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CURVE OF THE DYNAMIC COMPRESSIBILITY OF POWDER MEDIA

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A technique for constructing the curves of dynamic compressibility of powder media from the results of an experiment on a plant of hydraulic explosive pressing is suggested which makes it possible to construct a certain portion of the compressibility curve with the aid of one experimental shot for any powder material in the pressure-density coordinates to the total exclusion of the apparatus that could register the dynamic parameters of the process of pressing. The technique is used for predicting the results of pressing concrete articles from powder materials, in particular, to determine the parameters of a charge and the coordinates of its disposition in a transmitting liquid medium to obtain a blank with prescribed properties.

We will consider the possibility of applying a hydraulic explosive pressing plant (HEPP) for methodological purposes, that is, obtaining the curve of dynamic pressing of powder materials.

The mechanism of loading powder bodies in an HEPP (Fig. 1) is as follows: on explosion of a high explosive, the energy spent to press powder is transferred from detonation products through a transmitting liquid medium, and by means of subsequent motion of fluid flow (water).

Experiments have shown that the dynamics of the process of pressing has a distinct wave character. Indicative of this are the substantially nonuniform distributions of the density and thickness along the circle of a hollow cylindrical blank after pressing an equally dense powder body by a linear high-explosive charge displaced relative to the symmetry axis. Generally, the problem of determining the dynamic and technological parameters of pressing by such a scheme of loading is complex even in its statement. This is due to the fact that one has to consider unsteady-state, discontinuous, three-dimensional flows, whereas a powder is a rheologically very complex medium, for which there has been no reliable model up to now; therefore in constructing an engineering technique of calculation we shall introduce some substantial simplifications.

In order to describe the powder rheology, we will use the simplest hydrodynamic model of three-dimensional compression in Tait's form:

$$p = B\left[\left(\frac{\rho}{\rho_0}\right)^m - 1\right]. \tag{1}$$

For the transmitting medium (water), the equation of state, isentropic, and of the shock adiabat up to pressures of 3 GPa is taken in the form

$$p = A\left[\left(\frac{\rho}{\rho_0}\right)^n - 1\right].$$

We perform calculation in a plane approximation and ignore the change in the parameters of the state of the detonation product, transmitting medium, and powder over the height of the HEPP. We also consider that the secondary compression of the powder by the shock wave which was reflected from the wall of the matrix (the casing of the plant) is insignificant, i.e., we assume that the results of pressing are determined in the first approximation by the

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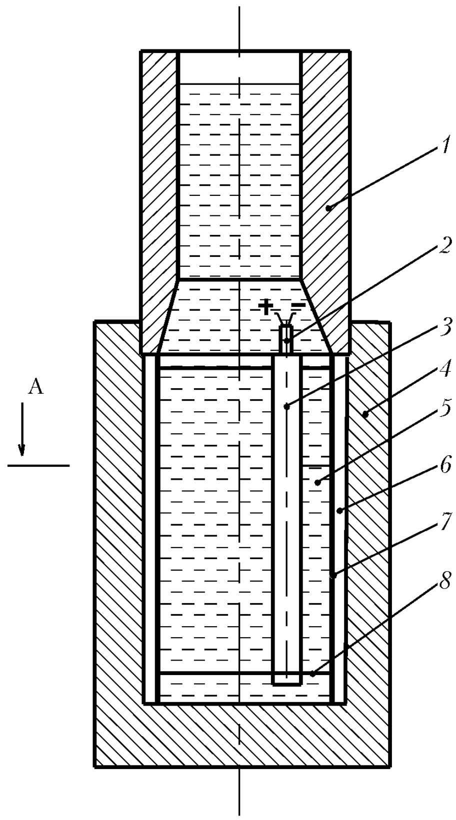


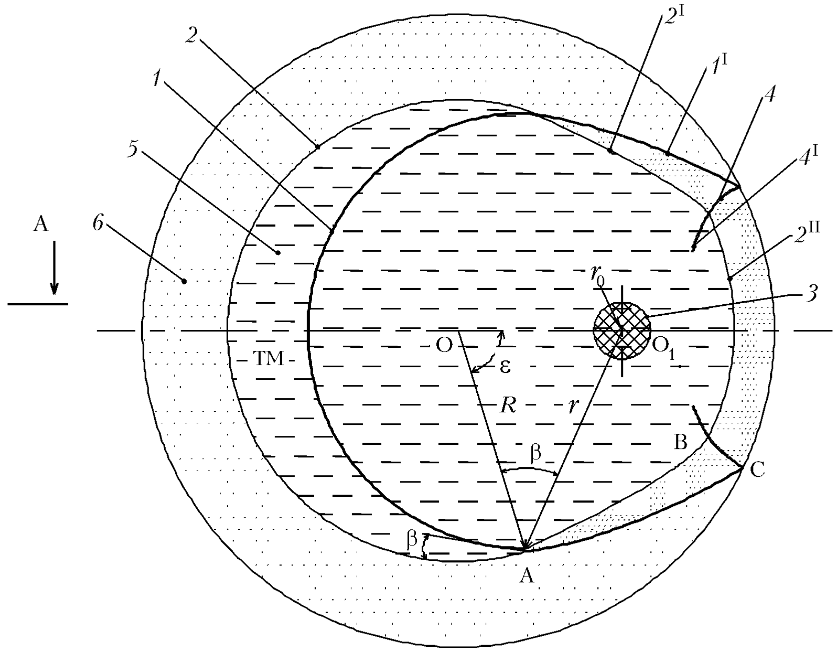


Fig. 1. Schematic diagram of a hydraulic explosive pressing: 1) detachable microtank; 2) electric detonator; 3) linear high-explosive charge; 4) casing of the plant; 5) transmitting liquid medium; 6) powder; 7) elastic shell; 8) fixing ring.

Fig. 2. Wave pattern of pressing with asymmetrical disposition of a charge at an intermediate time instant: 1) shock wave front in the liquid; 1^{I}) front of the shock wave refracted in the powder; 2) transmitting liquid medium–powder interface; 2^{I}) transmitting liquid medium–powder behind the refracted shock wave 1^{I}; 2^{II}) transmitting liquid medium–powder interface behind the refracted shock wave 4; 3) high-explosive charge; 4) shock wave refracted from the plant casing–powder interface; 4^{I}) reflected shock wave refracted into the transmitting medium; 5) transmitting liquid medium; 6) powder.

parameters of the primary shock wave which was refracted into the powder medium. We also neglect the influence of the relief that follows the shock-wave compression.

Figure 2 presents a shock-wave picture of pressing in an intermediate time interval in the A–A section (see Fig. 1). The points O and O_1 are the centers of the powder body being compressed 6 and of the displaced linear high-explosive charge 3 located on their symmetry axes; A is the point of refraction of a shock wave from transmitting liquid medium 5 into the compressed powder body 6; *C* is the point of reflection of a shock wave from the inner cavity of the plant, and *B* is the point of refraction of a shock wave from the pressed powder body 6 into the transmitting liquid medium 5.

We shall fix a coordinate system on the moving point of the refraction of the shock wave A at the place of its contact with the powder. The flow pattern in the vicinity of this point is depicted in Fig. 3. In solving the direct problem we assume the law of powder compressibility to be known in the form of Eq. (1).

This part of the procedure serves only to construct a simpler scheme with the aid of which we determine the law of powder compressibility. At an intermediate stage, it can be taken from the experimental results on determining the static compressibility of the powder medium under investigation.

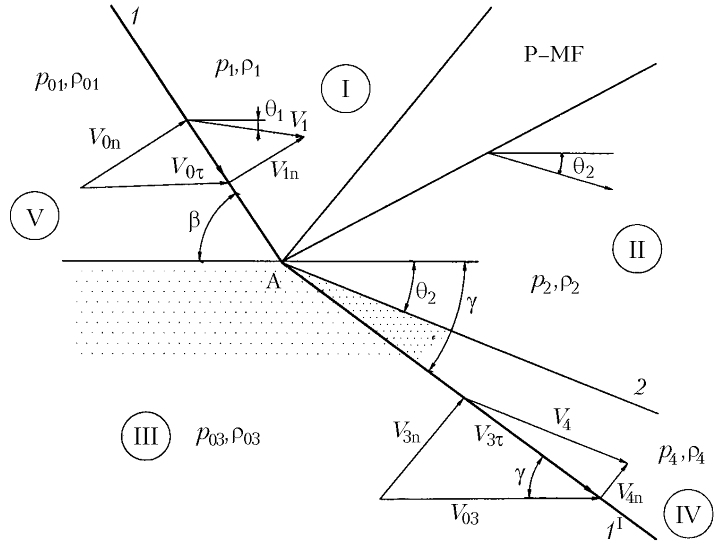


Fig. 3. Picture of the flow in the vicinity of point A: I) zone immediately following the shock wave in a transmitting medium; P–MF) zone of expansion (Prandtl–Meyer flow); II) zone following the P–MF in a transmitting medium; III) zone of a nonperturbed powder; IV) zone of the shock-compressed powder; V) zone in front of a shock wave in a transmitting medium (a nonperturbed medium); 1) incident shock wave in a transmitting medium; 1^{I}) incident shock wave in the powder; 2) powder-transmitting medium boundary behind the refracted shock wave 1^{I}.

The distribution of the pressing parameters is eventually determined by the value of β and the pressure behind the shock-wave front in water. For β the following dependence can be obtained:

$$\beta = \arctan \frac{\sqrt{\dfrac{4R^2a^2}{(R^2 + a^2 - r^2)^2} - 1}}{\left| \dfrac{2R^2}{R^2 + a^2 - r^2} - 1 \right|} . \qquad (2)$$

The pressure behind the shock wave is calculated from the formula [1]

$$p_1 = K \left(\frac{r_0}{r} \right)^{\eta} , \qquad (3)$$

where K and η are constants. For the values of D and flow velocity behind the shock wave in a laboratory coordinate system we write

$$\rho_{01} D = \rho_1 (D - u) , \quad p_1 = \rho_{01} D u , \quad p_1 = A \left[\left(\frac{\rho_1}{\rho_{01}} \right)^{n} - 1 \right] , \qquad (4)$$

$$D = \sqrt{\frac{p_{01}}{\rho_{01}} \left[1 - \left(1 + \frac{p_1}{A} \right) \right]^{-1}} , \qquad (5)$$

$$u = \sqrt{\frac{p_{01}}{\rho_{01}}\left[1 - \left(1 + \frac{p_1}{A}\right)\right]} \,. \tag{6}$$

At an oblique shock wave the following relations are valid:

$$V_{01} = \frac{D}{\sin\beta}\,, \quad V_{0\mathrm{n}} = D = V_{01}\sin\beta\,, \quad V_{0\tau} = V_{1\tau} = D\cot\beta\,, \tag{7}$$

$$V_{1\mathrm{n}} = D - u = D\cot\beta\tan(\beta - \theta_1)\,, \tag{8}$$

$$V_1 = \frac{D\cot\beta}{\cos(\beta - \theta_1)}\,. \tag{9}$$

Equations (4)–(6) and (8) yield a relation for θ_1:

$$\theta_1 = \beta - \arctan\left[\tan\beta\left(1 + \frac{p_1}{A}\right)^{-1/n}\right]. \tag{10}$$

The foregoing equations entirely determine the parameters of the liquid flow behind shock wave 1 (Fig. 3). Calculations have shown that the velocity V_1 behind the shock wave is supersonic. Then in the angle which is determined by the characteristics emanating from the point A and by the corresponding velocities V_1 and V_2 there is the Prandtl–Meyer mode of flow, i.e., the flow turns from the angle θ_1 toward θ_2 and is accelerated. A dependence which couples the parameters of the flow before and after its turning is known [2]:

$$\theta_2 = \theta_1 - \Phi(\mathrm{M}_1) + \Phi(\mathrm{M}_2)\,, \tag{11}$$

where $\Phi(\mathrm{M}) = \sqrt{\frac{n+1}{n-1}}\arctan\sqrt{\frac{n-1}{n+1}}(\mathrm{M}^2 - 1) - \arctan\sqrt{\mathrm{M}^2 - 1}$; $\mathrm{M} = V/c$ is the Mach number; $c = c_{00}(1 + p)/A^{(n-1)/2n}$ is the local speed of sound; c_{00} is the speed of sound in a nonperturbed medium. Dependence (11) relates the parameters θ_2, p_2, and V_2 to the known parameters θ_1, p_1, and V_1. At the boundary between the liquid and powder the following condition is obvious:

$$p_4 = p_2\,, \tag{12}$$

with

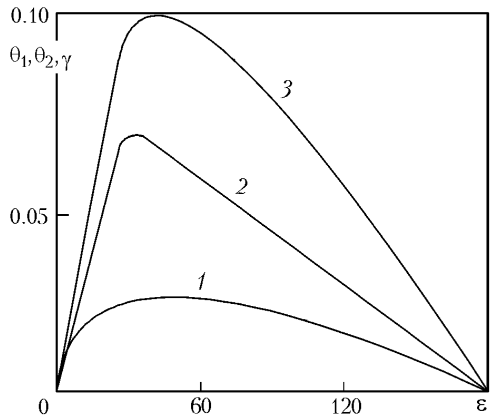
$$p_4 = B\left[\left(\frac{\rho_4}{\rho_{03}}\right)^m - 1\right], \quad p_2 = A\left[\left(\frac{\rho_2}{\rho_{01}}\right)^n - 1\right]. \tag{13}$$

Further, at the front of shock wave 1 the following relations hold:

$$\rho_{03}V_{3\mathrm{n}} = \rho_4 V_{4\mathrm{n}}\,, \quad p_4 = \rho_{03}V_{3\mathrm{n}}^2 - \rho_4 V_{4\mathrm{n}}^2\,,$$

$$V_{3\mathrm{n}} = V_{01}\sin\gamma\,, \quad V_{4\mathrm{n}} = V_{01}\cos\gamma\tan(\gamma - \theta_2)\,, \quad V_4 = V_{01}\frac{\cos\gamma}{\cos(\gamma - \theta_2)}\,. \tag{14}$$

We use the Bernoulli equation in the form



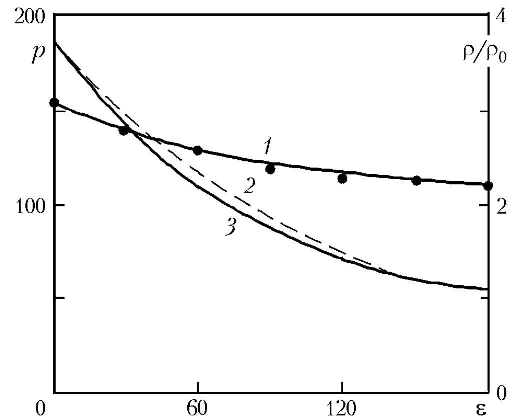


Fig. 4. The angles θ_1 (1), θ_2 (2), and γ (3) vs. the polar angle ε of the point of contact of a shock wave with the initial surface of the powder medium. θ_1, θ_2, and γ is in rad; ε is in deg.

Fig. 5. Curves of a change in the relative density (1) and pressure (2, 3) over the perimeter of a pressed article (dots, experimental data): 2) calculation by Eq. (16); 3) by Eqs. (1)–(15). p, in MPa; ε, in deg.

$$\frac{V_2^2}{2}+\frac{c_2^2}{n-1}=\frac{V_1^2}{2}+\frac{c_1^2}{n-1}, \tag{15}$$

where c_1 and c_2 represent the speed of sound in zones I and II.

Using Eqs. (1)–(15), we can calculate the parameters that characterize the state of the transmitting medium and powder in the process of pressing in the vicinity of the point A. Figures 4 and 5 present some of the results of calculations by the equations suggested.

The smallness of the parameters θ_1, θ_2, and γ allows one to considerably simplify the calculation technique: there are good grounds for assuming that the values of the parameters p_4 and ρ_4 will not differ from those obtained if we assume that the pressing at each point is done by a straight shock wave and that the pressure is determined by the distance r. In this case, one has to solve only one equation which determines the parameters at the water–powder interface after incidence of a shock wave on it:

$$\sqrt{\frac{p_4}{An}\frac{\rho_{002}}{\rho_{03}}\left[1-\left(1+\frac{p_4}{B}\right)^{-\frac{1}{m}}\right]}+\frac{2}{n-1}\left(1+\frac{p_4}{A}\right)^{\frac{n-1}{2n}}=\sqrt{\frac{p_1}{An}\left[1-\left(1+\frac{p_1}{A}\right)^{-\frac{1}{n}}\right]}+\frac{2}{n-1}\left(1+\frac{p_1}{A}\right)^{\frac{n-1}{2n}}, \tag{16}$$

where ρ_{002} is the water density at atmospheric pressure.

Curve 2 represented in Fig. 5 was calculated from Eq. (16). As is seen, the closeness of curves 2 and 3 quite justifies the simplification introduced. Other parameters of interest to us are determined from the simplified formulas with allowance for the smallness of θ_1, θ_2, and γ given in the present work:

$$\theta_2=\sqrt{\frac{p_4}{\rho_{03}V_{01}^2}\left[1-\left(1+\frac{p_4}{B}\right)^{-1/m}\right]}, \quad \gamma=\frac{\theta_2}{1-\left(1+\frac{p_4}{B}\right)^{-1/m}}.$$

We shall consider the technique of determining the curve of dynamic compressibility from the results of measurement of the pressing density obtained in the case of asymmetric disposition of a linear charge and the corre-

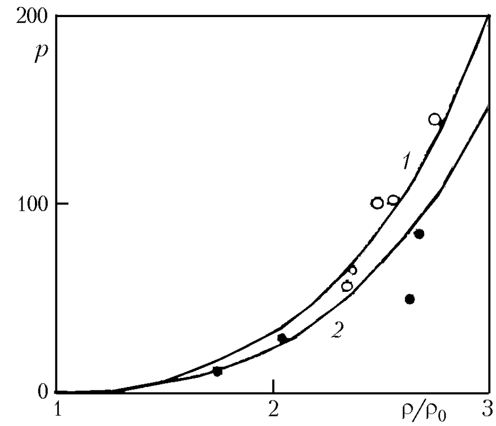


Fig. 6. Dynamic compressibility of titanium powder vs. pressure: 1) $p = 1.4\,[(\rho/\rho_0)^{4.5} - 1]$ (approximation of results obtained in the HEPP); 2) $p = 1.1\,[(\rho/\rho_0)^{4.5} - 1]$ (approximation of the data of [3]). p, in MPa.

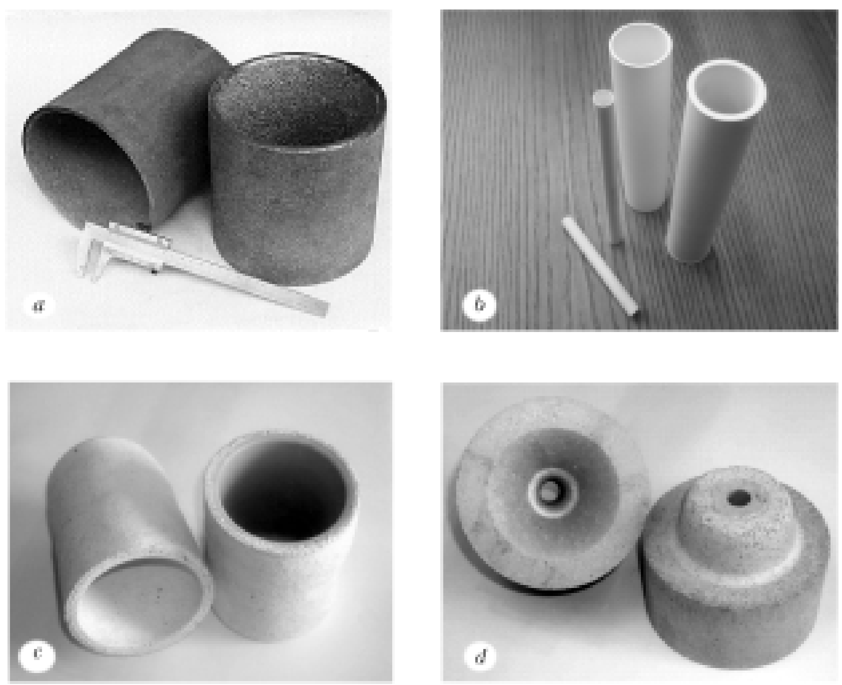


Fig. 7. Articles produced by the pulse method of pressing with account for the curves of the dynamic compressibility of powder materials: a) porous titanium filters; b) ceramic filtering elements and porous diaphragms for reactors of chemical treatment of water in an "Izumrud" plant; c) refractory one- and two-layer crucibles for melting and pouring ferrous and non-ferrous metals; d) two-layer batch-beakers made from ZrO_2 and Al_2O_3 for continuous casting machines.

sponding shock-wave loading of the powder medium. Let the experimental dependence $\dfrac{\rho_{4\mathrm{exp}}}{\rho_{03}} = \bar{\rho}_{4\mathrm{exp}}(\varepsilon)$, ($\varepsilon = \varepsilon(r)$) be obtained. Then Eq. (16) written as

$$\sqrt{\frac{p_4}{An}\frac{\rho_{01}}{\rho_{03}}\left[1-\left(\frac{1}{\bar{\rho}_{4\mathrm{exp}}}\right)\right]}+\frac{2}{n-1}\left(1+\frac{p_4}{A}\right)^{\frac{n-1}{2n}}=\sqrt{\frac{p_1}{An}\left[1-\left(1+\frac{p_1}{A}\right)^{-\frac{1}{n}}\right]}+\frac{2}{n-1}\left(1+\frac{p_1}{A}\right)^{\frac{n-1}{2n}}, \tag{17}$$

yields the computational dependence $p_2 = p_4 = f(\overline{\rho}_{4\exp})$. From the points obtained, we determine the values of the constants B and m by using the least-squares method for processing and, as a result, we obtain

$$p = B\left[\left(\frac{\rho}{\rho_{0\mathrm{p}}}\right)^m - 1\right]. \tag{18}$$

Figure 6 presents the results of processing experimental data by Eq. (17) which is approximated by Eq. (18), as well as the experimental data on determination of the shock adiabat of the powder under study that were taken from [3].

The curves obtained by the technique considered cannot in full measure be considered a shock adiabat (multiple loadings of the powder and the final relief in pressing are not taken into account), but they can successfully be applied to predict the results of dynamic compressibility of powders and moulding of various articles from them (Fig. 7).

Thus, an engineering technique for constructing the curves of dynamic compressibility of various powder media has been developed. Using it, on the basis of the data on a single cycle of experimental explosion of any concrete powder, a curve of dynamic compressibility is constructed in the pressure–density coordinates. Such dependences are used for predicting the results of pressing and the properties of the articles to be produced from metal and ceramic powders. The technique suggested is applicable to calculating both dynamic and technological parameters of pressing.

NOTATION

A and B, coefficients; a, distance between the symmetry axes of a powder blank and charge, m; D, velocity of a shock wave in a transmitting medium, m/sec; m and n, exponents; p_1, ρ_1, p_2, ρ_2, and p_4, ρ_4, pressure and density in regions I, II, and IV, MPa, kg/m^3; p_{01}, ρ_{01}, V_{01} and p_{03}, ρ_{03}, V_{03}, pressure, density, and velocity in regions V and III, MPa, kg/m^3 and m/sec; r and ε, polar coordinates of the point of refraction of a shock wave, m and deg; r_0, radius of a cylindrical high-explosive charge, m; R, inner radius of a powder body, m; u, velocity of medium flow, m/sec; V, flow velocity in a coupled coordinate system, m/sec; V_1, V_2, and V_4, flow velocities in regions I, II, and IV, m/sec; V_{1n}, V_{3n}, V_{4n}, V_{0n} and $V_{1\tau}$, $V_{3\tau}$, $V_{4\tau}$, and $V_{0\tau}$, normal and tangential flow velocity components in zones I, III, IV, and V, m/sec; β, angle between the shock-wave front in a transmitting medium and the initial transmitting medium–powder body interface at the point of refraction of a shock wave, rad; γ, angle between the shock-wave front in a powder and the boundary of a powder body at the point of refraction of a shock wave, rad; θ_1 and θ_2, angles of flow turning in transition through a shock wave into the transmitting medium in the powder, rad; ρ_0 and ρ, initial and current density, kg/m^3; I, region between a shock wave in the transmitting medium and the Prandtl–Meyer flow zone; II, region of flow between the Prandtl–Meyer zone and the boundary of a powder body behind a shock wave; III, region of an unloaded powder body; IV, region occupied by a compressed powder behind the shock wave; V, region in front of a shock wave in a powder body. Subscripts: n, normal; τ, tangential; p, powder; exp, experimental.

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