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NUMERICAL SIMULATION OF DRILLING FLUID FLOW IN ANNULAR THE SPACE OF THE BOREHOLE**

1. INTRODUCTION

Simulation of flow of drilling mud is one of the most important processes which reduced the costs of experimental study in the future design and planning work borehole. The ability to compare the results obtained in the numerical simulation of the flow of drilling fluid from the results obtained experimentally, allows setting in general parameters input to numerical solutions.

The possibility of numerical modelling of the flow of drilling fluids allows for rapid evaluation of hole hydraulic. There are many computer programs that allow for the solution of problems in fluid mechanics based on analytical assumptions of classical fluid mechanics on the market. However, a thorough analysis can be carried out only by numerical methods.

The possibility to use advanced computing systems enables an accurate analysis of mud flows, taking into account the actual geometry of the a tubular and the annular space of the borehole.

In the case of hydraulics of borehole drilling fluid is analyzed. Mud flow during normal flow goes through the drill string, then through the nozzles, arranged in the drill bit enters the annular space, in which space washer drill cuttings go back to the surface. Drilling a borehole in the conduit may be adopted for the analysis of the smooth tube, but an annular space is not uniform. The drill string consists of standard screwed drill pipes (usually segments of 9 meters) the where there is a change in geometry of drill pipes (tool joint), causes disturbances in the flow of the mud. Changes in geometry causes changes in fluid flow velocity and the local change in pressure. The vertical drill pipe holes are usually located centrally in the borehole but in the horizontal drilling (HDD) the drill pipe lies on the bottom of the borehole and are arranged eccentrically. In such cases, the geometry of the annular space is changing, thus the flow influences the elevation of the cutting.

A numerical analysis of mud flow makes possible a reduction of the cost of experimental studies and also allows for analyzing the real geometry of a borehole.

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2. NON-NEWTONIAN FLUID FLOW THROUGH CONCENTRIC AND ECCENTRIC ANNULI

Traditionally in the analysis of the behaviour that the drill pipe are concentric with the hole it was assumed of drilled cuttings in the wellbore annulus. The drill pipe are usually not concentric especially during directional drilling when the pipe weight causes a tendency for the pipe to lie against the hole. A realistic prediction of cutting behaviour through the annulus includes the necessary analysis of the velocity distribution of the transport fluid.

Tt is necessary to avoid complicated mathematical models, to ensure the filed applicability of the results. Since the equation describing non-Newtonian flow through parallel plates are easier to use then conventional annular flow equations, the eccentric annulus is presented as nonrectangular slot.

The behaviour and mud flow in tubular and annular space on a borehole is discussed in several related publications. In the beginning the problem was performed by Tao and Donovan in 1955 [6], they concentrated on theoretical and experimental work on the laminar and turbulent flow through the annulus. The next investigator Heyeda in 1959 [7] carried out an analytical solution of the annulus velocity distribution. He solved the Poisson equation for point velocities using the Green function and bipolar coordinates. In 1981 Iyoho [5] suggested to solve the problem of annular flow of mud using numerical methods like the finite difference method [8].

For the concentric example problem can be analysed in a simple way by staring by separating from mud stream part of volume as ring with external and internal radius $(r + \Delta r)$. Length of ring is ΔL [1–3].

Fluid flow of non-Newtonian fluid through the annular space must be set from the relationship:

$$Q_1 = \int_{R_1}^{R_2} v 2\pi r dr = \int_{R_1}^{R_2} \left[\frac{1}{4\eta} \frac{\Delta p}{\Delta L} \left(R^2 - r^2 \right) - \frac{\tau_y}{\eta} \left(R - r \right) \right] 2\pi r dr \tag{1}$$

Performing the necessary calculations we obtain:

$$Q = \frac{\pi}{8\eta} \frac{\Delta}{\Delta} \left[\left(R_2^4 - R_1^4 \right) - \frac{\left(R_2^2 - R_1^2 \right)}{\ln \frac{R_2}{R_1}} \right] - \frac{\pi\tau}{\eta} \left(R_2 - R_1 \right) \left[\frac{R_2^2 + R_1 \cdot R_2 + R_1^2}{3} - \frac{\left(R_2^2 - R_1^2 \right)}{2 \ln \frac{R_2}{R_1}} \right] \tag{2}$$

where $D_1 = 2R_1$, $D_2 = 2R_2$ obtained from the laminar flow resistance plastic-viscous fluid in the annular space between the concentrically two tubes:

$$\Delta p = \frac{128 \eta Q \Delta L}{\pi \left(D_2^4 - D_1^4 - \frac{\left(D_2^2 - D_1^2 \right)^2}{\ln \left(\frac{D_2}{D_1} \right)} \right)} + \frac{16 \tau_y \Delta L \left[\frac{D_2^2 + D_1 \cdot D_2 + D_1^2}{3 \left(D_2 + D_1 \right)} - \frac{\left(D_2 - D_1 \right)}{\ln \frac{D_2}{D_1}} \right]}{D_2^2 + D_1^2 - \frac{D_2^2 - D_1^2}{\ln \left(\frac{D_2}{D_1} \right)}} \tag{3}$$

The analytical solution for eccentric annular space is very complicated and this is the reason for using numerical methods for analysing the problem.

3. RHEOLOGICAL MODELS OF DRILLING FLUIDS

For a numerical analysis of flow it is necessary to choose an appropriate rheological model of fluid. In the horizontal directional drilling, in the vertical drilling, jacking, and microtunnelling methods of various fluids are used, e.g. drilling fluids, sealing slurries, buffer fluids, fracturing fluids and fracture support fluids. Their physical properties and rheological parameters vary and depend on the function of the fluid.

The proper selection of the rheological parameters of the drilling fluids is very important, from at utility point of view. It enables optimization of the applied technique and technology and minimization of cost of drilling works. For describing the cause-and-effect relations between the rheological parameters and the technology, rheological models are constructed. The presently applied drilling fluids are usually non-Newtonian fluids having characteristics close to plasticviscous or pseudoplastic fluids [4, 5].

For drilling technologies most frequently the following rheological models are applied:

– Newtonian: $\tau = \eta\left(-\frac{dv}{dr}\right)$ (4)

– Bingham: $\tau = \tau_y + \eta_{pl}\left(-\frac{dv}{dr}\right)$ (5)

– Ostwald de Waele: $\tau = k\left(-\frac{dv}{dr}\right)^n$ (6)

– Casson: $\tau^{\frac{1}{2}} = \tau_y^{\frac{1}{2}} + \eta_{cas}^{\frac{1}{2}}\left(-\frac{dv}{dr}\right)^{\frac{1}{2}}$ (7)

– Herschel–Bulkley: $\tau = \tau_y + k\left(-\frac{dv}{dr}\right)^n$ (8)

For an analysis in this article assumes Herschel–Bulkley rheological model of fluid for laminar flow. The following parameters of the rheological model were used:

Table 1

Parameters rheological Herschel–Bulkley model

Consistency index, *k* [kg/ms]	0.5859
Power Low index, *n* [–]	0.4
Yield Stress Threshold [pascal]	0.2777
Critical Shear Rate [1/s]	1000

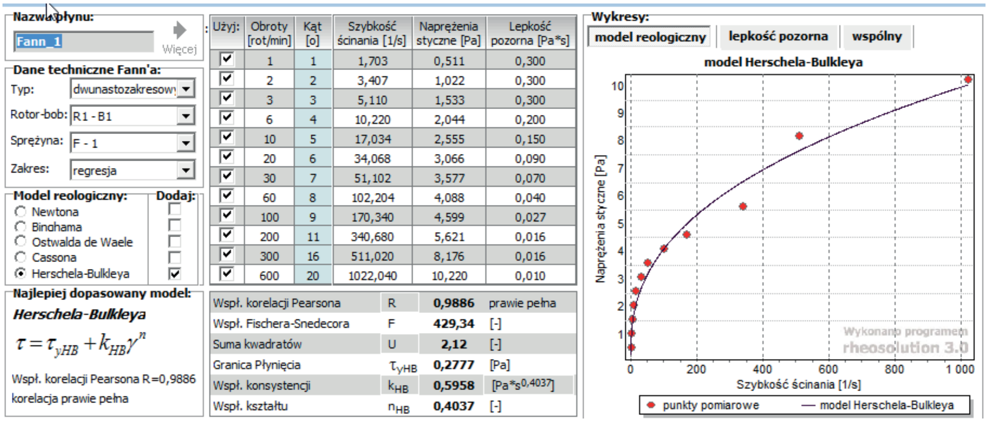

Fig. 1. Parameters of mud presented in program Resolutions

4. NUMERICAL ANALYSIS

ANSYS FLUENT system was used for numerical analysis of drilling fluid flow. The system FLUENT used numerical method based on finite volume method [9].

The finite volume method (FVM) is a discretization technique for partial differential equations, especially those that arise from physical conservation laws. FVM uses a volume integral formulation of the problem with a finite partitioning set of volumes to discretize the equations. FVM is in common use for discretizing computational fluid dynamics equations.

Equations used in FVM in ANSYS FLUENT are mass conservation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = S_m \tag{9}$$

and momentum conservation

$$\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla p + \nabla \cdot (\bar{\bar{\tau}}) + \rho \vec{g} + \vec{F} \tag{10}$$

The stress tensor $\bar{\bar{\tau}}$ is given by

$$\bar{\bar{\tau}} = \mu \left[\left(\nabla \vec{v} + \nabla \vec{v}^T \right) - \frac{2}{3} \nabla \cdot \vec{v} I \right] \tag{11}$$

where μ is the molecular viscosity and *I* is the unit tensor.

The analysis was performed on three examples. The first example: smooth drill pipe (without tool joint) concentric located, second: drill pipe with tool joint locally concentric, third: drill pipe with tool joint locally eccentric in borehole.

The geometry of the borehole was the same in all examples, the diameter of the hole $D = 311$ mm was assumed for the calculation. In the first example the diameter of the drilling pipe is $d_1 = 120$ mm, in the second the diameter of the drilling pipe is $d_1 = 120$ mm in the tool join D = 156 mm. In the third example the diameter of the drilling pipe is d_1 = 120 mm in the tool join D = 156 mm and eccentrics e = 75 mm. Sketches of the geometry are presented in Figure 2.

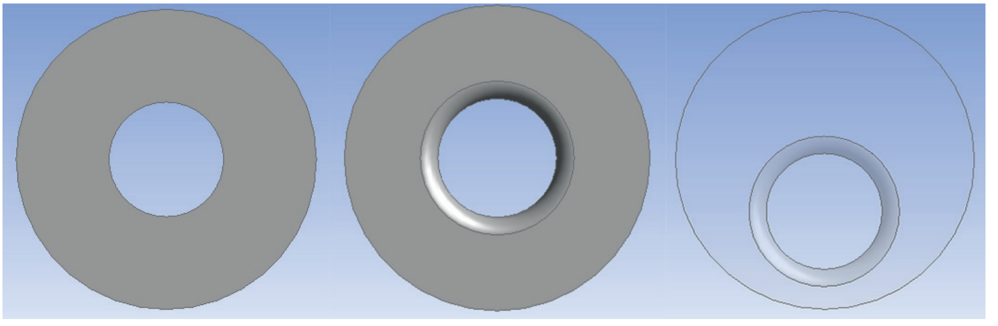

Fig. 2. Sketches of geometry of analyzed borehole

For the analysis of the drill pipes with a total length of 36 m for each example 4 segments are taken. Created mashes use quadrilateral and hexahedral elements and detailed information are presented in Table 2. Samples of mashes are presented in Figure 3.

Table 2

Mashes details: numbers of nodes and elements

	Example 1	Example 2	Example 3
Nodes	364914	337365	350415
Elements	307120	272952	285564

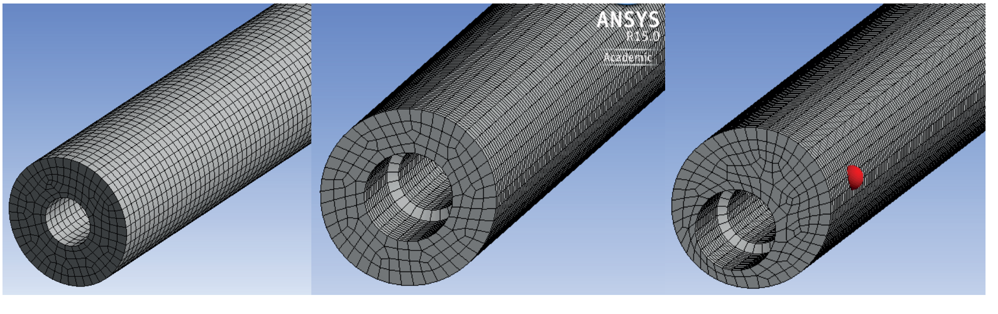

Fig. 3. Examples of used mashes

5. RESULTS

During the analysis the results of the calculations of the flow and dynamic velocity were obtained. The results of the analysed velocity of the flow are presented in Figures 4 and 5 streamlines of the velocities are presented. The pictures presented characteristic place of drill pipe with tool join. In the results of the third example, with the eccentric drill pipe, the values of the flow velocity are the highest.

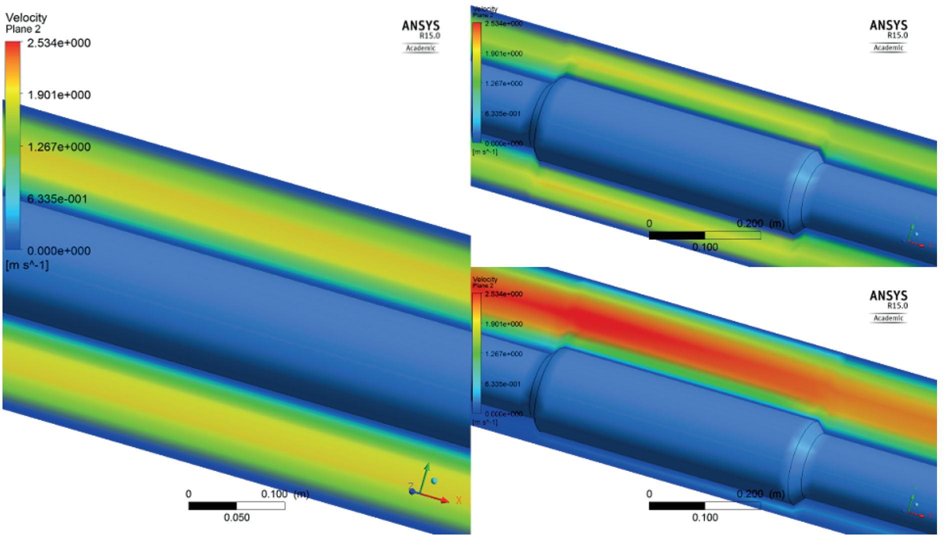

Fig. 4. Flow velocity in three cases

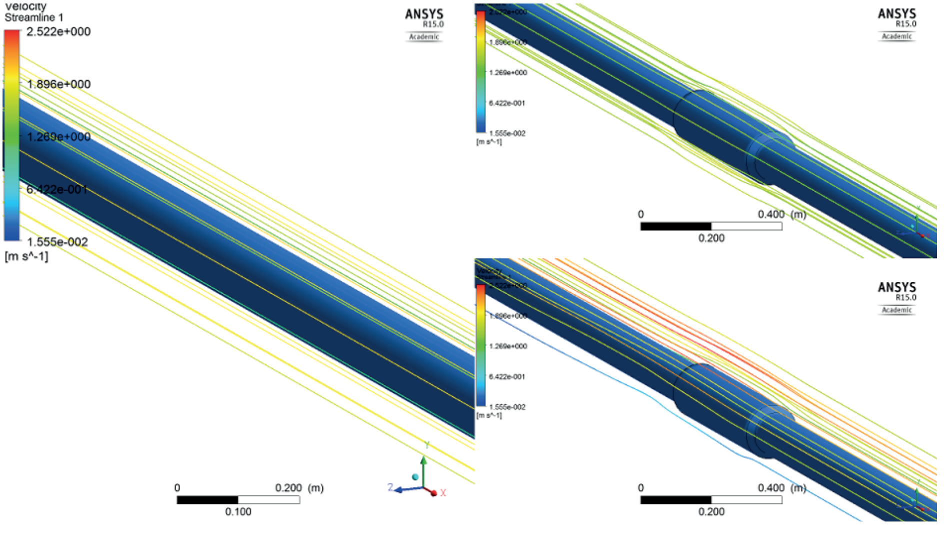

Fig. 5. Streamline of the velocity in three cases

Also, the results of the changes of pressure during the flow in the annular space with special focus on points of borehole with tool joints were obtained. The colour map of the dynamic pressure is presented in Figure 6 and the pressure gradient in Figure 7.

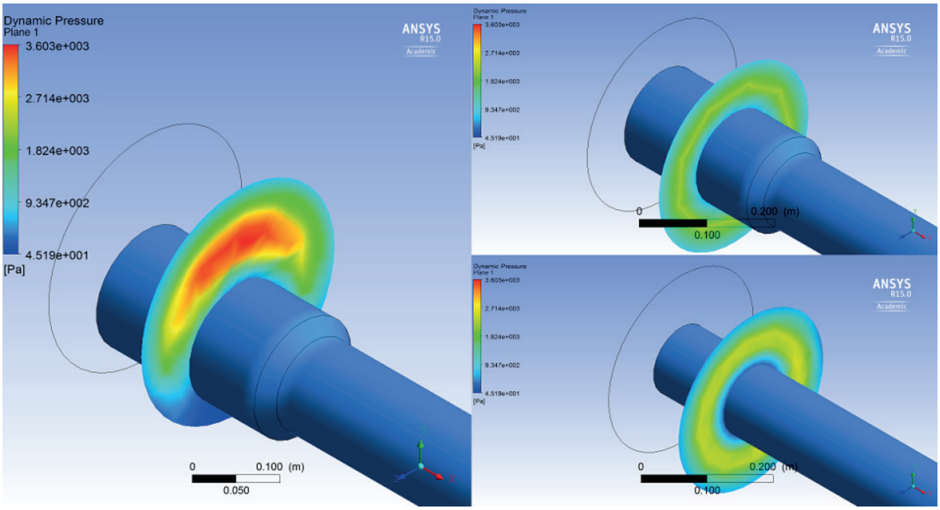

Fig. 6. Dynamic pressure in point on tools joint in three cases

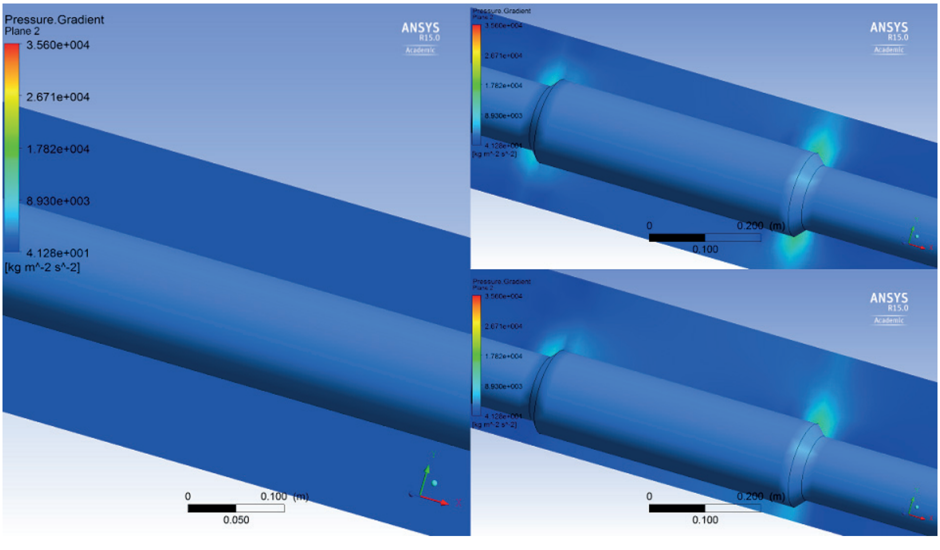

Fig. 7. Colour map of gradient pressure in point on tools joint in three cases

Numerical system ANSYS FLUENT gives also possibilities for the analysed dynamic changes of viscosity. The viscosity in the non-Newtonian fluid is not constant and is described by rheological models. The dynamic viscosity is presented in Figure 8.

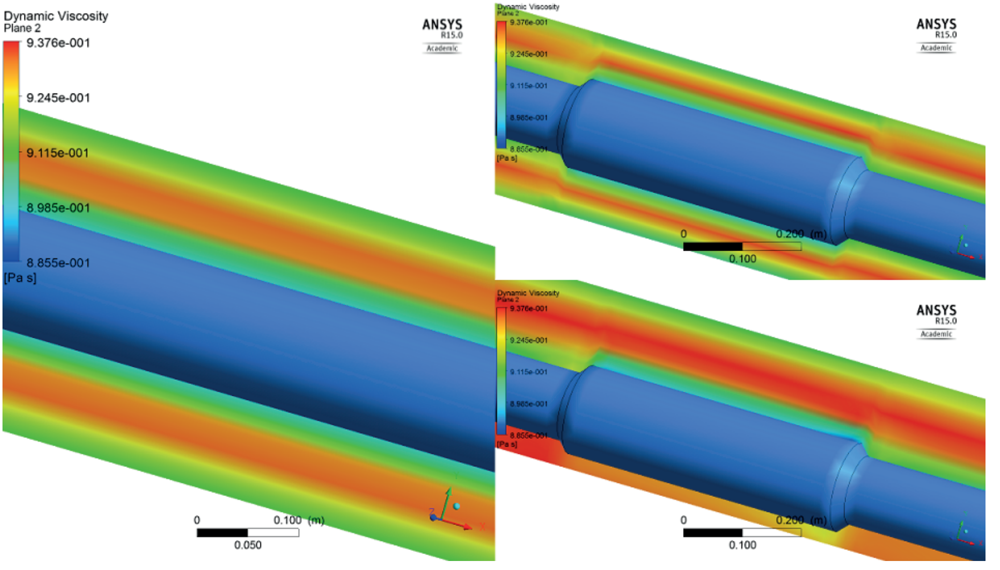

Fig. 8. Colour map of the dynamic viscosity in point on the tools joint in three cases

The changes of dynamic pressure during mud flow in annual space in borehole are presented on Figure 9.

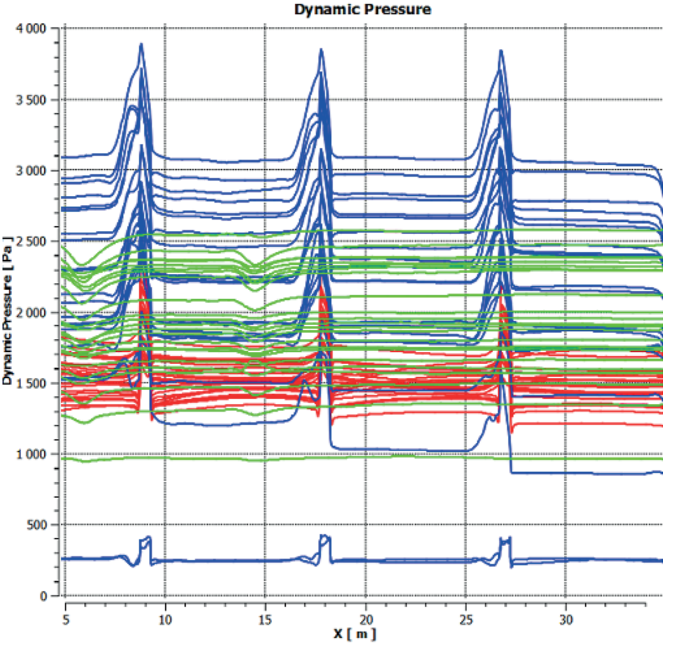

Fig. 9. Chart of dynamic pressure in three examples: blue – eccentric drill pipe, red – concentric drill pipe, green – strait drill pipe

6. CONCLUSION

An analysis of flow of drilling fluid in the annulus has shown that it is appropriate for the analysis of fluid flow taking into account a variable geometry of the drill string. Variable geometry is associated with a larger diameter drill in the joints of drill pipes, and consequently, with reduced flow cross-section. A comparison of pressure values at the end of the analyzed examples showed that in the example of a simple drill pipe without joints, pressure values were 30% higher than in the case, which takes into account changes in the geometry of the joints. Taking this factor in to account will result in a more accurate planning of borehole work.

In the future it is planned to analyze the turbulent flow of drilling fluid in tubular and annular space including the eccentric position the drilling pipe in the borehole.

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