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# IMPACT ASSESSMENT OF THE IGR GRAPHITE BLOCK UNEVEN IMPREGNATION WITH URANIUM ON THERMAL STRENGTH PROPERTIES

The paper presents the results of a numerical interdisciplinary analysis of the fuel element of a heat capacity type research pulsed reactor (IGR). The fuel element of the IGR reactor is a graphite block impregnated with a solution of uranyl dinitrate. During the operation of the reactor, graphite blocks can be heated to high temperatures in a short period of time, which, together with the uneven impregnation of the block with uranium, which is due to the technological process of its manufacture, leads to the appearance of internal structural stresses. The purpose of this work is to make numerical estimation of the magnitude of thermal stresses arising in a graphite block. To carry out such an assessment, two computational models of a graphite block were built. One model is designed to perform neutron-physical calculations using a verified model of the IGR reactor core and the MCNP code, the other is designed to perform thermal strength analysis in the ANSYS software package. Thermal strength analysis includes two stages of calculations – thermal and structural (strength). Both models developed in the way to have the most similar topology, since this directly affects the correct distribution of the energy release over the volume of the block when transferring the results of the neutron-physical calculation to the thermal model.

The operation of a graphite block as part of the reactor core was simulated during a start-up lasting 4 s at a stationary power of 2 GW, followed by cooling down for 5 s. Numerical values and distribution diagrams of temperature and stresses arising in the volume of the block are obtained. The results of the analysis confirm the effect of the uneven impregnation of the graphite block of the IGR reactor with a solution of uranyl dinitrate on its thermal strength characteristics.

**Key words:** IGR, graphite block, neutronic calculations, thermal analysis, structural analysis, ANSYS APDL

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# ИГР реакторының графитті блогында уранның біркелкі емес сіңірілуінің оның термоберіктік сипаттамаларына әсерін бағалау

Бұл жұмыста ИГР зерттеу реакторының отындық элементіне жасалған дисциплина аралық сандық есептеу нәтижелері көрсетілген. ИГР реакторының отындық элементі бойына уранилнитрат ертіндісі сіңірілген графит блогы болып табылады. Реактордың жұмыс жасау барысында графиттік блок қысқа уақыт аралығында үлкен температураға дейін қызуы мүмкін. Бұл эффект, отындық элементтердің графит блогының жасалу технологиясының әсерінен пайда болған уранмен біркелкі байытылмауымен қатар, ішікі құрылымдык кернеулерге әкеліп соғады. Жұмыстың мақсаты графиттік блокта пайда болатын жылулық кернеулерді бағалау болып табылады. Бағалауды жүзеге асыру мақсатында графит блогыың екі есептеу моделі жасалған. Біріншісі, ИГР реакторының активті аймақ моделімен верификацияланған және MCNP кодымен жасалған нейтронндық-физикалық модель. Екіншісі, ANSYS программалық комплексінде жылу-механикалық анализ жасауға арналған модель. Жылу-механикалық анализ қатарынан өткізілетін екі есептеуден тұрады – жылулық және механикалық. Екі модель максималды

тұрғыда ұқсас топология принципіне сүйеніп жасалды. Себебі бұл нейтрондық-физикалық есептеу нәтижелерін жылулық модельге енгізу кезінде энергиябөлінудің дұрыс үлестірілуіне тікелей әсер етеді.

ИГР реакторының активті аймақ құрамындағы графиттік блок жұмысы ұзақтығы 4 с, суыту уақыты 5 с, стационарлық қуат деңгейі 2 ГВт пуск кезінде модельденген. Графиттік блок көлемінде пайда болатын температура мен кернеу сандық мәндері және эпюрлері алынды. Жасалған анализ нәтижелері уранилнитраттың гарфиттік блокка біркелкі сіңірілмеуі оның жылу-механикалық сипаттамаларына әсер ететінің дәлелдейді.

**Түйін сөздер:** ИГР, графитті блок, нейтрондық-физикалық есептеу, жылуды талдау, беріктікті талдау, ANSYS APDL

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## Оценка влияния неравномерности пропитки графитового блока реактора ИГР ураном на его термопрочностные характеристики

В работе представлены результаты численного междисциплинарного анализа топливного элемента исследовательского импульсного реактора теплоемкостного типа (ИГР). Топливный элемент реактора ИГР представляет собой графитовый блок, пропитанный раствором уранилдинитрата. Во время работы реактора графитовые блоки могут разогреваться до высоких температур за короткое время, что, в совокупности с неравномерностью пропитки блока ураном, которая обусловлена технологическим процессом его изготовления, приводит к появлению внутренних структурных напряжений. Целью данной работы является расчетная оценка величины термических напряжений возникающих в графитовом блоке. Для проведения такой оценки построены две расчетные модели графитового блока. Одна модель предназначена для выполнения нейтронно-физических расчетов с использованием верифицированной модели активной зоны реактора ИГР и кода MCNP, другая – для проведения термопрочностного анализа в программном комплексе ANSYS. Термопрочностной анализ включает в себя два последовательных расчета – тепловой и структурный (прочностной). Обе модели были разработаны таким образом, чтобы иметь максимально схожую топологию, поскольку это напрямую влияет на правильное распределение энерговыделения по объему блока при передаче результатов нейтронно-физического расчета в тепловую модель.

Была смоделирована работа графитового блока в составе активной зоны реактора во время пуска продолжительностью 4 с на стационарной мощности 2 ГВт с последующим расхолаживанием в течение 5 с. Получены численные значения и эпюры распределения температуры и напряжений, возникающих в объеме блока. Результаты проведенного анализа подтверждают влияние неравномерности пропитки графитового блока реактора ИГР раствором уранилдинитрата на его термопрочностные характеристики.

**Ключевые слова:** ИГР, графитовый блок, нейтронно-физический расчет, тепловой анализ, прочностной анализ, ANSYS APDL.

## Introduction

The IGR impulse graphite reactor is a research reactor unique in the design and neutron characteristics [1]. Currently, in cooperation with the US Department of Energy, a program is being implemented at the reactor to convert its core to low-enriched uranium fuel [2]. In this regard, special attention is paid to the study of reactor physics. The results of the most significant works in this area are presented in a number of publications [3–10].

One of the unique design features of the reactor core is that there are no typical fuel elements [11, 12] (FE) similar to power reactors [13], and the fissile material (uranyldinitrate) containing enriched uranium is dispersed in graphite blocks from which columns are assembled. According to [1] the IGR reactor has several types of graphite blocks and sleeves, differing in uranium content, location in the core and geometric dimensions.

The manufacturing technology of graphite blocks impregnated with uranium involves the following stages: block formation (molding), making holes (grooves, chamfers), and impregnation in a uranyldinitrate solution and sintering in a furnace. Thus, at the stage of impregnation of the block, there is an uneven distribution of uranium over the volume of the block.

In this paper, a neutronic calculation of a graphite block and its analysis by the finite element method are performed in order to assess the degree of influence of the uneven impregnation of the block with uranium on its thermal and strength characteristics.

**Materials and methods**

The research object is a graphite block impregnated with a solution of uranyldinitrate, the physical configuration of which is shown in Figure 1. As part of this work, a graphite block located in the immovable stack of the core has been researched. The following geometric parameters of the block are adopted: $b$ = 98 mm, $h$ = 98 mm, $l$ = 148 mm, $D1$ = 60 mm, $D2$ = 60 mm, $d$ = 32 mm (Figure 2).

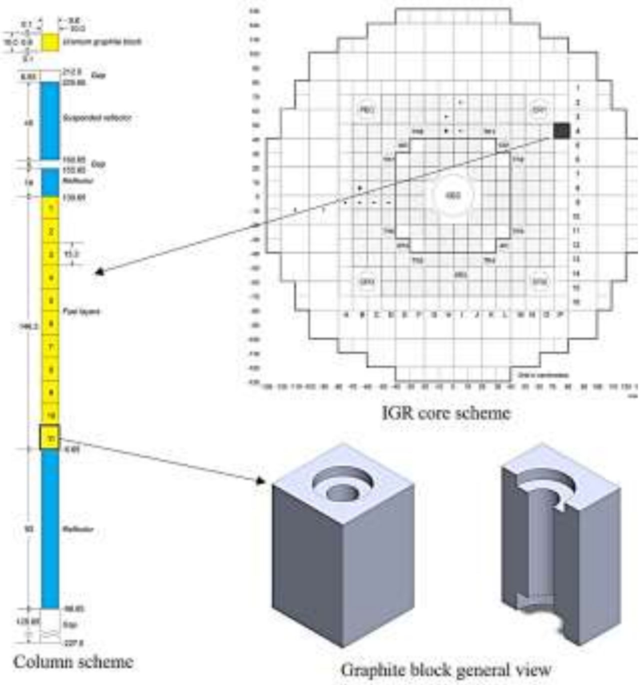


**Figure 1** – Object of the research

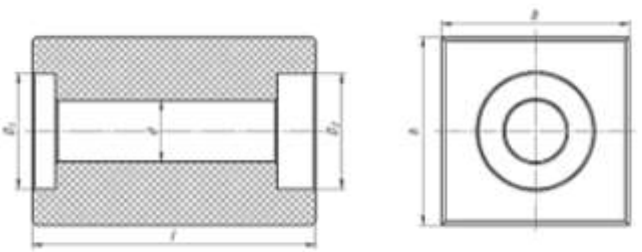

**Figure 2** – Graphite block sketch

The material of the block is ARV-2 graphite, which is one of the reactor type graphite [14]. The estimated weight of the block is 2.03 kg, which corresponds to the actual value.

All physical, strength and thermophysical properties are taken from [15–17]. They include: density – 1640 kg/m$^3$, Poisson distribution equal to 0.3, thermal expansion coefficient, which is 5.8E-06 K$^{-1}$, tensile strength – 17 MPa. The temperature-dependent properties of graphite were calculated using Eqs 1-3:

$$\lambda(T) = -1.746 \cdot 10^{-9} T^3 + 1.36 \cdot 10^{-5} T^2 - -3.868 \cdot 10^{-2} \cdot T + 67.72, \quad (1)$$

$$c_p(T) = 1.413 \cdot 10^{-7} \cdot T^3 - -1.03 \cdot 10^{-3} \cdot T^2 + 2.583 \cdot T - 9.25, \quad (2)$$

$$E(T) = -2.36 \cdot 10^{-7} T^2 + +1.48 \cdot 10^{-3} \cdot T + 4.43, \quad (3)$$

where $\lambda$ is thermal conductivity coefficient (W/m·K); $c_p$ is heat capacity (J/kg·K); $E$ is linear elasticity modulus (Pa); $T$ is temperature (K).

Table 1 shows the values of the volume elasticity modulus and shear modulus calculated based on the given linear elasticity modulus and the Poisson distribution.

**Table 1** – Structural properties

| Temperature, K | Bulk modulus, Pa | Shear modulus, Pa |
|---|---|---|
| 293 | 4.04E+09 | 1.86E+09 |
| 323 | 4.07E+09 | 1.88E+09 |
| 373 | 4.12E+09 | 1.90E+09 |
| 473 | 4.23E+09 | 1.95E+09 |
| 573 | 4.33E+09 | 2.00E+09 |
| 773 | 4.53E+09 | 2.09E+09 |
| 973 | 4.71E+09 | 2.17E+09 |
| 1273 | 4.94E+09 | 2.28E+09 |
| 1573 | 5.15E+09 | 2.37E+09 |
| 1873 | 5.31E+09 | 2.45E+09 |
| 2173 | 5.44E+09 | 2.51E+09 |
| 2373 | 5.51E+09 | 2.54E+09 |

The calculation studies implemented in this research included three sequential stages: neutronic calculation of the volumetric energy release of the block, thermal transient analysis and structural steady-state analysis.

The neutronic calculation is carried out in the MCNP program [18, 19] with evaluated nuclear data libraries ENDF/B-VII.0 [20] for which a computational model of the graphite block was built. The model takes into account all the dimensional and mass parameters and properties of the material. At the same time, special attention is paid to the uneven impregnation of the graphite block with uranyldinitrate solution.

A transient thermal analysis is performed to determine thermal state of the graphite block. The boundary condition of the calculation is the matrix of specific energy releases obtained after performing the neutronic calculation, which is integrated into thermal analysis as initial data.

At the stage of structural analysis, the input data are the temperature values (calculated for each node of the grid model) obtained during solving the heat problem. Geometry constraints are set separately for structural analysis, which in this problem are presented as "sliding surfaces" with restrictions on movement along the normal to each of the coordinate planes.

Thermal and structural analysis was performed using the Ansys software package [21–25].

## Results and discussion

Based on the sketch (Figure 2), a graphite block model was constructed for conducting neutronic calculations in the MCNP program. The block is integrated into the bench-mark model of the IGR reactor [26], in which it is located in the lower part of the core in the peripheral row. Figure 3 shows the vertical and horizontal cross-sections of the block model (nine layers are highlighted in color) and the cross-section of the reactor core model.

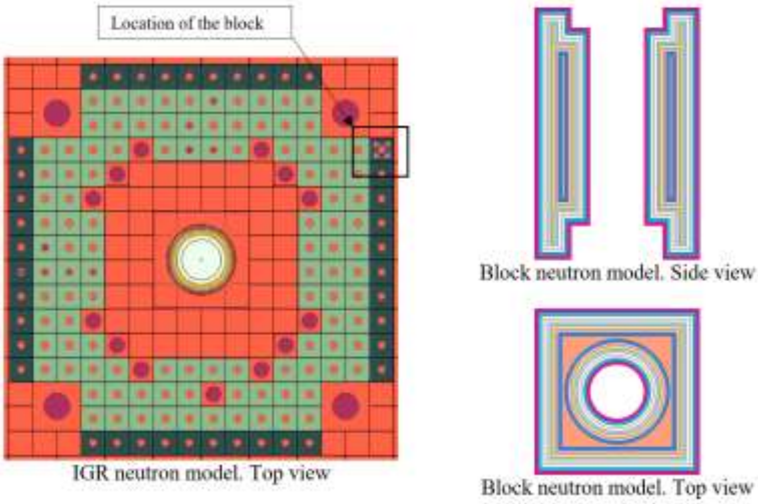


**Figure 3** – Bench-mark model of the IGR with the layered graphite block

The graphite block as a fuel element, heats up in the core under the action of a neutron flux. The power distribution over the volume of the block occurs in accordance with the neutron field and the distribution of uranium over the block. It is assumed that the field of thermal neutrons in a small volume of a graphite block is considered evenly distributed. Then the power distribution across the block will correspond to the distribution of the fissile material.

Because uranium enters the block through the surfaces, the uranium concentration decreases according to the depth. To account for this assumption, the graphite block was divided into 9 layers. Each layer is located at a certain minimum distance from any of the surfaces. All layers are numbered sequentially so that layer No. 1 is in the center of the block, and layer No. 9 is on its periphery (Figure 4). The distribution of uranium concentrations by layers is shown in Table 2.

**Table 2** – Graphite & Uranium concentration per layer

| Layer number | Graphite concentration, atom/(barn·cm$^2$) | Uranium concentration, atom/(barn·cm$^2$) |
|---|---|---|
| 1 (center) | 8.22E-02 | 4.34E-05 |
| 2 | 8.22E-02 | 4.66E-05 |
| 3 | 8.22E-02 | 5.01E-05 |
| 4 | 8.22E-02 | 5.38E-05 |
| 5 | 8.22E-02 | 5.78E-05 |
| 6 | 8.22E-02 | 6.21E-05 |
| 7 | 8.22E-02 | 6.67E-05 |
| 8 | 8.22E-02 | 7.16E-05 |
| 9 (periphery) | 8.22E-02 | 7.69E-05 |

It is important to note that taken into account the uneven distribution of uranium over the volume of the graphite block, it was assumed that the block had a central hole when immersing in a solution of uranium concentrate. The neutronic calculation was performed at a constant reactor power of 2 GW. The complete start-up diagram is shown in Figure 4.

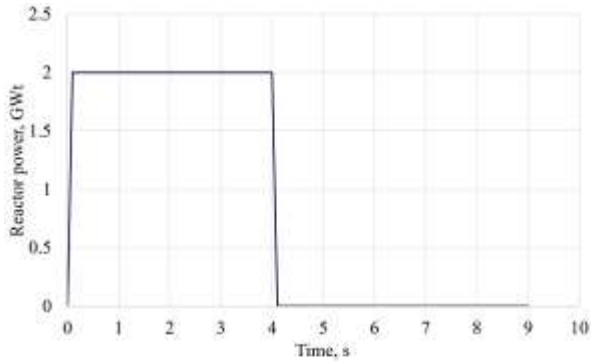


**Figure 4** – Start-up diagram

To calculate the energy release in individual parts of the block and transmission of these values to the corresponding elements of the thermal model, a hexahedral mesh in the form of cubic elements was constructed. The mesh size was about 2 mm.During the neutronic calculation, 10 million particles were simulated, the calculation lasted for 500 cycles, while the calculation uncertainty was less than 2%.

As a result of the neutronic calculation, 197 676 values of specific energy releases were obtained, which were transferred for further thermal calculation. The average specific energy release in the block is about 7.99E + 08 W/m$^3$.

In the Ansys program, a three-dimensional computer geometric model of a graphite block has been designed (Figure 5) and a mesh containing 1 049 657 finite elements has been generated. The average mesh pitch was about 2 mm.

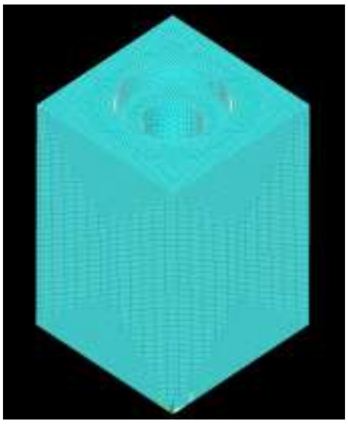

**Figure 5** – 3D meshed block model for ANSYS

The following scenario was considered: intensive heating of the graphite block for 4 s at the maximum integrated reactor power and rapid cooling of the block (from 4 s to 9 s) due to setting of forced convection ($\lambda$ = 1000 W/m × K) on three adjacent surfaces.

A picture of the temperature distribution over the volume of the block at the corresponding time points was obtained (Figure 6).

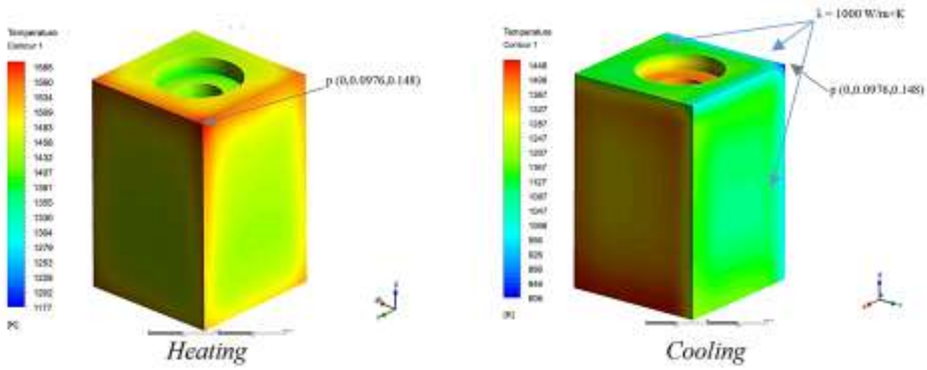


**Figure 6** – Temperature at 4 s (left) and 9 s (right)

Thus, two thermo-stressed states of the graphite block were obtained. The first state was at the end of the heating stage (4 s), the second state was at the end of the cooling stage (9 s). The first state is characterized by the following parameters: the maximum temperature in the block is 1585 K, the minimum is 1177 K, and the temperature growth rate is about 100 degrees per second. The second state is achieved by sharply cooling of a part of the block surfaces and is characterized by the following parameters: the maximum temperature of the block is 1448 K, the minimum is 806 K, and the rate of temperature decrease is more than 120 degrees per second. The obtained temperature values for each of these states are further transmitted to the structural analysis as initial conditions. The change in the temperature of the block over time is shown in the diagram (Figure 7). The temperature value at point *p* (0;0.0976;0.148) is given. This point was chosen in order to demonstrate the area with the maximum rate and amplitude of temperature change.

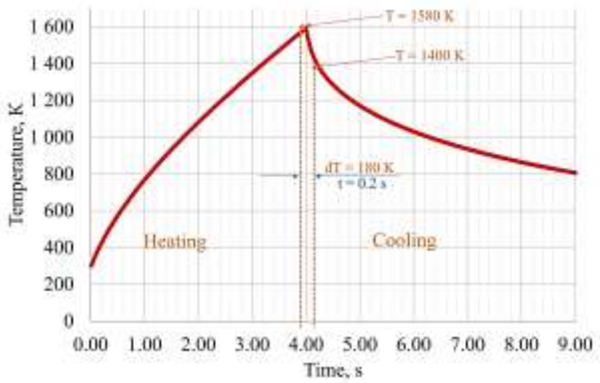


**Figure 7** – Block maximum temperature diagram at the point p (0;0.0976;0.148)

For structural analysis, the same finite element mesh (Figure 5) was used as for thermal calculation. In this analysis, the conditions for fixing the model in the form of sliding surfaces are additionally introduced. A nonlinear stationary structural analysis of the graphite block model for each thermo-stressed state has been performed. According to the calculation results, the diagrams of deformation and stresses in the block resulted from thermal loads have been obtained. Figures 8-10 show the distribution of stresses over the volume of the block in horizontal and vertical sections. The numerical values of the parameters are shown in Table 3.

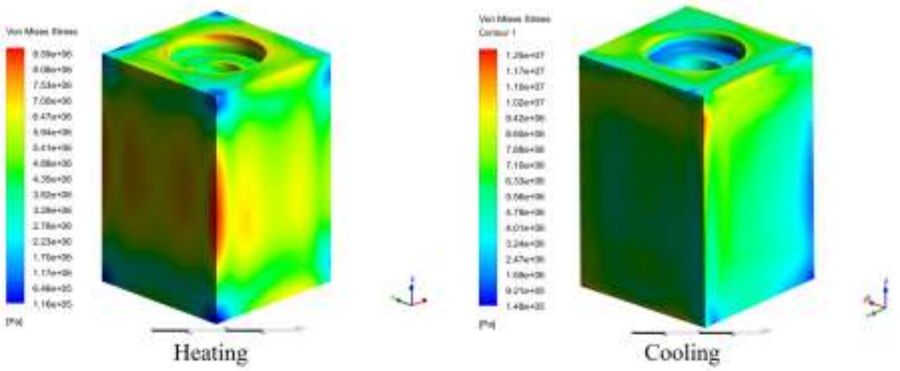


**Figure 8** – Von-Mises stress at 4 s (left) and 9 s (right). Isometric view

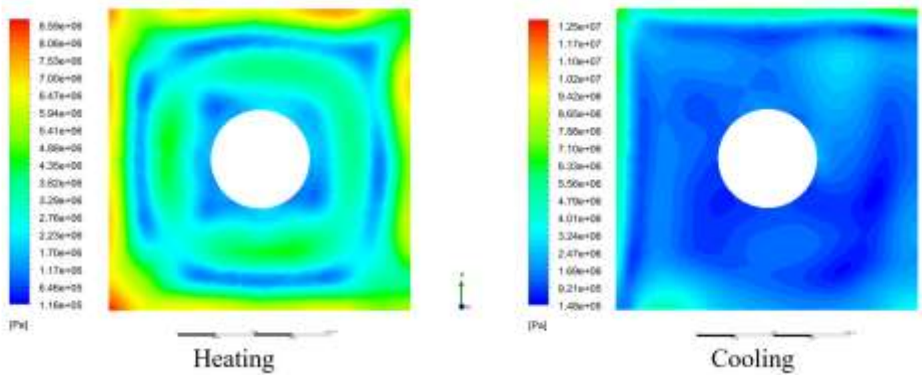


**Figure 9** – Von-Mises stress at 4 s (left) and 9 s (right). Top view

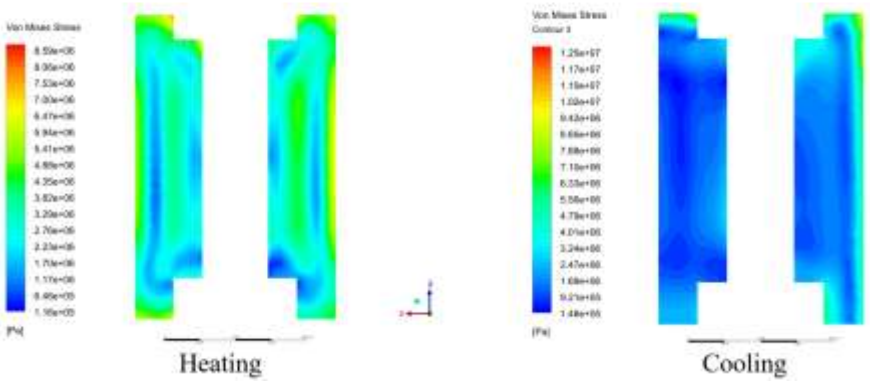


**Figure 10** – Von-Mises stress at 4 s (left) and 9 s (right). Side view

**Table 3 –** Structural analysis results

| Title | Heating (up to 4 s) | | Cooling (from 4 s to 9 s) | |
|---|---|---|---|---|
| | Min | Max | Min | Max |
| Stress (von-Mises), MPa | 0.12 | 8.76 | 0.15 | 12.77 |
| Displacement, m | 0 | 0.00161 | 0 | 0.00152 |
| Deformation, % | 0.0019 | 0.139 | 0.0024 | 0.218 |

As a result of the neutronic calculation, the distribution of specific energy release over the elements of the graphite block mesh model was obtained. A three-dimensional energy release matrix containing 197 676 values (as mentioned earlier) was constructed. The calculation uncertainty was less than 2%. Based on the results of the neutronic calculation, two thermal states of the graphite block were calculated at the stage of intensive heating and subsequent cooling. These modes are selected in such a way as to ensure the creation of the greatest temperature gradients, and, consequently, thermal stresses in the block.

The maximum temperature in the block as a result of heating at maximum energy release in the reactor for 4 seconds was 1585 K, the temperature difference in the volume of the block is 408 degrees. When cooling, due to convective heat exchange from the three surfaces of the block, a temperature drop of 642 degrees was reached.

According to the results of thermal strength calculation, the values of stresses in the block caused by a temperature drop were estimated. The maximum stress of 12.77 MPa and a deformation of 0.218% occur in the block at intensive cooling. When heating, these parameters take values of 8.76 MPa and 0.139%, respectively.

**Conclusion**

The uneven impregnation of the graphite block of the IGR reactor with uranium concentrate leads to the occurrence of thermal stresses both at the stage of heating the block in the reactor and during its intensive cooling. The maximum value of these stresses, estimated by the results of strength analysis, does not exceed 13 MPa. At the same time, the greatest temperature and voltage gradients occur in the first moments of time after the completion of the power diagram, i.e. at the reactor cooling stage.

**Acknowledgement**

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