LEU WWR-M2 fuel qualification

K.A. Konoplev, R.G. Pikulik, A.S. Zakharov, L.V. Tedoradze, G.V. Paneva, D.V.Tchmshkyan

Petersburg Nuclear Physics Institute of Russian Academy of Sciences

PNPI, Orlova Roscha, Gatchina, 188300, Russia
Tel.: +7 (81271) 46734
Fax: +7 (81271) 31282
e-mail: kir@pnpi.spb.ru

SUMMARY

LEU WWR-M2 fuel elements and their LEU WWR-MS modification have been developed for supplies from Russia abroad. They are designed to be used in pool-type research reactors.

The goal of testing was to obtain data needed for the manufacturer-factory to confirm its performance guarantees for these fuel elements. As a representative quantity, 5 FA have been taken with the enrichment by U-235 being equal to 19.75%. The testing has been conducted in the WWR-M reactor core in the conditions being close or somewhat heavier than it is given in the manufacturer-factory's guarantee conditions. By the main parameter – allowable burnup depth, the tests have been conducted up to the burnup value of 75–80% with the factory guarantee being equal to 40% for the MEU WWR-M. In the course of tests, FA have been repeatedly reloaded into various reactor core cells with the heat loads and design temperature being varied. Heat load values have been changed up to the maximal value of 320 kW/l and temperature values – up to 95°C. The cooling water velocity was practically invariable about to 4 m/s, the chemical composition of the coolant was also constant. The fuel element operation time at power was about 400 days and the full testing took more than 3 years.

A distinctive feature of these tests was systematic quantitative measurements of the fuel element tightness degree in the course of burnup. To this end, FA were periodically unloaded from the reactor core and loaded into the test loop. FAs were under a somewhat lesser load in the loop than in the reactor core. The ratio of the amount of fission products emerging from FA into the loop coolant to the amount of fission products being formed for the same period of time due to uranium fission in the FA was measured. This ratio called the non-tightness factor (β) was compared with the value being allowable for the safe reactor operation and with data for other fuel elements.

Even at the maximal burnup of 80% achieved, the value of β has not exceeded $5 \cdot 10^{-6}$, which is much less than the allowable value and is at the level being typical for the reactor operation.

The tests were stopped at the burnup level of 80% due to inexpediency of deeper burnup levels. As a result, the WWR-M2 fuel element operability with the enrichment below 20% has been proved not only up to the 40% level being required by factory guarantees but also for the level being about twice as deeper.

LEU WWR-M2 fuel assemblies have been recommended and adopted for serial production.

The work has been executed within the framework of the program drawn up by the Ministry of Atomic Energy of the Russian Federation and the Department of Energy of the USA according to contracts with TVEL Concern and Argon National Laboratory.

1. Introduction

The results of final tests conducted for licensing of the production low enrichment (LEU) of WWR-M2 and WWR-MS type fuel assemblies (FA) have been presented. The intermediate test results up to the burnup level of 50% were given earlier in [1]. The tests have been conducted in accordance with the Russian Program for the reduction of research reactor fuel enrichment and the American Program 'Reduced Enrichment for Research and Test Reactors' (RERTR). The Ministry of Atomic Energy of the Russian Federation and the US Department of Energy is financing the enrichment reduction program.

WWR-M2 type experimental FAs with the fuel enrichment of 19.75% have been tested in the WWR-M reactor at the B. P. Konstantinov Petersburg Nuclear Physics Institute of the Russian Academy of Sciences. The goal of the test was to determine a possibility of establishment of manufacturer burnup guarantees at the level of 40% as well as to determine an opportunity to use them up to deeper burnup levels. In the course of tests the program was amended to increase the burnup level. The definitive program provided achievement of the average burnup level of 75 % of the initial content of uranium-235 in each fuel assembly. Finally fuel elements have reached the burnup levels of ≈80% and have not lost the required tightness. The test results have shown fuel assembly operability at burnup levels being deeper than those being realised in practice.

2. Fuel Assemblies design

36% enriched uranium is used as fuel in WWR-M2 type fuel elements (Fig. 1). With them, maximal specific energy release in the reactor core up to 400 kW/l has been achieved [2]. These FAs have a simple design and are highly reliable in operation. The additional load of uranium-235 being necessary when reducing the enrichment has been achieved both due to increasing the volumetric concentration of dioxide in the meat and due to a small reduction of the cladding thickness, which is quite allowable for this type of fuel elements. The standard dispersion UO_2-Al fuel is used with the uranium density of 2.5 g/cm^3 in the nuclear fuel layer.

Since 1978, WWR-M reactor at PNPI has transferred to new FAs of the next generation of WWR-M5 type with thin-walled fuel elements with 90% of enrichment [3, 4]. Fig. 1 shows also the FA cross-section of the latest modification of WWR-M5 type with an outer hexagonal finned fuel element. The comparative technical specifications of experimental WWR-M2 FA, serial WWR-M2 FA (modification based on an uranium-aluminium alloy) and serial WWR-M5 FA with an oxide fuel are given in Table 1. Due to WWR-M5 FA, the maximal specific energy release in the reactor core can be increased up to 900 kW/l [5], the core volume being useful for experiments has grown by 1.5 times, which has considerably widened experimental potentialities of the WWR-M reactor. The fuel conversion for such fuel elements is essentially more complicated and can be considered with the use of new high-density kinds of fuel.

To a certain extent, the conversion problem gets easier by the fact that the WWR-SM modification used in foreign reactors, with the fuel layer length of 600 mm instead of 500 mm. In accordance with the program drawn up by the Ministry of Atomic Energy of Russia on the reduction of enrichment in the fuel of research reactors, an experimental lot of WWR-M2 type FAs has been manufactured at NZHC (Novosibirsk) with the fuel being 19.75% enriched.

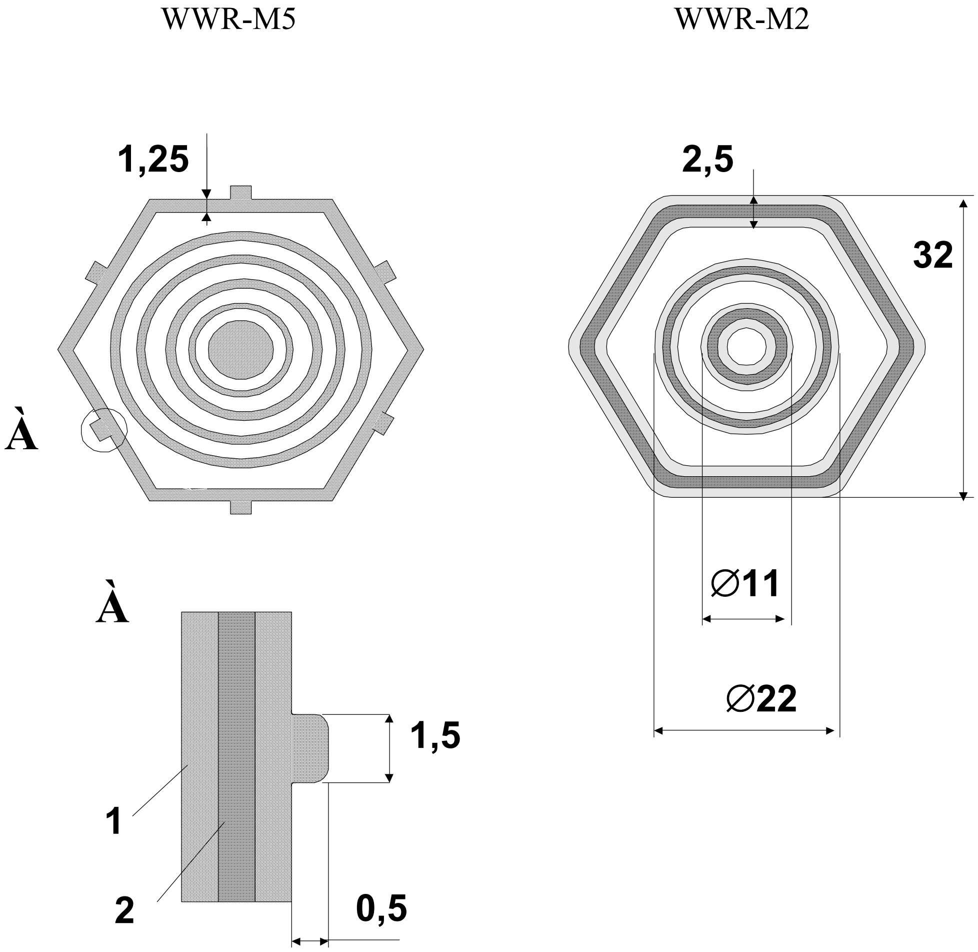


Fig.1 Cross-Sections of Fuel Assemblies WWR-M

1 – cladding 2 - nuclear fuel layer . Dimensions in mm.

As the calculations have shown [6], in order to maintain the operability of the majority of reactors under the reduction of enrichment, it is necessary at the same time to increase the uranium-235 load by 15–20%. The WWR-M2 FA modification being developed for the tests meets new physical requirements. However in order to transfer to serial FA production, it was necessary to thoroughly investigate their operability up to deep fuel burnup levels. The tests are needed to determine the FA operation resource and elaborate technical operating conditions.

Table 1
Comparative characteristics of experimental FA with LEU-based fuel and serial WWR-M2 and WWR-M5

No.	Parameter	WWR-M2 (Serial)	**WWR-M2 LEU**	WWR-M5 HEU (Serial version)
1	Enrichment	36%	**19.75%**	90%
2	Average mass of ^{235}U in FA, g	32.4	**41.7**	66
3	Fuel element thickness, mm	2.5	**2.5**	1.25
4	Uranium density in the fuel	1.4	**2.5**	1.21
5	Nominal cladding thickness, mm	0.9	**0.72**	0.43
6	Fuel	U-Al	**UO_2+Al**	UO_2+Al
7	Specific heat release surface in the reactor core, cm^2/cm^3	3.55	**3.55**	6.6
8	Average hydraulic diameter, mm	6	**6**	3.1
9	Concentration of ^{235}U, g/l	61	**79**	125

3. Test method

The tests have been conducted directly in the reactor core being loaded with WWR-M5 type fuel elements. WWR-M2 and WWR-M5 fuel assemblies are geometrically fully compatible with each other for their installation into the reactor core and their joint operation is possible, which facilitates the test tasks. Under joint loading of these fuel elements, it is only necessary to follow heat load on WWR-M2 fuel elements providing the given burnupt and heat load values. The operating parameters of experimental FA in the reactor core are calculated by means of HEXA, a two-dimensional diffusion software program designed for operating calculations of current loads of the reactor core and taking account of the burn-out in each fuel assembly. Under loading into the reactor core, the energy release calculation accuracy (±10%) has been proved by experiments with preliminary irradiation of one of the fuel assemblies equipped by gold foils jointly with the irradiation of the monitor-foils in vertical experimental channels. A reactor core loading example is given in Fig. 2. In the course of tests, experimental FAs have been repeatedly reloaded into various reactor core cells in order to provide the given burn-out rate. At the end of tests, when very deep burnup levels were achieved, special measures has to be taken in order to increase the neutron flux in these FAs.

The monitoring of the FA state has been conducted according to the method developed in PNPI [8]. In order to measure the tightness of each FA, it unloaded from the reactor core and loaded into an experimental water loop (WL). The test method consists of the following stages:

- Monitoring of fuel element tightness in the experimental loop before the fuel loading into the reactor core.

Owing to the coolant monitoring for the fission product content in the experimental loop, the quantitative non-tightness parameter is determined. Such preliminary tests allow to reveal beforehand possible defects of manufacture.

- Loading of fuel assemblies into the reactor core and subsequent trial operation in the operating mode for serial FA.

- Periodic non-tightness testing in the experimental loop upon reaching the required fuel burnup level. Normally from 3 to 5 measurements of the non-tightness parameter are taken in the WL during the full test cycle.

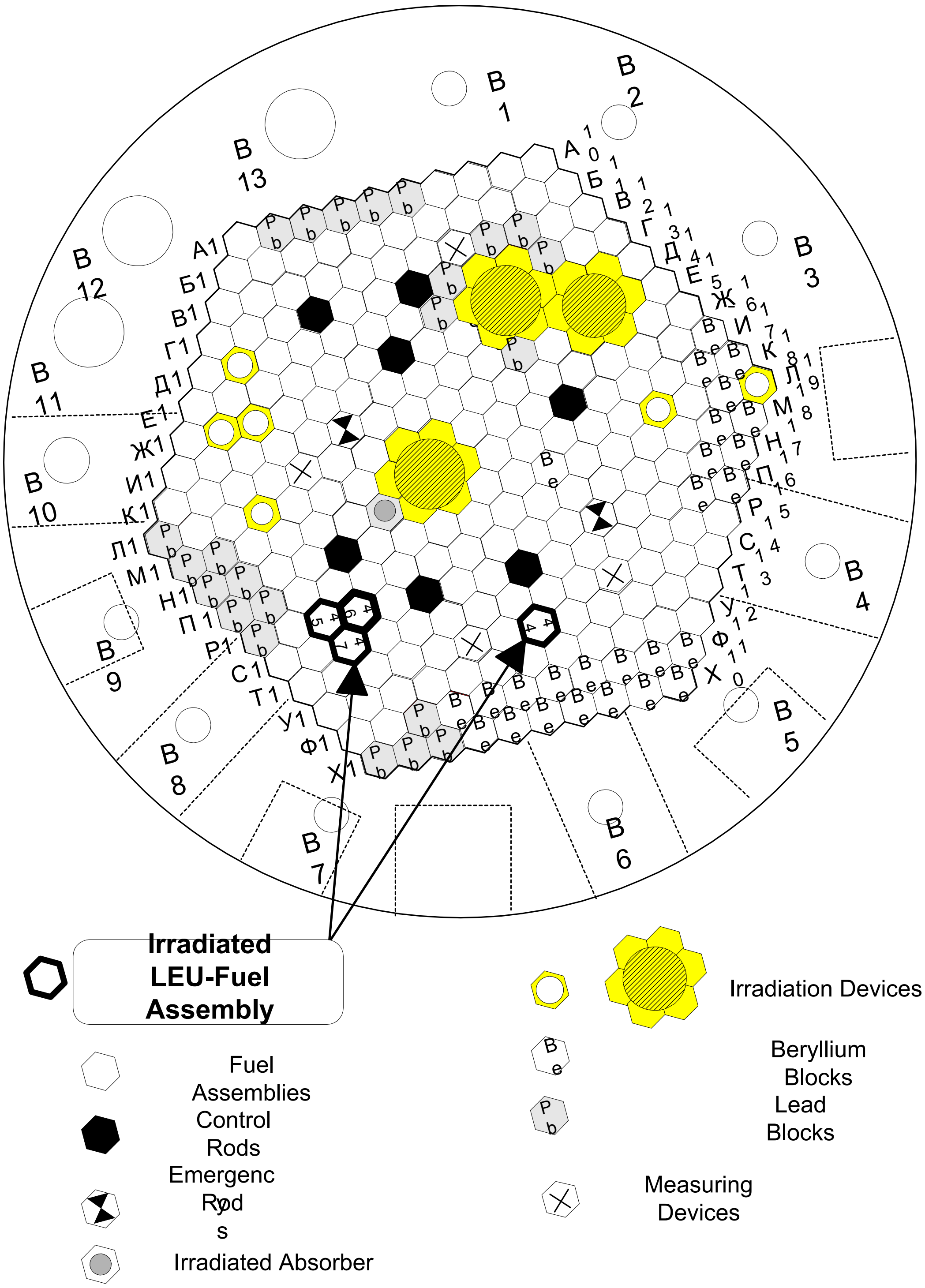
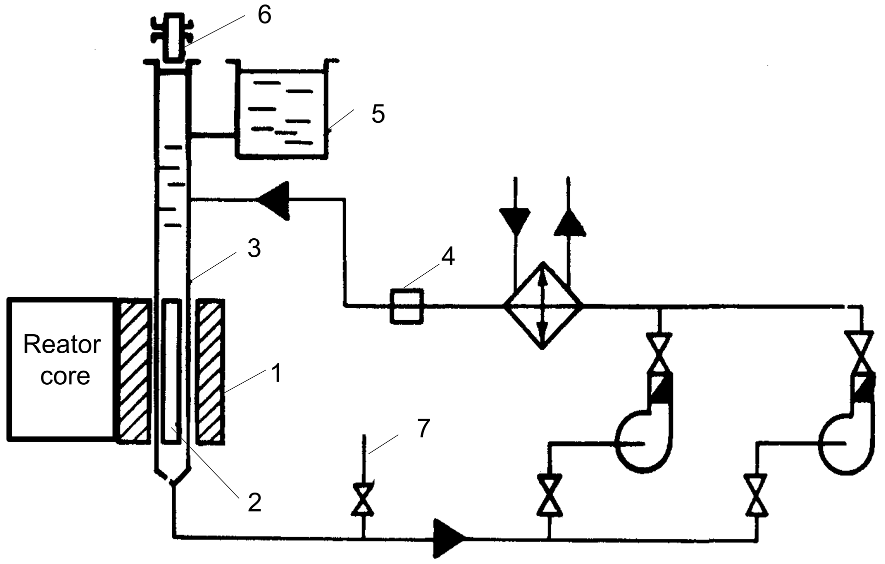


Fig. 2. The cartogram of the reactor core loading in the beginning of tests

In order to estimate the operating reliability of fuel assemblies and the fuel element manufacture quality, the quantitative non-tightness parameter **β=V/Q** is used, which is determined as the ratio of the velocity **V** of the fission product-nuclide entering from fuel elements into the coolant to the nuclide generation rate **Q** in the fuel [2,7]. Individual measurements for each FA are taken in WL. Normally the values of β are determined using the following five main radio nuclides: ^{85m}Kr, ^{87}Kr, ^{88}Kr, ^{135}Xe, ^{138}Xe. In addition, some other inert gas isotopes of fuel fission products can be used. Usually the value being averaged by all measured nuclides is used. The β parameter characterises the fraction of radioactive nuclides coming beyond the fuel element matrix and cladding being the first protection barriers on the path of radioactive substance release. The initial value of β is practically fully determined by the surface contamination by uranium in manufacturing process and β is at the level of 10^{-7}. As a result of fission product accumulation and action of other damaging factors, the fuel element non-tightness parameter value gradually rises. Our experience show that for aluminium dispersion fuel elements, the increase of β from the value of 10^{-7} to several units of 10^{-6} is normal.

The water loop (WL) consists of a straight-through channel located in the beryllium reflector, a fuel cooling system, a mechanism for the movement of an insert, into which the experimental FA is loaded. WL is equipped by relevant instrumentation and devices: heat monitoring instruments, a system for continuous fuel tightness control by means of delay neutron sensor, gas and coolant sampling devices (Fig. 3).



1- Beryllium reflector, 2- Fuel assembly, 3 - Loop channel, 4- Gas collector and gas sampler, 5-Water feeder, 6- Delayed neutron detector, 7-Water sampler

Fig. 3. Diagram of the experimental loop for fuel testing – WL .

4. Test results

The test mode and non-tightness data are given in Table 2 and in Fig. 4 and Fig.5. For the purposes of comparison, the β parameter is given, which has been obtained at testing other types of fuel elements including WWR-M5 type fuel elements being regularly used in the reactor.

Table 2
Technical characteristics of WWR-M2 SFA tests with the fuel enrichment of 19.75%.

FA No.	Burnup, %	Maximal specific energy release, kW/l	Maximal heat flux density, W/cm^2	Operating time at power, days	Maximal wall temperature, ^{o}C	Final non-tightness parameter β, Relative units
01IM43.95	79.8	274	74	372	87	$4.3 \cdot 10^{-6}$
01IM44.95	81.4	285	77	431	89	$4.1 \cdot 10^{-6}$
01IM45.95	81.5	268	73	429	87	$5.0 \cdot 10^{-6}$
01IM46.95	76.2	284	77	394	90	$4.1 \cdot 10^{-6}$
01IM47.95	80.9	326	88	419	95	$4.1 \cdot 10^{-6}$

The growth of the β parameter during the burnupt is similar to the growth being observed for all previously tested dispersion fuel elements with aluminium claddingl. High-enriched irradiated fuel based on uranium dioxide has some advantage as compared with low-enriched fuel by the capacity to retain fission products. Nevertheless, the product leakage increase is within admissible limits for normal operation even at considerably higher burn-out values than it is necessary and normally allowed at the fuel elements operation.

The radioactive emission quotas allow to operate with the non-tightness levels of $(5\text{-}10) \cdot 10^{-6}$ without any limitations. This quota is not exceed even at 80% burnup for LEU WWR-M2. The estimation of the dose for population in the conditions of normal operation of the WWR-M reactor corresponds to the level, which is approximately by 100 times as less as the established limit for population (1 mSv per year) in the Federal norms of radiation safety (NRB-99).

The visual inspection of the outer surface of hexahedral fuel elements during reloading has not revealed changes, which can be attributed to defects. A scratch detected previously during the first reloads on the surface of outer hexagonal fuel assembly 01IM43.95 had no signs of further opening or increase of dimensions.

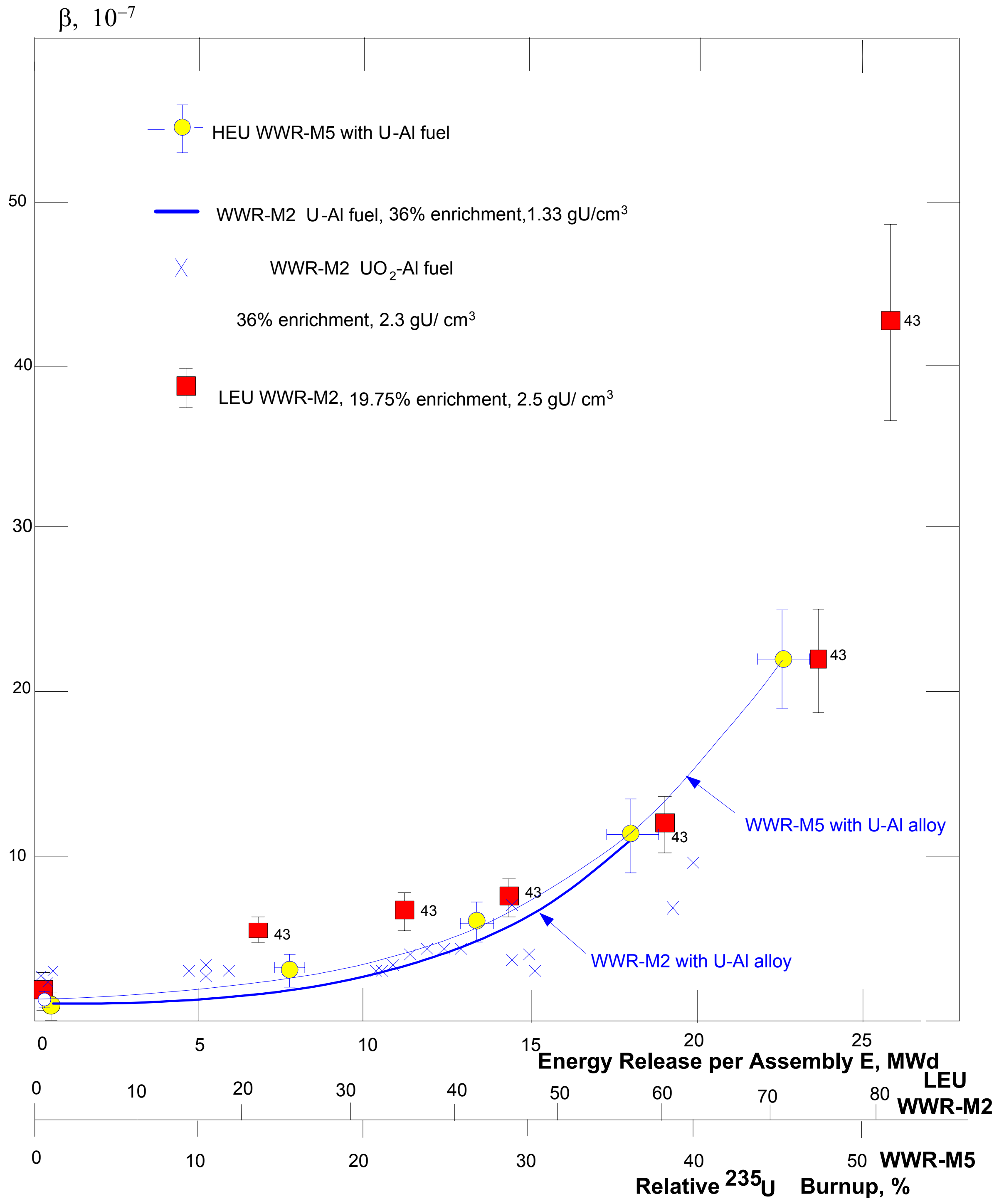


Fig.4. The value of β Vs. Energy Release for FA # 01 IM 43.95

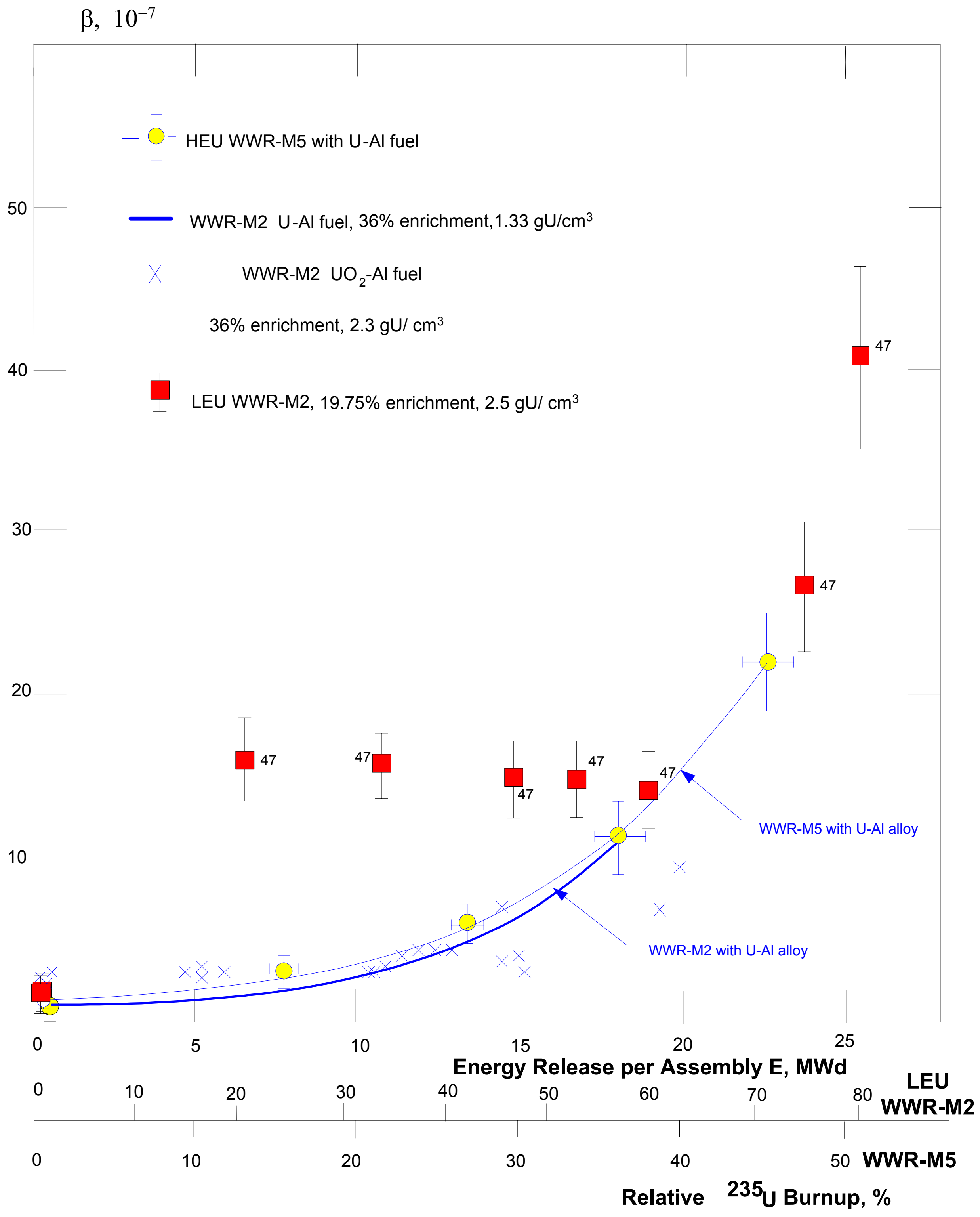


Fig.5. The value of β Vs. Energy Release for FA # 01 IM 47.95

5. Conclusion

1. The reactor tests have been successfully completed for all five experimental WWR-M2 type FAs with low-enriched fuel. New WWR-M2 fuel assemblies with low-enriched fuel have been recommended for serial production and fuel supply. The broad experience of our work with fuel elements did not give beforehand any doubts in successful testing of WWR-M2 fuel elements with LEU, though we did not expect that they would retain the operability even at the energy release at the same level as HEU WWR-M5. Basing on the tests conducted, the manufacturer-factory has obtained a basis to provide a certificate guarantee up to 60% burnup for WWR-M2 and WWR-SM types of FA with LEU.
2. At the present time, FA of the WWR-M2 type and WWR-SM with 36% of enrichment are being used in reactors in Hungary, Ukraine and Vietnam but the use of this fuel elements can be widened. Formerly they were successfully used in the WWR-M reactor at the Petersburg Nuclear Physics Institute and at similar reactors in Poland and German Democratic Republic.
3. A large work is being done in PNPI devoting to the development WWR-M type fuel elements. We have put in operation our reactor with WWR-M1 type fuel elements and gradually improving the design are now using WWR-M5 fuel elements, which, by their characteristics, are superior in comparison with many other fuel elements being used in the research reactirs. It is expedient to conduct a research on the reduction of enrichment in WWR-M5 fuel elements. The transfer from MEU WWR-M2 to LEU WWR-M5 will allow not only to retain the parameters available but also considerably improve the experimental potentialities of reactors. WWR-M5 fuel elements allow to load the reactor core with the same specific heat release surface as in a non-separable fuel of the HFIR type. At that there are opportunities to install experimental devices in the reactor core, which is impracticable for non-separable core.

The authors would like to thank the Argon National Laboratory for financial help in the implementation of work and Doctor Maitos in person for his fruitful discussions of the program and results. We would like to express our gratitude to P. I. Lavrenyuk for his serious support of this research as well as A. B. Aleksandrov, A. A. Enin and V. G. Aden for their great interest in the results obtained.

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