CRITICAL FACILITY "PHYSICAL MODEL OF PIK REACTOR" (PIK FM)

V.V. Gostev, A.S. Zakharov, K.A. Konoplev, S.L. Smolsky, P.A. Sushkov, D.V. Chmshkyan

1. General information and main features

The critical facility of PIK FM [1] with a heavy-water reflector and a light-water core is a full-scale mock-up of the high-flux PIK reactor [2], [3] for physical research. The critical facility has been operated since December, 1983. Besides the critical assembly (Fig. 1) and its control and protection system (CPS), the PIK FM complex contains a lot of engineering systems, which provide normal operation of a complex. The part of these systems is typical for any nuclear facility (electric power supply, heating, ventilation, quality water supply, radioactive waste removing , communication, alarm, radioactive control). There are some engineering systems which are considered as specific design features.

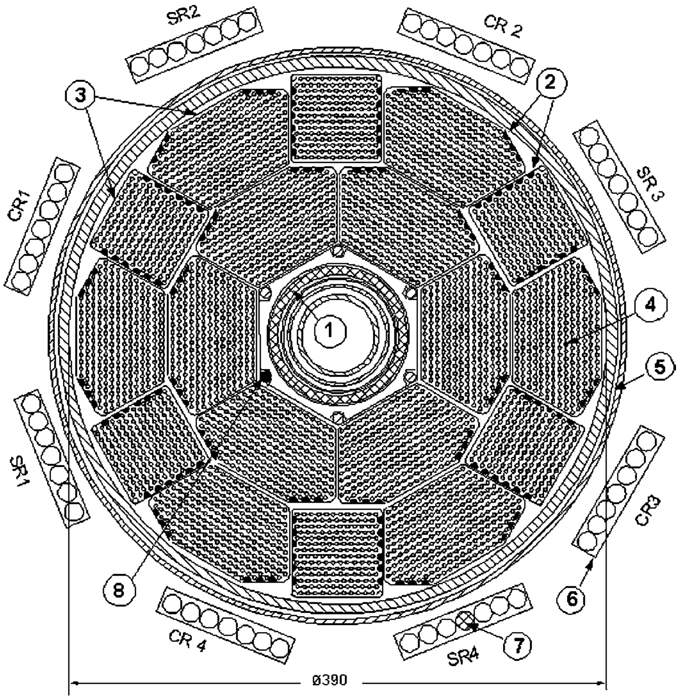

Fig.1. Core of critical assembly PIK FM
1 – absorber shutters; 2 – displacer or burnable poison rod; 3 – fuel assembly; 4 – fuel elements (extracted) $N_{max.}$ = 3858 items; 5 – gap; 6 – control (CR) and safety (SR rods; 7 – absorber element of CR or SR; 8 – neutron source

The pneumatic-hydraulic system (PHS) is used for the regulation of the light water level in a core before an experiment. For this purpose the moderator level is increased by displacement of water with a compressed air from the water reservoir into a core vessel. Compressed air is conveyed to the water reservoir in a step-by-step manner, therefore, a safe rate of reactivity insertion is insured. The water level uprise is a preliminary procedure. For safety insurance the critical state is achieved by means of extraction of control rods only. PHS is used as the second emergency protection system in addition to a system of absorber rods. Due to an emergency signal any (one of two) air valve at the water reservoir blows off and the water level drops by gravity lower than a fuel level. Refueling is carried out in the dry core without the moderator.

The facility for protium extraction is used to purify the heavy water of light water impurities. This facility provides reprocessing of D_2O taken from individual experimental volumes as well as from the main reflector volume. The D_2O concentration is supported in the interval of (99.85-99.9)%. The facility capacity provides the removal of up to 20 kg H_2O a year.

The heavy-water system of reflector is intended for a reliable storage of a margin of the heavy water in the monte-juses (special reservoirs) during a replacement of neutron beam tubes and other experimental devices in the unclosed reflector tank. A hot gas and vacuum drying are used for the collection of D_2O remaining after the experiment and for the preparing reflector surface before D_2O filling. The heavy water transition into reflector tank is provided by making an overpressure of the dry nitrogen gas in the monte-juses. The operations with the heavy water are ease due to the low tritium concentration. The maximal tritium activity of used D_2O for experiments is less than $2 \cdot 10^{-6}$ Ci/l.

The critical assembly and its facility for protium extraction are located in a special box with concrete walls 1.5 m thick, which guaranteed radiation safety for the personnel in the surrounding rooms.

The layout of core is given in Fig. 2. The layout of neutron beam tubes is given in Fig. 3.

The facility design is based on the original technical decisions developed for the critical facilities, which were operated earlier at the PNPI. A considerable part of the PIK FM equipment has been proved efficient in operation at previous facilities.

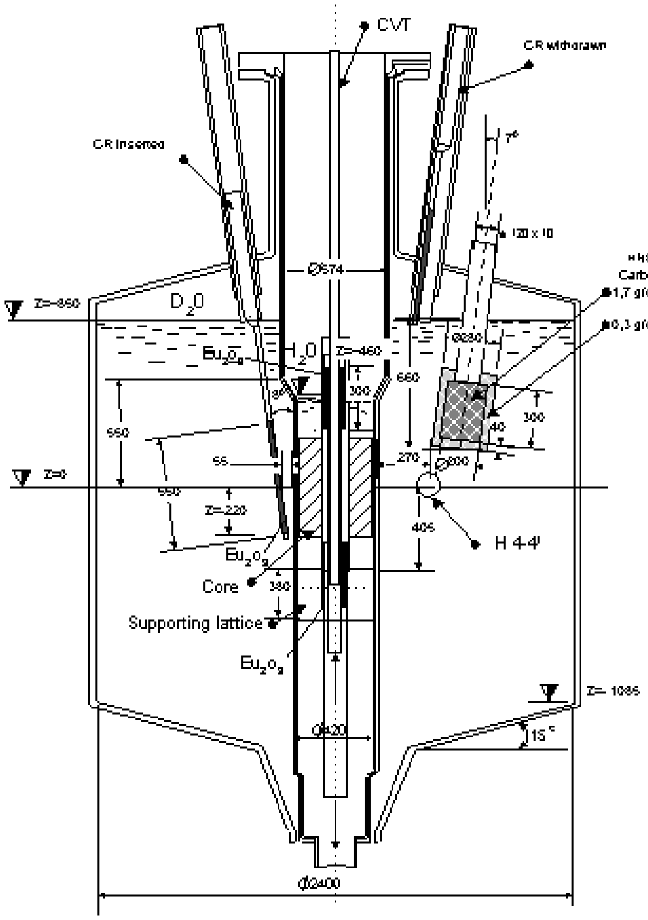

Fig. 2. Scheme of core in heavy water reflector.
CVT is central vertical tube, HNC is hot neutron source

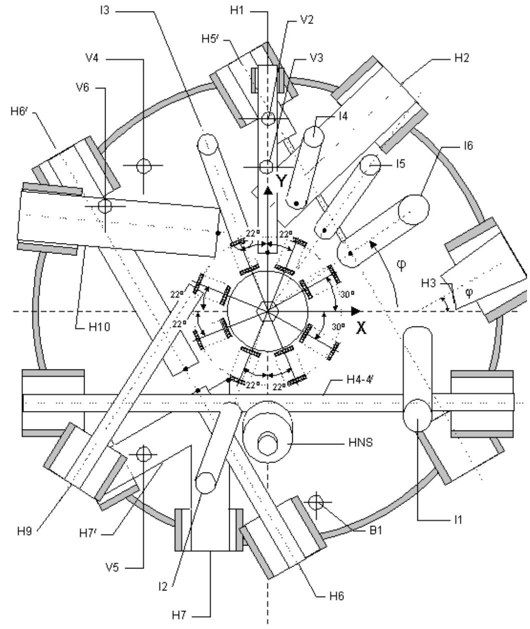

Fig. 3. Scheme of neutron beam tubes

The previous experiments performed on the critical facility aided the development of calculation models and the study of special features of the physics of reactor core with a high fuel concentration up to 600 *g* ^{235}U/l. The PIK FM experiments are a logical continuation of earlier critical experiments of simple cores of the type of PIK-04 [4] with a regular lattice of fuel elements (without casing of fuel assemblies) and of PIK-01 [5] with the same fuel elements in hexagonal casings of steel.

The experimental possibilities of the PIK FM significantly differ from the similar possibilities of the critical facilities operated earlier. The core, the control rods, the heavy-water reflector tank and the neutron beam tubes are in practice identical analogs of similar reactor objects. The experiments are carried out with a core and reflector of the mock-up of the same size as in reactor PIK. The experimental channels (neutron beam tubes) of the mock-up have a realistic geometry.

The core of the critical assembly (Fig. 1) consists of 18 demountable fuel assemblies (FA) with the fuel elements (FE) of the PIK reactor type (modification of fuel element of the SM-2 reactor with an active layer length of 500 mm).

The CPS rods are as follows:

– 5 safety rods (regulatory bodies) of the emergency protection including 4 safety rods (SR) in a reflector and one central regulator with two ring shutters, which are moved by one drive only. The shutter absorbers move in opposite directions in the neutron trap with the light water arranged symmetrically from the central plane of critical assembly. The absorber shutters combine function of the reactivity compensation regulator and function of emergency protection rod too. Such joining of functions is provided by necessary interlock excluding the possibility of operating with water and other rods without a preliminary moving of shutters for a minimal window between absorbers;
– 1 central regulator as main device for reactivity compensation;
– 4 control rods (CR) in the reflector.

The absorber elements of SR and CR in the reflector are identical. SR and CR are located in the reflector tank at an angle of 8° to the vertical line. The core is contained in a vessel of the stainless steel or an aluminium alloy. The vessel and most of the channels (neutron beam tubes) are detachable.

The function separation of the CPS rods in the PIK mock-up differs from the similar separation in the PIK reactor. This is caused by the difference between the nuclear safety regulations for critical assemblies and the similar regulations for research reactors. In the CPS design of the PIK 6 control rods and 2 safety rods are used in the reflector, 2 independent shutters in the core. Each of two shutters is controlled by individual drive. Both upper and lower shutter combines the functions of an automatic regulator, a compensating rod and a safety rod.

The safety assurance at the critical facility is mostly determined by the facility design and the management of experiments. The obligatory safety requirement for any manual operation with change of core composition is water removing from a core. This requirement is provided by technical method.

Such a concept of experiment technique has been developed in the process of the development of previous designs of critical fuel assemblies and has proved effective.

The core is changed by means of replacement of fuel elements in the fuel assemblies by imitators. The vessel consists of two shells and has an annular gap that can be filled up by heavy or light water, absorbing solutions or air. In a case of study of the reactivity temperature coefficients the gap is vacuumed in order to create a heat-insulating layer between the core and the reflector during experiments.

The main specifications of the critical facility are given in the Table below.

Table

Main specifications of the PIK FM critical facility

No	Name	Unit	Value
1	Date of commissioning	December 15, 1983	
2	Critical fuel assembly type	Heterogeneous	
3	Thermal neutron flux in the trap	n/cm^{2}s	$4{,}5 \cdot 10^9$
4	Thermal neutron flux in the reflector	n/cm^{2}s	$1{,}3 \cdot 10^9$
5	Fuel	Uranium dioxide in copper-beryllium matrix	
6	Enrichment	%	90
7	Moderator	Light water	
8	Reflector	Heavy water	
9	Limiting power value	W	100

2. Main trends of research:

- experimental determination of neutron and physical parameters of the PIK reactor [6];
- safety validation of some procedures for reactor operation [7,8]
- investigations on the core modification (use of burnable absorber [9] , replacement of FA constructional materials by zirconium, development of special FA for material irradiation, etc.);
- development of methods of reactivity control;
- verification of computation codes by experiments of the benchmark type (critical experiments with a simple core composition, poisoning experiments with boron acid in the moderator, replacement of D_2O by H_2O in the reflector, reflector screening by absorbing solutions, use of incomplete moderator level);
- investigation on the optimal fuel profiling in a core and investigation of design of the central neutron beam tube in order to obtain the maximum neutron fluxes and the needed reactivity reserve for reactor operating [10];
- determination of radiation parameters of neutron beam tubes and mock-ups of the experimental devices located in the reflector [6];
- development of some operation procedures with heavy water.

The existing set of mock-ups of neutron beam tubes allows to study dependence of the neutron flux at the exit of the beam on such parameters as shape, thickness and material type of tube. It allows to study and to prepare beforehand the optimal conditions for physical experiments. Such a preliminary experiment extremely difficult to perform at an operating reactor. The realistic geometry of experiments also allows to take into account such significant circumstances pertaining to the future reactor operation as the mutual influence of experimental facilities, that is essential for the correct planning of experiments.

During the period of the critical facility operation, some technological problems have also been solved. In the first place, the problems were concerned with the experience of operation with a large amount of heavy water. The process systems provide the constancy of the isotopic purity of the heavy water at a level of 99.9 %. The experience that we have gained in control rod drives has become a basis for their improvement.

3. Description of main experiments and their results

At the first stage, we focused mainly on determining the most important parameters of the future reactor. It was during the initial experiments that the reactivity worth of the system of absorbers was investigated and determined. It was revealed that the CPS-system was not adequate for effective operation and was unable to provide the project duration of the reactor cycle. Due to imperfection of the calculation methods and the new reactor uniqueness, the designed weight of the main regulator-shutters had been overestimated. This makes us to perform an urgent design correction. The most important and priority research task was connected with the increase of the regulation system efficiency.

A decision was made to replace the steel guide separating the core from absorber shutters in the neutron trap by the aluminium (or zirconium) guide. The material replacement has required to reconsider measure on lowering of non-uniformity of energy release in fuel near neutron trap.

A reduction of the energy release in this part of a core is achieved due to fuel profiling, i.e. decreasing of uranium loading in most "hot" elements near the trap. Low-absorbing materials are also used for the replacement of the shutter drive parts (upper shutter link permanently being in the core). The decisions we made have been verified in practice on the critical facility. Such a replacement has allowed us to increase the shutter reactivity worth twofold up to $9.1\beta_{eff}$ and to provide the originally prescribed design duration of the reactor cycle about 15 effective days. The maximal non-uniformity coefficient of energy release K_V is equal to 3.2. [10] and such a value is reasonable for reactor operation at nominal level of 100 MW power.

The radiation characteristics of the PIK reactor have been investigated [6], which has become the basis for further development of the reactor itself and a number of experimental facilities. The method of measurement of the distribution of energy release and the determination of the full power of core has been developed for purposes of using at a critical facility and for a start-up period of the reactor. Its technique is based on the measurement of an activity of fission products (for example, ^{140}La) after the core irradiation at low power [11].

Very important experiments for the improvement of the PIK reactor core were connected with development of a method of use of burnable poison in fuel assemblies. As a burnable material gadolinium was selected. In the PIK FA a little part of the volume is occupied by dumb elements (displacers) that are necessary in the hydraulic reasons (Fig.1). The special rods (BPR) with a cross section in a form of "half of cylinder" are developed for installation instead of displacers. Such a solution does not require additional volume for arranging the new devices and in practice does not change a design of FA. Cladding of BPR is zirconium alloy. The absorbing composition is based on use of such components as ZrO_2 and Gd_2O_3.

Due to critical experiments with BPR-mock-ups their reactivity worth and optimal range of gadolinium loading per element were defined. The study of the dynamics of burn-up of these BPR was carried out at the WWR-M reactor for verification of the calculation method for gadolinium burn-up. Afterwards, the neutron characteristic of advanced core with burnable poison rods were investigated at critical facility.

The total reactivity worth of 144 BPR in new FA is estimated in limits to be 4,2 β_{eff} – 4,8 β_{eff} depending on positions of other groups of absorbers. It is sufficient to compensate the reactivity related to more than 15 day of reactor operation additionally to the operation time that is provided by CPS rods. The total "weight'' of the system of shutters and control rods and the value of K_V practically are saved in limits of an error of their measurements.

In new FA with BPR zirconium was used as constructional material for BPR and FA casings instead of the stainless steel. The reactivity gain is estimated as +1.6 β_{eff} that allows to increase fuel burn-up. Due to use of BPR a maximal reactor cycle may be increased twice as much from 15 to 30 reactor-days [9].

The some procedures for the PIK reactor with a forming of reactor core configuration for initial critical ity and a putting the reactor in operation were substantiated at the critical facility. After that the correction of main physical parameters has been performed, such materials have been included into the Safety Analyses Report of PIK reactor.

For the purposes of a development of reactor calculation methods, special critical experiments of core poisoning with boron acid have been fulfilled. These experiments includes 60 measurements, differs by boron poisoning of light water of the core and by the position of the central control shutter. In two series the outer reflector was light water, in four others it was heavy water [12]. For these experiments the total experimental error of reactivity due to geometry and material uncertainty is estimated as $\sigma = \pm\ 0.2\ \%\ \Delta K/K$ and poisoning experiments are advised as benchmarks. Results of these experiments are represented in Fig 4.

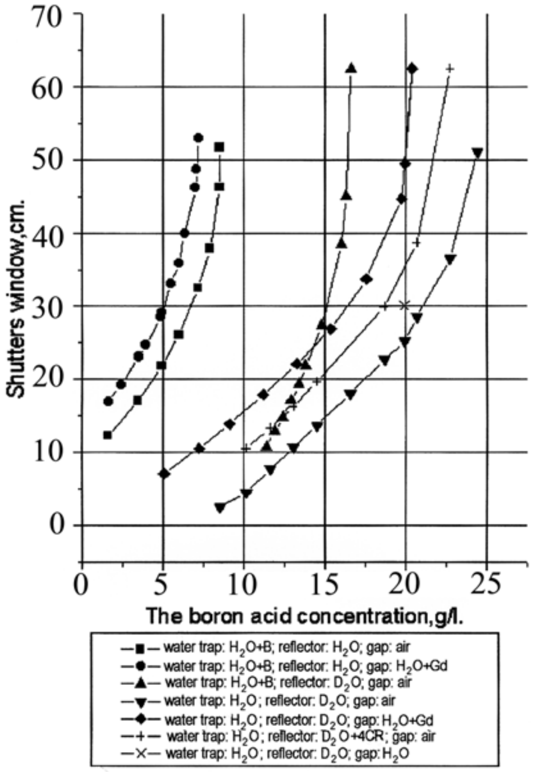

Fig. 4. Dependence of size of window between shutter absorbers on concentration of boric acid at critical state

The dependence of neutron fluxes in channels upon their design parameters has been studied (volume shape, wall thickness and material type). The materials obtained have been used for further improvements of calculation of fast and thermal neutron fluxes for purposes of a study of life limiting factors of experimental and reactor equipment [13].

The initial experiments have also determined the most important strategic task, which will remain relevant for a long time after reactor start-up. Such a task on the PIK project improvement is the development of the vessel of low-absorbing materials, supposedly from an aluminium alloy. Preliminary investigations with the aluminium vessel were performed at the PIK FM.

Due to vessel replacement the reactivity effect of $\approx +\ 6\beta_{eff}$ is quite substantial and can be compared with use of fuel elements based on construction materials with low neutron absorption. Its significant magnitude allows one to investigate advanced core configuration with the higher neutron leakage due to the reduction in the core volume. In perspective, it allows to increase neutron fluxes by 1.4 times [14] and at the same time to reduce fuel consumption for experiments by 30% for a new configuration of a core with the old fuel element type. In case of using new fuel elements with low-absorbing materials, one can reach a more higher benefit in neutron fluxes. The necessary modifications have been introduced into CPS-system for new experiments with the vessel replacement. These experiments will undoubtedly be continued.

After 1986, the main cycle of works has been related to a higher project safety. A new concept of main design decision increasing the safety and efficiency of the reactor has been researched and substantiated:

- separation of the shutter drive into 2 independent drives of the upper and lower shutters;
- change of the functional separation of control rods, accompanied by an increase of the number of compensating rods;
- use of the liquid absorber (LA) system for the reliable shutdown of the reactor in the event of a failure of one of regulators.

The research of the dependence of reactivity effects on the concentration of gadolinium nitrate in heavy-water solutions in the gap for cooling of the vessel with various numbers of rods in the heavy-water reflector was carried out [15]. The analysis of an algorithm of the extraction of control rods has shown, that the concentration of 0.08 moles per litre is sufficient to prevent negative consequences of a shutter failure (jamming) for safe norms of subcriticality of the shutdown reactor without other personnel efforts.

A method of measurement of the temperature reactivity coefficient (TRC) has been developed at the critical facility by means of an external electric heating. The temperature change is provided by the natural slow cooling. Such a method guarantees the safe performance of the experiment and a high temperature uniformity at all the points of the core. The temperature reactivity is compensated by the insertion of a calibrated rod and one can be measured directly by the asymptotic period method after withdrawal of the inserted part of rod. The dependence of the temperature reactivity coefficient on temperature at various positions of the absorbing shutters is shown in Fig. 5. It has been shown that the TRC has negative values in the whole temperature range of medium reactor temperatures and at any position of regulation rods. The temperature effect magnitude itself corresponds to the efficiency of the emergency protection rods and meets the requirements of nuclear safety standards. The works on TRC determination are important for demonstration of the inherent safety assurance of the PIK reactor [16].

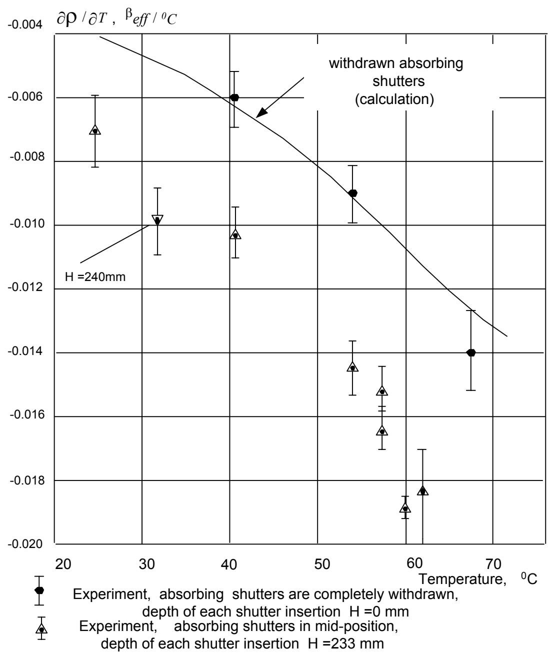

Fig.5. Temperature reactivity coefficient versus temperature

The current precision of the construction parameters affecting the reactivity and the improvement of technique of experiments has allowed us to limit errors due to geometry and material uncertainty to a level of about 0.1% ΔK/K. It corresponds to the modern requirements for the comparison of calculations and experiments. For the verification purposes of a new calculation program, new experimental methods have been developed (for example, with the variance of the critical level of the moderator).

At present time, PIK FM operation is connected with experiments and investigations on the PIK reactor preparation for start-up. In the future, a large part of the facility operating time will be used for the simulation of operating conditions for experimental physical facilities, for the continuation of the research needed to replace the vessel material and the use of new fuel elements.

REFERENCES

[1] E.L. Abramkov, A.A. Arkhipov, G.Ya. Vasiliev *et al., in Methodical and applied works by LNPI*. L., 1988, p. 157, in Russian.

[2] A.N. Erykalov, I.A. Kondurov, K.A. Konoplev *et al*., Preprint LNPI – 376, L., 1977, 25 p., in Russian.

[3] A.N. Erykalov, O.A. Kolesnichenko, K.A. Konoplev, V.A. Nazarenko, Yu.V. Petrov, S.L. Smolsky, Preprint PNPI – 1784, Gatchina, 1992, 39 p.

[4] I.A. Evdokimov, Yu.G. Kiselev, K.A. Konoplev, A.D. Kononykhin, I.G. Marchenko, V.N. Pak, Yu.V. Petrov, R.G. Pikulik, S.L. Smolsky, D.A. Yashin, Preprint PNPI – 2080, Gatchina, 1995, 21 p., in Russian

[5] A.I. Alechin, D.G. German, A.N. Erykalov, K.A. Konoplev, I.G. Marchenko, R.G. Pikulik, Preprint PNPI –2142, Gatchina, 1996, 26 p., in Russian.

[6] E.L. Abramkov, V.N. Avayev, V.V. Bolshakov, G.Ya. Vassiliev *et al*., Preprint LNPI – 1471, L., 1989, 29 p.

[7] E.L. Abramkov, G.Ya. Vasiljev, V.V. Gostev *at al*., Preprint PNPI – 1771, Gatchina, 1992, 14p., in Russian.

[8] G.Ya. Vasiljev, N.V. Levandovsky *at al*., Preprint PNPI – 1862, Gatchina, 1993, 16p., in Russian

[9] K. A. Konoplev,G.V. Paneva *et al*., *in PNPI Research Report 1998-1999*. Part 2. Gatchina, 2000, p. 196.

[10] G.Ya. Vasiliev, S.D. Egodurov, K.A. Konoplev *et al*., Preprint PNPI – 1783, SPb, 1992, 21 p., in Russian.

[11] G.Ya. Vasiliev, S.D. Egodurov, K.A. Konoplev *et al*., Preprint LNPI –1578, L., 1990, 16 p., in Russian.

[12] A.N. Erykalov, K.A. Konoplev, R.G.Pikulik,Yu.V. Petrov, V.F.Samodurov, S.L. Smolsky, A.S. Zakharov, Preprint PNPI – 2426, Gatchina, 2001, 50 p., in Russian.

[13] K.A. Konoplev, I.A. Potapov *et al*., *in PNPI Research Report 1994-1995*. SPb, 1996, p. 240.

[14] K.A. Konoplev, I.A. Potapov *et al*, *in PNPI Research Report 1992-1993*. Gatchina, 1994, p. 194.

[15] V.V. Gostev, A.S. Zakharov, K.A. Konoplev, S.P. Orlov, I.A. Potapov, S.L. Smolsky, *in PNPI Research Report 1994-1995*. SPb., 1996., p. 228.

[16] K.A. Konoplev, G.A. Kirsanov, R.G. Pikulik *et al*., *in PNPI Research Report 1998-1999*. Gatchina, 2000, 198.