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# Methods of quantitative estimation and reduction of uncertainty of the accidental risk in fire explosive facilities

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**Abstract.** *Currently, ensuring the industrial safety of hazardous industrial facilities involves – along with conventional oversight – the risk-oriented approach that is significantly more flexible. The procedure of quantitative estimation of an accidental risk for hazardous industrial facilities is essentially one of the procedures of conformity assessment, as it includes the comparison of the risk indicators obtained by means of calculation (or expert assessment) with their standard values. The* **Aim** *of the paper is to define the problem of uncertainty that is associated with all the stages of quantitative estimation of an accidental risk, make a brief historical account, analyze its types and sources, describe the approaches employed as part of quantitative estimation of this uncertainty. Currently, it is accepted to identify the terminological, parametric and model types of uncertainty, whose examples are provided in the paper. Analysis shows that a fourth – computational – type should be added, whose contribution in many cases may be considerable. It is shown that, due to a number of circumstances, scalar numbers that are normally used for defining parameter values of the physical-mathematical models of failure processes are in reality mere indicators of the ranges of their value variation. Currently, uncertainties in the values of accidental risk parameters are accounted for using probabilistic and deterministic approaches, as well as fuzzy numbers.* **Methods.** *For the purpose of quantitative estimation of uncertainty, the paper employs the method of interval analysis. In the most general case, without using the hypothesis on the behaviour of a parameter value within the range of its possible variation, the parametric uncertainty can be defined with an interval number. In that case, all the required calculations are performed using interval methods. The natural (naive) version of interval analysis has a serious drawback that consists in an unjustified increase of the width of the interval number deduced by means of interval calculations, if one or more input parameters of the model enter into the calculation formula more than once, or the input parameters are functionally interdependent. Modern interval analysis employs methods allowing to alleviate this effect. They are briefly described in this paper. It is shown that if statistical information is available on the behaviour of parameter values within their variation intervals, the results of interval calculations of the accidental risk indicators can be significantly improved. The suggested method of reducing the computational uncertainty of quantitative estimation of the accidental risk in the interval setting is illustrated with a numerical example of risk indicator calculation for the "fireball" accident scenario. The paper sets forth the results of interval calculation of an individual accidental risk for an explosion and fire hazardous facility "reservoir with a flammable liquid" in three ways: a) naive; b) accounting for the effect of parameter correlation; c) additionally, accounting for available statistical information.* **Conclusions.** *Interval methods allow not only taking into consideration the presence of uncertainty in the accidental risk parameters, but evaluating it quantitatively. There are efficient methods of alleviating the negative*

**Keywords:** *industrial safety, accidental risk, parametric uncertainty, interval methods of calculation, minimization of computational uncertainty.*

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## Introduction

Large-scale transportation of hazardous substances, including flammable ones, in hazardous industrial facilities (HIF) is fraught with uncontrolled emissions and leaks that may cause explosions and fires, toxic damage to people and pollution of large territories. Explosions may also occur within industrial equipment, if the process parameters exceed the safe limits.

Over the last two decades in Russia, along with the conventional, supervisory approach to industrial safety, an alternative method has been used that is based on the analysis and quantitative estimation of an accidental risk (QER). The risk-oriented approach is much more flexible, innovation-friendly as compared to the conventional method. It does not restrict specific engineering solutions. Instead of regulating many parameters of the design and process, it only requires a number of target indicators (individual, social risk of an accident) to be within the standard values [1].

The procedure of HIF QER is essentially one of the procedures of conformity assessment, as it includes the comparison of the risk indicators obtained by means of calculation (or expert assessment) with their standard values.

The QER methodology originated and developed almost simultaneously in the Old (in the chemical industry) and New World (in the nuclear industry and astronautics). As early as at the first stage of the application of the risk analysis methodology it became apparent that many parameters of the problem (e.g. the properties of a hazardous facility and its environment) in reality vary, change within certain ranges. In order to take such variations into account, initially the quantitative estimations of risk were performed according to the most conservative scenario, whereas the quantity of a hazardous substance involved in an accident is the highest, the weather conditions and location of the target facilities within the affected area are the least favourable.

However, with time, the conservative approach was abandoned, as the probability of a simultaneous combination of all marginal conditions is too low. As an alternative, it was suggested to use "average" parameter values for accident risk assessment. In our opinion, this approach is also unsatisfactory, because it: a) creates a dangerous illusion of "accurate" assessment of the risk indicators; b) does not allow evaluating the actual range an indicator value varies (or may be) within. Such changes of a parameter value are conventionally called and quantitatively estimated with its uncertainty (parametric).

## Types of uncertainty of the results of quantitative risk assessment

Uncertainty is associated with all stages of the QER procedure, just like any mathematic simulation. The causes, part objective, part subjective, are analyzed in [2]. For the purpose of quantitative estimation of uncertainty (QEU) of accidental risk and adoption of measures for its reduction, it is important to classify the uncertainty by origin. Conventionally, the terminological, parametric and model types of uncertainty are distinguished. To that should be added the computational uncertainty caused by the specificity of the computational methods used in the course of simulation.

The *terminological uncertainty* is due not only to the ambiguous definitions of the used terms and concepts in the QER guidelines, but also their different interpretation by experts. The latter is due to the differences in the mindsets of the people, their basic education, standards and stereotypes of the professional environment. It should be noted that the terminological uncertainties (ambiguous interpretation of a term, concept, parameter), along with the obvious qualitative, has a clear quantitative aspect. That can be seen using the example of the parameter "length of flame" $L$ (pool fire, flare). Most QER guidelines do not provide a clear and unambiguous interpretation of this parameter, which is fraught with serious differences:

a) $L$, average height (length) of the flame, m [3];

b) $L_f$, length of truncated cone (flare), m [3];

c) $L$, visible length of flame, m [4].

Meanwhile, the meaning of this parameter is not as obvious as it seems. The situation is similar to the case with the parameter of "fireball diameter" $D_F$. The matter is that the concepts of "visible" length of flame ("visible" ball diameter) and the concept of "size of the area efficiently radiating heat" should be distinguished. According to CPR-14E [3], in case of pool fire, the value $L$ defined using those two methods may differ up to three times! Only the AIChE CCPS Guidelines [4] clearly define the average length of the flame. Meanwhile, this parameter affects the magnitude of the adverse factors of an accident, i.e. the rate of the heat flow against the target facility $I$, kW/m$^2$.

The *parametric uncertainty* means that the parameter value of a model (problem) cannot be assigned a precise (point-wise, scalar) value. That is due to the fact that the parameter value:

a) either objectively varies, like the air temperature and windspeed (if the HIF is situated in the open), or the quantity of the hazardous substance inside a piece of equipment at the moment of accident, etc. that are not exactly known;

b) or is adopted as the result of measurements that are inevitably associated with measurement uncertainty;

c) or is quoted in reference literature in the form of an interval;

d) or, due to the scarcity of available information, was adopted by means of expert methods, etc.

The parametric uncertainty due to the first two circumstances is called aleatoric; its nature is objective. By contrast, uncertainty caused by c) and d) is subjective; it is called epistemic. Objective uncertainty cannot be eliminated in principles, while epistemic uncertainty can be reduced, and that should be done, when possible.

*Model uncertainty* occurs in the course of QER (but not only), if used for describing the nature of any physical-mathematical, mathematical, simulation and other models. It is obvious that, as any model simplifies, coarsens the simulated object or process, it has a limited applicability, because the simulation results will always differ from the reality. That is a fact simply because, within the scientific paradigm, experience is chosen as the main criterion of a theory's validity, while due to the presence of measurement uncertainty (error, as it used to be called) the calculation data obtained through the most advanced model will never exactly match the experimental data. Currently, HIF QER uses several alternative models that describe the progress of accident scenarios, development of the adverse factors of an accident, probability of damage to target facilities. It suffices to name at least the models recommended in [3–6], although the authoritative three-volume monograph [7] features dozens of such models. It was many times demonstrated that the variation in the results of quantitative estimation of risk obtained using various models may be as high as three or more orders of magnitude.

There are at least two methods of minimizing the model uncertainty while performing QER:

1) conventional for the USSR and now Russia, under which a certain model is adopted as reference and assigned as normative, the only allowed while performing QER;

2) development of the most adequate model, experimentally verified with a clearly defined application.

The existence of *computational uncertainty* is due to the approximate methods of solving model equations. Analytic solutions of model equations are now an exotic thing. Solutions are obtained using modern application software. However, even if all model parameters are set accurately, the use of floating-point numbers in the computer code, inevitably implying rounding, truncation of terms of series, interruption of the iterative computational process, etc., cause the uncertainty of approximate calculations. Another source of computational uncertainty that is due to the specificity of interval calculations will be examined below.

Conventional mathematic simulation operates on pointwise, scalar parameter values (both input and of model parameters). The calculation results are also normally represented in the form of a scalar number. Given the above circumstances, the result of mathematic simulation is always an interval. Naturally, the HIF QER procedure as part of the risk-oriented approach is not an exception. However, it is obvious that such scalar values of risk indicators are in reality just markers of the intervals, within which their value can vary in reality.

## Interval presentation of the parametric uncertainty

The active Guidelines for the quantitative estimation of the risk of accident in HIF [8] recommend assessing the uncertainty of the obtained risk indicators, yet do not indicate how to do that. Meanwhile, as it is known, there are a number of methods of solving the problem: a) using fuzzy numbers; b) in the probabilistic setting; c) using interval numbers.

In our opinion, the latter appears to be the most universal, as it does not require hypothesizing about the behaviour of a parameter value within the variation range [2], which is required for both the probabilistic description of uncertainty, and the use of fuzzy numbers. It should be understood that the probabilistic description of a value means it has the probability distribution function (in the differential or interval form). The latter is only possible if there is an entire assembly of objects of the given type, a statistical stability, when any sample parameters tend to the theoretical probabilistic values in case of infinite increase of the sample size.

In respect to real HIF, identifying sets of elements that could be made an entire assembly is unlikely. Manufactured by different companies, having different histories of load and maintenance, even such simple elements as a latch, in practice have significantly varied properties. Therefore, for instance, the hypothesis of normal distribution of strength with specified average and standard deviation, requires serious substantiation.

It is much more reliable to specify the same value with an interval number (interval). The latter will mean that the parameter value is within the specified limits. No assertions are made regarding its distribution within the range.

Defining parameter values of mathematical models with intervals complies with their nature, given the uncertainty. Today, interval analysis (the branch of mathematics that operates on interval numbers) is widely used and allows performing all calculations required for QER and deducing risk indicators in interval form.

A vast majority of mathematical models used in the active Guidelines for quantitative estimation of accidental risk are analytical (parametric). Therefore, calculating risk indicators implies finding the range of values of the objective function, or external assessment of the range of values in the interval setting.

Performing QER in the interval setting perfectly fits the purpose of QEU, as the width of the obtained interval numbers constitutes a direct quantitative estimation of their uncertainty. In practice, the situation is simplified by the fact that at this point there are commercially available special software products that support interval calculations. One of such programs is INTLAB toolbox developed by Professor S.M. Rump of the Institute for Reliable Computing, Hamburg University of Technology. INTLAB is an interval application of MATLAB that allows performing calculations with interval numbers.

Another obvious advantage of the interval expression of parametric uncertainty is the capability to simultaneously account for uncertainties of various types:

a) measurement, conventionally expressed as the average ± measurement uncertainty (± measurement error, as it used to be called);

b) epistemic, expressed in the form of intervals;

c) stochastic (if there is a probability distribution function) defined by a confidence interval.

## Negative characteristics of the interval methods and ways of their minimization

As it is known from experience, if risk indicators are calculated using natural (previously known as naive) interval methods, without taking special measures in order to reduce the calculation uncertainty, the result may constitute interval values of very significant width, which deprives the operation of any practical value.

Let us note that over the last few decades Russian and foreign experts have been actively furthering interval analysis (see, for instance, [9–11]). It has been shown that it helps solve some complex mathematical problems better that by using classical mathematical methods. Problems inherent to interval analysis alone have been identified and researched:

a) disproportionate widening of calculation results in cases when the parameters of the calculation expression enter into it more than once;

b) similar widening of the result in a situation when such parameters are associated with a functional relationship.

For the purpose of minimizing the above negative effects, several methods have been developed: Ramon Moore's interval splitting, branch-and-bound, global optimization, etc.

## Method of reducing uncertainty of the target risk metrics in the interval setting using information on the distribution of parameter values

In a situation when reliable, statistically stable information is available on the distribution of parameter values within the variation intervals, the uncertainty of the risk metrics can be significantly reduced. That can be done following on from the standard method of the EMERCOM of Russia [6], according to which the magnitude of the individual risk $R$, year$^{-1}$ for an employee within the facility is identified according to formula

$$R = \sum_{i=1}^{I} q_{im} P(i), \quad (1)$$

where $P(i)$ is the magnitude of the potential risk in the $i$-th area of the facility's territory, year$^{-1}$;

$q_{im}$ is the probability of the employee's presence in the $i$-th area of the facility's territory.

We will apply this idea not only to the location of personnel within a HIF's territory, but other parameters of the problem as well. Let us assume that the considered HIF has reliable statistical data, according to which:

1) $P_1$ of the time (unit fractions) personnel are at the distance $X_1$ away from the center of the considered production unit (PU), while the remaining time $P_2$ they are at the distance $X_2$;

2) the mass $m_0$ of hazardous substance in the PU, kg: a) during $P_m01$ of the time (unit fractions) $m_{01} \in \left[ \underline{m_{01}}; \overline{m_{01}} \right]$; b) $P_m02$ of the time $m_{02} \in \left[ \underline{m_{02}}; \overline{m_{02}} \right]$ and c) $P_m03$ of the time $m_{03} \in \left[ \underline{m_{03}}; \overline{m_{03}} \right]$;

3) based on the available meteorological information, the discrete density of the distribution probability of free air can be recovered, which can be illustrated with a specific example. According to SP 131.13330.2012 [12], the average monthly free air temperature $t_a$ in the area of a certain HIF, °C is: I, -12.1; II, -11.4; III, -4.6; IV, -4.7; V, 12.0; VI, 16.5; VII, 18.6; VIII, 16.1; IX, 10.3; X, 3.4; XI, -3.7; XII, -9.4. By introducing the designation $T_a = t_a + 273.15$, K, we have $T_a \in [261.05; 291.75]$ K. By rounding-off external interval boundaries to whole numbers, we will obtain $T_a \in [261; 292]$ K.

Let us use MATLAB to approximate the yearly variation of the temperature [13] with a sixth-degree polynomial and present the results in Fig. 1.

Then, let us split the temperature range $T_a$ into 31 subintervals with the width of 1 K and calculate the frequencies $n_j$ of the temperature being within such intervals ($j$ = 1, 2, … 31). As a discrete valuation of the probability $P_{Tj}$ of temperature distribution within the range [261; 292] K let us adopt the values $P_{Tj} = n_j/31$ (it is obvious that the normalization requirement $\sum_{j=1}^{31} P_{Tj} = 1$ is met).

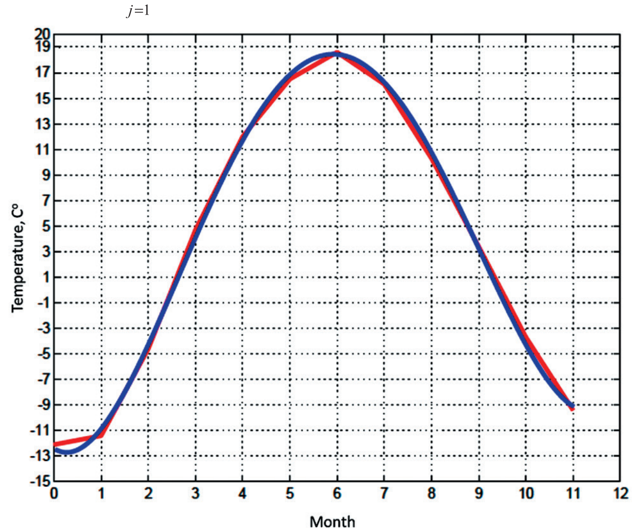


Fig. 1. Annual variation of free air temperature:
— per SP 131.13330.2012;
— polynomial approximation

Further, let us calculate the target risk metrics (e.g., individual risk $R_{ijk}$) for all combinations of parameter subintervals ($i$ = 1, 2, distance between the personnel and the epicenter of the accident at the moment of its occurrence; $j$ = 1, 2, … 31, free air temperature; $k$ = 1, 2, 3, quantity of the hazardous substance in the PU).

The considered parameters $X_i$, $T_j$ and $m_{0k}$ as independent random values, target metric (individual risk $R_{ind}$) of the examined production unit using formula

$$R_{ind} = \sum_{i=1}^{2} \sum_{j=1}^{31} \sum_{k=1}^{3} R_{ijk} P_{Xi} P_{Tj} P_{m_{0k}}. \quad (2)$$

The calculation of individual accidental risk performed using this method and INTLAB has shown that the suggested technique allows significantly reducing its uncertainty (interval width).

## Example of individual accidental risk estimation using the suggested method for the fireball scenario

Let us examine another example of application of the suggested method. As it is known, one of the scenarios of accidents affecting reservoirs containing a flammable substance in liquid, is the BLEVE-type explosion. Such scenario, as accident statistics show (see, for instance, [14]), may occur in situations, when a spherical or horizontal cylindrical reservoir with a flammable substance (LHCG, HIL) is within the body of fire. If the heat inflow from the outside is so high, that the vapour jets outflowing though the open valves of the reservoir are unable to prevent the pressure buildup in its steam space, at some point in time the shell of the reservoir will rupture. A cloud of overrich mixture will be released into the environment that will immediately catch fire on the outside and start floating up in the atmosphere releasing a powerful heat flow. Phenomenologically, a "fireball" (FB) is a glowing cloud of a varying shape, whose temperature and emission power are constant both in time, and in terms of the surface area. However, in the engineering practice, FB are normally imitated with a glowing sphere, that has a constant surface radiant heat intensity and floats up in the atmosphere under the action of the force of buoyancy.

As the target indicator of the risk of such accident scenario, let us consider the individual accidental risk, the probability of lethal injury to personnel by downward heat flow. The AIChE CCPS QER Guidelines [4] suggest calculating FB parameters (diameter $D_{FB}$, height of the center $H_{FB}$ and glow duration $t_{FB}$) using empirical dependences that are power relations: $D_{FB} = 5.8 \cdot m_0^{1/3}$; $H_{FB} = 0.75 \cdot D_{FB}$, where $m_0$ is the initial mass of the flammable substance in the reservoir, kg. The FB model has an interesting feature [4]. In it, the calculation formula for the parameter $t_{FB}$ depends on the value of $m_0$:

a) if $m_0 < 30\,000$ kg $t_{FB} = 0.45 m_0^{0.33}$, (3)

b) if $m_0 < 30\,000$ kg $t_{FB} = 2.6 m_0^{0.166}$. (4)

For the radiant emittance $E_f$, the FB caused by BLEVE, in the opinion of AIChE CCPS, the $E_f \in [200; 350]$ kW/m$^2$ is typical.

In the FB approximation with a point emitter, the heat flow $I$, kW/m$^2$ hitting the target facility, can, according to [4], be calculated as follows:

$$I = E_f \tau_a \left( R_{FB} - \frac{D_{FB}}{2} \right) F_q, \quad (5)$$

where $R_{FB}$ is the distance from the center of the FB to the target facility, m;

$\tau_a(X)$ is the transparence of the free air to the infrared flux;

$F_q$ is the geometric visibility factor for a vertical surface (e.g., a standing person).

As the atmospheric absorption of the thermal emission is primarily ensured by vapour molecules, the AIChE CCPS recommends estimating $\tau_a$ with the help of the Pietersen and Huerta correlation

$$\tau_a(X) = 2,02 \left( P_W X \right)^{-0,09}, \quad (6)$$

where $P_W$ is the partial pressure of vapour, PA;

$X$ is the distance travelled by the beam, m.

For the purpose of calculating $P_W$ under known relative humidity $R_H$, % and air temperature $T_a$, K, Mudan and Croce suggested a simple correlation that is true in respect to the range $10^4 < P_W \cdot X < 10^5$ H/m:

$$P_W = 1013,25 R_H \exp\left( 14,4114 - \frac{5328}{T_в} \right). \quad (7)$$

Let us specify the relative air humidity in the area of the HIF with the interval $R_H \in [50, 85]$ %.

According to [4], for distances $X$ that exceed the FB radius, $F_q$ is calculated according to formula

$$F_q = \frac{X \left( \frac{D_{FB}}{2} \right)^2}{\left( X^2 + H_{FB}^2 \right)^{3/2}}, \quad (8)$$

that, subject to the formula $H_{FB} = 0.75\ D_{FB}$ is easily modified into:

$$F_q = \frac{4\beta_X}{9\left( 1 + \beta_X^2 \right)^{3/2}}, \quad (9)$$

where $\beta_X = \frac{X}{H_{FB}}$ – is a dimensionless distance.

The probability of human injury caused by thermal radiation $P_{inj}$ in the course of QER is evaluated using the so-called probit-function Pr. This approach, first suggested by Finney, is suitable for describing the facility's response to the effect of any factor of accidental nature, if this effect is normally distributed [4]. The dependence $P_{inj}(\mathrm{Pr})$ can be expressed with a standard error function:

$$P_{inj}(\mathrm{Pr}) = 0,5\left[ 1 + erf\left( \frac{\mathrm{Pr} - 5}{\sqrt{2}} \right) \right]. \quad (10)$$

Guidelines [4] recommend calculating the function Pr of lethal human injury caused by heat flow using formula:

$$\mathrm{Pr} = -14,9 + 2,56 \cdot \ln\left( \frac{t_{\exp} \cdot I^{4/3}}{10^4} \right), \quad (11)$$

where $t_{\exp}$ is the duration of exposure, s (in case of FB $t_{\exp} = t_{FB}$);

$I$ is the intensity of the FB heat flow affecting a person, W/m$^2$.

It is obvious that, if the density of the incident heat flow I is expressed in kW/m$^2$,

$$\mathrm{Pr} = -14,9 + 2,56 \cdot \ln\left( t_{\exp} \cdot I^{4/3} \right), \quad (12)$$

**Table. Results of individual accidental risk estimation in interval setting by three methods**

| Parameter value | Interval estimation method | | |
|---|---|---|---|
| | "Naive" | accounting for the effect of parameter correlation | additionally, accounting for available statistical information |
| Value of individual accidental risk, year$^{-1}$ | $[0.0; 0.56]\times10^{-4}$ | $[0.0001; 0.54]\times10^{-4}$ | $[0.0034; 0.4]\times10^{-4}$ |

Let us evaluate in the interval setting the individual accidental risk of injury to personnel of a certain conventional HIF caused by FB heat flow:

$$R_{inj} = P_{inj} \cdot P_{av}, \qquad (13)$$

where $P_{av}$ is the probability of realization of this accident scenario, year$^{-1}$.

Let us assume that in the present case FB appears after the explosion of an RGS-100 (steel horizontal reservoir) situated in its territory and containing isopropyl alcohol that was affected by fire. Let the probability $P_{av}$ be evaluated with the value $P_{av} \in [3.8; 5.7]\times10^{-5}$ year$^{-1}$.

Let us further assume that:

- according to reliable statistical data:

a) HIF personnel within the lethal area of the accident: 1) during 25% of the time ($P_x1 = 0.25$) is at the distance of $X_1 \in [70; 80]$ m from the reservoir, while during the remaining time ($P_x2 = 0.75$) they are at the distance of $X_2 \in [80; 100]$ m;

b) mass $m_0$ of isopropyl alcohol in the reservoir: a) during 20% of the time ($P_m01 = 0.2$) $m_{01} \in [30\,000; 40\,000]$ kg; b) during 50% of the time ($P_m02 = 0.5$) $m_{02} \in [40\,000; 50\,000]$ kg, and c) during 30% of the time ($P_m03 = 0{,}3$) $m_{03} \in [50\,000; 60\,000]$ kg;

- the average monthly free air temperature in the HIF area is the same as the values cited in the previous section.

We will perform interval calculation of the individual accidental risk $R_{ind}$ of the considered accident scenario for HIF personnel using INTLAB by three methods: a) naive; b) with alleviation of the parameter correlation of the model using the simplest Moore method; c) accounting for available statistical information (by formula (2). Let us present the findings in the summary table.

An analysis of the table shows that the suggested methods allow significantly improving the results of interval calculations (narrowing the intervals) by reducing the computational uncertainty.

Along with those described in this paper, there are other methods (affine arithmetic, global optimization) that allow efficiently mitigating unjustified widening of the interval calculation results.

## Conclusion

Interval methods of accidental risk calculation allow not only taking into consideration the uncertainty inherent to the problem's parameters, but use it, which provides for quantitative evaluation of the problem's target indicators. As the result of calculations in the interval setting, the risk indicators are also presented in intervals, which is perfectly natural and adequate in the context of emergency safety of hazardous technical facilities.

At the same time, calculation in the natural (naive) version of interval analysis due to its specificity can be associated with significant disproportional growth of the width of the calculation result interval. As of today, there are efficient methods of finding the ranges of values of interval-valued functions enabling results free of parasite widenings.

The paper presents the results of interval calculations of the individual accidental risk of one of the simple emergency scenarios in three ways: a) the natural method; b) with reduction of the cohesiveness of model parameters; c) with the use of the available reliable information on the behaviour of a number of the problem's parameters within their intervals. It is shown that the second and, specificity, the third methods allow significantly reducing the width of the interval of the target accidental risk value.

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## The author's contribution

Kolesnikov E.Yu. is the sole author of the paper. Its idea belongs to the author, all calculations were performed by the author without anyone else's involvement.

## Conflict of interests

The author declares the absence of a conflict of interests.