Verification of the non-stationary neutronic calculation module in the ShIPR software system for modelling of experiments at the ASTRA HTGR type critical facility

Yu N Volkov¹, A E Kruglikov¹ M N Zizin², V F Boyarinov², V A Nevinitsa² and P A Fomichenko²
¹ National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), 31 Kashirskoe shosse, 115409 Moscow, Russia
² National Research Centre “Kurchatov Institute” 1, Akademika Kurchatova pl., Moscow, 123182, Russia

E-mail: KruglikovAntonE@gmail.com

Abstract. The paper presents the comparison of stationary and nonstationary experiments carried out at the ASTRA critical facility and calculation by SHIPR software-based system. The experiments to define of radial speeds distributions of $^{235}$U fission reactions rates were considered and simulated as stationary experiments. Experiments on the determination of kinetic parameters by the Simons-King pulse method were considered as nonstationary experiments. The results show good agreements with experiment in the calculations of both stationary and nonstationary experiments.

1. Introduction
A high temperature gas cooled reactor (HTGR) based on fuel coated particles technology is one of the Generation IV prospective nuclear reactors for future sustainable and safe electricity and heat generation. The world currently are underway to develop a modular type HTGR (HTGR-M) with sphere type fuel cells and GT-MHR with prism type fuel assembly. Reactors of this type have a fundamental advantage on safety related to the lack of core melting at the accidents with loss of coolant. High temperature reactors have the following features concerning their neutronic properties:

- Multilayer fuel coated particles placed in graphite matrix of fuel elements – this design causes so-called double heterogeneity of fuel arrangement in the core and thus requires verification of neutronic calculations with the use of results of integral experiments with fuel elements of similar type.
- High value of “core height to core diameter” ratio ($H/D=1.5…3$), that causes high sensitivity of axial spatial power distribution to control rod axial positions and necessity of experimental study of the safety rods worth and their interference factor, caused by the influence of safety rods for each other.
- Annular core is characterized by high radial non-uniformity of power distribution with local power peaks at the boundaries of active core and side and inner graphite reflectors, etc.

These features demand precise verification of the neutronic calculational codes. So, experiments on critical facilities modelling physical features of high temperature reactors are very important for benchmarking of the neutron computational codes.
A “zero power” ASTRA critical facility built in Kurchatov Institute [1-3] is intended for experimental investigations of neutronic peculiarities of modular HTGRs. Because of the “zero power” critical facility conditions, the uncertainties caused by material composition, temperatures and geometry are considerably lower than in a power reactor. In absence of temperature distribution uncertainties, burning, fission products accumulation, including xenon perturbation effects, the uncertainty of the fuel isotopic composition depends only on the technology of fuel fabrication. This feature allows using the results of experiments to verify neutronic codes used in HTGR calculations [4-10].

Experimental investigation at the ASTRA critical facility covers the following set of measurements:

- experimental investigation of spatial power density distributions (fission reaction rate measurements).
- measurements of the worth of safety rods mockups, their interference factor and calibration curves.
- measurements of neutron kinetic parameters (effective neutron lifetime).
- simulation of reactor physical startup.

The assessment of the experiment series and its description to benchmarking are currently being prepared. Unfortunately, the assessment has been done only for stationary problems and not for non-stationary conditions; moreover the calculation analysis for most part of non-stationary experiments has not been carried out yet.

The last task demands the calculation by neutronic code to be able to solve time-dependent problems in accordance to space distribution of neutron field. One of the codes is SHIPR software-based system, which contains space calculation modules including calculation of time-dependent problems.

The first step to implement the code is verification of the spatial calculation module in relation to experimental data and results of calculation obtained by design code JAR-HTGR [11]. The benchmarking to be discussed in the paper was carried out for two configurations of the ASTRA critical facility.

As a second stage, the nonstationary experiments to determine the parameters of neutron kinetics were modeled. These guidelines, written in the style of a submission to J. Phys.: Conf. Ser., show the best layout for your paper using Microsoft Word. If you don’t wish to use the Word template provided, please use the following page setup measurements.

2. Stationary experiment description

The ASTRA critical facility consisted of three radial zones: inner reflector (IR) of graphite, annular core containing spherical fuel elements of uranium dioxide and side reflector (SR) made of graphite (figure 1).

There were several experimental configurations at the ASTRA critical facility, two of them were chosen to the computational analysis. The simplest one was obtained from the series of experiments on investigation of the influence of Leave-in-Place Control Rods placed into the inner reflector on neutron flux distributions. The configuration describes condition preceding the control rods insertion in the inner reflector [4]. This configuration is named “configuration 1A”.

The next configurations was received in the course of the study of an influence of the set of Profiling Poison Elements (PPE) located in the inner reflector perimeter. After achieving of the neutron flux distribution flattening, the critical facility was rebuilt: the height of the core was increased, the top reflector (TR) was installed, and according to safety reasons the control rods were inserted for criticality. The inclusion of this configuration in the consideration was due to the fact that this configuration is one of the most well-planned experiments simulating of the reactor core state, which is closer to the real operational situation. The configuration is named “configuration 7A”. Thus the following two configurations of ASTRA critical facility were selected for calculations:

- Configuration 1A – the facility without top reflector, without PPE; height of LER plus pebble bed is about 244 cm;
- Configuration 7A – the facility with top reflector, with 8 PPE at the interface of the core and inner reflector in the channels of IR, height of LER plus pebble bed is about 320 cm;
3. Stationary calculation

Calculations of spatial fission rates distribution were carried out by utilization of the JAR-HTGR and ShIPR codes [11, 12], preparation of macroconstants was carried out by WIMS-D/4 code [13-15]. 13-group energy range division implemented in the reactor calculations is presented in the table 1. The group macroscopic cross sections were prepared by WIMS-D/4 taking into account the thermalization process at the energies lower than 4 eV.

| Group Number | Upper boundary, eV | Group Number | Upper boundary, eV |
|--------------|--------------------|--------------|--------------------|
| 1            | \(1.0 \times 10^7\) | 8            | 0,78               |
| 2            | \(1,83 \times 10^5\) | 9            | 0,625              |
| 3            | 906,898            | 10           | 0,40               |
| 4            | 15,968             | 11           | 0,30               |
| 5            | 4,00               | 12           | 0,10               |
| 6            | 2,10               | 13           | 0,058              |
| 7            | 1,30               |              |                    |

ShIPR [16] (Shell of Intelligent Package for Reactor) is an Integrated Development Environment of the Fortran codes application with automatic generation of main programs on the basis of the supply
chain of computational modules, which implement the main stages of the neutronic calculation of nuclear reactors. The benefit of this system is the openness of the codes, respectively, ease in the modernization of neutronic calculation under the specific tasks. In SHIPR there is a set of modules that provide a matched solution for the 3D stationary and non-stationary tasks in multi-group diffusion approximation. The square matrix for scattering cross sections and diffusion coefficient can be utilized.

At the deviation analysis both experimental and calculated values were normalized on average value. The distributions of fission reaction rate for configuration 1A and 7A are presented at the figures 2 and 4 respectively, and the relative deviations of experiment data and the data calculated by program codes JAR-HTGR and SHIPR are presented at the figures 3 and 5 respectively.

The deviations analysis of calculation results and experiment shows that the maximal deviations of calculated values of fission reaction rates from experimental ones are not above 5-7% with the exception of two points in the inner reflector in case of configuration 1A, where the values reached 8-9%.

Figure 2. Distribution of Fission of 235U reaction rates in radial direction for configuration 1A.

As it is clear from the figure 4 in absence of heavy absorption element in the inner and outer reflector the program codes SHIPR and JAR-HTGR show the similar results, so the dispersion in reaction rates calculation is not above 1 percent.
Figure 3. Relative deviations of experiment data and the data calculated by program codes JAR-HTGR and SHIPR for configuration 1A.

Figure 4. Distribution of Fission of 235U reaction rates in radial direction for configuration 7A.
The calculation of configuration 7A is more difficult compared to configuration 1 due to the complicated geometry and the need of taking into account of the heavy absorbing elements in the reflector. Herewith, the deviation value is not above 9% when the heavy control rod CR3 (the weight is more 3 effective fractions of delayed neutrons) was inserted in a vicinity of measurement. The maximal deviations are reached in a vicinity of heavy absorber insertion, where traditionally the diffusion calculation presents difficulties.

4. Non-stationary experiment description

To measure the kinetic parameters, the Simmons – King pulse method [17, 18] was used. This method is based on measuring of the decay of the flux of prompt neutrons in an assembly after the injection of fast (14 MeV) neutrons. For a system in a subcritical or critical state, a decrease in the flux of prompt neutrons after a certain period of time after a pulse (injection) of fast neutrons is described mainly by an exponent with an indicator (decay constant) $\alpha$ over several periods ($\alpha$-1), after which a noticeable contribution delayed neutrons begin to fall as well. The experiments were carried out for an assembly that was in a subcritical state with several values of subcriticality ($\rho/\beta_{\text{eff}}$) in the range of approximately from 1 to 6. Using the obtained value of the decay constant $\alpha$ for each subcritical state, the value of the constant decay of prompt neutrons in the critical state $\alpha_0$ can be define as

$$\rho/\beta_{\text{eff}} = 1 - \alpha/\alpha_0$$  \hspace{1cm} (1)

The following two configurations of ASTRA critical facility were selected for non-stationary calculations:

- Configuration 6B – the facility without top reflector, with 8 PPE at the core and 2 PPE at the inner reflector; height of LER plus pebble bed is about 253.2 cm;
- Configuration 8B – the facility with top reflector, with 8 PPE at the core and 2 PPE at the inner reflector; height of LER plus pebble bed is about 320 cm

The calculated and experimental dependences of the $\alpha$ parameter on the subcriticality $\rho/\beta_{\text{eff}}$ for configurations 6B and 8B are presented at figures 6, 7. The calculated values of the lifetime of prompt
neutrons obtained for these configurations, and the comparisons with experimental data, are presented in Table 2.

Figure 6. Experimental and calculated values of $\alpha$ vs reactivity for configuration 6B

Figure 7. Experimental and calculated values of $\alpha$ vs reactivity for configuration 8B.
Table 2. Calculated and experimental results of nonstationary experiments.

| Configuration | Prompt neutron decay constant for curve extrapolation to zero, ms\(^{-1}\) (calculation) | Prompt neutron decay constant for curve extrapolation to zero, ms\(^{-1}\) (experiment) | Life time \(l\), ms (calculation) | Life time \(l\), ms (experiment) |
|---------------|----------------------------------------------------------------------------------|-----------------------------------------------------------------|-----------------|-----------------|
| 6B            | 3.30±0.05                                                                        | 3.38±0.16                                                       | 2.19±0.03       | 2.14±0.10       |
| 8B            | 3.31±0.53                                                                        | 3.32±0.14                                                       | 2.17±0.35       | 2.07±0.09       |

As can be seen from the analysis of graphs and tables, the error in determining reactivity with deep subcriticality increases. It can be explained by the method of preparation of macroscopic cross-sections for the control rods. In the diffusion model used in the SHIPR, the cross section of the rod has the shape of a square, when in fact it is round. Therefore, the surface area of the rod, and hence its weight, is greater than they really are. Nevertheless, the results of the determination of the alpha parameter are very close.

5. Conclusion
The SHIPR software system was tested for analyses of both the stationary and nonstationary experiments. The experiments to define of radial speeds distributions of \(^{235}\)U fission reactions rates were considered and simulated as stationary experiments. Distributions were calculated for two different configurations of varying complexity and the results show good agreements with experiment for both configurations. Experiments on the determination of kinetic parameters by the Simons-King pulse method were considered as nonstationary experiments. Analysis of discrepancies in the simulation results of non-stationary experiments shows that with increasing subcriticals, the error in determining reactivity increases, while the asymptotic values of the decay constant determined by the set of subcritical states are very close to the experimentally obtained values, which indicates the adequacy of the non-stationary calculation module for different critical configurations assembly ASTRA. An error in determining the subcriticality value can be reduced by improving the macroscopic cross-sections for example using Monte-Carlo codes.

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