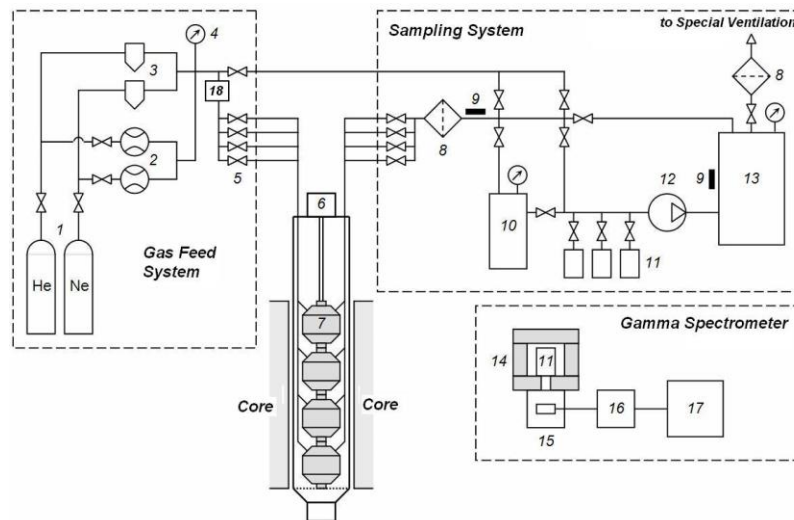


Fig.6. Irradiation rig for LWR-fuel testing

- control system providing control of electric valves of the gas sampling system, mechanism to move the capsule along the core, as well as collection, displaying and recording of pressure and coolant flow rate sensor readings.



- 1 – helium/neon casks, 2 – gas flow meter, 3 – gas metering pump, 4 – pressure meter,
 5 – gas collector, 6 – mechanism of capsule movement along the core,
 7 – capsule with fuel spheres, 8 – iodine filter, 9 – dosimeter, 10 – 1L decay bottle,
 11 – 0.27L gas sampler, 12 – fore-pump, 13 – 200L decay tank,
 14 – lead shielding (with collimator if necessary), 15 – Canberra GC2018 gamma-detector,
 16 – Canberra DSA-1000 digital spectrum analyzer, 17 – PC with Canberra Genie-2000 v3.1 software, 18 – system of gas coolant clean-up from moisture and oxygen

Fig. 7. RISK test facility

2.4 IZOL Test Facility [4]

Fig.8 shows IZOL test facility layout [4] for experimental studies of the steady-state (a) and accident (b) GFP and VFP release. Mock-up fuel pins with UO_2 fuel in a $\text{Zr}+1\%\text{Nb}$ cladding, 13.6 mm in outer diameter, were irradiated in helium media. Chemical forms of radioactive iodine were determined with gas thermochromatography, that is gas adsorption chromatography with negative temperature gradient along the gas line in the column (TCC). In the steady-state release experiment a thermochromatography device with a removable column was placed at the outlet of the piping heated up to 600°C in the glove box (Fig.8,a). In the experiment on accident radioactive iodine release TCC was placed close to the fuel pin mock-up (Fig.8,b).

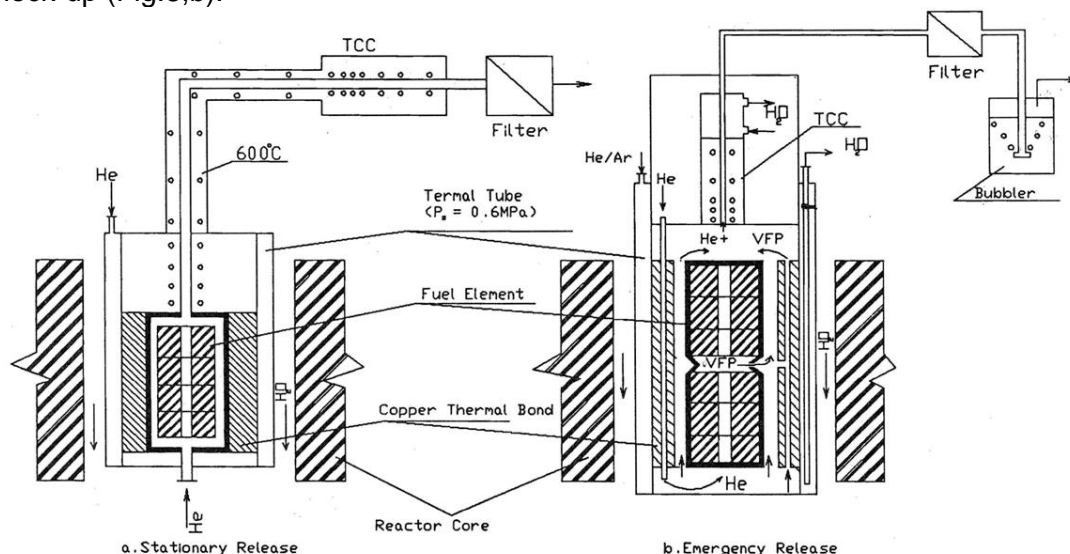


Fig. 8. IZOL test facility

3. Irradiation Testing Results

Table 1 gives the main parameters for fuel composition and model fuel element irradiation testing.

Tested objects	Fuel type	Temperature, °C	Power density	Burn-up, % FIMA	Fast neutron ($E > 0.1\text{MeV}$) fluence, $\times 10^{21} \text{ cm}^{-2}$	$(R/B)_{\text{Kr88}}$
HTGR Fuel Spheres	UO ₂	900 – 1800	1.5 – 2.7 kW/FS	0.5 – 21	0.2 – 2.2	from 2E-7 to 6E-3
HTGR Coated Particles	UO ₂ UO ₂ +(Al,Si) UCO	900 – 2000	0.2 – 1.0 mW/CP	5 – 18	0.4 – 2.0	from 3E-7 to 2E-1
LWR-fuel samples	UO ₂ UO ₂ +Er	1000 – 2500	200 – 300 W/cm ³	3.5	–	from 2E-3 to 2E-1

Table 1. Parameters of HTGR and LWR fuel irradiation testing in inert gases

3.1 HTGR-Fuel Irradiation Testing

Nominal and transient temperatures [2]

Irradiation testing of HTGR fuel spheres was carried out in cyclic (Vostok-2,3,4,5,6) and long-term tests (Vostok-6), up to target values of fuel burn-up and fast ($E > 0.1 \text{ MeV}$) neutron fluence at given irradiation temperatures. Fig.9 reviews the acquired level of irradiation testing basing on the graph of GFP (Kr-88 case) release kinetics dependency on fuel burn-up depth and irradiation temperature.

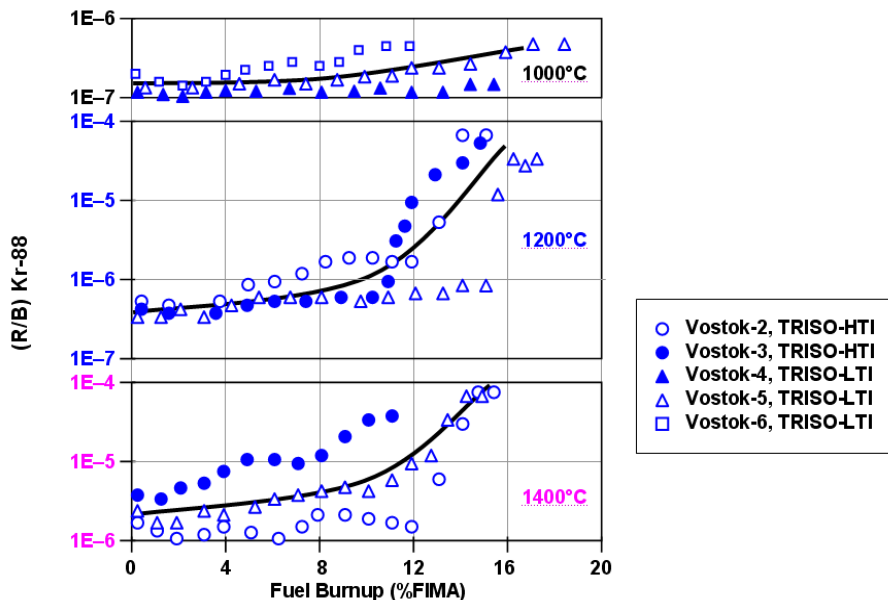


Fig. 9. Kr-88 release during irradiation of HTGR fuel spheres

During the investigation the following patterns were found:

- at $T_{\text{irr}} = 1000 \text{ }^\circ\text{C}$ insignificant increase in GFP release from HTGR fuel spheres is registered, critical burn-up is beyond 15–20 % FIMA (not reached); R/B values, as a rule, do not exceed 1×10^{-6} ;
- at $T_{\text{irr}} = 1200 \text{ }^\circ\text{C}$ some CPs in HTGR fuel spheres can lose tightness after burn-up of 10–15 % FIMA exceeding allowable R/B values = 1×10^{-5} ;
- at $T_{\text{irr}} = 1400 \text{ }^\circ\text{C}$ the irradiation was accompanied by increased GFO release reaching R/B = 1×10^{-5} at 5-13 % FIMA.

The given results show satisfactory capacity of tested HTGR fuel spheres in the temperature range between 1000 and 1400 °C under burn-up from 16 to 12 % FIMA, respectively.

Accident temperatures [2]

During some life tests with fuel spheres after burn-up reached 9–14 % FIMA a short-term (dozens-hundreds hours of irradiation) temperature increase (up to 1550 – 1720 °C) was made to simulate emergency HTGR core cooldown (Fig.10). In two experiments no significant increase in release was detected, when the temperature decreased to the initial level. One experiment resulted in mass CP loss-of-tightness, accompanied by (R/B) release at the level of 4×10^{-3} (in Kr-88).

HTGR fuel kernel testing [5,6]

Fig.11 shows the results of UO_2 kernel irradiation tests in MT3-2/1 and Vostok-U experiments. Two patterns are identified:

- less apparent temperature-GFP release dependency at burn-up depth more than 2% FIMA and energy release more than 0.8 W/kernel,
- increased GFP release at burn-up more than 2% FIMA, which can reach dozens of percents.

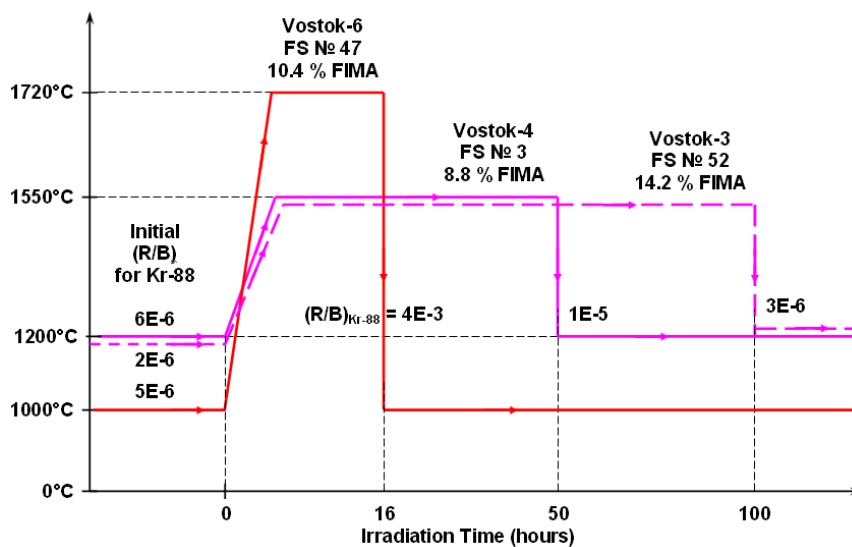


Fig. 10. Kr-88 release from HTGR fuel spheres at accident temperatures

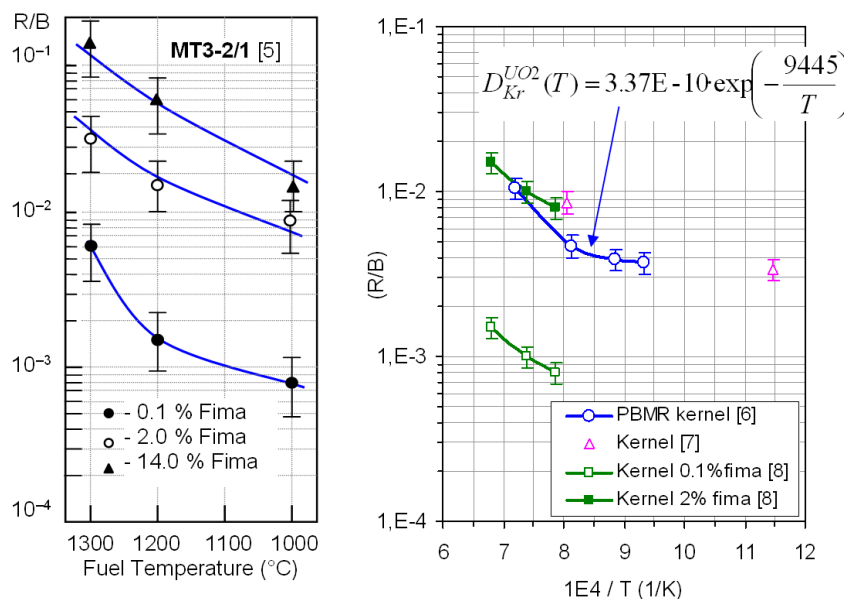


Fig. 11. Kr-88 release dependence on temperature and fuel burn-up

Defined GFP release kinetics is related to the fuel matrix state, which can be proven with post-irradiation metallographic examination of the fuel: at burn-up and temperature increase an additional honeycomb porosity is developed. On the basis of such a fuel state and increased GFP release values, it could be suggested that at the initial irradiation phase the GFP release with initial density of $10.45 - 10.80 \text{ g/cm}^3$ is caused by bulk diffusion and recoil nucleus from the surface kernel layer (recoil process), and due to intensely irradiated fuel (under increased fission density) the GFP release is mainly caused by recoil nucleus, emitted from internal fuel voids, and atoms, knocked out from recoil tracks (knock-out process).

3.2 LWR-fuel Irradiation Testing

Nominal temperatures [9]

Due to Russian RBMK reactor change-over to fuel pins with uranium-erbium fuel the comparative life tests of RBMK fuel pin mock-ups with standard and experimental erbium-doped (erbium concentration of 0.4 and 0.6 wt.%) UO_2 fuel have been carried out up to burn-up depth of 36 MWD/kg with determination of GFP release (ASU-18/3, ASU-18/35, ASU-18/60T experiments). Following Fig.12, GFP release from uranium-erbium fuel is lower than that from standard UO_2 fuel and more stable under similar irradiation conditions (the results of materials science microstructural post-irradiation examination).

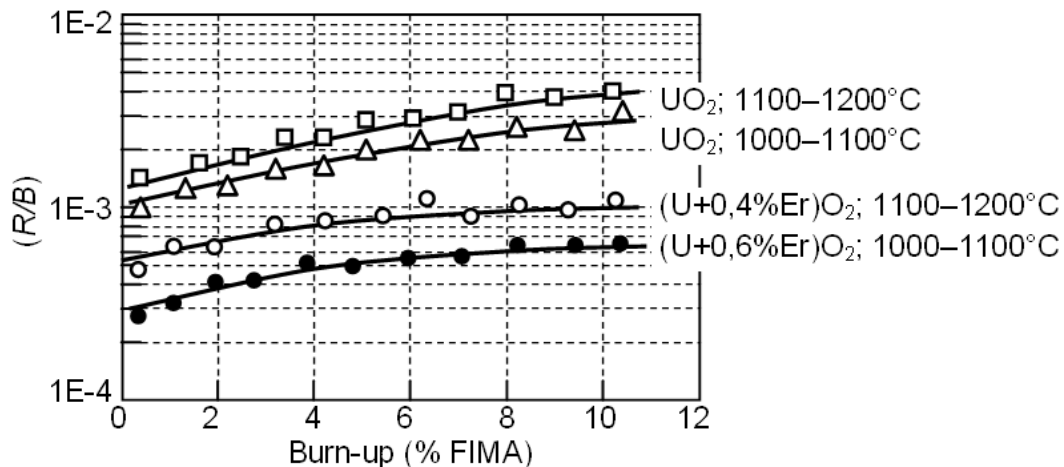


Fig. 12. Kr-88 release from standard and experimental Er-doped RBMK UO_2 fuel

Accident temperatures [9]

A number of experiments modelling the RBMK control rod self-removal accident have been performed to justify fuel pin operating capacity in case of emergency. Preliminary irradiated RBMK fuel pin mock-ups with standard and experimental erbium-doped UO_2 fuel have been moved along the IVV-2M core height in 20 seconds (in this case energy release increased by 1.4 to 2.5 times, and fuel temperature increased from 1250 to about 2500 °C) with GFP release determination. Estimation of gas samples showed that under abrupt capacity increase the GFP release increases as well, by 100 to 300 times as compared with steady-state irradiation, depending on the fuel temperature increase. As materials science post-irradiation examination of fuel showed, this fact is related to the fuel state: shutdown of the central hole in fuel pellets and further fuel cracking.

This correlation can be explained in the following way. Under abrupt capacity increase the fuel is almost immediately heated up. The most heated are inner layers, which become rather flexible, thus leading to the fuel swelling. Outer layers, being colder, stay solid. Moreover, the fuel pin is predeformed in the capsule radiator. As a result expansion of inner flexible fuel layers is directed towards the pellet axis, leading to the shutdown of the pellet central hole. As a result of the central hole shutdown the GFP release from the fuel decreases. Under cooling the fuel cracks and GFP release increases again.

Maximum design basis accident [4]

17 experiments simulating maximum design basis accident (MDBA) have been carried out to evaluate VFP and GFP release. Each experiment consisted of two phases: (1) irradiation for 500 h at linear energy release of about 330 W/cm and cladding temperature of 280 to 350°C, and (2) accident simulation (when helium/argon replaced water in a heat pipe the cladding temperature increase up to 850°C, while fuel temperature went up to 1100 to 1200°C. Then external pressure of 80 bar was applied to the cladding causing its deformation in the central part without fuel (Fig.8,b) and rupture. In some cases the cladding was punctured with a needle in the central part of the fuel pin without fuel. Testing results are given in Table 2 and Fig.13.

Experiment	Released activity distribution, %				Relative release	Cladding sectioning mode
	heated piping (1)	TCC (2)	capillary (3)	filter (4)		
EKIT-12	1.6	62.2	15.6	20.5	6.8E-6	deformation
EKIT-13	1.5	54.7	1.7	41.9	1.4E-6	deformation
EKIT-14	1.0	96.4	2.4	1.0	4.6E-7	deformation + puncture
EKIT-16	5.0	70.7	12.1	12.1	9.4E-3 *	puncture
EKIT-17	1.0	44.6	9.2	43.8	1.2E-2 *	puncture

* controlled by iodine and GFP release from fuel matrix.

Table 2. Distribution of iodine-131 released from the fuel pin mock-up during MDBA simulation

The given experimental data on MDBA simulation with cladding deformation show that:

- the relative radioiodine release in all the experiments did not exceed $1,5 \times 10^{-5}$,
- in case of the cladding rupture radioiodine release is controlled with holding capacity of the fuel matrix,
- four forms of radioiodine release into inert media in case of MDBA were detected: CsI, HI, molecular and atomic iodine;
- atomic iodine contribution into radioiodine release is more than 70%, while CsI contribution is not more than 1%.

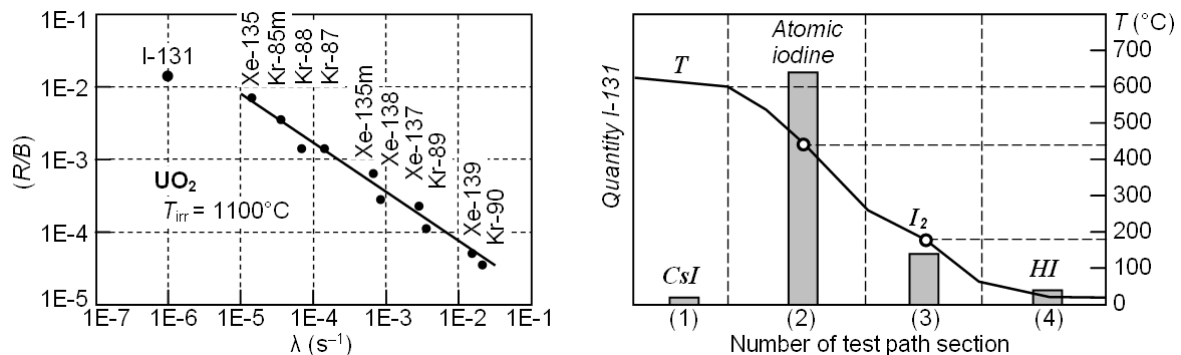


Fig. 13. Iodine-131 distribution

3.3 Other Fuel Type Testing

In 2017 the preparation for irradiation testing of compact fuel in liquid metal and inert gas media has started.

4. CONCLUSION

Since 1976 JSC "INM" performs ongoing irradiation testing of different fuel compositions in a wide range of parameters (from nominal to accident modes). Based on the long-term experience in irradiation testing of different kinds of fuel JSC "INM" is developing several new research facilities to satisfy future needs of manufacturers, users and regulatory authorities.

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