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ANALYSIS OF THE GAS NETWORK FAILURE AND FAILURE PREDICTION USING THE MONTE CARLO SIMULATION METHOD

ANALIZA AWARYJNOŚCI SIECI GAZOWYCH ORAZ PROGNOZOWANIE AWARII Z ZASTOSOWANIEM SYMULACYJNEJ METODY MONTE CARLO

The scope of the article includes the analysis of the gas network failure based on a material obtained from field tests covering the years 2004-2014, conducted on the gas network of 120 thousand city, allowing to specify the failure rate of the gas network with division into material, pressure and pipelines diameter and indicate the main causes of failure on gas networks. On the base of the results of this analysis the Monte Carlo method to predict failures in gas pipe network has been presented.

Keywords: *failure of gas network, Monte Carlo method, analysis of the failure structure, failure prediction.*

Artykuł swoim zakresem obejmuje analizę awaryjności sieci gazowej na podstawie uzyskanego materiału z badań eksploatacyjnych obejmujących lata 2004-2014 prowadzonych na terenie Zakładu Gazowniczego w 120 tys. mieście, co pozwoliło na podanie intensywności uszkodzeń sieci gazowych z podziałem na materiał, ciśnienie i średnice rurociągów oraz podanie głównych przyczyn powstawania awarii na sieciach gazowych. Na podstawie wyników analizy zaprezentowano zastosowanie metody Monte Carlo do prognozowania awarii sieci gazowych.

Słowa kluczowe: *awaryjność sieci gazowej, metoda Monte Carlo, analiza struktury awaryjności, prognozowanie awaryjności.*

1. Introduction

In the report of the Committee of Union Gas in the World Congress in Nice in 1972, the issue connected with the failure intensity of the gas network was presented. Operation of Gas Supply System is inseparably linked with the occurrence of the fire and explosion risk. Failures, explosions and fires long-term statistics conducted by the gas services and organizational units of the State Fire Service indicate that despite the continuous increase of the safety level of gas supply system and number of actions taken in this regard, still many failures are recorded, which often generate serious threat for the external and the inner environment of a man, as well as create risk for human health and life. The consequences of failures, during which the release and dispersion of natural gas occurs, depend on its type, nature and causes, as well as from the efficiency of its removal.

Failure frequency evaluation in the operation of gas supply subsystem should be one of the priorities of the gasworks, which should attach greater importance to assess the proper functioning of the newly designed, as well as the implemented systems [31]. With the increasing pressure from the environmentalists and stricter standards for acceptable environmental pollution and structures vulnerability in terms of its protection, it seems to be a necessity [6, 24, 28]. The issue connected with failure gas pipeline analysis in perspective of improper design, construction and maintenance is presented in work [11], the increased failure affected by the lack or improper conduct of repairs and modernization, also incorrect or lack of risk management program. When planning renovations or modernization of gas networks the gasworks employees should make the classification of pipelines, that means determine which sections of the network require immedi-

ate repair, and which can be repaired later [7, 15, 26]. For this reason, making the appropriate maintenance (repair, renovation, replacement) only after the damage of the element may be irrational, control human intervention detects and removes faults being a potential source of failure. Widely used solution become the preventive renewals, aimed at reducing the loss of utility of a given element in different environment [4, 8, 21]. Very important from operator perspective is the failure reason [18, 20, 29], as well as modernizing actions that should be taken to avoid such undesirable situations. The strategy of the preventive renewals is to establish such timing of the renewals which will enable to achieve the maximum profitability of the project, through the use of the periodic strategies involving the renewals after a certain period of element operation [5, 11]. Such classification can be made, for example, on the basis of failure prediction for certain sections of the gas network, using the Monte Carlo method [30, 34]. The Monte Carlo methods include all proceedings aimed at finding approximate solutions of some problems (mathematical, technical or operational) [27]. The Monte Carlo method involves estimating the probability of occurrence of certain events based on previous studies [1, 12]. The assessment of the polyethylene pipes properties of gas networks in terms of operation safety, as well as activities that influence the increase of operation reliability and safety improvement was proposed in [3]. Interesting approach for assessment of gas pipes defects was presented by [23], in which corrosion and gouges defects were included. In work [17] significant issues related to ensuring the safety of pipelines, through research methods and the improvement of the technical condition were presented. Such composition was also prescribed in [10, 14, 16, 19] as to identify the most common failure causes in

addition to the existing design and construction data, as well as visual physical inspection. Nevertheless random character of failure occurrence makes analysis and assessment in this area very complex and based mainly on the analysis of operational data and implementation of methods and analysis of the failure mechanisms under real conditions as shown in works [9, 22, 25, 32, 33].

According to US Department of Transportation the trend in pipeline safety has demonstrated a stable decline in incidents concerning deaths and injuries, in the last twenty years and decrease from about sixty in nineties to forty. But on the other hand still more than fifty percentage of gas network was constructed in fifties or sixties, what can cause much serious failures or even gas explosion. Also many programs were implemented to improve this situation, there is still necessity for continuous improvement of gas network condition in order to reduce the failure rate. As to perform this actions, the analysis of typical gas network was proposed in this work, which aim will be to eliminate failure or serious pipeline incidents.

Also the aim of the work is the possibility of forecasting (prediction) failure as to minimize their possible impact, what is very important for safety reasons for users in subsystem of natural gas supply (SNGS), for this purpose, the Monte Carlo simulation method was used.

2. Analysis of failure in subsystem of natural gas supply based on operational data

2.1. Preliminary assessment of pipelines' technical state

The SNGS is powered by a ring high-pressure network through the 43 first degree reduction and metering stations, which supply medium pressure rings of various districts of the city and the surrounding regions. The age and material structure of the network are presented in Fig. 1 and 2.
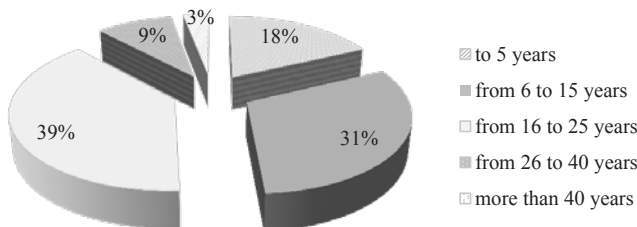

Fig. 1. The age structure of the gas network - a state for 2014, in %
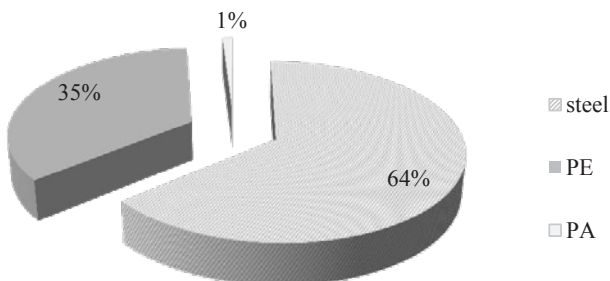

Fig. 2. The material structure of the gas network - a state for 2014, in %

Data on failures on the main taps and reduction points as well as distribution networks in the years 2004-2014 are presented in Fig. 3.
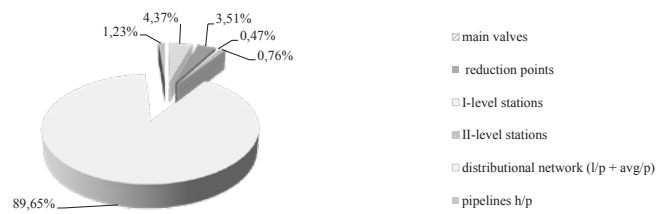

Fig. 3. Failures occurring in the gas network in the years 2004-2014, in %

Figure 4 shows graphically the results of the analysis of causes of failure in the l/p (low pressure) steel and plastic networks: PE - polyethylene and PA - polyamide and m/p (medium pressure) steel and plastic networks. Figure 5 summarizes the number of failures in the l/p steel and plastic networks and in m/p steel and plastic networks, in the assumed diameters ranges.
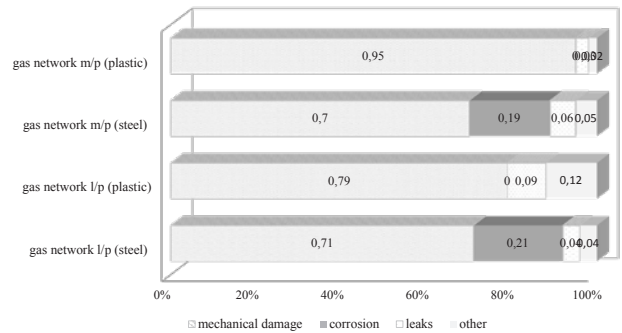

Fig. 4. Failures of gas networks l/p and m/p in the years 2004-2014 with division into the causes of their occurrence, in %
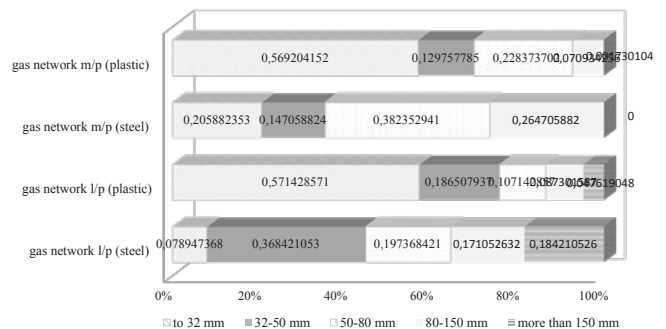

Fig. 5. Failures in the assumed range of pipelines diameters in the years 2004-2014, in %

2.2. Water network failure

The unit failure rate λ_i for l/p and m/p gas pipelines, with division into material, was calculated according to the formula (1):

$$\lambda_i = k_i(t, t+\Delta t)/(l_i \cdot \Delta t)$$

where:

λ_i –   unit failure rate for i^{th} type of network or i^{th} type of fittings, [number of failures / km · year];

$k_i(t, t+\Delta t)$ –   the total number of failures in the time interval Δt in a given type of network,

l_i –   length of a given type network, in a given period of time, in which failures occurred, [km];

i –   type of network;

Δt – the time interval, [one year].

2.3. Discussion of results

The detailed analysis showed that the average values of the failure rate index of gas pipelines are:
- failure rate of l/p gas pipelines $\lambda_{avgusteel}$ = 0.006987 [number of failures/km · year],
- failure rate of l/p gas pipelines $\lambda_{avguplastic}$ = 0.062352 [number of failures/km · year],
- failure rate of m/p gas pipelines $\lambda_{avgusteel}$ = 0.005432 [number of failures/km · year],
- failure rate of m/p gas pipelines $\lambda_{avguplastic}$ = 0.027429 [number of failures/km · year].

In detail the overall situation of failure rate can be distinguished as follows on the Figure 6.
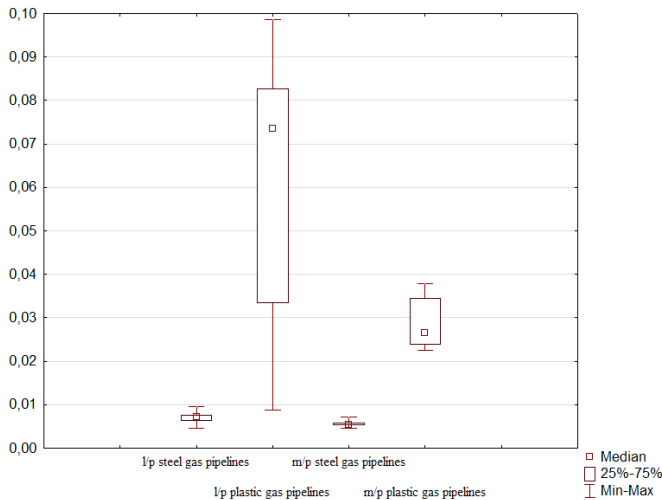

Fig. 6. Failure rate of a medium pressure gas pipeline, low pressure depending on the material type and on the network altogether

Most emergency pipes occurred to be plastic sections, they constitute nearly 65% of all, due to the fact that the sections made of this material constitute the most networks, what is confirmed by failure rate index. The mean operating time between failures T_{Pavg} in the considered years was 1.9 d. This analysis shows that the main cause of failures in gas distribution networks is the corrosion of steel pipes and mechanical damages of plastic pipes. The total average failure rate of gas pipelines was λ_{avg} = 0.02555 [number of failures/ km · year]. The analysis showed seasonality of the failures in the gas distribution networks, in spring and summer the number of failure increases and during autumn and winter it decreases, so it is important to increase the frequency of gas pipelines inspections and the use of monitoring during the periods of increased failure rate. The performed analyses show, among others, that the replacement of steel pipes by plastic pipes made in recent years, significantly reduced the number of network failures due to corrosion.

In the damage structure on all kinds of pipes, mechanical failure dominate and represent 78.7% of the total sum of failure. The effect of such situation could be negligent backfill placement of pipes, which during operation are susceptible to settlements and consequently breaking and too shallow laying pipes in the ground, so that they are exposed to high loads. The largest share of failures concerned network, which is older than 16 but having not more than 25 years. The cause of such situation is that many older pipes had already been replaced. The smallest number of failures occurred on the elements younger than 5 years.

3. The use of the Monte Carlo simulation method for predicting failures in SNGS

A concept of the adopted Monte Carlo simulation method can be presented in the simplest way by means of the following procedures [2]:
1. Calculate the probability $P(k,t)$ of the adopted subsystem reliability measure.

In the analysed example it is the probability of k failures in SNGS, calculated on the basis of data from exploitation. We used [13]:

$$P(k, t) = ((n \cdot \lambda \cdot t) \, k \, / \, k!) \exp(-n\lambda t) \qquad (2)$$

2. Establish equal intervals of random numbers with lengths corresponding to the calculated probabilities.
3. Generate a sequence of independent random numbers occurring with equal probability (N = (25÷100) · 10³), for each random variable included in the reliability analysis of SNGS. In the shown example it is a number of failures "k", which appears in SNGS within a specified period of time.
4. After making a sufficiently large number of operations (draws), calculate the number of results found in the emergency areas for every failure "k".
5. Calculate the U_k index, which determines the probability of the occurrence of k failures within a specified time interval.

$$U_k = N_1/N \qquad (3)$$

where N_1 is a number of hit random numbers in equal probability intervals, corresponding to a certain number of failures at time t and N is a number of all executed draws.

6. The measure of reliability in the analysed period is the index K calculated as:

$$K = 1 - U_k \qquad (4)$$

Generally, the Monte Carlo method can be used for every element of SNGS, if only the values of failure probability are known. Computer programs gives the possibility to use the simple Monte Carlo simulation method to assess the reliability of SNGS. Figure 7 shows the program algorithm performed for simulation calculations of the number of failures on distribution networks in SNGS.

Once you start the program you must provide the following inputs:
- t - time,
- L - the length of the network,
- k_{max} - the maximum number of failures at time t,
- λ - the average unit failure rate.

Based on these data, the program calculates the probability $P(k,t)$ and determines the intervals of random numbers. Then the random numbers are generated, at every number the program checks whether a given number falls within the numbers for the ith "k", at the same time counting how many of the generated numbers are within the proper range. After the appropriate number of draws is made the program calculates the index U_k and the procedure is repeated from the beginning for the next k.

The result of the program is a series of grouped indexes U_k for the corresponding k. A simulation of 1000000 draws was performed for each k failure for l/p steel and PE networks and m/p steel and PE networks. The results are shown in graphical form in Figures 8, 9, 10, 11.

Implementation of the Monte Carlo method shows the prognosis of technical condition of gas pipe. From the analysis of presented figure 8-11 it seems that the intensified time for inspection and then rehabilitation of network made from PE in case of average pressure is the range from 101 to 154 years of exploitation, which greatly ex-
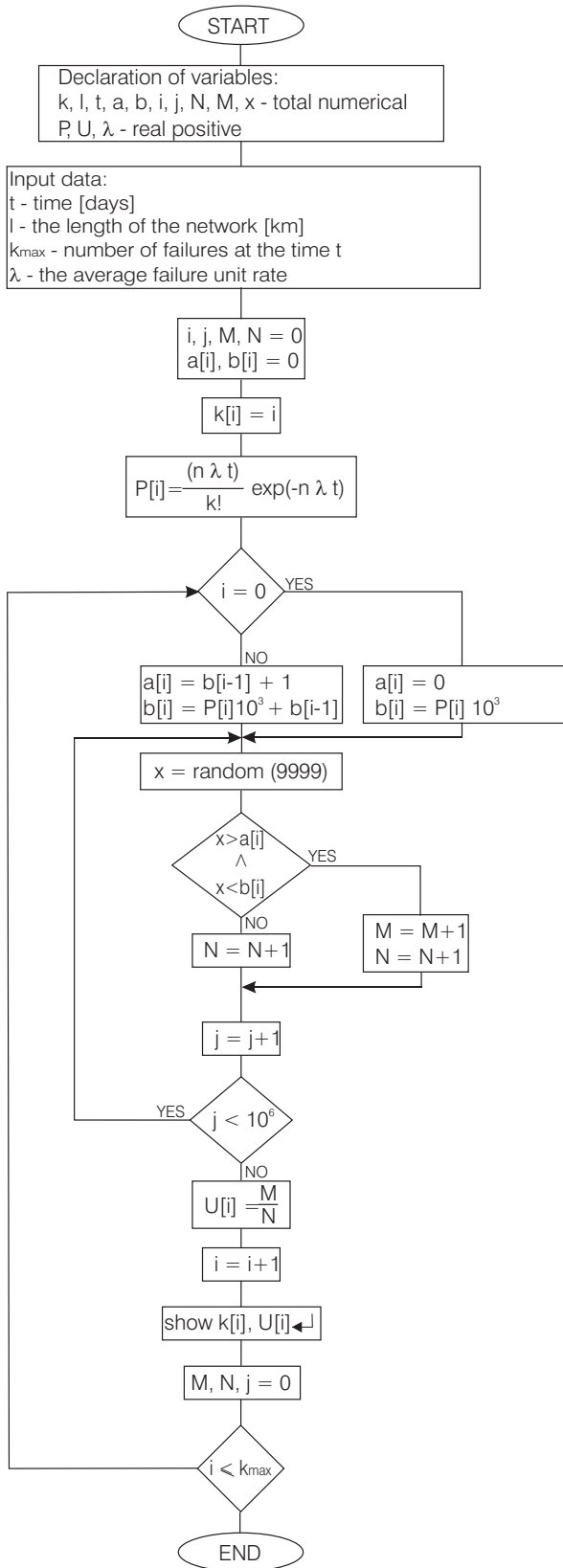
Fig. 7. The algorithm of the program to assess the reliability of the SNGS by the Monte Carlo method, where M is the number of random numbers getting hit with compartments of equal probability, N is number of all performed lotteries, U is the probability, a predetermined range of time when k failure occurs, P is the probability of k failure occurrence at the t time [27]
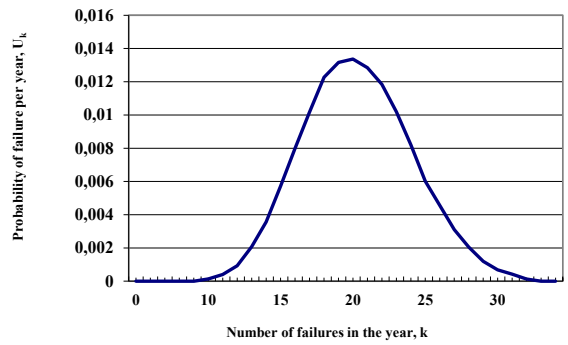

Fig. 8. Simulation using the Monte Carlo probability U(k,t) of the forecasted k failures in the network of steel l/p, $\Lambda_{avg} = 16,4$ failure/year
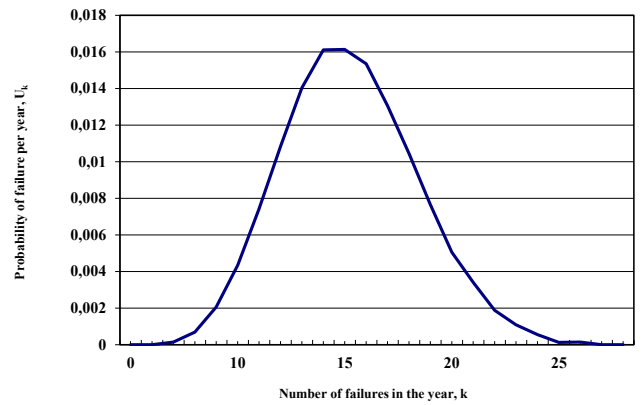

Fig. 9. Simulation using the Monte Carlo probability U(k,t) of the forecasted k failures in the network of PE l/p, $\Lambda_{avg} = 13,8$ failure/year
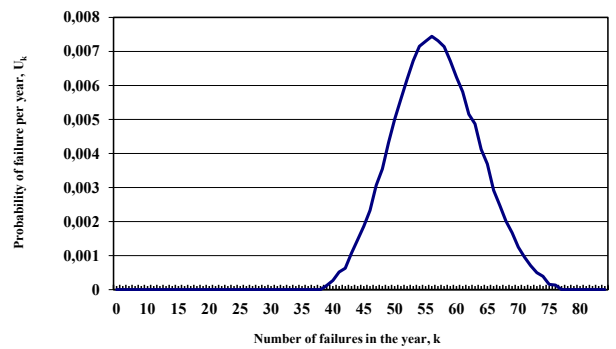

Fig. 10. Simulation using the Monte Carlo probability U(k,t) of the forecasted k failures in the network of steel avg/p, $\Lambda_{avg} = 53,6$ failure/year

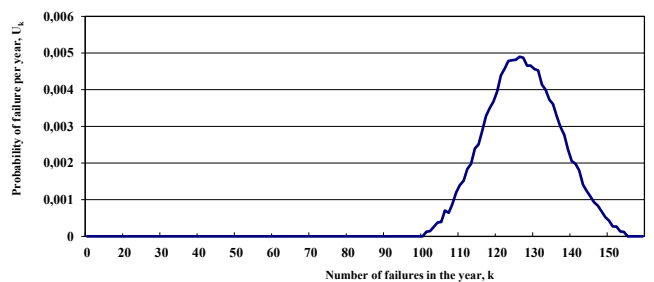*Fig. 11. Simulation using the Monte Carlo probability U(k,t) of the forecasted k failures in the network of PE avg/p, $\Lambda_{avg} = 137,2$ failure/year*

ceeds the lifetime of the gas network and constitute good prognosis for investments of network rehabilitation. Also on the example of steel pipes of average pressure the time of intensified observation should be delayed longer in time from 37 to 74 years. The situation is different in case of network of low pressure, it seems that the probability of failure considerably increases, for example U_k, which equal 1,20E-02 and is reached after eleven years of exploitation for PE pipe. For the same probability of failure, but for the steel pipe (l/p) it is attained after eighteen years of gas network functioning. Such prognosis should point a direction for conducting preventive modernization of gas pipes.

4. Conclusion and perspectives

The simulation Monte Carlo methods can be used to predict failures occurring in the gas networks, which allows to classify properly the elements of the subsystem requiring modernisation or general overhaul. It could be very helpful in performing and planning of operation strategy prediction.

As to perform the prioritisation pipes for rehabilitation, the failure and prognosis analysis of the gas network should be conducted. It constitute the crucial element of the management of urban gas network, mainly in the strategic modernization plans, as well as it supports the rehabilitation techniques.

Further research should address the introduction of methods for analyzing failure during which more information data from different gas network will be gathered and constitute guidelines describing the possibility of failure occurrence on the gas pipes. It also seems necessary to indicate to discuss the criterion concerning the effectiveness of the gas supply system functioning.

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