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Methodology for conducting in-pile experiments to study spectral-temporal characteristic of gas media upon excitation by the $^{6}Li(n,\alpha)^{3}H$ nuclear reaction

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Abstract. Almost all experimental studies of the characteristics of nuclear-excited plasma formed by the products of nuclear reactions were performed on impulse nuclear reactors, which differ in the composition and design of the core, the duration, flux and fluence of the neutron impulse, the volume and configuration of the area for irradiation, and the impulse repetition frequency. This work presents a description of the experimental (methodical and equipment) base of the National Nuclear Center of the Republic of Kazakhstan (Kurchatov) for conducting in-pile experiments at the impulse nuclear reactor IGR. The purpose of these works is to study the spectral-luminescent and spectral-temporal characteristics of optical radiation upon excitation of gas mixtures by $^{6}Li(n,\alpha)^{3}H$ nuclear reaction products. To conduct in-pile experiments at the IGR reactor, a new experimental facility was developed. The experimental facility functionally consists of: a gas-vacuum system, an in-pile irradiation device with lithium layer, recording and temperature control systems of the device case, and an optical radiation recording system. A technique for carrying out in-pile experiments at the impulse nuclear reactor is described. To justify the design of the irradiation device and the safety analysis of conducting reactor experiments, neutron-physical and thermophysical calculations were carried out.

Keywords: IGR reactor, $^{6}Li(n,\alpha)^{3}H$ nuclear reaction products, experimental facility, irradiation device.

1. Introduction

The study of optical radiation (laser and spontaneous) of nuclear-excited plasma, formed by the nuclear reactions products is interesting for developing a method of energy output from a nuclear reactor by directly converting it into light energy [1, 2]. The direct pumping of active media is carried out, as a rule, by the products of nuclear reactions with thermal neutrons of a nuclear reactor: $^{3}He(n,p)^{3}H$, $^{10}B(n,\alpha)^{7}Li$, $^{235}U(n,f)F$ or others. The laser working medium must contain ^{235}U, ^{3}He, ^{10}B, or a compound with these isotopes, which is deposited on the laser chamber walls. Less studied was the $^{6}Li(n,\alpha)^{3}H$ nuclear reaction.

Currently, in the National Nuclear Center of the Republic of Kazakhstan operates two research reactors: IVG.1M [3, 4] and IGR [5]. The main results of a series of reactor experiments performed on a stationary IVG.1M reactor are given in [6–9]. The specificity of experiments carried out under conditions of reactor radiation, due to the presence of powerful radiation neutron fields and γ-irradiation, creates certain difficulties and puts forward special requirements for the choice of experimental methods and for the development of the experimental devices designs. Based on the experience of conducting reactor experiments at the IVG.1M reactor and taking into account the specifics of conducting experiments at the IGR impulse reactor at a thermal neutron flux density of up to $7\cdot10^{16}$ n/cm^{2}s, a schematic diagram of the experimental facility was developed.

2. Experimental part

2.1. Experimental facility

A new experimental facility for studying the processes of converting nuclear energy into the energy of coherent optical radiation will be located in the reactor hall of the IGR research reactor.

At the first stage of the work on the development of a schematic diagram of the experimental facility, a block diagram was developed, shown in Fig.1.

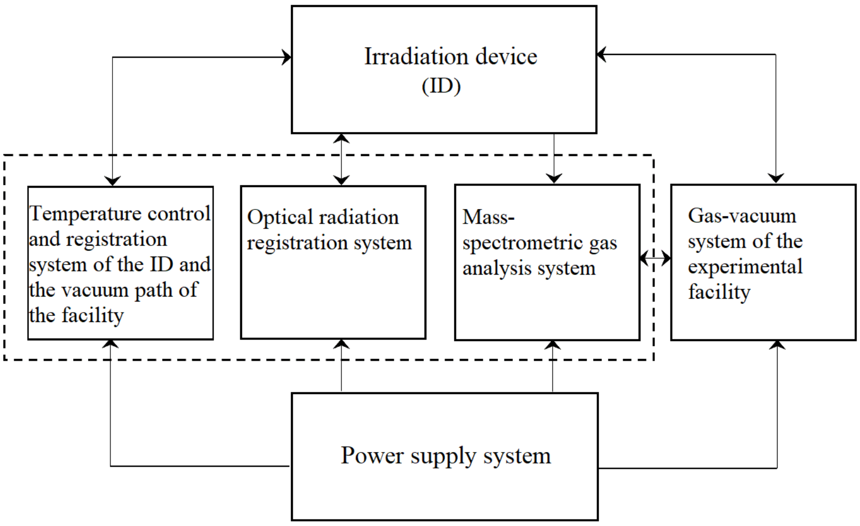


Fig.1. Block diagram of the experimental facility.

The irradiation device (ID) is manufactured based on the objectives of the study and the nature of the maintenance associated with these tasks, while the ID must provide:

– the possibility of placing an experimental cell with a sample of capillary-porous structure (CPS) filled with lithium (lithium CPS) and with the investigated gas mixture at the center of the IGR reactor core;

– pumping out and supply of the investigated gas mixtures into the volume of the ID experimental cell;

– regulation and maintenance of the walls investigated temperature conditions of the ID experimental cell.

Gas-vacuum system of the experimental facility makes it possible to create the necessary conditions (the lower limits of pumping out of the ID volume is 10^{-4} Torr) for conducting experiments.

Information and measurement system (IMS) ensures the control of parameters and control of the facility in the process of preparing and conducting research and ensures the registration of controlled signals. IMS consists of three subsystems:

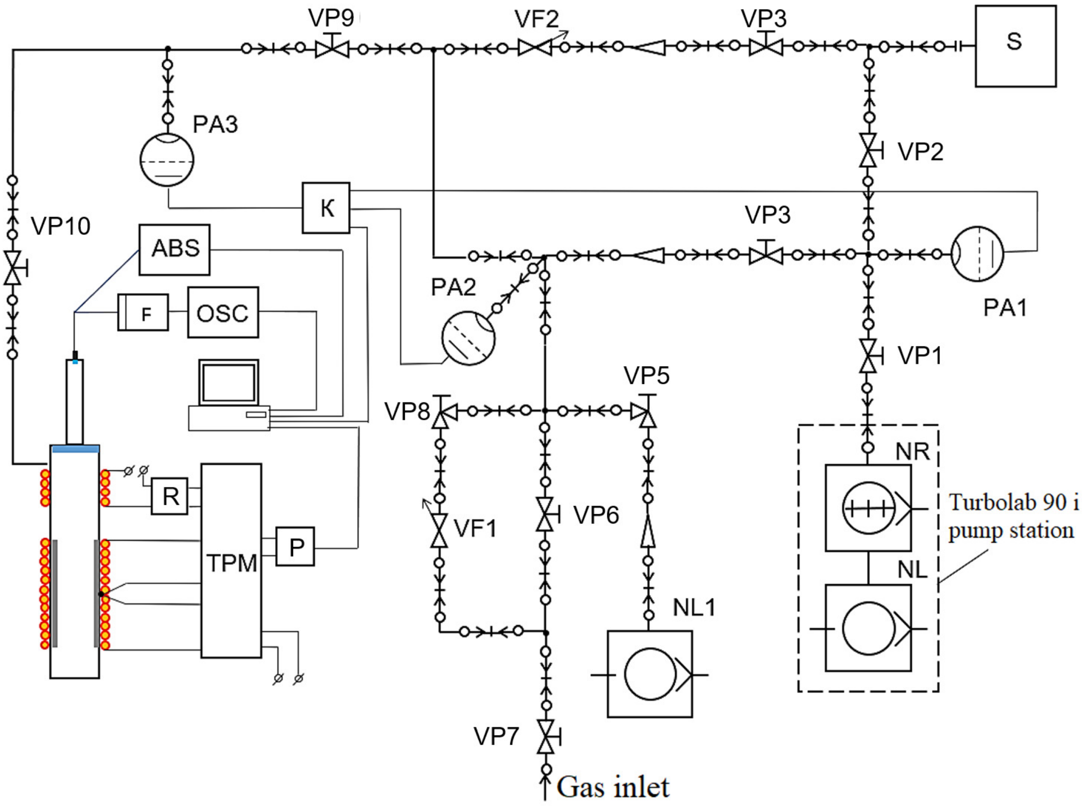
– control system and registration of the ID cell and vacuum path temperature (provides heating and stabilization of the ID housing and vacuum path set temperature during annealing at the preliminary stage and testing);

– optical system for recording a light signal (provides registration of light radiation in the wavelength range from 200 nm to 2500 nm, arising in the volume of the ID experimental cell, as a result of excitation of gas mixtures by the products of $^6Li(n,\alpha)^3H$ nuclear reactions;

– mass-spectrometric system of gas analysis (serves for identification of the gas phase in the ID volume and registration of partial pressures of gases in real time).

Registration and control of the facility parameters will be carried out using a personal computer located in the reactor hall, which is controlled by another personal computer via remote access.

In accordance with the block diagram of the experimental facility a schematic diagram of the experimental facility was developed (Fig.2).



NR – turbomolecular pump; NL – fore pump; VP1…VP10 – vacuum valves; PA1…PA3 – pressure sensors; VF1, VF2 – leak valve; S – quadrupole probe (sensor) of the RGA-100 mass spectrometer; ABS – QEPro-abs (Ocean Optics) optical spectrometer; F – photodetector; OSC – Tektronix TBS2204B oscillograph; K – pressure sensors controller; R – solid-state relay for voltage regulation; P – RS-485 interface converter <-> USB with galvanic isolation; TPM – two-channel controller with universal input and RS-485

Fig.2. Schematic diagram of the experimental facility.

2.2. Irradiation device design

Irradiation device (ID) design with a lithium source of excitation of gaseous medium for conducting experiments at the IGR reactor has been developed. Fig.3a shows a draft of the developed ID.

ID housing, ID experimental cell, and all ID component parts will be made of 12Cr18Ni10Ti steel. Device will consist of two main components: experimental cell (Fig.3b) with lithium CPS sample, and output channel of optical signal from the ID. The output of optical radiation arising in experimental cell volume of the ID as a result of excitation of the gaseous medium by the products of the nuclear reaction $^{6}Li(n,\alpha)^{3}H$, will be carried out through a radiation-resistant quartz collimating lens (74-UV-HT-VAC, with a lens diameter of 5 mm) placed inside the device. The output end of the lens through the optical vacuum input will be connected to the fiber optic cable. The other end of the fiber optic cable will be connected to the recording equipment.

To justify of ID design and the safety of the reactor experiments, neutron-physical and thermophysical calculations were carried out using the MCNP5 licensed programs with the ENDF/B-VII [10] nuclear cross-sections library and Ansys Fluent [11] software.

3. Results and Discussion

The main operating modes of the IGR reactor are the unregulated impulse mode – the self-extinguishing neutron burst mode “Flash” and the controlled mode “Impulse” [12].

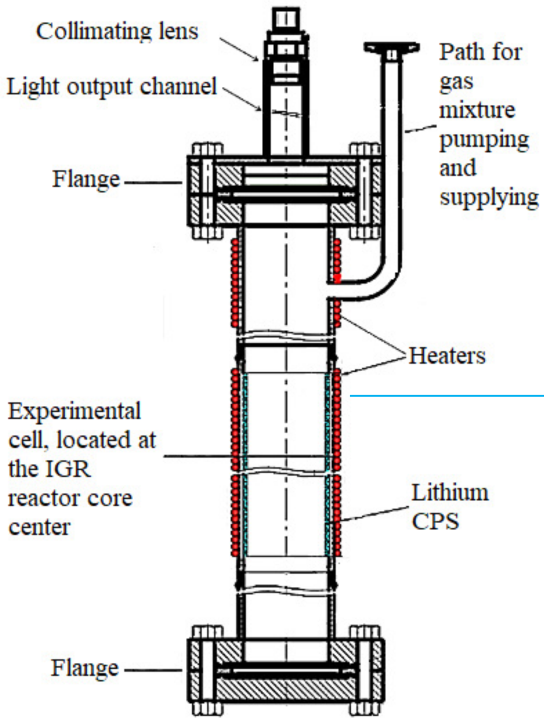


Fig.3a. Irradiation device design.

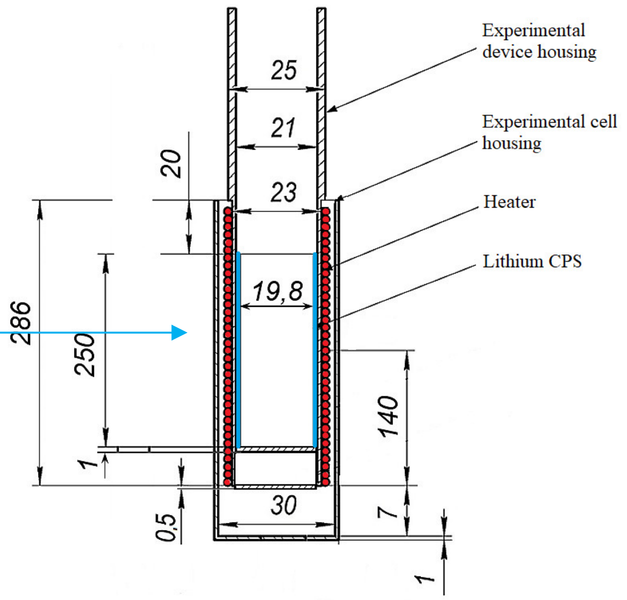


Fig.3b. Draft of the ID experimental cell.

3.1. Neutron-physical calculations

The purpose of neutron-physical calculations was to determine the energy release specific power of the design main elements of the experimental ID cell as a result of neutron and gamma irradiation in the IGR reactor at a reactor thermal power of 5 GW in the “Flash” mode. ID model was developed in the MCNP program code, the energy release specific power of the ID main elements design (ID housing, heater, cooling jacket, lithium CPS) as a result of neutron and gamma irradiation at the IGR reactor was determined. To calculate the distribution of the energy release in the ID main elements, geometry of the calculation model was divided into segments with a step of 100 mm along the height of the device. Neutron-physical calculations were performed for six iterations of the models with the initial temperature of the lithium CPS equal to 294 K, 400 K, 500 K, 600 K, 700 K, and 773 K.

The results of calculations showed that at a thermal power of the IGR reactor equal to 5 GW, the ratio of the specific energy release of lithium CPS to the energy release in the IGR reactor will be $3.19 \cdot 10^4$ W/g.

3.2. Thermal-physical calculations

Using the data obtained as a result of neutron-physical calculations, thermophysical calculations were performed. Tables 1 and 2 show the temperature calculated values of model elements, obtained as a result of the calculation after 0.2 and 0.4 seconds, respectively, for the given options for the ID initial temperature. The purpose of carrying out thermophysical calculations was to determine the temperature field distribution of the ID experimental cell at a thermal power of the reactor equal to 5 GW in the “Flash” mode and with an experiment duration of 0.2 and 0.4 seconds, and at the various initial values of the lithium CPS temperature equal to 294 K, 400 K, 500 K, 600 K, 700 K, 773 K.

The calculation results can be used to select the modes of conducting in-pile experiments.

Table 1. Estimated temperature values of the ID model elements after 0.2 seconds

Initial temperature of the experimental cell of the ID, K	**Temperature of the elements, K**			
	ID housing	Heater	Lithium CPS	Cooling jacket of ID
294	605	431	675	365
400	694	531	761	467
500	786	628	850	564
600	874	724	936	662
700	963	820	1022	759
773	1030	891	1088	830

Table 2. Estimated temperature values of the ID model elements after 0.4 seconds

Initial temperature of the experimental cell of the ID, K	**Temperature of the elements, K**			
	ID housing	Heater	Lithium CPS	Cooling jacket of ID
294	813	603	888	433
400	894	695	965	533
500	980	788	1049	627
600	1062	879	1128	722
700	1144	969	1211	817
773	1208	1036	1275	886

4. Conclusion

This work presents a description of the experimental (methodical technique and equipment) base of the National Nuclear Center of the Republic of Kazakhstan for conducting experiments at the IGR impulse nuclear reactor. The description and scheme of the experimental facility, as well as the ID design are presented. To justify the ID design and the safety of the reactor experiments, neutron-physical and thermophysical calculations were carried out. As a result of the neutron-physical calculations, the specific energy release of the ID design main elements were determined. As a result of the non-stationary thermophysical calculations, the temperature field of the ID model was determined. With a given initial value of the ID experimental cell temperature equal to 294 K, the calculated values of the temperature of the lithium CPS in 0.2 and 0.4 seconds after the start of the experiment will be 675 K and 888 K, respectively, while the temperature of the housing of the ID cell will not exceed 605 K and 813 K respectively. The maximum calculated temperature values of the lithium CPS (for 773 K) in 0.2 and 0.4 seconds after the start of the experiment will be 1088 K and 1275 K, respectively, while the temperature of the housing of the ID will not exceed 1030 K and 1208 K, respectively. Based on the results of the computer simulation calculations, a test program will be developed to study the spectral and temporal characteristics of optical radiation upon gas mixtures excitation by the products of the $^{6}Li(n,\alpha)^{3}H$ nuclear reaction in the IGR reactor core.

Acknowledgement

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