A. M. Buchynskyi[1],
orcid.org/0000-0001-7154-6404,
M. Ya. Buchynskyi[2],
orcid.org/0000-0001-7529-1680,
M. I. Vasylchenko[1],
orcid.org/0000-0002-9569-154X

1 — National University "Yuri Kondratyuk Poltava Polytechnic", Poltava, Ukraine, e-mail: abuchynskyi@ukr.net
2 — Expertnaftogas LLC, Poltava, Ukraine

FORECASTING THE TECHNICAL EFFICIENCY OF MOBILE WORKOVER RIGS

Purpose. To propose a method of comparative evaluation of technical efficiency of mobile workover rig by the criterion of life cycle cost.

Methodology. The proposed method is based on the determination of the specific discounted costs related to the technical condition of the machine, spent on a conventional unit of work performed. It combines economic and technical indicators that characterize the performance of the machine. This makes it possible to indirectly assess its technical efficiency. Procedures for obtaining and processing input information, analytical dependences for establishing the components of the mathematical model and its solution are shown.

Findings. Using the proposed method, a comparison is performed of three conventional similar models of workover rigs, which are positioned as more reliable, and two which are less reliable and cheaper. Their indicators are formed as a weighted average based on the analysis of an array of statistical information. The obtained values were used to indirectly determine the specific discounted costs for the maintenance of rigs in working order for a period of time; the rigs are characterized by the indicator of technical efficiency. The comparison of these indicators for similar workover rigs is performed for such characteristic points as the moment of balancing of expenses, expenses for the forecasted period of operation, the periods of operation at which expenses are balanced. It is confirmed that usually the gain from the greater durability far exceeds the reduction of the economic effect of the rise in price of the machine.

Originality. The proposed method for engineering forecasting of technical efficiency of technological machines using values of economic and technical indicators available to engineers of the petroleum industry.

Practical value. This assessment is intended to objectively compare several analogue models and make a reasonable choice of a more efficient technological machine.

Keywords: *workover operation, mobile rig, technological machine, life cycle cost, engineering forecasting*

Introduction. One of the priority areas for increasing production is the growth of hydrocarbon extraction, which especially depends on the timely and successful implementation of well workover operations [1]. After all, the efficiency of oil and gas development and financial losses of production companies are significantly affected by the simple operation of wells. And this requires justification and selection of effective technologies and technical means.

A well workover operation is a large-scale work directly in the wellbore of an oil and gas well. It occupies a significant share among all the work performed in the development of oil and gas fields, especially at the final stages. There is always a significant fund of wells that need workovers in order to restore their production characteristics. Currently, such works are in great demand in Ukraine's oil and gas fields, in many countries in the Middle East and North Africa. They are usually performed using mobile rigs. Stable demand for these services, and its growth in many oil and gas regions, poses a challenge for service companies to provide their production facilities with efficient technological machines, primarily through the renewal and expansion of the fleet of workover facilities.

After all, the difficult task of forming a fleet of machinery and equipment of the enterprise raises the need to choose the appropriate model that can not only fully meet the technological requirements, but also ensure maximum technical efficiency. The model is chosen based on the results of comparison and comparative analysis of alternative analogues. At the same time, the criteria they are guided by are often one-sided: in one case they choose exceptionally high reliability, in another — low purchase price, and in some cases — a long service life or high manufacturability of machines.

This is especially true in the petroleum industry, where the renewal of fixed assets is actively carried out, in particular, the

rigs, which are energy-intensive, expensive and with a long period of operation.

Therefore, the scientific justification of the choice of effective technical support for well workover operations is a technical task that has a significant practical value.

Literature review. Quantitative assessment of the efficiency of well workover, which depends not only on the organization of works, technological processes, but also on the technical equipment of production, is one of the indicators that are difficult to plan and determine. And this is especially true of the efficiency component, which depends on the technological machines.

In [2], the method for estimation of operational efficiency of well workover rigs is offered and the approach for measurement of the general efficiency of the equipment is covered. It is shown that efficiency can be achieved through rational management, and one of the indicators of quality is the ratio of effective time to total time of work on the well. The issue of optimizing the number and characteristics of installations for the implementation of well workover programs to minimize the cost of loss of hydrocarbon production and use of equipment over a period of time is also considered [3]. Articles [3–5] take into account the impact of maintenance and hourly rate of the rig.

But usually in scientific publications, mostly organizational measures to optimize the program implementation of work with mobile rigs are considered. And at the same time their technical efficiency as a component of quality of performance of works is insufficiently considered.

Let us consider the generally accepted conditions for the performance of work by the contractor who operates the equipment and performs work to the customer. During the workover of wells in the oil and gas fields, the work is usually performed on a contract basis. At the same time, they use both one-time rates for installation, dismantling, mobilization and demobilization of the rig, and "operating rate" to perform ba-

sic technological operations. It is divided into "during operation" and "during technological standby" modes. Among them, the duration of the operating rate "during operation", when the lifting unit is usually operating, exceeds 60 % and can reach 90 %. The daily rate on the Ukrainian market is from 0.5–1 % of the price of a new rig, and abroad it can reach up to 5 %. All the time of simple well workover operations in most cases in the Donetsk-Dnieper basin of Ukraine lasts 15–50 days. In the case of complex fishing operations or drilling of the branch hole with a waste of up to 200 m (which is interpreted as a major workover, which uses mobile units with a capacity of up to 225 tons) work can last 100–150 and more days.

We focus on the conditions of work, where the workover rig has a significant impact. Such works are: raising operations; drilling, including the processing of casing string; casing scraper of the production casing; wash-over fishing; casing reaming; fishing operations, including raising and lowering, and others.

Under the terms of the contract, the contractor usually guarantees the suitability of all equipment for operation during the entire period of work. They are responsible for the quality and performance of the equipment. The equipment must be high-tech, fully prepared for work and designed for its continuous maintenance. All the equipment is inspected before use, appropriate periodic maintenance is organized, and the necessary types of technical inspections and tests are provided. The Contractor, at their own expense, provides, installs, maintains the equipment in proper working order, inspects, repairs or replaces it where necessary. In addition, they provide the supply of all spare parts and materials required for maintenance and have a non-reducible list of spare parts and materials. And in case of violations of the technical condition of the rigs (missing, defective, incomplete, untested equipment) the customer stops the work on workover operations.

In case of poor performance of works, penalties are applied to the contractor. For example, for deviations and/or violations that may be caused by the technical condition of the rig. In particular, for exceeding the standard time of repair due to the fault of the contractor, in addition to performing work during this period at their own expense, a fine of 20–40 % of the operating rate is imposed. No fines are paid and imposed for downtime due to the contractor's fault and violation of the technology of a particular operation, which leads to a deterioration in the quality of work. At the same time, during downtime, the contractor bears the cost of maintaining equipment and crew in the amount of not less than 25 % of the cost of the operating rate. Elimination of complications and accidents through the fault of the contractor is also performed at their expense.

Thus, reducing downtime and increasing efficient time and productivity are an important factor influencing the profits of contractors and customers. It depends not only on the organization of work, but also on the workover rig.

The use of high-tech and reliable equipment will significantly improve the balance of calendar time, in particular reduce unproductive time and duration of operations. Such rational formation, renewal and modernization of the fleet of machines with effective technological equipment for well workovers will ensure maximum performance of useful work (production of proper quality) with minimal production costs.

In the global economy, decisions about the purchase and use of machines are made at the cost of their life cycle (LCC).

Life cycle cost is information that helps company executives determine investment strategies in an increasingly competitive market environment. The concept of the value of the life cycle of machines is applied, starting from the stage of creation of the machine [6, 7] setting its resource during the formation of technological processes of manufacturing the product. At the same time, it is used for decision-making and risk management during the purchase and operation of machinery

[8], design and construction of buildings [9], comparing the results of different costs over time. To make a more cost-effective decision, cost components are usually taken into account at all stages of the life cycle of the technical object [10, 11]. Determining the total cost of a project requires a large amount of accounting information, which has data sets that are difficult to account for. Automated economic calculation procedures and special software packages are commonly used in the analysis. There is no single theory for the use of LCC, many different algorithms are used (prognostic, research or normative), which cause difficulties in practical use [12, 13].

Unsolved aspects of the problem. Therefore, the algorithm of comparative engineering forecasting of technical efficiency of similar mobile rigs for well workover operation according to the criterion of life cycle cost, using technical and economic indicators available to engineers, is relevant.

Purpose. To propose a method of comparative evaluation of technical efficiency of mobile well workover rigs according to the criterion of life cycle cost.

Description of the methodology (structure, sequence) of the study. *Mathematical dependence for predicting efficiency.* To predict the technical efficiency of installations, we use J. Taylor's formula modified by the authors [14]

$$c = \frac{S_0 - f_S(t) + f_u(t)}{k_{tl} \cdot f_k(t)},$$

where c is specific accumulated costs, which is an indicator of technical efficiency; S_0 is the price of a new one; $f_S(t)$ is the price for a used one after t years of operation; $f_u(t)$ is the accumulated costs of maintaining the technical condition (operation expenses); k_{tl} is the coefficient of technical level; $f_k(t)$ is the coefficient of availability.

To compare the technical efficiency of several models, we use formulas for determining economic quantities, whose indicators in the numerator are reduced to the price of a new rig S_0.

$$c = \frac{S_0 - \dfrac{f_S(t)}{S_0} + \dfrac{f_u(t)}{S_0}}{k_{tl} \cdot f_k(t)} = \frac{1 - f_S(t) + f_u(t)}{S_0 \cdot k_{tl} \cdot f_k(t)}.$$

For the correctness of comparing the values of each of the installations, we reduce them to a single price − for example, the price of the new base S_0^b, i.e., multiplied by a factor that shows how many times the prices of rigs S_0/S_0^b. For the baseline, this factor is 1.

$$c_{reduce} = \frac{S_0}{S_0^b} \cdot \frac{1 - f_S(t) + f_u(t)}{S_0 \cdot k_{tl} \cdot f_k(t)} = \frac{S_0}{S_0^b} \cdot c.$$

Presentation of the main material and scientific results.
Formation and processing of arrays of statistical information. For the sake of correctness of comparison of the considered samples (prices of new models, residual cost of rigs, expenses for their operation and indicators of reliability) in each of them statistical information for homogeneous models of a range of loading capacity of 80–180 tons with the power capacity of 350–1,100 hp is processed. Countries of production are Canada, China, Russia, the USA, and Ukraine. The period of obtaining statistical information is 2005–2020. Quantitative characteristics of the samples are given below (in their detailed consideration).

The source information is a representative sample that reflects the long-term state of the market for the sale and operation of mobile well workover rigs and provides sufficient accuracy for practical purposes. A large sample size reduces the importance of each model for the final result.

The regression equations are calculated by the method of least squares. The adequacy of the obtained equations with statistical data is estimated by the criterion of reliability of the approximation

$$R^2 = 1 - \left(\frac{\sum (x - \bar{x})^2}{\sum x^2 \frac{i-1}{i}} \right),$$

where x is the indicator of installation in a certain time; $\bar{x}$ is the estimated value of the rig at the same time; i is the number of values in the series.

At $R^2 = 1$ the correlation is absolute, and the two indicators are related at $R^2 > 0.75$.

Let us consider some rigs with weighted averages counted for them. The procedure for obtaining the value of each of the components of the modified Taylor formula, which evaluates the indicator, will be discussed below.

Cost of a well workover rig (new and used ones after n years of operation). To determine the variability over time of the value of the used one, reduced to the value of the new one, consider the following two sets of statistical information.

Array 1 − Cost of a new rig S_0. For the analysis, we used a statistical sample of prices for new rigs in the amount of 26 units of seven different brands. Prices for rigs of the same completeness are considered on the terms of delivery of FOB Incoterms. Prices are based on official commercial offers from equipment manufacturers.

Array 2 − Residual value of the machine after n years of operation S_n. The array of statistical information includes the prices of equipment of the same type of basic equipment. The sample was obtained from open sites of companies specializing in the sale of used petroleum equipment, as well as from negotiations with their representatives.
- the number of rigs (sample size), units − 91;
- the number of trademarks, units − 11;
- age range of rigs, years − 3−37;
- technical condition − workable, after technical inspection.

At the same time, we use the relative value of the price of the used rig S_n / S_0, which allows us to correctly perform a comparative assessment and obtain an indirect indicator of technical and economic efficiency of the base model and comparison model.

Determining the relative price S_n / S_0, we were guided by the prices of the same type (according to the criteria of equal completeness and similar in terms of installed load and power capacity) of used and new rigs of one or similar quality of the manufacturer in the same period of high or low activity in the drilling rig market. In order to ensure the uniformity of the statistical sample, groupings were performed according to the criterion of load capacity and installed capacity, which did not show differences in values of more than 3.8 %. Therefore, the statistical sample is divided into two groups only on the basis of estimated reliability of the models.

The graphical dependence of the change in the price of used models over time is shown in Fig. 1.

The regression dependences of the prices for the used rig reduced to the price of the new one, are as follows:
- for the highly reliable equipment (Fig. 2, upper curve *1*)

$$\frac{S_n}{S_0} = e^{-\left(\frac{t}{56.82} \right)^{0.618}}, \quad R^2 = 0.959;$$

- for equipment of lower reliability (Fig. 2, lower curve 2)

$$\frac{S_n}{S_0} = e^{-\left(\frac{t}{16.43} \right)^{0.991}}, \quad R^2 = 0.967.$$

It should also be noted that according to the data, the largest sales volumes (over 2/3) of used more reliable rigs are at the age of 24−38 years, and less reliable − 17−27 years. This may mean that the period of effective operation of these groups differs by approximately 30−35 %.
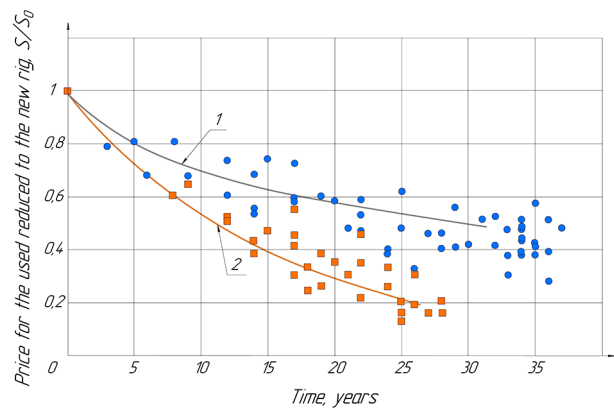

Fig. 1. Change in prices over time for a used workover rig

Operational expenses. To determine the costs paid by enterprises in the Ukrainian market of services for the system of technical operation of the workover rig, the following array of statistical information was used:
- the number of rigs (sample size), units − 8;
- the number of trademarks, units − 6;
- age range of installations, years − 5−34;
- total operating time, thousands of hours ≈131.

Assessing the technical component of the effectiveness of a particular model, we assume that the commercial conditions, technological process and organization of the operating system are the same. Therefore, this value includes only the cost of repairs (spare parts and services of contractors), which primarily ensure the operability of the equipment, i.e. its technical efficiency.

The costs of such technical systems and basic equipment, whose properties characterize the reliability and availability of the rig in general, are estimated. These are the drive (diesel, automatic transmission and other transmission mechanisms), hydraulic and pneumatic systems, mast, substructure, drawworks, travelling block and crown block, auxiliary draw-works, trailer etc. They did not take into account the cost of fuel, oils and other process fluids, the remuneration of their own repair and maintenance staff. The data were obtained from the financial and technical services of a number of enterprises.

During the creation of the regression model, the cost values were reduced to the same conditions: the annual service life is 4,500 operating hours, which is approximately 55 % of the annual time fund. That is, it is accepted that commercial operation is carried out approximately 75−80 % of the time, and downtime due to the specifics of the technological process and commercial organization of work − 30−35 %. During the grouping of sampling data (stratometric sampling) according to the criteria of the plant manufacturer, their initial cost, reliability, load and power capacity, no significant distinctive
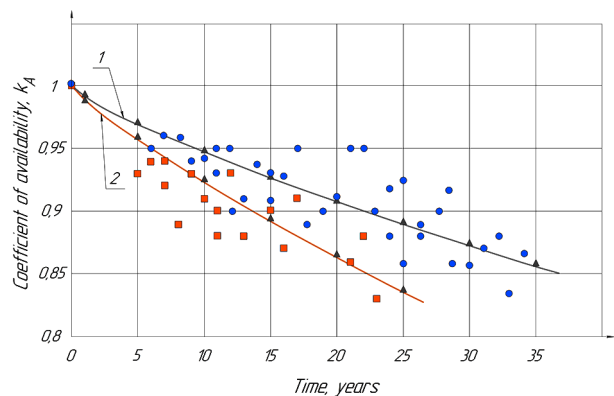

Fig. 2. Change in the coefficient of availability of rigs over time

characteristics were established by operating enterprises. This, in our opinion, is due to significantly different system of technical condition management of machines, especially differences in the system of operation and organization of maintenance (disaster recovery, technical condition, operating time, preventive, individual), adopted in different periods at each enterprise.

According to the results of regression analysis of the aggregate sample data, we have a dependence to determine the costs of maintaining the technical condition of the rigs

$$\sum_{i=1}^{n} U_i = e^{-\left(\frac{t}{13.75}\right)^{-0.871}} , \quad R^2 = 0.829.$$

Note that for 25 years of operation the cost was 46−69 % of the cost of the new one.

We also note that, in our opinion, these costs for the same organization of maintenance for rigs with different reliability can be approximately equivalent, as the increase in costs due to increased frequency of repairs is offset by lower prices for components and branded repair service, and differ significantly in one side or the other. At the same time, the most significant cost is the control system of the technical condition of machines. And even higher costs for a better system are more cost-effective due to the increase in availability.

Coefficient of technical level. To assess the impact of the coefficient of technical level on the efficiency of workover rigs, the opinion of industry experts from operational, scientific and control-expert enterprises of the industry is taken into account. We assume that in quantitative terms this value can be 3−5 % and more.

Coefficient of availability. The same set of statistical information was used to estimate the dynamics of changes in the readiness factor as in determining operating costs.

We determine the coefficient of readiness according to the formula

$$k_A = \frac{T_{ww}}{T_w} = \frac{T_{ww}}{T_{ww} + T_{nw}},$$

where T_w is working time; T_{ww} is a workable machine during working times; T_{nw} is a non-workable machine during working times.

To ensure uniformity (both from our own experience and from statistical data), two statistical samples were formed for models of higher and lower reliability in particular.

The graphical dependence of the change in the coefficient of readiness over time is shown in Fig. 2.

Regression dependences for its definition depending on the age of installation are as follows:

- for equipment of higher reliability (Fig. 3, upper curve *1*)

$$k_A = e^{-\left(\frac{t}{312.1}\right)^{0.861}} , \quad R^2 = 0.959;$$

- for equipment of lower reliability (Fig. 3, lower curve *2*)

$$k_A = e^{-\left(\frac{t}{168.2}\right)^{0.912}} , \quad R^2 = 0.967.$$

Comparison of technical efficiency. Using the established dependences of the components of J. Taylor's formula modified by the authors, we construct graphical dependences of the specific accumulated costs over a period of time for workover rigs. The duration of the period is 25 years, which is comparable to the operational period of their life cycle. For the basic we will take the rig of higher reliability, for comparison − the rig of lower reliability.
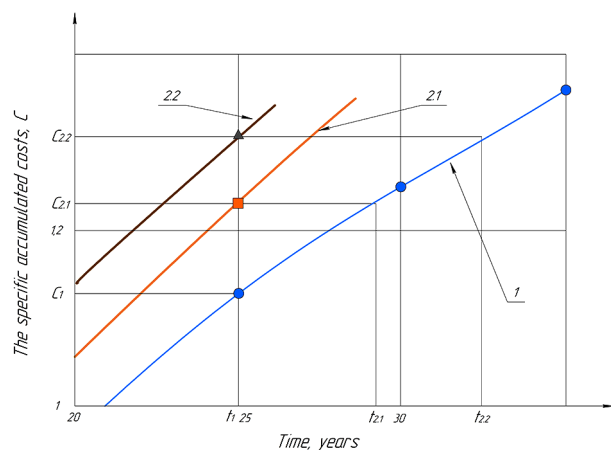
The calculations were performed for a more reliable option and two comparison options − less reliable rigs with different starting prices $S_0^{n1} = 0.8 S_0^b$ and $S_0^{n2} = 0.75 S_0^b$. The calculations are shown graphically in Fig. 3. As a result, we have a
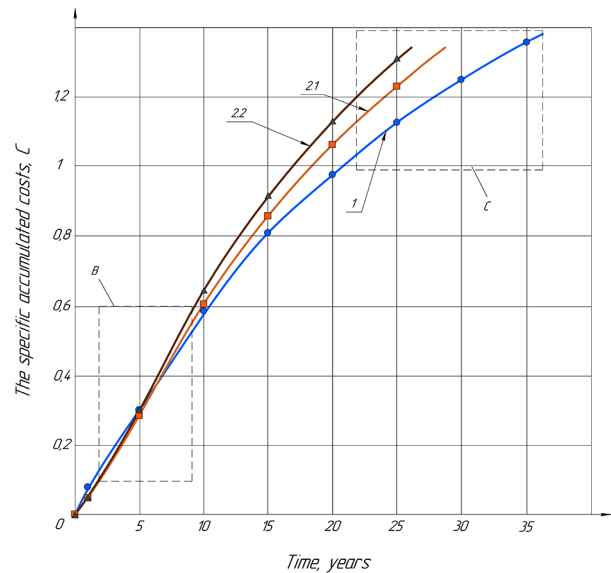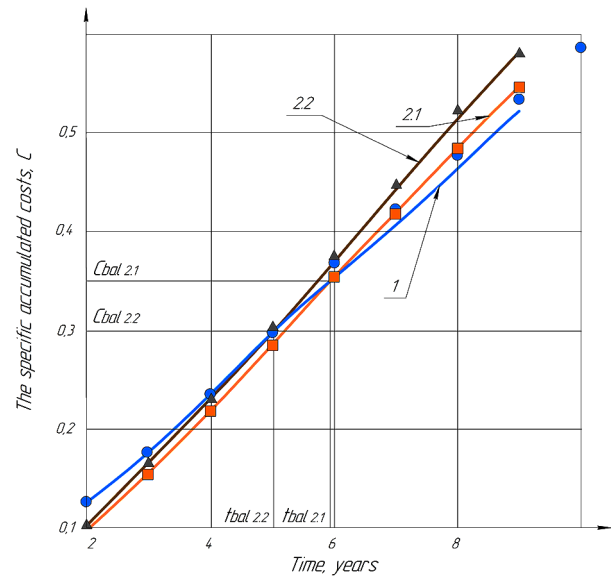
Fig. 3. Graphical comparison of technical efficiency of well workover rigs:

a − general view; b, c − enlarged areas to visualize the characteristic points of efficiency comparison

case where the curves intersect. Therefore, the values of technical efficiency of a more reliable rig are lower or higher relative to the efficiency values of other installations.

Let us consider the values of intersection points that show technical efficiency at characteristic points in time. We will compare the following two options:

Comparison option 1. The more reliable one (curve *1*) and the less reliable one (curve *2.1*) with the initial price $S_0^{n1} = 0.8 S_0^b$.

Comparison option 2. The more reliable one (curve *1*) and the less reliable one (curve *2.2*) with the initial price $S_0^{n2} = 0.75 S_0^b$.

Comparison of models shows that:

1. The moment of balancing t_{bal} of accumulated costs C_{bal} during the operation of machines (Fig. 3, *b*) occurs at the turn of the *4th* and *5th* years (comparison option 2, point ($t_{bal2.2}$; $C_{bal2.2}$)) and at the end of the *5th* year of operation (comparison option 1, point ($t_{bal2.1}$; $C_{bal2.1}$)). That is, after the *5th* year of operation, the base unit becomes more technically efficient in economic terms for both options.

2. The specific accumulated costs that the owner will have to ensure the operability of the base unit for the operational period of 25 years (Fig. 3, *c*, point C_1) are 9 and 16 % less than for comparison models (Fig. 4, *c*, points $C_{2.1}$ $C_{2.2}$).

3. The basic rigs for 29 and 33 years (Fig. 3, *c*, points $t_{2.1}$ $t_{2.2}$) of its operation reaches the level of costs (Fig. 3, *c*, points $C_{2.1}$ $C_{2.2}$) of the *25th* year of operation comparison. Therefore, provided that the specific accumulated costs of operability are equivalent, its service life is 20−30 % longer, and during this time the rig will bring additional income to the owner.

Let us also consider the possible unearned income $C^{"-"}$ during the operation of a lower reliability workover rig under the following initial conditions, which are given in the article:

- the daily rate from 0.5−1 % of the price of a new rig, $C_{day} = (0.005-0.01)S_0$;

- commercial exploitation is carried out approximately 75 % of a calendar time fund;

- duration of the rig's operating period $t = 25$ years or 9125 days;

- the coefficient of availability k_A averaged over the period of operation is 3 % lower than the rig of higher reliability, $\Delta k_A = 0.03$

$$C^{"-"} = C_{day} \cdot 75 \cdot t \cdot \Delta k_A = 1.02-2.04 \cdot S_0.$$

That is, it is within 1−2 of the cost of a new rig. At the same time, we did not take into account the probability of fines, which increases with the operation of a less reliable rig.

Conclusions and prospects for further development in this direction. A method for engineering forecasting of technical efficiency of mobile well workover rigs by the criterion of life cycle cost is proposed. This method establishes the relationship between reliability and economic criteria and offers an algorithm for quantitative comparative evaluation of similar machines for business projects of different durations at different periods of their life cycle. Therefore, all other things being equal (systems of commercial and technical operation of machines adopted at the enterprise), the specialist, using technical and economic indicators available to engineers, makes an informed choice of model for the business project.

Comparison of variants of technological machines under the conditions of identical commercial operation and system of technical operation:

- evaluates the technical efficiency of each of the compared options both for a specified period and at a certain point in time;

- predicts periods of relatively lower or higher technical efficiency of the rig;

- when forecasting, takes into account the duration of the project for which the machines are intended;

- provides a quantitative assessment of technical efficiency to justify the choice of more efficient technological machine for the forecast period of time.

On the example of well workover rigs it is shown that 20−25 % more expensive rigs with 5 % higher readiness factor (for 25 years of operation) have 10−15 % higher technical efficiency only due to technical level and reliability, and their period of operation (other things being equal) is longer by 20−30 %. At the same time, the owner receives additional income from increasing the operating time of the rig due to higher reliability and longer service life. And the additional income due to the higher coefficient of availability for the 25-year period of operation will be approximately 1−2 times the cost of a rig.

Quantitative assessment confirms that the gain from greater durability of technological equipment far exceeds the reduction of the economic effect of the rise in price of the machine.

The method proposed in the article can be used not only for well workover rigs. It is intended for any technological machines of petroleum and other industries which have high initial cost, long service life and are maintainable. Also, this method can be adapted to optimize the age structure of the fleet of technological machines, which will:

- ensure quality performance of production tasks;

- ensure high profitability of the enterprise;

- correspond to the modern technical level.

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Прогнозування технічної ефективності мобільних установок для капітального ремонту свердловин

А. М. Бучинський[1], *М. Я. Бучинський*[2],
М. І. Васильченко[1]

1 — Національний університет «Полтавська політехніка імені Юрія Кондратюка», м. Полтава, Україна, e-mail: abuchynskyi@ukr.net
2 — «Експертнафтогаз», м. Полтава, Україна

Мета. Запропонувати метод порівняльної оцінки технічної ефективності мобільних установок капітального ремонту свердловин за критерієм вартості життєвого циклу.

Методика. Запропонований метод базується на визначенні питомих дисконтованих витрат, пов'язаних із технічним станом машини, затрачених на умовну одиницю виконаної роботи. Він поєднує економічні й технічні показники, що характеризують роботоздатність технологічної машини. Це дає можливість опосередковано оцінити її технічну ефективність. Показані процедури отримання та опрацювання вхідної інформації, аналітичні залежності для встановлення складових математичної моделі та її розв'язку.

Результати. Використовуючи запропонований метод, виконане порівняння трьох умовних аналогічних моделей установок для капітального ремонту свердловин, що позиціонуються як надійніша та дві менш надійні й дешевші. Їх показники сформовані як середньозважені на основі аналізу масиву статистичної інформації. Отримані значення використані для опосередкованого визначення за період часу питомих дисконтованих витрат на утримання установок у працездатному стані, що характеризуються показником технічної ефективності. Порівняння цих показників для аналогічних установок виконується для таких характерних точок, як момент урівноваження витрат, витрати за прогнозований період експлуатації, періоди експлуатації, за яких урівноважуються витрати. Підтверджено, що зазвичай виграш від більшої довговічності технологічного обладнання значно перевищує зниження економічного ефекту від подорожчання машини.

Наукова новизна. Запропонований метод інженерного прогнозування технічної ефективності технологічних машин із використанням доступних для інженерів нафтогазової галузі значень економічних і технічних показників.

Практична значимість. Таке оцінювання призначене для об'єктивного порівняння декількох моделей-аналогів і обґрунтованого вибору ефективнішої технологічної машини.

Ключові слова: *капітальний ремонт свердловин, мобільна установка, технологічна машина, вартість життєвого циклу, інженерне прогнозування*

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