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Automatic Measurement and Monitoring Technology for Oil Well

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Abstract: Measurement technology of oil well develops and improves constantly at present. Reducing operation cost and energy consumption and improving efficiency of labor provides reliable technical guarantee for simplifying and optimizing ground process system. According to the needs of parametric measurement and monitoring for oil well, the paper combines with actual situation of the second factory in Dagang Oilfield, the second factory proposes the research on automatic measurement and monitoring technology for wireless oil well and application project, and scientific and information department in Dagang Oilfield ratifies the project. The paper studies automatic measurement and monitoring technology for wireless oil well, and evaluates the economic and social benefit. *Copyright © 2013 IFSA.*

Keywords: Oil well, Automatic measurement, Monitoring technology, Study, Application.

1. General Thought of Study

At present, automatic production of rod-pumped well based on the principle of measuring technology of diagram method is being applied and promoted. By investigation and analysis, the method has achieved some effect on the application in some areas or oil well, but the method of calculating liquid production capacity according to the area of pump indicator diagram has some disadvantages and has larger limitations of the application [1]. Therefore, we start from the study on pump efficiency, establish the mathematic mode with pump efficiency as the calculation bases and with pump indicator diagram assisting calculating liquid production capacity for oil well, and establish acquisition theory and method of indicator diagram of using precise kinematic model. The paper studies and develops automatic measurement and control system for beam-pumping, develops the corresponding software, and realizes remote wireless and automatic acquisition on production data of beam-pumping, automatic calculation of liquid production capacity, automatic diagnosis on operation condition of pumping wells, and automatic start-stop of equipment [2].

2. Analysis on Characteristic of Pump Indicator Diagram

Computer diagnosis of pumping well is that using mathematical methods to acquire sectional area of rod strings and load and displacement of the pump with the help of computer,, then draws downhole pump indicator diagram, and according to which analyzing and judging operation status of a full set of pumping equipment. And it includes calculating sectional stress at the top of all rod strings, estimating pump pressure, judging oil well potentials, calculating piston stroke coefficient and pump efficiency, and verifying mechanical condition of pump and tubing anchor [3-4].

Theoretical basis of diagnostic technology is that it makes rod strings as a dynamic transmission line underground. The inferior pump is set as the sender, and the superior resistance dynamometer is made as the receiver. The operation condition of downhole pump is transmitted to the ground with the form of stress waves along rod strings. The data recorded by the ground is for mathematical treatment, which can judge quantitatively the operation condition of pump [5]. The transmission process of stress wave in rod strings can be described by wave equation with damp.

$$\frac{\partial^2 U(x,t)}{\partial t^2} = a^2 \frac{\partial^2 U(x,t)}{\partial x^2} - c\frac{\partial U(x,t)}{\partial t},$$

where

$U(x,t)$ is the displacement of any section for rod strings;

a is the transmission velocity of stress wave in rod string;

c is the damping coefficient.

The expression is the basic differential equation describing the trends of rod strings in diagnostic technology.

The functions of suspension point dynamic load and displacement represented by truncated Fourier series are boundary conditions;

$$D(t) = \frac{\sigma_0}{2} + \sum_{n=1}^{\bar{n}}(\sigma_n \cos nwt + \tau_n \sin nwt)$$
$$U(t) = \frac{v_0}{2} + \sum_{n=1}^{\bar{n}}(v_n \cos nwt + \delta_n \sin nwt)$$

Because there is no invariable gravity item in the process of oil pumping for wave equation, dynamic load function D(t) after the weight of rod strings being reduced from the total load of suspension point is used to be as boundary conditions of force. Fourier coefficient of D(t) and $U(t), \sigma_0$, σ_n, τ_n and v_0, v_n, δ_n can be respectively solved by the following formula:

$$\sigma_n = \frac{w}{\pi}\int_0^T D(t)\cos nwtdt \quad (n = 0,1,2,..\bar{n})$$
$$\tau_n = \frac{w}{\pi}\int_0^T D(t)\sin nwtdt \quad (n = 1,2,..\bar{n})$$
$$v_n = \frac{w}{\pi}\int_0^T U(t)\cos nwtdt \quad (n = 0,1,2,..\bar{n})$$
$$\delta_n = \frac{w}{\pi}\int_0^T U(t)\sin nwtdt \quad (n = 1,2,..\bar{n})$$

where

w is the velocity of crank angle;

T is the swabbing period.

D(t) and U(t) are given with the form of curve or numerical value in actual work, so Fourier coefficient can be determined by approximate numerical integration.

Fourier expansion of the expression D(t) and U(t)is as the boundary condition, and method of separation of variables is used to solve wave equation, which can get the relation of the displacement of any deep x section for rod strings changing with time:

$$U(x,t) = \frac{\sigma_0}{2EA_r}x + \frac{v_0}{2} + \sum_{n=1}^{\bar{n}}[O_n(x)\cos nwt + P_n(x)\sin nwt]$$

According to Hooke's law:

$$F(x,t) = EA_r \frac{\partial U(x,t)}{\partial x}$$

The change of displacement of any deep x section for rod strings with time is:

$$F(x,t) = EA_r[\frac{\sigma_0}{2EA_r} + \sum_{n=1}^{\bar{n}}(\frac{\partial O_n(x)}{\partial x}\cos nwt + \frac{\partial P_n(x)}{\partial x}\sin nwt)]$$

At time t, the total load of x section is equal to F(x,t) adding the weight of rod strings under x section:

In the above formula,

$$O_n(x) = (K_n ch\beta_n x + \delta_n sh\beta_n x)\sin\alpha_n x +$$
$$+(u_n sh\beta_n x + v_n ch\beta_n x)\cos\alpha_n x$$

$$P_n(x) = (K_n ch\beta_n x + \delta_n sh\beta_n x)\cos\alpha_n x -$$
$$-(u_n ch\beta_n x + v_n sh\beta_n x)\sin\alpha_n x$$

The above formula is applicable for single rod string, and it only needs to do the corresponding extension for multistage sucker rod string to do the similar formula.

As calculating downhole indicator diagram according to ground indicator diagram, it is necessary to determine firstly damping coefficient. Damping force of rod string system includes viscous damping force and non-viscous damping force. Viscous damping force consists of viscous friction among rod strings, coupling and liquid, and fluid pressure loss of pump valve and valve seat inner hole. Non-viscous damping force includes non- viscous friction among rod strings, coupling and liquid, the fiction between polish rod and packing, and frictional loss between pump plunger and pump cylinder. Equivalent damping can be used to replace real damping. And the condition is that the energy in each cycle when equivalent damping is eliminated in the system is the same as that when real damping is eliminated [6]. And damping coefficient formula can be deducted, and downhole indicator diagram of pumping well can be obtained [7].

Diagnosis instrument measuring downhole pump diagram has strong regularity, and the diagram is easier to remember than ground indicator diagram, and is easy to compare. The regularity of standard graph is summarized as follows: the left-sided vertical line of the diagram is used to analyze pump valve problems of downhole pump, and is the key to diagnosing if traveling valve and standing valve leaks. When it presents plumb line or approximates to plumb line, the superior and inferior valve is leakproof, and when the superior valve leaks, upper-lift corner presents circular arc defect. When the inferior valve leaks, lower-lift corner presents.

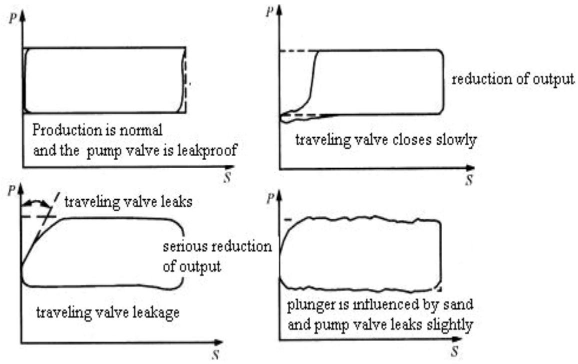

Fig. 1. Standard downhole pump indicator diagram (1).

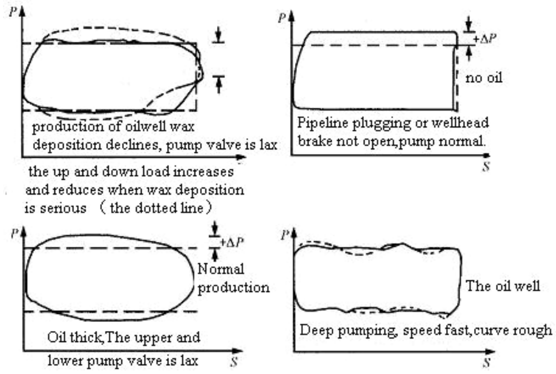

Fig. 2. Standard downhole pump indicator diagram (2).

In Fig. 1, the top left is normal pump indicator diagram in which pump valve is leakproof, pump efficiency is high and the producing oil is good. The top right is that traveling valve closes slowly and the production of oil well reduces [7]. The bottom left is the measured figure when traveling valve leaks, and the top left of the figure has loss angle, the larger the angle, the serious the loss, and the production of oil well reduces greatly, so it needs to change pump as early as possible. The bottom right is that the production of oil well is normal, the producing oil is very good, and only traveling valve is influenced by sand, which has little loss.

In Fig. 2, the top left is oil well wax deposition in which the curve has irregular raised increasing load and concave down load shedding, the production decreases, judgment on wax deposition degree can be observed in the right of the figure. The top right is that pipeline is obstructed or well head control block valve doesn't open, pump works normally but there is no oil, there is load on pump diagram, ΔP increases and the appearance is normal. The bottom left is the common diagram of viscous oil well producing in which the immediate part of the top and bottom curves bloats, which has the reason that the load increases when viscous oil well moves faster, the velocity near stroke dead center is slow, and the added load is small [8-9]. Therefore, viscosity reduction measure is generally used on viscous oil well to have better production, and pumping parameters should select slow speed which is less than 6 times/min [10, 11]. The bottom left has the problem that the inferior and superior pump valve are not tight, checking pump should be arranged as early as possible. The bottom left is downhole pump diagram with deep pump setting and faster speed, there is no wave form in the curve of the stroke process, but the pump operates normally, the pump valve is leakproof, and the producing oil is good.

3. Methods of Calculating

1) Oil well indicator diagram.

Indicator diagram is a closed curve. Indicator diagram makes measurement when oil well works, the data of load and displacement can be measured with the same time interval. Number of pairs for each indicator diagram is same and is measured in the constant time interval, and number of pairs for different stroke rates is different. In order to get rich information from indicator diagram data, the best time interval of measuring the load and displacement data is less than 0.055 s. The largest and smallest load of suspension center can be obtained from the indicator diagram.

2) Calculation method of oil well liquid production capacity.

The practice indicates that the actual output is lower than the theoretical yield generally, and the actual liquid production capacity can be written as:

$$Q = 1440\ \eta f_p s n\ , \tag{1}$$

where η is the pump efficiency, f_p is the pump plunger area, m^2; s is the stroke, m; n is the stroke rate, $\min^{-1}$.

The factors influencing pump efficiency mainly include four factors: 1) Rubber-sheeting of rod strings and tubing string, 2) Influence of gas and imitation dissatisfaction, 3) Influence of leakage, 4) Influence of clearance volume. Therefore, general expression of pump efficiency can be expressed as:

$$\eta = \eta_{\text{stroke loss}} \cdot \eta_{\text{fulling extent}} \cdot \eta_{\text{seepage loss}} \cdot \eta_{\text{clearance volume}} \tag{2}$$

The four factors influencing pump efficiency can be achieved by theoretical calculation [3].However; theoretical calculation needs more parameters of oil well and the produced oil-gas-water, which goes against gas-oil separator calculating the production of the oil well. Next, we use indicator diagram data to calculate.

3) Stroke loss calculation.

a) Stroke loss under static load.

As liquid column functioned on pump plunger is alternately and respectively transferred to rod strings from tube and transferred to tube from rod strings, which causes alternate increment of load and reduction of load on bolt supports and tube. And the stroke loss caused by the load of liquid column can be expressed as:

$$\lambda_{\text{static stroke loss}} = \frac{W_l^{'}}{E}\left(\sum_{i=1}^{m}\frac{L_{ri}}{f_{ri}} + \sum_{j=1}^{n}\frac{L_{tj}}{f_{tj}}\right), \qquad (3)$$

where W_l' means the load of liquid column functioned on pump plunger, N, and it can be obtained from the variation of initial value for two loss curves. E is the elasticity modulus of steel, $2.06\times10^{11}Pa$. L_n means the length of the i oil-sucking rod, m. f_{ri} is the cross section area of the i oil-sucking rod, m^2. L_{tj} means the length of the i tube, m. f_{tj} is the cross section area of the i tube, m^2.

b) Stroke loss under inertia load.

In up stroke, polished rod load is larger than static load, the reason for which is inertia load of oil-sucking rod and liquid column. When suspension center rises to top dead center, the speed tends to zero, but rod strings have the maximum acceleration for decurrent and the maximum inertial load for the upward, which makes rod strings reduce lad and shorten. Therefore, after suspension center reaching top dead center, rod strings continue to moving upward with pump plunger under inertia force, which makes pump plunger move upward a distance than static deformation . And the similar conditions also appear in the down stroke.

The formula of inertia load adding plunger stroke is:

$$\lambda_{\text{inertia stroke loss}} = \frac{W_r sn^2}{1790E}\sum_{i=1}^{m}\frac{L_{ri}}{f_{ri}}, \qquad (4)$$

where W_r is the inertia load, N. The load value of indicator diagram reaching top dead center subtracting the initial load of floating valve leakage curve can get inertia load.

c) Stroke loss under friction.

Paraffin blockage, sand and eccentric wear can produce friction on the sucker rod, which results in stoke loss of sucker rod. Because the direction of frictional forces opposites to the direction of motion, sucker rod receives the down frictional force in the up stroke, which can lead to traction of the sucker rod. Similarly, sucker rod can be shortened in the down stroke.

The formula of friction resulting in stokes loss of pump plunger is:

$$\lambda_{\text{frictional stroke loss}} = \frac{W_f^{'}}{E}\left(\sum_{i=1}^{m}\frac{L_{ri}}{f_{ri}} + \sum_{j=1}^{n}\frac{L_{tj}}{f_{tj}}\right), \qquad (5)$$

where W_f' is the additional load of frictional force on pump plunger, N, and it can be obtained by the mean value of all loads greater than that at top dead center on the indicator diagram substracting the load at top dead center in the up stoke, and it can be achieved by the mean value of the load at the down dead center substracting all the load.

4) Influence of gas and imitation dissatisfaction.

In the methods of computers justifying automatically indicator diagram, differential curve method not only can distinguish accurately the indicator diagram influenced by gas and imitation dissatisfaction ut also can figure out the proportion of stroke loss caused by the corresponding imitation dissatisfaction. The above starting point of stroke is reference level of differential curve, and it can be obtained by S-curve of indicator diagram line in the up stoke subtracting indicator diagram curve in the down stoke. There is a section of closing to zero line on the left side of indicator diagram for the pump which is not full, and the differential cure changes into negative value. The proportion of the part closing to zero line taking up the whole differential curve is equal to the proportion of stoke loss caused by imitation dissatisfaction. The following is a detailed introduction of principle and identification methods for differential curve:

(4) Principle of differential curve identifying pump indicator diagram.

1) Identification algorithm of differential curve.

The line segment with the most information in indicator diagram is the load bearing and unloading line segment which doesn't receive wave distortion of rod strings and liquid column. The length for the load bearing and unloading line segment depends on plunger path loss produced by sucker rod deformation λ_r and tube deformation λ_t, ΔS. Single rod string can be determined according to the following formula:

$$\Delta S = \lambda_r + \lambda_t = \frac{F_L \cdot H}{E}\left(\frac{1}{f_r} + \frac{1}{f_t}\right) \qquad (6)$$

And multistage rod can be determined according to the following formula:

$$\lambda = \frac{F_L}{E}\left(\sum_{i=1}^{n}\frac{L_i}{f_{ri}} + \frac{H}{f_t}\right), \qquad (7)$$

where F_L is the liquid column load, H is the pump depth, E is the elasticity modulus of sucker rod material, f_r is the cross section area of rod strings and f_t is the cross section area of tubing string.

Plunger stroke loss value depends on setting depth and specification of sucker-rod pump. If pump depth, pump diameter, stroke of polished rod S and swabbing cycle time T are known, it is not difficult to determine duration t_1 of the line segment including information on differential cure, $t_1 = T \cdot \Delta S/(2S)$, and knowing t_1 can figure out the points of differential curve containing message section. Symbol sequence code of differential curve containing message section can explain exactly main types of equipment state for sucker-rod pump, and it doesn't need to preprocess the indicator diagram for suppressing fluctuation. The threshold is determined according to the actual situation, the differential curve is converted into the change of information section symbol, and the value behind the information section is as the reference for further judgment.

Integral test of non-information part of differential curve shifting to positive or negative area is used to differentiate 2 types of pump-state with the same symbol sequence code of differential curve: fixed valve leakage and plunger lower pass resistance, floating valve leakage and resistance met on pump plunger.

The greatest advantage of differential curve method is that feature analysis corresponding to various main condition is evident, and that using identification algorithm can classify condition type more accurately. The method doesn't need human intervention in the recognition process, especially it is suitable for batch processing on a large number of oil well diagram in oilfield database.

2) Influence of leakage.

Leakage curve of traveling valve can figure out leakage Q'_{upperl} of traveling valve and piston in unit time. And indicator diagram can figure out the time Q_{upper} in the up stroke, the leakage in the up stroke can be figured out:

$$Q_{.\text{upper}} = Q'_{\text{upper}l} \cdot t_{\text{upper}} \tag{8}$$

Leakage curve of fixed valve can figure out leakage Q'_{belowl} of fixed valve in unit time. And indicator diagram can figure out the time Q_{below} in the down stroke, and the leakage in the downstroke can be figured out:

$$Q_{.\text{below}} = Q'_{\text{below}l} \cdot t_{\text{below}} \tag{9}$$

And the production losses caused by leakage can be achieved :

$$Q_l = Q_{\text{below}} + Q_{\text{below}} \tag{10}$$

3) Influence of clearance volume.

Influence of clearance volume can be obtained by using the following empirical formula:

$$\eta_{\text{Clearance volume}} = 1 - 0.387h/s \tag{11}$$

4. Study on Algorithm

1) Calculation on liquid production capacity for electric submersible pump

Calculation on liquid production capacity for electric submersible pump is mainly on the basis of multiphase flow throttling mathematical model on the ground, combines mathematical model of energy consumption and lifting mathematical model of electric pump for correction and simulation, gets the specific calculation rules of liquid production capacity, and the liquid production capacity under the ground can be figured out.

2) Calculation on liquid production capacity for flowing well

It is mainly on the basis of multiphase flow throttling mathematical model of choke on the ground for correction and simulation, gets the specific calculation rules of liquid production capacity applying to flowing well, and the liquid production capacity of flowing well under the ground can be figured out.

As shown in Fig. 3, the mixture of gas and oil gets through choke under the influence of oil pressure P_t before choke and the influence of back pressure P_h behind choke on reaching pithead from shaft bottom. As the gas inflates here, volume flux of the mixture is very large, but nozzle diameter is very small. Therefore, flow velocity of the mixture is extremely high when it flows through choke, which can reach critical flow. The so-called critical flow is flow velocity of fluid reaching propagation velocity of pressure wave in flowing medium, that is, the flow condition on acoustic wave velocity. And the flow of aerated liquid in choke can be regarded as nozzle flow of fluid in thermal in critical condition. The relationship P_2 / P_1 of pressure ratio for mass flow and before and after jet of gas or liquid passing jet is shown in Fig. 4.

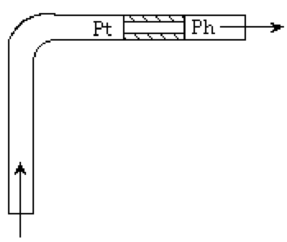

Fig. 3. Nozzle flow diagram.

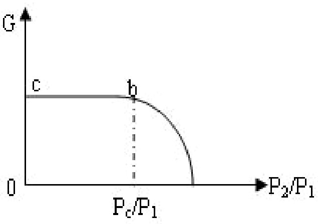

Fig. 4. $G = f(P_2 / P_1)$.

In Fig. 4, G is the quality of fluid, P_1 and P_2 are the pressures before and after jet. From Fig. 4, we can get that $G = 0$ when $P_1 = P_2$. On the line section of ab in curve, when the pressure ratio P_2 / P_1 decreases gradually, the flow G increases gradually. But when flow G increases to a certain value (maximum value) and the pressure ratio continues to be decreased, the flow doesn't increase, but the flow keeps definite value such as the show of line segment bc. The pressure ratio P_c / P_1 corresponding to the maximum flow is called critical pressure ratio. According to thermodynamics theory, critical pressure ratio of gas flow is:

$$\frac{P_c}{P_1} = \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}}, \quad (12)$$

where k is the adiabatic exponent of gas.

The maximum stream flow in the condition of critical pressure ratio is the flow of sound velocity.

The sound velocity in air, oil and saline solution is respectively 335.4 m/s, 1216 m/s and 1700 m/s. And the sound velocity of gas-oil mixture relates to the mixture composition and property.

The critical pressure ratio of air flowing through jet is:

$$\frac{P_c}{P_1} \approx 0.528 \text{ (Natural gas is 0.546)} \quad (13)$$

The flow of gas-oil mixture in choke is similar to the flow of single-phase gas. From the above formula, we can see that, when the pressure ratio is equal to or less than 0.546, the flow velocity which is equal to sound velocity is produced in choke in general. In the condition of critical flow, $\frac{P_2}{P_1} \le \frac{P_c}{P_1} = 0.546$, the flow is not influenced by the change of pressure behind choke, but it only relates to pressure before choke, choke diameter and gas-oil ratio. According to statistical analysis of field data, the relationship between them can be expressed as:

$$q = \frac{p_t d^m}{cR^n} \quad (14)$$

or

$$P_t = \frac{cR^n q}{d^m} \quad (15)$$

where P_t is the oil pressure (P_1);

R is the gas-oil ratio;

q is the oil production;

d is the choke diameter;

n, m, c are the constants.

Formula (14) shows the fundamental relation between main flow parameters of oil-gas mixture flowing through choke in the condition of critical flow. The difference of fluid property and hybrid mode of oil and gas makes choke flow complicated. According to data statistics of hundreds of wells at home and abroad, the common calculation formula of choke flow is:

$$q = \frac{4d^2}{R^{0.5}} P_t, \quad (16)$$

where P_t is the oil pressure, MPa;

q is the oil production, t/d;

R is the gas-oil ratio, m3/t;

d is the choke diameter, mm;

As for water-cut well, the following formula can be used:

$$q_t = \frac{4d^2}{R^{0.5}} P_t \left(1 - f_w\right)^{-0.5}, \quad (17)$$

where

q_t is the liquid production capacity, t/d;

f_w is the water-cut, decimals.

It should be pointed out that a large experienced characteristic for nozzle flow equation relates to oilfield conditions. Therefore, in practical application, the data pf parameters relating to nozzle should be collected and analyzed and the above formula should be corrected according to concrete conditions of oilfield, and the formula applying to the region is achieved.

When nozzle diameter and gas-oil ratio are certain, production q and portal oil pressure is linear relationship, as shown in Fig. 5. Only the critical flow of nozzle is met, the entire production system can produce steadily. Although portal back pressure changes, there is no change for oil well outputs.

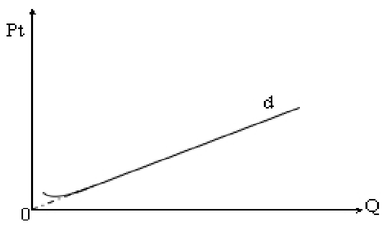

Fig. 5. Relation curve of nozzle, oil pressure and output.

5. Conclusion

The paper deepens theoretical research of automatic metering and monitoring, establishes and improves calculation quantitative basis of pump working condition applying to geology of Cai You Er Han and project characteristics, and forms a set of theories and methods of calculating liquid production capacity. Using wireless automatic metering mode not only can make computational accuracy of single well oil less than 10 %, but also satisfy the requirements of single-well measurement of oil well. The application of the technology has important guiding significance on accurately and timely mastering on reservoir conditions and formulating production decision. The implementation of automatic metering and monitoring technology truly not only realizes automatic extraction of teledata, but also makes sure individual well producing rate of blocks, improves automation technology and management technology of oilfield for striding forward digital management from manual administration, and saves manpower and material resources. Applying advanced and applicable oil well measurement technology can simplify the current there-level station distribution into one-level station distribution, reduces ground system pipeline, improves oil well production, improves the system efficiency, and reduces maintenance costs.

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