# Risks of hydraulic shocks in pressure pipelines during aboveground laying in permafrost conditions

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**Abstract.** Under permafrost conditions, there are a large number of factors that complicate the construction and operation of pressure hydraulic transport systems. While designing new pressure systems and reconstructing existing ones, it is necessary to take into account possible unsteady processes in pressure pipelines. Elimination of the consequences of emergency situations accompanied by water leakage is difficult in harsh climatic conditions, while thermal effects on soils are not always possible to avoid. The purpose of the study was to identify the factors that most affect the risk of hydraulic shocks in pressure pipelines during aboveground laying of pipelines characteristic of permafrost areas. The method of characteristics used to solve differential equations of unsteady fluid motion is the basis of a computational model for determining flow parameters in the event of hydraulic shocks. On the basis of the calculations carried out, the diagrams of pressure changes in a pressure pipeline made of steel pipes are analyzed in the article. The influence of the propagation velocity of the hydraulic shock wave and the velocity of the steady-state fluid flow on the nature of the flow of the unsteady process and the amount of pressure during hydraulic shock in the pressure pipeline during overhead laying is estimated. Applying of activities aimed at preventing the occurrence of hydraulic shocks, including combined ones in order to increase the reliability of their action, is much cheaper than replacing damaged pipes and equipment, eliminating washouts with leaking water, loss of drinking water.

## 1 Introduction

The development of the Arctic zone of Russia requires the timely development of transport infrastructure, which in turn cannot function without efficient, environmentally sound and reliable water supply and sanitation systems. Pressure pipelines are one of the elements of the water supply and sanitation system, but without their stable and predictable operation, the efficiency of the entire system as a whole decreases.

Laying pressure pipelines in permafrost areas, it is necessary to ensure the stability of pipelines and structures on them in conditions of subsidence and heaving soils. Freezing and thawing of moisture-saturated soils causes complex physico-chemical processes leading to

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heaving or subsidence of soils. When the soil freezes, the equilibrium of moisture contained in the pores of the soil is disturbed, and the process of its movement to the freezing front occurs. The migration of moisture leads to an increase in its volume in the freezing layers, and then to the heaving of soils. Positive temperatures lead to melting of ice in the pores of the soil, which leads to a sharp decrease in volume, causing loss of bearing capacity and soil precipitation. The soil subsides under its own weight even without the impact of external loads. All these processes lead to the destruction of the foundations of structures and the destruction of pipelines. While erecting structures in the conditions of the Arctic zone of Russia, it is necessary to follow the principle of maintaining the frozen state of the soil [1, 2].

Depending upon the permafrost-ground conditions, the length and diameter of the pipeline and other local factors, aboveground, surface and underground laying methods are allowed for the installation of water pipelines. Operational practice has proved that the most rational way is the aboveground laying of pressure pipelines.

This type of pipeline arrangement eliminates the thermal effect of water pipes on the soil, allows you to monitor the condition of the pipeline, simplifies and accelerates repair and emergency work. Aboveground laying allows you to significantly reduce excavation work and measures for special protection against external corrosion.

Meanwhile, the aboveground laying of pipelines has its drawbacks. While transporting water, heat losses increase, and, consequently, reinforced and expensive thermal insulation is required. However, with the development of the production of modern materials, new, more efficient, economically sound thermal insulation technologies appear [3]. The aboveground gasket imposes special requirements on the supports, which should not lead to a thermal load on the ground. This type of pipeline laying is recommended outside the territory of settlements in order to avoid its cluttering.

Steel or polymer materials are usually used as pipe material in such conditions. Pipelines made of cast iron, reinforced concrete or concrete require a complex butt joint of pipe sections and therefore are not recommended for use. Coupling and socket connections at subzero temperatures are difficult to produce.

Aboveground laying of pipelines requires compensation of stresses arising in steel and polymer pipes when the outside temperature changes. In case of emptying or filling of pipelines in winter, the temperature of the pipe walls changes dramatically and the most dangerous temperature deformations of pipes occur. To compensate for temperature deformations, a rectilinear gasket with special devices and a zigzag gasket on special supports for self-compensation are used.

Hydraulic shock, as one of the types of unsteady process, can occur during the operation of any pressure hydraulic transport system. The relationship between the parameters of hydraulic shocks and the material from which pipelines are made is considered throughout the history of the study of unsteady processes for solving practical problems [4-7].

In order to prevent catastrophic hydraulic shocks, the selection of shockproof equipment and the choice of a method for protecting pumping equipment, it is necessary at the design stage to calculate the amount of pressure exceeding the operating pressure at various points of the pressure pipeline, the speed of water movement during the wave process and to determine the places and magnitude of the occurrence of vacuum pressure in the pressure system. Most modern calculation methods are based on the numerical method using the "method of characteristics" [8-14].

Pipeline systems made of steel pipes on average last about three decades. The water transportation systems put into operation during the development of the territories of Russia with permafrost soils in the last century are gradually becoming completely unusable and require appropriate reconstruction.

**Fig. 1.** The current state of aboveground pipelines

The relevance of this study lies in the fact that there is a need for the reconstruction and development of pressure systems laid aboveground. In modern conditions, it is possible to choose the route of the water pipeline, the material of pipes, the method of connecting pipe sections, shockproof equipment on the basis of a comprehensive calculation taking into account the possibility of a hydraulic shock.

The aim of the study was to identify factors that increase the risk of hydraulic shocks in pressure pipelines during overhead laying. During the study , the following issues were solved:

- the influence of the pipe material on the propagation velocity of the hydraulic shock wave front was analyzed;
- the influence of the wall thickness of a steel pipe on the magnitude of the shock wave velocity and the magnitude of the maximum pressure along the entire length during hydraulic impact was investigated;
- the parameters of hydraulic shock were determined at different initial velocities of fluid movement on the basis of modern calculation methods;
- ways have been developed to reduce the risks of destructive unsteady processes in pipelines during aboveground laying.

## 2 Methods and materials

The subject of the study was a hydraulic shock in pressure pipelines during aboveground laying, characteristic of the territories of permafrost soils.

In order to solve the issues and achieve the final goal of the work, theoretical, general philosophical analysis and synthesis, observation and modeling were consistently applied.

The work assessed the impact of the velocity of propagation of the shock wave, the initial velocity of the fluid and the profile of the gasket on the possibility of discontinuities in the continuity of the fluid flow during hydraulic shock in pressure pipelines.

Hydraulic shocks occurring in a 171 m long pipeline with a 41 m rise from steel pipes with an internal diameter of 82 mm, with thickened walls were considered; most of the butt joints are welded, the rest are flanged. The pipeline is laid on supports on the ground surface.

The shocks were created by closing the valve at the beginning of the pipeline, the closing time of the valve was equal to 0.05 s. The vacuum pressure determined during the experiments was 8 m, the velocity of propagation of the shock wave front was 1250 m/s, and the static pressure was 40 m of water.

The method of analysis of infinitesimal quantities and the method of characteristics for a one-dimensional wave equation are chosen as the basis for the developed calculation method of hydraulic shock parameters with sufficient accuracy to solve practical problems.

## 3 Outcomes of the research

In pressure pipes, a shock wave propagation front occurs during hydraulic impact, the speed of which reaches the highest values in steel pipes compared to other pipe materials. The high speed of propagation of the wave process can contribute to the formation of discontinuities in the continuity of the fluid flow at the regulating body (gate valve, pump, check valve, etc.), as well as in areas of change in the slope of the conduit at elevated points of the profile. The discontinuity of the flow continuity occurs due to a decrease in the pressure in the pipeline below atmospheric to vacuum. Firstly, the fluid flow departs from the place of the discontinuity of the flow, and then moves in the opposite direction with increasing speed, which leads to the collapse of the rupture. Due to the interference of waves, the maximum shock pressure increases, which exceeds the operating pressure in magnitude with a steady process.

When calculating hydraulic shock, an important characteristic of the process is the velocity of propagation of the shock wave front *c*, m/s. Its value can be determined by the formula of D. Korteweg, proposed for use by the founder of the theory of hydraulic shock N. E. Zhukovsky:

$$c = \frac{\sqrt{\frac{E}{\rho}}}{\sqrt{1+\frac{E\cdot D}{E_D\cdot \delta}}} = \frac{1435}{\sqrt{1+\frac{E\cdot D}{E_D\cdot s}}} \tag{1}$$

where: $E$ – the volume elasticity modulus of the pumped liquid, Pa; for water at atmospheric pressure and temperature up to 20 $E = 206\cdot 10^{7}$ Pa;
$\rho$ – the density of the pumped liquid, kg/$^{m3}$;
$g$ – acceleration of gravity, g = 9.81 m/s $^{2}$;
$D$ – inner diameter of the pipeline, mm;
$E_D$ – elastic deformation modulus of the pipe material, Pa; for steel $E_D = 206\cdot 10^{9}$ Pa;
$s$ – pipeline wall thickness, mm.

As per GOST 8734-75, depending on the ratio of diameter to wall thickness, pipes are distinguished: extra-thick-walled, thick-walled, thin-walled and extra-thin-walled. At first glance, it seems that the greater the wall thickness of the pipe s, the better the pipeline of such pipes resists hydraulic shock. Along with the advantages (they withstand dynamic loads without loss of strength for a long time, they are designed for high operating pressures), thick-walled pipes also have disadvantages (pressure waves propagate faster in them during hydraulic shocks and therefore the maximum pressure values for such phenomena can be more significant).

Table 1 demonstrates the values of the propagation velocity of the shock wave front calculated by formula (1) for various types of steel pipes manufactured according to GOST 8734-75 and GOST 10704-91. These data show that with an increase in the thickness of the pipe, the value of *c* increases in steel pipes by almost 50%, while for thick-walled and extra-thick-walled pipes, the velocity of *c* has maximum values and does not depend much on the ratio $D_n / s$ (the difference in values does not exceed 5%).

**Table 1.** The value of the velocity of propagation of the shock wave front in steel pipes, taking into account the ratio of the outer diameter of the pipe $D_n$ to the wall thickness $s$.

| Velocity of propagation of the shock wave front $c$, m/s | Types of steel pipes | | | |
|---|---|---|---|---|
| | extra thin-walled $\frac{D_n}{s}$ >40 | thin-walled $\frac{D_n}{s} =$ 12,5 ÷ 40 | thick-walled $\frac{D_n}{s}$ = 6 ÷12.5 | extra thick-walled $\frac{D_n}{s} <$ 6 |
| | 926,3 - 1219,0 | 1221,5 - 1365,1 | 1365,7 - 1410,5 | 1407,9 – 1419,7 |

Plastic pipes as a whole are characterized by a much lower value of the elastic deformation modulus of the pipe material, the numerical value of which depends on the type of polymer material and is indicated by the manufacturer. Consequently, as per formula (1), the velocity of shock wave propagation in such pipes does not exceed 900 m/s and is usually in the range from 200 to 600 m/s. Meanwhile, for the aboveground laying of pipelines made of polymer materials, there is no need to take into account the elastic resistance of the soil, which significantly increases the speed of propagation of the shock wave [15].

Without taking into account the wave nature of the propagation of a hydraulic shock, when initially considered, it may seem that such low rates of propagation of a hydraulic shock wave contribute to a decrease in the values of maximum pressures in pipelines made of polymer materials. In aqueducts that have a significant rise from the regulatory body with subsequent fracture points of the main profile, despite the low speed of the shock wave, hydraulic shocks may occur with discontinuities in the continuity of the flow, which exist for a long period of time both at the fracture points and at the regulatory body. The negative consequence of such hydraulic shocks is not only the appearance of higher pressures, but also extensive discontinuities of the fluid flow. The occurrence of such flow breaks in pipelines made of polymer materials with a decrease in pressure to a vacuum gauge negatively affects the strength characteristics of the pipes themselves and their butt joints.

It is possible to trace the influence of the values of the propagation velocity of the hydraulic shock wave and the initial velocity of the fluid movement at steady state on the pressure during hydraulic shock applying the formula by N.E. Zhukovsky:

$$H = H_0 + \frac{c \cdot V_0}{g}, \tag{2}$$

where $H$– pressure in the process of hydraulic shock, m;
$H_0$ – pressure at steady flow of liquid in the pipeline, m;
$c$ – the speed of propagation of the hydraulic shock wave, m/s;
$V_0$ – the initial velocity of the fluid in the pipeline at steady state, m/s;
$g$ – acceleration of gravity, g = 9.81 m/s $^2$.

Formula (2) does not take into account numerous factors affecting the process of hydraulic shock. The water hammer, which has a wave character of propagation, is also affected by the profile of the pipeline laying, the response time of the regulatory body, the type of installed equipment and changes in the diameter and material of the pipeline in various sections of the network. The method of calculating the parameters of an unsteady process, based on the method of characteristics, allows us to take into account these features.

Using the known differential equations of unsteady motion [10-12], and converting them using the method of characteristics, we create a hydraulic shock model that takes into account the features of the entire pipeline system and allows us to determine its parameters at any design point and at any time period [14].

The peculiarity of the hydraulic shock in a pipeline with an ascending longitudinal profile is that with an increase in the initial velocity of the fluid in steady-state mode, the probability of discontinuities in the continuity of the fluid flow at the regulatory body at the beginning of the conduit increases. When cavitation cavities collapse, new pressure waves are formed, which, after interference, cause a sharp increase in pressure. The collapse of long-existing discontinuities in the continuity of the fluid flow contributes to the appearance of the reverse velocity of the fluid flow exceeding its initial value in a steady-state process.

These processes can be clearly traced by the pressure values manifested in both the first and second pressure increases, which are calculated and compared with the experimental data in Table 2. Table 2 presents a comparison of the experimental and obtained by the authors of the article when calculating the values of the maximum pressures in the second and fourth phases, respectively, at different initial fluid velocities. The first and second maxima of the pressure increase were also considered, since the maximum value of the shock pressure was observed both in the first and in the subsequent phases of the pressure increase, depending on the magnitude of the initial speed of movement.

In Table 2, in addition to the maximum pressure values for each value of the initial velocity, the values of relative errors are also given. The maximum margin of error is 12.1% and corresponds to the first increase in pressure. The value of the average relative error is 4.6%.

**Table 2.** Comparison of the maximum pressure value from the initial velocity of the fluid

| **Initial velocity of water moveme** | **The first increase in pressure** | | | **The second increase in pressure** | | |
|---|---|---|---|---|---|---|
| | **pressure values, m** | | **relative error, %** | **pressure values, m** | | **relative error, %** |
| | **experiment** | **calculation** | | **experiment** | **calculation** | |
| 0,18 | 65 | 62,0 | 4,8 | 60 | 61,8 | 2,9 |
| 0,36 | 80 | 77,5 | 3,2 | 66 | 74,7 | 11,6 |
| 0,4 | 90 | 82,8 | 8,7 | 79 | 78,1 | 1,4 |
| 0,5 | 116 | 116,9 | 0,8 | 90 | 85,8 | 5,0 |
| 0,6 | 132 | 134,2 | 1,6 | 105 | 100,8 | 4,2 |
| 0,8 | 160 | 172,8 | 7,4 | 135 | 134,6 | 0,3 |
| 1,0 | 182 | 191,7 | 5,1 | 170 | 163,3 | 4,1 |
| 1,06 | 165 | 188,4 | 12,1 | 168 | 170,6 | 1,5 |
| 1,2 | 175 | 195,5 | 10,5 | 210 | 218,8 | 4,0 |
| 1,25 | 200 | 207,9 | 3,8 | 215 | 217,4 | 1,1 |
| 1,4 | 218 | 235,1 | 7,3 | 215 | 211,5 | 1,7 |
| 1,5 | 220 | 238,2 | 7,6 | 245 | 217,0 | 12,0 |
| 1,63 | 247 | 247,6 | 0,3 | 250 | 247,2 | 1,1 |
| 1,7 | 230 | 250,0 | 8 | 250 | 250,0 | 0 |
| 1,82 | 265 | 269,7 | 1,7 | 230 | 255,3 | 9,9 |
| 2,0 | 285 | 292,0 | 2,4 | 290 | 289,6 | 0,1 |

The nature of the pressure change in time at the valve, depending on the magnitude of the initial velocity, can be traced in Figure 2 and Figure 3. At the initial speed of movement v = 0.8 m/s (Figure 2), the pressure in the first phase during the calculation and in the experiment falls below atmospheric. The high-frequency oscillations that appeared on the pressure diagram in the first compression phase indicate the appearance of small cavitation voids in the liquid along the flow length. In the experimental diagram, there are no long-term pressure drops below atmospheric pressure, therefore, no large cavitation voids (discontinuities of flow continuity) are formed. The calculation chart depicts short-term decrease in pressure with the formation of small cavitation voids.

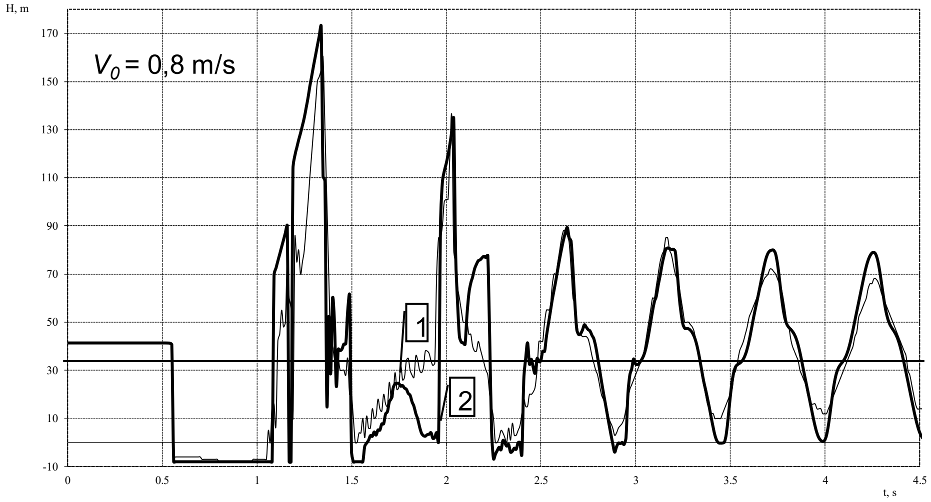

**Fig. 2.** Graphs of pressure changes at the gate valve: 1 – a graph based on experimental data; 2 –a graph obtained from calculated values.

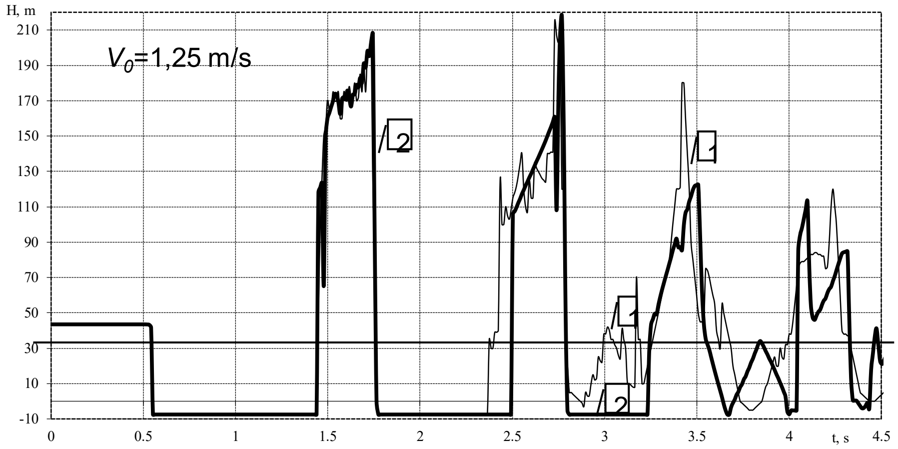

**Fig. 3.** Graphs of pressure changes at the gate valve: 1 – a graph based on experimental data; 2 –a graph obtained from calculated values.

At $V$ = 1.25 m/s (Figure 3), the experimental diagram clearly shows the formation of a discontinuity in the continuity of the flow (resonant vibrations in the second phase of compression) and the separation of the fluid flow from the valve. The graph demonstrates that the time of the pressure reduction phase increases, and the pressure increase phase acquires a columnar shape. The design diagram well reflects the separation of the fluid flow from the valve, while cavitation phenomena along the length of the conduit are less pronounced, the formation of a discontinuity in the continuity of the fluid flow also occurs in the third phase of pressure increase, that is, in the phase with a decrease in the flow velocity that occurs during a hydraulic shock, and this can be seen in both types of diagrams.

It can be concluded that the formation of small cavitation voids along the length of the pipeline in this case occurs at speeds of about 1 m/ s. At high initial speeds, first of all, there is a break in the continuity of the fluid flow at the valve, and only later, in the following phases of pressure reduction, with a decrease in the velocity of the fluid flow that occurs during the hydraulic shock, the formation of small cavitation voids along the length of the flow occurs.

The use of this calculation method allows us to take into account the factors affecting the process of hydraulic shock and to plot pressure change diagrams at any point of the pressure pipeline.

To reduce the likelihood of catastrophic manifestations of hydraulic shock, it is necessary first of all to carry out a full-fledged calculation of the entire pressure system. Based on the calculation results and diagrams of pressure changes in various characteristic points of the network, it is necessary, if necessary, to select measures and equipment to reduce the consequences of hydraulic shocks. Then, it is desirable to carry out a verification calculation of the simulated unsteady process taking into account shockproof measures and evaluate the effectiveness of the decisions taken.

## 4 Discussion

Under modern conditions, when laying pressure pipelines above ground, including in the permafrost distribution area, steel pipes remain a priority for customers. While designing and reconstructing, it is necessary to take into account that increasing the thickness of the pipe wall does not reduce the likelihood of hydraulic shocks. However, if you open the GOST corresponding to the type of steel pipe production, you can see that the theoretical mass of 1 m of pipe for the same diameter, but different wall thickness differs at times. It is evidently that the cost of pipes increases significantly with increasing wall thickness, and heavier pipes require reinforced supports for overhead laying. From the point of view of countering the negative consequences of hydraulic shock in water pressure pipes, the use of extra-thick-walled or thick-walled pipes is justified only by the working pressure of steady fluid movement, requiring the use of such high-strength pipes.

The speed of steady motion of the fluid flow, as can be seen from experiments and calculated data, directly affects the process of hydraulic shock. When operating pipelines made of different materials, it is known that over time the inner diameter of the pipes decreases due to the presence of deposits in the pipes. The thickness of the internal deposits of pipes that have been in operation for more than ten years reaches large values. Taking into account the heating of the transported water at low ambient temperatures, the process of accumulation of deposits inside the pipe is more active. The actual flow rate increases by 30-50% due to the narrowing of the cross-section.

In order to reduce the risks of hydraulic shock in pressure pipelines during aboveground laying, it is necessary to calculate the pipeline for the possibility of an unsteady process in a wide range of water flow velocities under steady-state conditions. In accordance with the outcomes of the calculation, in the event of pressure values many times higher than the pressure value during the steady-state process during the simulation of the water hammer process, it is even possible to consider changing the route of laying the pipeline system to exclude areas with a sharp rise.

In permafrost conditions, even small water leaks, especially warm water in winter, can lead not only to the destruction of the pipelines themselves, their supports, but also to environmental pollution [16, 17]. It is necessary to direct efforts to prevent the occurrence of hydraulic shock at the design stage of the pressure system, and not to deal with its consequences, especially in difficult climatic conditions. Changing the pipeline route, reducing the speed of water movement during a steady process, leading to an increase in pipeline diameters are expensive measures, but the long–term effect of reliability and trouble-free operation of the system as a whole is more valuable.

Shockproof protection should be based on the calculated values of pressure in the pipeline and include versatile measures to prevent not only pipeline ruptures, but also long-term pressure drops below atmospheric, excluding the development of reverse velocities of water movement of significant magnitude.

## 5 Conclusion

The calculations carried out show that an increase in the wall thickness of a steel pipe does not lead to a decrease in the velocity of propagation of the shock wave front, and, therefore, does not lead to a decrease in the magnitude of the resulting maximum pressure during hydraulic shocks. On the other hand, low values of the propagation velocities of the pressure wave in pipes made of polymer materials do not guarantee the impossibility of shocks accompanied by discontinuities of the continuity of the fluid flow, which are also accompanied by high values of shock pressure.

The results obtained confirm that the velocity of fluid movement at steady state in the pressure system has a direct effect on the pressure value in the pipeline during hydraulic shock. Reducing the speed of fluid movement in the pipeline in operation and determining the optimal speed range for the projected pipeline will avoid catastrophic manifestations of hydraulic shock.

Process modeling using the method of characteristics allows to calculate the parameters of hydraulic shock in the pressure pipeline with above-ground laying with sufficient accuracy, thereby contributing to the selection of the most effective and sufficient measures to reduce the risks of destructive unsteady processes.

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