Simulation of formation fluid withdrawal hydrodynamics using a downhole jet pump when studying the productive formation while well drilling

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Abstract. The article discusses hydrodynamics of the reservoir fluid withdrawal from the promising drilled formation interval with the use of a jet pump installed in the internal cavity of the drill pipe string in the wellbore bottom-hole part. The hydrodynamic problem of fluid production is solved. The solution connects the dynamics of injected, recoverable and upward flows of the circulating system.

1. Introduction
Combination of a well drilling technology with a productive formation testing technology significantly reducing the well construction time has undergone significant changes. Formation testing using a jet pump installed inside the string of drill pipes in the bottom-hole part of the wellbore is promising. Simultaneous use of an off-hole autonomous geophysical module equipped with sensors for measuring bottomhole pressure and a flushing fluid rate [1-5] allows for rapid testing of the prospective interval of the drilled formation.

2. Methods and materials
When solving the hydrodynamics problem, the basic laws of theoretical mechanics and hydromechanics were used in relation to the adopted technological scheme of formation fluid withdrawal.

3. Method content and efficiency
Well stimulation and withdrawal of formation are carried out after the rotary well drilling and drilling tool packing have been stopped, and the jet pump has run into the drilling tool and installed on the conical restrictor. The internal volume of the wellbore and drill pipes is filled with flushing fluid [6-8]. By pumping the flushing fluid from the drill pipe string through the channels of a direct-flow ejector pump, pressure drops due to an increase in its velocity through the channel. Depression of pressure on the well bottom and the entire sub-packer annulus is created. As a result, the bottomhole fluid is sucked into the mixing chamber of the pump. The mixed flow pumped through the pump and the liquid extracted from the reservoir rises along the tubing (or coiled tubing) to the surface.
Let us consider the hydrodynamic problem of the steady-state (stationary) process of borehole fluid withdrawal. Let us take pumped and extracted liquid incompressible.

Let $\rho_i$, $\rho_e$, $\rho_c$ be densities of the injected, extracted (bottom-hole) and mixed fluids. The geometrical parameters of all structural elements of the pumping system are known. Let us formulate the equations relating the hydrodynamic parameters (pressure $P$ and velocity $V$) of the moving fluid in all three flows. Pressure $P_0$ and flow rate $Q_0$ of the injected (pumped) fluid are the initial known parameters.

Figure 1. The design scheme of the downhole jet pump.

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Figure 1. The design scheme of the downhole jet pump.
In the injection flow near the pump inlet channels, let us denote a certain control liquid volume with horizontal (1-1) and vertical circular (2-2) sections and apply the theorem on the change in the amount of mass movement over an infinitely small time interval $dt$ projected on the horizontal axis [3]:

$$V_1 F_1 \rho_1 V_1 = (-P_1 F_1 + P_i F_i) dt,$$

where $V_1$ and $P_i$ are the speed and the pressure of fluid in the pump channel; $F_i$ is the total cross-sectional area of all pump channels; $P_i$ is the pressure in the injection flow of fluid at the level of the channel entrance.

We have

$$P_i = P_i - \rho_i V_i^2,$$  \hspace{1cm} (1)

Let us express $P_i$ through pressure $P_0$ at the wellhead

$$P_i = P_0 + \rho_i g H - \Delta P_s,$$  \hspace{1cm} (2)

where $H$ is the depth of the jet pump; $\Delta P_s$ is pressure loss in the drill string.

Neglecting the loss of pressure in the pump channels, let us assume that $P_i = P_{mf}$ is pressure of the fluid leaving the channels, i.e. pressure arising in the receiving mixing chamber. $P_{mf}$ should ensure suction of the downhole fluid and supply the injected and recovered mixture of fluids. Based on the assumptions and expression (1), taking into account (2), we have

$$P_c = P_0 + \rho_i g H - \rho_i V_i^2 - \Delta P_s,$$  \hspace{1cm} (3)

Since $V_1 = \frac{Q_0}{F_1}$, $F_1$ is the total cross-sectional area of all input channels; therefore,

$$P_c = P_0 + \rho_i g H - \rho_i \frac{Q_0^2}{F_1^2} - \Delta P_s,$$  \hspace{1cm} (4)

where $\Delta P_s$ is determined by calculation formulas or tables depending on the type and flow rate of the washing liquid [4]. $\Delta P_c = \alpha Q_0^2$, $\alpha = \text{const}$.

Let us present expression (4) for $P_c$ in the pump as

$$P_c = P_0 + \rho_i g H - A Q_0^2,$$ \hspace{1cm} (4*)

where $A = \left( \frac{\rho_i}{F_1^2} + \alpha \right) = \text{const}.$

The pump pressure is determined by formula

$$\Delta P_c = P_0 - P_c = \rho_i \frac{Q_0^2}{F_1^2} - \rho_i g H + \Delta P_s,$$ \hspace{1cm} (5)

In the general form, it can be expressed as

$$\Delta P_c = A Q_0^2 - \rho_i g H.$$ \hspace{1cm} (5*)

Based on expressions (4*) and (5*) in Figure 2, hypothetical graphs of pressure changes $P_c$ and $\Delta P_c$ depending on the flow rate $Q_0$ of the injected fluid and the depth of immersion $H$ of the jet pump are presented. While maintaining the rates of flow $Q_0$, pressure $P_i$ in the pump increases ($\Delta P_c$ depression decreases) with an increase in the pumping depth $H$ of the pump. As flow rate $Q_0$ of the injected fluid increases, pressure $P_i$ in the pump decreases ($\Delta P_c$ increases) in accordance with the depth of immersion of the pump. Constant pressure $P_c$ in the pump ($\Delta P_c = \text{const}$) is accompanied by an increase in the flow rate $Q_0$ of the injected fluid with an increase in the immersion depth $H$ of the pump.

To determine the relationship between $P_c$ in the receiving chamber and bottomhole pressure $P_e$, let us consider the hydrodynamics of the fluid flow withdrawn from the bottom. Let us take the control volume from the total flow of the recoverable fluid by cross sections (3-3) and (4-4) and construct the material mass balance equation

$$V_e F_e \rho_e dt = V_f F_f \rho_e dt,$$ \hspace{1cm} (6)

We have

$$V_e F_e = V_f F_f.$$  \hspace{1cm} (6)

Let us apply the theorem on the change in the amount of mass movement of the fluid volume

$$V_f F_f \rho_e dt V_f - V_e F_e \rho_e dt V_e = (P_e F_e - P_f F_f) dt - Rd dt - G dt,$$

where $R$ is the reaction force of the horizontal bearing surface of the pump limiter, $R = (P_e - \rho g h) (F_e - F_f)$; $G$ is the mass gravity of the liquid column, $G = \rho_e g h F_e$. 

\hspace{1cm}
Power of hydraulic resistance to flow is neglected. We have
\[
(V_f^2 F_f - V_e^2 F_e) \rho_e = (P_e - P_f) F_f - \rho_e g F_f h.
\]
Let us find pressure $P_f$ of the downhole fluid entering the pump nozzle.
\[
P_f = P_e - \rho_e g h - \rho_e \left( V_f^2 - V_e^2 \frac{F_f}{F_e} \right),
\]
where $h$ is the height of the suspension above the bottom of the jet pump. Taking into account expression (6) we obtain

Figure 2. Graphical representation of the relationship of the calculated parameters.
\[ P_f = P_e - \rho_e g h - \rho_e V_e^2 \left( \frac{F_e^2}{F_f} - \frac{F_e}{F_f} \right). \]

Since \( V_e = \frac{Q_e}{F_e} \),

\[ P_f = P_e - \rho_e g h - \rho_e Q_e^2 \left( \frac{1}{F_f^2} - \frac{1}{F_f F_2} \right), \quad (7) \]

where \( Q_e \) is the fluid flow supplied to the pump; \( P_e \) is fluid pressure at the well bottom.

Let us single out the subsequent control volume of the same fluid flow with cross sections \((4–4)\) and \((5–5)\), including the fluid flow at \( V_2 \) from the confuser with a cross section \( F_2 \) into the receiving mixing chamber. Similarly, let us construct a liquid mass balance equation

\[ V_f F_f = V_2 F_2 \]

and the expression of the theorem on the change in the amount of mass movement of the same volume of liquid

\[ (V_2^2 F_2 - V_f^2 F_f) \rho_e = P_f F_f - P_c F_2 - R_z, \]

where \( R_z \) is the component force of the pump nozzle surface reaction (confuser), \( R_z = P_f (F_f - F_2) \).

We have

\[ (V_2^2 F_2 - V_f^2 F_f) \rho_e = (P_f - P_c) F_2. \]

We find

\[ P_c = P_f - \rho_e \left( \frac{F_2^2}{F_f} - \frac{F_2}{F_f} \right). \]

From expressions (6) and (8) we have

\[ V_f = V_e \frac{F_e}{F_f}; \quad V_2 = V_f \frac{F_f}{F_2} = V_e \frac{F_e}{F_2}. \]

Then

\[ P_c = P_f - \rho_e F_f^2 V_e^2 \left( \frac{1}{F_2^2} - \frac{1}{F_f F_2} \right). \]

Replacing \( V_e = \frac{Q_e}{F_e} \), and taking account (7), we have

\[ P_c = P_f - \rho_e Q_e^2 \left( \frac{1}{F_2} - \frac{1}{F_f F_2} \right). \quad (9) \]

Accounting for (7), we have

\[ P_c = P_e - \rho_e g h - \rho_e Q_e^2 \left( \frac{1}{F_2^2} + \frac{1}{F_f} - \frac{1}{F_f F_2} - \frac{1}{F_f F_2} \right). \quad (10) \]

The general equation is

\[ P_c = P_e - \rho_e g h - B Q_e^2 ; \quad B = \text{const.} \quad (10^*) \]

Bottomhole depression caused by the pump is

\[ \Delta P_e = P_e - P_c = \rho_e g h + \rho_e Q_e^2 \left( \frac{1}{F_2^2} + \frac{1}{F_f} - \frac{1}{F_f F_2} - \frac{1}{F_f F_2} \right) \quad (11) \]

or

\[ \Delta P_e = B Q_e^2 + \rho_e g h. \quad (11^*) \]

On the basis of expressions \((10^*)\) and \((11^*)\), Figure 2b shows hypothetical dependencies of flow rate \( Q_e \) of the liquid extracted from the bottomhole depending on \( P_c \), \( \Delta P_e \) and height \( h \) of the jet pump suspension above the bottom hole.

With a constant value of \( P_c \) (constant depression \( \Delta P_e \)), the flow rate of extracted bottomhole fluid \( Q_e \) increases with a decreasing suspension height \( h \) of the pump and vice versa. At a fixed value of height \( h \), an increase in the flow rate of the bottomhole fluid \( Q_e \) decreases pressure \( P_c \) in the pump (by increasing depression \( \Delta P_e \) to the bottomhole). The constant downhole flow rate \( Q_e \) of the liquid when the height of the pump \( h \) changes (increases or decreases) is accompanied by a corresponding change (decrease or increase) in pressure \( P_c \) in the pump and depression of \( \Delta P_e \).
Let us consider the movement of a mixture of pressure and bottomhole fluids rising to the surface. Let us denote the control volume of the liquid enclosed in the cylindrical displacement chamber of the pump with sections (6-6) and (7-7). In this case, we assume that the intake (bottomhole) fluid flow entering section (6-6) retains its section area $F_2$ and its speed $V_2$. The injection fluid flow will have the same speed $V_1$ in its horizontal annular cross sections with area $F_1$ equal to the total cross-sectional area of all input channels.

$F_1 + F_2 = F_3$ is the sectional area of the flow channel of the mixing chamber.

The equation of material balance of the liquid for the control volume is

$$V_1F_1 + V_2F_2 = V_3F_3,$$

where $V_3$, is the average speed of the mixed fluid flow with flow rate $Q_c$ in the inlet section of the mixing chamber. The expression of the theorem on the change in the amount of mass movement of the allocated control volume of fluid is

$$V_3^2F_3\rho_c - V_1^2F_1\rho_1 - V_2^2F_2\rho_e = P_c(F_1 + F_2) - P_3F_3,$$

where $P_3$ is pressure of the mixture of fluid in the outlet section of the displacement chamber. Or

$$\frac{Q_3^2}{F_3}\rho_c - \frac{Q_1^2}{F_1}\rho_1 - \frac{Q_2^2}{F_2}\rho_e = P_c(F_1 + F_2) - P_3F_3. \tag{13}$$

Let us find

$$P_3 = P_c - \frac{Q_3^2}{F_3}\rho_c + \frac{Q_1^2}{F_1}\rho_1 + \frac{Q_2^2}{F_2}\rho_e. \tag{14}$$

In the same flow, let us take the subsequent control volume of the mixture of liquids with sections (7-7) and (8-8) which are boundaries for the mixing chamber and the pump diffuser.

The material balance equation is

$$V_3F_3 = V_kF_k,$$

where $V_k$, $F_k$ are the average velocity of the mixed flow of fluid leaving the pump cone into the coiled tubing and its cross-sectional area.

The expression of the theorem on the change in the amount of mass movement of the selected control volume is

$$\left( V_3^2F_k - V_2^2F_3 \right)\rho_c = (P_3 - P_k)F_3,$$

where $P_k$ is pressure of the mixture of fluid leaving the pump cone into the coiled tubing. Or

$$\left( \frac{Q_3^2}{F_k} - \frac{Q_2^2}{F_3} \right)\rho_c = (P_3 - P_k)F_3$$

$$Q^2\rho_c \left( \frac{1}{F_k} - \frac{1}{F_3} \right) = (P_3 - P_k)F_3. \tag{16}$$

Let us find

$$P_k = P_3 + Q^2\rho_c \left( \frac{1}{F_k} - \frac{1}{F_3} \right). \tag{17}$$

Taking into account (14), we find the expression linking $P_f$ and $P_c$

$$P_k = P_c + \frac{Q_3^2}{F_3}\rho_1 + \frac{Q_2^2}{F_2}\rho_e - \frac{Q_3^2}{F_k}\rho_c. \tag{18}$$

At the same time, pressure of the liquid mixture $P_k$ at the level of the pump immersion $H$ is expressed through outlet pressure $P_o$.

$$P_k = P_o + \rho_c gH + \Delta P_k, \tag{19}$$

where $\Delta P_k$ is pressure spent on overcoming hydraulic resistance in the coiled tubing.

Equating (18) and (19), we find the expression for outlet pressure of the liquid mixture

$$P_o = P_c + \frac{Q_3^2}{F_k}\rho_1 + \frac{Q_3^2}{F_k}\rho_e - \frac{Q_3^2}{F_k}\rho_c - \rho_c gH - \Delta P_k. \tag{20}$$

Taking into account expression (4) for pressure $P_c$ we have

$$P_o = P_c + g(\rho_1H - \rho_cH) - \frac{Q_3^2}{F_k}\rho_1 \left( 1 - \frac{F_1}{F_k} \right) - \frac{Q_3^2}{F_k}\rho_e - \frac{Q_3^2}{F_k}\rho_c - \Delta P_2 - \Delta P_k. \tag{21}$$
Assuming in (21) the value \( P_e = 0 \) (free flow of the fluid mixture from the wellhead), one can obtain an equation determining maximum possible immersion \( H_{\text{max}} \) of the jet pump.

Let us analyze the hydrodynamic parameters (pressure \( P \) and flow rate \( Q \)) of the liquid when withdrawing the formation (bottomhole) fluid. The main source parameter is reservoir fluid pressure \( P_e \) which is fixed by the bottomhole module when tapping the reservoir. At depth \( H \) of the jet pump and the height of suspension \( h \) above the well bottom, hydrostatic pressure \( P_e \) (in the mixing chamber) in the initial hydrostatic state of the flows corresponds to

\[
\rho_i g H = P_e^0 = P_e - \rho_e g h.
\]  

(22)

To bring the flow of downhole fluid to the jet pump, we pump (using a wellhead pumping unit) the fluid with pressure \( P_0 \) and flow rate \( Q_0 \). The resulting pressure (in a mixing chamber) \( P_e = P_0 + \rho_i g H - A Q_0^2 \) must be less than \( P_e^0 \); there is an influx of the downhole fluid. Therefore, the condition for the flow of downhole fluid to the pump is

\[
(P_0 + \rho_i g H - A Q_0^2) < (P_e - \rho_e g h).
\]  

(23)

With an influx of the downhole fluid to the jet pump at a certain flow rate \( Q_e \), the stationary process written by equation is settled

\[
P_0 + \rho_i g H - A Q_0^2 = P_e - \rho_e g h - B Q_e^2.
\]  

(24)

Based on dynamic equality (24) and expressions of pressure depressions (9 *) and (11 *) we find

\[
\Delta P_e = \Delta P_c + (P_e - P_0).
\]

that is, depression scale \( \Delta P_e \) (Figure 2, b) is represented by the drift of readings of depression scale \( \Delta P_c \) (Figure 2, a) by \( (P_e - P_0) \).

With regard to expression (22), dynamic equality (24) is

\[
P_0 - A Q_0^2 = -B Q_e^2.
\]

The interrelated expressions of the cost of injected \( Q_0 \) and extracted \( Q_e \) fluids are

\[
Q_e = \sqrt{\frac{A Q_0^2 - P_0}{B}}; \quad Q_0 = \sqrt{\frac{B Q_e^2 + P_e}{A}}.
\]  

(25)

where parameters \( A \) and \( B \) characterizing hydraulic resistance of the injected and extracted fluid flows, are determined by the expressions

\[
A = \left( \frac{\rho_1}{F_1^2} + \alpha \right); \quad B = \rho_e \left( \frac{1}{F_2^2} + \frac{1}{F_f^2} \right) - \frac{1}{F_f F_2} - \frac{1}{F_f F_e}.
\]  

(26)

On the basis of the solutions obtained above, we find the expressions for the individual parameters that determine the characteristic of the jet pump.

The pressure differential [9] for the injected (working) flow \( \Delta P_i \) is found from expressions (1) and (9), excluding pressure \( P_c \) of the receiving chamber of the pump displacement.

\[
\Delta P_i = P_i - P_f = \frac{Q_0^2}{F_1 F_3} \rho_i - \frac{Q_e^2}{F_2 F_3} \rho_e - \rho_i \frac{F_3}{F_2} \rho_e (1 - \frac{F_2}{F_f}).
\]  

(27)

Similarly, based on expressions (9) and (18), we find useful pressure differential \( \Delta P_f \) created by the jet pump [10].

\[
\Delta P_f = P_k - P_f = \frac{Q_0^2}{F_1 F_3} \rho_i + \frac{Q_e^2}{F_2 F_3} \rho_e (1 - \frac{F_3}{F_2} + \frac{F_2}{F_f}) - \rho_i \frac{Q_0^2}{F_1 F_3} \rho_e.
\]  

(28)

The working pressure differential \( \Delta P_w \) is found from expressions (1) and (18)

\[
\Delta P_w = P_i - P_k = \frac{Q_0^2}{F_1^2} \left( 1 - \frac{F_3}{F_2} \right) \rho_i + \frac{Q_e^2}{F_2 F_3} \rho_e + \frac{Q_0^2}{F_1 F_3} \rho_e.
\]  

(29)

Taking the values of densities \( \rho_i, \rho_e, \rho_c \) of liquids equal to averaged density value \( \rho_\alpha \), we can obtain an approximate estimate of the efficiency of the jet pump as the ratio of net power to the expended one, i.e.

\[
\eta = \frac{N_{\text{ex}}}{N_\alpha} = \frac{Q_e \Delta P_k}{P_0 \Delta P_p} = U \frac{P_k - P_f}{P_i - P_k}
\]

or

\[
\eta = U \frac{\Delta P_k}{\Delta P_f} = U \frac{\Delta P_k}{\Delta P_f}.
\]  

(30)
where \( U = \frac{Q_e}{Q_0} \) is the pump injection coefficient, \( \frac{\Delta P_k}{\Delta P_i} \) is the relative pressure differential. Using (27) and (28), we find the expression of the relative pressure differential which is the equation of jet pump characteristics [9].

\[
\frac{\Delta P_k}{\Delta P_i} = F_2 \left[ \frac{\frac{1}{F_1} \rho_i + U^2 \frac{1}{F_2} \rho_f - \rho_e - (1+U)^2 \frac{1}{F_1} \rho_i}{\frac{1}{F_3} \rho_i - U^2 \frac{1}{F_2} \rho_f + \rho_e} \right] \tag{31}
\]

As follows from equation (31), the relative pressure differential is determined by the value of the injection coefficient \( U \), cross sections \( F_1, F_2, F_3 \) and their relations. At a given value of \( U \), pressure differential \( \Delta P_k \) generated by the jet pump is directly proportional to pressure differential \( \Delta P_i \). When the injection coefficient is \( U = 0 \), the jet pump has the maximum pressure differential.

\[
\left( \frac{\Delta P_k}{\Delta P_i} \right)_{\text{max}} = \frac{F_1}{F_2} \left( 1 - \frac{F_1}{F_2} \frac{\rho_e}{\rho_i} \right). \tag{32}
\]

The determining geometrical parameter of the jet pump is the ratio of cross-sectional area \( F_2 \) of the injected (working) fluid flow to cross-sectional area \( F_3 \) of the flow channel of the displacement chamber. All the dependencies for calculating the required parameters and the optimal ratio of the cross-sectional area of the jet pump are in accordance with equation (31). In particular, at a given value of pressure differential \( \Delta P_i \) and injection coefficient \( U \), the optimal ratio \( \frac{F_2}{F_3} \) will correspond to the maximum (or minimum) value of pressure differential \( \Delta P_k \) of the jet pump [9] and is determined by the extremum conditions:

\[
\frac{d(\Delta P_k)}{d(\frac{F_2}{F_3})} = 0. \tag{33}
\]

Analysis of the jet pump characteristics and operation mode involves assessment of possible cavitation, when the stationary fluid pressure in a certain flow part of the pump decreases to critical value \( P_c \) equal to the vaporization pressure of the fluid or the saturation pressure for gases dissolved in the fluid. In the pump, this area is receiving mixing chambers with the lowest pressure \( P_c \), determined by the fluid of the injected (working) flow. Cavitation is absent if \( P_c > P_e \) near the inlet section of the mixing chamber. Critical pressure \( P_c \) depends on the temperature of mixed fluids \( t_i \) and \( t_e \) and injection coefficient \( U \). At the same heat capacities of the interacting media \( (C_i = C_e = C_e) \), the temperature of the mixed fluid flow is

\[
t_c = \left( \frac{t_i + U t_e}{(1+U)} \right). \tag{34}
\]

At temperatures \( t_i \) and \( t_e \), the injection coefficient corresponds to each temperature \( t_c \) of the mixed flow

\[
U = \frac{t_i - t_c}{t_c - t_e}. \tag{35}
\]

Given the values of the injection coefficient \( U \) at known temperatures of the injected \( t_i \) and recovered \( t_e \) fluid flows, we find the temperature of mixture \( t_c \) and critical pressure \( P_c \).

To calculate injection coefficient \( U_+ \), at which cavitation occurs in the jet pump, we use the expression of a relative static liquid pressure decrease which follows from equations (9) and (27)

\[
\frac{P_f - P_c}{P_c - P_f} = \frac{U^2 \rho_e (1 - \frac{P_f}{P_c})}{\frac{P_f}{P_1} - U^2 \rho_e (1 - \frac{P_f}{P_c})} \tag{36}
\]

Assuming in (36) \( P_c = P_s \) and \( U = U_+ \), we find

\[
U_+ = \frac{F_2}{F_1} \sqrt{\frac{\frac{P_f - P_c}{P_c - P_f} \rho_i}{1 - \left( \frac{P_f}{P_1}\right)^2 \rho_e}}. \tag{37}
\]

With a change in the mixture temperature \( t_c \), injection coefficients \( U \) and \( U_+ \) change according to their laws: \( U \) - according to (35), and \( U_+ \) - according to (37). From the graphical representation of dependencies (35) and (37), we find the value of cavitation injection coefficient \( U \) and corresponding temperature \( t_c \), of the mixture, i.e. we proceed from the equation (Figure 3): \( U( t_c) = U_+[P_c( t_c)] \).
Under pump operation modes, when $U < U_*$, there is no cavitation. If there is cavitation ($U = U_*$), a pressure decrease $\left(\frac{\Delta P_k}{\Delta P_i}\right)$ does not increase injection coefficient $U$ (figure 4) as could be expected from equation (31).

4. Conclusion
The hydrodynamic equations are used to solve various problems of implementation of the flow of reservoir (downhole) fluid, depending on the initial parameters of the technological process of well development. Preliminary construction of graphic dependences of the hydrodynamic parameters of the circulating fluid system depending on the depth of the jet pump for the well projected in a specific drilled oil-bearing area helps control the technological parameters of testing of the productive horizon during its initial development.

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