ASSESSMENT OF FIRE SAFETY OF EVACUATION ROUTES IN INDUSTRIAL PREMISES

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The paper presents results of the development of new scientific and methodological principles for assessing the fire safety of industrial premises evacuation routes. The basis of these principles is the scientific methodology for managing industrial safety, developed at the department of life safety at the Perm National Research Polytechnic University. Following is discussed in the paper: 1) method of modelling scenarios for fire break-out and development based on Ishikawa diagram, 2) mathematical model describing the stepwise process of fire break-out and development in accordance with diagram topology, 3) indicator of fire safety of evacuation routes, 4) model for estimating the probability of evacuation of people along through the evacuation routes, 5) model for estimating the probability of evacuation from the premises. The developments mentioned above took into account problematic issues related to the behavior of people during a fire (operational actions to turn off equipment or stop the process, speed of human response to fire signals and decision time), movement of people during evacuation inside confined or limited spaces (mines, containers, wells, vessels etc.), remoteness of workplaces from evacuation routes (scaffolding, crane tracks, work at height etc.), reliability of evacuation warning and control systems, absence of a clear algorithm for constructing fire scenarios. The areas of scientific research application are identified. A method for assessing the safety of evacuation routes in relation to fire extinguishing substances of automatic fire extinguishing units that pose a danger to human health is considered. Examples of the application of scientific developments in the assessment of evacuation routes fire safety and modelling a fire scenario at a specific production facility are given.

Key words: evacuation model, evacuation routes, evacuation, fire safety, fire danger, fire hazards, automatic fire extinguishing units, fire alarms, evacuation warning and control systems, Ishikawa diagram, fire hazardous situation, fire, decision-making time, psychology, people’s actions in case of fire.

Ключевые слова: модель эвакуации, эвакуационные пути, эвакуация, пожарная безопасность, пожарная опасность, опасные факторы пожара, автоматические установки пожаротушения, пожарная сигнализация, системы оповещения и управления эвакуацией, диаграмма Исикавы, пожароопасная ситуация, пожар, время принятия решения, психология, действия людей при пожаре.

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Introduction

One of the basic methods for protection of production facilities personnel from hazards in case of fire is timely evacuation of people from the premises where the fire occurred. Evacuation is considered to be timely if people manage to leave the premises before the fire hazards obstruct the evacuation paths. This condition is the basis for evaluation of probability of people’s evacuation along the evacuation paths, probability of people’s evacuation from the production premises, and for potential fire risk assessment. Based on the same condition, process parameters, nature and conditions of the work at the production facility can be changed.

Model for evaluation of fire evacuation time

Time of people’s evacuation from the premises where the fire occurred, $t_{si}$, s, is composed of two parameters: time of people’s movement along the evacuation paths and evacuation start time [1–4]:

$$t_{si} = t_{e.s} + t_{e.p}, \quad (1)$$

where $t_{e.s}$ – evacuation start time (EST), s; $t_{e.p}$ – time of people’s movement along evacuation path (EP) $i$, s.

Parameter $t_{e.p}$ is defined experimentally during evacuation drill at a specific production facility. It is also acceptable to use data concerning speed and time of people’s movement received during evacuation drills at similar oil-and-gas industry facilities. For instance, it can be the information received in the course of evacuation drill experiment with participation of gas refinery employees described by Yu.N. Shebeko [5]. $t_{e.p}$ can be defined on the basis of models of people’s flow used in firefighting standards [1, 2, 6], provided that they adequately describe the process of people’s evacuation at a given production facility based on the specific features of work process, location of temporary and permanent workplaces, and other factors.

Parameter $t_{e.s}$ describes people’s behavior during fire. Presently there is no universal mathematical model to adequately describe $t_{e.s}$ at any production facility [6]. In the opinion of the researchers, the existing method for determining $t_{e.s}$ used in the regulatory documents requires significant improvement [2, 6] to include multiple factors that impact people’s behavior during fire [2-18]. Our suggestion is to calculate $t_{e.s}$ based on parameters describing psychological characteristics of people, evacuation alerting and management system (EAMS) activation time and its reliability [3, 4, 19-21]:

$$t_{e.s} = t_{EAMS} + t_{h.r} + t_{d.m} \geq K_{g(EAMS)} \geq 0.95, \quad (2)$$

where $t_{EAMS}$ – EAMS activation time, s; $t_{h.r}$ – human reaction time, s; $t_{d.m}$ – decision making time, s; $K_{g(EAMS)}$ – EAMS readiness coefficient.

The $t_{EAMS}$ value is determined in the course of the system’s commissioning tests. $t_{h.r}$ and $t_{d.m}$ values define human psychological characteristics and can be determined on the basis of reference data or in the course of personnel testing with computer psychological diagnostic software used in organizations and institutions in order to evaluate professional qualities of workers [4, 10].

Other studies specify $t_{d.m}$ values depending on the type of fire signal (smoke, flame, siren, alarm) [2, 6, 22-27]. However, in order to use them for calculation of $t_{e.s}$ for personnel of a given organization or institution, special verification is required. Therefore it is more reasonable to use the diagnostic methods mentioned before. $K_{g(EAMS)}$ coefficient value $\geq 0.95$ suggests that EAMS has high reliability and can fulfill the personnel fire alerting function. Then $t_{e.s}$ is calculated by the formula (2) upon condition that the personnel was given proper firefighting training and that actions of employees correspond to the sequence of actions characteristic for a human HMI operator (see Table 1 in [28]).

If $K_{g(EAMS)} < 0.95$, it is believed that EAMS is not sufficiently reliable and cannot fulfill the personnel fire alerting functions. This instance is real and also has to be taken into account when assessing fire safety of evacuation paths. What is the advisable next step in such case? As an option, it is suggested to use experimental data characterizing EST value for the specific group of workers. In absence of such data, $t_{e.s}$ value can be assumed according to the method [1] for the case of EAMS absence in buildings.

Evacuation path fire safety indicator.

People’s evacuation probability assessment models

Quite often the production premises layout organizes workplaces in tight enclosed spaces, at upper levels of buildings, inside process equipment and utilities. People’s exit to evacuation paths from
such workplaces can be difficult and significantly increase \( t_{ei} \) [29]. Therefore \( t_{ei} \) value will be considered random and will change depending on the listed conditions.

Let us assume that \( U_{ei} \) – parameter of \( i \)-th event of random variation \( t_{e.pi}, s, M_{e} \) – mathematical expectation \( U_{ei}, s, \sigma_{ei} \) – mean square deviation \( U_{ei}, s, \) and variation \( t_{e.pi} \) is characterized by truncated normal distribution. Then expression

\[
\frac{C_{e}}{\sigma_{e}\sqrt{2\pi}} \exp \left\{ -\frac{\left(U_{ei} - M_{e}\right)^2}{2\sigma_{e}^2} \right\}
\]

will describe random variation of evacuation time, where \( C_{e} \) – truncation coefficient for truncated normal distribution \( U_{ei} \). Based on the hazard emergence and development model proposed by V.A. Trefilov [30, 31], we can convert the above expression into the evacuation path fire safety assessment model:

\[
b_{e.pi} = \frac{1}{\tau_{ob}} \left[ \tau_{ob} - t_{ei} \left( 1 + \frac{C_{e}}{\sigma_{e}\sqrt{2\pi}} \right) \times \exp \left\{ -\frac{\left(U_{ei} - M_{e}\right)^2}{2\sigma_{e}^2} \right\} \right]
\]

(3)

where \( b_{e.pi} \) – fire safety indicator for \( i \)-th evacuation path; \( \tau_{ob} \) – time of obstruction of evacuation paths by fire hazards or their accompanying phenomena, \( s \); \( P_{U} \) – probability of occurrence for \( U_{ei} \).

Scope of application (3) includes the following evacuation situations:

1. People’s movement during evacuation inside enclosed tight spaces (compartmentst of process equipment and structures, vessel reservoirs, air ducts, ventilation channels etc.). Probability \( P_{U} \) for this case is determined on the basis of the expression \( P_{U} = t_{shift}/24 \), where \( t_{shift} \) – time of people’s positioning at workplaces during the shift, if people’s positioning at such workplaces is normal operating practice (inspection, adjustment, parameter control etc.), h. In the event that people’s positioning in a certain area is caused by elimination of faults (repair), than \( P_{U} \) probability is determined on the basis of the reliability law describing the probability of failure of a device, apparatus, or other equipment. In other words, in case of failure occurrence, it is assumed that the personnel will take steps to rectify it, i.e. the personnel will be positioned in the exact place of the faulty equipment. In case of the equipment dismantling for repair outside of the room in regard to which the \( b_{e.pi} \) assessment is being carried out, \( t_{shift} \) value will stand for the period of the equipment replacement expressed in hours.

2. People’s movement during evacuation using appliances (descent along vertical surfaces of buildings using harnesses and other safety equipment, descent from hoisting devices etc.). Probability \( P_{U} \) for this instance is determined in the same way as in the first instance.

3. Activities involving electrical equipment shutdown, forced process shutdown, emergency discharge of fire hazardous substances into emergency reservoirs, launch of automatic firefighting equipment, rescue of injured people. Here \( P_{U} \) probability is equal to 1 if emergency actions are included in the personnel’s job functions and are specified in local regulatory documents (organization standards, instructions, action plans for emergency containment and elimination etc.). Otherwise \( P_{U} \) is determined on the basis of the personnel testing which is performed in organizations and institutions for assessment of employee professional competence. The assumption is that the emergency actions will be performed by employees with high readiness to risk (Schubert method):

\[
P_{U} = \frac{N_{th}}{N_{overall}},
\]

(4)

where \( N_{th} \) – quantity of employees with high readiness to risk; \( N_{overall} \) – overall quantity of respondents.

Evacuation path fire safety is considered to be ensured if \( b_{e.pi} > 0 \).

After determining \( b_{e.p} \) for each workplace, it is necessary to calculate probability of people’s evacuation along the \( i \)-th evacuation path \( P_{e.pi} \) by the formula [4]

\[
P_{e.pi} = 1 - \frac{N_{pi}(b_{p} \leq 0)}{N_{w,p}},
\]

(5)

where \( N_{w,p} (b_{p} \leq 0) \) – quantity of \( i \)-th workplaces with exit to \( i \)-th evacuation path which do not meet the established fire safety conditions, i.e. \( b_{p} \leq 0 \); \( N_{w,p} \) – overall quantity of workplaces with exit to \( i \)-th evacuation path. If \( P_{e.p} \) calculation is based on methods of simulation and static tests, then \( N_{w pi} \) (\( b_{pi} \leq 0 \)) in this instance is the quantity of iterations at which \( b_{pi} \leq 0 \), and \( N_{w pi} \) – overall quantity of iterations.
Value of probability of people’s evacuation from the production premises \( P_{ei} \) can be calculated using the expression [4]

\[
P_{ei} = \begin{cases} 
0.999, & \text{if } \prod_{i=1}^{N} b_{e,i} > 0, \\
1 - \frac{N_{eI}(b_{e,I} \leq 0)}{N_{eI}} \prod_{i=1}^{N} (1 - K_{ei}), & \text{if } \prod_{i=1}^{N} b_{e,i} \leq 0,
\end{cases}
\]

where \( N_{eI}(b_{e,I} \leq 0) \) – quantity of evacuation paths that do not meet the established fire safety conditions, i.e. \( b_{e,I} \leq 0 \); \( N_{eI} \) – quantity of all evacuation paths in the premise; \( K_{ei} \) – readiness coefficient of \( i \)-th firefighting system intended for ensuring safety of people’s evacuation.

Certain types of fire extinguishing substances that are used in automatic firefighting equipment (AFFE) can have harmful effect on people if the latter enter the coverage area of the former [32]. Check of evacuation paths fire safety in terms of effect of AFFE extinguishing substances is performed as follows. AFFE ramp-up time is determined according to the technical documentation (design documentation, equipment fire test results). This parameter is used to substitute \( \tau_{sh} \) in model (3). Then formula (5) will show the probability of people’s exposure to AFFE extinguishing substances for a given evacuation path, formula (6) – probability of AFFE extinguishing substances affecting all evacuation paths of the production premises.

### Fire scenario building method

When calculating \( \tau_{sh} \), it is very important to determine all possible scenarios of fire emergence and development (hereinafter – fire scenario, scenario) that can occur at the production facility, and to select the most hazardous out of them. To perform this task, it is suggested to use Ishikawa diagram (hereinafter – fire diagram) which will help identify all possible factors and conditions capable of forming cause-and-effect relationships for emergence and development of fire, as well as the conditions that counteract the development of this process [3, 4]. It is quite obvious that each fire scenario will have a certain probability of occurrence at the production facility. The mathematical model used to evaluate the probability of fire scenario occurrence is expressed in the following formula:

\[
x(t)_{ij} \left( 1 + \frac{C}{\sqrt{2\pi} \sigma} \exp \left[ -\frac{(x(t)_{ij} - M)^2}{2\sigma^2} \right] \right) - x_{allow},
\]

where \( d_{ij} \) – hazard indicator for \( i \)-th stage of \( j \)-th fire scenario; \( x(t)_{ij} \) – current value of the parameter describing the hazardous event of \( i \)-th stage of \( j \)-th fire scenario; \( C \) – truncation coefficient for truncated normal distribution \( x(t)_{ij} \); \( M \) – mathematical expectation for random value \( x(t)_{ij} \); \( \sigma \) – mean square deviation for random value \( x(t)_{ij} \); \( Q \) – probability of occurrence for \( x(t)_{ij} \); \( x_{allow} \) – allowable value for \( x(t)_{ij} \).

### Table 1

| Characteristic \( x(t) \) | Parameter \( x(t) \) name | \( Q \) selection |
|---------------------------|-----------------------------|-------------------|
| Disruption of pipelines with fire and explosion hazardous substances due to a pressure shock | Pressure value in the pipeline [33-36] | Based on “load-strength” model [37] |
|                          | Pipe wall thickness [33-36] | Based on normal distribution (describes gradual failure, material aging) [38] |
| Disruption of a vessel, reservoir, or tank with fire and explosion hazardous substances | Pressure value in the vessel, reservoir, tank [33-36] | Based on “load-strength” model |
|                          | Wall thickness of vessel, reservoir, tank [33-36] | Failure described by normal distribution |
| Emergence of electrical arc or sparking (short circuiting) in the combustible medium generation area | Value of current in the electrical equipment circuit | Exponential distribution is selected in case of electrical equipment failure |
|                          | In case of electrical welding works, \( x(t) \) shall be the value of distance between the place of works and the production premises where the combustible medium generated | Probability of electrical welding works in the production premises |
| Heating of parts of equipment, installations, assemblies up to combustible material ignition temperatures | Temperature of heating parts of equipment to temperature of combustible material ignition. Equipment operating parameter which reliably causes heating: rotation frequency, value of current etc. (to be determined according to the operating documentation) | If heating of parts of installation, equipment, assemblies is a normal condition during their operation, then \( Q \) is assumed equal to 1. If heating is the result of failure, then \( Q \) is assumed depending on the reliability law for each type of failure |
Values $C_x$, $M_x$, $\sigma_x$, $Q_x$ are calculated on the basis of statistical data. In their absence, the specified parameters are determined using simulation modeling methods and static tests.

The last multiplier in model (7) describes the probability of $x(t)_{ij}$ occurrence. As a rule, this is a function of reliability of the technical item (device, installation etc.), failure of which would reliably lead to an emergency and result in fire. Depending on the nature of failures distribution, the said multiplier can be expressed through the following reliability laws: exponential law, normal law, gamma law etc. In case of simulation of a disruption of pipe, vessel, or reservoir, “load-strength” model is used. Table 1 shows characteristics $x(t)_{ij}$, $Q_x$ which are proposed for building fire scenarios at production facilities.

For each fire scenario modeled according to the formula (7), $\tau_{ob}$ is calculated. The most unfavorable fire scenario which will be used as a reference for assessment of evacuation paths fire safety will be the one for which $\tau_{ob}$ will be the lowest of all considered values.

**Practical evaluation of scientific research**

Indicator (3) was tested during assessment of fire safety of evacuation paths located in the gas compressor plant (GCP) of Barda line operation section – branch of OOO Gazprom Transgaz Tchaikovsky. The evacuation paths in question can be entered from workplaces of the production shop personnel engaged in maintenance of the plant and other equipment (Fig. 1).

As $U_e$, random time of people’s exit to evacuation paths from workplaces was taken. Values $M_U$ and $\sigma_U$ were assumed on the basis of experimental data [29]. For a sample equal to 98 instances of people’s exit from GCP shell space to EP, mathematical expectation $M_U$ and mean square deviation $\sigma_U$ amounted to 10.16 and 4.23 s respectively. For the identical sample $M_U$ and $\sigma_U$ time of the people’s descent from the fire annunciators maintenance platform amounted to 7.16 and 2.09 s respectively. The obtained data was used for substitution into (3) in regard to each evacuation path:

$$b_{e(p1)} = \frac{1}{\tau_{ob}} \left[ \tau_{ob} - 4.2 + 13.81 \times \right]$$

$$\times \left[ 1 + \frac{1.028}{5.23} \exp \left[ - \frac{(U_e - 7.16)^2}{8.73} \right] \right],$$

$$b_{e(p2)} = \frac{1}{\tau_{ob}} \left[ \tau_{ob} - 2.9 + 13.81 \times \right]$$

$$\times \left[ 1 + \frac{1.028}{10.59} \exp \left[ - \frac{(U_e - 10.16)^2}{2 \cdot 4.23^2} \right] \right].$$

**Table 2**

Calculated characteristics of personnel movement along evacuation paths located at the GCP maintenance platform

| No of the workplace | Time of movement along EP from the workplace to EP, s |
|---------------------|-----------------------------------------------------|
| 1                   | 4.2                                                 |
| 2                   | 2.9                                                 |
| 3                   | 4.2                                                 |
| 4                   | 6                                                   |

Time of people’s movement along the evacuation paths (EP) was calculated on the basis of the following experimental data [5]: horizontal paths – 350 m/min; vertical paths (descent) – 48.5 m/min; inclined stairs (descent) – 100 m/min.

EAMS activation time based on the test results amounted to 4.5 s, readiness coefficient $K_{t(EAMS)} = 0.953$, time $t_{dm} = 8.31$ [25, 26], value $t_{hr} = 1.0$ s. Then value $\tau_{ex}$ will amount to 13.81 s. Next it is necessary to calculate the time of people’s movement along the EPs based on the assumed speed values (Table 2).

![Fig 1. Workplaces of production shop personnel at the gas compression plant maintenance platform: 1 – at the fire annunciators (FA) maintenance platform; 2 – in the GCP right side compartments; 3 – in the GCP left side compartments; 4 – in the air intake chamber](image-url)
Obstruction time $\tau_{ob}$ is a variable in respect to which $b_{ep}$ was evaluated for each evacuation path. $U_{e(1)}, U_{e(2)}, U_{e(3)}$ and $U_{e(4)}$ simulation was performed using random number generator. Quantity of iterations amounted to 24,891 per cycle (as per Chebyshev’s rule) [21, 39-40]. The calculation results are provided in Table 3.

Practical evaluation of the model (7) and method for building the fire scenario has been performed on the basis of the instance of an accident at the gas compressor plant. Fire diagram for GCP is provided in Fig. 2. To build the fire diagram, we used information from operating documentation, failure data, incident prerequisites and expert opinions.

Designations and abbreviations used in Fig. 2 are as follows: $P_{o}(t)$ – actual gas pressure, MPa; $P_{g(allow)}$ – allowable gas pressure, MPa; $P_{o}(t)$ – actual turbine oil pressure, MPa; $P_{o(allow)}$ – allowable oil pressure, MPa; $N_{rpm}(t)$ – actual gas turbine engine (GTE) rotation frequency, rpm; $N_{rpm(allow)}$ – allowable GTE rotation frequency, rpm; $I(t)$ – actual current in the electrical grid or electrical equipment, A; $I_{allow}$ – allowable current in the electrical grid or electrical equipment, A; $K_{r(EEV)}$ – emergency exhaust ventilation (EEV) readiness coefficient; $K_{r(EDS)}$ – readiness coefficient for oil emergency drainage system (EDS) into an underground reservoir; $K_{r(ACS)}$ – automatic control system (ACS) readiness coefficient; $K_{r(ESSS)}$ – energy supply system (ESSS) readiness coefficient; $K_{r(ESD)}$ – emergency shutdown (ESD) system readiness coefficient; $Q_{r}$ – probability of occurrence of event $P_{r}(t) > P_{r(allow)}$; $Q_{n}$ – probability of occurrence of event $P_{n}(t) > P_{n(allow)}$; $Q_{n,c}$ – probability of occurrence of contact resistance (short circuit) in the electrical equipment.

Fire diagram analysis allows to conclude that fire hazardous situation “combustible medium generation” in the compressor plant turbine room can occur in the event of an outburst of natural gas and (or) turbine oil from the utility lines. In the first instance, the cause of outburst is a pressure spike $P_{r}(t) > P_{r(allow)}$ in the fuel line gas duct. This is described by probability $Q_{r}$. For simulation of event $P_{r}(t) > P_{r(allow)}$ we took into account the impact of the emergency exhaust ventilation and actions of personnel on the development of fire hazardous situation described by coefficient $K_{r(EEV)}$.

### Table 3

| Workplace | $b_{e,p(1)}$, $b_{e,p(2)}$, $b_{e,p(3)}$, $b_{e,p(4)}$ from workplaces Fig. 1 |
|-----------|---------------------------------|
| **Workplace 1** | |
| $\tau_{ob}$ | $b_{e,p(1)} > 0$ | $b_{e,p(1)} \leq 0$ | $P_{e,p(1)}$ | $\tau_{ob}$ | $b_{e,p(2)} > 0$ | $b_{e,p(2)} \leq 0$ | $P_{e,p(2)}$ |
| 23.90 | 24,982 | 0 | 0.999 | 22.00 | 24,982 | 0 | 0.999 |
| 23.30 | 24,242 | 740 | 0.970 | 21.70 | 17,558 | 7,424 | 0.702 |
| 23.15 | 17,888 | 7,094 | 0.716 | 21.65 | 8,095 | 16,887 | 0.324 |
| 23.00 | 4,470 | 20,512 | 0.178 | 21.62 | 60 | 24,922 | 0.002 |
| 22.80 | 0 | 24,982 | 0.000 | 21.6 | 0 | 24,982 | 0.000 |
| **Workplace 2** | |
| $\tau_{ob}$ | $b_{e,p(3)} > 0$ | $b_{e,p(3)} \leq 0$ | $P_{e,p(3)}$ | $\tau_{ob}$ | $b_{e,p(4)} > 0$ | $b_{e,p(4)} \leq 0$ | $P_{e,p(4)}$ |
| 23.60 | 24,982 | 0 | 0.999 | 26.20 | 24,982 | 0 | 0.999 |
| 23.10 | 23,964 | 1,018 | 0.959 | 25.08 | 21,810 | 3,172 | 0.873 |
| 23.04 | 11,911 | 13,071 | 0.476 | 25.00 | 13,756 | 11,226 | 0.550 |
| 23.00 | 3,176 | 21,806 | 0.127 | 24.90 | 4661 | 20,321 | 0.186 |
| 22.80 | 0 | 24,982 | 0.000 | 24.80 | 0 | 24,982 | 0.000 |
| **Workplace 3** | |
| $\tau_{ob}$ | $b_{e,p(3)} > 0$ | $b_{e,p(3)} \leq 0$ | $P_{e,p(3)}$ | $\tau_{ob}$ | $b_{e,p(4)} > 0$ | $b_{e,p(4)} \leq 0$ | $P_{e,p(4)}$ |
| 23.60 | 24,982 | 0 | 0.999 | 26.20 | 24,982 | 0 | 0.999 |
| 23.10 | 23,964 | 1,018 | 0.959 | 25.08 | 21,810 | 3,172 | 0.873 |
| 23.04 | 11,911 | 13,071 | 0.476 | 25.00 | 13,756 | 11,226 | 0.550 |
| 23.00 | 3,176 | 21,806 | 0.127 | 24.90 | 4661 | 20,321 | 0.186 |
| 22.80 | 0 | 24,982 | 0.000 | 24.80 | 0 | 24,982 | 0.000 |
Simulation of oil outburst from oil duct is simulated likewise. Pressure spike in oil system $P_m(t) > P_{m(allow)}$ is caused by congestion of oil filters and safety valve failure. Their failures are described by probability $Q_m$. Impact of EDS protection and actions of personnel are described by coefficient of readiness of the system for oil emergency drainage into an underground reservoir $K_{r(EDS)}$. Fire hazardous situation “Emergence of ignition source” occurs when an electrical arc is generated as a result of short circuit $I(t) > I_{allow}$ in the electrical equipment. The reason of occurrence of event $I(t) > I_{allow}$ is related to deterioration of isolation properties, failure of an automatic safety system, which are described as $Q_{sc}$. Lack of readiness in the energy supply safety system is described by readiness coefficient $K_{r(ESSS)}$. The second source of ignition can occur in the event that GTE power turbine rotation frequency exceeds the maximum allowable value $N_{overall}(t) > N_{overall(allow)}$ and ACS is not ready to GTE shutdown at the alarm signal, personnel commits a mistake, or emergency shutdown system does not perform the required function.

For analysis we have selected the scenario of fire emergence and development along the branch “turbine oil outburst due to oil duct depressurization”. According to the scenario, the fire hazardous situation would develop as follows: as a result of congestion of oil filters, oil pressure would grow in the GCP oil system, resulting in oil duct disruption on the inlet to the oil tank. Oil outburst would occur within the area of 10 m², which includes GCP aft shaft. Due to the power turbine high rotation frequency, the aft shaft area would be heated up to the temperature of oil self-combustion. Mathematical model of the fire scenario (by stages) is provided below:
Static tests of models (12), (13) have shown that the fire scenario under consideration is realistic, since probability of occurrence of stages $d_{11}$ and $d_{12}$ exceeded zero. The event tree for the scenario is provided in Fig. 3.

**Conclusion**

New approaches to evacuation paths fire safety and a new method for building fire scenarios have been considered. A formula for evacuation paths fire safety indicator, a model for evaluation of probability of people’s evacuation along the evacuation paths, a model for people’s evacuation from the production premises and a model for fire emergence and development have been obtained. Examples are given for practical evaluation of the above-listed models at a given production facility.

Fig. 3. Event tree for fire scenario emerging as a result of oil combustion from heated GTE parts

References

1. Metodika opredeleniya raschetnykh velichin pozharnogo riska na proizvodstvennykh obektaakh [Method of determining the calculated values of fire risk at production facilities]: Utverzhdena Prikazom MChS Rossii ot 10 July 2009 no.404, available at: http://www.consultant.ru/document/cons_doc_LAW_91229/ (accessed 12 May 2018).

2. Kholshchevnikov V.V., Samoshin D.A., Parfenenko A.P. et al. Evakuatsiya i povedenie lyudey pri pozhare [Evacuation and behavior of people in case of fire]. Moscow, Akademiya MChS GPS Rossii, 2015, 262 p.

3. Kirilov A.E., Trefilov V.A. Matematicheskaya model otsenki pozharnoy bezopasnosti kompressornogo tsekhka gazotransportnogo predpriyatiya [The mathematical model for fire safety assessment of compressor shop of gas transmission enterprise]. Bezopasnost truda v promyshlennosti, 2016, no.9, pp.38-45.

4. Kirilov A.E., Chernyy K.A. Model otsenki pozharnoy bezopasnosti putey evakuatsii proizvodstvennykh pomeshcheniy i zdaniy [Fire Safety Assessment Model for the evacuation of industrial premises and buildings]. Gazovaya promyshlennost, 2018, no.9 (774), pp.120-124.

5. Shebeko Yu.N., Gordinenko D.M., Nekrasov V.P. et al. Issledovanie protsessa evakuatsii lyudey pri pozhare s etazherki tekhnologicheskoj linii gazoperebatyvayushchego zavoda [Study of the process of evacuation of people in case of fire from a shelf of the technological line of a gas processing plant]. Pozharnaya bezopasnost, 2008, no.1, pp.83-88.

6. Samoshin D.A. Metodologicheskie osnovy normirovaniya bezopasnoy evakuatsii lyudey iz zdaniy pri pozhare [Methodological bases of rationing of safe evacuation of people from buildings in case of fire]. Doctor’s degree dissertation. Moscow, 2017, 357 p.

7. Wood P.G. The behaviour people in fires. British Note 933, 1972, November, pp.27-90.

8. Nilsson D., Johansson A. Social influence during the initial phase of a fire evacuation – Analysis of evacuation experiments in a cinema theatre. Fire Safety Journal, 2009, vol.44, iss.1, pp.71-79. DOI: 10.1016/j.firesaf.2008.03.008

9. Bryan J.L. A phenomenon of human behaviour seen in selected high-rise buildings fire. Fire Journal, 1985, November, pp.27-90.

10. Brennan P. Timing human response in real fires. Fire Safety Science, 1997, 5, pp.807-818. DOI: 10.3801/1AFSS.FSS.5-807

11. Spearpoint M.J. The effect of pre-movement on evacuation times in a simulation model. Journal of Fire
Investigating the impact of culture on evacuation behavior.

12. Beloskikh I.R. K probleme formirovaniya prodolzhitelnosti vremeni nachala evakuatsii lyudey pri pozhare [To the problem of the formation of the length of time to start evacuating people in case of fire]. Tekhnologii tekhnosfernuy bezopasnosti, 2011, iss.2 (36), p.9.

13. Galea E., Deere S., Sharp G., Filipidis L., Hulse L. Investigating the impact of culture on evacuation behavior. Proceedings of the 12-th International Fire Science & Engineering Conference. Interflam, 2010, 5-7 July 2010, University of Nottingham, UK, vol.1, pp. 879-892.

14. Proulx G., Sime J.D. To prevent “panic” in an underground emergency: why not tell people The truth? Proceedings Of The Third International Symposium On Fire Safety Science, 1991, 3, pp.843-852. DOI: 10.3801/IAFSS.FSS.3-843

15. Sime J. Escape behaviour in fires: panic or affiliation? PhD thesis, University of Surrey, 1984, 321 p.

16. Jones B.K., Hewitt A. Leadership and group formation in high rise building evacuations. Proceedings Of The First International Symposium On Fire Safety Science. New York, Hemisphere Publishing Corp., 1986, pp.513-522. DOI: 10.3801/IAFSS.FSS.1-513

17. Machado Tavares R., Gwynne S., Galea E.R. Collection and analysis of pre-evacuation time data collected from evacuation trials conducted in library facilities in Brazil. Journal of Applied Fire Science, 2006-2007, vol.15, no.1, pp.23-40. DOI: 10.2190/AF.15.1b

18. Boyce K.E. Egress capabilities of people with disabilities. PhD Thesis. Belfast, University of Ulster, 1996, 43 p.

19. Kirilov A.E. Metod opredeleniya opasnykh situatsiy dlya personala kompressornogo tseka na etape planirovaniya operativnykh deystviy pri vozniknoveni pozhara [Method for determining hazardous situations for compressor shop personnel at the planning stage of operational actions in case of a fire]. Pozharnaya bezopasnost, 2017, no.3, pp.54-60.

20. Kirilov A.E., Trefilov V.A. Inzhenernaya otsenka bezopasnosti personala pri planirovaniy operativnykh deystviy po tusheniyu pozhara v proizvodstvennykh pomeshcheniyakh [Engineering safety assessment of personnel in the planning of operational activities to extinguish a fire in industrial premises with fire extinguishers]. Bezopasnost truda v promyshlennosti, 2017, no.7, pp.31-36. DOI: 10.24000/0409-2961-2017-7.31-36

21. Kirilov A.E., Dikeyeva M.N. Otsenka bezopasnosti rabotnikov kompressornogo tseka posredstvom statisticheskikh ispytaniy imitacienny modeli evakuatsii [Assessment of the safety of workers of the compressor shop through statistical tests of a simulation model of evacuation]. Aktualnye problemy okhrany truda i bezopasnosti proizvodstva. Materialy X yubileynoy mezhdunarodnoy nauchno-prakticheskoy konferentsii. Perm, 2017, pp.144-154.

22. Tadashes J. Visibility and human behaviour in fire smoke. The SFPE, Handbook of Fire Protection Engineering. 3 ed. Eds. D'InNenno et al. NFPA, Quincy, MA, 2002, pp.(2-42)-(2-53)

23. Shields T.J., Boyce K.E., Silcock G.W.H. Towards the characterization of large retail stores. Human Behaviour in Fire. Proceedings of the First International Symposium. Belfast, University of Ulster, 1998, pp.277-290.

24. Bellamy L.L., Geyer T.A.W. Experimental programme to investigate informative fire warning characteristics for motivation fast evacuation. Borehamwood, Fire Research Station, 1990.

25. Samoshin D.A. Primenenie konceptsi “chelovek – sreda – pozhar” dlya ponimaniya povedeniya personala torgovykh kompleksov pri pozhare [The use of the concept “man – environment – fire” for understanding the behavior of the personnel of shopping complexes during a fire]. Doctor’s degree dissertation. Olster, 2004.

26. Shtild D., Boys K.E., Kholschchevnikov V.V., Samoshin D.A. Povedenie personala torgovykh kompleksov pri pozhare. Part II. Deystvie v smodelirovannoy situatsii “pozhar v torgovom kompleke” [The behavior of the staff of shop complexes in case of fire. Part II. Action in a simulated situation “fire in a shop complex”]. Pozharno-ryzhovaya bezopasnost, 2005, vol.14, no.3, pp.47-58.

27. Bruck D. The who, what, where and why of waking to fire alarms: a review. Fire Safety Journal, 2001, vol.36, iss.7, pp.623-639. DOI: 10.1016/S0379-7112(00)00025-X

28. Borisov S.V., Denisov V.A., Dushkov B.A. et al. Spravochnik po inzhenernomu psikhologii [Handbook of engineering psychology]. Moscow, Mashinostroenie, 1982, 368 p.

29. Kirilov A.E. Otsenka vremeni dvizheniya lyudey po uchastkam evakuatsii povyshennoy slozhnosti [Estimation of the time of movement of people in complex areas]. Bezopasnost i upravlenie riskami, 2016, no.5, pp.34-41.

30. Trefilov V.A. Teoreticheskie osnovy bezopasnosti cheholoveka: kurs lektsiy [Theoretical foundations of human safety; a course of lectures]. Perm, Permskoe knizhnoe izdatelstvo, 2006, 100 p.

31. Trefilov V.A. Problemy issledovaniya bezopasnosti v sistemakh razlichnogo urovnya [Problems of safety research in systems of various levels]. Nauchnye issledovaniya i innovatsii, 2013, vol.7, no.1-4, pp.4-7.

32. Ugleksilota v sistem poshutorusheniy pervye ubila cheholoveka v rossi [Carbon dioxide in the fire extinguishing system for the first time killed a man in Russia]. RIA novosti, 26.08.2010, available at: https://ria.ru/incidents/20100826/269270419.html (accessed 12 May 2018).

33. Kalugin M.N. Povyshenie nadezhnosti teplosnabzheniya zdaniy s pomoshchyu upravleniya protivovarvinyom zashchitnoy kotelnikh [Improving the reliability of heat supply to buildings by controlling the emergency protection of boiler rooms]. Ph. D. thesis. Tyumen, 2015, 111 p.

34. Kalugin M.A., Trefilov V.A. Avtomatizirovannaya sistema sostoyaniya bezopasnosti gazovoy kotelnoy [Automated security system for gas boiler room]. Bezopasnost truda v promyshlennosti, 2014, no.3, pp.59-61.

35. Kostrov A.E. Avtomatizirovannoe upravlenie bezopasnostyu teknologicheskih truboprovodov [Automated safety management of technological pipelines]. Ph. D. thesis. Perm, 2010, 102 p.

36. Kostrov A.E., Trefilov V.A. Razrabotka avtomatizirovannoy sistemy upravleniya bezopasnostyu teknologicheskih truboprovodov [Development of automated system to provide safety control over technological pipeline operation]. Geology, Geophysics and Development of Oil and Gas Fields, 2010, no.12, pp.74-77.

37. Alkin V.N., Anokhin P.V. et al. Kriteriy prochnosti i nadezhnosti mezhduanodnyh naychno-prakticheskih konferenci [Strength criterion and calculation of the mechanical reliability of structures]. Perm, PSTU, 1999, 158 p.

38. Akimov V.A., Lapin V.L., Popov V.M. et al. Nadezhnost tekhnicheskih sistem i tekhnogennyy risk
[Reliability of technical systems and technological risk]. Moscow, Delovoy ekspress, 2002, 368 p.

39. Venttsel E.S. Teoriya veroyatnostey [Probability theory]. Moscow, Vysshaya shkola, 2001, 575 p.

40. Kirillo A.E., Trefilov V.A. Razrabotka metoda otsenki bezopasnosti personala kompressorного тsekha

при evakuatsii s ispolzovanii metodov imitationnogo modelirovaniya [Development of a method for assessing the safety of the compressor shop personnel during evacuation using simulation methods]. Gazoavaya promyshlennost, 2017, no.6 (753), pp.18-22.

Библиографический список

1. Методика определения расчетных величин пожарного риска на производственных объектах [Электронный ресурс]: утв. Приказом МЧС России от 10.07.2009 г. № 404: зарегистрировано в Минюсте России 17.08. 2009 г. № 14541 (в ред. Приказа МЧС России от 14.12.2010 г. № 649). – URL: http://www.consultant.ru/document/cons_doc_LAW_91229/ (дата обращения: 12.05.2018).

2. Эвакуация и поведение людей при пожаре: учеб. пособие / В.В. Холшевников, Д.А. Самошин, А.П. Парфененко [и др.]. – М.: Академия МЧС ГПС России, 2015. – 262 с.

3. Кирилов А.Э., Трефилов В.А. Математическая модель оценки пожарной безопасности компрессорного цеха газотранспортного предприятия // Безопасность труда в промышленности. – 2016. – № 9. – С. 38–45.

4. Кирилов А.Э., Черный К.А. Модель оценки пожарной безопасности путей эвакуации производственных помещений и зданий // Газовая промышленность. – 2018. – № 9 (774). – С. 120–124.

5. Исследование процесса эвакуации людей при пожаре с этажеркой технологической линии газоперерабатывающего завода / Ю.Н. Шебeko, Д.М. Гордienenко, В.П. Некрасов [и др.] // Пожарная безопасность. – 2008. – № 1. – С. 83–88.

6. Самошин Д.А. Методологические основы нормирования пожарной безопасности людей в зданиях при пожаре: дис. … канд. техн. наук. – М., 2017. – 357 с.

7. Wood P.G. The behaviour people in fires. British Note, 933. – 1972. – November. – 113 p.

8. Nilsson D., Johansson A. Social influence during the initial phase of a fire evacuation – Analysis of Evacuation experiments in a cinema theatre // Fire Safety Journal. – 2009. – Vol. 44, iss. 1. – P. 71–79. DOI: 10.1016/j.firesaf.2008.03.008

9. Bryan J.L. A phenomenon of human behaviour seen in selected high-rise buildings fire // Fire Journal. – 1985. – November. – P. 27–90.

10. Brennan P. Timing human response in real fires // Fire Safety Science. – 1997. – 5. – P. 807–818. DOI: 10.3801/IHFSS.S.5-807

11. Spearpoint M.J. The effect of pre-movement on evacuation times in a simulation model // Journal of Fire Protection Engineering. – 2003. – Vol. 14, № 1. – P. 33–53. DOI: 10.1177/1042391504034742

12. Белосохов И.Р. К проблеме формирования продолжительности времени начала эвакуации людей при пожаре // Технология техносферной безопасности. – 2011. – Вып. 2 (36). – С. 9.

13. Investigating the impact of culture on evacuation behaviour / E. Galea, S. Deere, G. Sharp, L. Filippidis, L. Hulse // Proceedings of the 12-th International Fire Science & Engineering Conference, Interflam 2010, 5–7 July 2010, University of Nottingham. – 2010. – Vol. 1. – P. 879–892.

14. Proulx G., Sime J.D. To prevent “panic” in an underground emergency: why not tell people the Truth? // Proceedings Of The Third International Symposium On Fire Safety Science. – 1991. – 3. – P. 843–852. DOI: 10.3801/IHFSS.FSS.3-843

15. Sime J. Escape behaviour in fires: panic or affiliation? PhD thesis, University of Surrey, 1984. – 321 p.

16. Jones B.K., Hewitt A. Leadership and group formation in high rise building evacuations // Proceedings of the First International Symposium on Fire Safety Science. – New York: Hemisphere Publishing Corp., 1986. – P. 513–522. DOI: 10.3801/IHFSS.FSS.1-513.

17. Machado Tavares R., Gwyne S., Galea E.R. Collection and analysis of pre-evacuation time data collected from evacuation trials conducted in library facilities in Brazil // Journal of Applied Fire Science. – 2006–2007. – Vol. 15, № 1. – P. 23–40. DOI: 10.2190/AF.15.1b

18. Boyce K.E. Egress capabilities of people with disabilities: PhD Thesis. – Belfast: University of Ulster, 1996. – 43 p.

19. Кирилов А.Э. Метод определения опасных ситуаций для персонала компрессорного цеха на этапе планирования оперативных действий при возникновении пожара // Пожарная безопасность. – 2017. – № 3. – С. 54–60.

20. Кирилов А.Э., Трефилов В.А. Инженерная оценка безопасности персонала при планировании оперативных действий по тушению пожара в производственных помещениях огненосителями // Безопасность труда в промышленности. – 2017. – № 7. – С. 31–36. DOI: 10.24000/0409-2961-2017-7-31-36

21. Кирилов А.Э., Дикарева М.Н. Оценка безопасности работников компрессорного цеха посредством статистических испытаний имитационной модели эвакуации // Актуальные проблемы охраны труда и безопасности производства: материалы XX Юбилейной междунар. научн.-практ. конф. – Пермь, 2017. – С. 144–154.

22. Tadahisa J. Visibility and human behaviour in fire smoke // The SFPE, Handbook of Fire Protection Engineering. 3 ed. Eds. DiNenno et al. NFPA, Quincy, MA, 2002. – Ph. (2-42)–(2-53).

23. Shields T.J., Boyce K.E., Silcock G.W.H. Towards the characterization of large retail stores // Human Behaviour in Fire: Proceedings of the First International Symposium. – Belfast: University of Ulster, 1998. – P. 277–290.

24. Bellamy L.L., Geyer T.A.W. Experimental programme to investigate informative fire warning characteristics for motivation fast evacuation. – Borehamwood, Fire Research Station, 1990.

25. Самошин Д.А. Применение концепции ‘человек – среда – пожар’ для понимания поведения персонала торговых комплексов при пожаре: дис. …
д-ра философии / Инженерный факультет Ольстера университета. – Ольстёр, 2004.

26. Поведение персонала торговых комплексов при пожаре. Часть II. Действие в смоделированной ситуации «пожар в торговом комплексе» / Д. Шилльц, К. Е. Бойл, В. В. Холщевников, Д. А. Самошин // Пожаровзрывобезопасность. – 2005. – Т. 14, № 3. – С. 47–58.

27. Bruck D. The who, what, where and why of waking to fire alarms: a review // Fire Safety Journal. – 2001. – Vol. 36, iss. 7. – Р. 623–639. DOI: 10.1016/S0379-7112(01)00025-X

28. Справочник по инженерной психологии / С. В. Борисов, В. А. Денисов, Б. А. Душков [и др.]. – М.: Машиностроение, 1982. – 368 с.

29. Кирилов А. Э. Оценка времени движения людей по участкам эвакуации повышенной сложности // Безопасность и управление рисками. – 2016. – № 5. – С. 34–41.

30. Трефилов В. А. Теоретические основы безопасности человека: курс лекций. – Пермь: Пермское кн. изд-во, 2006. – 100 с.

31. Трефилов В. А. Проблемы исследования безопасности в системах различного уровня // Научные исследования и инновации. – 2013. – Т. 7, № 1–4. – С. 4–7.

32. Углекислота в системе пожаротушения впервые убила человека в России [Электронный ресурс] // РИА Новости. – 26.08.2010. – URL: https://ria.ru/incidents/20100826/269270419.html (дата обращения: 12.05.2018).

33. Калугин М. Н. Повышение надежности теплоснабжения зданий с помощью управления противоаварийной защитой котельных: дис. … канд. техн. наук. – Тюмень, 2015. – 111 с.

34. Калугин М. А., Трефилов В. А. Автоматизированная система состояния безопасности газовой котельной // Безопасность труда в промышленности. – 2014. – № 3. – С. 59–61.

35. Костров А. Е. Автоматизированное управление безопасностью технологических трубопроводов: дис. … канд. техн. наук. – Пермь, 2010. – 102 с.

36. Костров А. Е., Трефилов В. А. Разработка автоматизированной системы управления безопасностью технологических трубопроводов // Геология. Геофизика и разработка нефтяных и газовых месторождений. – 2010. – № 12. – С. 74–77.

37. Критерий прочности и расчет механической надежности конструкций / В. Н. Аликян, П. В. Анохин [и др.]. – Пермь: Перм. гос. техн. ун-т, 1999. – 158 с.

38. Надежность технических систем и техногенный риск / В. А. Акимов, В. Л. Лапин, В. М. Попов [и др.]. – М.: Деловой экспресс, 2002. – 368 с.

39. Вентцель Е. С. Теория вероятностей: учеб. для вузов. – 7-е изд., стер. – М.: Высш. шк., 2001. – 575 с.

40. Кирилов А. Э., Трефилов В. А. Разработка метода оценки безопасности персонала компрессорного цеха при эвакуации с использованием методов имитационного моделирования // Газовая промышленность. – 2017. – № 6 (753). – С. 18–22.

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