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MODELING OF TWO PHASE FLUID FILTRATION IN RESERVOIR WITH HIGH PERMEABILITY COLLECTOR

1. INTRODUCTION

Problems of oil recovery completeness and wells permeability increasing are one of the first priority problems in increasing of recovery profitability and rational using of natural resources of oil deposits especially with low filtration capacitive properties of collectors. Reducing of irretrievable losses in deposits gains in main importance at emaciated deposits which had been exploited long time. Methods of highly remunerative oil production with maximal possible hydrocarbon excavation rate should be based on mutual coupling of closed hydrodynamic system, which consist on following units: oil seam – extracting well – recovery and preparation system – system of seam pressure maintenance (SPM) – injection well – oil seam. At this time development of new methods and technology for oil recovery growth is a base for improvement efficiency of hydrodynamic system work.

One of the modern way to increase oil recovery is a radial drilling technology. At radial drilling collectors with high permeability are constructed for oil recovery from high thickness seam with low filtration capacitive properties. Radial drilling is a method of horizontal high permeability collector creation on basis of using modified technology of flexible pump-compressor pipe [1]. Lateral holes with diameter 50mm are drilled at distance 150 m from borehole under high pressure. Radial holes could be drilled at several levels.

Advantages of radial drilling technology [1]:

- increasing of well production and recoverable reserves of low production wells;
- improvement of water supply rates in injection wells;
- allow to make directed well treatment for example by acid and etc.;
- allow multilayer using in zones with big seam thickness;
- decelerate process of bottom water coning.

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Investigation of bottom water influence in bottom hole zone is of important practical interest. This problem is known at oil deposits exploitation by vertical and horizontal wells [2–7].

In present paper motion of bottom water in a seam with high permeability collector is investigated, i.e. how and how fast bottom water reaches to high permeable collector depending on capability of seam and reservoir fluids. Elaboration of mathematical model of fluid filtration in the layer with high-permeability collector and calculations presents practical meaning for definition of radial drilling efficiency and estimation of flow rate to high permeability collector.

Filtration of fluid in the seam could be described with a model of cracked-porous medium by representing collector with high permeability as a crack [8]. However for this model it is necessary to solve system of filtration equations in crack and porous block with satisfaction of conjugate condition on medium's division boundary [8]. Problem formulation and solution is complicated for this model in case of two phase fluid filtration.

Approach based on conception of interpenetrating continuums is simpler [9, 10]. In this case two phase fluid filtration in porous block with high permeable collector is described from a uniform position. Some calculation results of proposed generalized two-phase filtration model are led below.

2. MATHEMATICAL MODEL

As it shown above in practice kickoff of horizontal lateral borehole is made by drilling hole with diameter 0.05 m and length till 150 m. Direct simulation of lateral borehole is possible by 3D modeling and required good computer resources. Therefore for testing proposed approach of high permeable collector mathematical model elaboration two-dimension problem with plane crack which height is 0.05 m., length – 95 m. and extended width is investigated. Filtration domain for this problem formulation is shown in Figure 1. As it shown in Figure 1 filtration domain is a plane high permeable collector for fluid recovery from seam with low permeable properties. Collector has the same porosity, but its permeability is higher than seam permeability and it is located above the bottom water level. High permeable collector is connected with well, pressure in it is lower than in the seam, and pressure sink is occurred and caused fluid inflow. As it is noted above technology of radial drilling is used to stimulate oil recovery of low permeable blocks therefore filtration velocities will be small and obey to linear Darcy's law. Both fluids are incompressible, gravity forces are taken into account.

Experimental data shows that almost all seams are anisotropic and permeability coefficient by vertical is lower than in horizontal direction. At initial time both fluids are rest in equilibrium and water oil contact is a plane surface. It is required to define pressure distribution in system, position and shape of boundary between oil and water and time of water inrush to well.

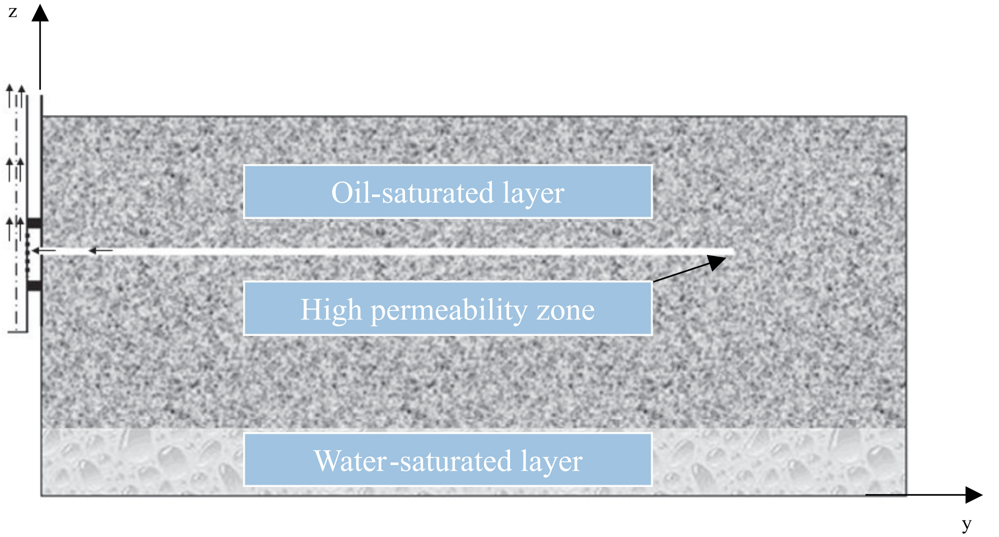

Fig. 1. Scheme of seam with high permeable collector

Generalized system of equations of two-phase filtration with following assumptions could be written as [11, 12]:

$$\nabla \cdot (\tilde{\lambda} \nabla p) = -\nabla \cdot ((\gamma_w \tilde{\lambda}_w + \gamma_o \tilde{\lambda}_o)) \nabla z) \tag{1}$$

$$\vec{u}_T = -\tilde{\lambda} \nabla p - (\gamma_w \tilde{\lambda}_w + \gamma_o \tilde{\lambda}_o) \nabla z \tag{2}$$

$$\phi \frac{\partial S_w}{\partial t} + \nabla \cdot (f_w (\vec{u}_T - \tilde{\lambda}_o (\gamma_w - \gamma_o) \nabla z)) = 0 \tag{3}$$

$$\tilde{\lambda}_i = K \lambda_i, \lambda_i = \frac{k_i(S_w)}{\mu_i}, \gamma_i = \rho_i g,\ i = o, w,\ \tilde{\lambda} = \tilde{\lambda}_o + \tilde{\lambda}_w \tag{4}$$

$$f_w = \lambda_w / (\lambda_w + \lambda_o) \tag{5}$$

where:

S_w – water saturation,
p – pressure,
ϕ – porosity,
$\vec{u}_T$ – summarized filtration velocity,
μ_i – viscosity,
k_i – relative phase permeability,
ρ_i – density,
g – gravitational acceleration, tensor
K – tensor of rock permeability.

Relative phase permeability for oil and water are defined experimentally. It is known [13] that structure of equation's solution which describe two-phase fluid filtration and definition of technologic characteristics such as time of water inrush strongly depend on relative permeability. Power approximation of relative permeability is often used in numerical calculations [14]:

$$k_{\mathrm{w}} = A_1(S_w - \underline{S}_w)^{\beta_1}, k_{\mathrm{o}} = A_2(\overline{S}_w - S_w)^{\beta_2}, \underline{S}_w \le S_w \le \overline{S}_w \tag{6}$$

here:

$\underline{S}_w, \overline{S}_w$ – bound and maximal values of water saturation correspondingly,

$A_1, A_2, \beta_1, \beta_2$ – number described porous medium structure and its hydrophilic property.

In numerical calculations the numbers are taken I following ranges $1 < \beta_1, \beta_2 < 4$. For example in Uzen deposits' natural cores dependence (6) are taken as:

$$k_w = 0,2\left(\frac{S_w - 0,3}{0,7}\right)^{2,85}, \quad k_o = 0,95\left(\frac{0,72 - S_w}{0,42}\right)^{1,95}.$$

Boundary condition for pressure: at roof and bottom – no cross-flow condition, at well – well production or pressure constancy (bottom hole pressure), far away from well – pressure constancy (contour pressure); and for saturation: on bottom – constancy, in another parts – zero normal derivative.

System of equations (1)–(3) is solved with following initial and boundary conditions:

$$p(y,z,0) = p_o(z) \tag{7}$$

$$S_w(y,z,0) = \begin{cases} \overline{S}_w, & npu \;\; 0 \le z \le h_w \\ \underline{S}_w, & npu \;\; h_w < z \le h \end{cases} \tag{8}$$

$$S_w\big|_{z=h_w} = \overline{S}_w \tag{9}$$

$$\left.\frac{\partial S_w}{\partial y}\right|_{y=L} = 0 \tag{10}$$

$$\left.\frac{\partial p}{\partial z}\right|_{z=0} = -\gamma_w, \quad \left.\frac{\partial p}{\partial z}\right|_{z=h} = -\gamma_o \tag{11}$$

$$
\begin{cases}
\int\limits_{h_d - r_0}^{h_d + r_0} \tilde{\lambda} \nabla p \Big|_{y=0} dz = q, \quad h_d - r_0 < z < h_d + r_0 \\
\dfrac{\partial p}{\partial y}\Big|_{y=0} = 0, \qquad otherwise
\end{cases}
\tag{12}
$$

$$
p\big|_{y=L} = p_0 \tag{13}
$$

where:

h – thickness of layer,

h_w – thickness of water-saturated layer,

$\overline{S}_w, \underline{S}_w$ – upper and lower limit of water saturation,

$2r_0$ – height of high permeable collector,

q – rate of liquid picked up at section $y = 0$ (in interval $h_d - r_0 < z < h_d + r_0$),

h_d – position of high permeable collector in vertical section,

L – length of oil reservoir.

Thereby generalized equations' system (1)–(5) with initial and boundary conditions (7)–(13) is used to describe two immiscible fluids filtration in porous seam with high permeable collector. Proposed common approach allows constructing efficient numerical algorithm with automatic satisfaction of conjugate condition at medium interface.

3. NUMERICAL METHODS

For numerical implementation of equation's system (1)–(11) computational grid which allow to visual demonstrate each cell as volume's element are taken [15, 16]. Pressure equation (1) is solved by implicit method of alternating directions [17]. Saturation is calculated by explicit upstream scheme. Distribution the pressure field is calculated from equation (1) by known initial pressure. The velocity field is obtained from equation (2) using defined pressure fields, saturation distribution is obtained from equation (3).

Calculation of water coning process in bottom hole zone of vertical well are led for mathematical model of two phase fluid filtration and numerical method approbation. Calculations are led for comparison with similar results of other authors [5]. However direct maintenance of all regime parameters (structural, seam, hydrodynamic, thermal) and reservoir fluids and rock properties in calculations are impossible because of shortage of published data in paper [5].

Pressure, saturation and velocity fields at different time have been obtained. Comparison of numerical results by definition of water saturation distribution with data from paper [5] is shown in Figure 2. Results are obtained for seven variants of empirical dependences of relative permeability, i.e. power of β_1, β_2 in dependence (6) were varied in calculations.

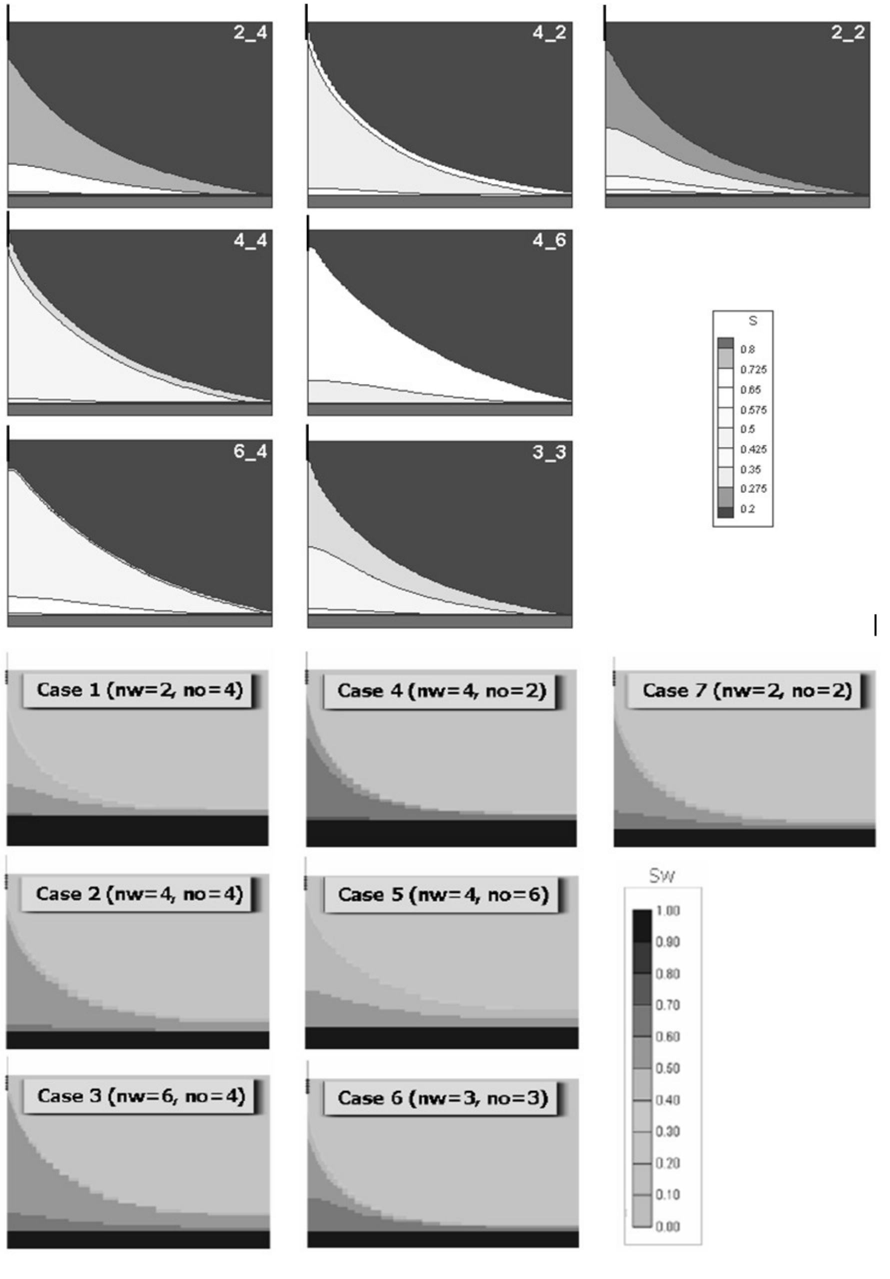

Fig. 2. Comparison of numerical results with similar data [5]:
upper – author's calculation, lower – [5]

It is shown that qualitative coincidence is obvious from Figure 2. Quantitative difference is explained by disagreement of regime's parameters and conditions [5].

4. RESULTS AND DISCUSSIONS

Investigation of mathematical model and method of two phase filtration solution of mixable liquids is carried out in [6,7]. The influence of seam and reservoir fluids characteristics on oil recovery process at deposits exploited by horizontal and inclined wells are studied there numerically. Seam anisotropy is important geologic characteristic which has big influence on deposit's exploitation. Influence of seam anisotropy rate on oil recovery dynamic at deposit exploitation by vertical well is considered in paper [6]. Effects of anisotropy ratio on horizontal well watering are studied in [7]. Values of vertical permeability to horizontal one [6, 7] are varied in the range from 0.01 to 1.0. Analysis of results [6,7] shows that increasing of seam anisotropy rate lead to growth of oil recovery and reduction of well watering.

Influence of seam anisotropy rate on exploitation parameters is studied by proposed model and comparison of calculation results with known ones are led. This problem is described interaction between ground water motion and oil recovery from sandstones and has big practical meaning in connection with ubiquitous spreading of groundwater near oil-saturated rock.

Calculation are led for following seam size: length of oil reservoir – 100 m., thickness – 30 m., length of high permeable collector – 95 m., height – 0.05 m.

Following parameters of seam and formation fluid have big influence on bottom water moving:

$k_{vh} = \dfrac{k_v}{k_h}$ – anisotropy ratio.

Calculation results for different values of anisotropy rate k_{vh} with the values of seam and collector permeability $k_{ch} = 50$, well production $q = 10$ m^3/day, mobility ratio $\mu = 0.07$ in all cases are shown in Figures 3–7.

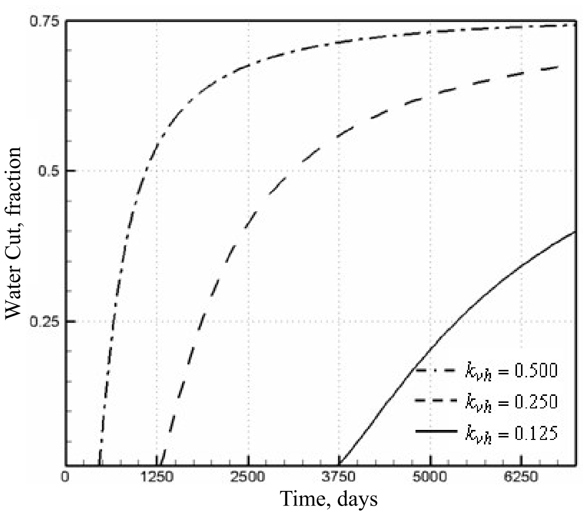

Fig. 3. Influence of anisotropy rate on seam watering

Watering is an important integral characteristic of process (Watering is water portion in extracted fluid at y = 0 section). Influence of seam anisotropy rate on watering is shown in Figure 3.

It is shown in Figure 3 that with reducing of seam anisotropy ratio bottom water moves quickly to high permeability collector and have bad influence to oil recovery. Water breaks to high permeable collector at anisotropy ratio k_{vh} =0.5 in 473 days, whereas at values of anisotropy rate k_{vh} = 0.125 in 3700 days (Fig. 4). It is easy to note that dependence of reducing of seam anisotropy ratio on water inrush to high permeable collector falls by non-linear law with horizontal asymptote. It might be concluded from received results that water could not arbitrary fast achieve high permeable collector [6, 7].

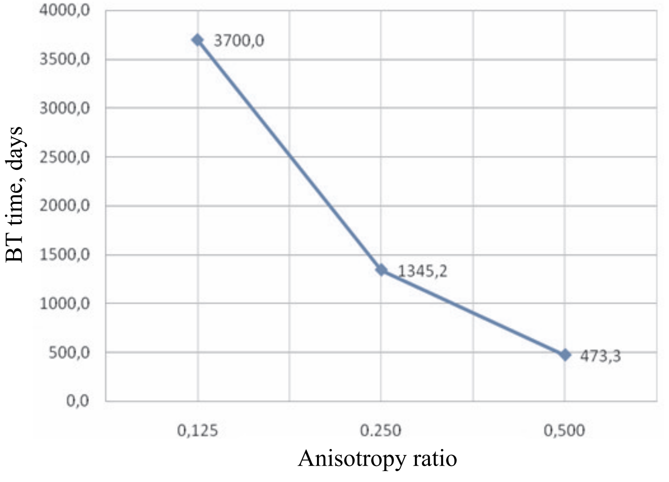

Fig. 4. Dependence of time of water break on anisotropy ratio

Distribution of water saturation front by time for different values of anisotropy rates are shown in Figures 5–7. Front of water saturation with value S_w = 0.32 is separated for analysis convenience.

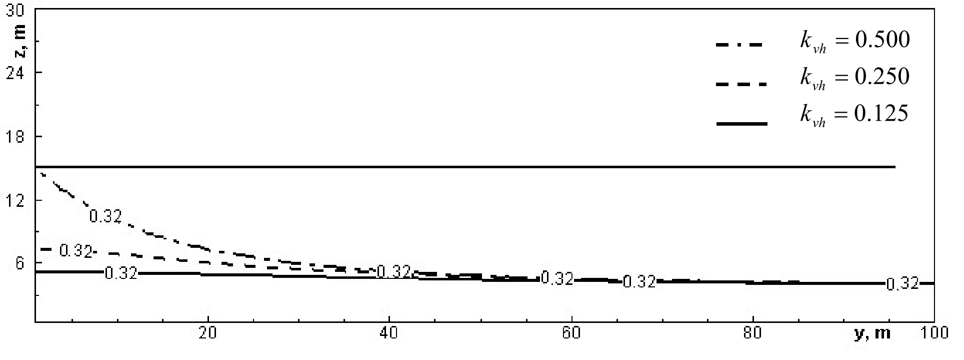

Fig. 5. Saturation front distribution for different values of anisotropy ratio at time moment 420 days

Figures 5–7 shows that saturation fronts are distributed irregularly among the length of horizontal high permeable collector. Occurrence of this effect is increasing with reducing of anisotropy rate.

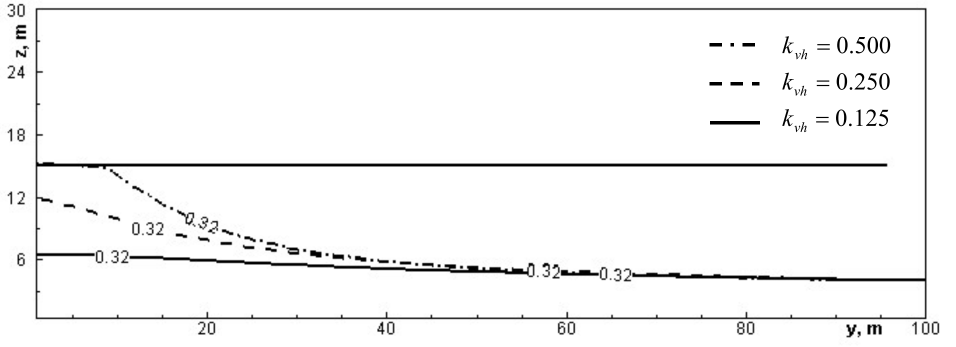

Fig. 6. Saturation front distribution for different values of anisotropy ratio at time moment 2.7 years

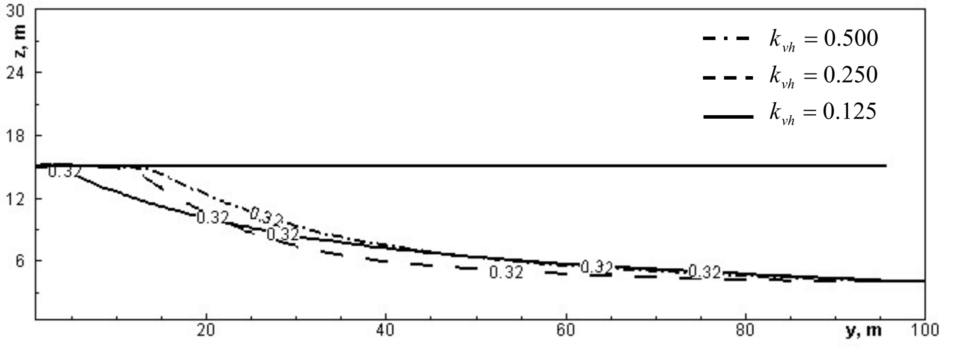

Fig. 7. Saturation front distribution for different values of anisotropy ratio at time moment 10.2 years

For anisotropy ratio k_{vh} =0.125 water-oil contact uniformly distributes along all length of collector. Fluid recovery takes place in the beginning of high permeable collector. In connection with it this circumstance has good quantity agreement with hydrodynamic of channel with fluid inflow through porous walls [18–20]. Last fronts of saturation achieve leading overtaking each other much time later (in adduced example – about 10 years). Water-oil contacts appropriate to different various values of anisotropy rates is combined.

5. CONCLUSIONS

Thereby water front with saturation value S = 0.32 moving for three k_{vh} values by time shows that reducing of anisotropy rate results in quicker watering of high permeable collector. It is also notably from watering dependence on time of water breakthrough for different

k_{vh} values. Saturation front had reached high permeable collector the faster at low values of seam anisotropy rate. Physically it could be easy explained. Reducing of anisotropy rate caused increasing of vertical seam permeability therefore water-oil surface front faster reach high permeable collector. For example at anisotropy rate k_{vh} = 0.5 time of water inrush is equal to 473 days, whereas at k_{vh} = 0.125 time of water inrush is equal to 3700 days. It is to be noted that dependence of time of water breakthrough on seam anisotropy rate is non-linear with horizontal asymptote. Well watering is changed similarly, i.e. well watering is increasing as seam anisotropy reduces. The influence of seam anisotropy rate on well exploitation characteristics could be seen from following result: at value k_{vh} = 0.5 watering of production achieves 75% whereas at k_{vh} = 0.125 watering is raised to 40% in 7000 days.

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