RISK AND INDUSTRIAL SAFETY

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Abstract

Developments in science, technologies, complexity of industrial infrastructure facilities sustaining life necessary systems are associated with an increased dangers of their functioning at all stages of the life cycle. These dangers are characterized by man-made risks that determine the likelihood of hazardous processes and damage from them. Industry-related risks together with natural and anthropogenic risks are integral risks. The tasks of ensuring safety are coming down to the achievement through calculations and experiments of an acceptable level of risks with the necessary estimated economic costs. Approbation of the described approach is carried out on the example of nuclear power plants.

Keywords: safety, risk, durability, accident, disaster, technosphere

I. Introduction

For centuries people, society, states and humankind in general have developed in rough conditions that were intertwined with dangers from natural, industry related and anthropogenic causes. At the same time problems of human life activities and their systems had to be resolved, factoring in endless increase with time τ of the risks spectrum R(τ). Risks spectrum included risk of large numbers *N* of casualties and loss of health $R_N(\tau)$, risk of damage and loss of number of industry related facilities $R_T(\tau)$ and risk for environment $R_S(\tau)$. In the context of the contemporary comprehensive safety S(τ) and risks R(τ) theory functional relation between integrated safety S(τ) and integral risks R(τ) and their components $R_N(\tau)$, $R_T(\tau)$ and $R_S(\tau)$ must be considered as generally accepted. Its analysis was carried out in a multivolume edition [1].

$$S(\tau) = F_S\left\{R(\tau)\right\} = F_S\left\{R_N(\tau), R_T(\tau), R_S(\tau)\right\} \tag{1}$$

In turn, the risks included in formula (1) for the analyzed time τ can be quantitatively assessed through the probabilities P(τ) of the occurrence of hazardous processes, phenomena and events and the accompanying degrees of damage U(τ) to humans, the natural environment and the technosphere

$$R(\tau) = F_R\left\{P(\tau), U(\tau)\right\} \approx P(\tau)\cdot U(\tau) \tag{2}$$

As the generalization of a large number of social hazards, natural disasters and man-made accidents shows that between P(τ) and U(τ) there is a power-law dependence

$$U(\tau) = C_u \cdot P(\tau)^{m_p} \tag{3}$$

Where C_u, m_p – hazard type parameters (m_p>1).

If time τ is measured in years, then values P(τ) evaluate through [1/year]. If U(τ) is put through ratio of N_n damaged or destroyed objects at a given time (year) to the total *N* of analyzed objects in a given territory, then U(τ) = N_n / N and then dimension R(τ) will be [1/year].

Tens and hundreds of thousands of people died in natural disasters (floods, tsunamis, earthquakes), in man-made disasters - up to 30 thousand people, in social upheavals (wars, military conflicts, pandemics) - millions and tens of millions of people.

For the social, natural and technogenic spheres, an assessment of economic damage is carried out, measured, for example, in [USD], then the dimension of risks R(τ) will be in [USD./year]. In this case, to determine the integral risks at the moment τ, it is possible to summarize the risks *R* in the expression (1)

$$R(\tau) = R_N(\tau) + R_T(\tau) + R_S(\tau) \quad (4)$$

Risks R(τ) in expressions (1) – (4) of the most dangerous processes and phenomena observed and analyzed over long intervals of time Δτ ($10^0 \le \Delta\tau \le 10^2$ years), could be considered as unacceptable (critical) $R_c(\tau)$. The tasks of modern risk theory, science and technology are pivoted to reduction of risks $R_c(\tau)$ to an acceptable level

$$R(\tau) \le \left[R(\tau)\right] = R_c(\tau) / n_R \quad (5)$$

where n_R – risk margin ($2 \le n_R \le 5$).

Then safety S(τ) can be quantitatively assessed by expression (1) and risk parameters in expression (5)

$$S(\tau) = \left[R(\tau)\right] - R(\tau) \quad (6)$$

Safety is considered secured if S(τ)≥0 and vice versa. If safety is not ensured for a facility at a given stage of the life cycle τ, then it is necessary to carry out comprehensive measures of a scientific, technological, supervisory, personnel nature with the costs $Z_R(\tau)$ of reducing risks R(τ) to an acceptable level [R(τ)]

$$Z_R(\tau) = \frac{1}{m_z}\left\{\left[R(\tau)\right] - R(\tau)\right\} \quad (7)$$

Where m_z - economic cost efficiency ratio ($1 \le m_z \le 10$).

II. Methodology for the analysis of industrial safety by risk criteria

For the modern technosphere of life sustenance, which is one of the most changing in comparison with the natural and social components, over the past decades of the XX – XXI centuries, was carried out [1, 2] a statistical analysis of the parameters P(τ) and U(τ) of man-made failures, accidents and severe disasters at facilities of various potential hazards in the civil and defense complexes of Russia and other countries was carried out [1, 2] (Fig. 1).

The analyzed facilities and industrial sectors included:

- energy: large nuclear – 1 and hydraulic – 2 power plants, liquefied gas factories – 3, trunk pipelines – 4
- defense facilities: rocket and space complex – 5, nuclear submarines – 6;
- transport complex: railway and aviation – 7
- petrochemical complex – 8;
- unique buildings and structures – 9;
- offshore development facilities: offshore platforms – 10.

Shown in fig. 1, the data refer to industry related accidents and disasters associated with the dangerous manifestation of anthropogenic (*N*), natural (*S*) and man-made (*T*) factors that create risks R(τ) according to expression (4).

Based on the results of the analysis, taking into account the damage U(τ), a classification (1 – 7 classes) of accidents and catastrophes was carried out: 1 – areal for the elements of the facility, 2 – on site with damage to the facility; 3 – local with damage to the industrial site; 4 – regional with municipal damages; 5 – national with damage to the country; 6 – global with damages for neighboring countries; 7 – planetary with damage to continents or the planet as a whole.

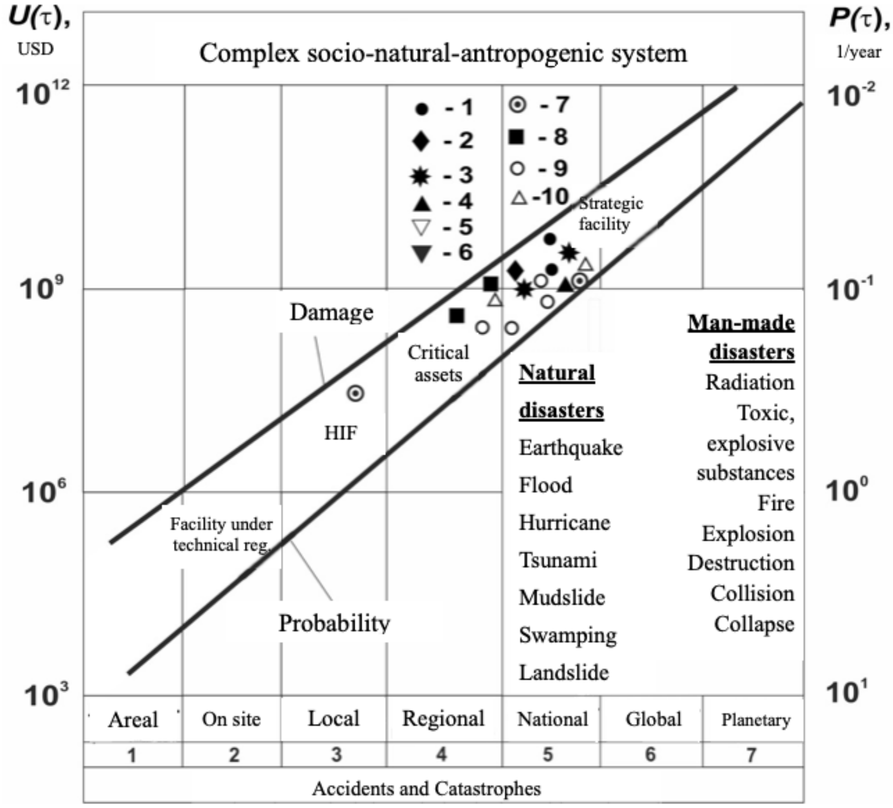

Figure 1: *Schematic diagram for determining risk parameters, classifying hazardous situations and categorizing facilities*

Taking into account U(τ) and P(τ) industrial facilities were categorized by risk levels: facilities under technical regulation - mass or large-scale facilities with *N* up to$10^6 \div 10^7$; hazardous industrial facilities (HIF) – serial facilities with *N* up to $5 \cdot 10^4 \div 10^5$; critical assets with *N* up to 10^3-$5 \cdot 10^3$; strategic facilities with *N* up to $10^2 \div 5 \cdot 10^2$. The corresponding dots in Fig. 1 shows data for critical assets and strategic facilities.

Using expression (2) and values P(τ) and U(τ), according to the scales in Fig. 1, it is possible to determine the critical industry-related risks $R_c(\tau)$ included in expression (5). Justifying and assigning the values of margins n_R, according to this expression, it is possible to establish acceptable economic risks [R(τ)] for the analyzed facilities. Having determined the state of facilities through the methods of technical diagnostics and monitoring, according to (2) it is possible to assess the formed risks R(τ). This makes it possible to assess industrial safety S(τ) according to (1) and (6) and the necessary costs $Z_R(\tau)$ for its achievement according to (7).

III. Analysis results

Of key importance for the substantiation of industrial safety S(τ) according to (1) and (6) is the computational and experimental determination of the risks R(τ) of hazardous and safe states of the analyzed facility for a given stage of its life cycle. This definition is linked to the solution of criterion issues of strength, resource, reliability and integrity of critical elements of the object at the most dangerous points in the most dangerous situations – design, beyond design and hypothetical [1 – 3]. In this case, one can proceed from the assumption that accidents and disasters are ultimately caused by damage and destruction of critical elements of the facility.

Damage and destruction according to the above criteria are assessed taking into account:

- spectrum of hazardous impacts Q(τ), consisting of operational technological $Q_T(\tau)$, natural $Q_S(\tau)$ and anthropogenic $Q_N(\tau)$ impacts;
- emerging reactions of load-bearing elements to these impacts, expressed in terms of maximum stress $\sigma_{max}(\tau)$ and deformation $e_{max}(\tau)$ at critical points;
- resistance to damage and destruction, expressed through the critical values of stresses σ_k and strains e_k, depending on temperatures t^S, time τ^s, environment *s*, number of cycles N^s, formation and development of cracks ℓ^s. When destroyed, these figures reach critical values. For this purpose, based on the results of calculations and experiments, three-dimensional surfaces of limiting and permissible states are constructed (Fig. 2):
- by the initial damage with the formation of cracks ℓ_0;
- by the final failure with the formation of critical cracks ℓ_c;
- according to the current state at the moment τ at *n*(τ) and *t*(τ) with a crack ℓ.

These states comply with the corresponding loads Q(τ), stresses σ_{max}, σ_o, σ_c, deformations e_{max}, e_o, e_c, characterized by the position of point *A*(τ) in three-dimensional space with coordinates ℓ(τ), { $\sigma_{max}(\tau)$, $e_{max}(\tau)$}, {τ, *n*(τ), *t*(τ)}.

For this point, using an expression similar to (5), one can determine the position of the surface of admissible states

$$\{[\sigma],[e]\} = \left\{\frac{\sigma_c}{n_\sigma}, \frac{e_c}{n_e}\right\};\ [e] = \frac{\ell_c}{n_\ell};\ \{[\tau],[N],[t]\} = \left\{\frac{\tau_c}{n_\tau}, \frac{n_c}{n_N}, \frac{t_c}{n_t}\right\} \quad (8)$$

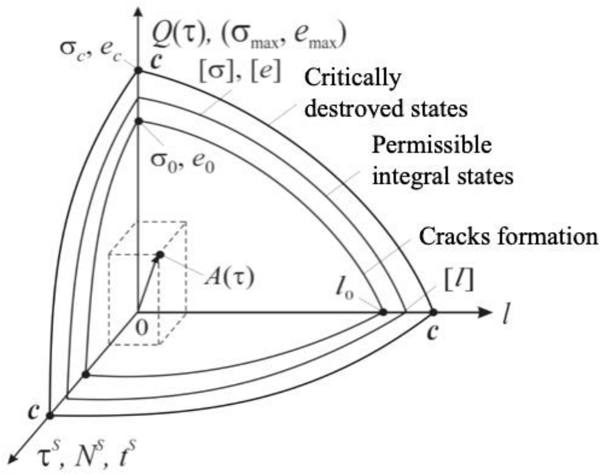

Figure 2: *3D surfaces of the load-bearing elements' states*

All parameters of operational influences Q(τ), reactions to them {$\sigma_{max}(\tau)$, $e_{max}(\tau)$}, levels of defectiveness ℓ and operational loading {τ^s, N^s, t^s}, as well as critical values {σ_c, e_c } , ℓ_c, {τ^s, N^s, t^s} are stochastic, which determines the probabilistic nature of the surfaces of limiting and permissible states according to Fig. 2.

The probabilistic position of point *A*(τ) relative to the zero point "0" determines the probabilistic vector «0-*A*(τ)» characterizing *P*(τ) in expression (2). If this vector does not go beyond the surface of permissible states, then, taking into account (8), the integrity of the facility and its technogenic safety *S*(τ) according to (6) are ensured and vice versa.

In the latter case, it is necessary to carry out measures to fulfill conditions (5), (6) with economic costs according to (7).

IV. Debate

The above methodology was tested for nuclear power plants with pressurized water reactors [1 – 5] with a capacity of 1000 MW.

Fig. 3 shows the relation between the probability $P(\tau)$ and damage $U(\tau)$ for critical $P_c(\tau)$ and $U_c(\tau)$ and admissible $[P(\tau)]$ and $[U(\tau)]$ states.

In this case, we used data on real disasters and accidents at nuclear power plants (see Fig. 1, points 1), as well as on current damage to steam generators and turbine generators. Considering the extremely high danger of nuclear disasters belonging to classes 4 – 5 in Fig. 1, the margin in expression (5) was taken to be increased ($n_R \geq 10$).

Achievement of negligible risks at the stage of cracking ℓ_0 according to Fig. 2 is practically impossible (complex equipment of nuclear power plants has non-zero initial technological defects $\ell_0 \neq 0$).

For severe disasters at nuclear power plants (such as Three Mile Island, USA; Chernobyl, USSR; Fukushima-1, Japan), social and environmental damages can significantly (by 1 – 2 orders of magnitude) exceed the direct ones indicated in Fig. 3. This leads to a large necessary additional calculated costs $Z_R(\tau)$ according to expression (7) to reduce risks $R(\tau)$ to an acceptable level $[R(\tau)]$. According to Fig. 2 and 3, they turn out to be in the range of $(5 \div 10) \cdot 10^6$ USD/year for one nuclear power plant.

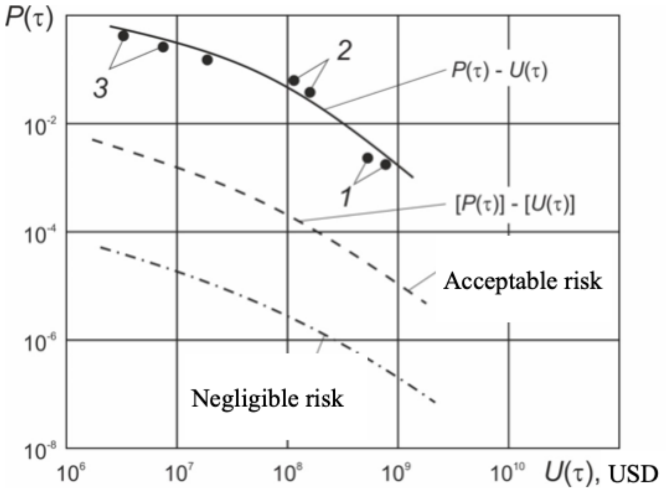

Figure 3: *Probabilities and direct man-made damages from accidents and disasters at nuclear power facilities: NPP – 1, steam generators – 2, turbine generators – 3*

The implementation of the outlined risk-oriented approach requires a phased realization of fundamental research and applied developments in mathematics, mechanics, physics, chemistry, biology, sociology, economics, ecology of crises, accidents and disasters in a scientific interconnected system that includes technogenic, natural and social spheres with their own risks.

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