Damage and fracture under dynamic loading on the example of a model space nuclear powerplant

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Keywords: equation of state, shock waves; high-velocity impact.

Abstract. Problems of destruction of a space nuclear propulsion system reactor are solved in the paper for the two cases: 1) at its crash landing on the Earth surface (the impact velocity being up to 400 m/s); 2) at its impact (with velocity up to 16 km/s) with the space debris fragments.

Equation of state. We consider a three-term equation of state with the solid-phase free energy being determined as

$$F(V,T) = E_x(V) + c_{v,l} T \ln\left(\frac{\theta(V)}{T}\right) - \frac{1}{2} c_{v,e0} T^2 \left(\frac{V}{V_0}\right)^{2/3} \tag{1}$$

where V is the specific volume, $E_x(V)$ is the "cold" energy, T is the temperature, $c_{v,l} = 3R/A$ is the specific heat of the lattice at constant volume, A is the mean atomic weight, R is the gas constant, $\theta(V)$ is the Debye temperature, and $c_{v,e0}$ is the experimental value of the electron heat capacity under standard conditions. The elastic (cold) component of energy $E_x(V)$ is related exclusively to interaction forces between the body atoms and is equal (including the energy of zero vibrations) to the specific internal energy at the absolute zero temperature.
The thermodynamic model of a few-parameter equation of state is based on the dependence of the Gruneisen coefficient γ on the volume [1]

$$\gamma(V) = \frac{2}{3} - \frac{2}{(1 - aV_0/V)} \qquad a = 1 + \frac{2}{(\gamma_s - 2/3)} + \frac{2P_{t,0}}{K_s} \tag{2}$$

where $\gamma_s = \beta K_s V_0 / c_v$, K_s is the adiabatic modulus of volume compression, c_v is the specific heat at constant volume, and $P_{t,0}$ is the thermal pressure in the initial state.
The general expression for the volume dependence of the Gruneisen coefficient has the form

$$\gamma(V) = -\left(\frac{2-t}{3}\right) - \frac{V}{2}\left[\frac{d^2}{dV^2}\left(P_x V^{\frac{2t}{3}}\right) \Big/ \frac{d}{dV}\left(P_x V^{\frac{2t}{3}}\right)\right] \tag{3}$$

In Eq. (3), the situation value corresponds to the Landau-Slater theory [2, 3] at *t=0*, to the Dugdale-McDonald theory [4] at *t=1*, and to the free-volume theory [5] at *t=2*.

To determine the zero isotherm, we equated the expression for the Gruneisen coefficient (2) at the zero temperature ($T = 0\text{K}$) to the expression for the generalized Gruneisen coefficient (3):

$$\frac{2}{3} - \frac{2}{1 - a_x V_0 / V} = -\left(\frac{2-t}{3}\right) - \frac{V}{2}\left[\frac{d^2}{dV^2}\left(P_x V^{\frac{2t}{3}}\right) \Big/ \frac{d}{dV}\left(P_x V^{\frac{2t}{3}}\right)\right] \qquad (4)$$

Here, a_x is the value of the parameter $a|_{T=0}$ at the zero temperature in Eq. (2), which can be taken as $a_x = a(0) = 1 + 2/(\gamma_S - 2/3)$ as the first approximation.
The differential equation (4) has an analytical solution for "cold" pressure and energy:

$$P_x(V) = C_1 V^{-2t/3} + C_2 H_2(V), \quad E_x(V) = -\left(C_1 V^{1-2t/3} / (1 - 2t/3) + C_2 H_1(V)\right) + C_3 \qquad (5)$$

Using the definition of the Gruneisen coefficient in the Debye approximation $\gamma = -(d \ln\theta / d \ln V)_T$ and Eq. (2), we obtain the characteristic Debye temperature on the volume:

$$\theta(V) = \theta_0 \left[\frac{(a - V/V_0)}{(a-1)}\right]^2 \left(\frac{V_0}{V}\right)^{\frac{2}{3}}$$

where $\theta_0 = \theta(V_0)$ is the Debye temperature at the initial conditions.

The constants for Eq. (5) were determined and calculated in [6]. It was also demonstrated there that the set of semi-empirical relations (1)-(5) describes the behavior of thermodynamic properties of solids within 5-10% in a wide range of pressures and temperatures. For the equation of state to be applied, it is sufficient to know only six constants V_0, β, K_t, c_v, Θ_0, and $c_{v,e0}$ corresponding to the values of these quantities under standard conditions, which can be found in reference books on physical and mechanical properties of substances.

Two-dimensional problem of the impact of a model nuclear powerplant "Topaz"onto the Earth's surface. In emergency situations, modern space vehicles with thermionic reactors "shoot off" (jettison) the nuclear powerplants (a simplified sketch of such a powerplant is shown in Fig. 1). There is a certain probability, however, that the reactor fragment containing the nuclear fuel reaches the Earth's surface despite considerable thermal and mechanical loads in dense atmospheric layers. The velocity of the impact of the remaining part of the reactor system can reach 400 m/s. As the Earth's surface is fairly versatile, the reactor can hit a water surface, rocks, or soft soil.
It is next to impossible to solve impact problems of real engineering objects though the computational engineering development level is rather high and fairly realistic mathematical models of material behavior are available. The reasons are the complicated spatial locations of the reactor fragments and the multiscale character of the problem. In such situations, the object considered is simplified, which makes it possible to construct a number of models aimed at studying the influence of the impact parameters on particular basic fragment of the object.

The simplification used implies that the materials of small-scale parts were averaged inside the reactor zone in the additive approximation. The mass of the non-principal materials was assumed to be too small (beryllium, uranium dioxide, and zirconium hydride compose 95—97 % of the reactor mass) to exert any significant effect on the shock-wave amplitude. As such a medium (mixture) does not have the volume defects, its specific volume on the wave front can be calculated as

$$V_{\text{mix}}(P) = \sum_{i=1}^{n} \alpha_i V_i(P),\ \alpha_i = \frac{m_i}{\sum_{i=1}^{n} m_i}, \quad \sum_{i=1}^{n} \alpha_i = 1,$$

where V_i is the specific volume of the i-th species under shock compression of each species separately, n is the number of species in the mixture, and α_i is the mass concentration, m_i is the mass of the i-th species.

Thus, our study is based on the assumption that the additivity rule is satisfied rather accurately. In the additive approximation, the volume of the shock-compressed mixture is assumed to be equal to the sum of the volume of the species obtained at the same pressure with their separate shock compression in the form of homogeneous monolithic samples.

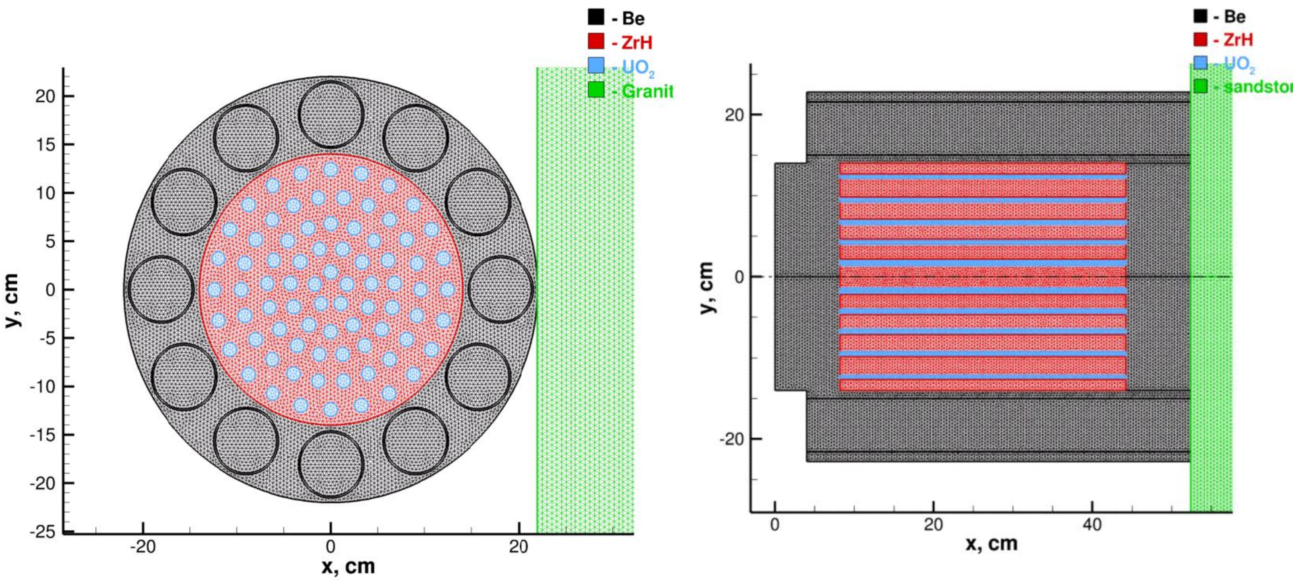

Fig.1 Reactor "Topaz" with plane geometry Reactor "Topaz" with axial geometry

The simplification used implied that the materials of small-scale parts were averaged in terms of the additive approximation inside the reaction zone. It was further assumed that the external elements of the structure burn down when the reactor enters the dense atmospheric layers, and the reactor remainder is an object with a complicated internal structure illustrated in Figs. 1. The reactor consists of a beryllium shell, uranium dioxide fuel cells, and zirconium hydride fillers. The end-face (longitudinal) and side impacts were considered. In the first case, we have a problem of an impact of the cylinder side surface onto a deformed target (granite and sandstone). A specific feature of this formulation of the problem is a multiply connected computational domain with a large number of contact surfaces. In the second case, the reactor model is formed as a ring-shaped structure, while the computational domain is again multiply connected and numerous contact surfaces are formed. As the first example, we consider an impact of the reactor on sandstone with the initial velocity of 400 m/s in the axial formulation. In the case of the reactor impact onto sandstone, the wave pattern is complicated by the fact that sandstone is destroyed by compressive stresses. This specific feature is induced by the inner structure of sandstone where strong crystals of sand are bound with brittle cement mass. As sand and cement have different compressibility, the shock wave forms shear stresses on interfaces between the media, which destroy the connections on the boundary, i.e., the resultant product is sand with a fine fraction of cement. Free sand exerts practically no resistance to shear strains. Thus, the impact compression forms a domain of a fractured material near the reactor-sandstone contact surface and, as a consequence, an unloading wave. The interaction of the side unloading waves and the unloading wave from the fracture zone leads to formation of a zone of tensile stresses with a higher amplitude, leading to fracture of the reactor materials (zirconium hydride filler and fuel cells). Beryllium shell fracture follows the mechanism of shear-induced quasi-static fracture.

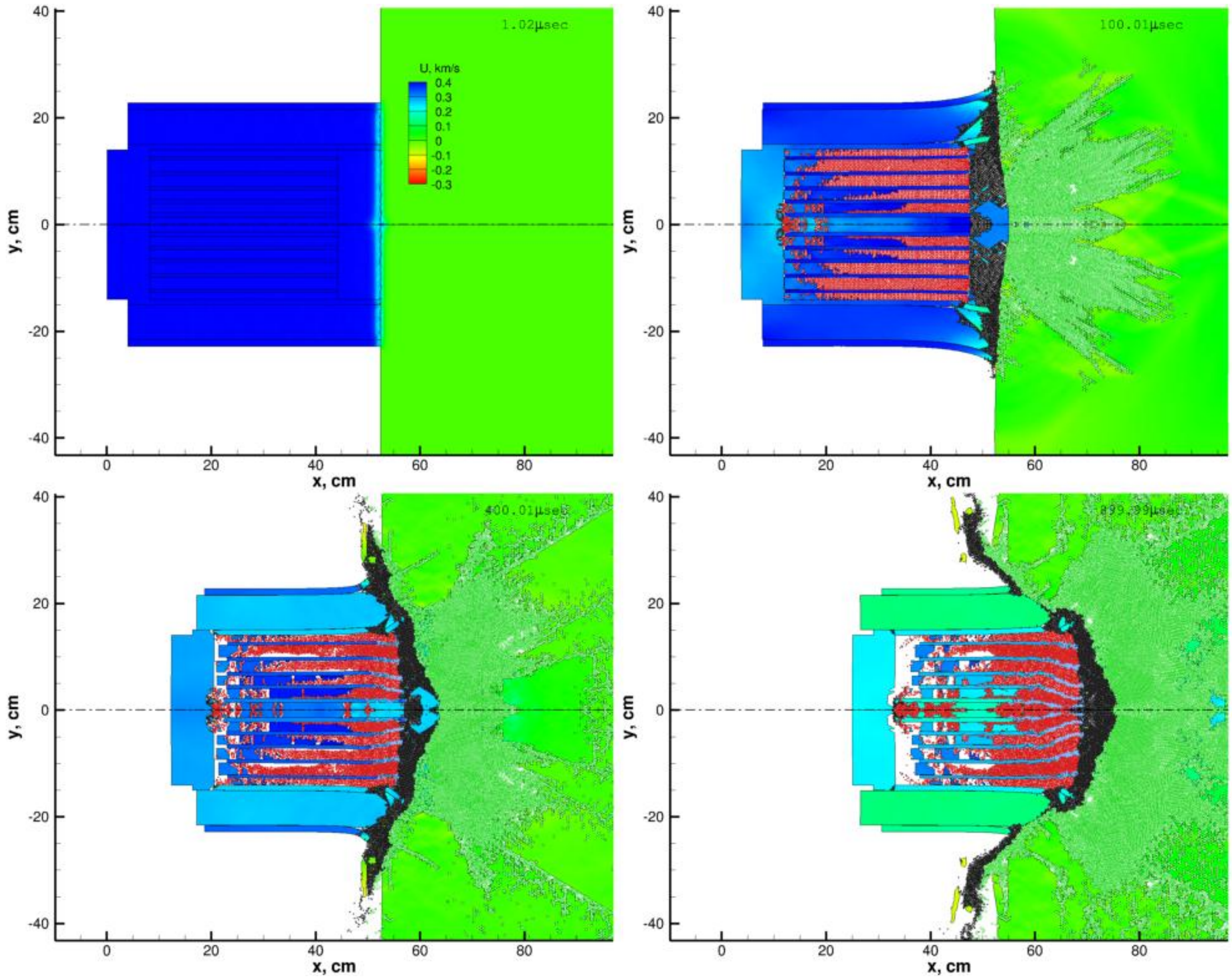

Fig. 2. Impact of a reactor model with a sandstone plate surface

Fig. 2 shows the frames of the impact of the reactor model onto sandstone. Let us further consider the computation of the side impact of the nuclear powerplant. Fig. 3 shows the frames of the computed side impact of the reactor on a granite plate with an impact velocity of 400 m/s. This computation shows that the side impact of the reactor is more critical in terms of the impact velocity than the end-face impact because of higher strains in the contact area. While moving, the reactor filler (which is heavier) weighs on the beryllium shell, thus, inducing shear fracture in the contact area with the granite plate and inner fracture of the casing material, which violates the reactor leak-proofness. Numerous cracks appear in the ZrH filler, which results in disintegration of fuel cells and, as a consequence, possible radioactive contamination of the place of incidence of the reactor.

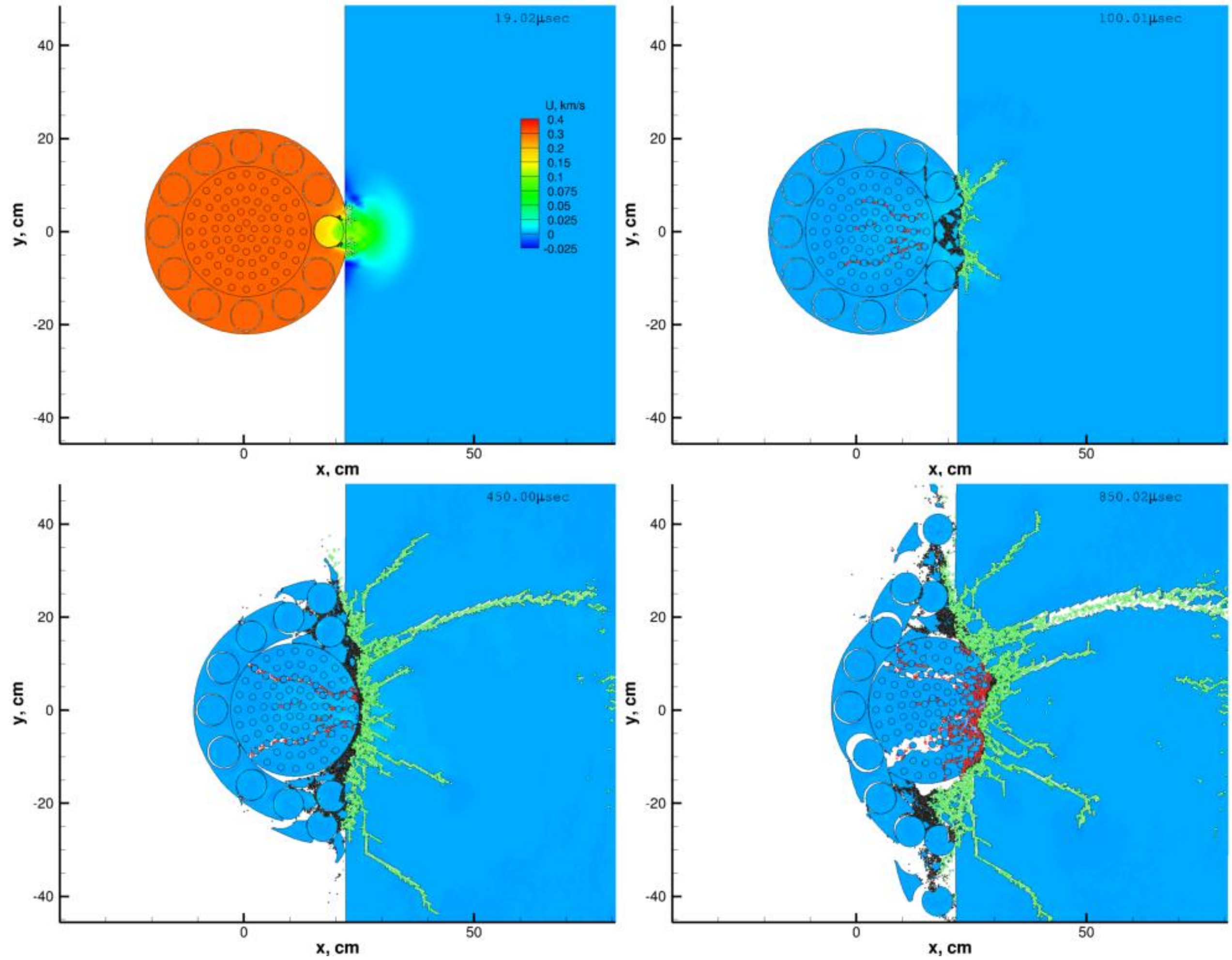

Fig. 3. Frames of the calculated side impact of the reactor model onto the granite plate surface

Calculations of reactor destruction due to its collision with space debris on the orbit ("Topaz")

In the first calculation, a two-dimensional reactor model interacts with a steel object 3 cm in diameter with a velocity of 12 km/s. This velocity is the most probable one for collisions with space debris fragments. The calculation is performed for a reactor model protected by the Whipple shield (aluminum sheet 2mm thick surrounding the reactor).

The experiment shows that the kinetic energy of the object with such a velocity is sufficient for penetration through the target, acceleration of the expelled mass, and fragmentation of the impinging object and expelled part of the target. Shock waves arising during target penetration are reflected from free surfaces as unloading waves whose interference generates strong tensile waves in the materials of the Whipple shield and the impinging object. The parameters of the resultant waves are substantially higher than the strength characteristics of the materials, which leads to fragmentation of the structure and to formation of a cloud of fragments behind the target. The further interaction between the cloud and the reactor model proceeds in accordance with the following scenario. The cloud of fragments of the destroyed projectile almost with the initial impact velocity reaches the beryllium shell of the reactor. The remaining part of the cloud also contacts the reactor shell with a certain delay. Despite the presence of the Whipple shield, the kinetic energy of the cloud of particles is sufficient for destroying the reactor shell made of beryllium. Multiple interactions of particles form a stable spherical shock wave, which destroys not only the shell, but also the zirconium hydride interior and uranium fuel cells. Fig. 4 shows the frames of the interaction of the cloud of fragments with the reactor. The presence of beryllium cylinders in the shell structure is manifested only as an additional stress concentrator and results in more expressed destruction on the shell edges, but exerts practically no effect on the overall pattern of shell failure.

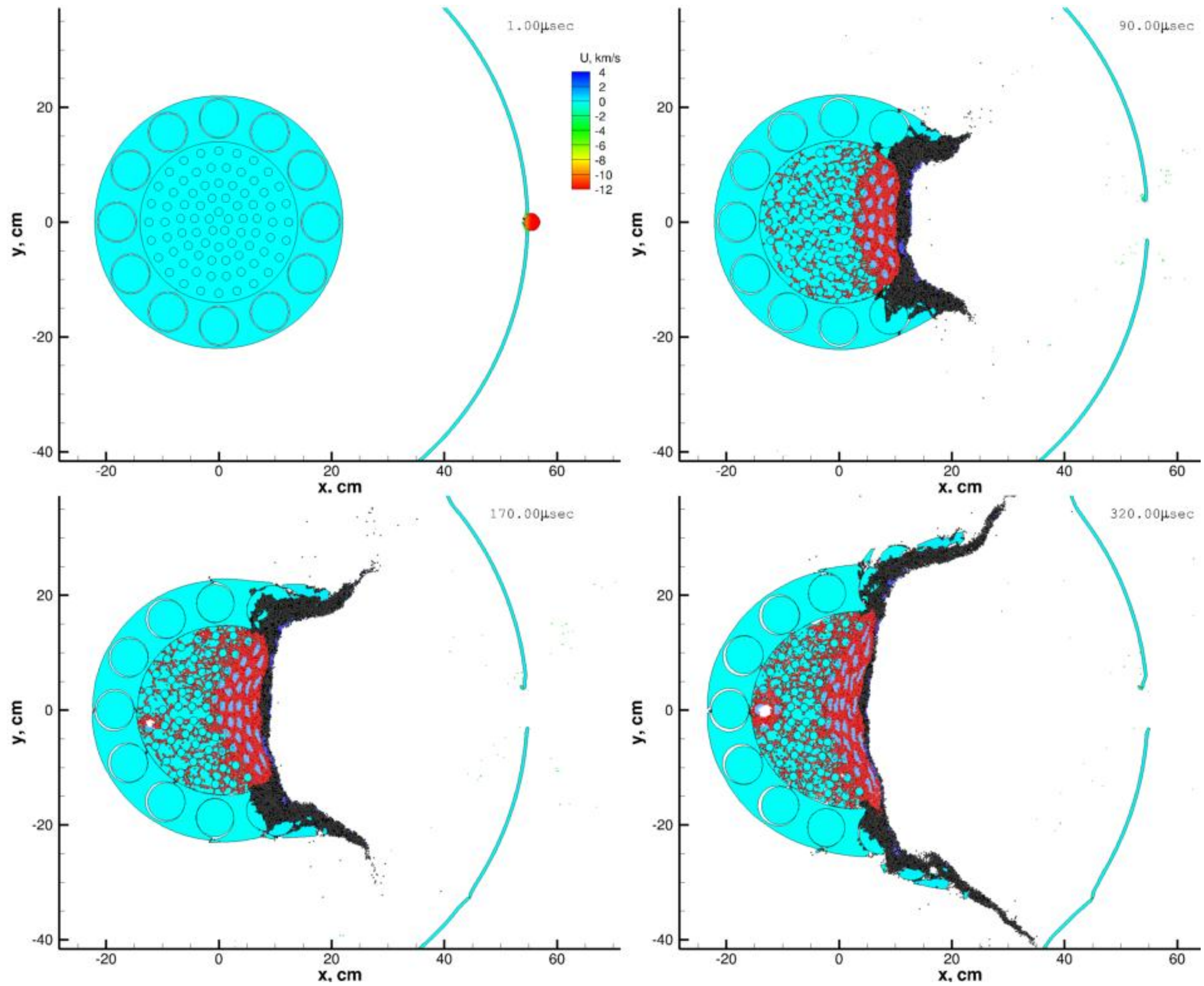

Fig. 4. Photographic records of the impact of space debris with a reactor equipped with the Whipple shield

After that, the interaction of a steel object 3 cm in diameter impinging along the reactor axis with a velocity of 12 km/s is calculated. Fig. 5 shows the photographic records of the impact process. A powerful spherical shock wave propagates from the contact surface. Free surfaces at the periphery of interacting bodies allow the materials of these bodies to unload by acquiring velocities directed away from the "center of pressure," thus, forming zones of tensile strains and stresses. The destruction process begins. As the size of the impinging particle are small, as compared with the reactor size, an analogy can be found with a point source of pressure applied on the boundary of interaction of bodies, moving along the reactor axis. As the central part of the reactor has a complicated structure, multiple interactions of compression-unloading waves lead to its failure even at the stage of overall compression behind the shock wave front (mainly due to shear strains). The acquired velocity induces systematic tensile strains, which rapidly reach critical values, and fragmentation of the materials of the central part of the reactor. Massive deformation of the central part appreciably alleviates peripheral loads, which allows the beryllium shell to remain in the non-destroyed state.

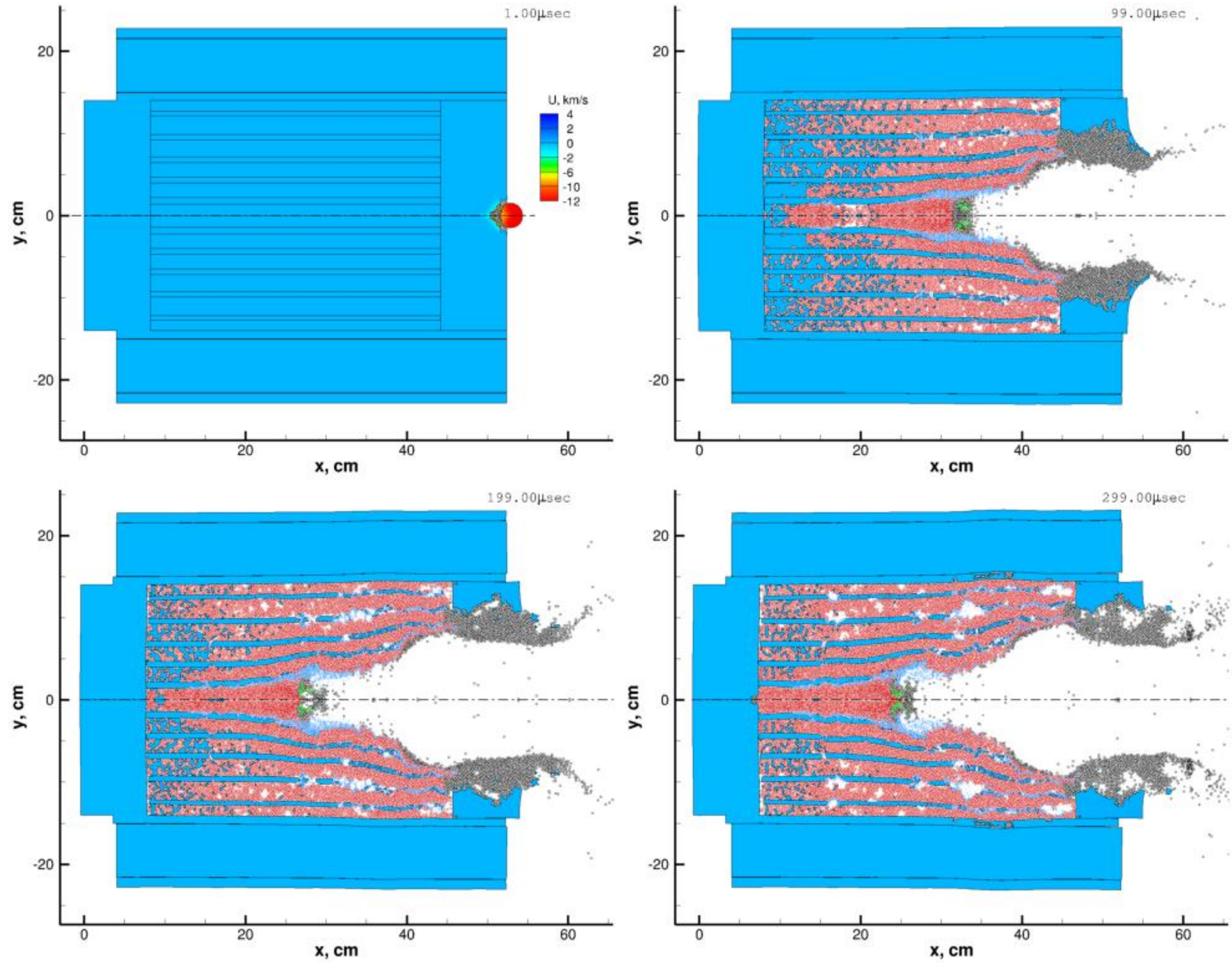

Fig. 5 Photographic records of the impact of space debris with a reactor (axial formulation)

Calculations of reactor destruction due to its collision with space debris on the orbit ("Buk")

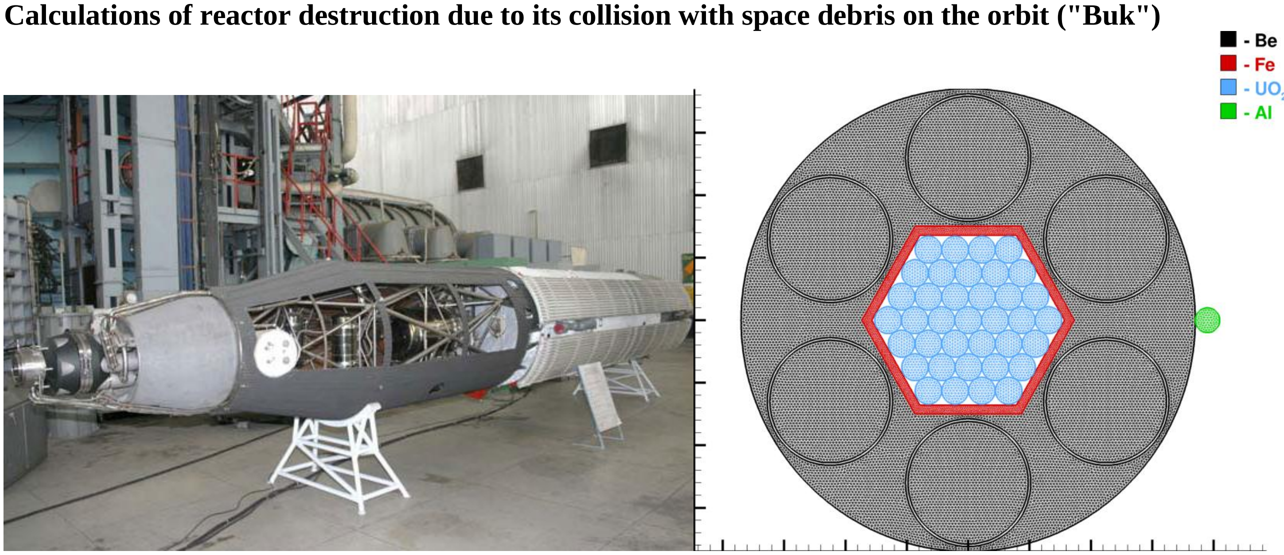

Fig. 6. Nuclear powerplant with thermionic reactors for space applications "Buk"

In the calculation, a two-dimensional reactor model interacts with an aluminum object 2 cm in diameter with a velocity of 11.7 km/s. Both realistic photo and geometry of the nuclear powerplant with thermionic reactors for space applications "Buk" illustrated in Figs. 6.

The interaction of an object 2 cm in diameter impinging along the reactor axis with a velocity of 11.7 km/s calculates. Fig. 7 shows the photographic records of the impact process.

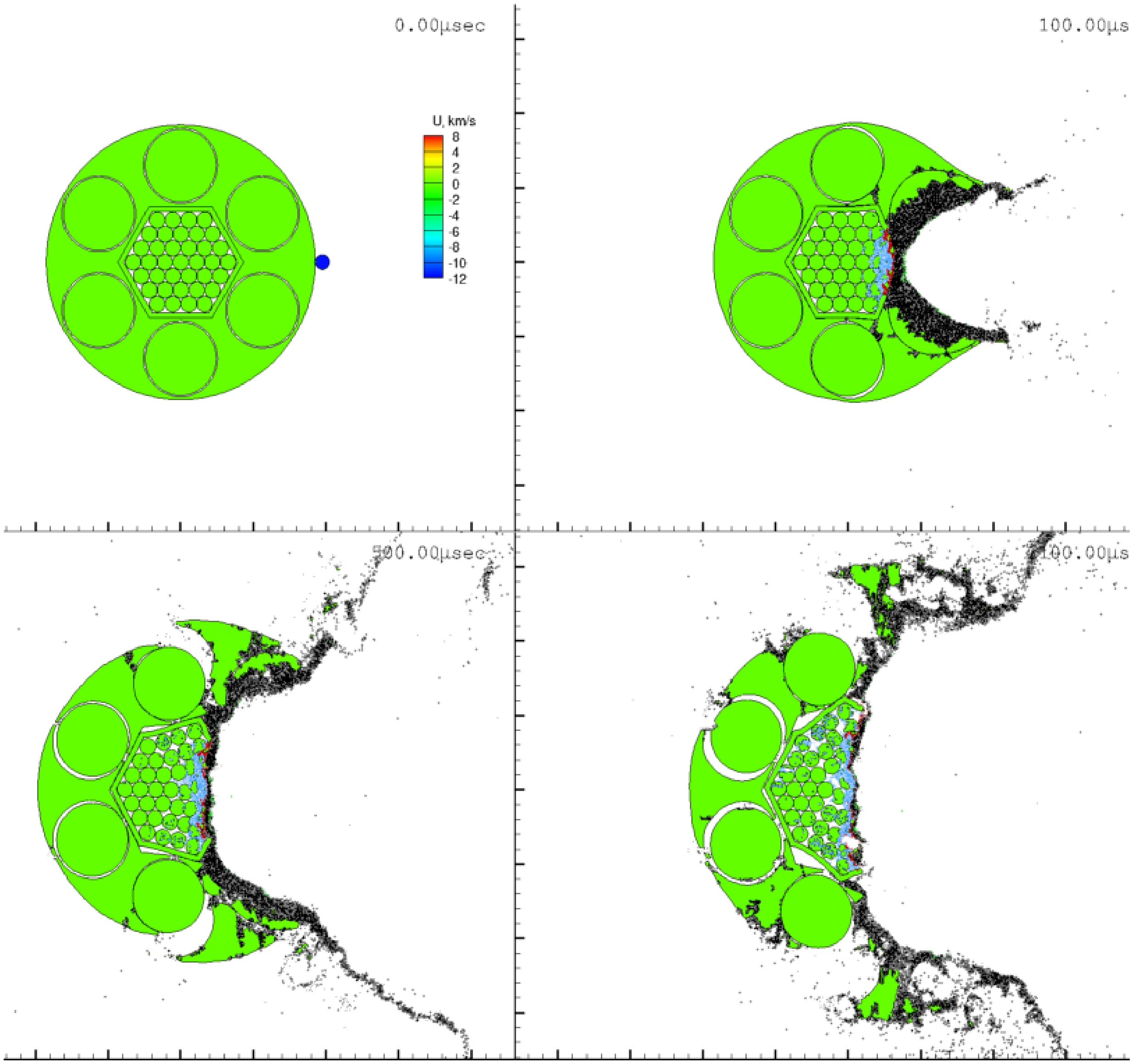

Fig. 7 Photographic records of the impact of space debris with a reactor "Buk"

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