works of the classics of soil science. These works considered effective stress in soil as a stress transmitted to soil skeleton excluding pore pressure. The main provisions of the new approach describe formation of effective stress in the clay soils most accurately.

**Methodology**. The main methods of research were theoretical and experimental study of sandy soils of different origin; generalization analysis of the experimental data which consider the structural characteristics of sand: grain size distribution; morphological characteristics of grains; formation of coagulation, phase, and transition power contacts.

**Findings**. The analytical synthesis showed that the difference in structural characteristics and sand grains morphology (particles' shape and surface nature) causes different values of ultimate composition density, optimum moisture content for firming, and strength characteristics. The sand structural features effect on the number of real contacts between its grains and the formation of different types of bound water in soil has been considered.

**Originality**. The theoretical approach and its experimental proof allowed the new physical-chemical theory of effective stress formation in cohesive soils which can be applied for sandy soils widespread in the earth crust.

**Practical value**. We now have the possibility to assess the influence of effective stresses on formation of the stress condition of the soils of different lithological and petrographic composition more accurately. The development of the classical theory of effective stresses formation on the basis of physico-chemical concepts is a promising area of soil science and soil mechanics.

**Keywords**: *effective stresses, soil, sand, structural features, morphology, power contacts, density, strength, water, physical and chemical theory*

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# PORE PRESSURE PREDICTION IN THE DONGFANG 1-1 GAS FIELD, YINGGEHAI BASIN

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# ПРОГНОЗУВАННЯ ПОРОВОГО ТИСКУ В ГАЗОВОМУ РОДОВИЩІ DONGFANG 1-1 ГАЗОНОСНОГО БАСЕЙНУ YINGGEHAI

Dongfang 1-1 gas field is a high temperature and high pressure area. An accurate pore pressure prediction is very important for safe drilling in this area. The authors have analyzed and classified the overpressure mechanisms on the base of loading and unloading, which are the relationships of vertical effective stress and acoustic velocity. Then, the logging responses for different overpressure mechanisms have been discussed. Based on the above, the new method of pore pressure prediction by means of the DT-density crossplot and DT-density-depth crossplot has been proposed. The method has been applied to analyze the overpressure causes and predict a high temperature and high pressure well in DF1-1 gas filed, Yinggehai Basin. The results show that the overpressure in DF1-1 gas filed is caused by three factors: disequilibrium compaction, aquathermal expansion and hydrocarbon generation. Their contribution to the overpressure in different formations is different. By using the DT-density crossplot and the DT-density-depth crossplot the contribution can be distinguished and feasible prediction model can be chosen. The authors have proved that the Eaton method is only suitable for disequilibrium compaction; but the Bowers method is effective for the overpressure caused by disequilibrium compaction or fluid volume expansion. This method improves the pore pressure prediction accuracy in DF 1-1 gas filed effectively. It is of importance to the drilling engineering.

**Keywords:** *DF 1-1 gas filed, high temperature, high pressure, overpressure mechanism, loading, unloading, pore pressure prediction*

**Introduction.** The Dongfang 1-1 (DF1-1) gas filed is the largest gas filed in China. It is located in the Yinggehai Sea Basin, about 100 km to the west of Yinggehai town, Hainan province (Fig. 1). The water depth is about 64–70 m. The gas reserve of the field is estimated to excess a hundred billion cubic over the gasbearing area of 287,7 km$^2$ [1]. The high temperature and high pore pressure (HTHP) are the important characteristics of this gas field. So, there is an extreme challenge to the drilling. The research of accumulation process and pore pressure mechanism of Yinggehai Basin proved that the overpressure of this area is caused by disequilibrium compaction, aquathermal expansion, and hydrocarbon generation [2–4]. However, the pore prediction methods for these different overpressure mechanisms are quite different. The Eaton [5] method is a conventional pore pressure estimation method. It has been used in many regions, but it works effectively only for mudstone formations with disequilibrium compaction. It has never been discussed how to judge and distinguish the overpressure mechanism of Yinggehai Basin. Therefore, it is important to determine the overpressure mechanism for DF1-1 gas field and estimate the pore pressure.

The accurate estimation of pore pressure could let to avoid overflow, leakage, sticking, and collapse effectively. It is also significant to the mud density optimization, well bore configuration design, and the choice of well completion. In this paper, the interval transit time (DT)-density crossplot and the DT-density-depth crossplot have been proposed to determine the overpressure causes in DF1-1 gas filed. Then the Eaton method and the Bowers method have been introduced respectively to predict the pore pressure of a HTHP well.

**Geologic setting.** Yinggehai Basin is located to the west of Hainan Island and to the west of Indo-China Peninsula. The basin looks like rhomb and lies northwest and southeast. Its length is about 805 km and in the widest place it reaches 200 km. The area is about $1{,}13\times10^5$ km$^2$ (fig. 1). Yinggehai Basin is a mud diapir basin with a rapid burial rate. It has been proved that the overpressure partly results from the rapid burial rate during the period from Neocene to Quaternary. In addition, aquathermal expansion and hydrocarbon generation have also contributed to the overpressure. The geothermal gradient is about 4,55°C/100 m and even can reach 6,28°C/100 m [6].

DF1-1 gas filed has been in production since 2003, the main intervals of interest include Yinggehai-Huangliu formation with shallow marine and half deep marine mudstone, and Huangliu formation with mainly sand. The reservoir geothermal gradient is about 4,56°C/100m and the pore gradient could excess 1.,8SG [7].

**The method of overpressure mechanism judgment.**

***Overpressure mechanism.*** The overpressure mechanisms include disequilibrium compaction, fluid volume increase, tectonics, and density-buoyancy. The fluid volume increase can be divided into aquathermal expansion, mineral transformation, hydrocarbon generation, fluid movement, osmosis, and hydraulic head. The tectonics includes tectonic compression and uplift tectonic movement.

Disequilibrium is the most encountered overpressure mechanism around the world. In the case under consideration the sedimentation rate is too fast and the permeability is low, then the fluid is trapped in the pore and supports a part of the increased vertical load. There are many causes for fluid volume expansion, but in the end it results from the increase of fluid volume and the high pore pressure.

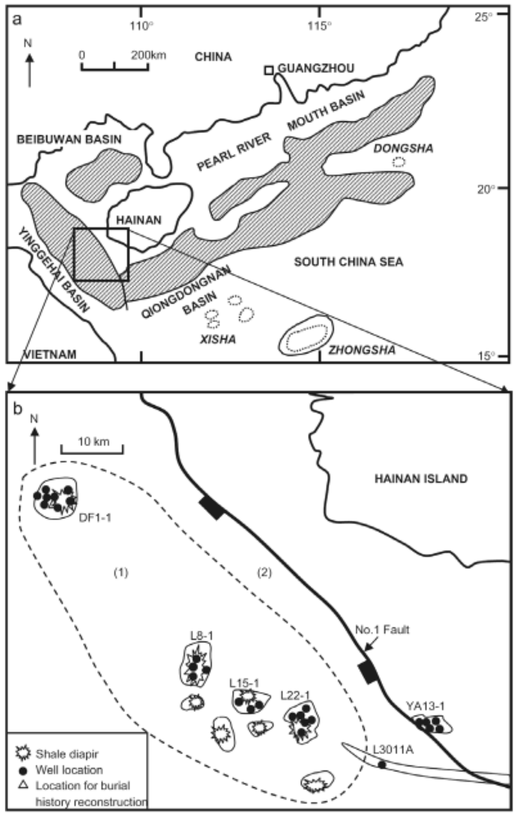


*Fig. 1. Location of DF1-1 gas field*

***Loading and unloading.*** Fig. 2 is $\sigma - V$ curve which reflects the relationship between the vertical effective stress and the formation interval velocity. During the normal compaction, with the increase of depth the vertical effective stress increases; the porosity decreases; and the interval velocity rises. According to Bowers [8], this kind of relationship fits the virgin curve, i.e., loading curve.

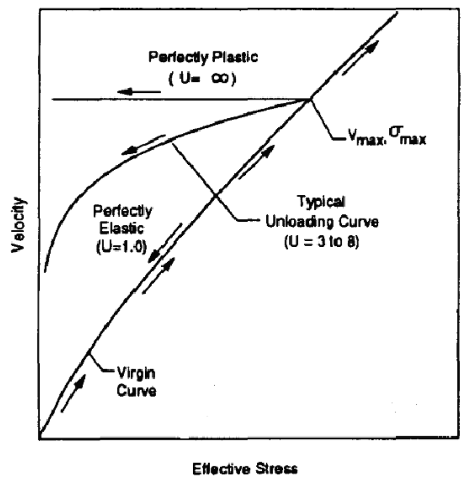


*Fig. 2. Typical loading and unloading curve*

During the disequilibrium compaction, with the increase of the overburden pressure the pore fluid starts supporting pressure. The vertical effective stress would stop increasing and the porosity does not decrease anymore, which 'freezes' in a kind of point. Meanwhile, the vertical velocity and formation density no longer increase. Therefore, the disequilibrium compaction still conforms to loading curve, just being frozen in some points.

The overpressure caused by fluid volume expansion happens after the compaction. So the overburden pressure is constant, when the pore pressure increases, the vertical effective stress decreases, and then the unloading occur. At the same time, the porosity would be released and vertical velocity decreases. However, the degree of porosity increase results from rock mechanical properties. As if the rock is completely plastic ($U = \infty$), the porosity and vertical velocity would remain unchanged which would be illustrated by the perfectly plastic curve. If the rock is an elastic material with some kind of plasticity, the unloading would lead to the porosity increase and the interval velocity decrease to a certain extent which is the typical unloading curve. Assuming that the rock is completely elastic, the porosity can recover totally and fit the loading curve. So loading curve is an extremely special example of unloading curve.

Fig. 2 shows that given equal interval velocity, the effective stress of the loading curve is larger than of the unloading curve; so the pore pressure is smaller. It indicates that although the interval velocity is the same, if loading and unloading cannot be determined, the estimation of pore pressure would be fault.

***Logging response.*** In the real process of drilling, the vertical effective stress is hard to obtain directly; but it is easy to get logging data. Thus, the key point is how to judge the overpressure mechanism through the logging response. The acoustic velocity and the electrical resistivity are determined by the rock conductivity, such as pore size, pore shape, and the connected situation. When the unloading happens, the acoustic velocity and the electrical resistivity are sensitive to the increase of pore space; and the decreasing trend of those logging data is obvious. On the other hand, the formation density is affected by the rock bulk properties. The increase of pore space during the unloading has no obvious effect on density logging and the data decrease slightly or do not decrease at all.

The logging response of the overpressure resulting from tectonics and density-buoyancy is more complicated; and the formation of tectonic structure movement is required; so it is not considered in this paper.

According to the above, the relationship between overpressure mechanisms, loading and unloading, and logging response are reflected in тable. 1.

***The optimized choice of prediction model.*** The conventional pore pressure prediction models have been summarized in table. 2. Among these models the Eaton model and the Bowers model have been commonly used around the world. In 1975, Eaton [5] proposed the overpressure prediction model taking into account the degree of disequilibrium compaction. This model has been proved to be very effective but only for the shale with disequilibrium compaction. In 1995, Bowers [8] put forward the prediction method for fluid volume expansion which includes loading model and unloading model. The Bowers method achieved good results in Gulf of Mexico and Nile Delta, Egypt [9]. In this paper, these two methods have been adopted to predict the pore pressure and compare the difference of the overpressure mechanisms.

*Table 1*

Judgment of Overpressure Mechanism

| **Overpressure mechanism** | **Loading or Unloading** | **Logging response** |
|---|---|---|
| Disequilibrium compaction | Loading | Acoustic velocity and density both decrease and along with the loading curve |
| Fluid volume expansion | Unloading | Acoustic velocity decreases but density varies slightly |

*Table 2*

Pore pressure prediction models, [10]

| **Overpressure mechanism** | **Prediction models** | |
|---|---|---|
| Disequilibrium compaction | Vertical method | Bryant; Alixant & Desbrandes |
| | Horizontal method | Eaton |
| | Others | Holbrook; Drauo; Bowers |
| Aquathermal expansion; Mineral transformation; Hydrocarbon generation; Fluid movement; Osmosis; Hydraulic head | Bowers | |

1. The Eaton method

The Eaton model of prediction of pore pressure is as follows

$$G_p = G_{op} - (G_{op} - \rho_w)(\frac{\Delta t}{\Delta t_n})^n,$$

where – $G_p$ is the pore pressure gradient, $g/cm^3$; $G_{op}$ is the overburden pressure gradient, $g/cm^3$; $\rho_w$ is the formation water density, $g/cm^3$; $\Delta t$ is the real interval transit time, $\mu s/ft$; $\Delta t_n$ is the normal interval transit time, $\mu s/ft$; $n$ is the Eaton index.

2. The Bowers method

Loading curve: the relationship between effective stress and acoustic velocity in the loading curve can be expressed by the following equation

$$V = V_O + A\sigma^B,$$

where – $V$ is the acoustic velocity, m/s; $V_O$ is the acoustic velocity of uncommented saturated clay, usually take 1480–1520 m/s; $\sigma$ is the vertical effective stress, MPa; A and B are experience indexes which can be obtained by the offset well.

Unloading curve can be expressed by the following formula

$$V = V_O + A[\sigma_{\max}(\sigma/\sigma_{\max})^{(1/U)}]^B,$$

where – $\sigma_{\max}$ is the maximum effective stress, is the effective stress when unloading begins, MPa; $U$ is the formation elastic index; $U=1$ indicates the formation is completely elastic and $U=\infty$ indicates the formation is completely plastic; in the petroleum industry it is usually between 2~8.

After obtaining the vertical effective stress, the pore pressure can be calculated by the compaction model

$$P_o = S_v - \sigma,$$

where – $P_o$ is the pore pressure, MPa; $S_v$ is the overburden pressure which can be achieved by the integration of formation density, MPa; $\sigma$ is the vertical effective stress, MPa.

***Judgment method.*** Based on the above analysis, the process of pore pressure prediction considering overpressure mechanism is as follows:

1) to collect and deal with the logging data, mainly including DT, density and gamma. To get rid of abnormal point on the basis of lithology;

2) to pick out the data of clear mudstone according to gamma;

3) to draw the normal DT and density trend line and make a preliminary judgment of an overpressure region;

4) to make the DT-density crossplot and the DT-density-depth crossplot. To judge the loading region and unloading region;

5) to choose the suitable prediction model according to the overpressure mechanism.

**Case study.** The well A is located in the west of DF1-1 anticline structure in Yinggehai Basin, which is a HTHP well. The normal DT and density trend lines are shown in fig. 3. DT and density data both start to deviate from the normal trend line from the point of 1500 m. Deal with the data and pick out the data of clear mudstone according to the process mentioned above. Fig. 4 is the DT-density crossplot and fig. 5 is the DT-density-depth crossplot. In fig. 4, the different color represents different formation, and Yinggehai Formaiton Member 2 is divided into three intervals. In fig. 5, the density data are picked out at an interval of 50 m.

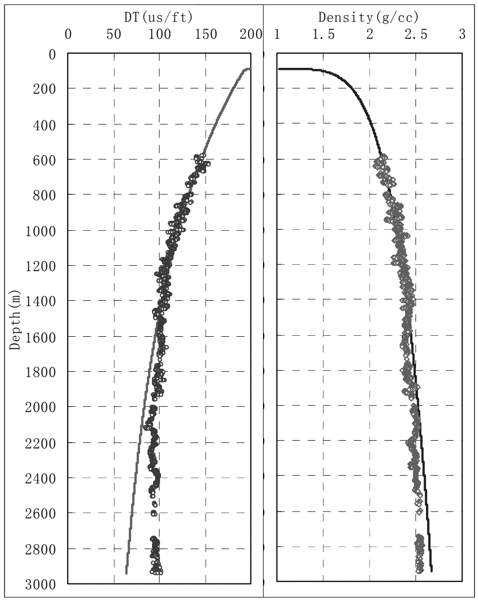


*Fig. 3. DT and density logging data of the well A*

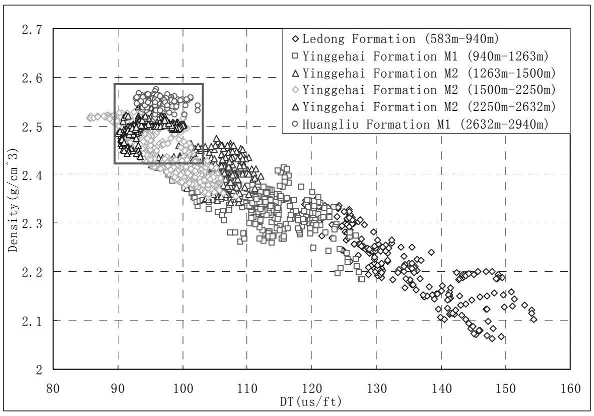


*Fig. 4. DT-density crossplot of the well A*

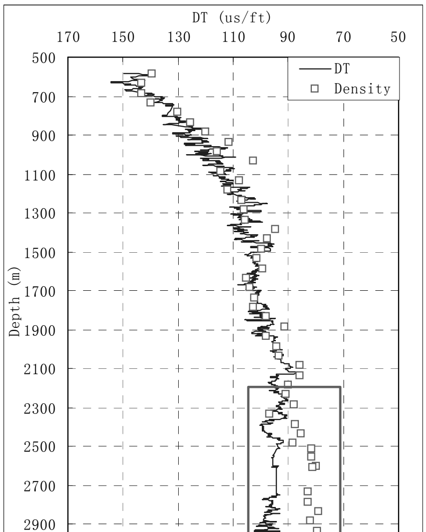


*Fig. 5. DT-density-depth crossplot of the well A*

The DT and density data from Ledong formation to the depth of 2250 m in Yingegehai Formation M2 both are in accordance with normal trend. However, the abnormity occurs in the depth of 2250 m which isillustrated in Fig. 4. In Yingegehai formation M2 (2250–2632 m) the DT no longer decreases and the density do not increase, both DT and density are like ‘freezed’ in the normal trend, which is the typical phenomenon of disequilibrium compaction. In addition, fig. 5 shows that in this interval, there are still some normal density data and DT data are larger, which indicates unloading. Therefore, the overpressure of Yinggehai formation M2 is caused by the combination of disequilibrium compaction and fluid volume expansion.

Fig. 4 shows that in Huangliu formation M1, the density data are normal and DT data are larger, so the overpressure mechanism of this interval is the fluid volume expansion, including the aquathermal expansion and the hydrocarbon generation. The unloading takes place at a depth of 2632 m.

The results of pore pressure prediction of the well A by means of the Eaton method and the Bowers method are shown in fig. 6. The Eaton index n = 2,5; A = 100,31; B = 1,0437; U = 6,326; $\sigma_{max}$ = 17,42 MPa.

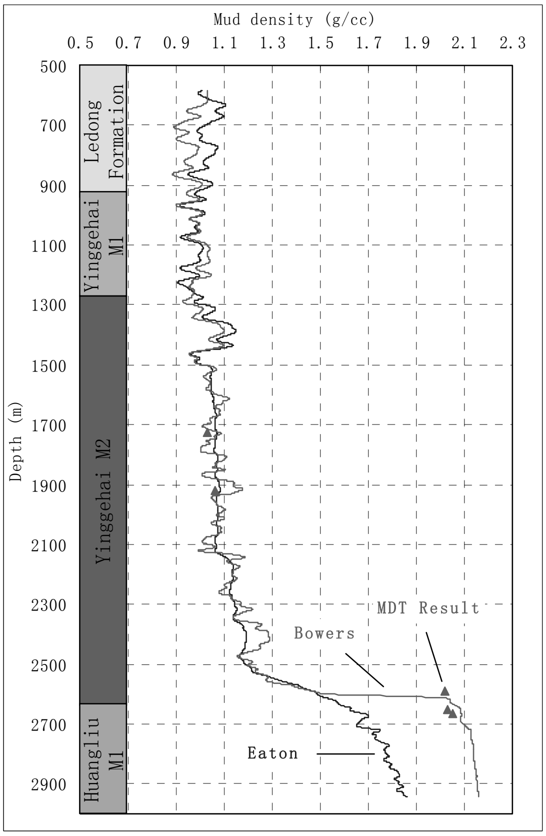


*Fig. 6. Pore prediction result of the well A*

The results show the following three points:

1. The overpressure does not appear at a depth of 1500 m, and the results show that it should be about 2250m. Thus, if we determine the overpressure initiation only by the normal trend line, the pore pressure predicted would be higher.

2. In Yinggehai formation M2 (2250–2632 m), the prediction results received by the Eaton method and the Bowers method are nearly the same. Therefore the main overpressure mechanism is the disequilibrium compaction. The influence of the fluid volume expansion is slight.

3. In Huangliu formation M1, the result received by the Eaton method is smaller than the real measured value by 19%; while the difference between the result received by the Bowers method and the measured value is only 2,3%.

**Conclusions.** The overpressure caused by the disequilibrium compaction fits loading curve. The logging response is that both acoustic velocity and density decrease. While, the overpressure conforms to unloading curve due to fluid volume expansion, the density logging data remain the same; but acoustic velocity would decrease.

The overpressure mechanisms in Yinggehai Basin include the disequilibrium compaction and fluid volume expansion; but their contribution to the overpressure in different formation is different. The DT-density crossplot and the DT-density-depth crossplot have good effects on judging different overpressure mechanisms. The pore prediction made simply by normal trend line might be higher.

The pore pressure prediction on the basis of overpressure mechanism has been proposed in this paper. The results show that the Eaton method and the Bowers method are both suitable for disequilibrium compaction. But in case of fluid volume expansion overpressure, the result received by the Eaton method would be smaller. So the Bowers method is more accurate. By this method we have achieved a good result in DF1-1 gas filed.

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Газова область Dongfang 1-1 є високотемпературною площею та площею з високим тиском. Точний прогноз порового тиску є дуже важливим для безпечного буріння на цій території. У роботі вперше аналізуються та класифікуються механізми надлишкового тиску на підставі навантаження й розвантаження, що пов'язані з вертикальною ефективною напругою та акустичною швидкістю. Також обговорюються каротажні дані для іншого механізму аномально високого тиску. На підставі вищевикладеного, пропонується новий метод прогнозування порового тиску на підставі графіків залежності DT-щільність і DT-щільність-швидкість. Метод використовується для аналізу природи аномально високого тиску, прогнозування високої температури й тиску в газовій області DF1-1 басейну Yinggehai. Результати показують, що, хоча надлишковий тиск у газовій області DF1-1 викликаний нерівноважним ущільненням, акватермальним розширенням і генерацією вуглеводнів, внесок до аномально високого тиску в різних формаціях різний. Використовуючи графіки залежності DT-щільність і DT-щільність-глибина, можна оцінити різний внесок, вибрати підходящу уточнену модель прогнозу. Доведено, що метод Етона підходить тільки для нерівноважного ущільнення, а метод Бауерса є ефективним при аномально високому тиску, викликаним нерівноважним ущільненням або об'ємним розширенням рідини. Цей метод дозволяє підвищити точність прогнозування порового тиску в газовій області DF1-1 і має істотне значення для буріння свердловин.

**Ключові слова:** *газова область DF1-1, висока температура, високий тиск, механізм аномально високого тиску, навантаження, розвантаження, прогноз порового тиску*

Газовая область Dongfang 1-1 является высокотемпературной площадью и площадью с высоким давлением. Точный прогноз порового давления является очень важным для безопасного бурения на этой территории. В работе впервые анализируются и классифицируются механизмы избыточного давления на основании нагрузки и разгрузки, которые связаны с вертикальным эффективным напряжением и акустической скоростью. Также обсуждаются каротажные данные для другого механизма аномально высокого давления. На основании вышеизложенного, предлагается новый метод прогнозирования порового давления на основании графиков зависимости DT-плотность и DT-плотность-скорость. Метод используется для анализа природы аномально высокого давления, прогнозирования высокой температуры и давления в газовой области DF1-1 бассейна Yinggehai. Результаты показывают, что, хотя избыточное давление в газовой области DF1-1 вызвано неравновесным уплотнением, акватермальным расширением и генерацией углеводородов, вклад в аномально высокое давление в различных формациях разный. Используя графики зависимости DT-плотность и DT-плотность-глубина, можно оценить различный вклад, выбрать подходящую уточненную модель прогноза. Доказано, что метод Этона подходит только для неравновесного уплотнения, а метод Бауэрса является эффективным при аномально высоком давлении, вызванным неравновесным уплотнением или объемным расширением жидкости. Этот метод позволяет повысить точность прогнозирования порового давления в газовой области DF1-1 и имеет существенное значение для бурения скважин.

**Ключевые слова:** *газовая область DF1-1, высокая температура, высокое давление, механизм аномально высокого давления, нагрузка, разгрузка, прогноз порового давления*

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