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# CALCULATION OF THERMOMECHANICAL STRESSES AND DEFORMATIONS IN A REACTOR AMPOULE DEVICE WITH LITHIUM CERAMICS UNDER NEUTRON IRRADIATION

Reactor experiments remain one of the few available methods for evaluating the performance of promising functional materials for fusion reactors under conditions of simultaneous exposure to neutron and gamma radiation, a gaseous environment, and thermal loads. Testing under neutron irradiation together with the application of numerical simulations (Finite Element Method) can lead to a complete understanding of the complex mechanical behavior of packed layers of pebbles by relating the macroscopic response of the infill to the microscopic interactions in a single pebble.

The objective of this paper is describing the procedure and results of modeling of thermomechanical stresses and deformations that occur in the pebble bed of ceramic balls and in the irradiation device housing, in which the studied ceramic samples are placed during irradiation at the WWR-K reactor (Almaty, Kazakhstan).

Calculation results show that ceramic pebbles, densely filled into the capsule of the WWR-K irradiation device so that they cannot move inside the filling, when heated to 1073K, will undergo thermomechanical loads from 10 to 80MPa, which exceeds the ultimate strength of 60MPa of ceramics $Li_4SiO_4$. The share of pebbles, the load on which exceeds the tensile strength, will be from 5 to 10% of their total number. In this case, the capsule will move down by 1-2mm, and expand by 200 microns radially under the influence of thermal elongation of the steel vacuum tubes connecting the capsule to the mounting flange. The strength of the tubes will not be affected.

At a certain value of external pressure, the pebbles will abruptly move ("jump") into the empty area above the pebble bed, reducing the pressure on the remaining pebbles. It is not possible to describe such behavior within the framework of this model. The above calculations are relevant for the case of compacted pebble bed of lithium ceramics under neutron irradiation.

A possible way to avoid the potential destruction of ceramic pebbles is to reduce the thickness of the capsule wall by 2-3 times, which will lead to an increase in the plasticity of the capsule walls, a decrease in the wall pressure on the pebble bed, and a decrease in the heating temperature of the capsule and ceramics.

**Key words:** simulation, lithium ceramics, pebble bed, deformations, irradiation

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# Нейтронды сәулелену кезіндегі литий керамикасы бар реакторлық ампулалық құрылғыдағы термомеханикалық кернеулер мен деформацияларды есептеу

Реакторлық эксперименттер термоядролық қондырғылардың перспективалы функционалды материалдарының нейтронды және гамма – сәулеленудің, газ ортасының және жылу жүктемелерінің бір мезгілде әсер ету жағдайында жұмыс қабілеттілігін бағалаудың бірнеше қол жетімді әдістерінің бірі болып қала береді. Нейтронды сәулелену жағдайында сынақтар сандық модельдеуді (ақырлы элементтер әдісі) қолданумен бірге толтырудың макроскопиялық реакциясын жеке шардағы микроскопиялық өзара әрекеттесулермен байланыстыра отырып, оралған шар қабаттарының күрделі механикалық әрекетін толық түсінуге әкелуі мүмкін.

Бұл жұмыстың мақсаты ВВР-К (Алматы, Қазақстан) реакторында сәулелену кезінде зерттелетін керамика үлгілері орналастырылатын керамикалық шарлардан және сәулелендіру құрылғысының корпусынан толтыруда туындайтын термомеханикалық кернеулер мен деформацияларды модельдеу тәртібі мен нәтижелерін сипаттау болып табылады.

Есептеу нәтижелері көрсеткендей, ВВР-К сәулелендіру құрылғысының капсуласына тығыз құйылған керамика шарлары толтыру ішінде қозғала алмайтындай етіп, 1073 К дейін қызған кезде 10-дан 80 МПа-ға дейінгі термомеханикалық жүктемелерге ұшырайды, бұл $Li_4SiO_4$ керамикасының 60 МПа беріктік шегінен асады. Жүктемесі беріктік шегінен асатын шарлардың үлесі олардың жалпы санының 5-тен 10% - на дейін болады. Бұл жағдайда капсула 1-2 мм төмен қарай жылжиды және капсуланы монтаж фланецімен байланыстыратын болат вакуумдық түтіктердің термиялық ұзаруының әсерінен радиалды түрде 200 мкм-ге кеңейеді. Түтіктердің беріктігі бұзылмайды.

Сыртқы қысымның кейбір мәндерінде шарлар толтырудың үстіндегі бос аймаққа күрт ауысады ("секіреді"), қалған шарларға қысымды төмендетеді. Осы модель шеңберінде мұндай мінез-құлықты сипаттау мүмкін емес. Жоғарыда келтірілген есептеулер нейтронды сәулелену кезінде литий керамикасының тығыздалған толтырғыштары үшін мәндерге ие. Керамикалық шарлардың ықтимал бұзылуын болдырмаудың мүмкін әдісі капсула қабырғасының қалыңдығын 2-3 есе азайту, бұл капсула қабырғаларының икемділігінің жоғарылауына, толтыру қабырғасының қысымының төмендеуіне және капсула мен керамиканың қыздыру температурасының төмендеуіне әкеледі.

Түйін сөздер: модельдеу, литий керамика, шарлар толтыру, деформация, сәулелену.

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## Расчет термомеханических напряжений и деформаций в реакторном ампульном устройстве с литиевой керамикой под нейтронным облучением

Реакторные эксперименты остаются одним из немногих доступных способов оценки работоспособности перспективных функциональных материалов термоядерных установок в условиях одновременного воздействия нейтронного и гамма-излучений, газовой среды и тепловых нагрузок. Испытания в условиях нейтронного облучения вместе с применением численного моделирования (метода конечных элементов) могут привести к полному пониманию сложного механического поведения упакованных слоев из шариков, связав макроскопический отклик засыпки с микроскопическими взаимодействиями в отдельном шарике.

Целью настоящей работы является описание процедуры и результатов моделирования термомеханических напряжений и деформаций, возникающих в засыпке из керамических шариков и в корпусе облучательного устройства, в котором размещаются исследуемые образцы керамики во время облучения на реакторе ВВР-К (Алматы, Казахстан).

Результаты расчетов показывают, что шарики керамики, плотно засыпанные в капсулу облучательного устройства ВВР-К так, что не имеют возможности перемещаться внутри засыпки, при нагреве до 1073 К будут претерпевать термомеханические нагрузки от 10 до 80 МПа, что превышает предел прочности в 60 МПа керамики $Li_4SiO_4$. Доля шариков, нагрузка на которые превысит предел прочности, составит от 5 до 10 % от общего их количества. При этом капсула будет смещаться на 1-2 мм вниз, и расширяться на 200 мкм радиально под воздействием теплового удлинения стальных вакуумных трубок, соединяющих капсулу с монтажным фланцем. Прочность трубок не нарушится.

При некотором значении внешнего давления шарики будут резко перемещаться ("выпрыгивать") в пустую область над засыпкой, снижая давление на оставшиеся шарики. Описать такое поведение в рамках данной модели не представляется возможным. Приведенные расчеты имеют значения для случая уплотненных засыпок литиевой керамики под нейтронным облучением.

Возможным способом избежать потенциального разрушения шариков керамики является снижение толщины стенки капсулы в 2-3раза, что приведет к увеличению пластичности стенок капсулы, снижению давления стенки на засыпку и снижению температуры разогрева капсулы и керамики.

Ключевые слова: моделирование, литиевая керамика, засыпка из пебблов, деформация, облучение.

**Introduction**

Lithium ceramics in the form of packed spheres (pebble bed) was chosen as a source of tritium in the concept of a solid breeder blanket for the DEMO fusion reactor [1–3]. Various designs of solid-state breeder blankets with lithium ceramics will be tested at the ITER reactor [4–9].

Qualification of lithium ceramic pebble bed as a material for generating tritium is necessary to demonstrate its acceptable behavior under harsh environmental conditions such as thermal cycling due to plasma pulses, temperature gradients, and thermal expansion coefficient mismatches between ceramic and structural materials of the blanket module structure. Ceramic pebble bed exhibits quite complex thermomechanical behavior due to the discrete nature of the individual pebbles.

Reactor experiments remain one of the few available methods for evaluating the performance of promising functional materials for fusion installations under conditions of simultaneous exposure to neutron and gamma radiation, a gaseous environment, and thermal loads. Testing under neutron irradiation conditions, together with the use of numerical simulations (finite element method), can improve understanding of the complex mechanical behavior of packed layers of pebbles by relating the macroscopic response of the pebble bed infill to the microscopic interactions in a single pebble.

In turn, to carry out experiments on the irradiation of lithium ceramic samples in a research reactor, it is necessary to calculate the thermomechanical stresses and strains that occur both in the ceramic filling of pebbles itself and in the materials of the irradiation ampoule device under neutron irradiation. This is necessary not only from the point of view of the safety of the reactor experiment, but also from the point of view of assessing the probability of destruction of individual pebbles from the mechanical loads that have arisen in the ampoule device, caused by the difference in the thermal expansion coefficients of ceramics and structural steel of the irradiation capsule.

This paper describes the procedure and results of modeling of thermomechanical stresses and deformations that occur in the filling of ceramic balls and in the irradiation device housing, in which the studied ceramic samples are placed during irradiation at the WWR-K reactor (Almaty, Kazakhstan).

**Method**

The design of the irradiation device (ID), in the part that is used for thermophysical and thermomechanical calculations, is shown in Figure 1 and is an analogue of the typical design of the irradiation device, which is used in experiments at the WWR-K reactor [10]. The ID consists of an external case (12Cr18Ni10Ti austenitic stainless steel pipe), which contains a long ampoule (a pipe of smaller diameter), at the end of which there is a replaceable capsule with samples. The pressure in the capsule is not more than $5\cdot10^{-2}$ Torr. The ampoule and capsule are cooled by convection air flows located in the space of the dry peripheral channel of the WWR-K reactor between the ampoule and the channel wall. The outer surface of the channel wall is in contact with the water of the cooling circuit of the WWR-K reactor. The material of the channel wall is aluminum alloy SAV-1. An ohmic heater with a power of 50 W was wound on the lower part of the ampoule for additional heating of the area where the samples were located (if necessary). The heater consists of seven turns of copper wire, insulated with powdered aluminum oxide, enclosed in a thin stainless steel sheath.

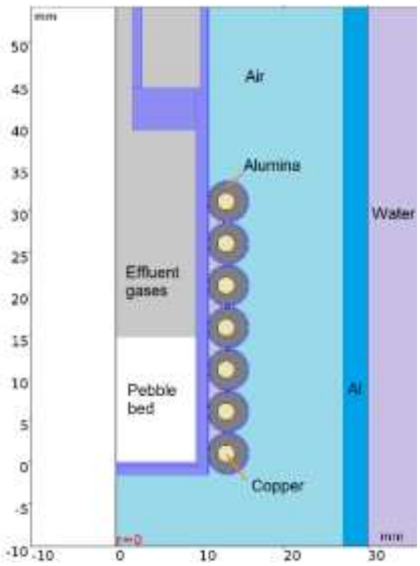



**Figure 1** – Radial section of the irradiator (enlarged)

To control the temperature of the test samples, the ID is equipped with two external K-type (chromel-alumel) thermocouples: one is located at the bottom of the ampoule, the other is on its wall in the area of the capsule with samples under the heater.

The calculations were carried out using the Comsol Multiphysics software package [11], designed for modeling complex physical problems. Previously, a model was created to describe heat transfer [12], taking into account thermal conductivity, convection, and thermal radiation, which was supplemented by a description of thermal expansion, thermomechanical stresses, and deformations. To do this, the Solid Mechanics module was added to the model, which includes the Nonisothermal Flow module from the Comsol Multiphysics library, which combines the heat transfer equations (Heat Transfer in Fluids) in solid and gaseous media with the Navier-Stokes equation (Laminar Flow module) for a laminar cooling air flow, the Solid Mechanics module was added, realizing, together with Heat Transfer in Fluids, the Thermal Expansion mode.

All materials of the equipped irradiation device (including irradiated ceramics) in the temperature range of 300-1100 K can be assumed to be predominantly elastic. As is known, stresses and strains inside a continuous elastic material (in this case, a ceramic pebble and an ampoule/capsule wall) are related by a linear relationship, which is mathematically analogous to Hooke's spring deformation law and is often associated with his name. However, the state of deformation in a solid medium around a certain point cannot be described by a single vector. The same piece of material, no matter how small, can be compressed, stretched, and shifted simultaneously along different directions. To take this circumstance into account for three-dimensional bodies, the corresponding state of the medium around a point must be represented by second-order tensors: the strain tensor $\boldsymbol{\varepsilon}$ and the stress tensor $\boldsymbol{\sigma}$. Then Hooke's law for a continuous medium is written as:

$$\boldsymbol{\sigma} = \boldsymbol{C}:\boldsymbol{\varepsilon}, \quad (1)$$

where the colon denotes the doubly scalar product of tensors, $\boldsymbol{C}$ is the fourth order tensor, which is commonly referred to as the stiffness tensor or the elasticity tensor.

In the Cartesian coordinate system, the strain tensors $\boldsymbol{\varepsilon}$ and stress $\boldsymbol{\sigma}$ are represented by 3×3 matrices:

$$\boldsymbol{\varepsilon} = \begin{bmatrix} \varepsilon_{11} & \varepsilon_{12} & \varepsilon_{13} \\ \varepsilon_{21} & \varepsilon_{22} & \varepsilon_{23} \\ \varepsilon_{31} & \varepsilon_{32} & \varepsilon_{33} \end{bmatrix}, \boldsymbol{\sigma} = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} \end{bmatrix}. \quad (2)$$

Being a linear mapping between nine values of $\sigma_{ij}$ and nine values of $\varepsilon_{kl}$, the stiffness tensor $\boldsymbol{C}$ is represented by a 3×3×3×3 = 81 matrix of real numbers $C_{ijkl}$. That is, Hooke's law can be written as

$$\sigma_{ij} = \sum_{k=1}^{3}\sum_{l=1}^{3} C_{ijkl}\varepsilon_{kl}, \quad (3)$$

where $i,j$ = 1,2,3.

All three tensors change from point to point within the medium, and can also change over time. The strain tensor $\boldsymbol{\varepsilon}$ determines the displacement of a particle of the medium in the vicinity of a point, while the stress tensor $\boldsymbol{\sigma}$ determines all possible forces with which neighboring areas of the medium (solid body) act on each other. Therefore, they do not depend on the composition and properties of the material. On the other hand, the stiffness tensor $\boldsymbol{C}$ is a material property and in most cases depends on the physical parameters of the medium, such as temperature, pressure or microstructure.

Adding the Solid Mechanics module (with its limitation only to isotropic elastic materials) to the considered model mathematically means supplementing the system of heat and mass transfer equations with the following set of equations for describing mechanical displacements inside the structural elements of the irradiation device:

$$0 = \nabla \cdot \boldsymbol{\sigma} + \boldsymbol{F}_V, \quad (4)$$

$$\boldsymbol{\sigma} = \boldsymbol{\sigma_{ad}} + \boldsymbol{C}:\varepsilon_{el}, \quad (5)$$

$$\varepsilon_{el} = \varepsilon - \varepsilon_{inel}, \quad (6)$$

$$\boldsymbol{\sigma_{ad}} = \boldsymbol{\sigma_0} + \boldsymbol{\sigma_{ext}} + \boldsymbol{\sigma_q}, \quad (7)$$

$$\varepsilon_{inel} = \varepsilon_0 + \varepsilon_{ext} + \varepsilon_{th} + \varepsilon_{hs} + \varepsilon_{pl} + \\ + \varepsilon_{cr} + \varepsilon_{vp}, \quad (8)$$

$$\varepsilon = \frac{1}{2}[(\nabla \boldsymbol{u})^T + \nabla \boldsymbol{u}], \quad (9)$$

$$\boldsymbol{C} = \boldsymbol{C}(E, \nu), \quad (10)$$

where $\boldsymbol{\sigma}$ is the stress tensor (N/m$^2$); $\boldsymbol{\sigma_{ad}}$ is the total stress tensor, (N/m$^2$); $\boldsymbol{\sigma_{ext}}$ is the external stress tensor (N/m$^2$); $\boldsymbol{\sigma_0}$ – initial stress tensor (N/m$^2$); $\boldsymbol{\sigma_q}$ is the viscoelastic stress tensor (N/m$^2$); $\varepsilon_{el}$ – elastic strain tensor (dimensionless); $\varepsilon_{inel}$ – inelastic strain tensor (dimensionless); $\varepsilon$ is an overview of the strain tensor; $\varepsilon_0$ is the initial strain tensor; $\varepsilon_{ext}$ is the external strain tensor; $\varepsilon_{th}$ is the thermal strain tensor; $\varepsilon_{hs}$ is the hygroscopic strain tensor; $\varepsilon_{pl}$ is the plastic strain tensor; $\varepsilon_{cr}$ is the creep strain tensor; $\varepsilon_{vp}$ is the volumetric plastic strain tensor; $\boldsymbol{F}_V$ – body force vector (N/m$^3$); $E$ is Young's modulus (Pa); $\boldsymbol{u}$ is the displacement field (m); $\nu$ - Poisson's ratio (0-1); $\boldsymbol{C}$ is the elasticity tensor (N/m$^2$); $\boldsymbol{\nabla}$ – differentiation operator, nabla (m$^{-1}$).

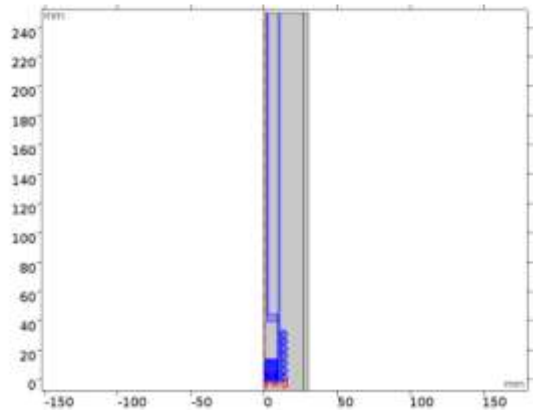
Since the sample is small and not subject to external mechanical loads, in this case it can be assumed that the inelastic strain tensor is equal to the thermal strain tensor:

$$\varepsilon_{inel} = \varepsilon_{th} = \alpha(T) \cdot (T - T_0), \quad (11)$$

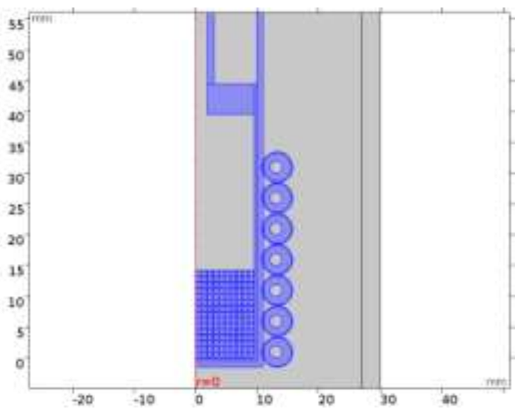
where $\alpha(T)$ is the temperature-dependent coefficient of thermal expansion of the material $T$, $T_0$ is the initial temperature of the material (K).

In the case under consideration, only gravity acts as $\boldsymbol{F_V}$. Thus, knowing $\alpha(T)$, Young's modulus $E$, and Poisson's ratio $\upsilon$ for the materials used in the model, one can start finalizing the model geometry and calculating thermomechanical stresses and strains in the irradiated capsule during its heating and cooling.

Figure 4 shows the final view of the axisymmetric geometry of the calculation model, in which the domains included in the calculation of the Solid Mechanics module are highlighted in blue for calculating thermomechanical stresses and strains in them.



a)



b)

**Figure 4 –** Geometry of the ampoule model and areas for calculating thermomechanical stresses (highlighted in blue): a) capsule with tubes fixed on top; b) view of the ceramic pebble bed in a capsule and a heater

As can be seen from Figure 4, the studied ceramic pebble bed in the model is presented as an array of 15 layers of pebbles with a diameter of 1 mm, which corresponds to reality. The ceramic is described as $Li_4SiO_4$ (lithium orthosilicate, a standard material from the Comsol Materials Library). The values of Young's modulus and Poisson's ratio for $Li_4SiO_4$ are taken to be 90 GPa and 0.25, respectively [13, 14].

The “porous” portion of the pebble bed not occupied by the pebbles and the region of low gas pressure above it are filled with gaseous products desorbed from the ceramics under pumping action, described in the model as “stationary” helium at a pressure of 50 Pa (thermal conductivity 0.2 W/m/K; density 0.03 g/m$^3$; heat capacity 5 kJ/kg/K). To take into account cooling air flows, it is described in the model as a laminar flow of a weakly compressible gas under the action of heat and gravity sources. Part of the air in a small closed volume between the outer surface of the ampoule and the ohmic heater does not participate in the main convection and is described as "stationary" transparent air (Solid). All other media (materials) are described as Solid with the ability to radiate and receive thermal energy according to the Stefan-Boltzmann law.

In the Solid Mechanics module, as can be seen from Figure 5, all solid materials that make up the capsule are indicated as Linear Elastic Material. The behavior of the outer aluminum jacket of the reactor channel is not taken into account, since it is separated from the capsule by an air layer and does not affect the pattern of thermomechanical stresses in the capsule. Thus, the capsule and heater materials include lithium orthosilicate, 321 stainless steel, alumina, and copper.

Further, in the Solid Mechanics settings (Figure 5, the Free tab on the left of the panel), those domain boundaries are selected that are supposed to move during the heating process (Figure 6a), and those boundaries that are rigidly fixed (in this case, these are the fastening of the outer and inner tubes of the ampoule on the upper boundary of the geometry, Figure 6b) are designated as fixed in the Fixed Constraint tab.

At the last stage of the settings in the Gravity tab (Figure 7), it is indicated that all domains (materials) of the capsule are affected by gravity.

Next, the heat release over the pebble bed is set in accordance with the results of neutron-physical calculations, as shown in Figure 8. The heat release inhomogeneity is explained by the shielding effect of lithium with respect to thermal neutrons.

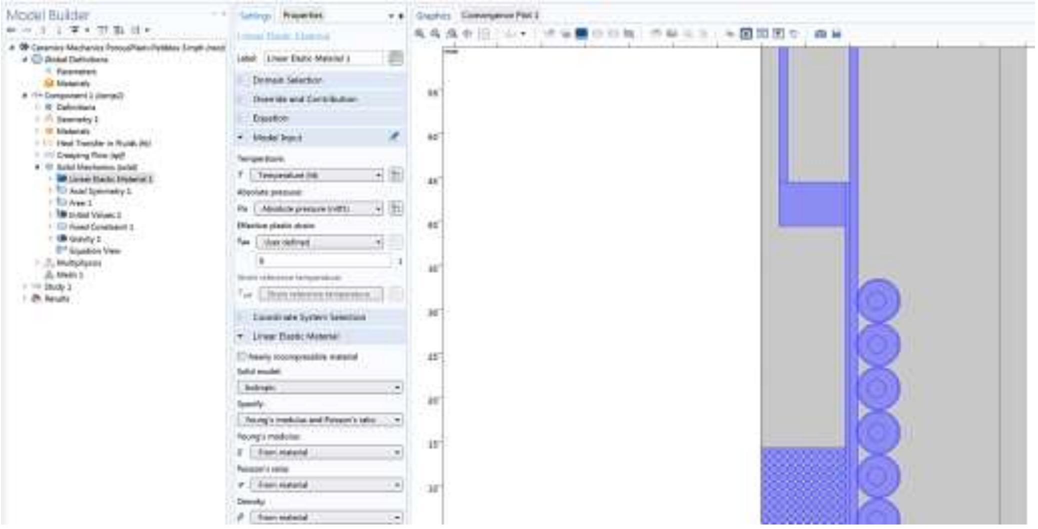
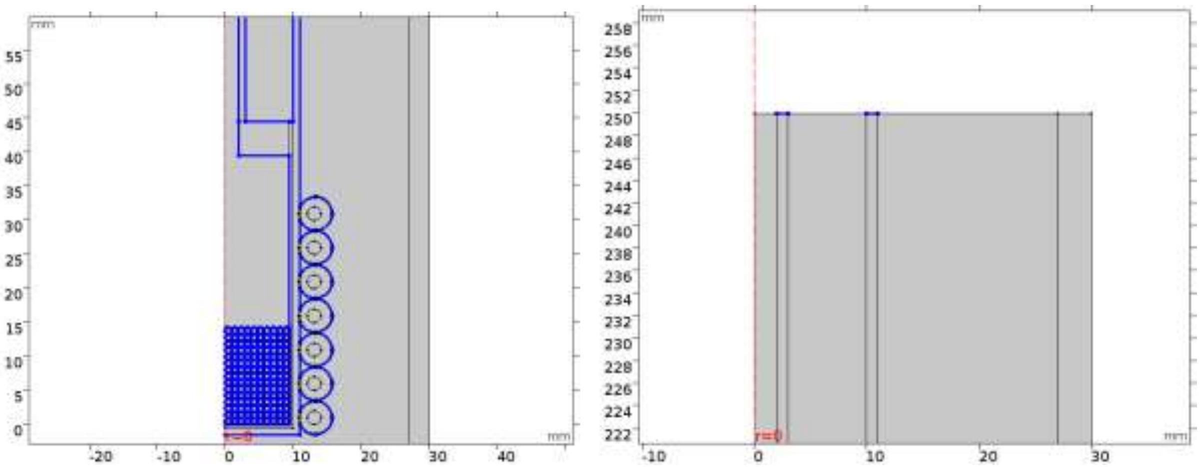


**Figure 5 –** Defining Linear Elastic Materials parameters




a) b)

**Figure 6 –** Definition of moving and fixed boundaries: a) moving boundaries; b) fixed boundaries

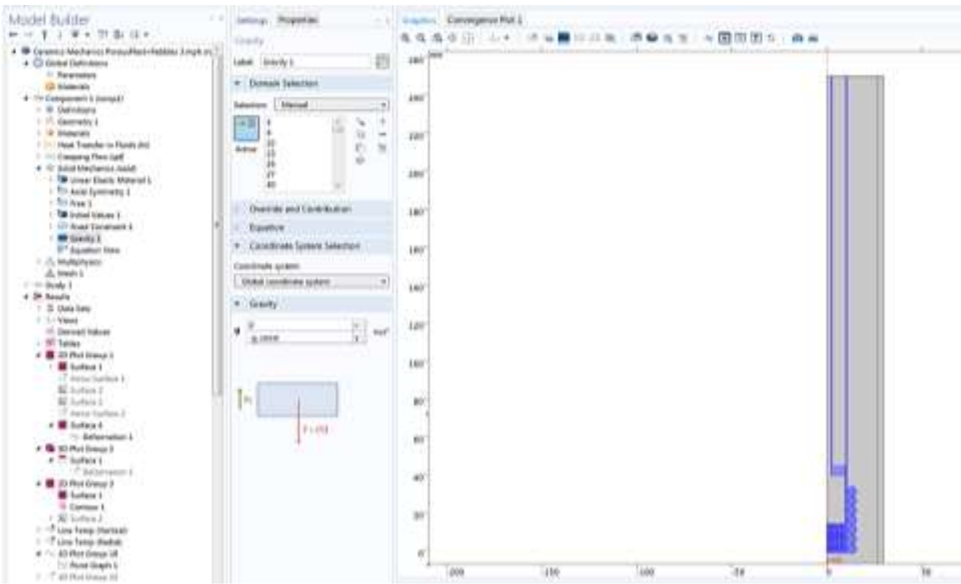


**Figure 7 –** Inclusion of gravity as an external body force

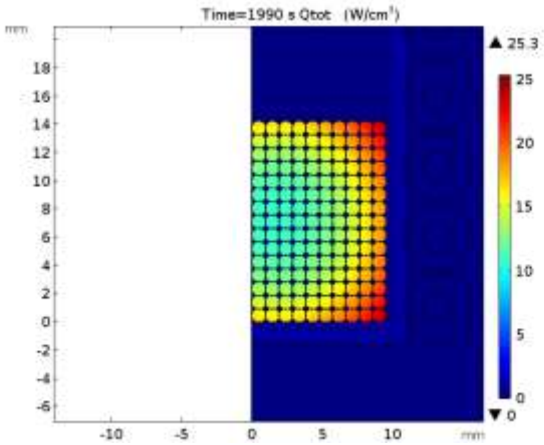



**Figure 8 –** Distribution profile of the power of radiation heating in the pebbles of pebble bed of lithium ceramics at a power of 6 MW

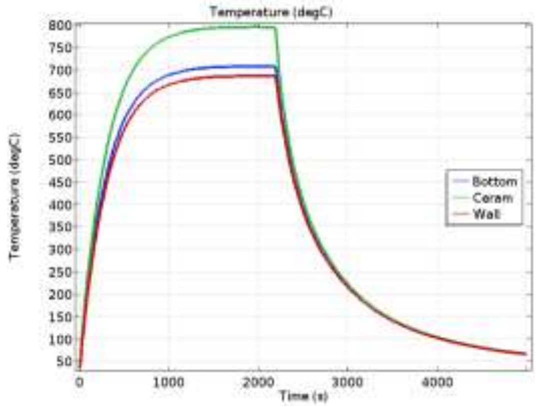



**Figure 9 –** Calculation of radiation heating and cooling of the ceramic pebble bed and capsule walls

### Simulation results

Next, modeling was carried out in the mode of calculating temporal temperature changes in all materials of the irradiation device during operation of the reactor at a power of 6 MW with simultaneous calculation of displacements and stresses in the materials of the capsule. It was assumed as the initial values that at the time t=0 all bodies in the system are heated to 310 K, while the air does not move and is under a pressure of 100 kPa over the entire height of the pipe (excluding the hydrostatic additive). After reaching stationary temperatures, after 2200 s from the start of heating, heat release in ceramics and steel is turned off (reactor irradiation stops) and then the cooling process of the ampoule device is calculated.

Figure 9 shows the results of calculating the dynamics of changes in the average temperature of the ceramic filling, as well as the temperatures of the bottom and side wall of the ampoule in the ceramic filling zone during its gradual heating during reactor operation at a power of 6 MW and subsequent cooling after the termination of irradiation.

Figure 10 shows the temperature field along the radial section of the ampoule at the time of its maximum heating (t=2200 s), and Figures 11 and 12 show the field of thermomechanical displacements of the capsule caused by thermal expansion.

As can be seen from Figures 11-12, when heated, the capsule moves down. The maximum vertical displacement caused by the expansion of the long steel tubes of the ampoule is -1.43 mm (down), the maximum radial displacement due to the joint expansion of the ceramics and the walls of the capsule is 0.22 mm. The full view of the radial component of thermomechanical displacements is shown in Figure 13, from which it is clear that the presence of an external heater reduces the radial expansion by more than 2 times.

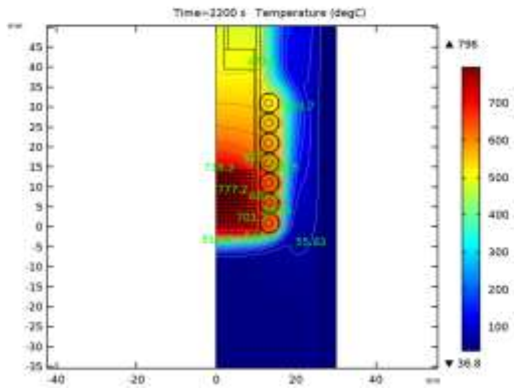



**Figure 10 –** Capsule temperature field at the moment t=2200 s

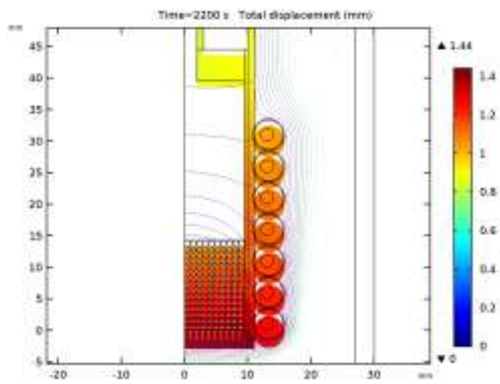



**Figure 11 –** Capsule temperature shift field at the moment of maximum heating (t=2200 s)

Figure 14 shows the result of the calculation of structural stresses according to von Mises, which also shows that the main stresses (about 170 MPa) occur in the three lower turns of the heater and are partially transferred to the ceramic in the capsule, the stresses in individual balls of which vary from 11 to 80 MPa. As can be seen from Figures 13-14, the greatest stresses occur on the balls located at the same height as the upper turn of the heater and in the vertical axis zone in the center of the pebble bed.

Figure 15 shows the calculation of the probability of ceramic pebble failure along the pebble bed for a ceramic tensile strength of 60 MPa [15].

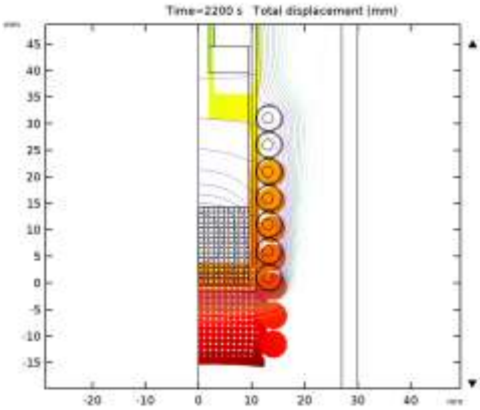



**Figure 12 –** The field of temperature displacements of the capsule at the moment of maximum heating (increased 10 times)

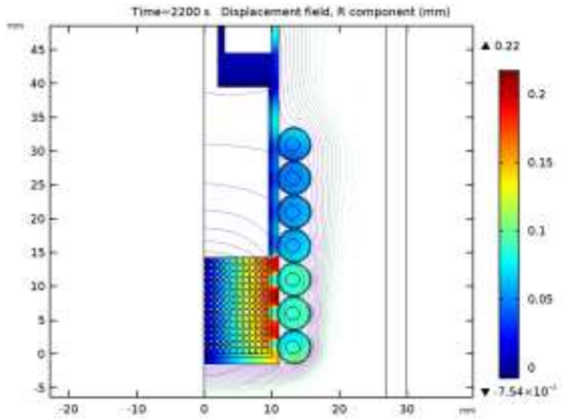



**Figure 13 –** Distribution of the radial component of thermomechanical displacements of capsule materials at maximum heating of ceramics up to T=1073 K (t=2200 s)

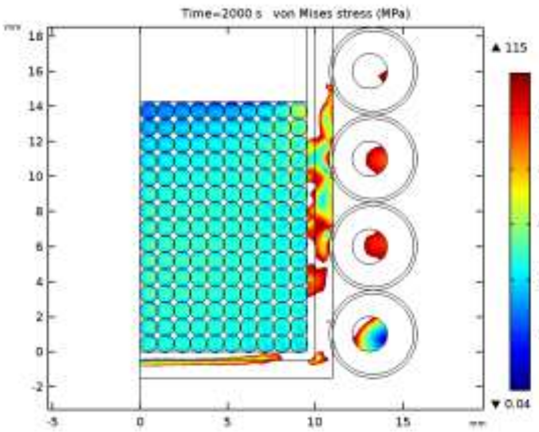



**Figure 14 –** Von Mises stress distribution in capsule materials at maximum ceramic heating up to T=1073 K (t=2000 s)

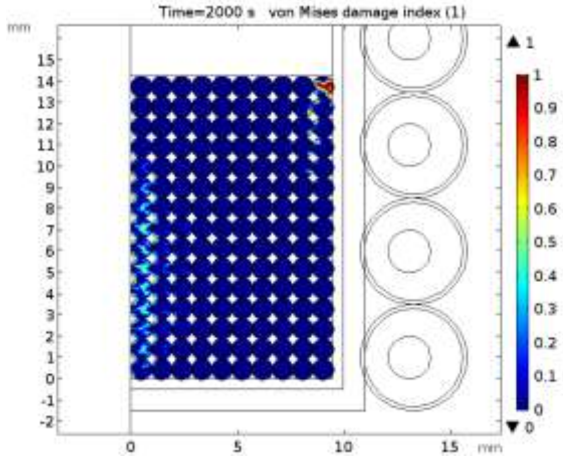



**Figure 15 –** Fracture index according to von Mises in balls of filling ceramics (fracture stress 60 MPa) into capsules at maximum heating (t=2000 s)

**Conclusions**

Calculation results show that ceramic pebbles, densely filled into the capsule of the WWR-K reactor's irradiation device so that they cannot move inside the filling, when heated to 1073 K, will undergo thermomechanical loads from 10 to 80 MPa, which exceeds the ultimate strength of 60 MPa of ceramics $Li_4SiO_4$ [15]. The share of pebbles, the load on which exceeds the tensile strength, will be from 5 % to 10 % of their total number. In this case, the capsule will move down by 1-2 mm, and expand by 200 μm radially under the influence of thermal elongation of the steel vacuum tubes connecting the capsule to the mounting flange. The strength of the tubes will not be affected.

Since in the modeled case the ceramic pebbles are not restricted from moving upwards, then at a certain value of external pressure they will abruptly move ("jump") into the empty area above the pebble bed, reducing the pressure on the remaining pebbles. It is not possible to describe such behavior within the framework of this model. The above calculations are relevant for the case of compacted pebble beds of lithium ceramics under neutron irradiation.

A possible way to avoid the potential destruction of ceramic pebbles is to reduce the thickness of the capsule wall by 2-3 times, which will lead to an increase in the plasticity of the capsule walls, a decrease in the wall pressure on the pebble bed, and a decrease in the heating temperature of the capsule and ceramics.

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## References


1 Someya Y., Tobita K., Utoh H., et al. Design study of blanket structure based on a water-cooled solid breeder for DEMO //Fusion Engineering and Design. – 2015. – Vol.98–99. – P.1872–1875.

2 Federici G., Kemp R., Ward D., Bachmann C., et al. Overview of EU DEMO design and R&D activities //Fusion Engineering and Design. – 2014. – Vol.89. – P.882–889.

3 Boccaccini L., Giancarli L., Janeschitz G., et al. Materials and design of the European DEMO blankets //Journal of Nuclear Materials. – 2004. – Vol.329–333. – P.148–155.

4 Cismondi F., Kecskés S., Ilic M., et al. Design update, thermal and fluid dynamic analyses of the EU-HCPB TBM in vertical arrangement //Fusion Engineering and Design. – 2009. – Vol.84. – P.607–612.

5 Hernández F., Cismondi F., Kiss B. "Thermo-mechanical analyses and assessment with respect to the design codes and standards of the HCPB-TBM breeder unit //Fusion Engineering and Design. – 2012. – Vol.87. – P.1111–1117.

6 Bhattacharyay R. Status of indian LLCB TBM program and R&D activities //Fusion Engineering and Design. – 2014. – Vol.89. – P.1107–1112.

7 Cao Q., Zhao F., et al. Neutronic calculation analysis for CN HCCB TBM-Set //Plasma Science and Technology. – 2015. – Vol.17. – P.607–611.

8 Enoeda M., Tanigawa H., Hirose T., et al. R&D status on water cooled ceramic breeder blanket technology //Fusion Engineering and Design. – 2014. – Vol.89. – P.1131–1136.

9 Lee D.W., Jin H.G., Lee E.H., et al. Integrated design and performance analysis of the KO HCCR TBM for ITER //Fusion Engineering and Design. – 2015. – Vol.98–99. – P.1821–1824.

10 Shaimerdenov A.A., Shaimerdenov A.A., Gizatulin Sh.Kh., Nakipov D.A., Kenzhin E.A., Chikhray E.V., Zaurbekova Zh.A., Tolenova A.U., Nesterov E.A., Kizane G. Experimental base of the WWR-K reactor for studying the release of tritium from materials during their irradiation //Bulletin of NNC RK. – 2020. No.1 – P.104-111. (in Russ.).

11 COMSOL Multiphysics Simulation Software / Software developers website [Electronic resource]. Access mode: https://www.comsol.com/comsol-multiphysics (Accessed 05/11/2023).

12 Akhanov A.M., Aitkulov M.T., Sairanbayev D.S., Gizatulin Sh.Kh., Romanova N.K., Shaimerdenov A.A., Chikhray Y.V., Ualzhanov Zh., Zholdybayev T.K. Irradiation capsule design for neutron coloration of topaz in a WWR-K reactor //Applied Radiation and Isotopes. – 2022. – Vol.190. – Art.No 110472.

13 Pupeschi S., Moscardini M., Gan Y., Knitter R., Kamlah M. Cyclic behavior of ceramic pebble beds under mechanical loading //Fusion Engineering and Design. – 2018. – Vol.134. – P.11–21.

14 Pupeschi S., Knitter R., Kamlah M. "Effective thermal conductivity of advanced ceramic breeder pebble beds //Fusion Engineering and Design. – 2017. – Vol.116. – P.73–80.

15 Chu Cha-Yang, Bär Kai, Singh Jitendra P., Goretta Kenneth C., Billone Michael C., Poeppel Roger B., Routbort Jules L. Mechanical Properties of Polycrystalline Lithium Orthosilicate //Journal of American Ceramic Society. – 1989. – Vol.72, Iss.9. – P.1643-1648.


## References


1 Y. Someya, K. Tobita, et al., Fusion Engineering and Design 98–99, 1872–1875 (2015).

2 G. Federici, R. Kemp, et al. Fusion Engineering and Design, 89, 882–889 (2014).

3 L. Boccaccini, L. Giancarli, et al. Journal of Nuclear Materials, 329–333, 148–155 (2004).

4 F. Cismondi, S. Kecskés, et al., Fusion Engineering and Design, 84, 607–612 (2009).

5 F. Hernández, F. Cismondi, B. Kiss, Fusion Engineering and Design, 87, 1111–1117 (2012).

6 R. Bhattacharyay Fusion Engineering and Design, 89, 1107–1112 (2014).

7 Q. Cao, F. Zhao, et al., Plasma Science and Technology, 17, 607–611 (2015).

8 M. Enoeda, H. Tanigawa, et al. Fusion Engineering and Design, 89, 1131–1136 (2014).

9 D.W. Lee, H.G. Jin, et al., Fusion Engineering and Design, 98–99, 1821–1824 (2015).

10 A.A. Shaimerdenov, et al., Bulletin of NNC RK, 1, 104-111 (2020). (in Russ.).

11 COMSOL Multiphysics Simulation Software / Software developers website [Electronic resource]. Access mode: https://www.comsol.com/comsol-multiphysics (Accessed 05/11/2023).

12 A.M. Akhanov, M.T. Aitkulov, et al., Applied Radiation and Isotopes, 190, 110472 (2022).

13 S. Pupeschi, M. Moscardini, et al., Fusion Engineering and Design, 134, 11–21 (2018).

14 S. Pupeschi, R. Knitter, M. Kamlah Fusion Engineering and Design, 116, 73–80 (2017).

15 Chu Cha-Yang, Bär Kai, et al., Journal of American Ceramic Society, 72 (9),1643-1648 (1989).