Computational analysis of experiments to determine the kinetic parameters at the ASTRA HTGR type critical facility

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Abstract. The zero power ASTRA critical facility is intended for experimental investigations of neutronic features of modular High Temperature Gas Cooled Reactors. The computational analysis of non-stationary experiments carried out at the ASTRA critical stand to determine the kinetic parameters is carried out using SHIPR diffusion program. To measure the kinetic parameters, the impulse Simmons-King method was used. The computational analysis were carried out for 4 different configurations of ASTRA critical stand. Since in case of nonstationary calculation by implementation of the spatial kinetics approximation, it is necessary to set the neutron group velocities the full-scale calculations of neutron spectra were carry oild using the MCU program in order to take into account the spectrum that is established in the full-scale reactor model. On the basis of a comparison of the experimental and calculated results, a conclusion was made about the applicability of the applied effective calculation models for neutronic calculations of HTGR-type reactors.

1. Introduction

A high-temperature gas reactor based on micro-fuel is one of the promising types of nuclear power plants included in Generation IV. At present, many countries with a high level of nuclear power development in the world are developing small and medium-power high-power modular-type HTGRs with two different core designs: using spherical fuel cells and with prismatic fuel assemblies. Reactors of this type have fundamental safety advantages associated with the absence of core melting and a low degree of damage to fuel elements in any possible beyond design basis accidents. In addition, the high temperature of the coolant at the exit from the core in reactors of this type makes it possible to achieve a high value of efficiency, which in turn makes it possible to use energy resources more efficiently and reduce the harmful effect of the electric power industry on the environment. In addition to the high efficiency, high coolant temperatures in HTGR reactors make it possible to effectively use the heat generated by the reactors in technological processes, such as hydrogen production, metallurgy, oil refining, seawater desalination, etc., while expanding the scope of nuclear power applications [1-4].

High-temperature reactors have the following features that affect their neutron-physical characteristics:
Fuel in the form of particles with a multilayer coating, placed in a graphite matrix of fuel elements (double heterogeneity of fuel placement in the core),

A large ratio of the height of the core to its diameter \((H / d = 1.5 - 3)\), leading to the sensitivity of the high-altitude energy distribution to the position of the control rods,

The annular core, characterized by high radial non-uniformity of energy distribution, etc.

These features have a decisive influence on the neutron-physical parameters of reactors of this type and, in accordance with the requirements of the national safety regulatory authorities, require careful verification of the neutron-physical programs used to calculate reactors of this type and to prove the possibility of their application to a real object. In this regard, the experimental data obtained on critical assemblies and experimental reactors of this type are of decisive importance for the verification and validation of codes.

To date, most of the experiments and tests described so far, used for the verification and validation of programs for the neutron-physical calculation of HTGR, are a description of the critical state used to analyse the uncertainties of the input data of neutron-physical calculations, as well as the initial state of the reactor with coupled neutronic and thermal-hydraulic calculations.

Therefore, special attention should be paid to three series of experiments performed at the ASTRA critical stand to substantiate the neutron-physical characteristics of the project of a modular high-temperature reactor with an annular GT-MGR core.

These experimental studies cover a wider range of issues, namely:

- Fuel in the form of particles with a multilayer coating, placed in a graphite matrix of fuel elements (double heterogeneity of fuel placement in the core),
- Investigation of critical parameters of various assembly configurations,
- Determination of the efficiency of absorbing rods and their interference,
- Measurement of calibration characteristics of single absorber rods,
- Measurement of the spatial distribution of the rates of fission reactions along the assembly,
- Determination of the kinetic parameters of the assembly.

For configurations 1A, 5A, 6B, 7B, 8B of the ASTRA critical stand, experiments were carried out to determine the kinetic parameters.

### 2. Methodology

To measure the kinetic parameters, the impulse Simmons-King method was used. This method is based on measuring the decay of the prompt neutron flux in the assembly after the injection of fast (14 MeV) neutrons with a time analyser. For a system in a subcritical or critical state, the decay of the prompt neutron flux after a certain period of time after a pulse (injection) of fast neutrons is described mainly by an exponential with exponent (decay constant) \(\alpha\) for several periods \((\alpha-1)\), after which a noticeable contribution the delayed neutron decay also begins.

In the point approximation of the kinetic equations, the decay constant is related to the kinetic parameters of the assembly as follows:

\[
\alpha = \frac{\beta_{\text{eff}}}{\Lambda} - 1
\]

where \(\Lambda\) is the time of prompt neutron generation. In the considered range of changes in the subcriticality of the assembly, under the assumption that \(\beta_{\text{eff}}\) and \(\Lambda\) are independent of the value of the subcriticality, \(\Lambda \approx 1\), where 1 is the neutron lifetime; \(\rho\) is the reactivity of the assembly. For the critical state of the system, when \(\rho / \beta_{\text{eff}} = 0\), the following relation is valid:

\[
\alpha = - \frac{\beta_{\text{eff}}}{\Lambda}
\]

whence follows:
\[
\frac{\rho}{\beta_{\text{eff}}} = 1 - \frac{\alpha}{\alpha_0}
\]  

The determination of kinetic parameters by the Simmons-King method is reduced to the measurement of \(\alpha\) and the determination of \(\alpha_0\) [5-6].

3. 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. The experiments were carried out for an assembly in a subcritical state at several values of subcriticality \(\frac{\rho}{\beta}\) in the range from about 1 to 6. The horizontal cross section of the ASTRA with positions of its main components is shown in figure 1.

![Figure 1. Scheme of the ASTRA Cross Section (CR1 – CR7 – Control Rods; SR1 – SR8 – Safety Rods; MR1 (MR) Manual Control Rod; LIPR1, LICR2 – Leave-In-Place Control Rods; EC – Experimental Channels; NG – neutron generator; IC – Ionization Chambers; NM – Neutron Meters (Neutron Counters); Dark regions in the side reflector – Graphite Blocks with Plugs).](image)

To determine the parameter \(\alpha\), we measured the decay of the neutron flux in the assembly with a time analyzer after injection using a pulsed neutron generator of fast (14 MeV) neutrons. On the surface of the spherical fill, two neutron counters were installed, connected to the experimental pulsed measuring channels, or standardized pulse signals from the standard pulse channels of the critical stand were used. The emitter of a pulsed neutron generator was installed on the outside of the BO approximately at the level of the middle of the height of the core. Specially prepared software controlled the components of the time analyzer - a timer giving a reference time signal with a resolution of 160 ms to 1 \(\mu\)s, two 16-bit standardized pulse counters and a digital output for periodically triggering a pulsed neutron generator.
The neutron flux decay measured with a time analyzer for a known (specially obtained) subcritical state of the assembly was processed using a semi-automatic processing program. The areas corresponding to the decay of prompt neutron flux and slowly decaying background of delayed neutrons are selected manually. Next, the program uses the least squares method to determine the exponent and the shift of the exponent describing the background of delayed neutrons. In the region corresponding to the decay of the prompt neutron flux, the extrapolated exponential background of delayed neutrons is subtracted and, using the least squares method, a subregion with the smallest decay constant $\alpha$ is selected. From the obtained value of the decay constant $\alpha$, the value of the decay constant of prompt neutrons in the critical state $\alpha_0$ is calculated.

4. Calculation analysis

The calculation of the experiments was carried out using the intelligent SHIPR system, based on deterministic method [7]. The implementation of deterministic method especially diffusion method for subcritical systems can be found, for example, in the calculations of the well-known subcritical system KUCA [8-9]. In this case, since for a nonstationary calculation by implementation of the spatial kinetics approximation, it is necessary to set the neutron group velocities. The neutron group velocities were prepared using MCU Monte Carlo code to take into account the real spectrum of neutrons in the main components of the assembly, taking into account their environment. For this, multi-group neutron fluxes were calculated in the main physical zones of the critical side: the core, side, internal and top reflectors, areas of the CPS, as well as throughout the entire assembly. The obtained spectra were used to prepare the group velocities of neutrons for 13 energy groups, which were previously used in the computational analysis of stationary experiments using the JAR and SHIPR diffusion programs [10-12]. The calculated neutron spectra are shown in Figure 2.

![Neutron Spectrum](image)

**Figure 2.** Neutron spectrum in the main physical regions of the critical ASTRA assembly.
The calculated and experimental dependences of the parameter on the subcriticality $\rho/\beta_{\text{eff}}$ for configurations 1A, 5A, 6B, 7B, 8B are presented at figures 3–7 respectively.

**Figure 3.** Calculated and experimental values of the parameter $\alpha$ depending on the value of subcriticality for configuration 1A.

**Figure 4.** Calculated and experimental values of the parameter $\alpha$ depending on the value of subcriticality for configuration 5A.
Figure 5. Calculated and experimental values of the parameter $\alpha$ depending on the value of subcriticality for configuration 6B.

Figure 6. Calculated and experimental values of the parameter $\alpha$ depending on the value of subcriticality for configuration 7B.
The results of calculating the constant decays of prompt neutrons in subcritical states are in good agreement with experiment, correcting for differences in subcriticality values, which are caused by the macroconstants of the rods. Nevertheless, the values of the decay constant in the subcritical state lie on one straight line, the angle of which is close to the angle of the straight line constructed from the values of the parameter \( \alpha \) obtained experimentally for all considered configurations.

After calculations for each independent measurement at different levels of subcriticality, the prompt neutron decay constant in the subcritical state is calculated, and then the value of the prompt neutron decay constant in the critical state is determined; then the values of the prompt neutron decay constants are averaged for all experiments and calculations (with the exception of the discarded values). The experimental and calculated values of \( \alpha_0 \) are presented in the table 1.

Table 1. Experimental and calculated values of \( \alpha_0 \) for different configurations.

| Configuration | Experimental value \( \alpha_0 \) | Calculation value \( \alpha_0 \) | (C-E)/E, % |
|---------------|-------------------------------|-------------------------------|-----------|
| 1A            | 3.151                         | 2.848                         | 10.6      |
| 5A            | 3.281                         | 3.559                         | -7.8      |
| 6B            | 3.524                         | 3.611                         | -2.4      |
| 7B            | 3.596                         | 3.868                         | -7.0      |
| 8B            | 3.349                         | 3.914                         | -14.4     |

5. Conclusion
The computational analysis of non-stationary experiments carried out at the ASTRA critical stand to determine the kinetic parameters is carried out. For this, the corresponding computational models were created in the SHIPR diffusion program. The neutron velocities for time-depended calculations were prepared using the MCU Monte Carlo code in order to take into account the spectrum that is established in the full-scale reactor model. Based on the results of comparison of experimental and calculated results, it was concluded that the developed diffusion models for each configuration show a good agreement with experiment, correcting for differences in subcriticality values, which are caused by the macroconstants of the rods.
convergence with experimental results taking into account the uncertainty of the input data and the error of the diffusion approximation for calculations of complex systems with void regions and pebble bed core. As our next step we consider the implementation of Monte Carlo code for modelling these experiments.

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