Research paper

# Condetions of fire and explosion safety at a determination of operation parameters of industrial facilities

Yury Shebeko* and Aleksey Shebeko*†

*All Russian Scientific Research Institute for Fire Protection
VNIIPO 12, Balashikha-3, Moscow Region, 143903, RUSSIA
TEL : +7-495-524-82-09
† Corresponding address : ay_shebeko@mail.ru

Received : December 27, 2010 Accepted : February 22, 2011

## Abstract

Conditions of fire and explosion safety at a determination of permissible parameters for an operation of industrial facilities are considered. Relationships were obtained which describe a dependence of safe values of the parameters at an established probability of an occurrence of an unfavorable event (that is hazardous event with fire or explosion characterizing by an inadmissible risk level). The proposed method was tested on the basis of calculations of a probability of a successful evacuation from buildings and constructions in the case of a fire and safety coefficients to fire and explosion hazard indexes of substances and materials.

***Keywords*** : conditions of fire and explosion safety, permissible parameters for an operation of industrial facilities, fire risk, evacuation, safety coefficients.

## Introduction

A correct determination of permissible parameters for a safe operation (or safety conditions) of industrial facilities is one of the most important problem of fire and explosion safety insuring of industrial plants. Because an absolute safety hardly can be ever reached, the safety parameters are usually determined for a given trust probability (that is the probability that the unfavorable event will not occur). For example, the following events can be considered as unfavorable one : an exceeding by an equivalent fire duration the values of fire resistance limits of structures, an exceeding by the estimated evacuation time of people in the case of fire (estimated evacuation time) the value of a time to the critical event (blocking of evacuation ways) determined by a fire dynamics, an exceeding by the liquid temperature its flash point etc. The mentioned above parameters have a probabilistic nature, and it is convenient to speak on the trust probability that the unfavorable event will not occur.

This approach was realized in some scientific works and normative documents on fire safety[1)-6)]. The so called safety coefficients to the parameters of the industrial facility are often used for a description of safety conditions. The safety coefficient to the fire and explosion indexes of substances and materials (flammability limits, flash points, minimum inertization concentrations etc.)[1),2)], the fire resistance limits (the so called fire resistance coefficient)[3)-5)], the time to the critical event[6)] etc. are used in this case. Usually the safety coefficient are calculated taking into account the trust probability[1)-5)], but in some cases these coefficients are determined by expert estimations (for example, the safety coefficient 0.8 to the values of the time to the critical event and autoignition temperature[6)]). An application of such fixed safety coefficient without taking into account the trust probability can cause some difficulties. We can illustrate this idea by the following example.

According to[5),6)] if a sum of the estimated evacuation time $t_s$ (that is the time duration required for a people evacuation to a safe place) and the time interval till a beginning of the evacuation $\tau_n$ exceeds the time to the critical event $t_n$ (that is the time duration when evacuation must have completed, which is determined by hazardous factors of a fire), the conditional probability of the successful evacuation $P_{ev}$ is accepted to be equal to 0.999. At the same time a relationship between the values $t_n$, $\tau_n$ and $t_s$ is taking into account on a very simplified manner. The value $P_{ev}$ is calculated by a formula[6]:

$$P_{ev} = \begin{cases} (t_n - t_s)/\tau_n, & \text{if } t_s < t_n < t_s + \tau_n \\ 0.999, & \text{if } t_s + \tau_n < t_n \\ 0, & \text{if } t_s > t_n. \end{cases} \quad (1)$$

According to this formula $P_{ev}$=0.999, if $t_s + \tau_n \leq t_n$, irrespective of the case, when the values $t_s + \tau_n$ and $t_n$ differ on 1% or ten times. This fact can cause an underestimation or an overestimation the fire risk value.

Therefore this study is aimed on an investigation of a correct determination of fire safety conditions for industrial facilities.

## Theory

Usually the safety condition can be expressed as a relationship between two parameters $x_1$ and $x_2$ (for example, $x_1$ is a sum of the estimated evacuation time and the time interval till a beginning of the evacuation, and $x_2$ is the time to the critical event), which can be written by the formula

$$x_1 < x_2. \quad (2)$$

The parameters $x_1$and$x_2$ are random values, which are characterized by the normal distribution of probability densities $P_1$ and $P_2$[7]:

$$P_1 = \frac{1}{\sqrt{2\pi}\sigma_1} \exp\left[-\frac{(x_1 - x_{10})^2}{2\sigma_1^2}\right], \quad (3)$$

$$P_2 = \frac{1}{\sqrt{2\pi}\sigma_2} \exp\left[-\frac{(x_2 - x_{20})^2}{2\sigma_2^2}\right], \quad (4)$$

were $x$ is a random value; $x_{10}$ and $x_{20}$ are the center values of the distributions $P_1$ and $P_2$; $\sigma_1$ and $\sigma_2$ are the dispersions of the distributions $P_1$ and $P_2$. The values $x_1$ and $x_2$ can not be negative, but usually $x_{10} \gg \sigma_1$ and $x_{20} \gg \sigma_2$. Therefore for a convenience of calculations we can formally consider also negative values of $x_1$ and $x_2$. In the case of calculations of the evacuation times the values $x_{10}$ and $x_{20}$ are calculated by methods stated in the standards[5),6)]. The dispersion $\sigma_2$ is determined by differences in velocities of a motion of various groups of people at an evacuation in the case of a fire. The dispersion $\sigma_1$ reflects qualitative and quantitive variations of a fire load at an operation of the industrial facility. For the clarity we consider the example of the evacuation times, but the methodology is applicable for other parameters determining fire safety of the industrial facilities. The safety conditions are illustrated in Fig. 1.

In Fig. 1 the shared area corresponds to the case, when the condition (2) is fulfilled. In order to obtain probability $Q_0$ of non-fulfilment of the safety condition (2) an appropriate integration should be made. The value $Q_0$ can be expressed by the formula:

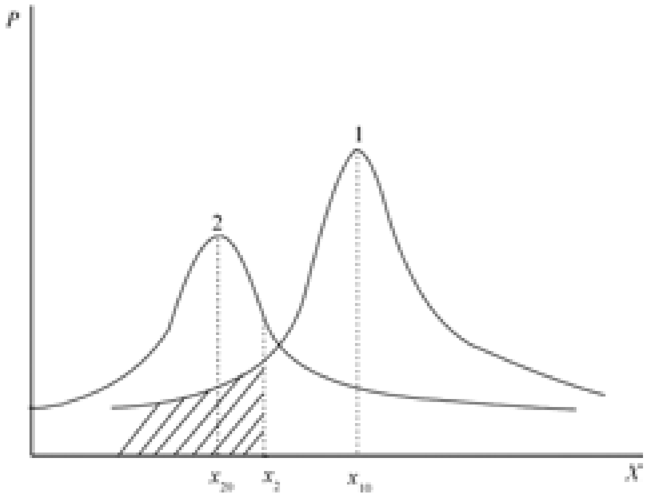

Fig. 1 Qualitative interpretation of safety conditions.1,2– graphs of the functions (3)and (4).The area under the curve1is shaded, which is numerically equal to the probability of a fulfillment of the safety condition (2)at the given $x_2$ value. P is probability densities for the distributions (3)and (4).

$$Q_0 = \frac{1}{2\pi\sigma_1\sigma_2} \int_{-\infty}^{\infty} dx_2 \int_{x_2}^{\infty} dx_1 \exp\left\{-\frac{(x_1 - x_{10})^2}{2\sigma_1^2} - \frac{(x_2 - x_{20})^2}{2\sigma_2^2}\right\}. \quad (5)$$

For this integration the following change of the variables of the integration can be performed: $x_1 = X_1 + X_2$, $x_2 = X_1 - X_2$, $x = 2X_2/\sigma_s - \gamma$. The integration $X_1$ can be done before the integration values change $x = 2X_2/\sigma_s - \gamma$. This procedure was executed following the study[3)]. The appropriate formula for the $Q_0$ value was obtained:

$$Q_0 = F(-\gamma) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{-\gamma} \exp(-x^2/2)\, dx, \quad (6)$$

where $F(-\gamma)$ is the probability integral, which values are stated in the reference book[7)]; $\gamma$ is a parameter described by the formulas:

$$\gamma = (x_{10} - x_{20})/\sigma_s, \quad (7)$$

$$\sigma_s = (\sigma_1^2 + \sigma_2^2)^{1/2}. \quad (8)$$

The dependence of the $Q_0$ value on the parameter $\gamma$ is shown in Fig. 2.

This dependence can be used for calculations of such parameters as a probability non-successful evacuation at a fire and the safety coefficients for fire hazard indexes. The graph in Fig. 2 is characterized by a rapid decrease of the $Q_0$ value with an increase of the $\gamma$ parameter, and the highest speed of the decrease is realized at $\gamma = 0$. The dependence in Fig. 2 is universal and can be used for the determination of the safety conditions in many branches of the fire safety science and practice.

## Calculations of the probability of a successful evacuation from buildings and structures at a fire

For a testing of the proposed methodology calculations of the probability of the non-successful evacuations from buildings and structures at various values of $t_n$ and $t_s$ were

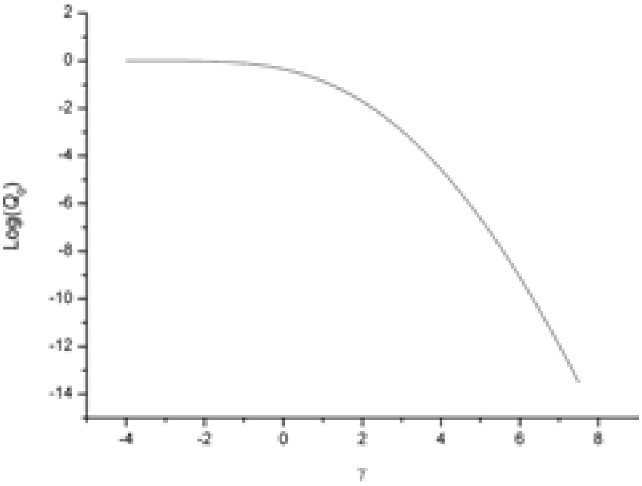


**Fig. 2** Dependence of the probability of non fulfillment of the safety conditions (2) on the $\gamma$ parameter.

performed. The value of the time interval till a beginning of the evacuation $\tau_n$ was accepted to be equal 0.5 min according to the standard[5)]. In this case

$$\gamma = (t_n + \tau_n - t_s)/\sigma_s. \quad (9)$$

Since the following calculations are mostly illustrative one, we will accept for the simplicity the dispersion of the time to the critical event $\sigma_1$ to be equal 0 (that is we consider the fixed fire load). In this case $\sigma_s = \sigma_2$, where $\sigma_2$ is the dispersion of the estimated evacuation time. For the determination of the $\sigma_2$ value we will use experimental data for an evacuation of people from a technological pipe rack using horizontal ways and inclined stairs[8)]. According to these experimental data dispersions of velocities of a motion on the horizontal and inclined parts of the evacuation ways are 5-10% from experimental measured values. These $\sigma_2$ values are relatively small, and this is due to a participation in the experiments well trained personnel of the plant. In other cases the $\sigma_2$ values can be larger, but for an approximate estimation it is possible to accept $\sigma_2$ to be equal 10% from the estimated evacuation time. For more complete analysis we considered also other values of $\sigma_2$. The calculated dependence of $Q_0$ on $\Delta = t_n + \tau_n - t_s$ at various values of $\sigma_2$ are presented in Fig. 3. The graph of the dependence (1) is also presented for comparison.

It can be seen that the $Q_0$ value depends substantially on a difference between the time to the critical event $t_n$ and the estimated evacuation time $t_s$, and the lower is the value of the dispersion $\sigma_2$ the more rapid decrease of $Q_0$ with an elevation of $\Delta$ takes place. At low values of $\Delta$ the $Q_0$ parameters calculated according to our model is substantially higher than it is predicted by the formula (1) proposed by the standards[5),6)]. In this case rather low but positive values of $\Delta$ the methodology of the standards[5),6)] underestimates a real level of a fire hazard, and fire risk values determined by this methodology will be underestimated. But at the higher values of $\Delta$ the methodology[5),6)] overestimates the fire hazard.

It is interesting to determine, at what values of $\Delta$ the standard method for an evaluation of $Q_0$ will give the

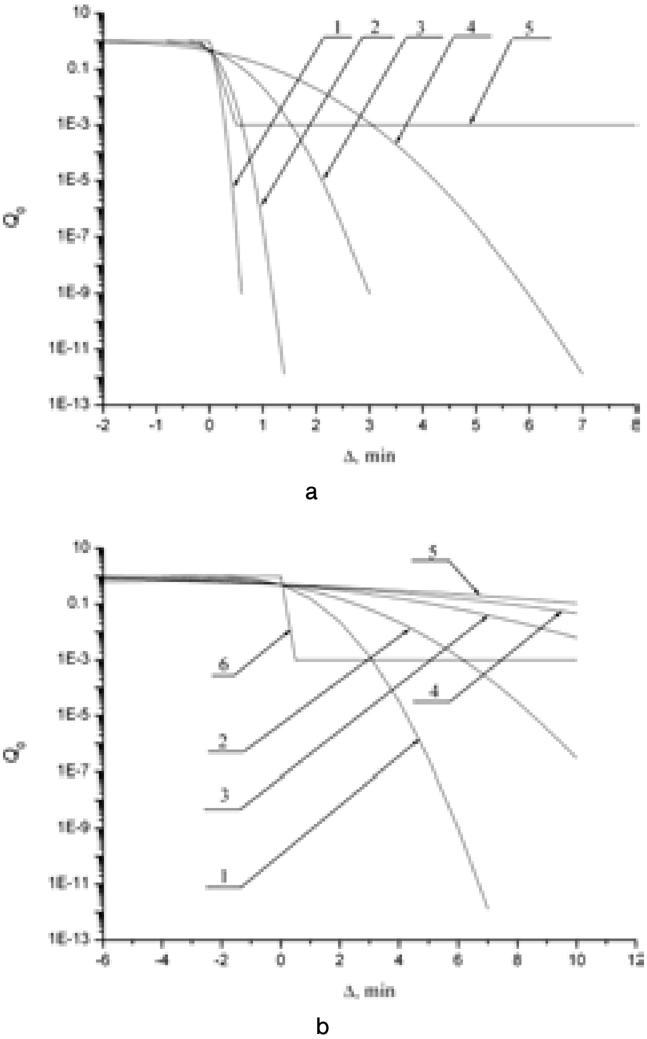


**Fig. 3** Dependence of the probability of nonsuccessful evacuation $Q_0$ on the parameter $\Delta$ at various $\sigma_s$. a $-\sigma_s$ = 0.1 (1), 0.2 (2), 0.4 (3), 1.0 (4) min ; $b - \sigma_s$ = 1.0 (1), 2.0 (2), 4.0 (3), 6.0 (4), 8.0 (5) min. Lines 5 and 6 are the results of the calculations according to the formula (1).

underestimated fire risk value. For this purpose we considered the typical for industrial plants value of the estimated evacuation time $t_s$, which is equal to 4 min. If we accept the value of the dispersion to be equal to 10% from the $t_s$ value (that is $\sigma_s$ = 0.4 min), according to Fig. 3a (line3) we find that at $\Delta \leq 1.5$ min the formula (1) overestimates the probability of a successful evacuation $P_{suc} = 1 - Q_0$. But at $\Delta > 1.5$ min the formula (1) overestimates the fire hazard.

## Calculations of safety coefficients to fire and explosion hazard indexes of substances and materials

Methods for calculations of the safety coefficients to fire and explosion hazard indexes of substances and materials will be considered on examples of lower flammability limits (LFL) of flammable gases and vapors and flash points of flammable liquids ($t_f$). According to the standard[2)] safety conditions for these parameters can be expressed by the formulas :

$$C_s \leq 0.9\,(\mathrm{LFL} - 0.7R\,), \quad (10)$$

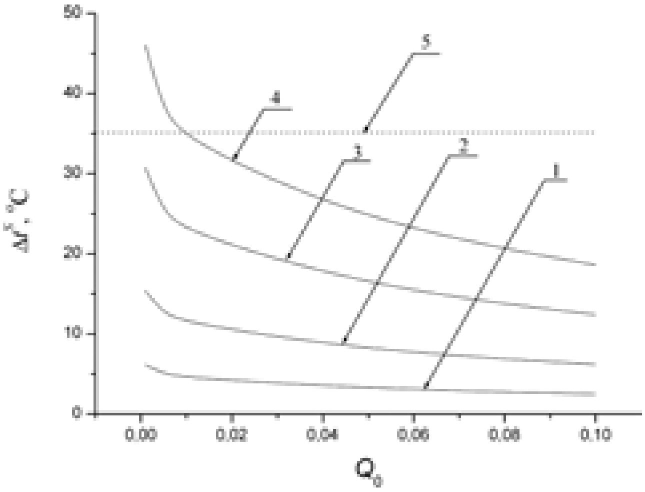


**Fig. 4** Dependence of $\Delta t^s$ on $Q_0$ for the error of a determination of the flash point $\sigma_s$=2(1), 5(2), 10 (3), 15 (4)°C. Line5is the graph of the dependence (11).

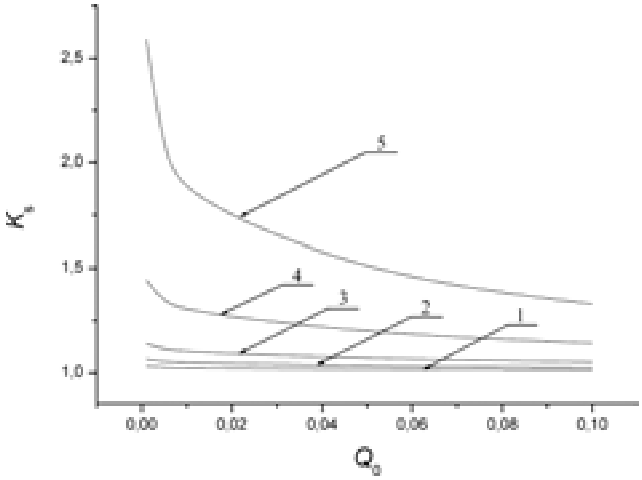


**Fig. 5** Dependence of the safety coefficient $K_s$ to the lower flammability limit of methane on $Q_0$ for the error of a determination of LFL $\sigma_s$ = 0.05 (1), 0.1 (2), 0.2 (3), 0.5 (4), 1.0 (5) % (vol.).

$$t_s \le t_f - 35^{\circ}C, \quad (11)$$

where $C_s$ is the safe concentration of a flammable gas or vapor, % (vol.); LFL is the lower flammability limit, % (vol.); $t_s$ is the safe temperature of a flammable liquid, °C; $t_f$ is the flash point, °C; $R$ is a reproducibility of a method of a determination of LFL, % (vol.).

Let us use the proposed method for a more precise definition of the safety coefficients to the fire and explosion hazard indexes. For LFL the safety coefficient $K_s$ can be described by a relationship:

$$K_s = \mathrm{LFL}/C_s. \quad (12)$$

For $t_f$ the safety condition can be written by a following formula:

$$t_f - t_l \ge \Delta t^s, \quad (13)$$

where $t_l$ is a maximum allowable liquid temperature, °C; $\Delta t^s$ is a minimum allowable difference between the flash point and the liquid temperature, °C. The value $\Delta t^s$ depends both on the trust probability $P_0 = 1 - Q_0$ and the error $\sigma_s$ of a determination of $t_f$.

Using the proposed methodology we can obtain the following formulas for calculations of the values $K_s$ and $\Delta t^s$:

$$\Delta t^s = \gamma_f \sigma_s^f, \quad (14)$$

$$K_S = \mathrm{LFL}/(\mathrm{LFL} - \gamma_{\mathrm{LFL}} \sigma_s^{\mathrm{LFL}}), \quad (15)$$

where $\sigma_s^{\mathrm{LFL}}$ and $\sigma_s^f$ are mean square deviations of a determination of the values LFL and $t_f$, and the parameters $\gamma_{\mathrm{LFL}}$ and $\gamma_f$ are determined by the trust probability $P_0 = 1 - Q_0$.

The dependence of the parameters $\Delta t^s$ on $Q_0$ for various values of $\sigma_s^f$ are presented in Fig. 4. Data calculated according to the formula (11) are shown for comparison.

It can be seen that the value $\Delta t^s$ decreases with an elevation of $Q_0$ (a decrease of the trust probability $P_0$). A qualitative character of this dependence is quite clear. The lower are the requirements to the fire and explosion safety provision (that is the lower is the trust probability $P_0$ or the higher is the probability of unfavorable event $Q_0$) the more high liquid temperature can be used as safe for a technological process. It should be noted that the formula (11) in the case $\sigma_s^f \le 15^0$C overestimates the value $\Delta t^s$ for the trust probability $P_0 \le 0.99$ ($Q_0 \ge 0.01$).

In practice the value of the trust probability $P_0 = 0.95$ ($Q_0 = 0.05$) is often used for a determination of the safety coefficients to the fire and explosion hazard indexes [2].

Let us suppose $\sigma_s^f = 15^0$C, which is a typical value of a reproducibility at an experimental measurement of the flash point of flammable liquids. In this case $\Delta t^s = 25^0$C, that is a safe temperature of a flammable liquid should be at least on $25^0C$ lower its flash point. This value of $\Delta t^s$ can be recommended for a practical application for the cases, when we want to prevent a formation of flammable vapor-air mixtures over the liquid surface.

In Fig. 5 the dependence of the safety coefficient $K_s$ to the lower flammability limit of methane in air (LFL=5% (vol.)[9] on the $Q_0$ value for various $\sigma_s^{\mathrm{LFL}}$ is presented.

**Table 1** Comparison of the $K_s$ values calculated by various methods.

| | $\sigma_s$, % (vol.) | 0.05 | 0.1 | 0.2 | 0.5 | 1.0 |
|---|---|---|---|---|---|---|
| $K_s$ | Calculation according to the proposed method | 1.02 | 1.03 | 1.07 | 1.20 | 1.51 |
| | Calculation by the formula (10) | 1.11 | 1.12 | 1.14 | 1.19 | 1.29 |

A qualitative character of this dependence is analogous to that shown in Fig. 4, that is the $K_s$ value decreases with a diminishing of the trust probability $P_0$ (elevation of $Q_0$). It is interesting to compare the results of the calculations of $K_s$ according to the formula (10) and to the proposed method. The results of the comparison are presented in Table 1 (the value $R$ was accepted to be equal to $2\sigma_s$, and $Q_0 = 0.05$). It can be seen that the results of the calculations by two methods are close to each other at $\sigma_s \le 0.5$ % (vol.), but at $\sigma_s = 1$ % (vol.) the safety coefficient calculated according to the proposed method exceeds remarkably the value obtained by the formula (10).

## Conclusions

In this study the conditions of a fire and explosion safety at a determination of safe operation parameters of industrial plants are considered. Relationships were obtained, which describe a dependence of the safe operation parameters on a probability of an unfavorable event (accident characterizing by intolerable risk level). The proposed method was realized on the example of calculations of a probability of successful evacuation from buildings and constructions in the case of a fire and safety coefficients to fire and explosion hazard indexes of substances and materials. It was found that in the case of an assessment of a safe evacuation at a fire the proposed method gives a possibility for a more exactly evaluation of a fire risk and a safe temperature at a using of flammable liquids.

## References

1) V. Monakhov, "Methods of investigation of fire hazard of substances", p. 434 Moscow, Khimiya (1979) (in Russian).
2) Standard GOST 12.1.044-89*, "Fire and explosion hazard of substances and materials. List of indexes and methods for their determination" (in Russian).
3) V. Prisadkov, "A reliability of structures at a fire", In : Fire Resistance of Structures, pp. 70-73, Moscow, VNIIPO (1986) (in Russian).
4) V. Prisadkov, "A creation of methods of optimal fire safety systems for industrial buildings", Thesis on a scientific degree of doctor of technical sciences, Moscow, VNIIPO (1990) (in Russian).
5) Standard GOST 12.3.047-98, "Fire safety of technological processes. General requirements. Methods of control" (in Russian).
6) Standard GOST 12.1.004-91*, "Fire safety. General requirements" (in Russian).
7) E. Yanke, F. Elide and F. Lesh, "Special functions", p. 324 Moscow, Nauka, (1968) (in Russian).
8) Yu. Shebeko, D. Gordienko and V. Nekrasov, Fire Safety, 1, 83 (2008) (in Russian).
9) A. Baratov and A. Korolchenko, "Fire and explosion hazard of substances and materials and tools for their fire extinguishing. Reference book", Vol. 1, 2, Moscow, Khimiya, (1990) (in Russian).