INVESTIGATION OF CRITICALITY PARAMETERS OF HIGH-TEMPERATURE REACTORS AT THE KURCHATOV INSTITUTE'S ASTRA CRITICAL FACILITY

N.E. KUKHARKIN, E.S. GLUSHKOV, G.V. KOMPANIETS,
V.A. LOBYNTSEV, D.N. POLYAKOV, O.N. SMIRNOV

Institute of Nuclear Reactors
RRC Kurchatov Institute, Kurchatov sq. 1, 123182, Moscow, Russia

ABSTRACT

The basic parameters of critical assemblies created at the ASTRA critical facility of the RRC Kurchatov Institute for simulation of high-temperature reactors are given in the paper. Capability to simulate different HTGR reactors at the ASTRA critical facility is presented. Brief description of the experiments simulating the PBMR reactor being developed in Republic of South Africa is given. Spherical graphite elements with the outer diameter of 6 cm containing about 2.4 g of uranium with the enrichment of about 21 % are used as fuel elements at the facility. Fuel particles (kernels) made of uranium dioxide with the diameter of about 500 micrometers, having four-layer coating are evenly distributed in the graphite matrix in the central part (5 cm in diameter) of each spherical fuel element. Graphite blocks are used as moderator in reflectors. Up to 46000 spherical elements were loaded in the core in the most recent experiments. Anticipatory computations of critical parameters of the assemblies performed at the RRC KI for the substantiation of criticality safety of the experiments are described in the paper. The calculations were performed with the Russian MCU program complex, which uses Monte-Carlo method. The MCU code was modified for calculations of the double heterogeneity of the HTGR fuel. Kernels of coated fuel particles were not smeared with graphite matrix of fuel elements, and their heterogeneous structure was directly taken into account in the calculations. Results of the implemented experiments are intended for validation of calculational codes used in HTGR designing and justification of neutronics of HTGRs under development.

1. Description of the ASTRA Critical Facility

The ASTRA critical facility at the Kurchatov Institute is intended for experimental investigation of neutron - physical characteristics of HTGR reactors. At the moment the ASTRA critical assembly represents graphite block masonry in the form of a cylinder with internal cavity to form a core. The outer diameter is 380 cm, equivalent inner diameter is 181 cm, height is 460 cm and thickness of the bottom reflector that is also made of graphite blocks is 40 cm (Fig. 1). The central cavity is filled with spherical elements. The set of spherical elements available at the facility includes 2500 absorbing elements (AE), about 15000 graphite elements (GE), and about 50000 fuel elements (FE). Additional graphite blocks available at the facility can be used for mounting of an internal reflector and/or top reflector. All the graphite blocks are made of reactor-grade graphite (the impurity concentration in terms of boron equivalent is about 1.1 ppm wt.) and have the cross section of 25x25 cm and height of 60 or 40 cm. The average density of the graphite mass is about 1.65 g/cm^3.

Spherical fuel elements with the diameter of 6 cm represent a graphite matrix in the central part of which the fuel particles with multilayer coatings (diameter of this central part is 5 cm) are evenly distributed. The density of the fuel element graphite matrix is 1.85 g/cm^3. A fuel particle represents a kernel made of uranium dioxide with the diameter of about 500 μm with four layers of coatings applied to it. Layer 1 (buffer) is made of pyrocarbon (PyC) with the graphite density of 1.1 g/cm^3, the thickness of this layer is 90 μm. Layer 2 (dense layer) is made of pyrocarbon (PyC) with the graphite density of 1.8 g/cm^3, its thickness is 70 μm. Layer 3 is made of silicon carbide (SiC) with the density of 3.2 g/cm^3, the thickness of the layer is 60 μm. Layer 4 is made of pyrocarbon (PyC) with the graphite density of 1.8 g/cm^3 and its thickness is 60μm.

The central fueled zone (5 cm in diameter) of each spherical fuel element contains 2.4g of uranium of the following isotopic composition (wt. %): U-234 - 0.15, U-235- 20.66, U-236 - 0.09, U-238 - 79.10.

A spherical absorbing element with the outer diameter of 6 cm represents a graphite matrix, in central part of which the tiny particles made of boron carbide with the average diameter of about 60 micrometers are evenly distributed. The diameter of this central part is 4 cm. The total mass of natural boron in one absorbing element is 0.1 g. The isotopic composition of the natural boron (at. %) is: B-10 - 19.8, B-11 - 80.2. The density of graphite matrix of the absorbing element is 1.75 g/cm^3.
A spherical graphite element is made of reactor-grade graphite. The outer diameter of the spherical graphite element is 6 cm. The graphite density is 1.68 g/cm^3.
Up to 24 control rods can be used at the ASTRA critical facility. Each absorbing control rod represents a cluster consisting of 15 steel pipes. The outer diameter of the pipe is 12.5 mm and wall thickness is 1.2 mm. The pipes are filled with natural boron carbide with the density of 1.53 g/cm^3. The centres of the pipes are uniformly located on a circle with the diameter of 76 mm. Material of the pipes is stainless steel. The control rod consists of two parts along the height, and the total height of absorber is about 380 cm. The manual control rod has a different design. It represents an aluminium pipe without any additional absorber. All control rods are placed in the central channels (11.4 cm in diameter) of specified side reflector graphite blocks (Fig. 1).

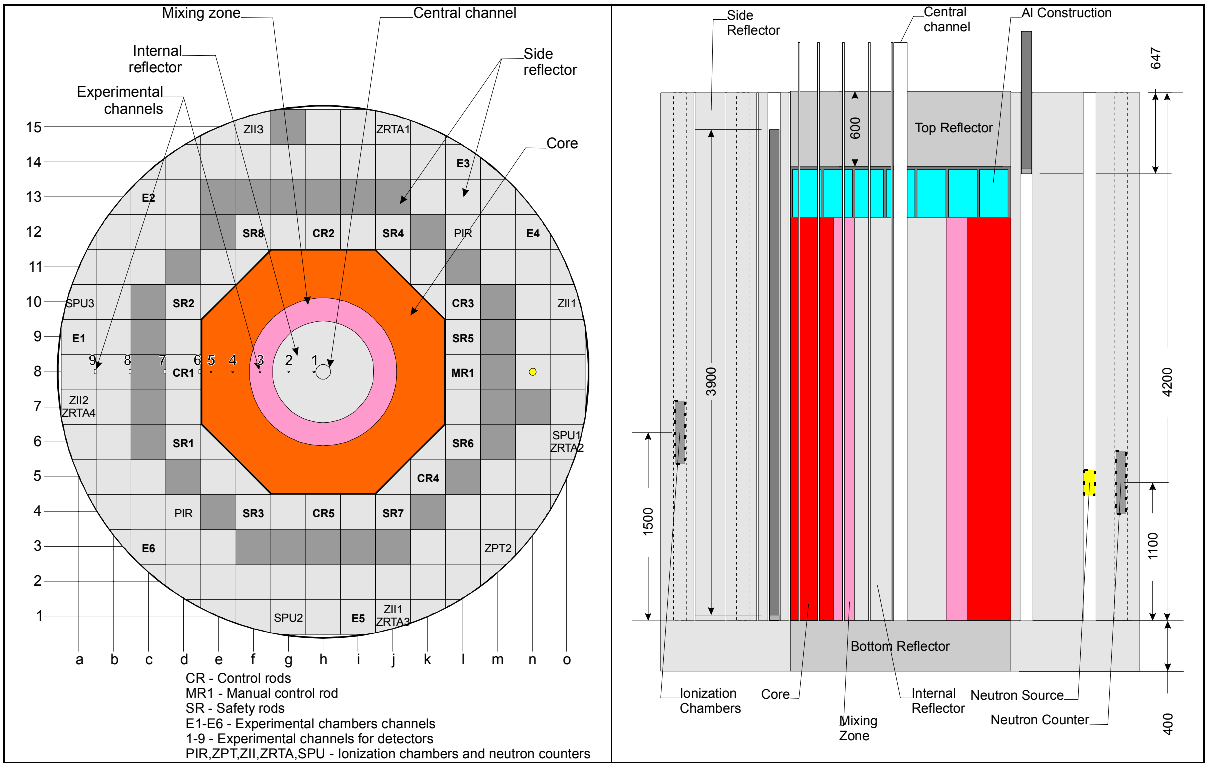

Fig. 1. Cross section and axial section of a critical assembly.

2. Configurations of the Critical Assemblies

A lot of experiments on investigation of high-temperature reactors have been performed at the ASTRA critical facility [1]. The cavity inside the reflector described above (graphite block masonry) represented squares, octagons, and circles of different dimensions without an internal reflector. Some examples of the previously investigated core configurations are given in Table 1.

Table 1. Examples of the Core Configurations at the ASTRA Facility

Configura-tion	Cross Section	Core Height, m (Total Number of FE)	Spherical Element Ratio in the Core
1	Octagon ∅eff=1.8 m	1.76 (23600)	FE/AE=100/5
2	Circle ∅ =0.938 m	3.02 (11300)	FE/AE=100/0

3	Circle ∅ =0.938 m	3.8 (14050)	FE/AE=100/1
4	Circle ∅ =0.938 m, density of polythene in the core 10.6 kg/m^3	3.2 (11920)	FE/AE=100/1
5	Square 1*1 m	2.27 (12330)	FE/AE=100/0
6	Square 1*1 m	2.91 (12790)	FE/GE=4/1

The recent experiments carried out at the ASTRA critical facility were intended for simulation of the PBMR high-temperature modular reactor with annular core being developed in South Africa [2,3]. The works were performed under the contract with the ESKOM company. In these experiments the core represented a pebble bed consisting of three radial zones (see Fig. 1). In the central part of the core the graphite spherical elements forming the internal graphite reflector were placed. Around the internal reflector, a so-called mixing zone representing a mixture of spherical fuel elements, graphite elements and absorbing elements was formed. Between the mixing zone and the side graphite reflector a zone consisting of fuel elements and absorbing elements was created. One of the goals of the experiments carried out at the ASTRA facility was to investigate the influence of dimensions and composition of the mixing zone on the reactor neutronics. All zones were equal in core heights.
Three series of experiments were carried out at the ASTRA facility. Each of the series is characterized by its own type of critical assembly. These types of the assemblies were created one after another and they differ in dimensions and composition of the radial zones. Within each series of the experiments different configurations of critical assemblies were created. They differ from each other by the core height (reactivity margin) and the presence of the top reflector.
Critical parameters of the basic configurations of the assemblies simulating the PBMR reactor are given in Table 2. Critical states of the assemblies were attained with control rods. Measurements of the critical states of the assemblies were performed with the accuracy of 0.0005βeff.

Table 2. Critical Parameters of the Basic Configurations of the Assemblies Simulating the PBMR Reactor

#	Assembly Type	FE/PE/GE Total	H, (cm)	K eff	Reactivity Margin ρ/β_{eff}
1	Series 1, configuration 1, no top reflector	27477/9659/1448 38584	268.9	1.000	0.10
2	Series 1, configuration 2, no top reflector	32929/11553/1734 46216	320.8	1.000	3.7
3	Series 1, configuration 3, top reflector	32929/11553/1734 46216	320.8	1.000	5.8
4	Series 2, configuration 1, no top reflector	27144/9545/1434 38123	267.3	1.000	0.09
5	Series 2, configuration 2, no top reflector	27477/9659/1448 38584	270.3	1.000	0.39
6	Series 3, configuration 1, no top reflector	25308/8884/1334 35526	247.6	1.000	0.09
7	Series 3, configuration 3, no top reflector	27477/9659/1448 38584	268.7	1.000	2.48

Total – Total number of spherical elements in the assembly,
H – Average height of the pebble bed,
K eff – Multiplication factor,
ρ – Reactivity margin with all control rods withdrawn.

Different configurations for simulation of the annular core at the ASTRA critical facility can be proposed under the GT-MHR international project (Russia, USA, France, Japan). The internal and side reflectors can be assembled of graphite blocks, and the annular core can be made up of spherical fuel elements or actual prismatic assemblies with fuel compacts as they are fabricated. One variant of such configurations is shown in Fig. 2. It should be emphasized that the design of the control rod system at the ASTRA critical facility allows placing control rods not only in the side reflector, but also in the core and/or internal reflector. The equipment available at the critical facility allows performing measurements of the following characteristics: criticality parameters, worth of control rods (and plotting of their calibration curves), distributions (profiles) of neutron fluxes (reaction rates) along the radius and height of assemblies simulating HTGR, etc. It is possible to investigate methods of power density distribution profiling over the core volume, influence of synchronous insertion of a group of control rods on power density distribution, etc.

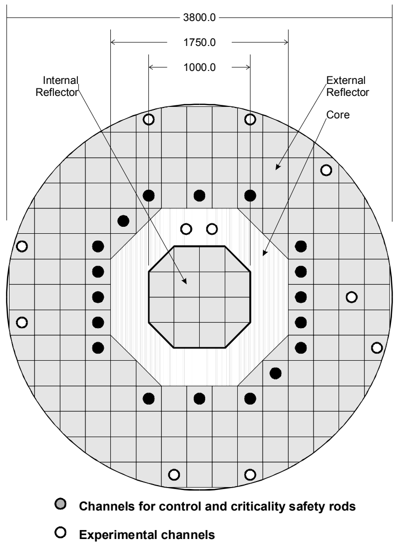

Fig. 2 Variant of cross section of a critical assembly simulating the GT-MHR reactor.

3. Anticipatory Computations of the Critical Assemblies

The anticipatory computations with the goal of substantiation of criticality safety of the experiments implemented at the ASTRA facility have been generally performed with the MCU program complex [4,5]. This code is intended for solution of critical problems of neutron transport with the Monte-Carlo method. The continuous energy range from 20 MeV up to 10^{-5} eV and combinatorial geometry modules allowing computations of real three-dimensional configurations of critical systems are used in the MCU code. In the thermal energy region the Monte-Carlo method uses the S (a, b) scattering model or the free gas model.

The MCU uses an original system of nuclear data libraries. This system includes: ABBN library (26 groups), LIPAR library of resonance parameters in the resolved resonance region, VESTA library of thermal cross sections based on phonon data from the ENDF. In cell computations the TEPCON library can be used instead of the VESTA library. The TEPCON library represents a multigroup library of data for thermal neutrons for energies below 1eV at different temperatures.

Scientists at the RRC Kurchatov Institute developed a special approach on the basis of the Monte-Carlo method for calculation of systems with tiny fuel particles [6]. So, in the calculations of the ASTRA critical assemblies the fuel kernels were not homogenized with the graphite matrix of spherical fuel elements, and the heterogeneous structure of fuel kernels was directly taken into account in the calculations. Two procedures (two systems) are considered for neutrons. The first procedure is used for neutron migration in a fuel zone and the second one is used for neutron migration in a kernel only. The heterogeneous distribution of poison particles (B_4C) in spherical absorbing elements is similarly taken into account.

A stochastic pebble bed was modeled with a regular three-dimensional lattice of spheres of 6 cm in diameter. This lattice (Fig. 3) is characterized by a set of packing factors – spherical element spacing in the layer, and the distance between the layers. Each cell represents the rectangular parallelepiped with square cross section (in the XY plane). In all eight corners of a parallelepiped the centers of spheres are located, and 1/8 part of each sphere belongs to this cell. A centrally located sphere wholly belongs to the cell. FE, AE, or GE can be placed in the center of the cell, and FE, GE – in the corners.

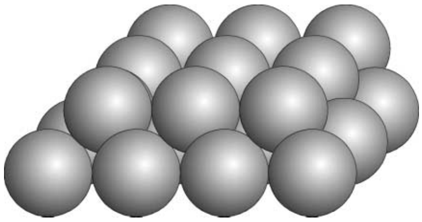

Fig. 3 Model of a pebble bed.

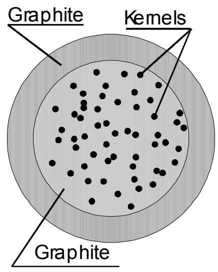

Fig. 4. Model of a fuel element.

The computations predicted critical states of the assemblies with the accuracy of about 0.5 %.
Further, on the basis of the refined benchmark models of the investigated configurations of critical assemblies (including detailed description of their structure, dimensions, and compositions), the work on validation of computational methods and codes used in HTGR designing is planned.

4. Conclusion

The experimental investigations performed at the ASTRA facility demonstrate the following:

- For the designing of new HTGR reactors, it is very important to perform experimental modeling of the reactor, and results of the experiments should be used for validation of calculational codes used in HTGR designing and HTGR criticality safety analysis.
- The cost of experimental investigations at the ASTRA critical facility, in view of the available materials, equipment, and licensed personnel, is relatively low.
- Works with critical assemblies are safe, there is no radiation release or other environmental impacts.
- Computational methods used in support of experimental investigations (substantiation of criticality safety of experiments, prediction of results of the experiments, etc.) are acceptable for analysis of neutron - physical characteristics of HTGR under development.

5. References

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