Assessment of the resource of vertical cylindrical tanks taking into account the parameters of the technical condition

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Abstract. The question is about assessing the residual life of vertical welded cylindrical tanks after carrying out their full technical diagnostics on the technical operating parameters, taking into account the combined influence of the technical condition parameters of the tank equipment of oil and gas refining industries. The authors developed a mathematical model, established diagnostic coefficients and the informational content of the indicator for each of the periods considered, determined by the expert. A methodology for assessing the residual life of vertical cylindrical tanks with the possibility of applying a measure of informational content Kullback is presented. The values that fall outside the field of the developed model are demonstrated. Conclusions are made on the appropriateness of using the developed methodology to solve the problems of predicting the residual life of vertical cylindrical tanks of oil and gas refining industries.

1. Introduction
Vertical welded cylindrical tanks (VWCT) of oil and gas refining complexes are used for storing oil and oil products and occupy a leading position in terms of the usable capacity of hydrocarbon feedstocks and products. Large volumes of stored hydrocarbons create conditions of especially great danger in case of emergencies for technical reasons. Therefore, VWCT during operation especially requires timely and high-quality diagnostics and assessment of the technical condition, the frequency of which is established by the current regulatory and technical documentation.

With a complete diagnostics of the technical state of the VWCT, the following work is usually performed: visual inspection of the tank and its equipment; measurement of the thickness of the sheets of the wall, roof; measurement of deviations forming from the vertical, local deformations of the wall and the horizontal of the protrusion of the edge and base under it; check the condition of the blind area; making up a conclusion on the technical condition of the tank; visual inspection of the wall, roof and bottom from the inside; visual inspection of the pontoon (if any); measurement of wall thickness, roof bottom and pontoon; control of welded joints by physical methods; mechanical tests, metallographic studies and chemical analysis of metal (if necessary); sounding of the bottom and base of the tank in order to detect leaks; verification calculations for strength; calculation of residual life; test for strength and density.

The residual life of the tanks is determined based on the analysis of operating conditions, the results of technical diagnostics and the criteria for the limit state. Steel tanks undergo periodic loading and corrosion-erosion destruction during operation; therefore, the limiting state can come either from
low-cycle fatigue or due to loss of bearing capacity caused by thinning of the wall. The residual resource is determined separately for each criterion, and the minimum of the two found values is assigned as the final one.

As a rule, mathematical methods that are used by expert calculations allow estimating the upper limit of the residual resource. In some instances, this border is overstated by several times in relation to the real value in the conclusion of the industrial safety examination.

The amount of data on similar objects is several tens to hundreds of pieces of equipment. Even with such a small capacity, it is possible to develop a mathematical model that more accurately provides an estimate of the residual life \[1, 2, 10-13\] based on the parameters of the technical condition \[6-9\].

In the works \[References to works 2, 4\], a conclusion was made on the appropriateness of the Kullback information content measure, which provides sufficient accuracy, allows estimating outliers even on data volumes of several tens of objects, in contrast to regression analysis, neural networks, and others mathematical models of mathematics \[4, 5, 6\].

2. Mathematical model
The influence of signs on the residual resource of tanks is carried out by calculating their information content \[1\] using the Kullback – Leibler measure.

The range of values of the objective function is divided into an array of values. For example, for the residual resource of the tank, the expert assessment of the residual resource \{6, 8, and 10\} can serve as values. Further, all the objects of the training sample are divided into 2 classes - those with a residual resource in a given number of years, for example, 6 years and not having such a resource. The process of evaluating the information content of signs is performed iteratively for the entire array of values of the objective function.

Each iteration consists of 9 stages:
1. We divide the entire range of values of each characteristic into \( N \) intervals.

\[
N = 1 + 3.22 \log_{10}(n)
\]  \hspace{1cm} (1)

where \( n \) is the size of the training sample.

The first and last intervals are increased by 10\%, moving the lower border down for the first interval and the upper border up for the last interval. This is done in order to include in the interval data from the test sample, which may go beyond the minimum and maximum values by insignificant values.

2. All objects of the training sample are divided into two groups: “A” - reaching the current value of the objective function for the given iteration; “B” - not reaching that value.

3. We consider the frequencies \( A_{ij} \) and \( B_{ij} \) of hits according to the \( i \) attribute and \( j \) interval of objects of group A and B.

4. As an example, the calculation of information content for the sign "Wall thickness minimum actual", denoted as \( h_2 \).

5. We determine the relative frequency of getting into a particular group within the interval

\[
y_A = A_{ij}/A
\]

\[
y_B = B_{ij}/B
\]

We find the weighted smoothed frequency to level the effect of the distribution on the intervals by the formula \[1\]:

\[
\tilde{y} = \left( y_1 + 2 \cdot y_2 + 4 \cdot y_3 + 8 \cdot y_4 + 16 \cdot y_5 + 8 \cdot y_6 + 4 \cdot y_7 + 2 \cdot y_8 + y_9 \right) / 46
\]  \hspace{1cm} (4)

where \( y_1 \ldots y_9 \) - frequencies in intervals.

The intervals preceding interval No. 1 are zero, minus the first - have a zero frequency.
6. Find the ratio of the smoothed frequencies of the groups “A” and “B” for each interval:

\[ \frac{\bar{y}_{Ai}}{\bar{y}_{Bi}} \]  

(5)

7. Determine the diagnostic coefficient (DC) for the i-th interval according to the formula [7]:

\[ DC_i = 10 \cdot \lg \left( \frac{\bar{y}_{Ai}}{\bar{y}_{Bi}} \right) \]  

(6)

8. According to the Kullback formula, the coefficient of information content of a sign in the i-th interval [7]:

\[ J_i = 0.5 \cdot DC_i \cdot \left( \frac{\bar{y}_{Ai}}{\bar{y}_{Bi}} \right)^{-1} \]  

(7)

9. The sum of the information content coefficients at all intervals will determine the information content of the attribute. At the first calculation, we discard signs if the sum of the information content coefficients is less than 0.1. Next, we re-calculate.

In order to evaluate the quality of the constructed model, a loss function is introduced \( L(a, x) \) - the error value of the algorithm \( a \in A \) on an object \( x \in X \).

P - predictive model.
X - many objects.
Y - many answers.

Since the classification problem is being solved in our case, \( L(z, x) = [p(x) \neq y(x)] \) is an error indicator. In this case, the empirical risk is the quality function of the algorithm \( a \) on \( X^l \):

\[ Q(p, X^i) = \frac{1}{l} \sum_{i=1}^{l} L(p, x_i) \]  

(8)

Minimization of empirical risk (Empirical Risk Minimization) is carried out according to the formula:

\[ \mu(X^i) = \arg \min_{x \in X} Q(p, X^i) \]  

(9)

The equation of the dividing surface for each set \( X^i \) is \( g(x, w) = \{ \text{Sum } DC = dc \mid \mu = \min \} \)

3. Experiment
Let us evaluate the influence of the characteristics listed below on the residual resource of tanks by calculating their information content [1] using the Kullback – Leibler measure.

For building a model, features are selected (technical characteristics, technological parameters, results of technical control). Initially, 76 characteristics were selected.

In 40 expert opinions on tanks, there are examination results from 4 and 8 years (Table 1). In the sample, there are no data on tanks for which the examination would give a negative conclusion.

We randomly divided all expert opinions into training and test samples. Fifteen different sets of training data \( X^l \in X \) and test data \( X^k \in X \) were created in the ratios 75% and 25%.

Since there is a range of values of the objective function — the residual resource of the tank, the information content is evaluated iteratively (for 6, 8, and 10 years): all objects in the training sample are divided into 2 classes — having a residual resource in a given number of years, for example, 6 years and not having such a resource.

We show the calculation results for the sign "Full heights, m". The results are shown in Table 2.
Table 1. Data on the results of the examination

| № | p/p | Year of commissioning | Service life, years | Nominal volume, m$^3$ | Inner diameter, m | Full height Ho, m | Estimated resource by the criterion of low-cycle fatigue, years | Residual life at the conclusion, years |
|---|-----|-----------------------|---------------------|-----------------------|------------------|------------------|-------------------------------------------------------------|--------------------------------------|
| 1 | 1954 | 56 100 | 5.53 | 4.18 | > 10 | 8 |
| 2 | 1954 | 56 100 | 5.53 | 4.15 | > 10 | 8 |
| 3 | 1954 | 56 200 | 6.67 | 5.55 | > 10 | 8 |
| 4 | 1954 | 56 200 | 6.67 | 5.55 | > 10 | 8 |
| 5 | 1954 | 56 200 | 6.67 | 5.57 | > 10 | 8 |
| 6 | 1954 | 56 200 | 6.67 | 5.57 | > 10 | 8 |
| 7 | 1954 | 56 200 | 6.67 | 5.57 | > 10 | 8 |
| 8 | 1954 | 56 200 | 6.67 | 5.55 | > 10 | 8 |
| 9 | 1983 | 27 200 | 6.67 | 5.96 | > 10 | 8 |
| 10 | 1954 | 56 300 | 8 | 5.52 | > 10 | 8 |
| 11 | 1954 | 56 300 | 8 | 5.52 | > 10 | 8 |
| 12 | 1954 | 56 400 | 8.24 | 8.24 | > 10 | 8 |
| 13 | 1954 | 56 400 | 8.24 | 8.24 | > 10 | 8 |
| 14 | 1954 | 56 400 | 8 | 8.23 | > 10 | 8 |
| 15 | 1954 | 56 400 | 8.24 | 8.24 | > 10 | 8 |
| 16 | 1954 | 56 400 | 8 | 8.28 | > 10 | 8 |
| 17 | 1954 | 56 1000 | 12 | 9.67 | > 8 | 8 |
| 18 | 1954 | 56 1000 | 12 | 9.77 | > 8 | 8 |
| 19 | 1954 | 56 1000 | 12 | 9.62 | 5.6 | 3 |
| 20 | 1954 | 56 1000 | 12 | 9.6 | > 8 | 8 |
| 21 | 1968 | 42 1000 | 12 | 9.6 | > 8 | 8 |
| 22 | 1954 | 56 1000 | 12 | 9.67 | > 8 | 8 |
| 23 | 1971 | 39 1000 | 12 | 9.76 | > 8 | 8 |
| 24 | 1971 | 39 5000 | 22.81 | 11.44 | 4.2 | 4 |
| 25 | 1954 | 56 5000 | 22.88 | 11.7 | 4.3 | 4 |
| 26 | 1954 | 56 5000 | 22.88 | 11.7 | 4.3 | 4 |
| 27 | 1954 | 56 5000 | 22.84 | 11.44 | 4.1 | 4 |
| 28 | 1954 | 56 5000 | 22.84 | 11.44 | 4.3 | 4 |
| 29 | 1954 | 56 5000 | 22.84 | 11.44 | 4.7 | 4 |
| 30 | 1954 | 56 5000 | 22.8 | 11.92 | 6.6 | 6 |
| 31 | 1954 | 56 5000 | 22.8 | 11.92 | 6.6 | 6 |
| 32 | 1954 | 56 400 | 8 | 8.31 | > 10 | 8 |
| 33 | 1954 | 56 400 | 8.53 | 7.33 | > 10 | 8 |
| 34 | 1954 | 56 700 | 10.67 | 8.3 | > 10 | 8 |
| 35 | 1954 | 56 700 | 10.67 | 8.3 | > 10 | 8 |
| 36 | 1954 | 56 700 | 10.6 | 8.24 | > 10 | 8 |
| 37 | 1953 | 57 700 | 10.43 | 8.85 | 8.6 | 4 |
| 38 | 1953 | 57 700 | 10.43 | 8.85 | 8.1 | 4 |
| 39 | 1953 | 57 1000 | 12 | 9.63 | 5.6 | 4 |
| 40 | 1957 | 53 1000 | 12 | 9.63 | 9.6 | 8 |

After the first calculation, it was decided to leave only the following diagnostic signs based on the sum of the information coefficients of the signs: Nominal volume, m$^3$ ($p_1$); Inner diameter, m ($p_2$); Full height, m ($p_3$); Overpressure, kPa ($p_4$); Number of belts ($p_5$); Design thickness of the I, II, III belts, mm ($p_6$, $p_{10}$, $p_{13}$); Minimum measured thickness of I, II, III belts, mm ($p_7$, $p_{11}$, $p_{15}$); Estimated thickness of the I, II, III belts, mm ($p_8$, $p_{12}$, $p_{16}$); Screening thickness of I, II, III belts, mm ($p_9$, $p_{13}$, $p_{17}$).

The results of determining the information content of the first five signs are shown in Table 3.
The sign “Design thickness of the third belt” has the least information content ($J = 0.111$), and the sign “Pressure excessive” has the highest information content ($J = 0.476$).

Next, we found the sum of diagnostic coefficients for all the signs for each tank and compared the loss function for fifteen different sets of training data $X' \in X$.

As the optimal set of $X'$, we select the 7th data set, since in this case, the minimum function of empirical risk and the minimum interval of uncertainty.

Table 2. Determination of the information content of the sign "Full height, m".

| Interval       | Range of change, $h_2$, mm | The number of tanks in the group | Relative frequency, % | Smoothed frequency, % | $\bar{\gamma}_{Ai}$ | $\bar{\gamma}_{Bi}$ | $\bar{\gamma}_A$ | $\bar{\gamma}_B$ | $J_i$ |
|----------------|----------------------------|---------------------------------|-----------------------|-----------------------|----------------------|---------------------|------------------|------------------|-----|
| 1              | Less than 9                | 8                               | 0                     | 50                    | 0                    | 26.9                | 3.8              | 7.06             | 8.49 | 0.979 |
| 2              | (9 - 12)                   | 4                               | 0                     | 25                    | 0                    | 23.8                | 7.6              | 3.12             | 4.94 | 0.398 |
| 3              | (12 – 15]                  | 3                               | 8                     | 19                    | 38                   | 17.5                | 20.5             | 0.855            | -0.68 | 0.01  |
| 4              | (15 – 18]                  | 0                               | 0                     | 0                     | 0                    | 6.25                | 19.0             | 0.328            | -8.4  | 0.31  |
| 5              | (18 – 21]                  | 0                               | 11                    | 0                     | 52                   | 2.5                 | 26.7             | 0.094            | -10.3 | 1.242 |
| 6              | (21 – 24]                  | 0                               | 2                     | 0                     | 10                   | 1.25                | 14.3             | 0.088            | -10.6 | 0.69  |
| 7              | More than 24               | 1                               | 0                     | 6                     | 0                    | 2.5                 | 7.1              | 0.35             | -4.56 | 0.106 |
| Sum            |                            | 16                               | 21                    | 100                   | 100                  | -                   | -                | -                | -     | 3.75  |

Table 3. The results of determining the diagnostic coefficient and the information content

| Parameter | Nominal volume | Amount |
|-----------|----------------|--------|
| Range     | 18.333 916.667 | 1733.333 | 2550 | 3366.667 | 4183.333 | 5081.667 |
| ДС        | 3.038 3.038    | 1.168  | 0.15 | -2.349   | -6.064   | -10.537  |
| J         | 0.014 0.027    | 0.004  | 0    | 0.006    | 0.039    | 0.145    | 0.235  |
| Parameter | Inner diameter | Amount | 5.241 | 8.422    | 11.313   | 14.205   | 17.097   | 19.988   | 23.169  |
| ДС        | 5.306 5.306    | 0.808  | -0.381 | -2.025   | -5.154   | -9.342   |
| J         | 0.028 0.056    | 0.002  | 0    | 0.006    | 0.034    | 0.131    | 0.257  |
| Parameter | Full height    | Amount | 4.021 | 5.445    | 6.74     | 8.035    | 9.33     | 10.625   | 12.05   |
| ДС        | 9.089 7.553    | 4.864  | 1.335 | -0.298   | -2.08    | -5.249   |
| J         | 0.024 0.039    | 0.031  | 0.003 | 0        | 0.013    | 0.071    | 0.181  |
| Parameter | Overpressure   | Amount | -0.033 | 0.333    | 0.667    | 1        | 1.333    | 1.667    | 2.033   |
| ДС        | 5.379 5.379    | 3.83  | 1.092 | -3.238   | -7.784   | -13.072  |
| J         | 0.039 0.078    | 0.023  | 0.001 | 0.01     | 0.069    | 0.256    | 0.476  |
| Parameter | Number of belts | Amount | 3.933 | 4.667    | 5.333    | 6        | 6.667    | 7.333    | 8.067   |
| ДС        | 10.881 9.27    | 3.202  | 0.478 | -0.591   | -2.248   | -5.549   |
| J         | 0.045 0.076    | 0.011  | 0    | 0.001    | 0.015    | 0.077    | 0.225  |
Table 4. The result of diagnostic for fifteen different sets of training data $X' \in X$

| No | L(a, Xl) | Distance | Partition point | Object numbers |
|----|----------|----------|----------------|----------------|
| 1  | 4        | 236.40   | -103.67        | 30, 19, 37, 38 |
| 2  | 3        | 242.69   | -82.73         | 30, 38, 39     |
| 3  | 4        | 217.01   | -96.45         | 30, 39, 37, 19 |
| 4  | 2        | 42.20    | 86.63          | 35, 19         |
| 5  | 3        | 246.98   | -69.41         | 30, 38, 39     |
| 6  | 5        | 206.48   | -154.54        | 30, 37, 38, 19, 39 |
| 7  | 2        | 39.98    | 201.29         | 35, 38         |
| 8  | 3        | 242.55   | -128.19        | 30, 37, 38     |
| 9  | 5        | 211.94   | -181.96        | 30, 19, 39, 37, 38 |
| 10 | 2        | 311.44   | -79.10         | 30, 37         |
| 11 | 3        | 243.98   | -108.41        | 30, 19, 39     |
| 12 | 5        | 205.34   | -157.41        | 30, 38, 19, 39, 37 |
| 13 | 4        | 31.10    | 99.17          | 35, 38, 19, 39 |
| 14 | 5        | 201.23   | -135.16        | 30, 39, 19, 37, 38 |
| 15 | 4        | 244.04   | -157.24        | 30, 38, 39, 37 |

Comparing the simulation results with the conclusion of the industrial safety examination, it is clear that the model holds for all tanks of the primary and control samples and shows a similar result with the expert's assessment. This circumstance suggests that for tanks, there are no additional characteristics that are not reducible to numerical values and affect expert decisions.

4. Conclusions
It is proposed to apply the VWCT resource forecasting methodology, which is presented in this article, in individual situations, when there is fairly significant inaccuracy in the information received for the implementation of an expert assessment. The advantage of the developed methodology is the ability to create a mathematical model for managing technical parameters that affect the numerical indicator of the resource and determine the effect of each of the parameters on the entire tank. This methodology makes it possible to most likely predict the residual resource, bringing the results closer to the results of expert assessments, as compared to the resource assessment according to standard methods specified in the normative and technical documentation for diagnosing and extending the safe life of VWCT of oil and gas refining industries.

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