Influence of technical condition parameters on the residual resource of capacitive equipment

P A Kulakov¹, A V Rubtsov¹, V G Afanasenko¹, O E Zubkova¹, R R Sharipova¹ and A A Gudnikova¹

¹Ufa State Petroleum Technological University, 1, Kosmonavtov street, Ufa, 450062, Russia

E-mail: kulakov.p.a@mail.ru

Abstract. The work solved the problem of resource assignment to the safe operation of capacitive devices after carrying out technical diagnostics on permissible technical parameters, depending on the combined effect of the parameters of the technical condition of the equipment oil and gas refining and petrochemical industries. 10 technical and technological parameters of capacitive devices were selected, and the evaluation was carried out using such an indicator as the residual service life of capacitive devices. The authors developed a mathematical model, calculated diagnostic coefficients and informative value of the indicator for each period adopted by the expert. An algorithm for estimating the residual service life of capacitive devices based on the measure of information content of Kulbak is proposed. The estimates of the residual life, which are out of the constructed model, are shown. Conclusions about the rationality of the proposed algorithm for solving problems of this type are made.

1. Introduction
Capacitive equipment of production facilities in the oil and gas industry occupies one of the leading places, both in terms of metal content and participation in technological processes. Such equipment is used for the processes of settling, separation, collection and storage, etc., established by the process technology and technological regulations.

Capacities of the oil and gas industry relate to technical devices that are operated at a hazardous production facility and, therefore, according to legislation in the field of industrial safety, they must periodically undergo an assessment of the technical condition and residual life.

The operational reliability of capacitive equipment depends on many different factors, such as, for example, working pressure and temperature, technological environment, design features, material performance, etc. The determining factors for assessing reliability are the determination of the dominant damage mechanism, the degree of degradation, and the level of material defectiveness.

All determining factors can be determined in the course of work on the assessment of the technical condition and residual resource of the object under consideration.

The scope of work on the assessment and forecasting of a resource includes such works as: documentation analysis; non-destructive and destructive control; necessary strength calculations and resource calculation; tests for strength, density and tightness.

The predominant mechanism of damage to the capacitive equipment of the oil and gas industry is corrosive wear, due to various corrosion processes.
In order to quantify the degree of corrosive wear of structural elements and predict the residual life of the wall thickness, it is necessary to measure the residual wall thickness of the elements and to make a comparative analysis with the design and reject thicknesses. In some cases, the minimum probable wall thickness is calculated taking into account uncontrolled surface areas and increasing reliability.

Mathematical methods used in expert assessments allow the resource to be estimated at the upper boundary (table 1). In certain cases, this boundary is very high in relation to the value given in the conclusion of the industrial safety expertise [1].

The data obtained in the form of bulk arrays of necessary indicators make it possible to analyze the final result of future examinations, to develop a mathematical model that can most fully characterize the considered type of technical device [1-6].

The parameters of the technical state of the capacitive equipment make it possible to get an idea about their state, as well as about the change of parameters in time intervals, which will entail the diverse trajectories and forms of wear and the possible failure scenarios [7–10].

Currently, the influence of technical parameters of heat exchange systems [11, 12] is widely evaluated, the residual resource is modeled using computer technology [12, 13], mathematics [12, 13, 14], neural networks [4-6] are used. However, even such an extensive arsenal does not always provide the required accuracy of the outcomes and the simplicity of the applicability of complex equations.

2. Mathematical model

10 signs were selected that affect the residual life of heat exchange systems: Commissioning year ($\tau_1$), Expert evaluation year ($\tau_2$), Pressure ($P$), Temperature ($T$), Housing shell (inner diameter) ($D$), Wall thickness passport ($h_1$), minimum wall thickness ($h_2$), lifetime ($\tau_3$), corrosion rate per year ($\varepsilon$), thickness margin ($n_h$).

We have data on 46 expert opinions on heat exchangers with an expert opinion from 4 to 10 years (table 1). In the sample there are no data on containers for which the examination would give a negative conclusion. The effect of the listed parameters ($\tau_1$, $\tau_2$, $P$, $T$, $D$, $h_1$, $h_2$, $\tau_3$, $\varepsilon$, $n_h$) on the residual capacity of the containers can be determined by calculating their informativeness [1].

Informativeness assessment is carried out by Kullback measure [1]. Since the Kullback measure makes it possible to evaluate the information content as a measure of the discrepancy between the two classes, already with the three classes difficulties arise. Therefore, we will evaluate for several iterations: at the first iteration, we will divide the heat exchangers into two groups - having a residual life of 10 years and not having such a resource, at the second iteration we divide the remaining life of 8 years, at the third - 6 years and at the fourth iteration - 5 years.

There are ten signs ($\tau_1$, $\tau_2$, $P$, $T$, $D$, $h_1$, $h_2$, $\tau_3$, $\varepsilon$, $n_h$), as well as the result - the residual resource for the first iteration - 10 years, or its absence. We divide containers into two groups: "A" - having a residual life of 10 or more years; "B" - not having such a resource. As data for building a model, we take tanks 1-37, and to test the model - heat exchangers 38-46.

We find the information content of each of the ten signs.

We will consider an example of calculating the information content on the basis of the “Date of commissioning”, which is denoted by $\tau_1$.

The range of variation of this parameter is from 1955 to 1999. All values $\tau_1$ are divided into intervals: [1955; 1965], (1965; 1975], (1975; 1985], (1985; 1995), (1995; 1999). With 4 intervals, we determine the frequency of tanks falling into one of the groups (“A” or “B”). In our sample, there are no tanks with a commissioning date between 1955 and 1965 that would fall into group “A”, but there are 11 containers that fall into group “B.” In the interval (1975; 1985) there are three containers from the group “A” and also three containers from group “B”.

Determining the relative frequency of falling into one group or another within the interval: if for group “A” there are 3 heat exchangers from 4 heat exchangers of group “A”, then for the third interval the relative frequency of falling into group “A” is $y_A = 75\%$ (table 2).
### Table 1. Data on heat exchangers and factors affecting the residual life.

| N  | Date of commissioning, year | Date of examination, year | Pressure | Temperatur e | Shell of the body (inner diameter) | Wall thickness | Time of maintenance | Corrosion velocity | Residual resource |
|----|---------------------------|---------------------------|---------|-------------|-----------------------------------|---------------|-------------------|-------------------|------------------|
| 1  | 1960                      | 2005                      | 1.35    | 50          | 1000                              | 10            | 9.13              | 45                | 0.19             |
| 2  | 1973                      | 2004                      | 0.45    | 50          | 1400                              | 6             | 5.6               | 31                | 0.22             |
| 3  | 1967                      | 2008                      | 0.06    | 50          | 1400                              | 8             | 4.6               | 41                | 1.04             |
| 4  | 1970                      | 2008                      | 0.03    | 50          | 2800                              | 5             | 4.1               | 38                | 0.47             |
| 5  | 1977                      | 2008                      | 2       | 20          | 1000                              | 12            | 10.8              | 31                | 0.32             |
| 6  | 1978                      | 2008                      | 0.8     | 100         | 1000                              | 12            | 10.6              | 30                | 0.39             |
| 7  | 1967                      | 2008                      | 4       | 50          | 1200                              | 22            | 20.5              | 41                | 0.17             |
| 8  | 1962                      | 2007                      | 0.018   | 60          | 1600                              | 8             | 7.6               | 45                | 0.11             |
| 9  | 1961                      | 2010                      | 0.1     | 100         | 2400                              | 28            | 22.3              | 49                | 0.42             |
| 10 | 1961                      | 2010                      | 0.2     | 350         | 2000                              | 8             | 6.8               | 49                | 0.31             |
| 11 | 1962                      | 2007                      | 0.014   | 100         | 1400                              | 6             | 3.7               | 45                | 0.85             |
| 12 | 1956                      | 2005                      | 0.028   | 60          | 2780                              | 10            | 6.1               | 49                | 0.80             |
| 13 | 1968                      | 2007                      | 2.5     | 50          | 1200                              | 14            | 12.3              | 39                | 0.31             |
| 14 | 1968                      | 2007                      | 2.5     | 50          | 1200                              | 14            | 12.3              | 39                | 0.31             |
| 15 | 1996                      | 2008                      | 0.2     | 100         | 2400                              | 10            | 9.5               | 12                | 0.42             |
| 16 | 1967                      | 2008                      | 2.5     | 50          | 1200                              | 16            | 11.7              | 41                | 0.66             |
| 17 | 1997                      | 2010                      | 0.9     | 100         | 1600                              | 8             | 6.3               | 13                | 1.63             |
| 18 | 1978                      | 2008                      | 1.5     | 200         | 2400                              | 14            | 12.8              | 30                | 0.29             |
| 19 | 1978                      | 2007                      | 0.02    | 50          | 1200                              | 8             | 6.1               | 29                | 0.82             |
| 20 | 1967                      | 2007                      | 0.02    | 100         | 1800                              | 6             | 4.9               | 47                | 0.39             |
| 21 | 1994                      | 2005                      | 2.3     | 200         | 406                               | 8             | 6.1               | 20                | 1.19             |
| 22 | 1999                      | 2004                      | 0.9     | 100         | 2000                              | 8             | 7.2               | 5                 | 2.00             |
| 23 | 1958                      | 2003                      | 0.03    | 20          | 2800                              | 6             | 4.4               | 45                | 0.59             |
| 24 | 1968                      | 2008                      | 0.03    | 100         | 2800                              | 8             | 7.1               | 40                | 0.28             |
| 25 | 1967                      | 2008                      | 0.5     | 70          | 2732                              | 34            | 23.9              | 41                | 0.72             |
| 26 | 1978                      | 2008                      | 0.06    | 100         | 2000                              | 14            | 12.7              | 30                | 0.31             |
| 27 | 1959                      | 2007                      | 0.03    | 100         | 1800                              | 6             | 5.6               | 48                | 0.14             |
| 28 | 1955                      | 2005                      | 1.1     | 200         | 1139                              | 8             | 7.6               | 50                | 0.10             |
| 29 | 1967                      | 2002                      | 1.4     | 50          | 2800                              | 6             | 5.4               | 35                | 0.29             |
| 30 | 1993                      | 2013                      | 0.2     | 100         | 1200                              | 10            | 7.6               | 20                | 1.20             |
| 31 | 1967                      | 2008                      | 2.5     | 100         | 1000                              | 18            | 17.3              | 41                | 0.09             |
| 32 | 1967                      | 2008                      | 0.2     | 150         | 800                                | 6             | 5.1               | 41                | 0.37             |
| 33 | 1967                      | 2008                      | 0.2     | 20          | 1000                              | 8             | 7.3               | 41                | 0.21             |
| 34 | 1972                      | 2010                      | 0.2     | 100         | 3000                              | 14            | 13                | 18                | 0.40             |
| 35 | 1955                      | 2010                      | 0.1     | 100         | 2732                              | 34            | 32.5              | 55                | 0.08             |
| 36 | 1985                      | 2010                      | 0.3     | 100         | 1600                              | 6             | 4.5               | 25                | 1.00             |
| 37 | 1959                      | 2008                      | 0.1     | 100         | 2400                              | 8             | 6.9               | 49                | 0.28             |
| 38 | 1962                      | 2008                      | 0.03    | 100         | 2800                              | 6             | 4.4               | 46                | 0.58             |
| 39 | 1967                      | 2008                      | 0.2     | 100         | 3400                              | 20            | 18.5              | 41                | 0.18             |
| 40 | 1966                      | 2003                      | 0.02    | 50          | 2800                              | 6             | 5.1               | 28                | 0.33             |
| 41 | 1959                      | 2008                      | 0.07    | 100         | 600                               | 5             | 3.5               | 49                | 0.15             |
| 42 | 1968                      | 2007                      | 0.2     | 130         | 1600                              | 6             | 5.5               | 39                | 0.19             |
| 43 | 1985                      | 2004                      | 0.2     | 25          | 500                                | 10            | 7.5               | 19                | 0.39             |
| 44 | 1977                      | 2002                      | 0.3     | 40          | 1600                              | 6             | 5.1               | 25                | 0.30             |
| 45 | 1985                      | 2007                      | 0.011   | 40          | 1000                              | 10            | 9.3               | 22                | 0.34             |

### Table 2. The information content of the feature «Date of commissioning».

| Interval | Range of the number of heat exchangers | Relative frequency, % | Smoothed | DC | $\bar{I}$ |
|----------|----------------------------------------|------------------------|----------|----|----------|
|          |                                       |                        |          |    |          |
The determination of the weighted smoothed frequency is intended to level the influence of the distribution on the intervals. It is necessary to take into account the frequency of the feature in two intervals of the preceding and two intervals of the subsequent ones. The intervals that precede interval 1, zero and minus one, have zero frequency.

To compensate for the subjective effect of the distribution on the intervals, we find the coefficient of the weighted smoothed frequency using a continuous approximation of the piecewise linear function \([1, 12]\). It takes into account two preceding and following intervals with empirical coefficients depending on the number of intervals and on the number of heat exchangers in the sample. When calculating the interval No. 1, the previous intervals, as well as the subsequent intervals for the last interval, have a frequency equal to zero.

Weighted smoothed frequency is found by the formula \([1]\):

\[
\bar{y} = \frac{(y_1 + 2 \cdot y_2 + 4 \cdot y_3 + 2 \cdot y_4 + y_5)}{10}
\]

where \(y_1, \ldots, y_5\) - frequencies in intervals.

The value of the weighted smoothed frequency in the first interval for the group "A" is equal to:

\[
\bar{y}_{A1} = \frac{(0 + 2 \cdot 0 + 4 \cdot 0 + 2 \cdot 75)}{10} = 7.5\%.
\]

The value of the weighted smoothed frequency in the first interval for the group "B" is equal to:

\[
\bar{y}_{B1} = \frac{(0 + 2 \cdot 0 + 4 \cdot 33.3 + 2 \cdot 42.4 + 9.09)}{10} = 22.7\%.
\]

The value of the weighted smoothed frequency in the third interval for group "B" is equal to:

\[
\bar{y}_{B3} = \frac{(33.3 + 2 \cdot 42.2 + 4 \cdot 9.09 + 2 \cdot 9.09 + 6.06)}{10} = 32.5\%.
\]

For each of the intervals we determine the value of the ratio of smoothed frequencies. For the first interval:

\[
\frac{\bar{y}_{A1}}{\bar{y}_{B1}} = \frac{7.5}{22.7} = 0.33
\]

For each interval we find the value of the diagnostic coefficient (DK) \([7]\):

\[
DC_i = 10 \cdot \lg \frac{\bar{y}_{A_i}}{\bar{y}_{B_i}}
\]

The value of the dynamic coefficient in the first interval:

\[
DC_1 = 10 \cdot \lg 0.33 = -4.8
\]
According to the formula Kullback coefficient informativity of the sign in the i-th interval [7]:

\[ J_i = 0.5 \cdot DC_i \cdot (\overline{y}_{ni} - \overline{y}_{ni})/100 \]

The value of the coefficient of information for the first interval:

\[ J_1 = 0.5 \cdot (-4.8) \cdot (7.5 - 22.7)/100 = 0.367 \]

The informativeness of feature 1 is determined by the sum of the coefficients of informativeness over all intervals. The results of determining the informativeness of all ten signs are given in table 3.

The sign “Thickness margin” has the greatest information content \((J = 1.88)\), and the sign “Pressure” possesses the smallest information content \((J = 0.23)\).

**Table 3.** The results of determining the diagnostic coefficient and informative signs.

| Parameter                        | Commissioning date | Amount |
|----------------------------------|--------------------|--------|
| Range                            | 1965               | 1975   | 1985   | 1995   | 2035   |
| DC                               | -4.815             | -2.449 | 2.595  | 2.632  | 5.311  |
| J                                | 0.367              | 0.139  | 0.19   | 0.12   | 0.328  |

| Parameter                        | Year of examination | Amount |
|----------------------------------|---------------------|--------|
| Range                            | 2004                | 2006   | 2008   | 2010   | 2012   | 2020   |
| DC                               | 0                   | -2.139 | -0.193 | 2.573  | 0.953  | 1.035  |
| J                                | 0                   | 0.068  | 0.001  | 0.23   | 0.019  | 0.011  |

| Parameter                        | Pressure            | Amount |
|----------------------------------|---------------------|--------|
| Range                            | 0.3                 | 0.6    | 0.9    | 1.2    | 1.5    | 1.8    | 2.1    | 2.4    | 3.6    |
| DC                               | 0.015               | 0.044  | 1.895  | 0.714  | 1.148  | 4.393  | 1.035  | -2.297 | 0      |
| J                                | 0                   | 0      | 0.05   | 0.004  | 0.001  | 0.14   | 0.005  | 0.02   | 0.329  |

| Parameter                        | Temperature         | Amount |
|----------------------------------|---------------------|--------|
| Range                            | 50                  | 100    | 150    | 200    | 250    | 300    | 500    |
| DC                               | -3.224              | -2.449 | 1.113  | 1.568  | 3.998  | 3.724  | 1.383  |
| J                                | 0.133               | 0.139  | 0.041  | 0.048  | 0.211  | 0.054  | 0.005  |

| Parameter                        | Diameter of shell   | Amount |
|----------------------------------|---------------------|--------|
| Range                            | 800                 | 1200   | 1600   | 2000   | 2400   | 2800   | 3200   | 4800   |
| DC                               | -1.805              | -1.717 | -3.918 | -1.006 | 2.068  | 3.483  | 0.839  | 0.134  |
| J                                | 0.023               | 0.042  | 0.215  | 0.016  | 0.078  | 0.24   | 0.009  |

| Parameter                        | Wall thickness according to the passport | Amount |
|----------------------------------|------------------------------------------|--------|
| Range                            | 6                                        | 10     | 14     | 18     | 22     | 26     |
| DC                               | -4.453                                   | -2.596 | 1.895  | 3.329  | 4.159  | 0.714  |
| J                                | 0.199                                    | 0.159  | 0.08   | 0.209  | 0.192  | 0.003  |

| Parameter                        | Minimum wall thickness | Amount |
|----------------------------------|-------------------------|--------|
| Range                            | 10                       | 15     | 20     | 25     | 30     | 35     | 40     | 45     | 50     |
| DC                               | 3.724                    | 5.185  | 1.035  | 2.881  | 3.522  | 4.905  | -0.13  | -4.126 | 0      |
| J                                | 0.054                    | 0.181  | 0.005  | 0.007  | 0.147  | 0.498  | 0      | 0.245  | 0.2    |

| Parameter                        | Corrosion rate per year | Amount |
|----------------------------------|-------------------------|--------|
| Range                            | 0.2                      | 0.4    | 0.6    | 0.8    | 1      | 1.2    |
| DC                               | 0.292                    | 2.301  | 2.005  | 0.591  | -5.149 |
| J                                | 0.002                    | 0.166  | 0.093  | 0.005  | 0.146  |

| Parameter                        | Thickness margin        | Amount |
|----------------------------------|-------------------------|--------|
| Range                            | 1.2                      | 1.5    | 1.8    | 2.1    | 2.4    | 2.7    | 3      | 3.3    | 3.7    | 4.1    | 4.5    | 6.1    |
| DC                               | -4.815                   | -2.739 | -4.058 | -1.249 | 2.796  | 5.807  | 6.154  | 2.175  | 6.154  | 7.404  | 9.165  | 3.144  |
| J                                | 0.244                    | 0.12   | 0.235  | 0.021  | 0.1    | 0.321  | 0.175  | 0.011  | 0.038  | 0.151  | 0.403  | 0.04   |

Diagnostic factors were summarized for each tank. The distribution of the amounts of diagnostic features for tanks that have and do not have a residual resource of 10 years is shown in figure 1.

By analogy with the tanks investigated above and using the obtained diagnostic coefficients, we will estimate the residual life of nine tanks from the control set.
From figure 1 it is clear that when the sum of diagnostic factors is less than 16, the residual life is less than 10 years, with the sum of diagnostic factors more than 24, the residual life is more than 10 years, there is uncertainty in the interval (16, 24).

Then they applied this algorithm to build a model and estimate the possible residual life of containers equal to 8 years, 6 years and 5 years.

The simulation results were brought together into a single database and evaluated their correctness.

Having made a comparative analysis of the simulation results with an expert conclusion, we see that there are 2 units of capacitive equipment out of 46, which show erroneous results. Capacities 40, 46 and 17 require more detailed analysis in the direction of increasing the residual life.

![Figure 1. Distribution of heat exchangers by the sum of diagnostic factors for a residual life of 5 years.](image)

A larger number of pieces of equipment (from 100 or more) in the model should improve the accuracy of the forecast, allowing for a more detailed analysis of the uncertainty interval. On the other hand, expert assessments of the state, normative documents that cannot be converted to numerical indicators, as well as previous expert opinions, have a great influence. In addition, a number of parameters, such as, for example, the working medium in a vessel, are difficult to convert to numerical values.

References

[1] Kulbak S 1967 *The Theory of Information and Statistics* (Nauka – Science, Moscow)
[2] Steklov A S, Serebrakov A V and Titov VG 2016 *Bulletin of Ivanovo State Energy University* 5 21–6
[3] Pan Z, Liang S and Garmestani H 2019 *Proceedings of the Institution of Mechanical Engineers Part B-Journal of Engineering Manufacture* 233(4) 1103–11
[4] Moraes J F, Jordon J B and Su X 2019 *Engineering Fracture Mechanics* 209 92–104
[5] Roxas C L and Lejano B A. 2019 *International Journal of Geomate* 16(56) 79–84
[6] Paulsen O and Sejnowski T J 2000 *Current Opinion in Neurobiology* 10(2) 172–9
[7] Kulakov P A, Apparow I H and Afanasenko V G 2018 *IOP Conference Series: Materials Science and Engineering* 451(1) 012201
[8] Bogdanovich A V 2017 *Ore dressing* 4 22–7
[9] Shabelnikov S I 2017 *Mining journal* 12 21–4
[10] Kucheraviy V I and Milkov S N 2016 *Problems of mechanical engineering and machine
reliability 1 105–10
[11] Anoshkin AN, Pospelov AB and Yakushev R 2014 Bulletin of the Perm National Research Polytechnic University. Mechanics 2 5–28
[12] Kutubbalatov A A and Kulakov P A 2017 Proceedings of the Tula state university, Science of earth 2 88–102
[13] Okladnikova E N and Sugak EV 2011 Siberian Journal of Science and Technology 2 132–6
[14] Kulakov P A, Kutubbalatov A A and Afanasenko V G 2018 Socar Proceedings Issue 2 41–8