INSTITUTE OF ATOMIC ENERGY BRANCH
OF THE NATIONAL NUCLEAR CENTER OF THE REPUBLIC OF KAZAKHSTAN

Down-Blending and Immobilization Methods for Uranium-Graphite and Uranium-Zirconium Fuel of NNC Research Reactors

Technical Meeting on Operating Experience and Lessons Learned on Managing Non-Standard Legacy Spent Fuels from Power and Research Reactors

Yuliya Baklanova*,*
Head of Materials Testing Department

February 18 – 21, 2025

IMPULSE GRAPHITE REACTOR (IGR)

Reactor Hall

Maximum neutron flux density - 7×10^{16} n/cm^2·s

Maximum thermal neutron fluence – 3.7×10^{16} n/cm^2

Pulse half-width is minimum – 0.12 s

Geometric dimensions of the core – 1800×1000×1000 mm

Operation of the reactor: since 1960

Core modernization: 1966–1967

Core weight ≈ 2.6 t

Charge with ^{235}U:

First core (1960 – 1966) – 7.3 kg

Second core (1968 to present) – 9.1 kg

Core

RESEARCH WATER-COOLED HETEROGENEOUS REACTOR IVG.1M

Reactor Hall

Thermal power 72 MW

Effective core diameter 548 mm

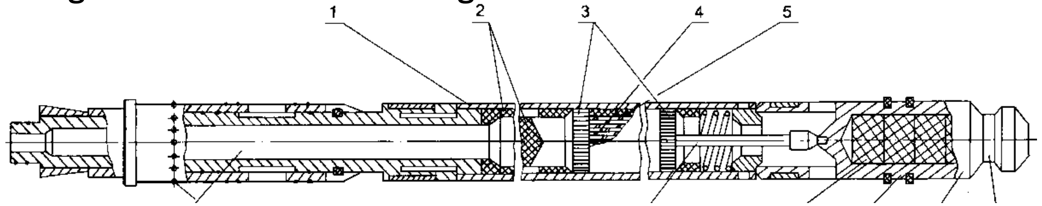
Core height 800 mm

Thermal neutron flux density 3.5×10^{14} n/cm^2·s

Operation of the reactor since : 1975

Conversion to LEU: 2024

Charge with ^{235}U 4.6 kg



1 – vessel; 2 – bio shield; 3 – end grid; 4 – FA;

WCTC-HEU scheme

Core

PURPOSES AND TASKS OF RESEARCH

Purposes:

1. Reduce enrichment
2. Produce a reliable matrix for fuel immobilization
3. Exemption of fuel from IAEA safeguards

Tasks :

1. Develop a concept for down-blending irradiated HEU fuel from research reactors to LEU fuel parameters (IGR, IVG.1M)
2. Develop a concept for immobilizing down-blended irradiated fuel from research reactors (IGR, IVG.1M) for subsequent exemption of fuel from IAEA safeguards
3. Demonstrate the possibility of implementing the proposed technology within the R&D

Down-Blending and Immobilization Criteria for Irradiated HEU Fuel

Criteria	Reference
Exposure of personnel to γ-irradiation: MED ≤ 20 mSv/year	SERRS
Fuel enrichment in ^{235}U: ≤ 20 wt.%	RRRFR, RERTR
Uniform distribution of uranium in the matrix volume	IAEA
Impossibility of extracting ^{235}U at any stage of the technological process	IAEA
^{235}U concentration in matrix: ≤ 50 ppm	IAEA
Fuel particle size: ≈ 200 µm	IAEA
Proportion of graphite in the cement mixture: ≤ 15 wt.%	Papers
Requirements for the stability of the matrix with LEU fuel:	GOSTs
- mechanical strength: ≥10 MPa	
- leaching rate < 10^{-3} g/(cm^{2day})	
- frost resistance: strength ≥10 MPa, strength reduction < 25%	
- resistance to immersion in water: strength ≥ 10 MPa, strength reduction< 25%	

CONCEPTUAL SOLUTIONS FOR HANDLING IGR HEU FUEL

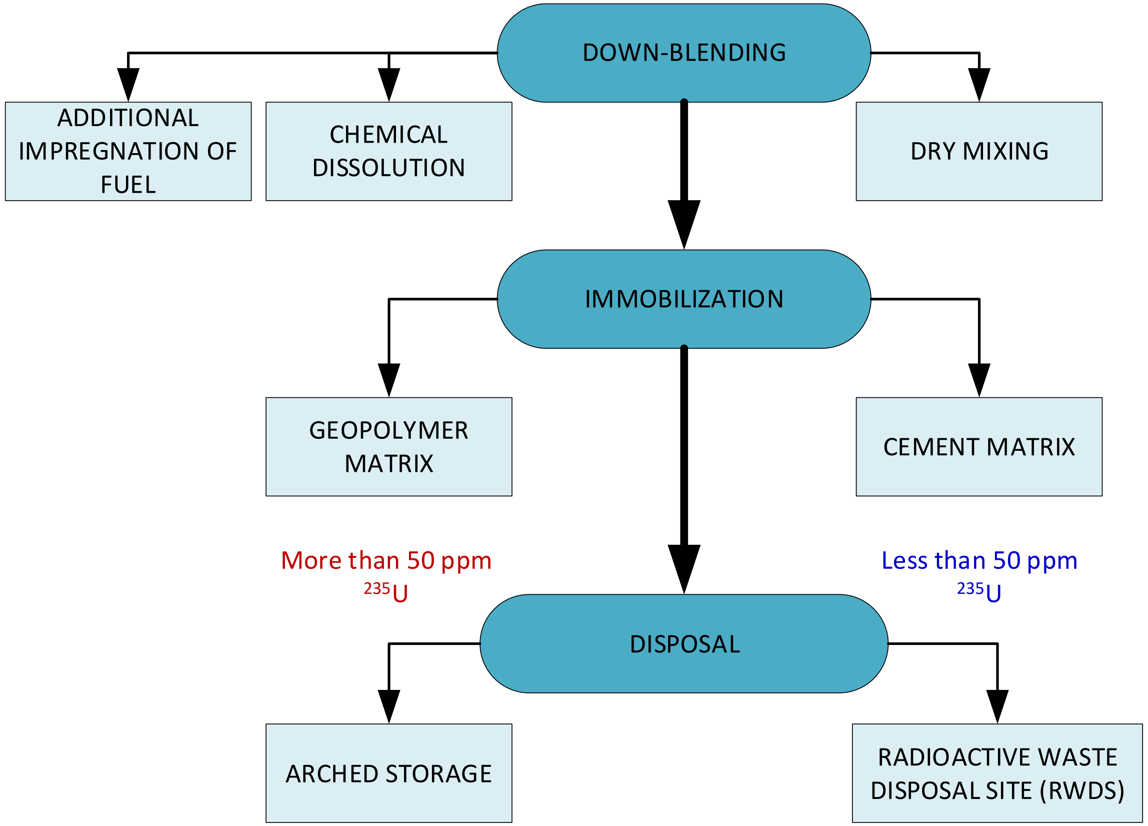
Fuel – uranium-graphite blocks and rods

Fuel enrichment (HEU): 90%

Core weight ≈ 2.6 t

Mass concentration of uranium in fuel : 0.3%

Block *Rods*



Radionuclide composition of IGR fuel irradiated with HEU

#	Nuclide	No. (number of nuclei of nuclides)	Q (nuclide activity), s^{-1}
1	^{137}Cs	$9.65 \cdot 10^{20}$	$7.03 \cdot 10^{11}$
2	^{90}Sr	$8 \cdot 10^{20}$	$6.15 \cdot 10^{11}$
3	^{151}Sm	$9.03 \cdot 10^{19}$	$2.2 \cdot 10^{10}$
4	^{99}Tc	$2.71 \cdot 10^{21}$	$2.21 \cdot 10^{8}$
5	^{155}Eu	$1.36 \cdot 10^{16}$	$6.04 \cdot 10^{7}$
6	^{93}Zr	$3.11 \cdot 10^{21}$	$4.38 \cdot 10^{7}$
7	^{135}Cs	$3 \cdot 10^{21}$	$2.86 \cdot 10^{7}$
8	^{129}I	$5.93 \cdot 10^{20}$	$8.3 \cdot 10^{5}$
9	^{107}Pd	$1.3 \cdot 10^{20}$	$4.2 \cdot 10^{5}$

TESTING THE DRY MIXING METHOD

1. Crushing of HEU fuel and UO_2 (0.27%) → 2. Crushing of HEU fuel and UO_2 (0,27%) up to particle size of ≈200 μm → 3. Transfer to the cementing unit

Automatic press
ELE International

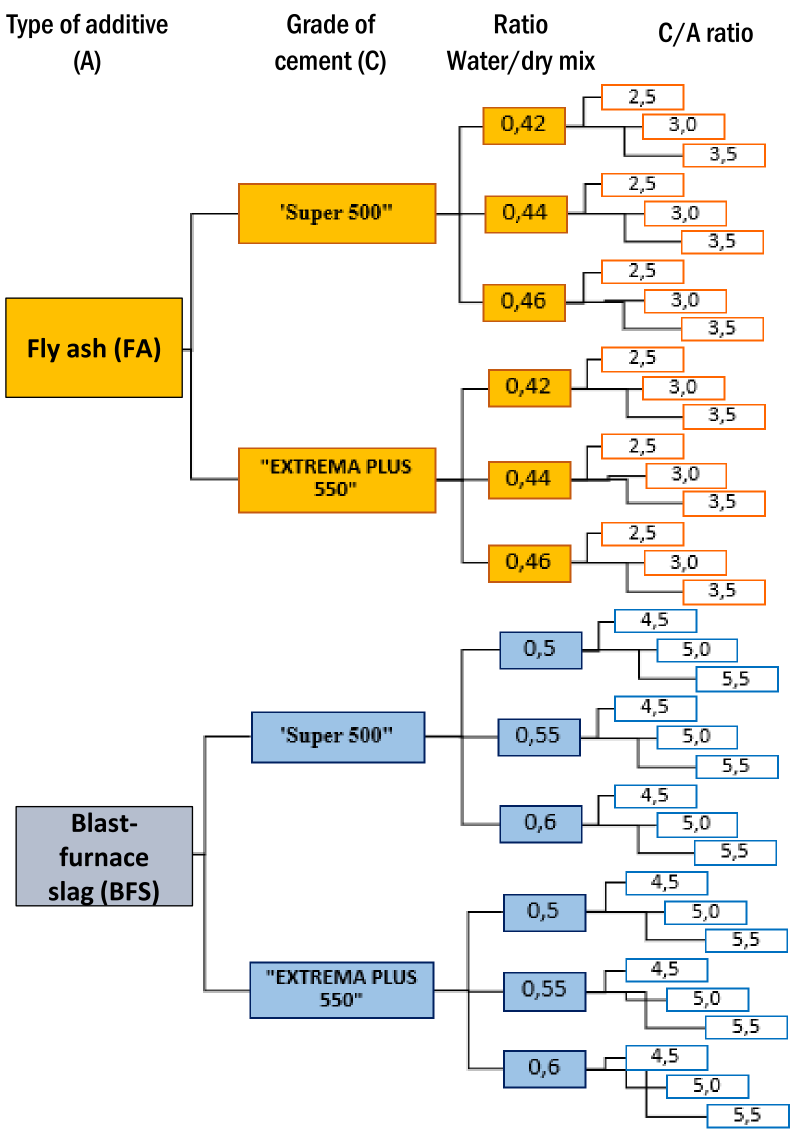
Jaw crusher and disc mill
FRITSCH

Impact mill
NETZSCH

Jaw crusher
SIEBTECHNIK

Universal rotor mill
SIEBTECHNIK

DETERMINATION OF MATRIX COMPOSITION AND COMPONENT RATIOS



Water bleeding:

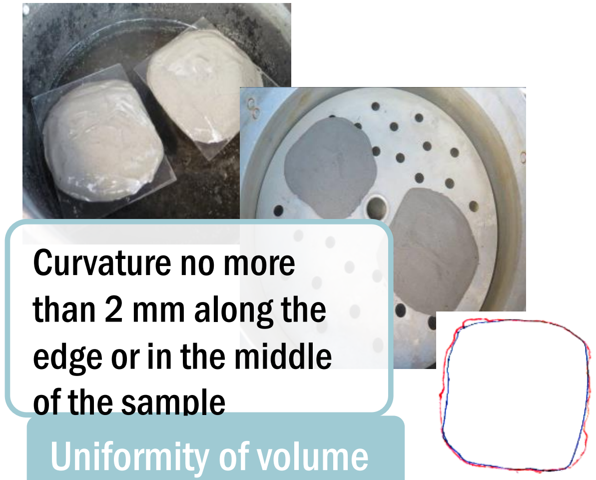
Less than 3 vol.%

Viscosity :

Control of solution spreadability (150 – 250 mm)

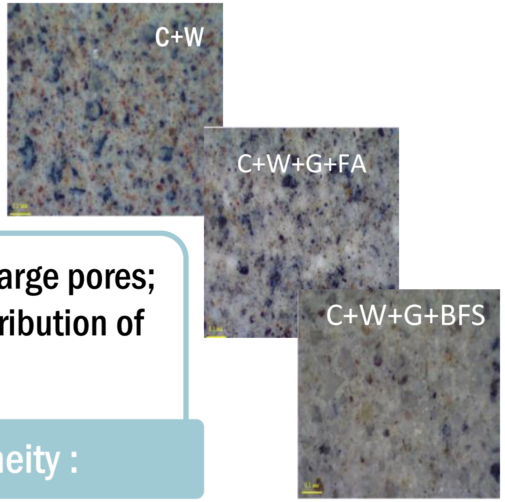
Setting time:

Start of setting - the needle does not reach the glass by 2-4 mm; end of setting - the needle is immersed by 1-2 mm in the suspension



Uniformity of volume change

Curvature no more than 2 mm along the edge or in the middle of the sample



Matrix homogeneity :

- Absence of large pores;
- Uniform distribution of graphite

TESTING THE MATRIX FOR COMPLIANCE WITH DURABILITY REQUIREMENTS

Mechanical strength

Strength measurement (not less than 10 MPa)

Immersion in water for 90 days, strength measurement (not less than 10 MPa, and strength reduction not more than 25%)

Moisture resistance

Frost resistance:

Thermal cycling in the range of -40 to +40, strength measurement (not less than 10 MPa, and strength reduction by no more than 25%)

Determination of ^{137}Cs in solutions (leaching rate of ^{137}Cs - no more than 1 • 10^{-3} g/(cm^2×day)

Leaching rate:

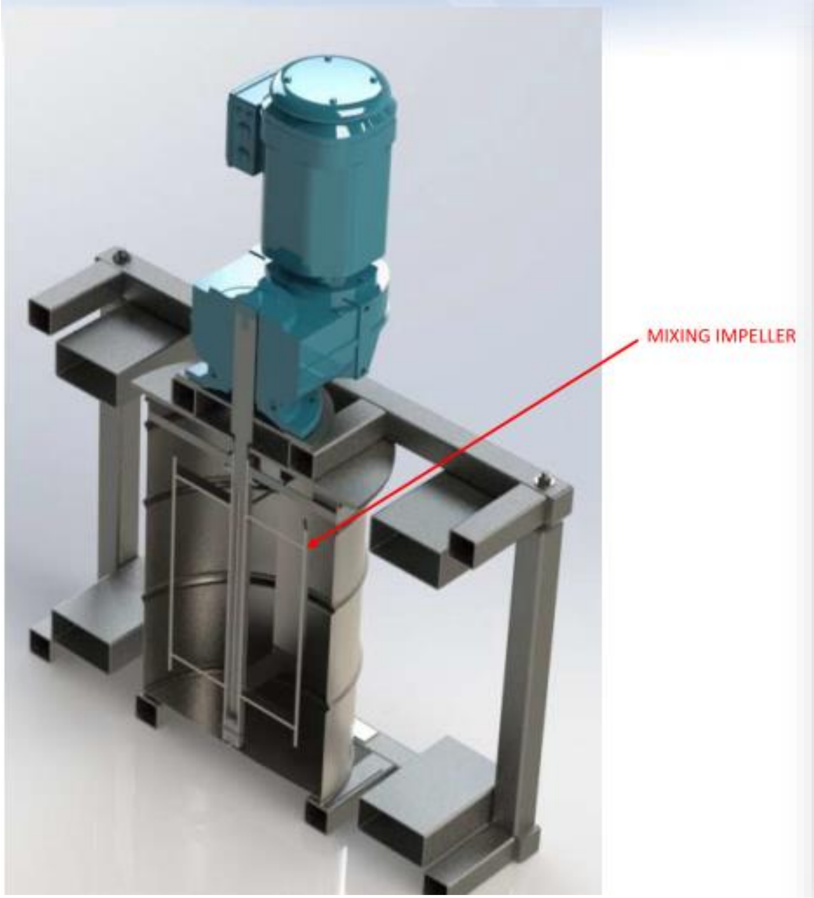
The matrices of the compositions passed the tests in full
W/C = 0.40 ± 0.02, C/FA = 1 / 2.5;
W/C = 0.42, C/FA = 1 / 1.77
Work with the selected compositions continued in full-scale experiments.

FULL-SCALE TESTS

Tasks to be completed in full-scale experiments

- ✓ Obtaining optimal mixing conditions:
  - ➢ Sequence of unloading components;
  - ➢ Component loading speed;
  - ➢ Mixer operating modes during unloading and mixing of components;
  - ➢ Duration of mixing components;
- ✓ Measuring parameters:
  - ➢ Water bleeding
  - ➢ Heat release
  - ➢ Uniformity of uranium distribution throughout the matrix volume
  - ➢ Enrichment

Mixing unit project by INL and AVANTech

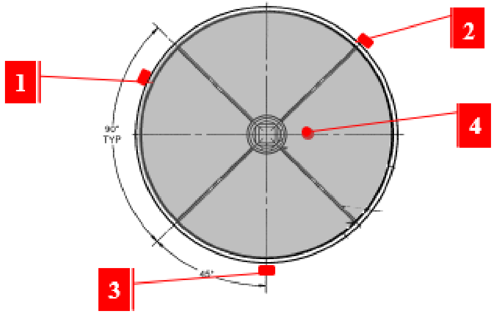


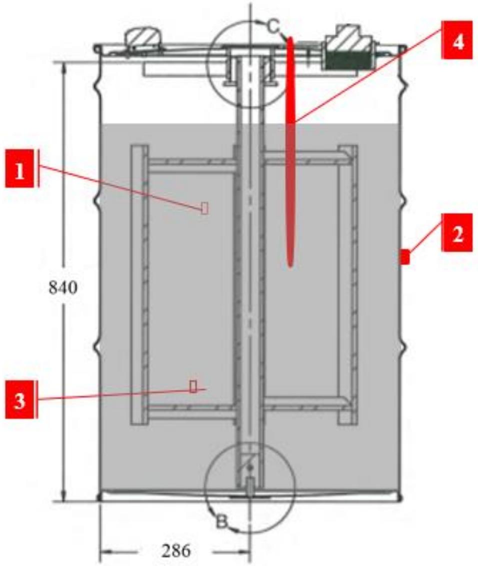
Experimental mixing unit for full-scale experiments by NNC RK

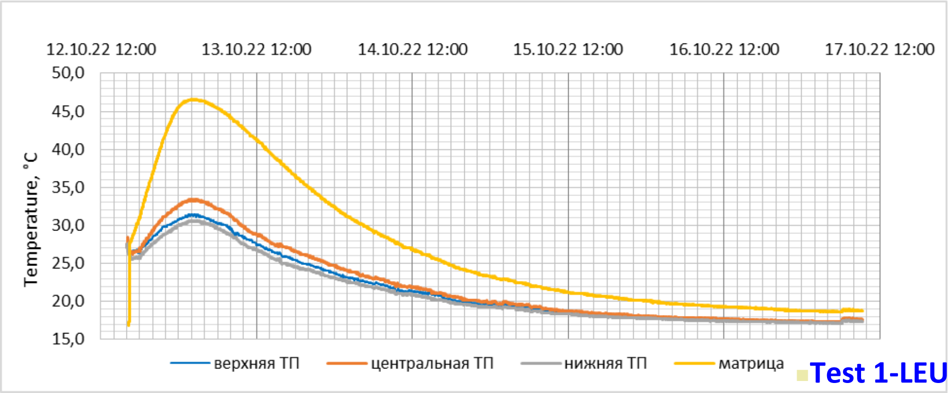
55-gallon drum from Skolnik CQ5508
Built-in mixer from NNC RK

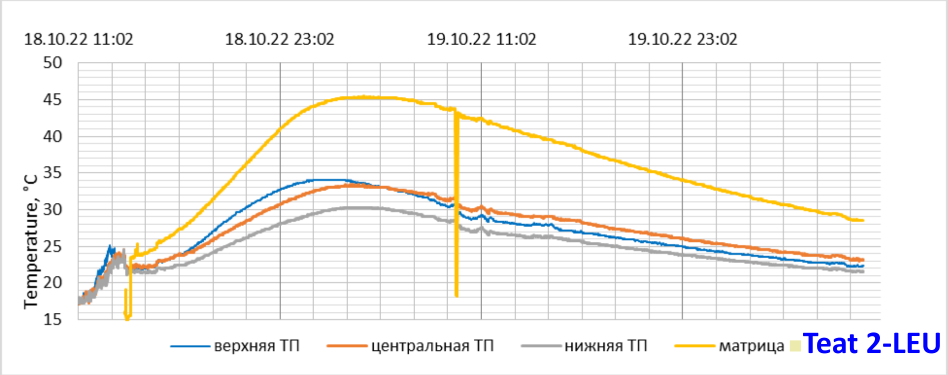
DEFINITION OF WATER BLEEDING AND HEAT RELEASE

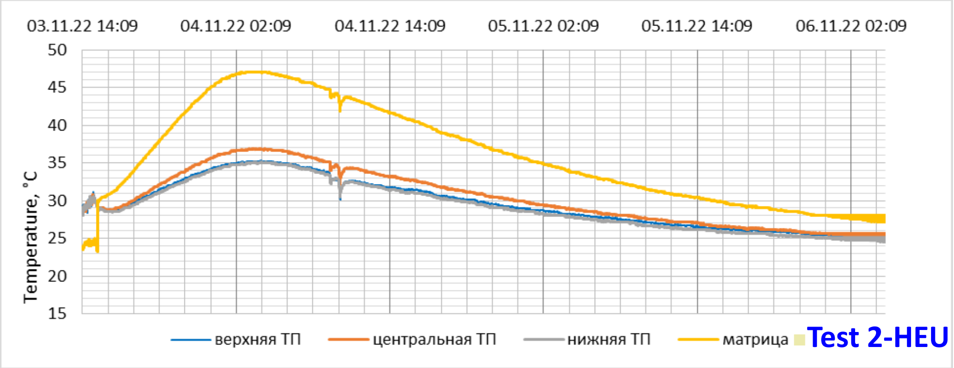
Test	Water bleeding coefficient, wt. %		
	2 hours later V_1, qt_2,	30 mins later V_2, qt_3	24 hours later, qt_4
1-LEU	1.5	1.5	0.7
2-LEU	2.2	2.2	1.5
2-HEU	2.2	2.2	1.5





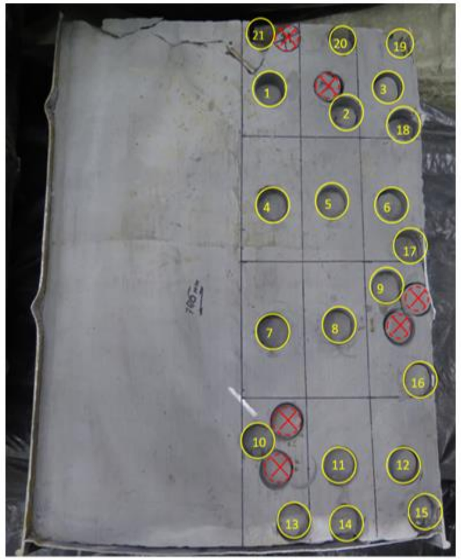






EVALUATION OF THE URANIUM DISTRIBUTION UNIFORMITY IN THE MATRICES AND ENRICHMENT MEASUREMENT

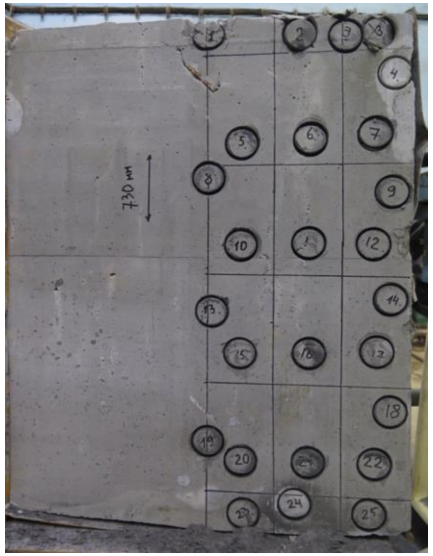
Test 1-LEU



UO_2

0,10					0,11			0,13
	0,12						0,13	
					0,12			0,11
	0,13			0,12			0,10	
								0,10
						0,10		
	0,12			0,11				
								0,12
0,11								
				0,11			0,11	
		0,04		0,13				0,15

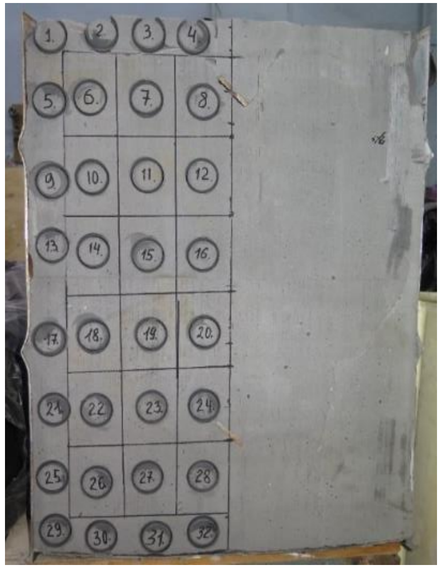
Test 2-LEU



UO_2

0,11			0,10			0,11		
								0,00
	0,09			0,12			0,11	
0,11								
								0,09
	0,10			0,11			0,10	
0,10								0,10
	0,11			0,10			0,10	
								0,11
0,11								
	0,11			0,10			0,10	
	0,24		0,01				0,10	

Test 2-HEU



UO_2

0,10	0,09	0,11	0,09
0,09	0,10	0,09	0,10
0,09	0,09	0,11	0,09
0,09	0,11	0,10	0,11
0,08	0,10	0,10	0,14
0,10	0,10	0,09	0,09
0,10	0,11	0,10	0,10
0,09	0,11	0,09	0,09

Results of determination of 235U enrichment in samples (MGAU)

Sample #	Isotope content, wt. %		
	^{234}U	^{235}U	^{238}U
IS-1	0.167 ± 0.037	4.996 ± 0.076	94.837± 0.076
IS-10	0.157 ± 0.037	4.898 ± 0.110	94.946± 0.110
IS-18	0.173 ± 0.038	5.200 ± 0.081	94.627± 0.081
IS-26	0.254 ± 0.059	5.167 ± 0.113	94.579± 0.113
IS-30	0.113 ± 0.028	4.976 ± 0.105	94.911± 0.105

EVALUATION OF MATRIX COMPLIANCE WITH WAC

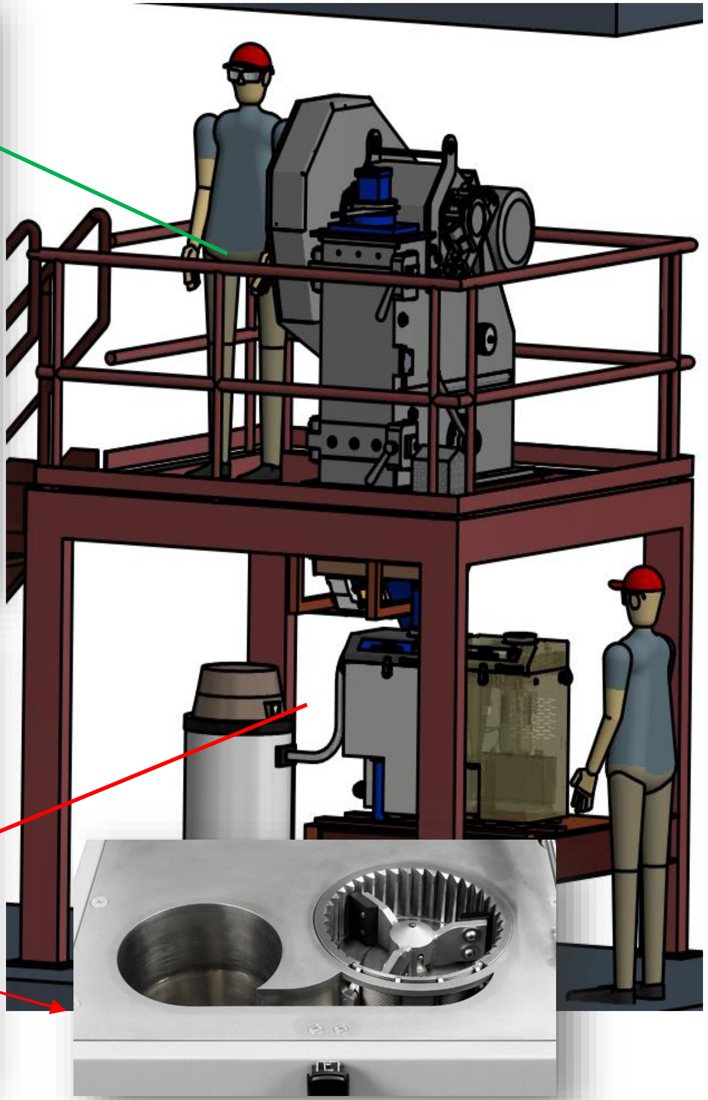
Conditions for Down-blending and immobilization of irradiated HEU fuel from the IGR reactor

- Packaging: Type A drum with a capacity of ≈208 l (55 gallons) with a built-in mixer
- Matrix: 58÷76 kg of Portland cement, 147÷134 kg of fly ash, 84÷90 l of water
- Fuel: 1 drum contains - 4 kg of fuel (12 г ^{235}U) and 300 g of UO_2 (0,27%);
- Total number of drums – 640 pcs.
- Productivity - 2 drums/day

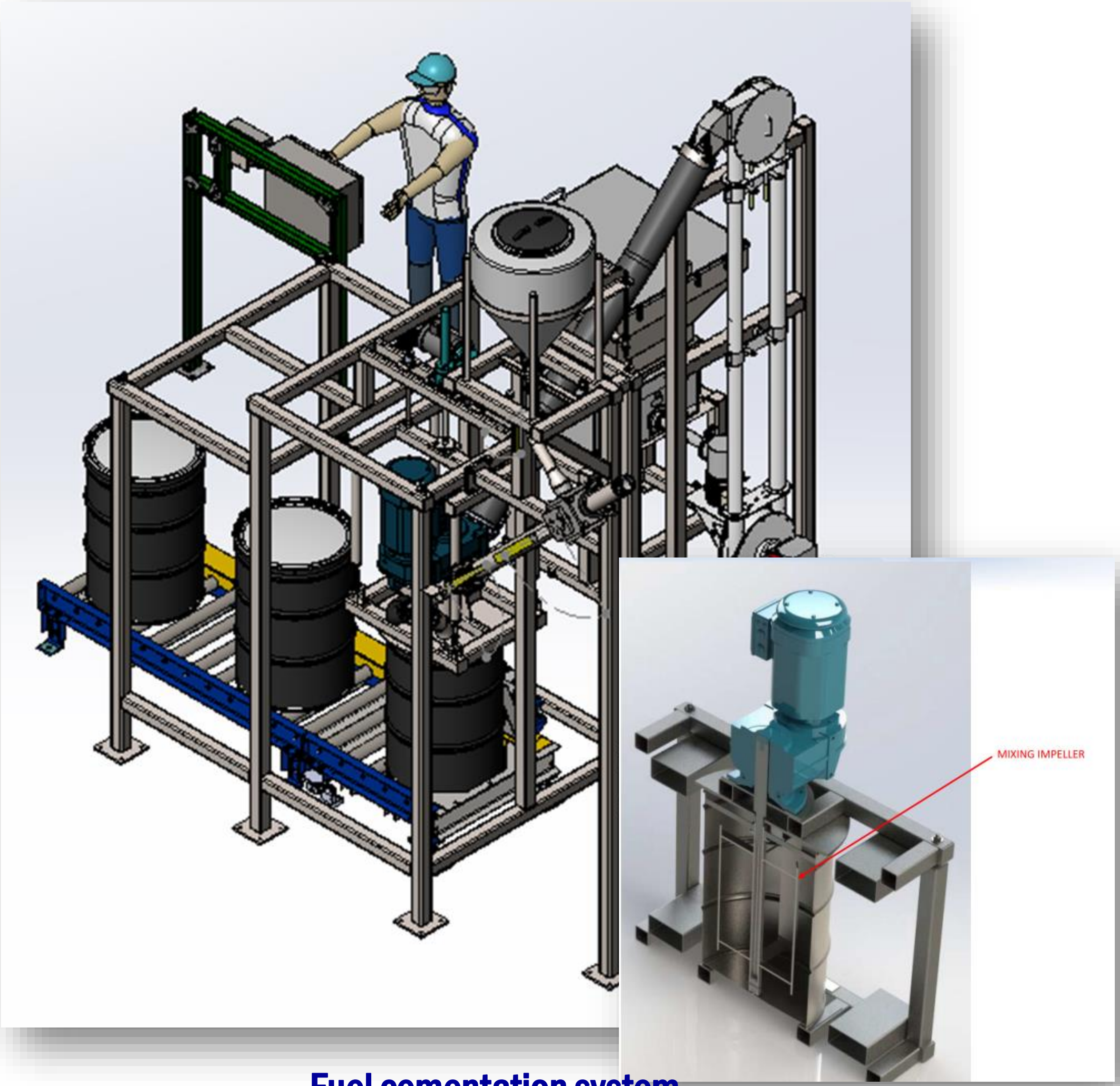
Expected results for compliance with the criteria

- ✓ MED on the cementing line: up to 0.02 mSv/h;
  MED at the stage of fuel extraction from the daily container: up to 0.3 mSv/h;
- ✓ Targeted enrichment through dry mixing : 5±0.17 %;
- ✓ Concentration of ^{235}U in a concrete block : 40 ÷ 45 ppm;
- ✓ Proportion of graphite in the cement mixture: 1.6÷2 %;
- ✓ Strength: not less than 14 MPa;
- ✓ Leaching rate of ^{137}Cs in water medium: ≤ 5.1×10^{-5} g/(cm^2×day);
- ✓ Resistance to long-term exposure to water (90 days): increase in strength up to ≈29 MPa;
- ✓ Uniformity of uranium distribution throughout the matrix volume: more than 81%;
- ✓ Frost resistance (30 cycles, temperature range from -40 to +40, cycle duration – 4.5 hours) : 13.7 ± 2.2 MPa, decrease in strength by no more than 20%

IMPLEMENTATION OF THE IMMOBILIZATION TECHNOLOGY FOR HEU FUEL FROM THE IGR REACTOR

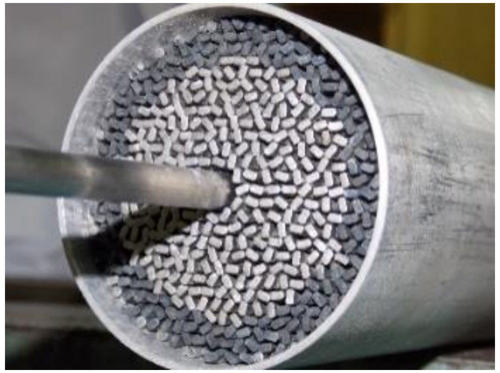


System for crushing/grinding/down-blending of HEU fuel

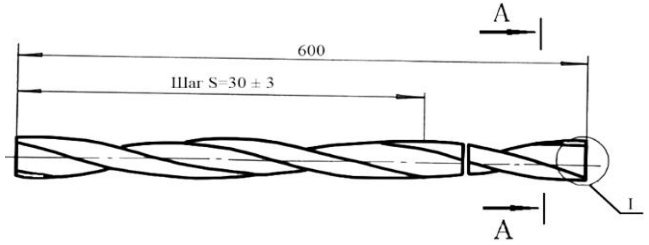


Fuel cementation system

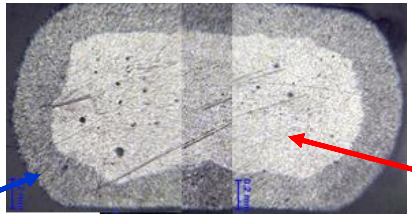
CONCEPTS FOR HANDLING HEU FUEL FROM THE IVG.1M REACTOR



SFA

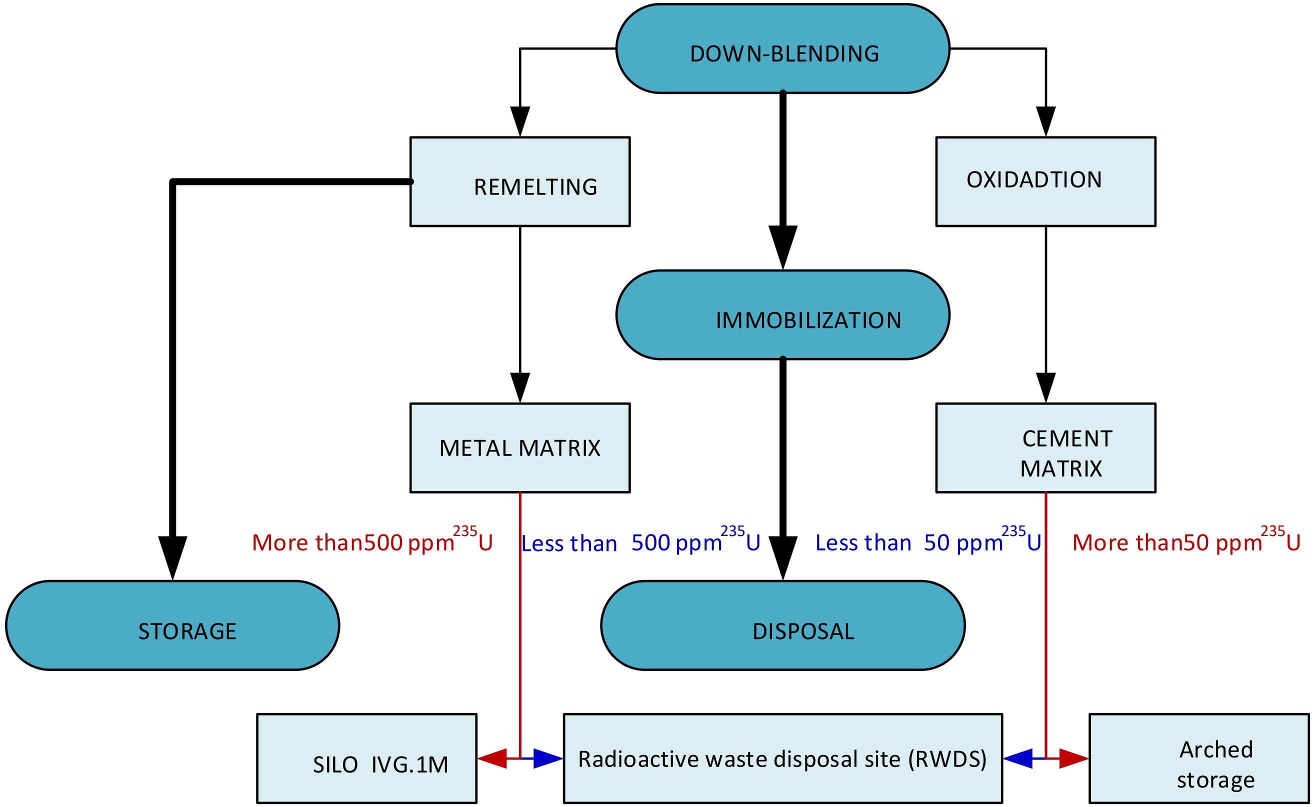


FUEL ROD



Fuel cladding – Zr+1%Nb

Fuel meat – Zr+(3-5%)U



Fuel – uranium-zirconium fuel elements

Fuel enrichment (HEU): 90%

Number of SFA– 33 pcs;

Mass concentration of uranium in fuel: ≈3-5%

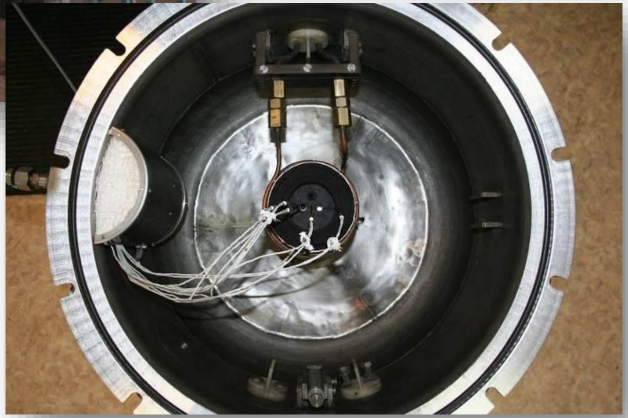
EXPERIMENTAL BENCH FOR TESTING THE METHOD FOR REMELTING IVG.1M HEU FUEL

VCG-135 Test-bench

The stand allows for controlled heating of any small-sized samples to a high temperature (3000°C) with subsequent cooling due to heat leaks into a water-cooled inductor when the generator is switched off.

Specifications:

- Generator frequency, kHz: 66;
- Inner diameter of the working chamber, mm: 600;
- Working chamber height, mm: 700;
- Inductor dimensions, mm: Ø80x150, Ø120x150;
- Temperature sensors: thermocouples, pyrometers;
- Gas environment in the working chamber: vacuum, argon;
- Mass of the loaded batch, g: 100-500



Working chamber

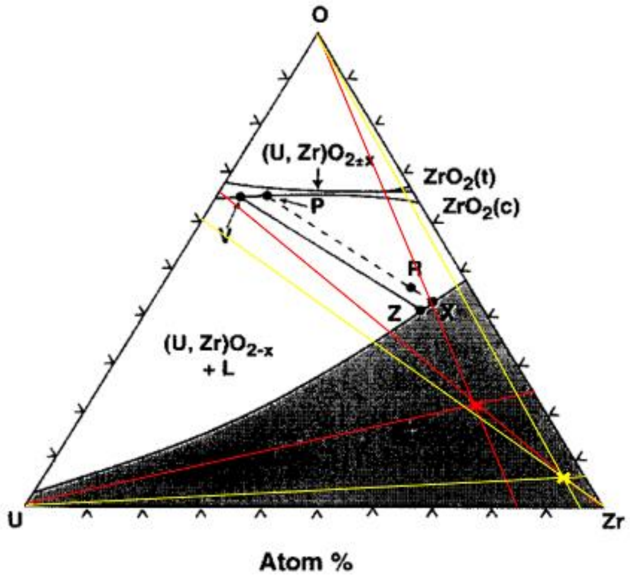
Experimental assembly

Double graphite crucible

CONDITIONS FOR DOWN-BLENDING OF IVG.1M HEU FUEL BY REMELTING METHOD

Purpose of the experiment:

- to obtain data on the phase state of uranium during remelting of zirconium alloy E110 (fuel model) and UO_2 powder (model of "diluent") enriched to 0.27 wt.% in ^{235}U)



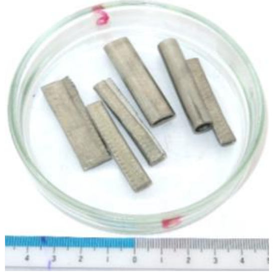
Schematic diagram of the phase diagram of the U-Zr-O system at 2000ºC

[P.J. Hayward, I.M. George/Journal of Nuclear Materials 232 (1996) 13-22]

Weight parameters of burden loading for RSNF-1 experiment

Name	Weight (g)
W1 (cup-1)	104.08
W2 (cup-2)	99.71
Chip 1(UO_2 <200>100)	6.07
Zr 1 (E110 plates)	63.93
Chip 2(UO_2 <200>100)	23.63
Zr 2 (E110 plates)	46.37

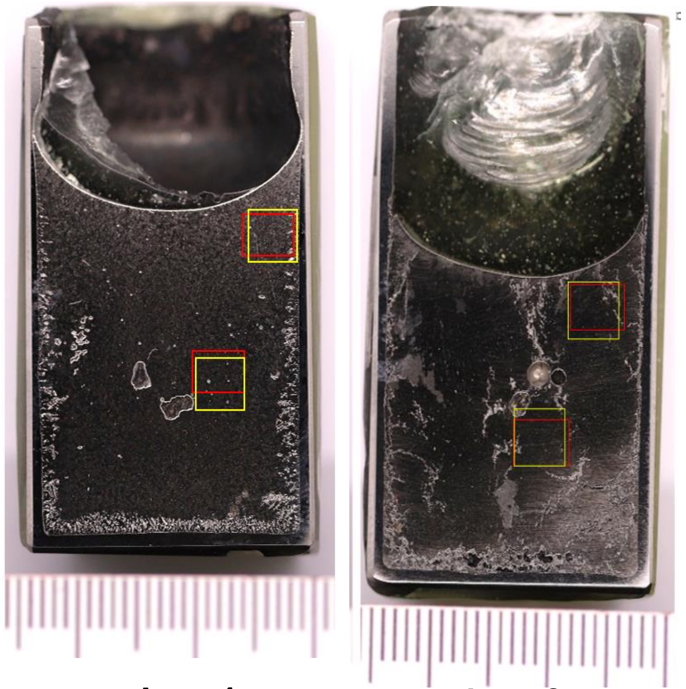
Loading tungsten cups:
cup 1 – 19.75 wt.% in ^{235}U
cup 2 – 5,00 wt.% in ^{235}U



Main conclusion :

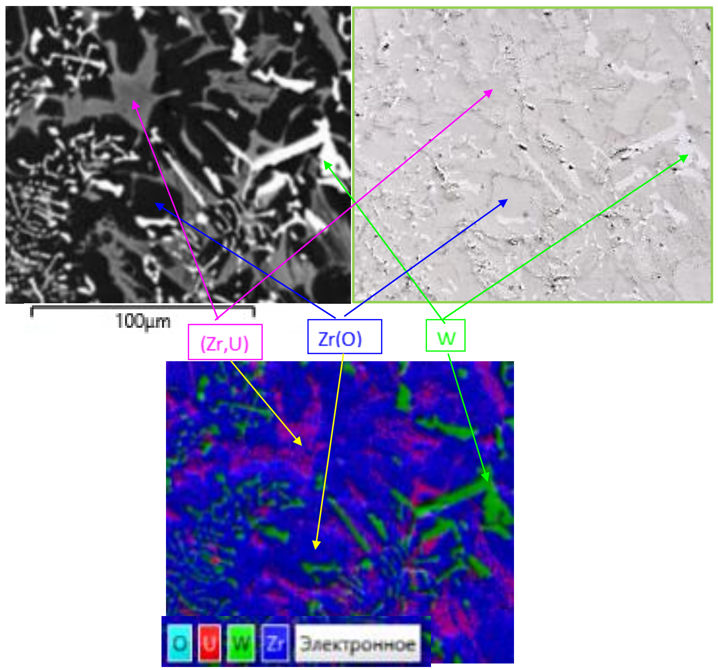
- The red marker indicates the composition of the burden when simulating fuel enrichment up to 5%, yellow – up to 19.75%. As diagram shows, both compositions confidently lie in the region of existence of a homogeneous melt upon reaching 2000ºC

RESULTS OF TESTING THE REMELTING METHOD FOR DOWN-BLENDING HEU FUEL

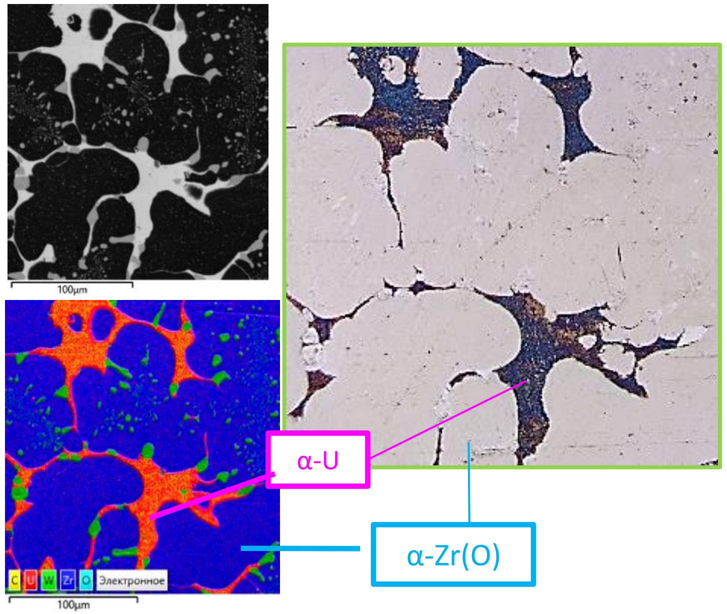


Ingot 1 Ingot 2

Research areas



Phase distribution in ingot 1 (×40, section 4×4 mm)



Phase distribution in ingot 2 (×40, section 4×4 mm)

Main conclusions:

- During remelting, the uranium in the fuel rod of the high-explosive uranium fuel and the uranium in the “diluent” (depleted UO_2 pellet) predominantly crystallizes into an intermetallic phase with zirconium.
- Simulating enrichment reduction to ≈5%, non-uniform uranium distribution was revealed.

CONDITIONS OF IMMOBILIZATION OF IVG.1M FUEL BY REMELTING IN AN AL MATRIX

Purpose of the experiment:

- to obtain a uniform distribution of uranium and zirconium in the aluminum matrix

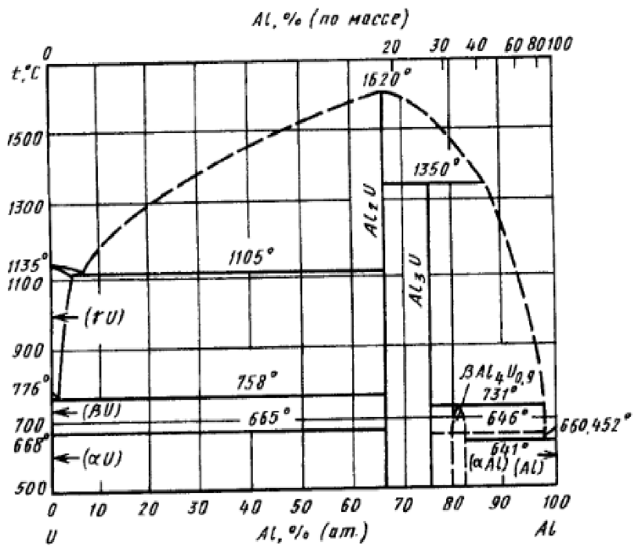


Рис. 126. Al—U

Phase diagram of the U-Al system

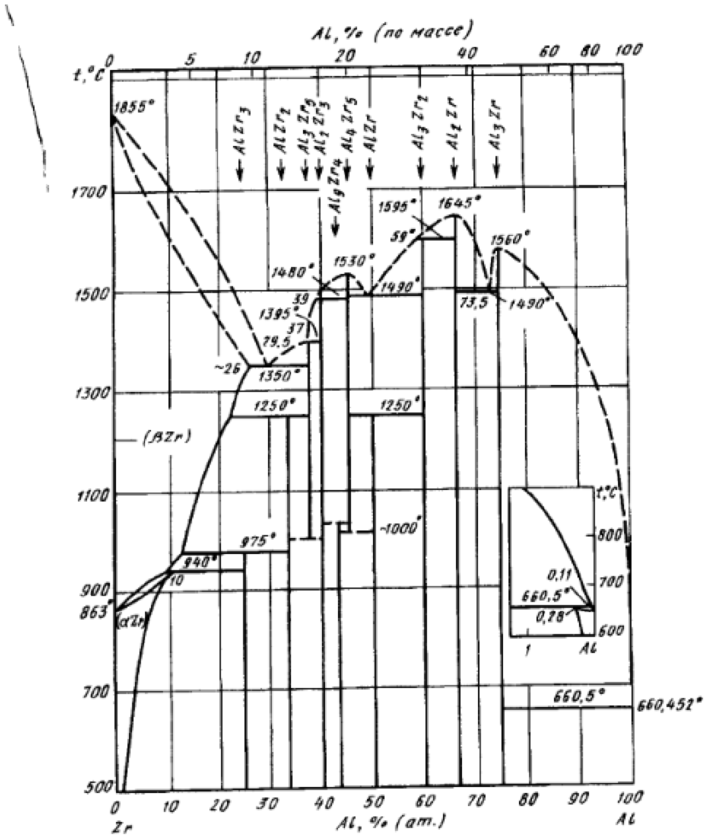


Рис. 132. Al—Zr

Phase diagram of the Al-Zr system

Main conclusions:

UO_2-Al phase diagram not found

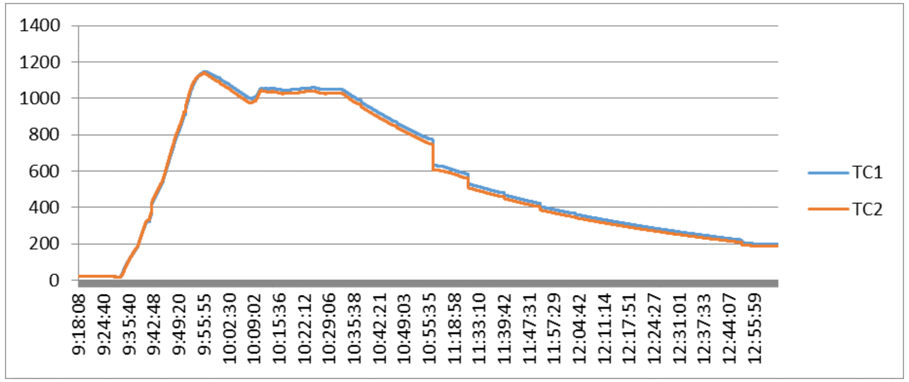
U-Al phase diagram shows that:

- Above the melting point of Al, a liquid phase of U is formed with an atomic concentration of about 2-2.5% and the concentration of dissolved uranium will increase
- Theoretically it is possible to dissolve all uranium (~0.4% at.) in molten aluminum

The Al-Zr diagram shows that:

- Above the melting point of Al, a liquid phase with a very low atomic concentration of zirconium and a solid phase Al_3Zr with a melting point above 1500°C are formed.
- At a temperature of about 900 °C, all zirconium (fuel element) at its target concentration of ~0.7% at can be dissolved in the liquid phase of Al.

TESTING THE METHOD OF REMELTING HEU FUEL FOR IMMOBILIZATION IN AN AL MATRIX



Experimental assembly heating diagram

Weight parameters of burden loading for MMI-1 experiment

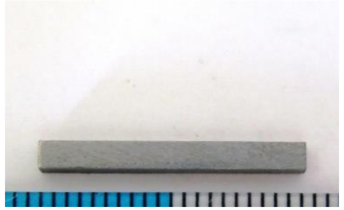
Name	Weight (m), g
G (cup-1) MPG-8	19.97
G (cup-2) MPG-8	20.44
Chip 1(UO_2 <400>200)	0.282
Al rods	23.91
Al rods	23.91
Zr (E110 bar)	0.566

Weight parameters of burden loading for MMI-2 experiment

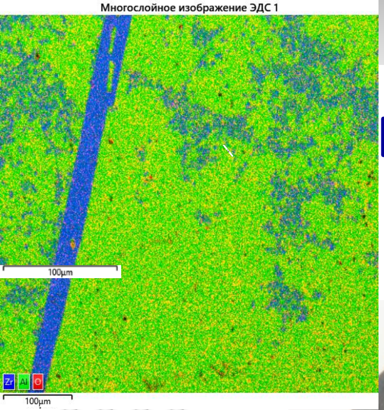
Name	Weight (m), g
G (cup-1) MPG-8	20.11
G (cup-2) MPG-8	20.29
UO_2 chip 1	0.205
UO2 chip 2	0.210
Al rods 1	17.56
Al rods 2	17.68
Zr1 (E110 bar)	0.429
Zr1 (E110 bar)	0.431

UO_2 Chip

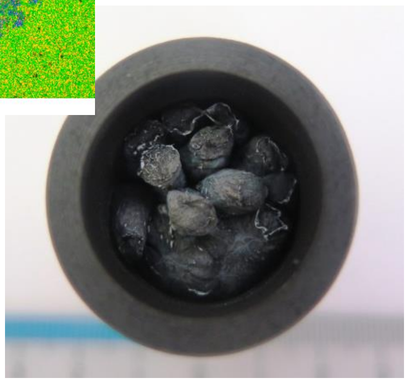
Al rods

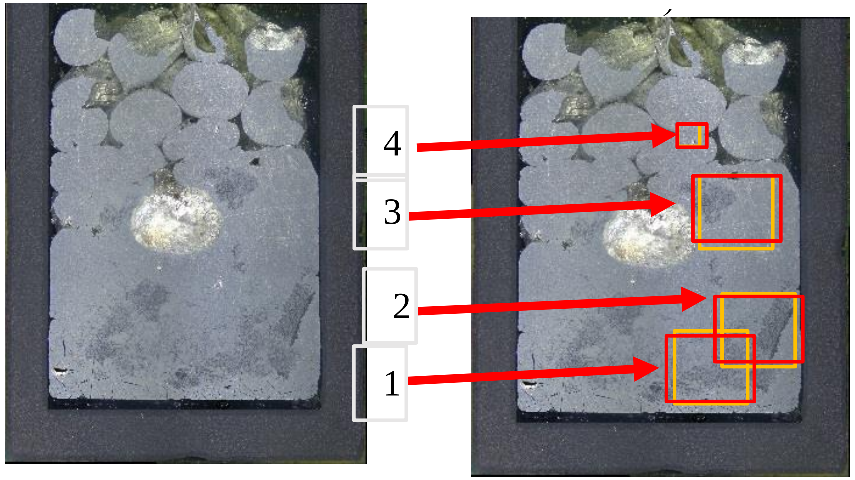


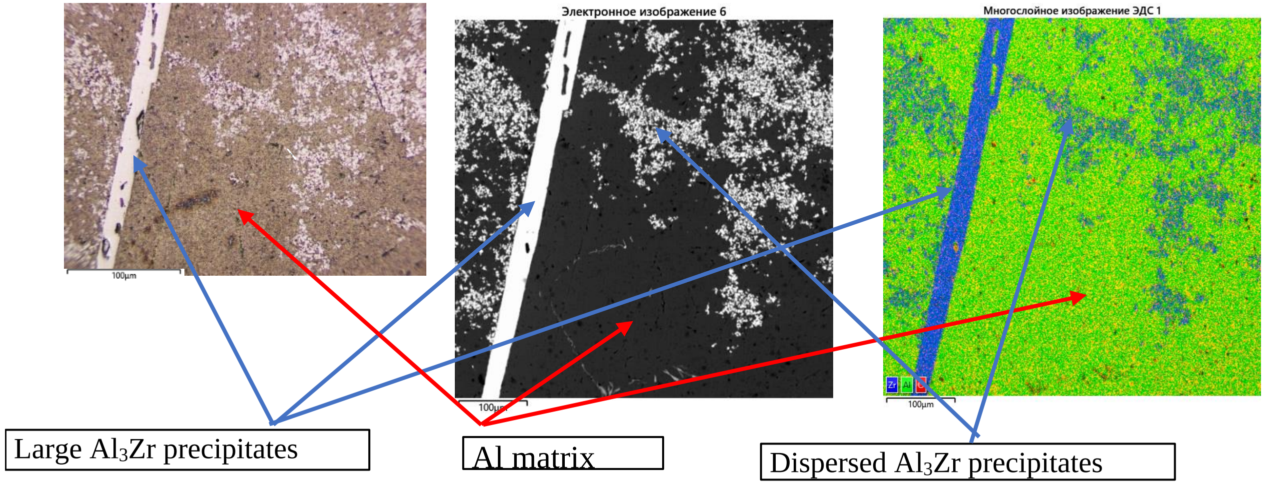
Zr bar



ESULTS OF TESTING THE REMELTING METHOD FOR IMMOBILIZATION OF IVG.1M FUEL IN AN AL MATRIX



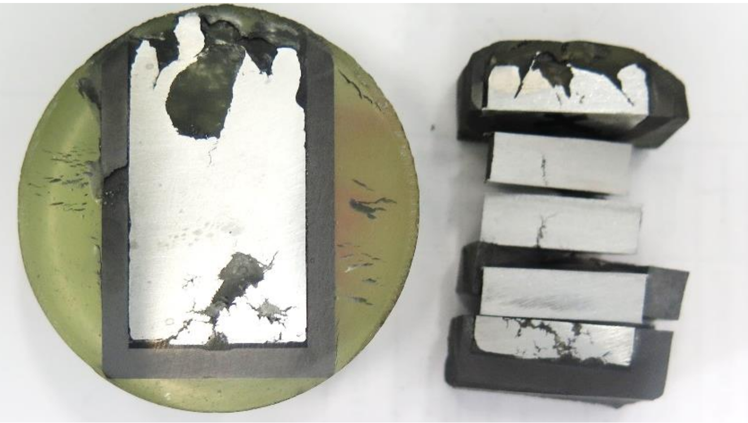




Main conclusions:

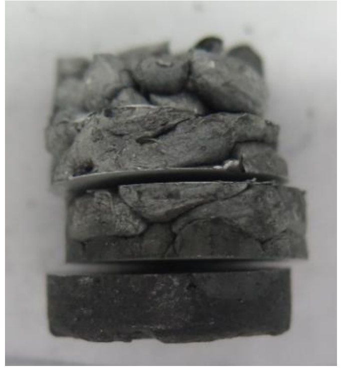
- Absence of expected melt mirror;
- The result of EDS microanalysis showed the following ratio of elements: ~75% at. Al and ~25% at. Zr, which corresponds to the intermetallic phase Al_3Zr

RESULTS OF TESTING THE REMELTING METHOD FOR IMMOBILIZATION OF IVG.1M FUEL IN AN AL MATRIX



t1_5
t1_4
t1_3
t1_2
t1_1

t2_4
t2_3
t2_2
t2_1



t2_4(н,в)
t2_3(н,в)
t2_2(н,в)
t2_1в

Samples for elemental analysis

Results of elemental analysis

MMI-1, ingot 2 (Al – UO_2 composition)		
Sector	Al	U
t1_5	99,938±0,007	0,062±0,007
t1_4	99,953±0,018	0,047±0,018
t1_3	99,785±0,020	0,215±0,020
t1_2	99,33	0,67±0,10
t1_1	98,32	1,68±0,13

MMI-2, ingot 1 (Al –E110 - UO_2 composition)				
Sector	Al	Zr	Nb	U
t2_4	99,81±0,08	0,19±0,08	-	-
t2_3	97,5±0,6	2,5±0,6	0,030±0,012	-
t2_2	97,9±0,6	2,1±0,6	0,026±0,011	-
t2_1	91,5±1,8	8,2±1,5	0,091±0,015	0,24±0,26

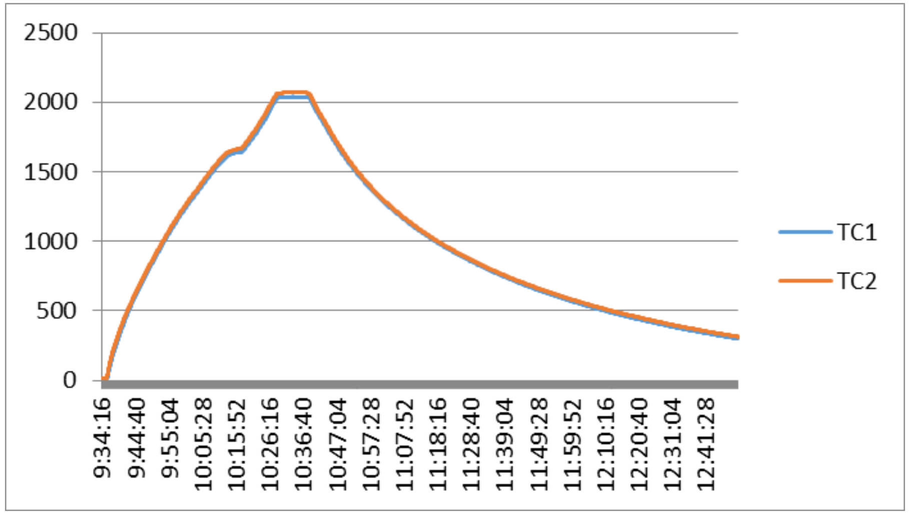
MMI-2, ingot 1 (Al – E110 - UO_2 composition)				
Sector	Al	Zr	Nb	U
t2_4в	99,79±0,05	0,21±0,05	-	-
t2_4н	99,68±0,04	0,32±0,04	-	-
t2_3в	99,04±0,19	0,94±0,19	0,014±0,005	-
t2_3н	98,68±0,02	1,30±0,02	0,021±0,008	-
t2_2в	99,35±0,12	0,63±0,12	0,01±0,02	0,02±0,07
t2_2н	95,2±0,4	4,7±0,4	0,053±0,005	
t2_1в	93,3±0,4	6,6±0,4	0,069±0,005	

CONDITIONS FOR IMMOBILIZATION OF IVG.1M FUEL BY REMELTING IN A Zr MATRIX

Purpose of the experiment:

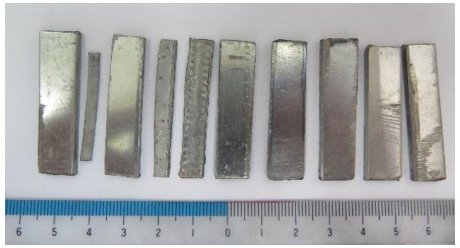
- to obtain a uniform distribution of uranium throughout the metal matrix

Experimental assembly heating diagram



Weight parameters of burden loading for MMI-3 experiment

Name	Weight (m), g
UO_2 chip 1	0,687
UO2 chip 2	0,687
Zr1 (E110 plates)	60,0
Zr2 (E110 plates)	60,0



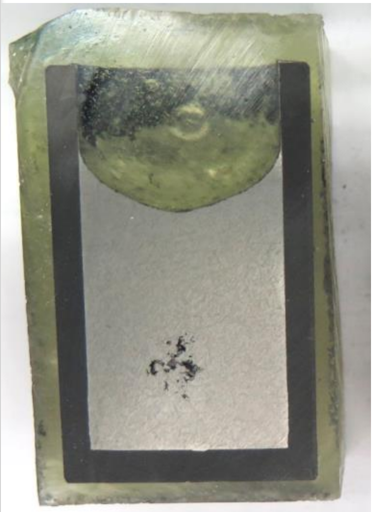
Zr (E110 plates)

UO_2 chip

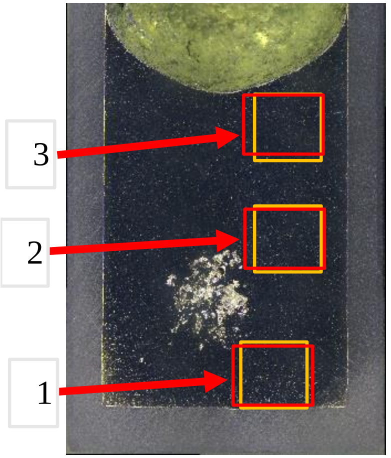
Loading graphite cups (identical for both cups)

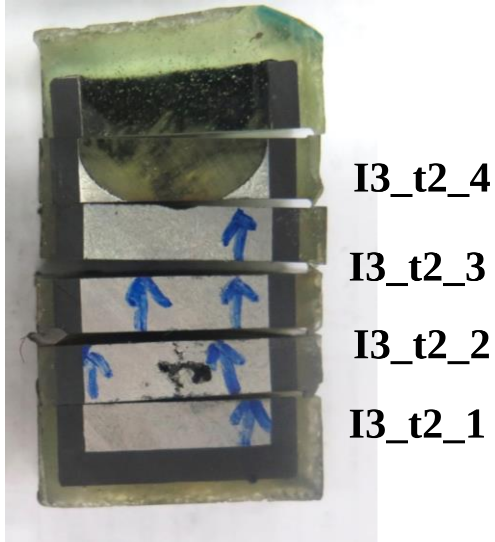
Loading materials into a double crucible

RESULTS OF TESTING THE REMELTING METHOD FOR IMMOBILIZATION OF IVG.1M FUEL IN A ZR MATRIX

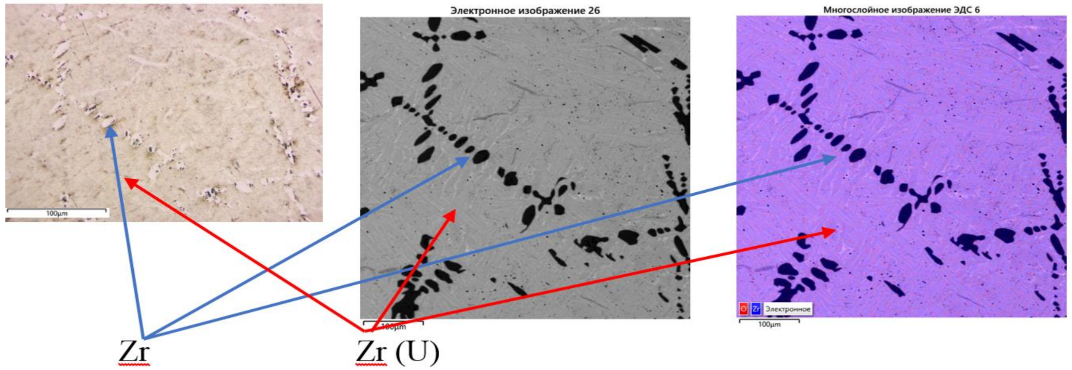


Ingot structure





Samples for elemental analysis



Distribution of phases in the microstructure of the MMI-3 ingot

Distribution of elements by height in a diametrical section

	Zr	Nb	U
	Aver. value	Aver. val.	Aver. val.
I-3_t2_4	97,94	1,07	0,99
I-3_t2_3	98,00	1,06	0,93
I-3_t2_2	97,97	1,08	0,95
I-3_t2_1	97,99	1,06	0,95

U	Aver. value	$\Delta_{0,95}$ Ave. Val.	Rel. $\Delta_{0,95}$	$\Delta_{0,95}$ u.val	Dabs	Drel
	0,96	0,04	4%	0,05	0,10	10%

Distribution of elements by height in cross sections

	Zr	Nb	U
	Aver. val.	Aver. val.	Aver. val.
I3_4_в	98,05	1,04	0,91
I3_4_н	98,04	1,05	0,91
I3_3_в	98,00	1,06	0,93
I3_3_н	97,97	1,08	0,95
I3_2_в	97,99	1,06	0,95
I3_2_н	98,02	1,07	0,91
I3_1_в	98,00	1,07	0,93

U	Aver. val.	$\Delta_{0,95}$ Aver. val.	Rel. $\Delta_{0,95}$	$\Delta_{0,95}$ u.val	Dabs	Drel
	0,927	0,016	2%	0,04	0,07	8%

CONCLUSIONS ON TESTING THE REMELTING METHOD FOR DOWN-BLENDING AND IMMOBILIZATION OF IVG. 1M FUEL

Main conclusions:

- When down-blending the HEU fuel of the IVG.1M reactor with depleted UO_2 pellets at T=2000 °C in an inert environment, the uranium of the fuel and the uranium of the diluent (UO_2) are converted into a metallic phase. Thus, the identity of the uranium phases of the HEU and LEU is ensured, which makes the dilution process possible
- In terms of structural homogeneity and uniform distribution of uranium-containing phases, the zirconium matrix is more promising.
- Remelting can be carried out in a graphite crucible of an induction heating unit. Remelting is possible using both "cold" and "hot" crucible methods.

Preliminary data for the technological process:

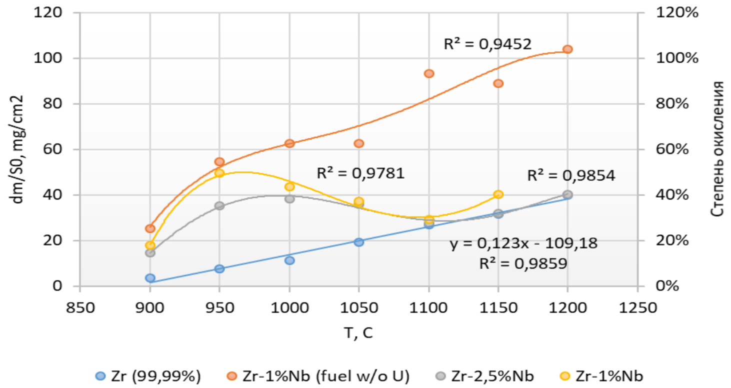
1) When diluting one SFA with UO_2 (enrichment of 0.27% in ^{235}U)
   - ingots weighing from 7.5÷10 kg will be formed in the amount of 33 pcs (according to the number of SFAs);
   - the volume of the ingot will be 1.5÷2 l, crucible V ~3-5 l.

2) To immobilize all the fuel, with a total mass of SFAs of ≈289 kg, it will be necessary:
   - ≈120÷135 kg of pellets of depleted UO_2 (the data is also relevant for dilution by oxidation);
   - ≈24.55 t of aluminum ($47,500) or ≈ 10.2 t of zirconium ($316,200) ;

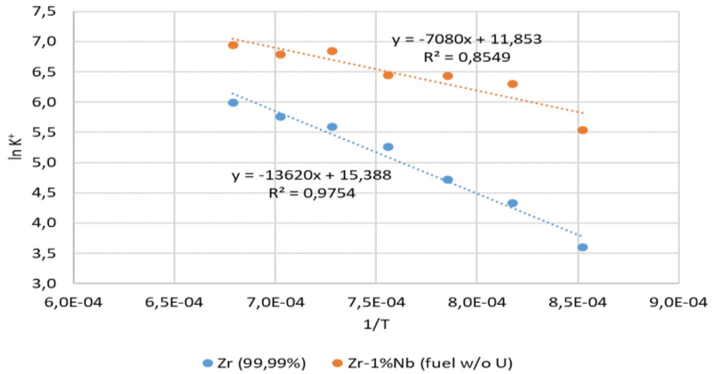
3) If the immobilized fuel is not exempted from IAEA safeguards, the following options are possible for expanding SILO (V≈39):
   - Up to 99 cells, S=600-700 m^2 (Al matrix, immobilization without crucible)
   - Up to 180 cells, S=1300-1500 m^2 (Al matrix, crucible immobilization);
   - Up to 43 cells, S=250-300 m^2 (Zr matrix, without crucible);
   - Up to 75 cells, S=500-600 m^2 (Zr matrix, with crucible)

RESULTS OF TESTING THE OXIDATION METHOD FOR DOWN-BLENDING THE IVG.1M HEU FUEL

Change in specific weight gain after oxidation in the range of 900÷1200 °C for 0.5 h



Temperature dependence of oxidation rate

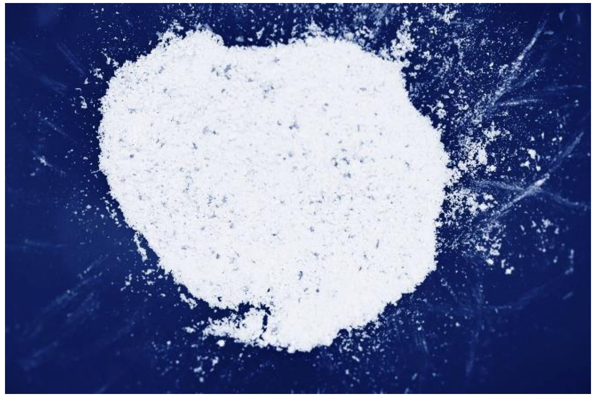


Fuel rod

900 °C

1000 °C

Grinding



Main conclusions:

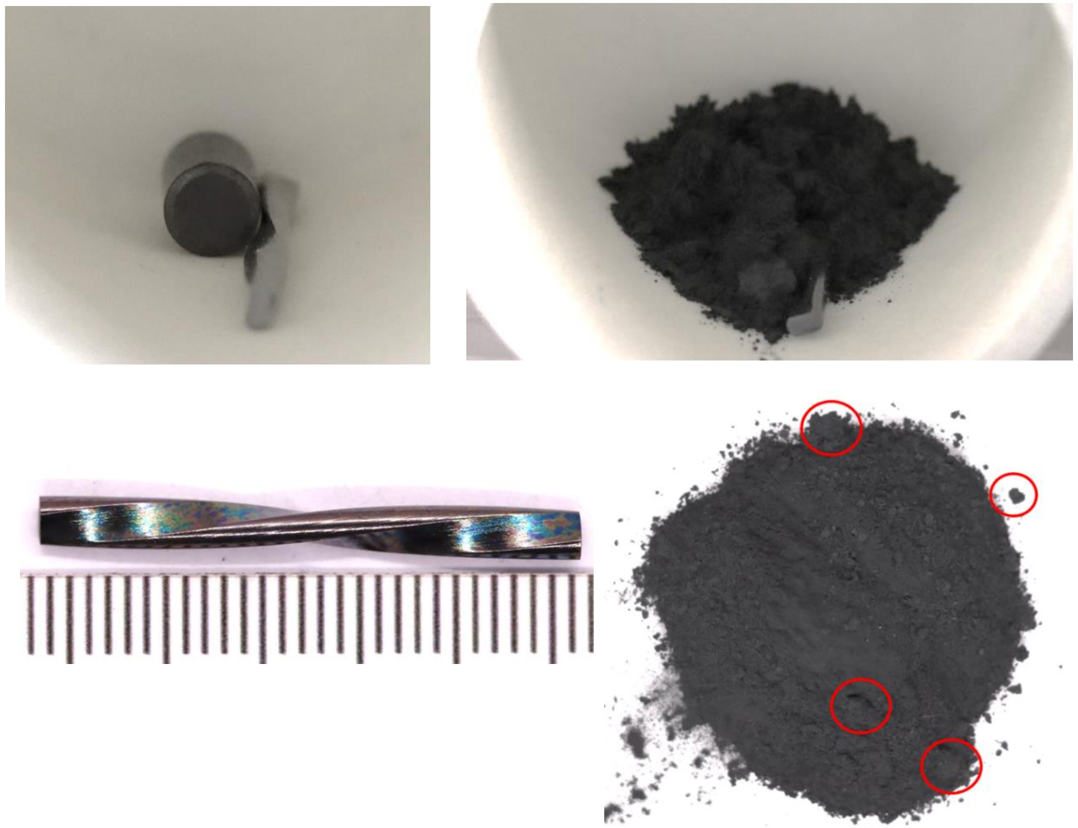
- When oxidizing a fuel rod under T=900 ºC for 3 hours, the oxidation degree is 100%
- During oxidation of a fuel rod under T=1000 ºC for 3 hours, the oxidation degree is 98%, the main phase of uranium is α-U_3O_8
- After oxidation, the fuel rod is easily crushed.

RESULTS OF OXIDATION OF DEPLETED UO2 PELLETS

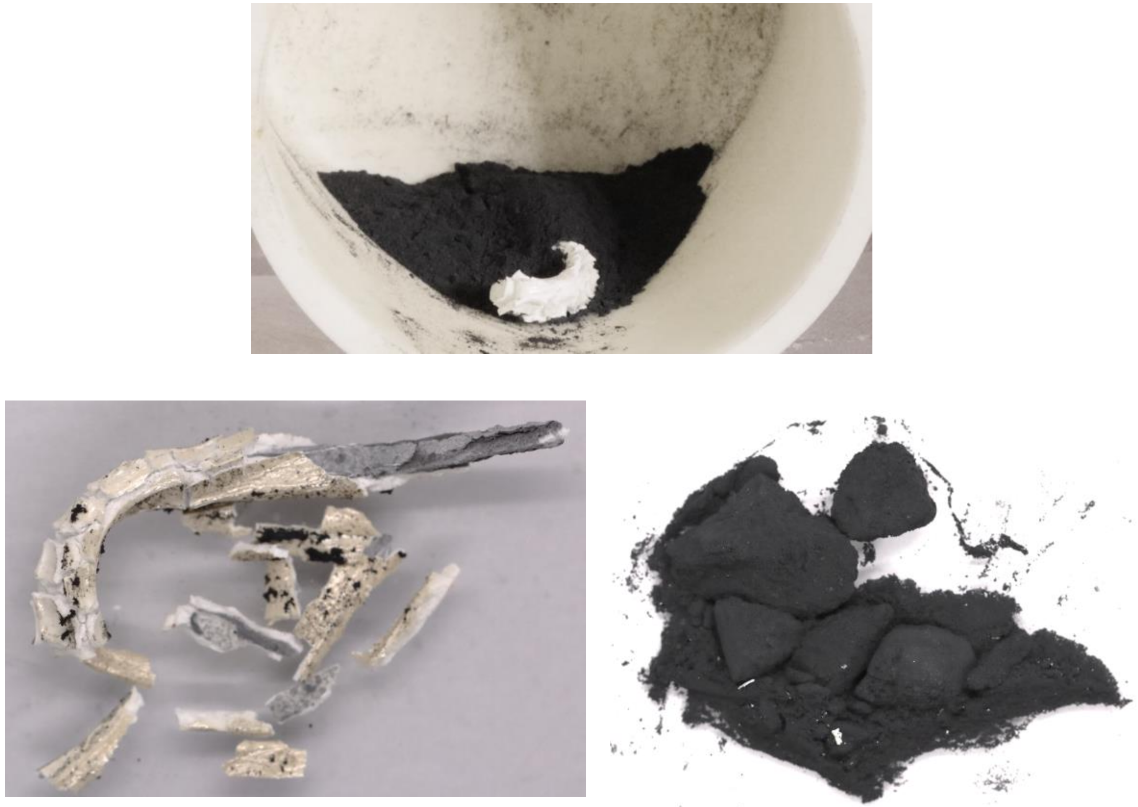
Main conclusions:

- In the sample annealed at 500 degrees for 1 hour there are two phases: α-U_3O_8 (≈ 66 wt.%) and β-U_3O_8 (≈ 34 wt.%)
- In the sample annealed at 1000 degrees for 3 hours: α-U_3O_8 (≈ 94%) and β-U_3O_8 (≈ 6 wt.%)
- When U_3O_8 is annealed at a temperature above 1000°C, the uranium oxide is reduced to UO_2, but when cooled in air, the resulting uranium dioxide again turns into U_3O_8

RESULTS OF COMBINED OXIDATION OF FUEL ROD AND DEPLETED UO2 PELLET



The result of the combined oxidation of a model fuel rod (E110 alloy) and a depleted UO_2 pellet at T=500°C and conditioning for 0.5 h



The result of the combined oxidation of a model fuel rod (E110 alloy) and a depleted UO_2 pellet at T=1000°C C and conditioning for 3 h

MAIN CONCLUSIONS ON TESTING THE OXIDATION METHOD FOR DOWN-BLENDING THE IVG.1M HEU FUEL

Main conclusions:

- At T=1000°C in an air environment and holding for about 3÷6 h, h, the fuel uranium and the diluent uranium (UO_2) transfer into the α-phase U_3O_8, i.e. the identity of the uranium phases of HEU and LEU is ensured. Thus, when they are mixed, the dilution process can be considered feasible.
- For more complete oxidation of fuel, it is necessary to dismantle SFAs and fragment fuel rods.
- When fuel and diluent are oxidized, the fuel becomes brittle and is easily crushed even by hand, and the UO_2 pellet is transformed into powder. To obtain a single fraction, the components after oxidation are simultaneously crushed in a disk mill to a specified size (≈200 μm).
- Simultaneous oxidation of fuel rods of the IVG1.M fuel with depleted UO_2 pellets should be performed with mixing of the components, for which it is proposed to use a rotating and tilting tubular furnace.

Preliminary data for the technological process:

1) When down-blending IVG.1M SNF with UO_2 pellets (enrichment 0.27% in 235U) using the oxidation method
   - SFA cutting and fuel rod fragmentation (up to 200 mm);
   - the daily batch of fuel rod fragments (l=200 mm) will be 99 pcs (554 g)
   - the mass of oxidized (LEU) fuel will be 1017 g

2) To immobilize all the fuel, with a total mass of SFAs of ≈289 kg, it will be necessary :
   - Number of oxidation batches – 524 pcs.
   - ≈120÷135 kg of depleted UO_2 pellets (data also relevant for dilution by oxidation method);
   - ≈70.2 t of fly ash ($1,404)
   - ≈39,6 t of Portland cement ($3,165);

3) If the immobilized fuel is not removed from IAEA safeguards, then options for expanding the arch storage facility by 80% are possible.

Nabertherm single-zone rotary and tilting tube furnace model RSRC 80/500/11

CONCLUSION

1. As the technology for down-blending irradiated HEU fuel from the IGR reactor, it is proposed to use dry mixing of HEU fuel powders and depleted UO_2 (0.27%);
2. It is proposed to use the cementation method to immobilize IGR fuel;
3. For handling highly enriched spent nuclear fuel from the IVG.1M research reactor, it is proposed to use:
   - Oxidation method for fuel down-blending stage (up to enrichment of 5 wt.% in ^{235}U);
   - Cementation method for the immobilization stage (developed earlier for irradiated IGR fuel).
4. For a more detailed study of the oxidation method of uranium-zirconium fuel, several issues need to be addressed as part of research work.

Thank you for attention!

IAE NNC RK

071100, Kazakhstan,
EKR, Kurchatov
10, Beybit Atom Str.,
iae@nnc.kz