MAJOR RESULTS on the DEVELOPMENT of HIGH DENSITY U-Mo FUEL and PIN-TYPE FUEL ELEMENTS EXECUTED under the RUSSIAN RERTR PROGRAM AND IN COOPERATION with ANL (USA)

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ABSTRACT

VNIINM is active participant of "Russian program on Reduced Enrichment for Research and Test Reactors". Institute Works in two main directions: 1) development of new high-density fuels (HDF) and 2) development of new design of fuel elements with LEU. The development of the new type fuel element is carried out both for existing reactors, and for developing new advanced reactors.

The "TVEL" concern is coordinator of works of this program. The majority enterprises of branch (NIIAR, PIYaF, RRC KI, NZChK) take part in this work.

Since 2000 these works are being conducted in cooperation with Argonne National Laboratory (USA) within the RERTR program under VNIINM with ANL contract.

At the present, a large set of pre-pile investigations has been completed. All necessary fabrication procedures have been developed for utilization of U-Mo dispersion fuel in Russian-designed research reactors. For irradiation tests the pin-type mini-fuel elements with HDF dispersion fuel with LEU and the uranium density equaled to 4,0 and 6,0 g/cm^3 (up to 40 vol.%) have been manufactured. Their irradiation began in August 2003 in the MIR reactor (NIIAR, Dimitrovgrad).

A large set of works for preparation of lifetime tests (WWR-M reactor in Gatchina) of two full-scale fuel assemblies with new pin-type fuel elements on basis LEU UO_2-Al and UMo-Al fuels has been completed. The in-pile tests of fuel assemblies began in September 2003.

The summary of important results of performed works and their near-term future are presented in paper.

1. Introduction

Since the end of 70-th years the fuel elements with UO_2-Al dispersion fuel are being used in Russian-built research reactors. The development of design and fabrication process have been carried out by VNIINM in collaboration with NZChK and NIKIET. The fuel elements and fuel assemblies have been developed individually for each type of reactor (WWR-M, MR, IRT, WWR-K, IVV-2M). The utilization of dispersion fuel and development of method of extrusion of three-layer tubular blank allows to manufacture the tube-type thin-walled fuel elements with different shapes and sizes. All types of fuel elements ensure the required operation parameters and have enough high reliability, which is confirmed by successful long-term operation of research reactors. The manufacturing and experimental experiences of using of dispersion fuel on the basis of uranium dioxide have been allowed to complete the first stage of fuel enrichment reduction up to 36 %.

However a design complexity (thin-walled three-layer tubes with different shapes) and hence complexity of fabrication process of fuel elements, the absence of their unification make difficult the increase of a volume fraction of nuclear fuel in the meat and the LEU using, which is obligatory for prevention of non-proliferation risk of the nuclear weapon.

So experts of our institute initiated the development of fuel assembly on the basis of new type fuel element for the Russian-designed research reactors. The main goal of these works is to produce the advanced as much as possible unified fuel element, which will be competitive and will provide high technical and economic parameters of manufacturing. The development of the new type fuel element is carried out both for existing reactors, and for developing new advanced reactors.

During the past few years this direction has been under intensive development. Since 2000 year these works are carried out by order of Ministry of Atomic Energy of Russian Federation in the frame of Russian RERTR Program. The "TVEL" concern is coordinator of works of this program. The majority enterprises of branch (NIIAR, PIYaF, RRC KI, NZChK) take part in this work. And also the works are being carried out in cooperation with Argonne National Laboratory (USA) and at its funding support within the RERTR program under VNIINM with ANL contract.

2. Main results

The main results of fulfilled works were in details presented in 13 reports /1-13/ at the various international meetings and in 13 deliveries under contract with ANL /14-26/.

Work is being conducted in two main directions: 1) development of new high-density fuels (HDF) for using in the fuel elements of the research reactors and 2) development of new design of fuel elements for research reactors.

During the past three years the following scope of work has been carried out.

<u>At the first direction</u>

A large set of works for preparation of irradiation test of new high-density fuels has been completed.

– On the basis of analysis of the irradiation results of U-Mo dispersion fuels obtained by ANL and the results investigations carried out by VNIINM a few types of U-Mo alloys differing by Mo amount in the range from 6 up to 10 wt.% have been selected for irradiation tests [9 ,14].

– Necessary pre-pile investigations of structure and properties of the chosen alloys and dispersion fuels on their basis have been executed [15, 16].

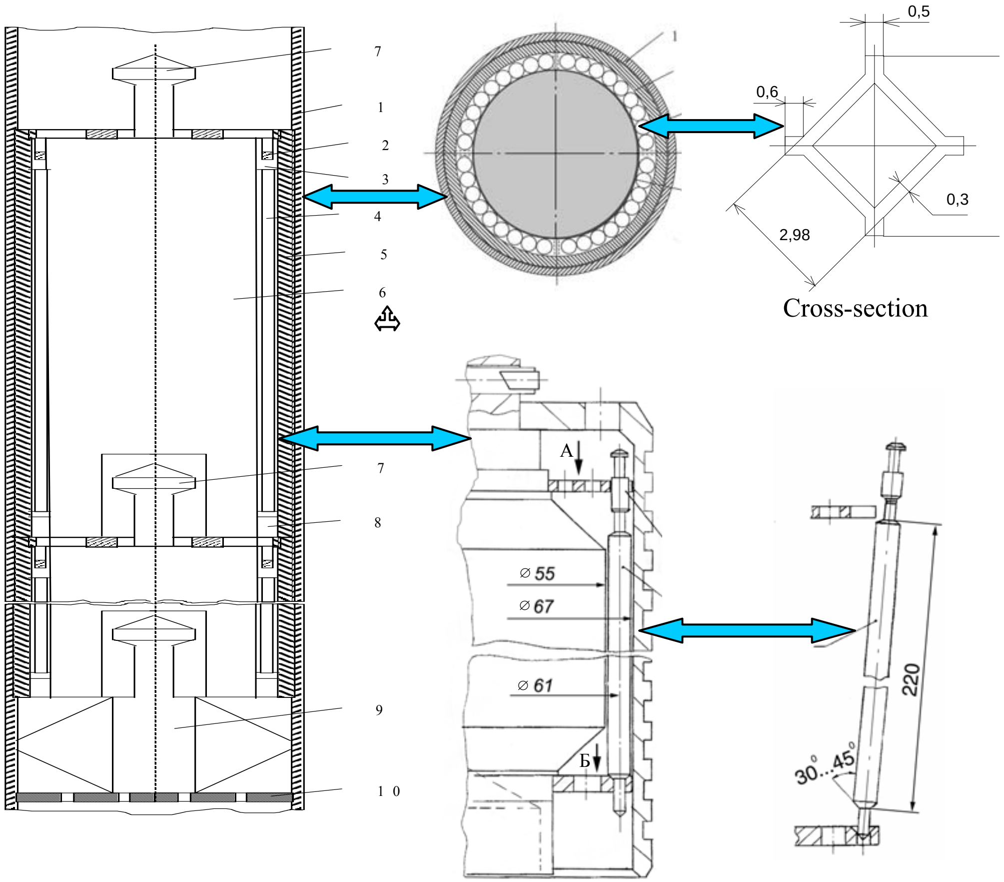
– The design of «GARLAND» type experimental device (Fig.1) [9, 13, 19, 20] and the irradiation test schedule in the MIR reactor has been developed. This design provides the required irradiation conditions of U-Mo dispersion fuels with the necessary control of parameters of tests (Fig.2) [17].

– The neutronics, thermal-hydraulic and stress-strain calculations have been carried out for substantiation of conditions and safety of irradiation tests of mini-fuel elements with HDF (Fig.2) [18].

– For irradiation tests the pin-type mini-fuel elements with HDF dispersion fuel with low enrichment (19,7%) uranium and the uranium density equaled to 4,0 and 6,0 g/cm^3 (volume fraction of - up to 40 %) have been manufactured [13, 20].

The irradiation of two capsules, each containing 32 mini-fuel elements, begun on 25 August 2003 in the MIR reactor (NIIAR, Dimitrovgrad). This experiment will provide the first irradiation results of pin-type U-Mo dispersion fuel elements in characteristic operation conditions of pool-type research reactors.

At the present moment average burnup is reached ~ 4,5 %. When average burnup will be reached (in middle of December 2003) ~ 20 % several mini-elements will be removed from one capsule and sent for post-irradiation examinations (PIE), both nondestructive and destructive.



1-Casing of WC; 2- Upper ring; 3- Upper rib; 4- Fuel mini-elements; 5- Displacer; 6- Stanchion; 7- Head of stanchion; 8- Lower rib; 9- Lower support; 10- Stop collar.

Fig.1 Drawing of experimental device

List of high density alloys to be tested

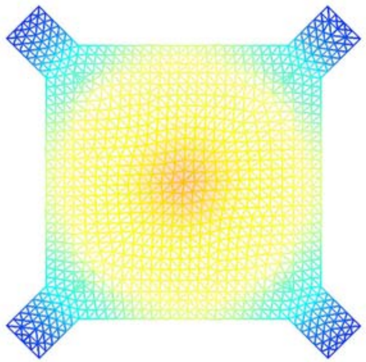
Alloy №	Conven-tional designa-tion	Basic elements, % wt.		Alloying elements, % wt.		Structure		Density (ρ_t), g/cm³
		U	Mo	Al	Sn	type 1	type 2	
1	UM-9	basis	9-9,5	-	-	1-phase	2-phase	17,51
2	UM-6,5	basis	6,5-7	-	-	1-phase	2-phase	17,84
3	UM-6,5L1	basis	6,5-7	0,1	-	1-phase	-	17,5
4	UM-6,5L2	basis	6,5-7	0,2	-	1-phase	-	17,17
5	UM-6,5L3	basis	6,5-7	0,2	0,2	1-phase	-	17,82
6	UM-1,5L	basis	1,3-1,5	0,2	0,2	-	2-phase	18,13
7	UZN-10	U+5Zr+5Nb				1-phase	2-phase	16,43

Initial materials for fuel mini-elements

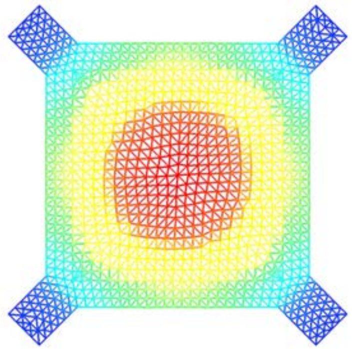
Parameter	Value	
Cladding	Aluminum alloy SAV-1	
Fuel meat	UMo+Al powder PA4	
Fuel enrichment, %	19,7±0,3%	
U density, g/cm³	4	6
U^{235} loading, g	0,82±0,1	1,22±0,1
Volume fraction of Fuel, %	23-25	34-38

Basic parameters of tests

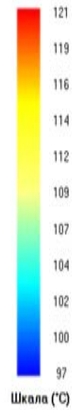
Characteristic	Value
Fuel mini-element capacity, kW	1,3 - 1,9
Input pressure of coolant, MPa	1,1 – 1,3
Pressure fall, MPa	0,3
Input temperature of coolant, °C	48 - 60
Coolant flow, m^3/h	6 - 8
Average velocity, m/s	2,3 - 3
Heat flux, MW/m^2	
average	0,4 – 0,6
maximum	0,9
Peak fast neutron flux, $(n/cm^2 \cdot s)$	
E>0,1 MeV	$1{,}4 \bullet 10^{14}$
E>0,5 MeV	$1{,}1 \bullet 10^{14}$
E>1,0 MeV	$0{,}6 \bullet 10^{14}$
Maximum temperature of meat, °C	120
Maximum temperature of cladding, °C	110
U^{235} burn-up, %	
average	50
maximum	75



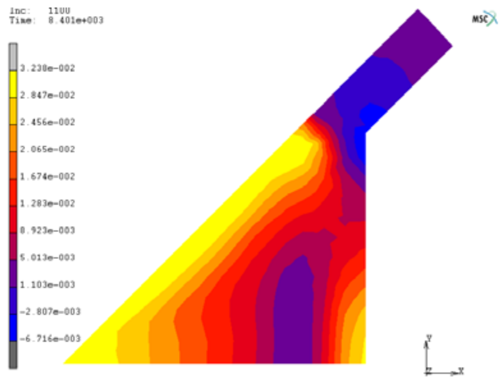
a) at the beginning of irradiation
(section at h ~30 mm below of core center)



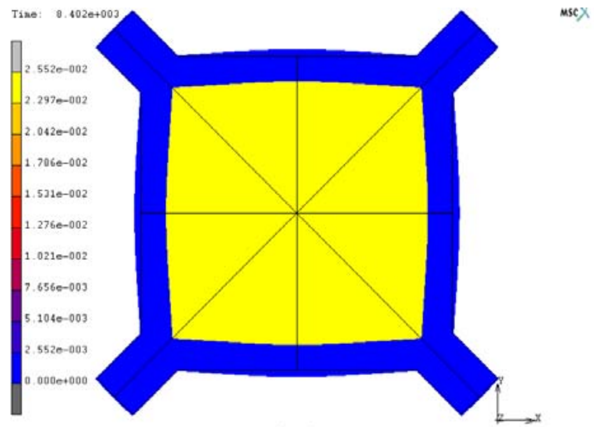
b) at the end of irradiation
(section at h~200 mm below of core center



Temperature distribution in the most heated cross-section
of most heated fuel mini-element



a) Distribution of tangential deformation (%)



b) Strained contour of fuel mini-element

Distribution of basic parameters of stress-stain state and forming in the fuel mini-element cross-section with max burn up at the end of irradiation

Fig. 2. Results on substantiation of irradiation conditions

Thus, all necessary fabrication procedures have been developed for utilization of U-Mo dispersion fuel in Russian research reactors: fabrication processes for alloys and fuel granules, fabrication processes for dispersion fuels with different uranium density. These fabrication procedures are ready for transfer to the plant for the organization of industrial production.

The final selection of fuel will be made on the basis of results of irradiation tests and post-irradiation examinations.

At the second direction
The development of the fuel element design has been carried out on the basis of the following main criteria:
- preservation of the core design of existing reactors;
- preservation of the operation parameters of existing reactors;
- as mush as possible unification of fuel elements for different types of reactor;
- using of uranium enrichment no more than 20 %.

As a result of large set of calculated and technological investigations the new pin-type self-ranging fuel elements have been developed. The optimum sizes of three designs of fuel element have been chosen. These sizes are available for fuel assemblies of any research reactor without its modifications and with preservation of its operating parameters (Fig.3) [1, 2, 8].

A large set of works for preparation of lifetime tests (WWR-M reactor in Gatchina) of two full-scale fuel assemblies with new pin-type fuel elements has been completed. The development and manufacturing of IRT-type fuel assembly with pin-type fuel elements began.

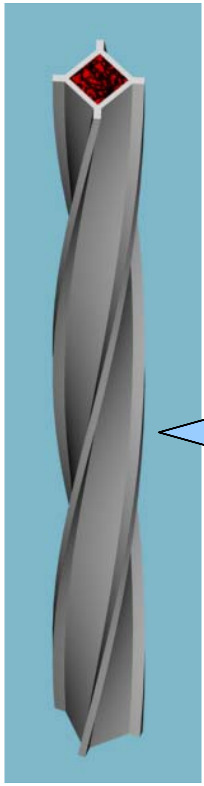
The laboratory fabrication processes of fuel elements and WWR-M2-type fuel assembly has been developed [10, 11, 23, 24]:
- specification of optimum technological parameters of technological procedures;
- debugging of procedures and devices of quality control of fuel element manufacture;
- fabrication process for shroud tube was finalized;
- development of optimum design of grids;
- process of FA assembling;
- development of required drawing-design and technological documentations.

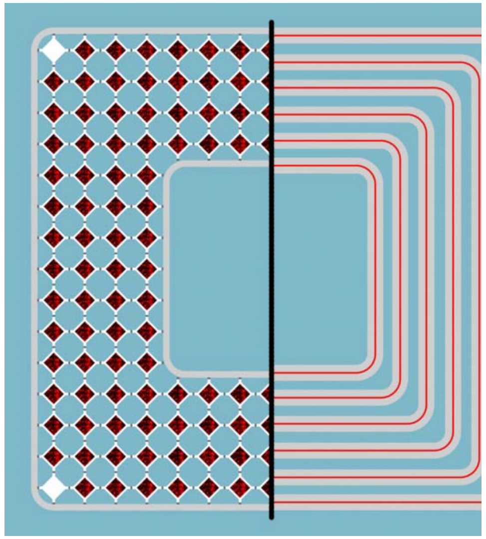
The obtained results showed, that fabrication process of pin-type fuel elements ensures the necessary quality, which is defined two main parameters: uniformity of cladding thickness along height and perimeter of fuel element and uniformity of fuel distribution in meat [11].

A WWR-M2-type fuel assemblies with pin-type fuel elements containing LEU UO_2+Al dispersion fuel (uranium density ~ 2,7g/cm^3; volume fraction of fuel up to ~31%) and U-9%Mo+Al dispersion fuel (uranium density ~ 5,3 g/cm^3; volume fraction of fuel up to ~34,5%) have been manufacturing for lifetime tests in the WWR-M reactor in Gatchina (Fig.4) [10, 11, 23].

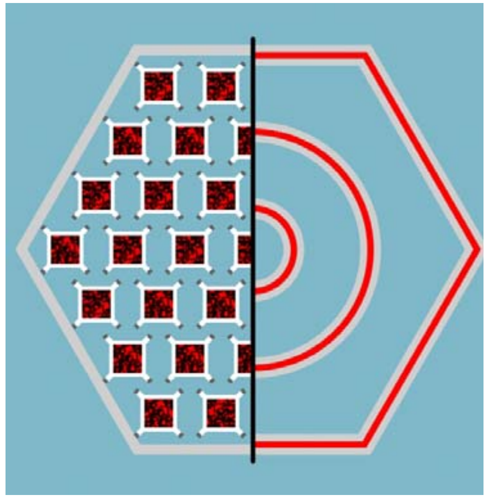
The in-pile test conditions, basic thermal-hydraulic and neutronics parameters of fuel assemblies, the stress-strain state characteristics and size changes of fuel elements at the end of testing have been defined. The results of calculations justified the serviceability of fuel elements during irradiation (Fig.5) [22, 23].

Results of these developments allow to transfer the fabrication procedures to the plant for its finishing in industrial conditions and also to use the received experience for manufacturing of fuel elements and fuel assemblies for other types of research reactors, in particular for IRT-M type FA.

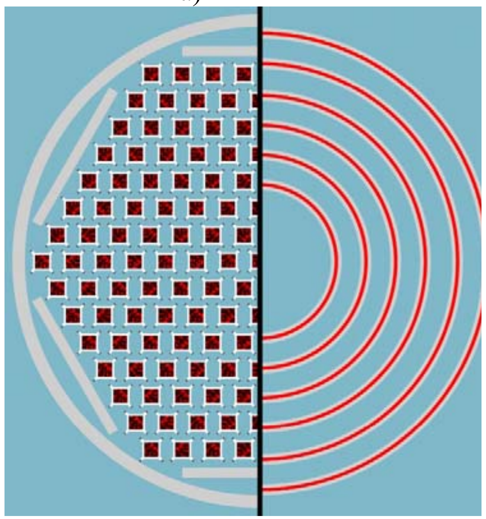




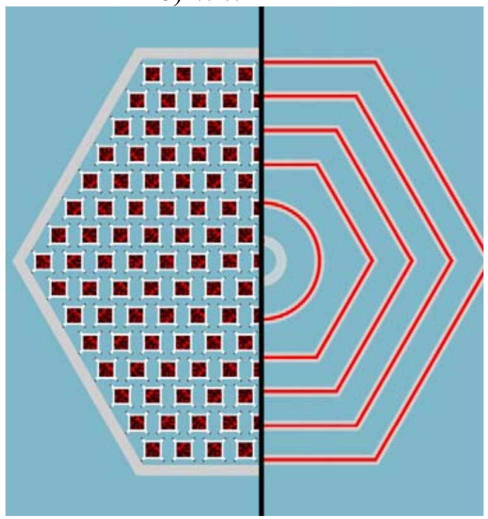
a) IRT-M



b) WWR-M2



c) MR



d) WWR-K

Fuel Element Geometrical Characteristics

d, mm	Δ, mm	h, mm	A, mm	δ, mm	S_f, mm^2	P_f, mm	S_m, mm^2
5,20	0,5	0,75	2,97	min 0,3	10,07	17,05	5,65
4,85	0,4	0,6	2,86	min 0,3	9,0	15,6	5,12
4,50	0,4	0,4	2,9	min 0,3	8,9	14,13	4,4

Notes. S_f - FE area; P_f - FE perimeter; S_m – meat area.

a) Pin-type fuel element

b) Cross-section of FA

Fig.3. Pin-type FE and FAs in Russian-designed research reactors

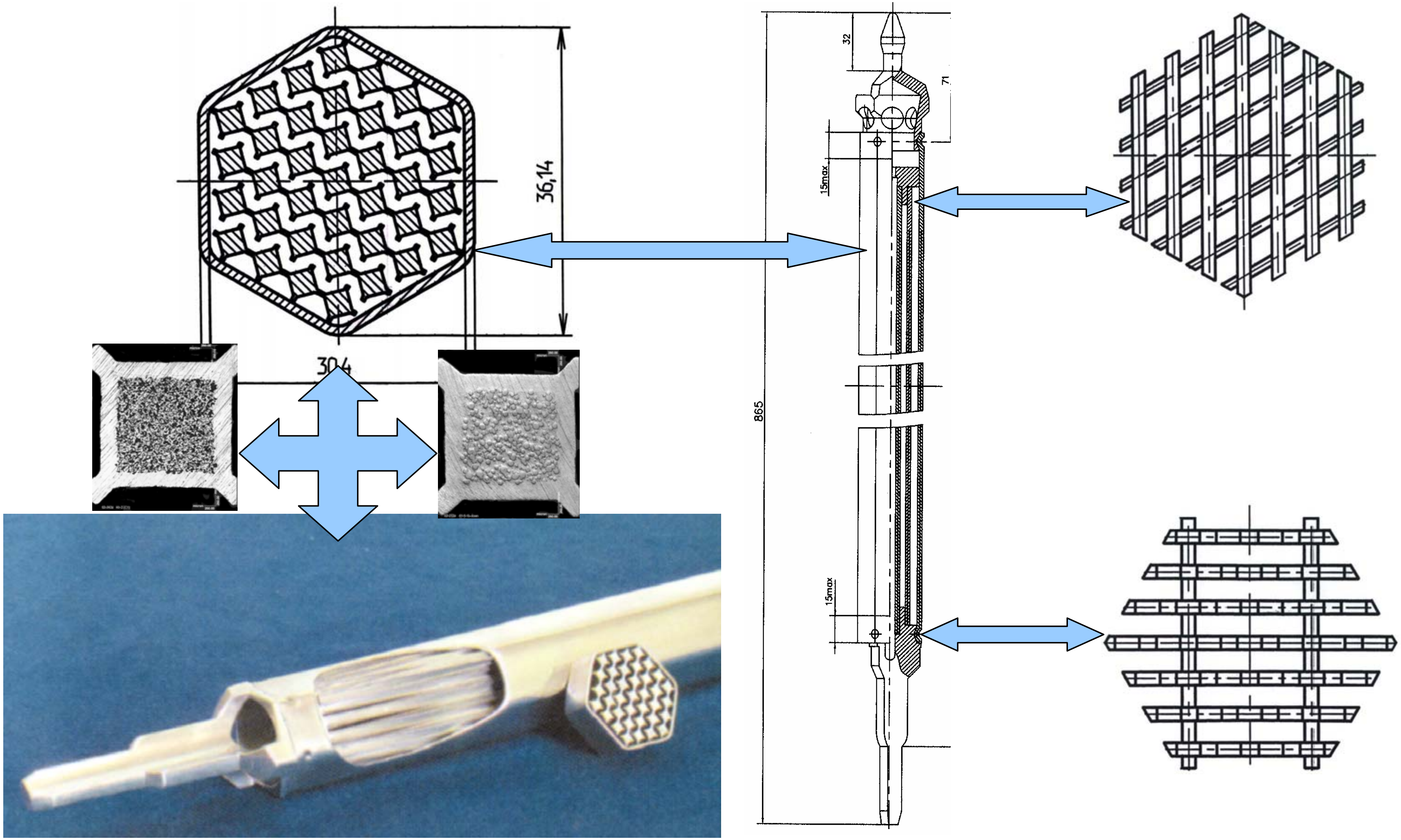
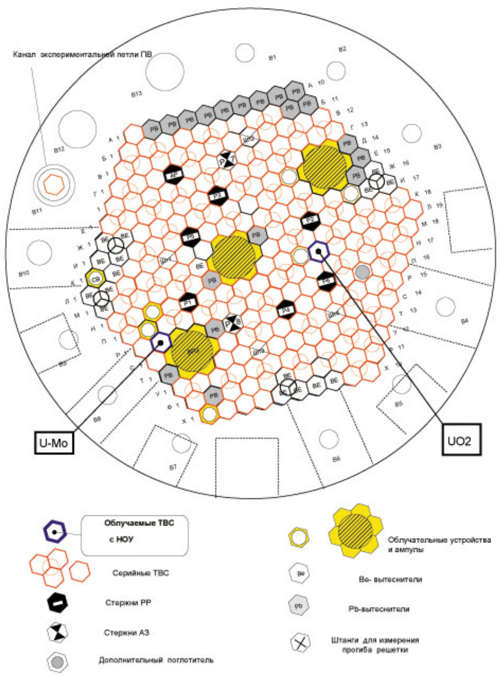
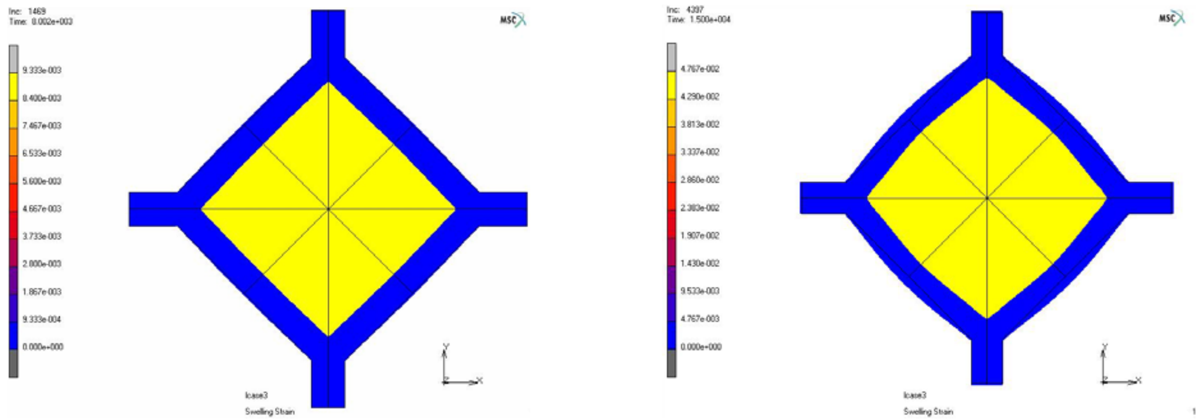
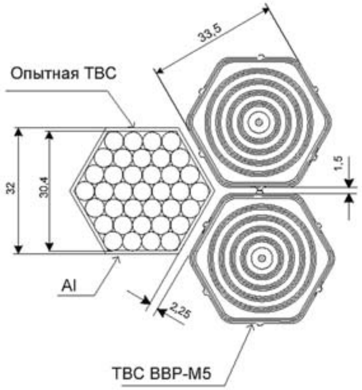


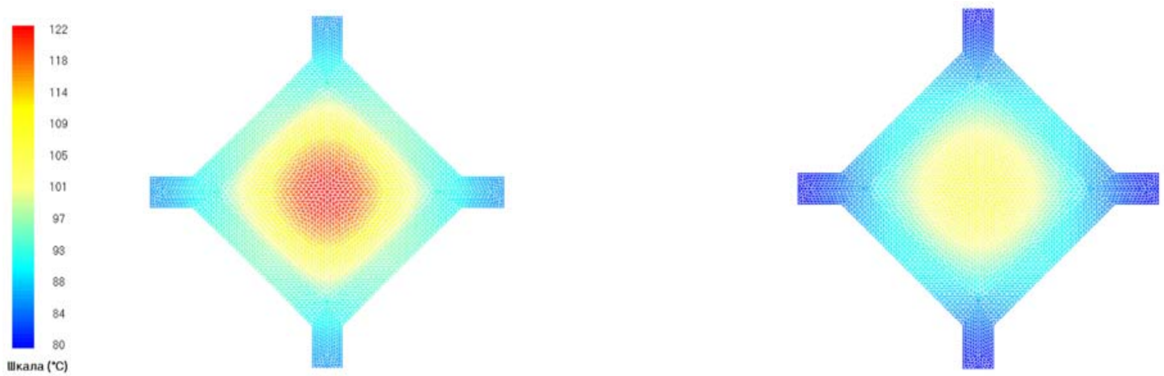
Fig.4.The design of WWR-M2 FA with pin-type fuel elements



The most stressed fuel element in EFA







a) EFA-1 based on UO_2+Al b) EFA-2 based on UMo+Al

Fig. 5. Irradiation conditions of WWR-M2 pin-type EFA

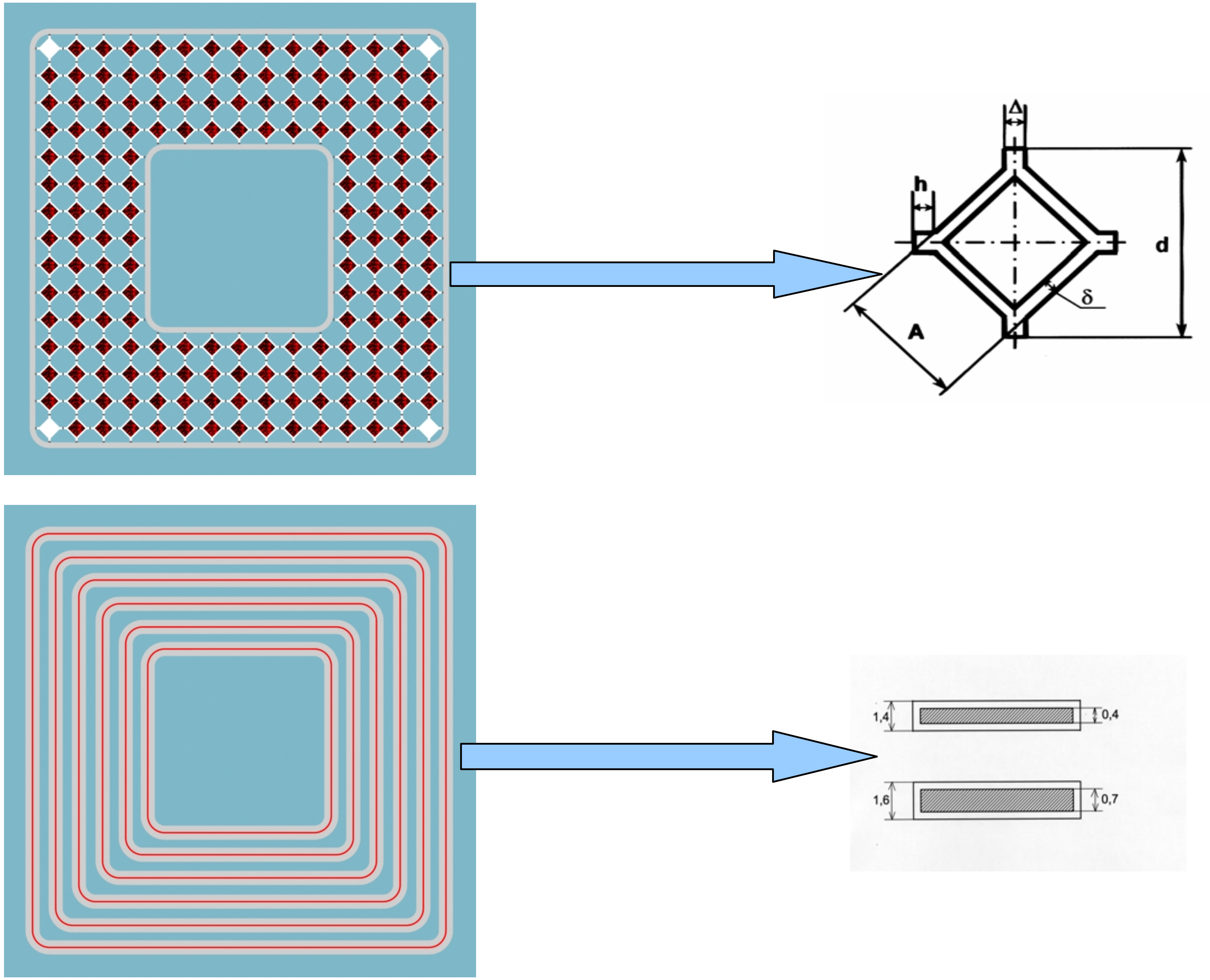


Fig.6. The design of IRT-type FA

At the present moment the initial measurements of the leak tightness of two fuel assemblies have been performed in experimental loop of WWR-M reactor (PIYaF, Gatchina). Irradiation lifetime test of FA began.

Now the development and manufacture of IRT-type fuel assembly with pin-type fuel elements (Fig.6) is being conducted in cooperation with staff of the Novosibirsk plant (NZChK) in conditions of industrial production. The principle design of an IRT-type FA with pin-type fuel elements based on dispersion fuel U-9%Mo in Al matrix has been developed. Two full-scaled dummy of FA for hydraulic tests have been manufactured by NZChK. Computational research on substantiation of FE and FA design are being performed in close collaboration with ANL and RRC KI.

3. Expediency of development

Performed large set of the technological and design studies and preliminary the comparison analysis of two fabrication methods showed, that the industrial production of pin-type fuel elements should be simpler in comparison with tubular one. The simple design of pin-type fuel elements ensure the following advantages over the tube-type fuel elements [2, 19, 20]:

- the heave press equipment isn't required (the smaller capacity of press is necessary for manufacturing of pin-type fuel elements. The press capacity is reduced in 2,5-5 times that reduces its cost much the same times);
- the reduction of nomenclature of the technological procedures and tools that decreases the power inputs and laboriousness;
- the absence of calibration dragging to provide the required size and shape allows to increase the yield ratio in ~ 1,5 times in comparison with tubular one;
- the shape of pin-type fuel element is more convenient for extrusion and so allows to increase the content of nuclear fuel in the meat in ~1,3 times;
- Higher uniformity of cladding thickness along height and perimeter of fuel element and higher uniformity of distribution of fuel in meat are assured.

Thus, the utilization of fuel assemble with pin-type fuel elements allows to automate the process of manufacturing and quality control of fuel elements that increases the productivity and decreases the their cost, and also to ensure the stability of manufacturing and quality of fuel elements.

4. Program of further works

The further works are planned to conduct in following simultaneous directions:

I. The lifetime tests of two full-scaled WWR-M2-type fuel assemblies with pin-type fuel elements in WWR-M reactor (Gatchina). Finishing of these tests is expected around the end of 2005.

II. The irradiation tests of U-Mo dispersion high–density fuels in the MIR reactor (NIIAR, Dimitrovgrad). Finishing of these tests is expected around the end of 2004. The first PIE (post-irradiation experiment) is expected to begin around the beginning of 2004.

III. The development and manufacture of two full-scaled IRT-type fuel assemblies with LEU pin-type fuel elements for lifetime tests in the WWR-SM reactor (Uzbekistan). Finishing of these works is expected around the middle of 2004.

IV. Continuation of development of new types of high-density fuel on the basis of monolithic U-Mo.

V. Conducting of set of necessary works for application of the developments to industrial production; feasibility studies of fabrication processes for pin-type fuel elements and FA on their basis.

VI. Feasibility studies of utilization of fuel assemblies with LEU pin-type fuel elements in other type of Russian-built research reactors, such as WWR-K (Kazakhstan) and MIR (Russia).

VII. Further scientific collaboration with ANL in the area of modeling of the behavior of fuel materials, fuel elements and assemblies.

5. Conclusions

The most important accomplishments can be summarized as follows.

- The fuel development and its qualification are in progress.
- Pins with of LEU U-Mo dispersion fuels in Dimitrovgrad and two full WWR-M2 pin-type assemblies with LEU in Gatchina are under irradiation.
- Development of two full IRT-M pin-type assemblies is in progress.
- The development of fuel elements with monolithic U-Mo fuel began.

These results show that at this stage it is reasonable to develop this direction. If the irradiation tests are successful, the U-Mo dispersion pins will then be available for conversion of most Russian-designed HEU research reactors. Then both types (tube-type and pin-type) of fuel assemblies with LEU U-Mo fuel would provide attractive competing alternatives for reactor operators.

Acknowledgements

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[14] Report, containing a description and analysis of past Russian work on HDF, including, U-Mo and other fuels, as well as recommendations on the selection of most promising types of HDF. Work plan on manufacture of and research on HDF, including a list of fuels to be tested and methods for out-of-pile tests (Delivery № 2.1).

[15] Report, containing a description of samples of high-density uranium alloy and samples of dispersion fuel: quantity of samples, chemical composition of high-density uranium alloys, shape and sizes of samples, as well as a description of the principal technological scheme of the fabrication process and equipment, without specifying the technological parameters (Delivery № 2.2).

[16] Report, containing a description of the test equipment, as well as methods and results of the study: metallographic characteristics, physical and mechanical properties, etc., according to the coordinated plan. (Delivery № 2.3).

[17] Plan for irradiation tests of mini-fuel element, containing technical information on the reactor experimental facility, HDF to be tested, and test conditions (Delivery № 2.4).

[18] Report, containing results of neutronics and thermal-hydraulics calculations needed for designing the mini-fuel element and experimental assembly (Delivery № 2.5).

[19] Report, containing a design and description of the mini-fuel clement and experimental fuel assembly, together with all required design documentation (Delivery № 2.6).

[20] Report, containing a description of major parameters of the mini-fuel elements and the experimental assembly manufactured for irradiation tests, as well as a description of the fabrication process without specifying the technological parameters (Delivery № 2.7).

[21] Report, describing the previous work on development of the prospective fuel element designed for the use of HDF (Delivery № 3.1).

[22] Report, containing the justification of reactor selection for irradiation tests. Test plan, containing information about the test-site and test conditions (Delivery № 3.2).

[23] Report, containing the justification of fuel element and fuel assembly designs, as well as parameters, specified by the test plan (Delivery № 3.3).

[24] Report, describing the fabrication processes, without specifying the technological parameters, and the fuel element/assembly design (Delivery № 3.4).

[25] Analysis of a design and operation conditions of FE and FA for selection of the most important parameters (Delivery № 2.13.1).

[26] Determination of the approaches for estimation of influence of various factors on serviceability of FEs (Delivery № 2.13.2).