Quantitative risk-analysis methods and mechanical systems safety

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Abstract
The features of the Farmer's diagram building as a basic tool of quantitative risk- analysis, which is complemented by the analytic hierarchy process and safety index, are considered. It is shown that the level of risk and safety index are diagnostic parameters to assess the technical condition of the mechanical systems. The problem of their safety in the metallurgy is described. With regard to the metallurgical equipment there shown the advantages of risk analysis unit as compared with reliability theory method.

Key words: FARMER'S DIAGRAM, RISK- ANALYSIS, MECHANICAL SYSTEMS, SAFETY

The term «safety» is used in many fields of human activity, as in the fields of technology. In each of them it is given a different interpretation. The industrial safety is often understood as activity related to the minimization of harm to human health and life, as well as damage to the environment from industrial production. In this formulation the issues of safety and labor protection, health and safety come to the fore and are solved mainly by organizational techniques. However, growth in the number of man-made disasters scale, the number of serious industrial accidents showed that in addition to organizational methods there should be used specific methods, integrated by the concept of technical safety.

Experts appealed to the problem of technical safety in the 50-ies of the last century, linking it primarily with errors of humans, controlling technical systems. It was established their limit frequency (0.01...0.02), which is used when assessing the reliability of systems. [10] In the 60s attention began to be payed to the impact of failures that led to the emergence of risk-analysis and the method of «fault tree». There were developed documents governing the acceptable level of risk and the procedure of its determining for the branches of technology. It is believed that the first standard MIL STD- 882, in which the systems safety is featured as an independent concept, appeared in 1962 in the Ministry of Defense of the United States [10].

Methods for the safety assessment evolved from structural mechanics when in 1959 V.V. Bolotin first used statistical theory to estimate the seismic risk [8]. Since then, the concept of safety as a synonym of reliability was used for technical facilities, the operation of which is provided to limit state. Since the 70-ies tge probabilistic safety analysis of nuclear power stations started to develop in the world, and was initially designed to show that harm from their operation to the health of the individual and to the ecosphere does not exceed the losses from operation of other energy systems. The solution of a similar problem that the air transport is safer than passenger transport on other modes of transport contributed to the intensive development of aviation. The success of probabilistic methods of safety development in nuclear power and aviation prompted their use for assessment of potential dangerous mechanical systems in practically all branches of technology.

There was no uniform established definition of security formulated. With regard to the technical systems safety is determined either as their property (like reliability, being one of its indicators), or as their condition. In our opinion the latter definition is true, because it reflects not only the stages of design and manufacture, but also the operation process. The second part of the definition the safety is universally characterized by non-exceedance of current risks of their permitted levels. From this it follows that there was a departure from the concept of absolute reliability to the concept of acceptable risk. This concept is clearly manifested by the 90-ies. Thus, the technical system safety is a state when operational risks do not exceed acceptable levels.

The transition from the reliability to security coincided on time with the introduction of the concept of acceptable risk, which reflected the need to establish the budget for energy- and material consumption, as well as on maintenance of machines and constructions. Consumer is interested in not so much reliability, but in minimization of the damage from failures. Other words, it is important the function (result), implemented by reliability, and not as a means itself . Because for complex technical systems (and those are the power constructions of technological equipment and vehicles, with a lot of potentially dangerous places and damaging processes affecting them) the absolute reliability is unattainable, then the necessary level of safety should provided, which purpose is closely linked to risk-analysis [10].

Indicators of risk and Farmer curve

Risk is a measure of dangerous condition. Its decrease corresponds to an increase of safety. The risk calculation is taken as a function of two variables by the formula:

$$i=f\cdot S, \tag{1}$$

where f- the frequency of emergency nature failures [failure/ time], and S- the intensity of the damage caused by them individually [damage/ failure].

Consequently, the risk is measured by [damage/ time]. The peculiarity of this approach lies in the fact that both variables are interdependent. F. Farmer established it in 1967, when researched the link between quantity of radioactive leaks from the nuclear reactor and the period of their occurrence. Based on this it is postulated that more serious by damage accidents occur less frequently than smaller ones. This relationship is called the Farmer curve (or chart) or F-N curve. Its analogue in statistical mechanics is the distribution curve of emissions (overloads). Farmer curve can be represented in two ways: a) a discrete relative frequency f of failures with damage S is delayed on the ordinate; b) a cumulative frequency $F_n=f_1+f_2+\ldots+f_n$ is delayed on the ordinate for numbers of levels n with an accident severity N (here- F-N curve), n=1 $N=N_{max}$.

Having the level of risk i as a parameter, the F-N curve is a line of equal risk, showing how many minor accidents match with one major by damage. For a perfect Farmer curve (called neutral risk curve) from the definition (1) it follows that a 10-fold increase in the damage caused by the accident represents a 10-fold decrease in the frequency of its appearance (Figure 1). F-N curve is obtained a posteriorily by observing the operation of a number of similar technical systems or by testing the pieces of equipment (machines) for reliability. The process of obtaining such information is long and expensive. Although such results characterize the technical system in general (which is positive), but its cost is high (tested specimen is usually unfit) and damages from failures are large.

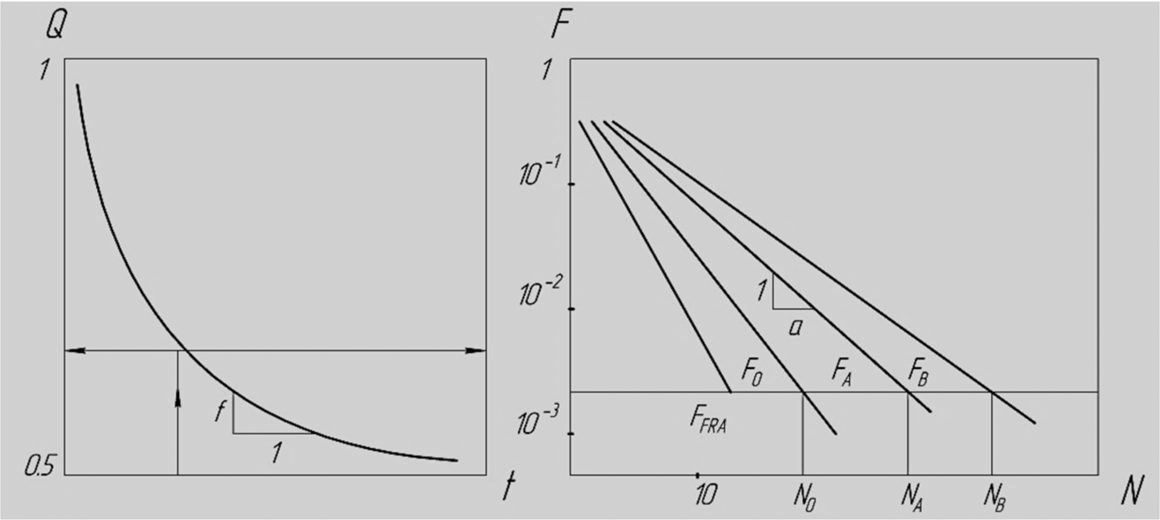

Figure 1. The function of the reliability of Q-t and F-N diagram for a neutral risk F_0, as well as for the risks by scenarios and consequences (F_A and F_B).

The results of observations can be projected on a particular technical system using the seriality of object. For example, in metallurgy accidents with damage of 100 thsd.- 100 mln. dollars occur with a frequency of 0.001 - 0.0001 [16]. That is one big accident happens at Z= 10^3-10^5 of objects. However, it is unclear how many objects Z should appear in the analysis: either Z<10 - the number of unique blast furnaces or Z≈500 - the approximate number of blast furnaces, which were monitored.

It is more productive to treat the safety through the work time of technical system till the accident of an appropriate scale [1]. Then the frequency is $f = Q/t$ (Fig. 1). Substituting this expression in (1), obtain $i = Q \cdot S/t$. Turning to the individual assessment of the failure risk of a particular element of technical system it can be assumed that:

$$i = Q_t \cdot S_i \qquad (2)$$

where Q_t – the probability of failure during the operation time t,

S_i – the damage caused by failure of the i-th element of technical system, or damage from an accident of the i-th category of technical system.

In such form the risk receives connection with time of operation and can characterize technical condition of object (fig. 2). For technical system according to the rule of summation of probabilities of refusals, and risks as well, we obtain:

$$i_\Sigma = \sum Q_{ti} \cdot S_i \; . \qquad (3)$$

Having the level of damage caused by failure of the entire technical system S_Σ, marking the significance from the failure of the i-th element as a criticalness $u_i = S_i / S_\Sigma$, we get:

$$i_\Sigma = S_\Sigma \cdot \sum Q_{ti} \cdot u_i \; . \qquad (4)$$

Thus, the comparison of risks within a single object can be implemented by the dimensionless expression under the sign of the sum, which can be called a dimensionless risk:

$$\rho_\Sigma = \sum \rho_i = \sum Q_{ti} \cdot u_i \; . \qquad (5)$$

On this basis, the risk can be interpreted as the product of failure probability on its significance. For basic constructures elements and critical parts that have significant potential for the damage, the failure of which is equivalent to a loss of technical system efficiency, and which $u_i = 1$, the safety is represented as probability of failure-free operation: $R = 1 - \rho$. A significant number of specialists in the field of strength are involved in the study of probabilistic safety aspects, using the probabilistic-physical methods, that take into account the nature of the failures. Farmer diagram is a product of mathematical-statistical methods of processing, indifferent to the nature of damaging processes.

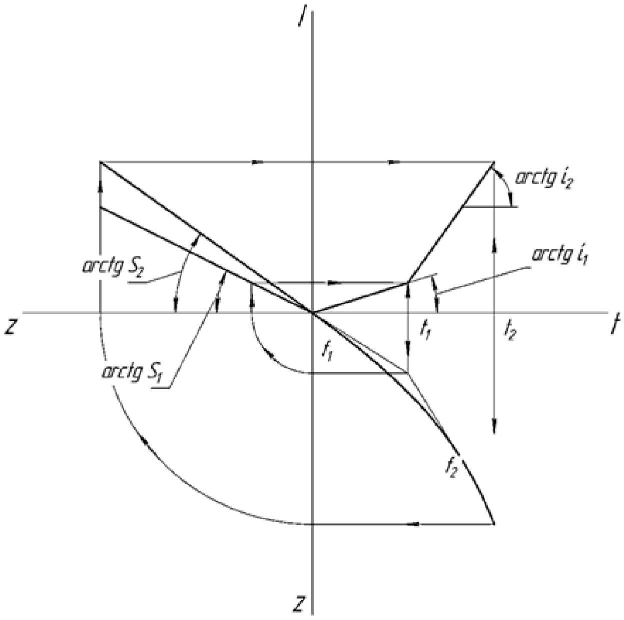

Figure 2. Scheme of the formation of kinetics of absolute damage I in the process of operation (I quadrant) on the basis of the failures curve z during the operation time t (II quadrant)

In the theory of maintenance, the analog of risk is the intensity of operating costs (unit costs) c on the maintenance and repair (MandR), measured in the same units (line C, Fig. 3). In fact, the risk is an unscheduled part of the costs for MandR I_0, referred to the guaranteed operation time (line I, Fig. 3). But the risk accounts not only the costs of restoring C_p, but also the losses of production, including social ones I_A. In the M theory there is also an analog - the coefficient of lost profits [4]. Persistence of risk indicates the linear nature of the growth of costs for MandR, and the time losses (lines C, I, Fig. 3).

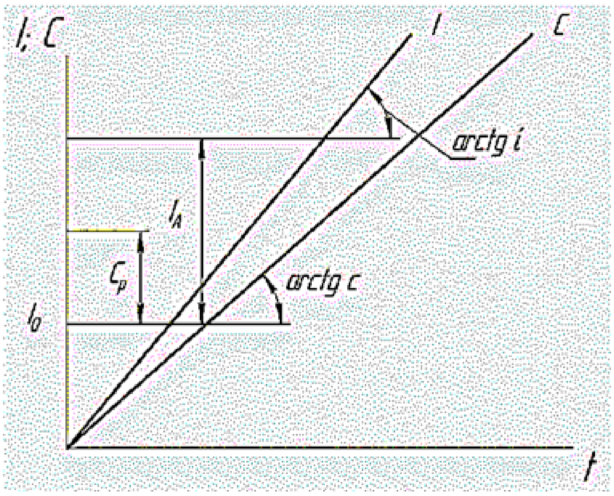

Figure 3. Comparative kinetics of the absolute growth of damage I and rise in costs for MandR C

The risk, being a measure of the damage intensity can be a diagnostic parameter that determines the recovery time or operation period. This is evident from its connection with the failure curve *z-t* (Fig. 2), which is a monotonic function with the increasing intensity [4]. If the value of$i=const$, the operation process is established. The sharp increase in the slope of the losses function *I-t*, when $i_2>i_1$ (Fig. 2) illustrates the need for repair actions.

The disadvantage of Farmer diagrams is due to the imperfect assessment of the impact of failures with a low frequency of occurrence and a high damage level [18]. It should be noted that the obtained by Farmer relationship between the radioactivity of reactor and the time of its operation did not meet the curve of neutral risk, settling in the zone of acceptable risk (F_{FRA}, Fig. 1). It is formed the situation when the object does not take the risk at the expected level, performing a more optimistic scenario. The corresponding to such a situation F-N diagram is called a risk aversion curve (RA- risk aversion) with equation:

$$F = F_1 \cdot N^{-a} \tag{6}$$

F_1- the frequency of failures occurrence with a conditionally single damage,

a – the aversion factor.

Apparently, this effect is associated with the properties of mechanical system, laws of the aging of its elements and has an objective character.

For a neutral risk curve $a=1$. Usually for a FRA-curve $a=2$ (by the way, Farmer obtained $a=1.5$). From this it follows that in order to 10 «light» accidents bring the same damage as one «heavy», they must occur 100 times more than it.

There are also known the equations of risk aversion curve of the form [13]:

$$i = Q^{1/a} \cdot S \text{ or } i = Q^{1-a_1} \cdot S \text{ or } i = Q \cdot S \cdot Q^{-a_1} \tag{7}$$

where $a_1=1-1/a$.

Considering that the probability of failure is usually measured through the multiplier 10^{-n} (n-integer) for RA-curve we have: $i= 10^{-n/a} \cdot S$. In this case, the accidents frequency can be a times higher to obtain a «neutral» damage. Or: at $a=1.5$ for $Q=10^{-6}$ the expected level of losses will be 100 times less, and for $Q=10^{-9}$- 1000 times less. The lower the probability of failure, the greater the risk reduction from its neutral value.

However, for the rare failures with a significant damaging effect the opposite pattern is possible. Such failures, with the same frequency, can bring various damages. The same failure can be eliminated in the short or longer term. This is due to the nature of accident development, which can be formalized by an appropriate scenario which is a kind of continuation of the fault tree until the restoration of technical system. That is, the different effects of the same failure should be taken into account. Its minimal severity corresponds to the fastest replacement of the failed component. If failure provokes the following chain of failures, its severity is $N_B > N_A > N_0$ (Fig. 1). Then the neutral risk curve is transformed into the high risk curves (F_A, F_B Fig. 1). Since the failures of low severity (the upper part of diagram) are conjugated with smaller effects, the new F-N curves will have a smaller slope and value $a<1$. This phenomenon reflects not only the properties of technical system, but also the organization of production with the MandR system. It is subjective.

Analytic hierarchy process (AHP)

According to some experts, the use of the coefficient of risk aversion does not solve this problem of F-N curves, but rather adds uncertainty to risk analysis [18]. A more promising is the AHP (analytic hierarchy process). Its point is associated with the representation of F-N diagram of a stepped shape like a histogram. As a result, there are areas i, with the damage scale N_i and probability Q_{ti} (Fig. 4). Each scenario has its own configuration j, and each step in it has a local criticality $u_i=N_i/N_{max}$. Then by (5) the dimensionless risk level ρj can be found for each scenario. On the basis of this the total failure criticality of each area in each scenario is determined:

$$u_{ij} = \frac{1/\rho_j}{\sum 1/\rho_j} \cdot u_i \tag{8}$$

Note that $\sum_i^n \sum_j^k u_{ij} = 1, \quad \sum_i^n u_i = 1$. The sum of total criticality levels within the script $\sum_i^n u_{ij} \neq 1$.

Its maximum value determines the most preferred scenario of failure. Substituting the values u_{ij} in (5) instead of u_i for $i=n$ steps and for $j=k$ scenarios the generalized (total) value of risk is obtained.

Used in the risk-analysis the AHP is similar to the procedure of finding of generalized (equivalent) loading mode on i steps and j operating conditions.

Despite some shortcomings the Farmer diagram is the basic tool of quantitative risk analysis. There are many options for its evolution. In particular, it is effectively to add to it the formation of logical-probabilistic models in the form of a fault tree and accident scenarios. With their help it is possible to go from the posteriori nature of getting the F-N diagram to its priori nature [10]. In addition, fault tree allows you to find the probability of occurrence of emergency situation, which in many cases is equivalent to the probability of failure.

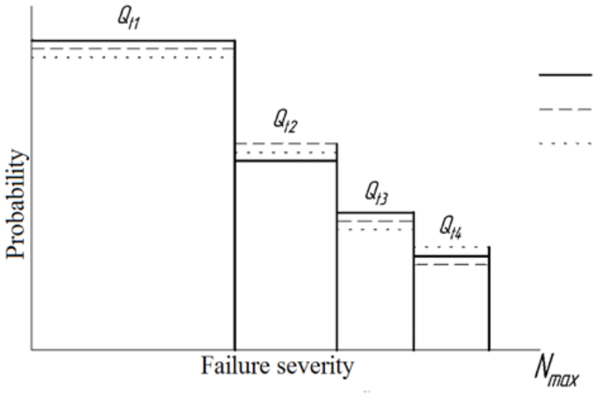

Figure 4. The F-N diagram parting into the areas to explain the algorithm for determining the total (generalized) criticality of failure

For example, the explosion of the gas mixture inside metallurgical unit leads to the loss of his working capacity, but to predict confidently enough that the corresponding damage is difficult. So, the basic concept to ensure the safety is linked to the prevention of accidents and, therefore, it is necessary to diagnose and prevent the initiating failures. Accident scenario together with AHP enables to enhance the importance of initiating failures in varying degrees, causing the increase of current risk (Fig. 5). Controlling it the staff insures the equipment from potentially unacceptable damage.

In 1993, at the Dneprovsky Integrated Iron&Steel Works was, perhaps, the largest in the steel industry accident that destroyed blast furnace №7 and killed about 30 people. Directly the explosion inside it caused the destruction of furnace construction. It was preceded, according to the act of investigations, by the chain of events and actions of staff, which violated the 11 points of provisions on technical operation. Moreover, each violation separately could not lead to such a result. There was the adverse combination of 8 production factors. Such a scenario is difficult to predict without a precedent. All this shows the relevance of the accident scenarios development.

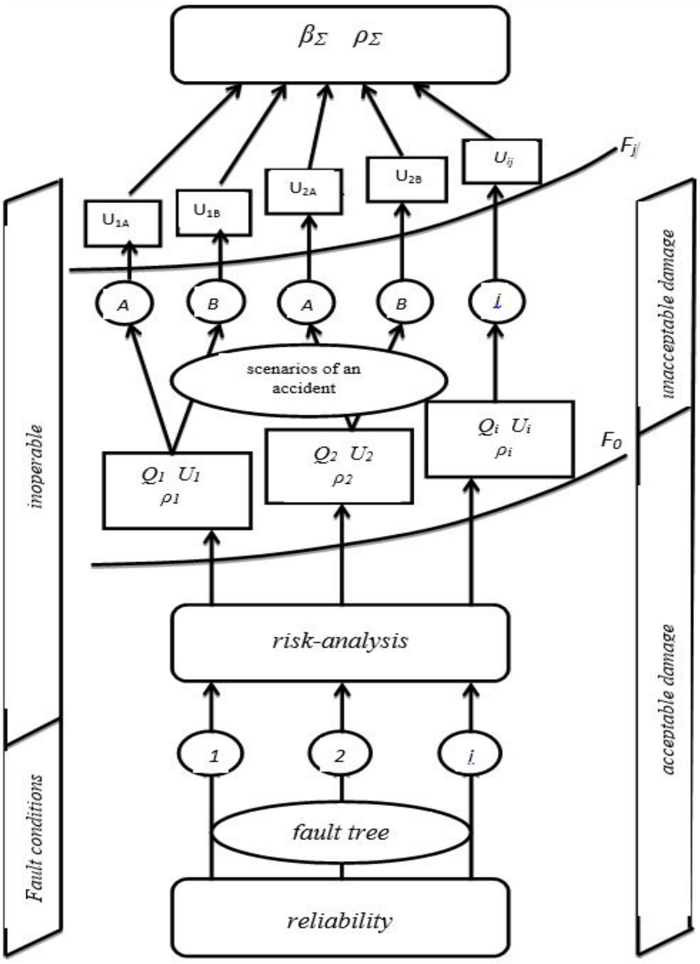

Figure 5. The scheme of risk-analysis algorithm and safety

Method of safety index

To use the risk directly as a diagnostic parameter to control the technical state can be uncomfortable. This is due to some peculiarities.

1) The risk ρ, due to its connection with the probability of failure-free operation, is less sensitive to changes in the system technical condition at a rather long interval of operation [5].

2) It is difficult to objectively establish a maximum permissible level of risk.

3) The reliability of its depends on the reliability of the initiating failure evaluation. Usually it is done by means of mathematical and statistical methods, the accuracy of which is sufficient to predict the economic losses. To control the technical condition it is necessary to apply probabilistic-physical methods.

All this accounts such a measure of risk as the safety index, which is a log of the guaranteed reserve of durability:

$$\beta_R = \lg \frac{n_{0R}}{n_{\Sigma(1-R)}}, \qquad (9)$$

where n_{0R} – durability found by function of its distribution for a given probability of failure-free operation R

$n_{\Sigma(1\text{-}R)}$ – measure of operating time.

Operating time of the mechanical system is conveniently to control in the process of operation, the value β_R is quite sensitive to it, and the limit value guaranteeing the safety, will be $\beta_R=0$.

For reliability function of exponential type in high probabilities area.

$$R = \exp(-d) \approx 1 - d, \qquad (10)$$

where d –damage as the relative longevity.

It follows that the current damage of the element of mechanical system i from the degradation process j will be dij=Qt. That is, the accumulated damage completely characterizes the risk of exploitation and loss of efficiency. Then it is possible to determine the risk of the system as

$$\rho_\Sigma = \sum (d_{ij} \cdot u_{ij}). \qquad (11)$$

Since the damage d_{ij} changes with operating time, the value ρ_Σ changes like it. Considering that a guaranteed reserve of durability is inversely proportional to guaranteed damage $n_{NR} = d_R^{-1}$, and safety index - its logarithm we have: $\beta_R = -\lg d_R$ or $d_R = 10^{-\beta_R}$.

Using (11) we finally obtain:

$$\beta_{\Sigma R} = \lg\left(\Sigma u_{ij} \cdot 10^{-\beta_{ijR}}\right)^{-1}, \qquad (12).$$

where β_{ijp} – the safety index of the *i* - th element for *j* - th damaging process, obtained from the function of resource allocation and operating time for the probability *R*.

Due to resource treatment of failure probability the safety index method is suitable for assessing the risk of sudden and gradual failures. On its basis, a strategy of maintenance with safety control and the transport resource extension algorithm [5-7].

The issue of equipment safety in metallurgy

By intensity of damage from accidents metallurgy takes the 4-5 place after the rocket and space technology, nuclear energy, chemical reactors, ahead of the mining industry, transport, building, mechanical engineering [16]. In the metallurgical complex of Ukraine, there are 70 high-risk facilities. **Every year** from 42 to 114 people died in it (in 15 years of observation) [2]. This is quite a lot. In Russia, where the number of steelmakers is approximately 2 times higher mortality rate is almost 2 times lower. There is no correlation between the volume of production and the number of fatal accidents. There is no system statistics of accidents, not related to the injury in Ukraine. [2] A negative trend appears, when the companies management is reluctant to illuminate the facts of accidents, does not agree to the publish the results of surveys of the equipment technical condition, made by third-party specialized organizations. According to public information in the metallurgical complex of Ukraine there are 3-6 accidents per month. [2] This corresponds to the annual number of major accidents in one Magnitogorsk Iron & Steel Works (MMK) [11].

Even this data is enough to note the existence of problems with the accident rate and safety in the Ukrainian metallurgy. If one does not take adequate measures, the situation will only get worse, as the depreciation of fixed assets is extremely large (according to various sources - 60-80%).

In 2013, Ukrainian Cabinet of Ministers adopted the «Technical Regulations of machinery safety», which requires to assess the risk after major repairs of equipment, if it is dangerous not only for health, but for the integrity of the property. In metallurgy, flammable aspects of risk are more worked out in detail, but not enough attention is paid to the so-called constructional safety [11]. Although the construction elements failures are the sources of initiating failures, which are the cause of such accidents as dropped loads, injury from moving parts of machines. Their share - not less than 60% of all causes of accidents [3]. Destruction of constructions is also a source of many accidents with the release of the molten metal. For example, in January 1998 at MMK the lance fell into the converter, causing an explosion. There were three injured people, one of them died. The source of failure - destruction of lift mechanism drive clutch collar and subsequent disconnection of main circuit [3]. In December 2012 in Ilyich Iron and Steel Works at MNLZ-2 the 150 t ladle with molten steel dropped and flooded the 250 m^2 area of the workshop and took 2 lives. The source of accident - fatigue cracks and further destruction of the cantilever supporting beam of rotary pouring stand.

The methodology of reliability, dominating in addressing issues of the effective operation of mechanical systems in metallurgy, does not fully meet the conditions of use of technological equipment. As it is known, the problem of the creation of technological equipment has two components: 1) maintenance and 2) to ensure the strength and service life. While the first component is not fulfilled, not enough attention is paid to the second one, solving it by material consumption. By the mid-20th century, basic circuits of steel machines, for which the problems of reliability became relevant, were worked out and became ty- pical. The post-war intensification of production has also contributed to it. The increased frequency and amplitude of the cyclic loadings, not taken into account in the calculations of strength in static setting, lead to premature failures.

Reliability methods were designed to envisage them. Their development is connected with the the rapid growth of electronics, which systems often failed. Reliability theory based on mathematical statistics, is focused on electronic engineering systems. In an aspect of this work theme it can be noted that the value of elements of these systems are generally of the same order as the damage caused by their failures. Therefore, finding the reliability of the whole system in terms of reliability of its separate elements can be without the use of «weight» ratios. But as a result the calculation reliability of the system consisting of a large number of elements is low compared to the actual one. And this is despite the use of various laws of generalization. Therefore it is necessary to test all the technical system, not its elements [15]. In any case, the reliability (and failure) function of a technical system, including failure of all sizes, turns too «fuzzy» (Fig. 6). The illusion of a low real safety, when after a relatively small operating time appears the probability of failure, causes: a) to bear additional costs for repairs even of suitable equipment; b) to ignore the forecast indicators of reliability and operate the facility till its failure.

With regard to the metallurgical equipment the conceptual approach to reliability as the probabilistic strength became widespread. It allows to find the distribution function of durabilities for the detail, opening up the possibilities of reducing their materials consumption in the design and individual prediction of residual life at the operation. But as the 50-years term of this concept popularity has shown, it did not receive a proper distribution in the metallurgy. In our opinion, this is due to the relative complexity and the complexity of use of probabilistic -physical methods for the reliable determination of the resource. At the same time the incentives to create the economical by material- and energy consumption, as well as economical by maintenance and repair equipment were reduced. Easier to use «hard» under the rules the system of scheduled-preventive repairs, grounded by mathematical and statistical methods. It is noteworthy that in metallurgy the greatest effect from the application of the criteria of reliability is felt when linking technological lines of metallurgical units.

For reliable assessment of the probability of failure-free operation of all technical system the representative sample of the results obtained for identical test conditions is needed. Mathematical and statistical methods of reliability are based on it. For unique, in most, metallurgical machines it is unrealistic to receive such a sample: large failures happen, but not often, and frequent small failures have little effect on safety. Processing the results as a Farmer diagram does not involve a large number of similar tests of the technical system (Fig. 6). The unit of risk-analysis is more susceptible to probabilistic-physical methods, because it allows to move to the indicators of the entire system by the summation of individual indicators of elements risks. Indicators of separate elements can relatively easy and inexpensive be obtained by their direct testings.

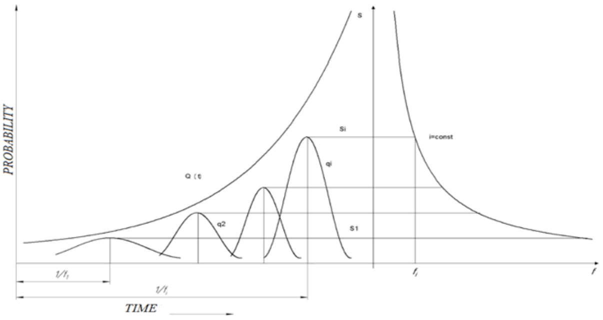

Figure 6. Formation of the failure probability function Q(t) of technical system for the distribution functions of durability of its elements (shown by densities q_i), as well as the formation of the Farmer curves by damage intensity S and failures periodicity $T_i=1/f_i$.

Conclusion

One organizational methods related to compliance with the rules of operation and safety, it is impossible to achieve a sufficient long-term presence of a technical system in a safe state. In addition to these methods the maintenance and repair system brought to the technology is needed. From an economic standpoint the equipment with a high potential for damage is expedient to serve in controlling the risk of its operation. The current safety index can be one of diagnostic parameters, when calculating the value of which is determined by taking into account various scenarios of failures.

At present the efforts of specialists-engineers are focused primarily on the assessment of the probability of failure-free operation as universal means to ensure the reliability, failure operation and safety. Very little attention is paid to the development of logical-probabilistic models - fault tree, accident scenarios for mechanical systems. But thanks to them it can be more objectively to evaluate the significance of initiating failure affecting the current risk and operation life.

In this regard, the noted above tendency of non-disclosure of data on accidents should be overcomed. Thanks to them, experts, in fact, get another result in the joint research of mechanical systems under operating conditions. Conducting such trials by forces of the same organization is contrary to the trends of modern science.

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