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# Method development of the integral specific failure rate determination considering time in service and diameter of gas pipelines

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**Abstract**. Gas consumption increase and also a large scale of gas-distributing networks create new and ever more challenging problems for the engineers, associated with the development and modernization, safety and reliability improvement of the systems. These problems can be solved only by using new technologies and methods of calculation. Analysis of the statistical data on the underground distributing gas pipeline damages in the Gorlovka city of Donetsk region revealed that most of the failures are from the corrosion damage. Based on the statistical data on all types of the underground gas pipeline damages, which is the source of the gas leak, the determination method of integral specific failure rate was developed considering time in service and diameter of the gas pipelines. This method is based on the determination of the optimal step of the gas pipeline time in service, during which the failure rate is taken as constant, and on the integral specific failure rate calculation. It was discovered that the integral specific failure rate depends on the gas pipeline diameter and its time in service. Due to the fact that the coefficient SDR jumps at the diameter 219x7 mm, the dependence equation of the integral specific failure rate on time in service and diameter of the gas pipeline is derived for two diameter ranges 57-159 mm and 219-530 mm. The diameter decrease and the time in service increase lead to the integral specific failure rate increase.

## 1. Introduction

The modern distributing gas pipeline network is a complex branched system, where the underground gas pipeline reliability is one of the main objectives. It is the most vulnerable element in the system and requires considerable material and human resources for repair and maintenance works.

The reliability of the system can be achieved either through its elements reliability improvement or backups, meaning that the backup should be justified in a way that the level of reliability is in tune with the current requirements.

Rational implementation of measures for network reliability improvement also requires new algorithms and methods development [1].

The probability of failure-free system operation is defined mainly by the failure rate [2], the numerical values of which is impossible to determine without experimental and statistical research, and also its forecast in a long run. This kind of research was done in the papers [3 - 5] and revealed the main causes of failures and influence of different factors on it. It was established that the gas pipeline diameter and wall thickness of tubing are the major influence factors on the gas network reliability [6, 7]. Dependence of the failure rate on gas pipeline diameter was also confirmed in the research presented in the paper [8].

Having in mind that gas-distributing pipeline systems are systems for long-lasting use, an increase of the time in service increases the probability of failure occurrence [9 - 12]. This fact should be considered when choosing the gas network technical maintenance strategy and risk assessment in its different points [13].

The calculated time, which is used for the reliability justification, should be such that no serious system modernization is planned for this period, that is for its reliability improvement [2]. It should be noted that during the determination of the failure rate dependence on time in service, the experimental data approximation accuracy is influenced by the choice of the step of time in service, during which the failure rate is taken as constant.

The objective of this paper is a development of the determination method of integral specific failure rate considering gas pipeline diameter and time in service.

It is necessary to resolve the following problems to achieve the desired objective:

- choose the optimal step of time in service for reliability measures determination;
- derive the dependence of the integral specific failure rate on the time in service and diameter of the gas pipeline.

## 2. Materials and Methods

To obtain data of dependences all damage incidents of gas networks with all types of pressure in Gorlovka city over a period 1966-2011 were analyzed. The length of the underground steel distributing gas pipelines is 204.01 km, of which the high pressure first category – 21.4 km (10%), high pressure second category - 51.75 km (25%), medium pressure – 51.99 km (25%), and low pressure – 78.87 km (40%).

The gas-distributing networks are presented by the diameters from 32 to 500 mm.

The analysis of the distributing gas pipelines damages in Gorlovka city during 1966-2011 have shown that 64% of all leaks in the underground gas pipelines are due to the corrosion damages (92 leaks), 31% - due to undermining (45 leaks), 3% - mechanical damages (4 leaks), and 2% - due to weld connection rupture (3 leaks) (see Figure 1).

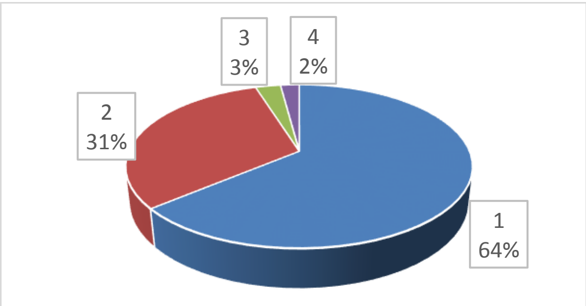


**Figure 1.** Causes of gas leaks from the underground distributing gas pipelines: 1 – corrosion, 2 – influence of undermining, 3 – mechanical damages, 4 – weld connection rupture.

Table 1 presents the example of initial data on distributing gas pipeline damages in Gorlovka city.

The gas pipelines have the following diameters (outer diameter x wall thickness of tubing, mm): 57x3, 76x4, 89x4, 108x4, 114x4, 133x4, 159x4,5, 219x7, 273x7, 325x8, 426x9 and 530x10 mm.

The coefficient SDR, which presents relation of the outer diameter to wall thickness of tubing, for this range of diameters is as follows, respectively: 19; 19; 22.3; 27; 28.5; 33.3; 35.3; 31.3; 39; 40.6; 47.3; 53.

To increase the approximation accuracy of the experimental data during the study of its damages at gas pipeline failure rate determination, it is necessary to optimize the step of gas pipeline time in service, during which the failure rate is taken as a constant.

**Table 1.** Data on the distributing gas pipelines damages in Gorlovka city.

| № | Year of leak detection, year | Number of leaks n, pcs. | Outer diameter of the gas pipeline D, mm | Year of laying, year | Total gas pipeline length at the laying year, $L_k$, m | Gas pipeline length at the laying year with diameter $L_{ki}$, m | Cause |
|---|---|---|---|---|---|---|---|
| 1 | 1966 | 1 | 530 | 1954 | 3688 | 161 | Influence of undermining |
| 2 | 1978 | 1 | 133 | 1962 | 13052 | 2199 | Influence of undermining |
| 3 | … | | | | | | |
| 143 | 2011 | 1 | 108 | 1966 | 5869 | 2291 | corrosion |
| 144 | 2011 | 1 | 108 | 1963 | 11269 | 1272 | corrosion |

For this purpose, the selection method of the step of gas pipeline time in service was developed.
Let`s introduce the following notations:
$i$ – gas pipeline outer diameter; $i$ = 57, 76, 89, 108, 114, 133, 159, 219, 273, 325, 426, 530 mm;
$j$ – step of the gas pipeline time in service, $j=\overline{1,\ 10}$;
$k$ – calendar year of gas pipeline laying;
$c$ – calendar year of gas pipeline leak detection;
$L_k$ – length of all diameters gas pipelines of $k$-th year of laying, m;
$L_{ki}$ – gas pipelines length of $i$-th diameter of $k$-th year of laying, m;
$T_k$ – gas pipeline time in service of $k$-th year of laying, at which damage was detected, $T_k = c - k$.

Specific failure rate is calculated by the formula:

$$w_k=\begin{cases}\dfrac{n_k}{T_k\cdot L_k}, & n'=1,\\ \dfrac{\sum w_k\cdot L_k}{\sum L_k}, & n'\neq 1,\end{cases} \tag{1}$$

where $n_k$ – number of damages in the gas pipeline of $k$-th year of laying, at which the damage was detected, pcs., during the calculated time period $T_k$, which is taken as 1 year;
$L_k$ – gas pipeline length of $k$-th year of laying, m,
$n'$ – number of data with the same values of gas pipeline time in service $T_k$, calculated by the formula

$$T_k = c - k. \tag{2}$$

Considering that the depreciation period of the steel gas pipelines according to RLALP 0.00-1.20-98 “Safety regulations of the Ukraine`s gas supply systems” is 30 years, one can calculate the failure rate during time in service from $p$ = 1, which corresponds to value $T_{k\ \min}$=15 years, to $p$ = 30, which corresponds to value $T_k$ = 44 years, with step $j = (\overline{1,10})$ by the formula

$$w_{jp-m;\,j}=\frac{1}{j}\sum_{m=0}^{j-1} w_{jp-m}, \tag{3}$$

where $m=\overline{0,j-1},\ p=\overline{1,30}$.
Table 2 summarizes the results of the calculation.
The arithmetic mean value of the failure rate, calculated with step j, is determined by the formula

$$E_{w_p} = \frac{\sum_j w_{jp-m;j}}{\alpha}, \tag{4}$$

where α – variant numbers of the chosen step, α = 10.

Mean squared error of the results is calculated

$$\Delta S_w = \sqrt{\frac{p_{\max} \sum_p (w_{jp-m;j} - E_{w_p})^2}{p_{\max} - 1}}. \tag{5}$$

Choice of the step is conditioned by $\Delta S_w \longrightarrow \min$.

Table 3 summarizes the results of the calculation.

**Table 2.** Specific failure rate in relation to the step of gas pipeline time in service.

<table>
<tr><th rowspan="2">p</th><th rowspan="2">T<sub>k</sub>, year</th><th colspan="10">$w_{ip-m,j} \cdot 10^{-5}$, 1/(m·year)</th></tr>
<tr><th>j=1 year</th><th>j=2 year</th><th>j=3 year</th><th>j=4 year</th><th>j=5 year</th><th>j=6 year</th><th>j=7 year</th><th>j=8 year</th><th>j=9 year</th><th>j=10 year</th></tr>
<tr><td>1</td><td>15</td><td>7.7543</td><td rowspan="2">8,0418</td><td rowspan="3">5.3612</td><td rowspan="4">5.1341</td><td rowspan="5">6.5519</td><td rowspan="6">8.2997</td><td rowspan="7">9.5826</td><td rowspan="8">9.8621</td><td rowspan="9">9.7523</td><td rowspan="10">9.3368</td></tr>
<tr><td>2</td><td>16</td><td>8.3292</td></tr>
<tr><td>3</td><td>17</td><td>0.0000</td><td rowspan="2">2.2264</td></tr>
<tr><td>4</td><td>18</td><td>4.4528</td><td rowspan="3">11.2383</td></tr>
<tr><td>5</td><td>19</td><td>12.2234</td><td rowspan="2">14.6311</td><td rowspan="4">14.5901</td></tr>
<tr><td>6</td><td>20</td><td>17.0387</td><td rowspan="5">12.1217</td></tr>
<tr><td>7</td><td>21</td><td>17.2801</td><td rowspan="2">14.5491</td><td rowspan="3">12.6574</td><td rowspan="6">12.4401</td></tr>
<tr><td>8</td><td>22</td><td>11.8181</td><td rowspan="7">14.4440</td></tr>
<tr><td>9</td><td>23</td><td>8.8739</td><td rowspan="2">7.2359</td><td rowspan="4">11.3856</td><td rowspan="8">13.8630</td></tr>
<tr><td>10</td><td>24</td><td>5.5979</td><td rowspan="3">12.2228</td><td rowspan="9">13.6343</td></tr>
<tr><td>11</td><td>25</td><td>8.2291</td><td rowspan="2">15.5353</td><td rowspan="5">17.4116</td><td rowspan="10">13.4240</td></tr>
<tr><td>12</td><td>26</td><td>22.8415</td></tr>
<tr><td>13</td><td>27</td><td>17.8069</td><td rowspan="2">21.8736</td><td rowspan="3">18.6625</td><td rowspan="4">16.3404</td><td rowspan="6">14.3400</td></tr>
<tr><td>14</td><td>28</td><td>25.9403</td></tr>
<tr><td>15</td><td>29</td><td>12.2404</td><td rowspan="2">10.8071</td><td rowspan="7">11.5053</td></tr>
<tr><td>16</td><td>30</td><td>9.3738</td><td rowspan="3">10.0174</td><td rowspan="5">9.4363</td></tr>
<tr><td>17</td><td>31</td><td>12.4906</td><td rowspan="2">10.3393</td><td rowspan="4">9.4520</td><td rowspan="8">10.4303</td></tr>
<tr><td>18</td><td>32</td><td>8.1879</td></tr>
<tr><td>19</td><td>33</td><td>12.6611</td><td rowspan="2">8.5647</td><td rowspan="3">12.7481</td><td rowspan="6">10.4607</td><td rowspan="9">10.6128</td></tr>
<tr><td>20</td><td>34</td><td>4.4683</td></tr>
<tr><td>21</td><td>35</td><td>21.1149</td><td rowspan="2">16.4407</td><td rowspan="4">11.4087</td><td rowspan="5">11.5900</td><td rowspan="10">12.3123</td></tr>
<tr><td>22</td><td>36</td><td>11.7666</td><td rowspan="3">8.1733</td><td rowspan="7">10.3292</td></tr>
<tr><td>23</td><td>37</td><td>12.7532</td><td rowspan="2">6.3766</td></tr>
<tr><td>24</td><td>38</td><td>0.0000</td></tr>
<tr><td>25</td><td>39</td><td>12.3155</td><td rowspan="2">10.2141</td><td rowspan="3">10.9170</td><td rowspan="4">11.9461</td><td rowspan="6">12.9147</td><td rowspan="6">12.9147</td></tr>
<tr><td>26</td><td>40</td><td>8.1127</td><td rowspan="5">13.0346</td></tr>
<tr><td>27</td><td>41</td><td>12.3229</td><td rowspan="2">13.6781</td></tr>
<tr><td>28</td><td>42</td><td>15.0333</td><td rowspan="3">14.9125</td><td rowspan="3">14.9125</td></tr>
<tr><td>29</td><td>43</td><td>24.7097</td><td rowspan="2">14.8520</td><td rowspan="2">14.8520</td><td rowspan="2">14.8520</td></tr>
<tr><td>30</td><td>44</td><td>4.9944</td></tr>
</table>

**Table 3.** Mean squared error of the results in relation to the step of gas pipeline time in service.

| $j$, year | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| $\Delta S_w$ | 27.10 | 16.85 | 10.76 | 11.14 | 9.88 | 9.12 | 10.11 | 9.63 | 9.92 | 11.11 |

Mean squared error of the results takes the minimum value 9.12 when step $j$ = 6 years, therefore, for the reliability values calculation the step of time in service is taken as 6 years.

To obtain dependences of the integral specific failure rate on time in service and gas pipeline diameter only corrosion damages are taken into consideration since the insulating wrapping wears out and the risk of corrosion propagation increases as time goes by.

Specific failure rate is calculated by the formula

$$w_{ki} = \begin{cases} \dfrac{n_{ki}}{T_{ki} \cdot L_{ki}}, & n_i' = 1, \\ \dfrac{\sum w_{ki} \cdot L_{ki}}{\sum L_{ki}}, & n_i' \neq 1, \end{cases} \tag{6}$$

where $n_{ki}$ – number of damages in the gas pipeline of $k$-th year of laying with $i$-th diameter, pcs., during the calculated time period $T_k$, which is taken as 1 year;
$L_{ki}$ – length of the gas pipeline of $k$-th year of laying with $i$-th diameter, m;
$n_i'$ – number of data with the same values of gas pipeline time in service with $i$-th diameter $T_{k\,i}$.

Dependence of the specific failure rate on gas pipeline time in service for all diameters of tubing where leaks were detected is calculated.

The determination method of the specific failure rate dependence on time in service of the gas pipelines with an outer diameter 57 mm is presented below.

The failure rate calculation is conducted at the integral distribution within the range from $p$ = 1, which corresponds to value $T_{k\,\min}$=15 years to $p$ = 30, which corresponds to value $T_k$ = 44 years, with step 6 years. To form the initial data table the interval $p = \overline{1, 30}$ is divided into spacing with data quantity that equals the optimal step of time in service ($r$ = 6 years). In this way, five intervals are obtained, where the integral specific failure rate is determined for each of them.

The mean value of time in service is determined for each interval.

For the first interval ($p = \overline{1, 6}$) $T_{k\,\text{ave}} = (2T_{k\,\min} + r\text{-}1)/2$,

for the second ($p = \overline{7, 12}$) $T_{k\,\text{ave}} = (2T_{k\,\min} + 3r\text{-}1)/2$,

for the third ($p = \overline{13, 18}$) $T_{k\,\text{ave}} = (2\ T_{k\,\min} + 5r\text{-}1)/2$,

for the fourth ($p = \overline{19, 24}$) $T_{k\,\text{ave}} = (2\ T_{k\,\min} + 7r\text{-}1)/2$,

for the fifth ($p = \overline{25, 30}$) $T_{k\,\text{ave}} = (2\ T_{k\,\min} + 9r\text{-}1)/2$.

The failure rate in each interval is calculated by the formula

$$w'_{k_i} = \frac{1}{tr} \sum_{s=1}^{tr} w_{ks,} \quad t = \overline{1,5}. \tag{7}$$

Table 4 summarizes the results of the calculation.

CurveExpert Professional software helped to find out that dependence data of the integral specific failure rate on time in service can be described by the formula [14, 15]

$$w_{ki}' = a - be^{-cT_{k\,\text{ave}}{}^{d}} \tag{8}$$

where $a$ = 0.00076171, $b$ = 0.000519813, $c = 9.23027 \cdot 10^{-13}$, $d$ = 7.409882874.

**Table 4.** The integral specific failure rate values in relation to the time in service.

| $T_{k\ ave}$, year | $w_{ki}'$, $10^{-5}$, 1/(m·year) |
|---|---|
| 17.5 | 25.3678 |
| 23.5 | 25.3678 |
| 29.5 | 25.3678 |
| 35.5 | 38.0518 |
| 41.5 | 54.9512 |

Figure 2 shows how this dependence approximates the initial data, which presented in Table 4.

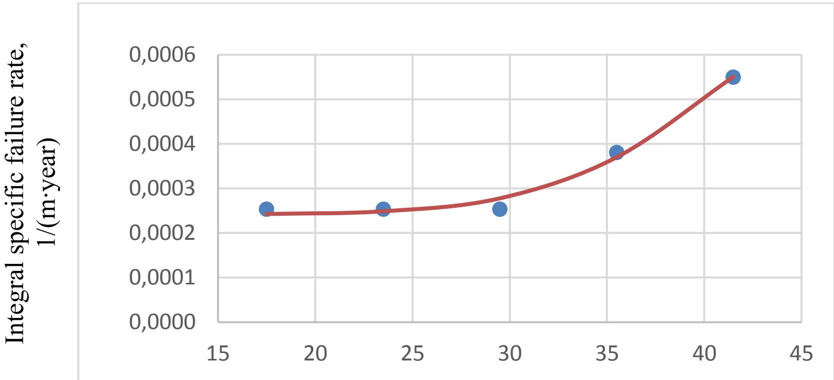


**Figure 2.** Dependence of the integral specific failure rate on the time in service for diameter 57 mm.

**Table 5.** Regression equation coefficients, correlation coefficients and Fisher`s number for different gas pipeline diameters.

| Gas pipeline diameter, mm | *a* | *b* | *c* | *d* | *r* | *F* |
|---|---|---|---|---|---|---|
| 57 | 0.00076171 | 0.000519813 | 9.23027E-13 | 7.409882874 | 0.9938 | 60.4241 |
| 76 | 0.00150811 | 0.001323264 | 4.62404E-14 | 7.942866158 | 0.9971 | 128.8695 |
| 89 | 0.000712857 | 0.000565445 | 6.60878E-13 | 7.218912082 | 0.9991 | 438.3271 |
| 108 | 0.003900034 | 0.003840688 | 2.94848E-12 | 6.320063587 | 0.9988 | 302.0516 |
| 114 | 0.000332768 | 0.000271129 | 1.3809E-13 | 7.607780763 | 0.9969 | 121.6554 |
| 133 | 0.003962853 | 0.003929531 | 1.11444E-12 | 6.40375686 | 0.9723 | 13.7460 |
| 159 | 0.00011605 | 9.75718E-05 | 1.3438E-11 | 6.881897005 | 0.9994 | 610.4012 |
| 219 | 5.54411E-05 | 2.21226E-05 | 2.42253E-11 | 6.722438028 | 0.9803 | 19.1943 |
| 273 | 7.66961E-05 | 5.67662E-05 | 2.18826E-12 | 6.835020334 | 0.9356 | 6.0153 |
| 325 | 2.82324E-05 | 2.38965E-05 | 2.04977E-13 | 7.534467805 | 0.9962 | 98.4803 |
| 426 | 2.58746E-05 | 1.9152E-05 | 2.14933E-12 | 6.838531966 | 0.9356 | 6.0200 |
| 530 | 2.62731E-05 | 7.30762E-06 | 3.40327E-07 | 3.400748446 | 0.9624 | 10.1640 |

Verification of the regression equation significance was conducted by using Fisher`s number, calculated by [16], $F = 60.4241$.

The tabular values of the Fisher`s number $F^m_{(n-1;n-2;p)}$ are $F^m_{(4;3;10\%)} = 5.3427$, $F^m_{(4;3;5\%)} = 9.1172$, $F^m_{(4;3;2,5\%)} = 15.101$.

$F > F^m_{(n-1;n-2;p)}$, 60.4241>15.101, therefore, the equation (8) gives the statistically significant description of the experimental results.

Similar equations were obtained for the other diameters. Coefficients *a, b, c, d* of the obtained regression equations, correlation coefficients *r* and values of the Fisher`s number *F* are presented in Table 5.

Figures 3, 4, 5 shows how the obtained dependences approximate the initial data for different gas pipeline diameters.

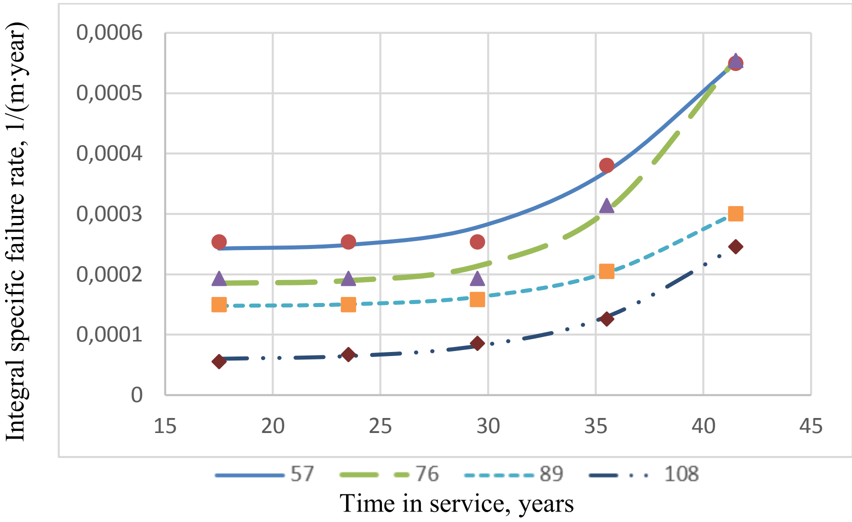


**Figure 3.** Dependence of the integral specific failure rate on the time in service for diameter 57, 76, 89 and 108 mm.

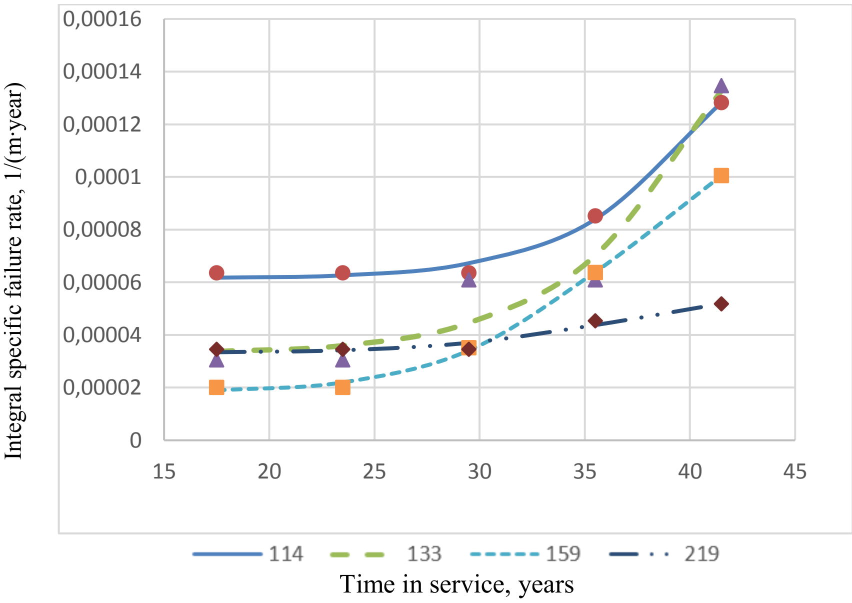


**Figure 4.** Dependence of the integral specific failure rate on the time in service for diameter 114, 133, 159 and 219 mm.

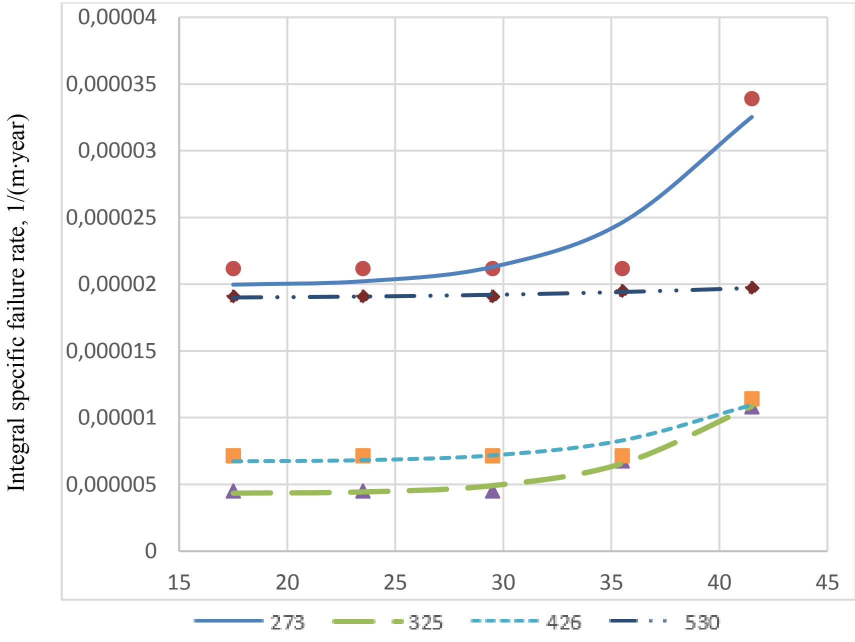


**Figure 5.** Dependence of the integral specific failure rate on the time in service for diameter 273, 325, 426 and 530 mm.

The initial data for calculation of the integral specific failure rate dependence on time in service and diameter of the gas pipeline are presented in Table 6.

**Table 6.** Integral specific failure rate at given outer diameters $D$ and gas pipeline time in service $T_{k\ \text{ave}}$.

| № | Time in service $T_{k\ \text{ave}}$, year | Gas pipeline diameter $D$, mm | $w_{ki}'$, 1/(m·year) | № | Time in service $T_{k\ \text{ave}}$, year | Gas pipeline diameter $D$, mm | $w_{ki}'$, 1/ (m·year) |
|---|---|---|---|---|---|---|---|
| 1 | 17.5 | 57 | 0.0002537 | 16 | 17.5 | 108 | 5.582E-05 |
| 2 | 23.5 | 57 | 0.0002537 | 17 | 23.5 | 108 | 6.716E-05 |
| 3 | 29.5 | 57 | 0.0002537 | 18 | 29.5 | 108 | 8.591E-05 |
| 4 | 35.5 | 57 | 0.0003805 | 19 | 35.5 | 108 | 0.0001263 |
| 5 | 41.5 | 57 | 0.0005495 | 20 | 41.5 | 108 | 0.0002463 |
| 6 | 17.5 | 76 | 0.0001936 | 21 | 17.5 | 114 | 6.353E-05 |
| 7 | 23.5 | 76 | 0.0001936 | 22 | 23.5 | 114 | 6.353E-05 |
| 8 | 29.5 | 76 | 0.0001936 | 23 | 29.5 | 114 | 6.353E-05 |
| 9 | 35.5 | 76 | 0.0003146 | 24 | 35.5 | 114 | 8.518E-05 |
| 10 | 41.5 | 76 | 0.0005547 | 25 | 41.5 | 114 | 0.0001282 |
| 11 | 17.5 | 89 | 0.0001502 | 26 | 17.5 | 133 | 3.047E-05 |
| 12 | 23.5 | 89 | 0.0001502 | 27 | 23.5 | 133 | 3.047E-05 |
| 13 | 29.5 | 89 | 0.0001584 | 28 | 29.5 | 133 | 6.094E-05 |
| 14 | 35.5 | 89 | 0.000205 | 29 | 35.5 | 133 | 6.094E-05 |
| 15 | 41.5 | 89 | 0.0003007 | 30 | 41.5 | 133 | 0.0001347 |

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Continuation of Table 6.

| № | Time in service $T_{k\ \text{ave}}$, year | Gas pipeline diameter $D$, mm | $w_{ki}'$, 1/(m·year) | № | Time in service $T_{k\ \text{ave}}$, year | Gas pipeline diameter $D$, mm | $w_{ki}'$, 1/ (m·year) |
|---|---|---|---|---|---|---|---|
| 31 | 17.5 | 159 | 2.011E-05 | 46 | 17.5 | 325 | 4.514E-06 |
| 32 | 23.5 | 159 | 2.011E-05 | 47 | 23.5 | 325 | 4.514E-06 |
| 33 | 29.5 | 159 | 2.011E-05 | 48 | 29.5 | 325 | 4.514E-06 |
| 34 | 35.5 | 159 | 2.011E-05 | 49 | 35.5 | 325 | 6.771E-06 |
| 35 | 41.5 | 159 | 2.011E-05 | 50 | 41.5 | 325 | 1.083E-05 |
| 36 | 17.5 | 219 | 3.457E-05 | 51 | 17.5 | 426 | 7.148E-06 |
| 37 | 23.5 | 219 | 3.457E-05 | 52 | 23.5 | 426 | 7.148E-06 |
| 38 | 29.5 | 219 | 3.457E-05 | 53 | 29.5 | 426 | 7.148E-06 |
| 39 | 35.5 | 219 | 4.534E-05 | 54 | 35.5 | 426 | 7.148E-06 |
| 40 | 41.5 | 219 | 5.181E-05 | 55 | 41.5 | 426 | 1.144E-05 |
| 41 | 17.5 | 273 | 2.119E-05 | 56 | 17.5 | 530 | 1.908E-05 |
| 42 | 23.5 | 273 | 2.119E-05 | 57 | 23.5 | 530 | 1.908E-05 |
| 43 | 29.5 | 273 | 2.119E-05 | 58 | 29.5 | 530 | 1.908E-05 |
| 44 | 35.5 | 273 | 2.119E-05 | 59 | 35.5 | 530 | 1.948E-05 |
| 45 | 41.5 | 273 | 3.391E-05 | 60 | 41.5 | 530 | 1.972E-05 |

## 3. Results

Due to the fact that the coefficient SDR jumps at the diameter 219x6 mm, the behavior of curve is changing, the dependence equation of the integral specific failure rate on time in service and diameter of gas pipeline is derived for two diameter ranges 57-159 mm and 219-530 mm.

The dependence equation of the specific failure rate on time in service and diameter of gas pipeline can be presented as follows

$$w_{ki}' = a + b\cdot T_{k\ \text{ave}} + c\cdot D + d\cdot T_{k\ \text{ave}}^2 + e\cdot D^2 + f\cdot T_{k\ \text{ave}}^3 + g\cdot D^3 + h\cdot T_{k\ \text{ave}}\cdot D + i\cdot T_{k\ \text{ave}}^2\cdot D + j\cdot T_{k\ \text{ave}}\cdot D^2, \quad (9)$$

in the range 57-159 mm

$$w_{ki}' = 0.000614484 - 2.56741\cdot10^{-5}\cdot T_{k\ \text{ave}} - 4.18555\cdot10^{-7}\cdot D - 3.20662\cdot10^{-8}\cdot T_{k\ \text{ave}}^2 - 9.23756\cdot10^{-8}\cdot D^2 + 1.86872\cdot10^{-8}\cdot T_{k\ \text{ave}}^3 + 3.32416\cdot10^{-10}\cdot D^3 + 4.31828\cdot10^{-7}\cdot T_{k\ \text{ave}}\cdot D - 1.0681\cdot10^{-8}\cdot T_{k\ \text{ave}}^2\cdot D + 3.21759\cdot10^{-10}\cdot T_{k\ \text{ave}}\cdot D^2, \quad (10)$$

in the range 219-530 mm

$$w_{ki}' = 0.000235718 - 1.49368\cdot10^{-7}\cdot T_{k\ \text{ave}} - 1.47445\cdot10^{-6}\cdot D - 1.56316\cdot10^{-8}\cdot T_{k\ \text{ave}}^2 + 2.96547\cdot10^{-9}\cdot D^2 + 1.10756\cdot10^{-9}\cdot T_{k\ \text{ave}}^3 - 1.97219\cdot10^{-12}\cdot D^3 + 8.86527\cdot10^{-11}\cdot T_{k\ \text{ave}}\cdot D - 1.55135\cdot10^{-10}\cdot T_{k\ \text{ave}}^2\cdot D + 9.26483\cdot10^{-12}\cdot T_{k\ \text{ave}}\cdot D^2. \quad (11)$$

Figure 6 and 7 shows how the obtained dependences (10) and (11) approximate the initial data, which presented in Table 6.

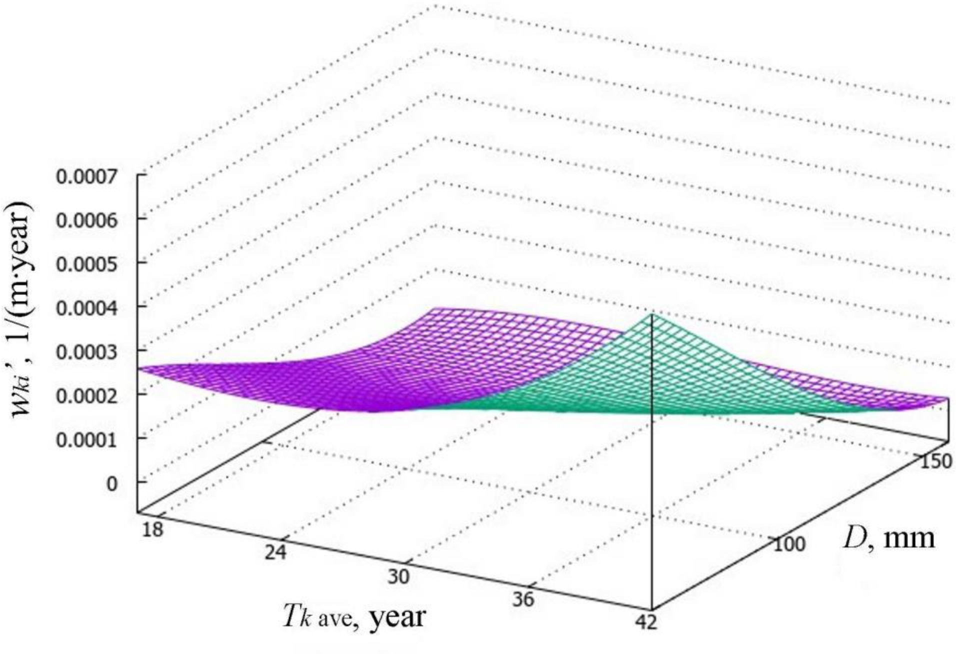


**Figure 6.** Dependence of the integral specific failure rate on time in service and diameter of gas pipeline in diameter range 57-159 mm.

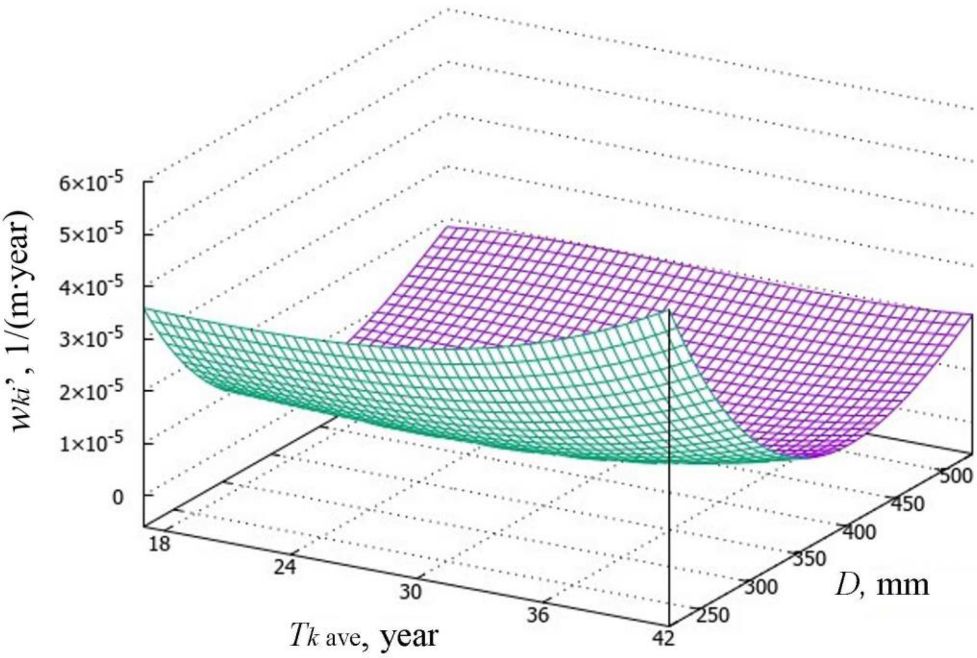


**Figure 7.** Dependence of the integral specific failure rate on time in service and diameter of gas pipeline in diameter range 219-530 mm.

## 4. Discussion

The study of the dependence of integral specific failure rate on time in service and diameter of gas pipeline allows to make a conclusion that diameter decrease and time in service increase leads to the failure rate increase. The obtained dependencies allow to calculate values of the integral specific failure rate for diameters that have no data based on the results of operation.

Further study will continue in the direction of the numeric values of reliability measures justification, which are recommended as normative, and also forecast gas pipeline accidents.

## 5. Conclusion

In modern conditions gas supply system reliability improvement can be achieved by using reliability control tools based on data about the actual technical condition of the gas networks. Statistical analysis of the gas pipeline damages in Gorlovka city has established that the main causes of damage are corrosion and influence of the undermining, while weld connection rupture and mechanical damage give a small number among all accidents. It should be noted that during the calculation of the reliability the experimental data approximation accuracy is influenced by the choice of the step of time in service, during which the failure rate is taken as constant. The developed selection method of the calculated step of gas pipeline time in service, which is 6 years, and calculation of the integral specific failure rate allowed to obtain dependences of the integral specific failure rate on time in service and diameter of the gas pipeline for two diameter range 57-159 mm and 219-530 mm.

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