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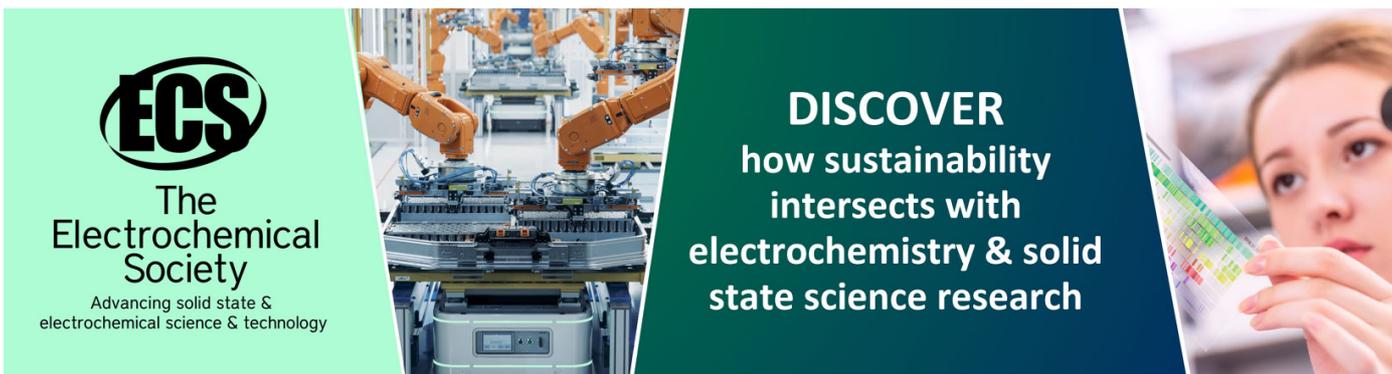
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Modeling of objects for reception and storage of spent nuclear fuel

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Abstract. Facilities for the storage of nuclear fuel are distinguished from other objects by high standards of safety in any operating conditions. A feature of these structures is the large thickness of the walls and floors. This feature should be taken into account in the calculations of seismic effects and thermal stresses caused by uneven temperature fields in concrete. In the work, calculations of joint effects on the building of thermal stresses and earthquakes are made. The calculations allowed us to distinguish the features of the deformation of concrete structures.

1. Introduction

A significant amount of nuclear fuel waste explains the interest in the storage and transport of spent fuel elements. One of the problems that must be solved for the organization of water transportation of nuclear fuel is the creation of facilities capable of storing these goods at a safe level.

The building and equipment of nuclear waste storage facilities are calculated on a combination of loads, such as operational, design basis accidents and seismic effects of the maximum estimated earthquake. The last impact is determined by the construction region and is taken into account in the design model of the port facility by the influence of a three-component accelerogram. The features of the operating mode of storage of spent nuclear fuel should include significant heat generation, which is compensated by cooling systems. The most effective system is that of "wet" storage when fuel assemblies are placed in pools with water. However, as the accident at the Fukushima nuclear power plant showed, the failure of any of the heat removal systems can lead to overheating of the equipment and leakage of radiation. The air cooling system is considered to be more secure, since the cooling is carried out due to the free convection of air with its discharge into the environment. Among the problems one should note the low density and heat capacity of the air, which inevitably causes zones of local overheating of fuel elements and storage structures [1-9]. It is obvious that the influence of temperature fields on the strength of the structure in the system of normative combinations of loads must be taken into account [10]. The schematic diagram of the "dry" storage of spent fuel elements is shown in Fig. 1.



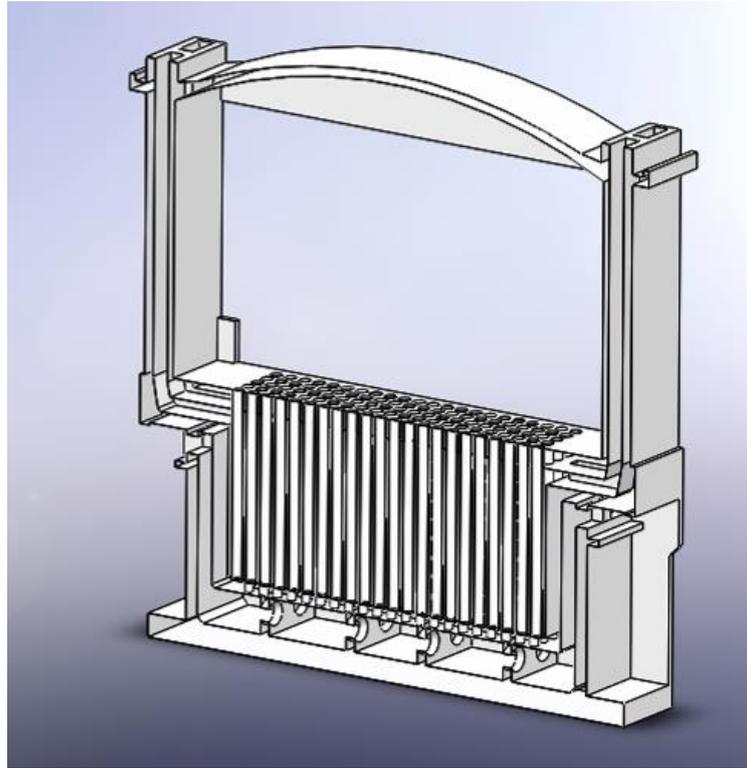


Figure 1. Schematic diagram of the "dry" port storage of spent fuel elements

2. Materials and Methods

The complex geometric shape of the structure, the combination of structural elements of materials differing in their properties, the nonstationary effects when it is impossible to conduct a full-scale experiment at such facilities determine numerical modeling as the only possible method of research. The tasks of modeling freely convective heat transfer in combination with the thermal conductivity in the solid bodies of an object to determine static loads from gravity and thermal stresses, which are the basis for subsequent seismic analysis, are solved separately.

In general, single-phase homogeneous fluid cooling air in a dry storage is characterized by:

1. The temperature field $T(x_i, \tau)$ - a scalar field.
2. Field of speed $\vec{W}(x_i, \tau) = W_x \vec{i} + W_y \vec{j} + W_z \vec{k}$ - vector field.
3. Pressure field $P(x_i, \tau)$ - a scalar field,

where: W is the speed of free convection movement, m/s; P - pressure, Pa; x_i - orthogonal coordinate system, m; τ - time, s.

To calculate the temperature, pressure and, in general, the three components of the velocity vector, it is necessary to solve five differential equations:

- differential equation of energy transfer in fluid - Fourier-Kirchhoff equation;
- three differential equations of momentum transfer in a fluid - Navier – Stokes equations;
- differential equation of continuity or continuity [11-14].

In vector form, the equation of energy transfer in a fluid has the form [15-16]:

$$\rho * c * \left(\frac{\partial T}{\partial \tau} + \vec{W} * \nabla T \right) = \text{div} \left[\lambda * \text{grad}(T) + \mu * \Phi - P * \text{div} \vec{W} \right], \quad (1)$$

where: $\rho * c * \partial T / \partial \tau$ is the term on the right side of the energy equation, which reflects the nonstationarity of the heat exchange process;

$\rho * c * \vec{W} * \nabla T$ - the convective term of the energy equation - takes into account the heat transfer due to the movement of the medium;

$div[\lambda * grad(T)]$ - diffusion term of the equation - takes into account the heat transfer by thermal conductivity;

$\mu * \Phi$ - the term of the energy equation, which takes into account the heating of the medium due to the dissipation of the kinetic energy of motion due to friction;

μ - dynamic viscosity coefficient;

Φ - dissipative function;

$-P * div\vec{W}$ - the term of the equation, taking into account the change in the energy of the fluid during its compression or expansion.

The last two terms in the energy transfer equation largely depend on the speed of movement and for speeds less than 100 m / s, characteristic of energy and heat technology units, they are not taken into account in the heat transfer calculations. Taking the assumption that the physical properties of the medium are independent of temperature and the absence of internal sources of heat, the Fourier-Kirchhoff equation takes the form [17-21]:

$$\rho * c \left(\frac{\partial T}{\partial \tau} + \vec{W} * \nabla T \right) = div[\lambda * grad(T)]. \quad (2)$$

To solve the Fourier-Kirchhoff equation, you must first calculate the velocity field by solving the Navier – Stokes equations.

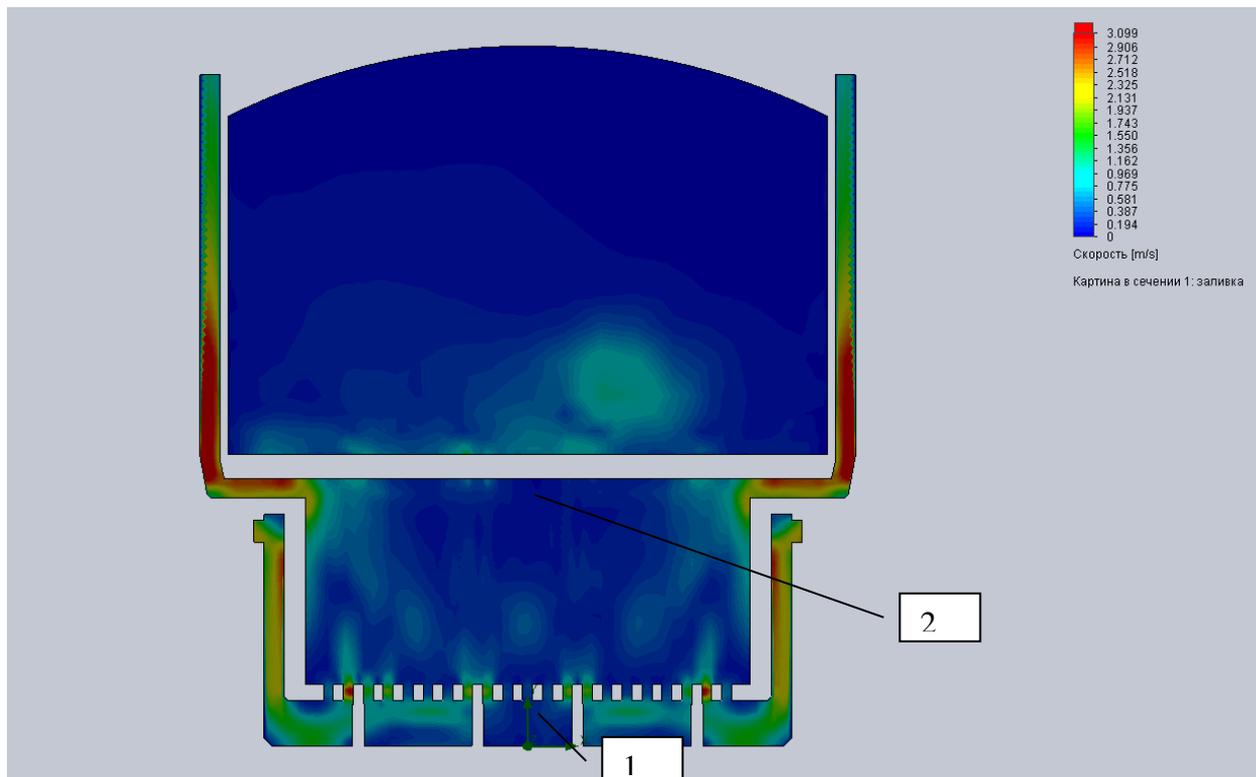


Figure 2. Estimated speed (m / s) of the air flow in the air ducts for cooling the storage area of canisters with SNF in the slots of the storage facility; 1 - zone of "stagnation" of the air flow in the air ducts; 2 - zone of "stagnation" of the air flow in the storage

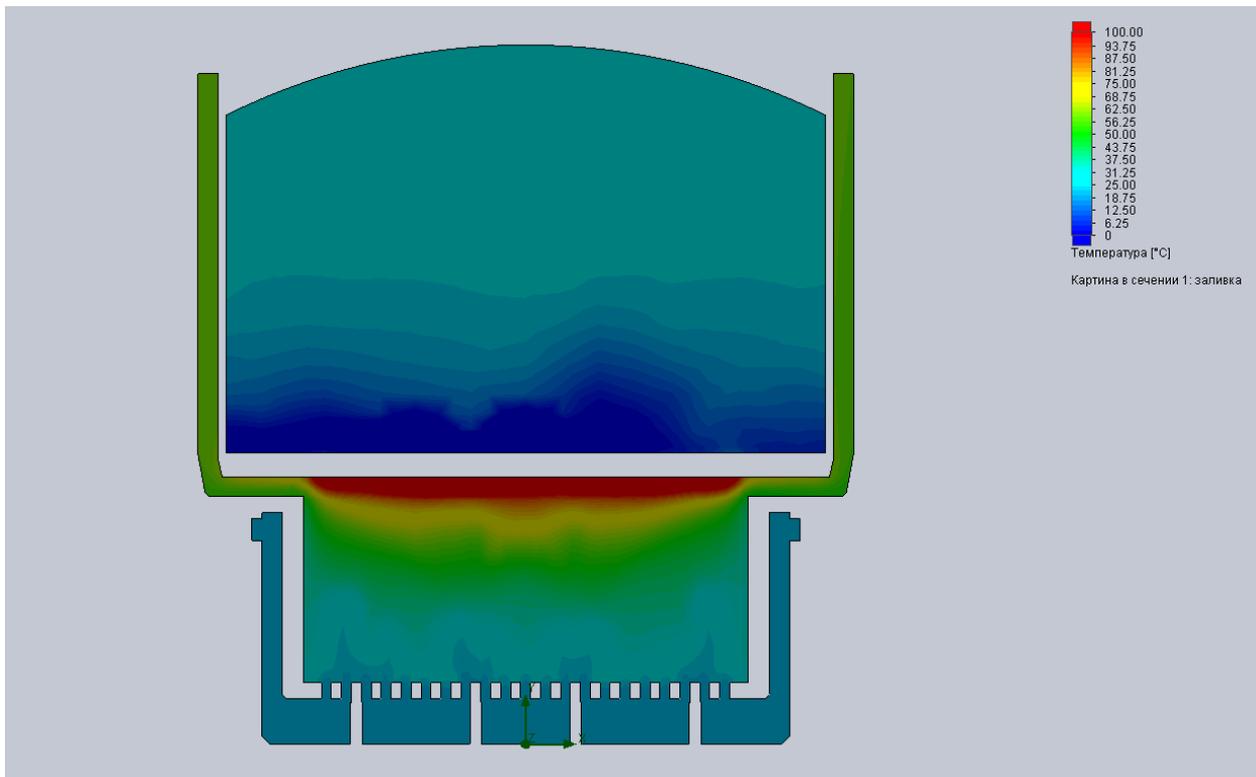


Figure 3. Calculated temperature field ($^{\circ}\text{C}$) and temperature load on the storage building structures at the initial heat flux density from canisters of 400 W/m^2

The calculated values of temperatures are shown in Figure 4. The calculated values of stresses, displacements and deformations of the plate due to thermal effects are shown in Fig. 5 - 8.

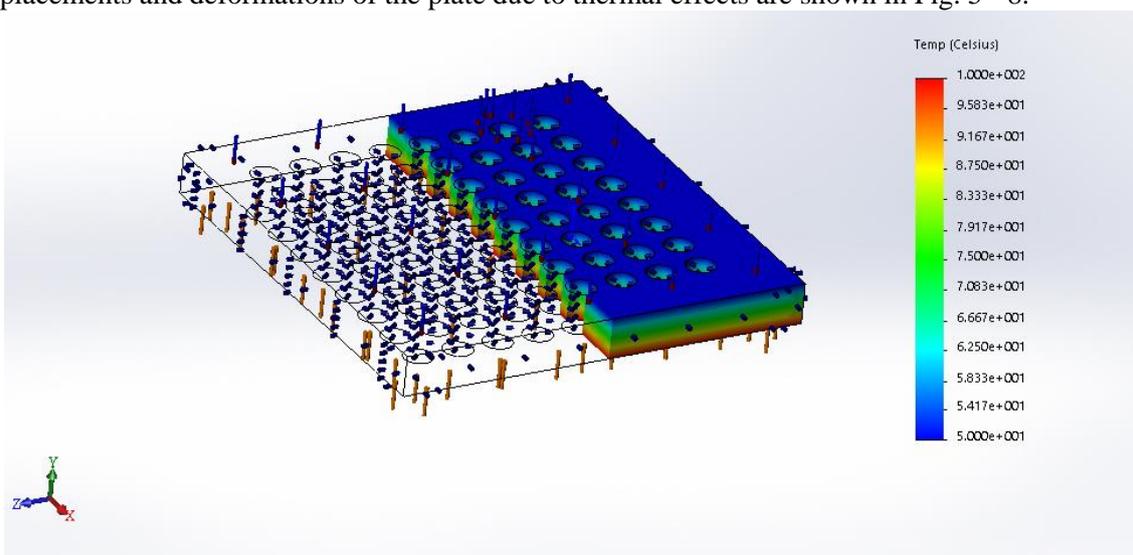


Figure 4. Calculated temperature field of the storage plate (in section), $^{\circ}\text{C}$

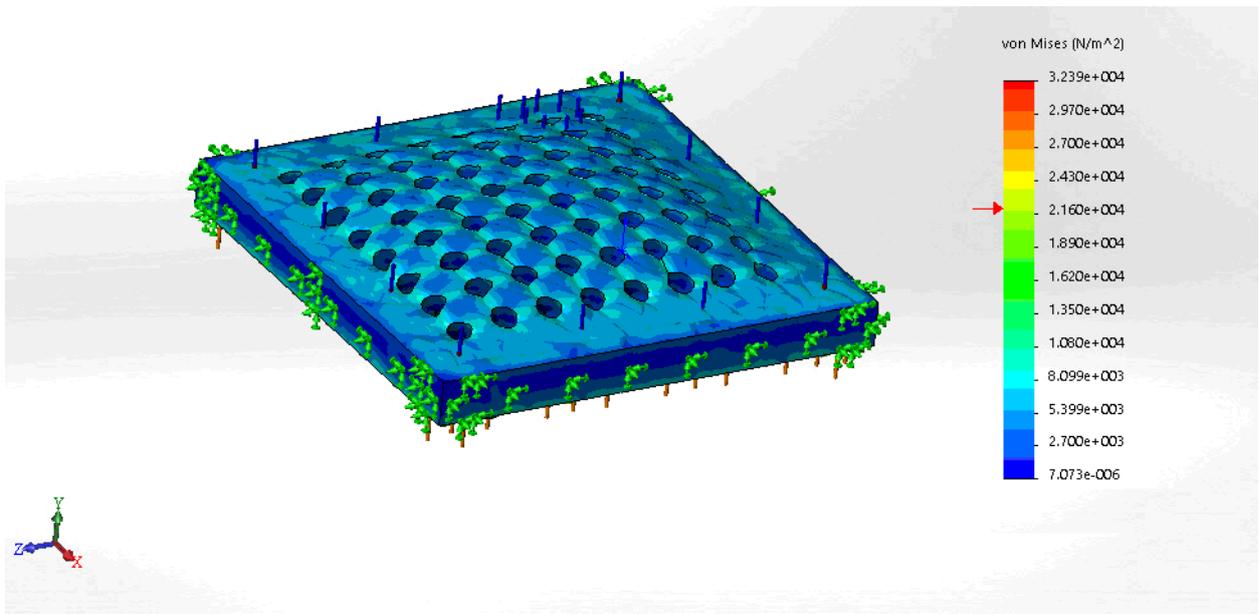


Figure 5. Estimated voltage in the storage plate due to thermal effects on the plate, Pa

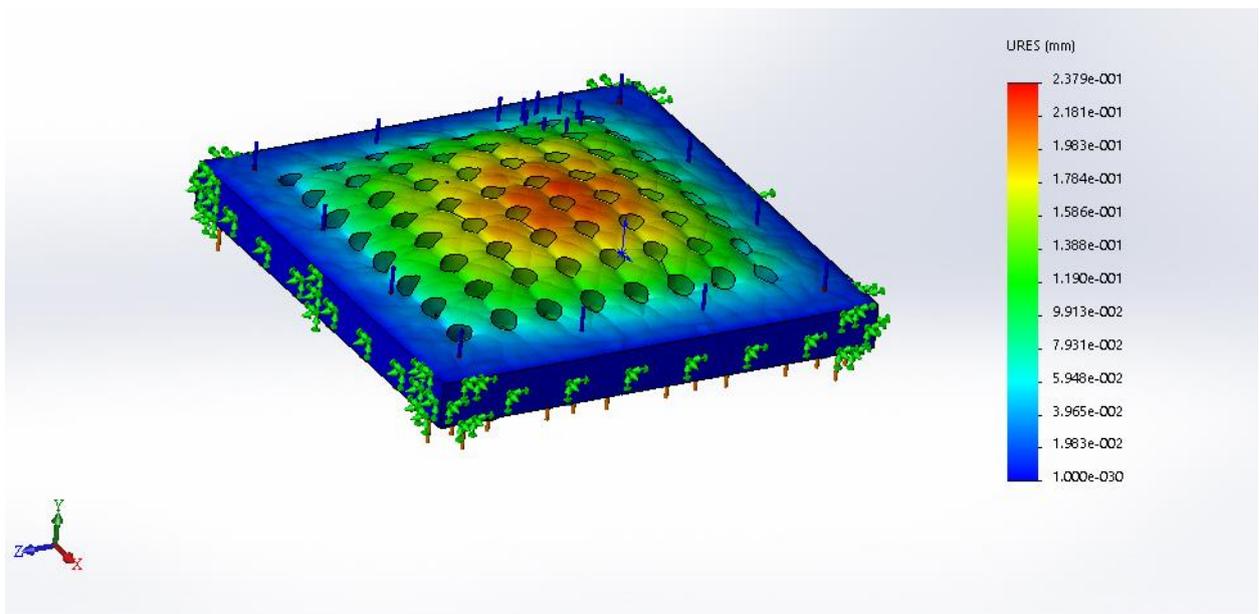


Figure 6. Estimated deformations of the storage plate due to thermal effects on the plate, mm

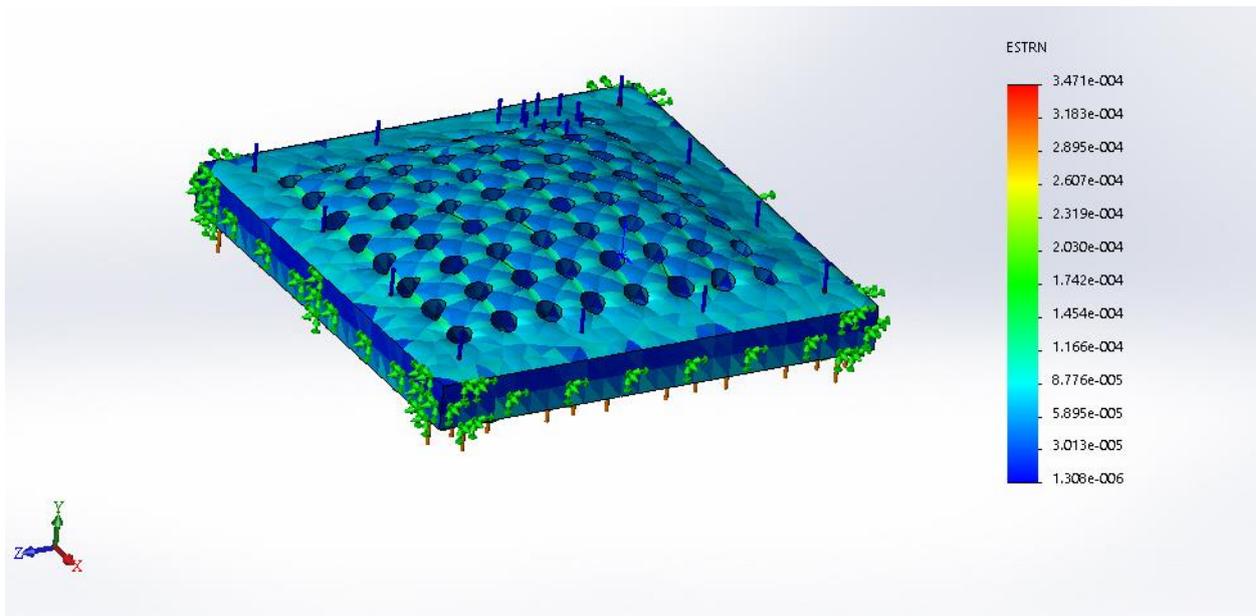


Figure 7. Estimated relative deformations of the storage plate due to thermal effects on the plate

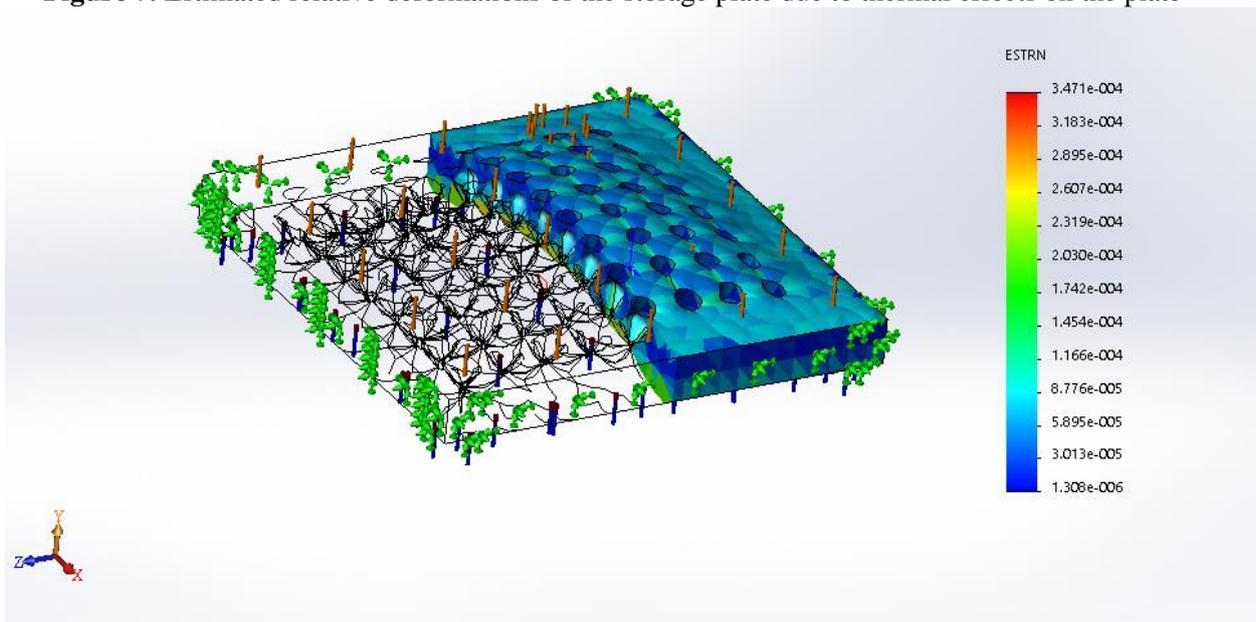


Figure 8. Estimated relative deformations of the storage plate due to thermal effects on the plate (in section)

The Navier – Stokes equation is based on the law of conservation of momentum: for a fixed fluid mass, according to which the change in momentum is equal to the sum of external forces acting on a volume of mass M.

The Navier – Stokes equation for fluids with constant density in vector form has the form [10, 11]:

$$\frac{\partial \vec{W}}{\partial \tau} + \vec{W} * \nabla \vec{W} = \vec{g} - \frac{1}{\rho} \nabla P + \nu * \nabla^2 \vec{W} . \tag{3}$$

In this case, the continuity equation takes the form:

$$div \vec{W} = 0 .$$

Uniqueness conditions necessary for solving the system of differential equations of convective heat transfer are defined in [22-27].

To single out a single solution, the uniqueness conditions were set:

- geometry of the computational domain and its dimensions, for which the three-dimensional computational dynamic model of the dry storage was used;

- boundary conditions for calculating the velocity field: the zero speed of air movement on solid surfaces (adhesion condition) and the atmospheric pressure at the inlet and outlet of the ventilation system;

- boundary conditions for calculating heat transfer: boundary conditions of the second kind on the surface of canisters and boundary conditions of the third kind on the remaining surfaces of air contact with solid surfaces;

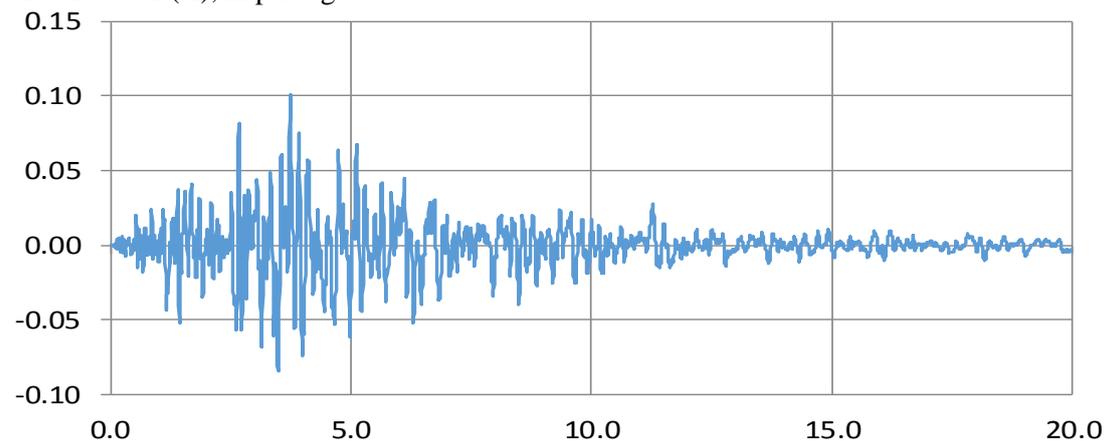
- ambient temperature is assumed to be 20°C.

3. Results

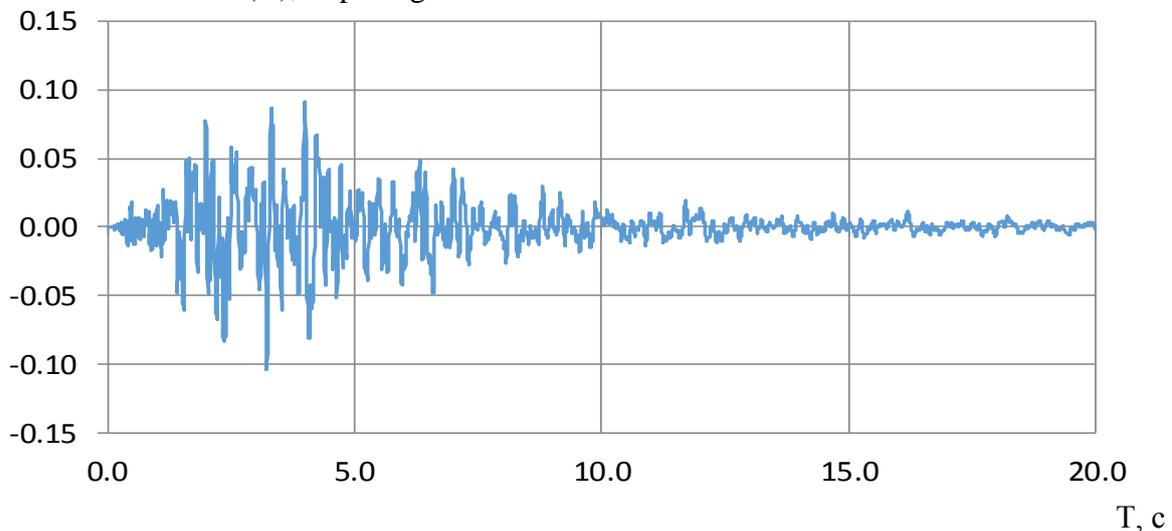
The calculation was performed by a numerical method using an implicit difference scheme. The results of calculating the velocity field are shown in Fig. 2, the temperature fields - in Fig. 3

To compare different types of operational loads, a port terminal block was calculated for the effects of static (weight) loads in combination with the seismic effect of a three-component accelerogram (Fig.9) with a magnitude of 7 points.

Acceleration (X), in parts g



Acceleration (Y), in parts g



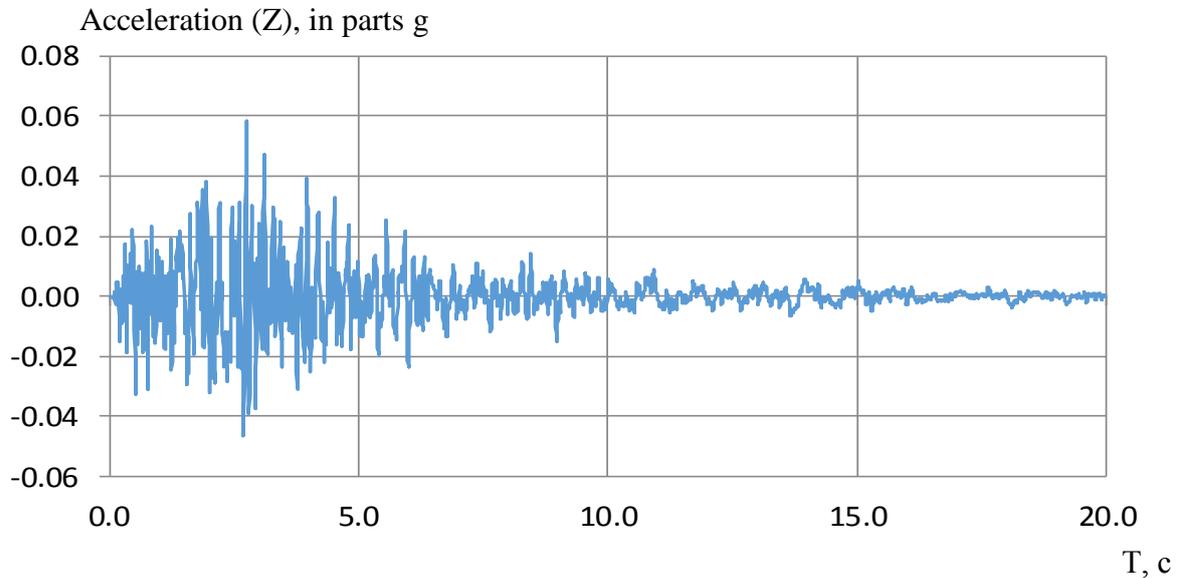


Figure 9. Synthesized accelerogram of 7 points

The results of calculating the maximum deformations of bearing structures are presented in Fig. 10.

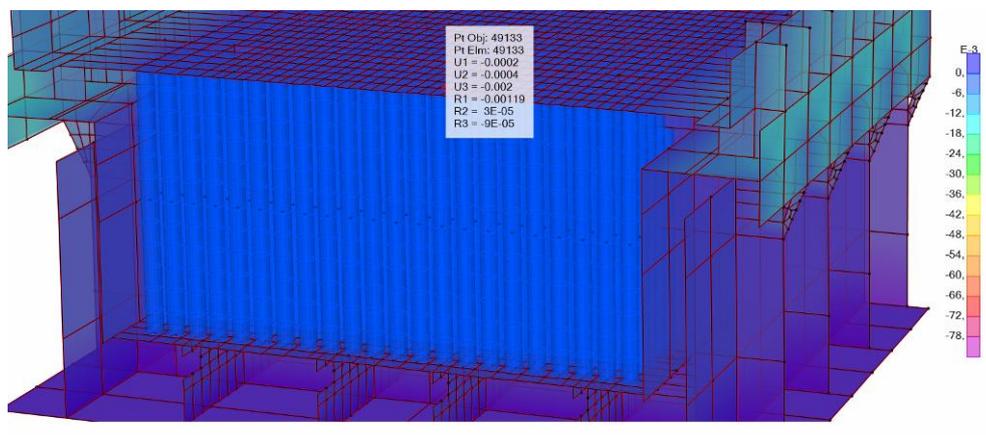


Figure 10. Deformation of building structures as a result of seismic effects, m

4. Discussion

Analysis of temperature fields, stresses and deformations of the slab shows that overheating of the lower part of the slab with a thickness of 1100 mm leads to significant thermal stresses, comparable in magnitude to the limit values for concrete B40. As can be seen from fig. 6, thermal stresses lead to noticeable deformations of the storage plate, in magnitude up to 2 mm or more for every 10 m length of the plate. Taking into account the dependence of the heat flux on the state of fuel elements and the nonstationarity of the thermal conditions of the port storage when the climatic conditions change, it can be concluded that the real figures are likely to exceed the calculated deformations. In addition, deformations of the lower part of the plate can lead to pinching of the plugs.

Among the features of the deformation of reinforced concrete slabs should be noted its deformation upwards, towards the low temperature region. This is due to the characteristics of the strength of concrete, perceiving significant compressive stress and significantly less tensile.

Shown in Fig. 10, the results of the calculation of the impact of static loads in combination with seismic effects show a significantly smaller amount of deformations, differing by an order of magnitude compared with thermal stresses.

5. Conclusion

The calculated analysis of deformations of the storage plate of spent fuel elements determines the feasibility of the further study of the temperature fields and the resulting loads in the load-bearing elements of the building, taking into account the nonstationarity of the heat generation of fuel cells in combination with the uneven storage load and their effect on the integrity and load-bearing capacity of the building elements as a single and interconnected system. The identified problem of the occurrence of thermal stresses implies the need to develop new design solutions for the terminal, reducing operating loads and increasing the reliability and safety of port facilities.

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