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ASSESSMENT OF FIRE SAFETY OF EVACUATION ROUTES IN INDUSTRIAL PREMISES

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ОЦЕНКА ПОЖАРНОЙ БЕЗОПАСНОСТИ ПУТЕЙ ЭВАКУАЦИИ ПРОИЗВОДСТВЕННЫХ ПОМЕЩЕНИЙ

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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.

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.

Изложены результаты разработки новых научно-методических принципов оценки пожарной безопасности путей эвакуации производственных помещений. В основе указанных принципов лежит научная методология по управлению безопасностью на производстве, разработанная на кафедре безопасности жизнедеятельности Пермского национального исследовательского политехнического университета. В статье рассмотрены: 1) метод построения сценариев возникновения и развития пожара на основе диаграммы Исикавы, 2) математическая модель, описывающая постадийный процесс возникновения и развития пожара в соответствии с топологией диаграммы, 3) показатель пожарной безопасности путей эвакуации, 4) модель оценки вероятности эвакуации людей по путям эвакуации, 5) модель оценки вероятности эвакуации из производственного помещения. В перечисленных разработках учтены проблемные вопросы, связанные с особенностью поведения людей при пожаре (оперативные действия по отключению оборудования или остановке технологического процесса, скорость реакции человека на сигналы о пожаре и время принятия решения), движением людей при эвакуации внутри замкнутых или ограниченных пространств (шахты, емкости, колодцы, сосуды и др.), удаленностью рабочих мест от путей эвакуации (средства подмащивания, крановые пути, работа на высоте и др.), надежностью систем оповещения и управления эвакуацией, отсутствием четкого алгоритма построения сценариев пожара. Определены области применения научных разработок. Рассмотрен метод оценки безопасности путей эвакуации относительно огнетушащих веществ автоматических установок пожаротушения, представляющих опасность для здоровья людей, которые являются сопутствующими проявлениями опасных факторов пожара. Приведены примеры применения научных разработок в оценке пожарной безопасности путей эвакуации и построении сценария пожара на конкретном производственном объекте.

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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, $t_{эi}$, s, is composed of two parameters: time of people's movement along the evacuation paths and evacuation start time [1–4]:

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

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

Parameter $t_{\mathrm{e.p}i}$ 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]. $t_{\mathrm{e.p}i}$ 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 $\tau_{\mathrm{e.s}i}$ describes people's behavior during fire. Presently there is no universal mathematical model to adequately describe $\tau_{\mathrm{e.s}i}$ at any production facility [6]. In the opinion of the researchers, the existing method for determining $\tau_{\mathrm{e.s}i}$ 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 $\tau_{\mathrm{e.s}i}$ based on parameters describing psychological characteristics of people, evacuation alerting and management system (EAMS) activation time and its reliability [3, 4, 19-21]:

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

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

The t_{EAMS} value is determined in the course of the system's commissioning tests. $t_{\mathrm{h.r}}$ and $t_{\mathrm{d.m}}$ 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 $t_{\mathrm{d.m}}$ 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 $\tau_{\mathrm{e.s}i}$ for personnel of a given organization or institution, special verification is required. Therefore it is more reasonable to use the diagnostic methods mentioned before. $K_{\mathrm{g(EAMS)}}$ coefficient value ≥ 0.95 suggests that EAMS has high reliability and can fulfil the personnel fire alerting function. Then $\tau_{\mathrm{e.s}i}$ 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 $K_{\mathrm{g(EAMS)}} < 0.95$, it is believed that EAMS is not sufficiently reliable and cannot fulfil 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, $\tau_{\mathrm{e.s}i}$ 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_U – mathematical expectation U_{ei}, s, σ_U – mean square deviation U_{ei}, s, and variation $t_{e.pi}$ is characterized by truncated normal distribution. Then expression $\frac{C_U}{\sigma_U\sqrt{2\pi}}\exp\left[-\frac{(U_{ei}-M_U)^2}{2\sigma_U^2}\right]$ will describe random variation of evacuation time, where C_U – 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:

$$b_{e.pi} = \frac{1}{\tau_{ob}}\left[\tau_{ob} - t_{ei}\left(1 + \frac{C_U}{\sigma_U\sqrt{2\pi}} \times \right.\right.$$
$$\left.\left. \times \exp\left[-\frac{(U_{ei}-M_U)^2}{2\sigma_U^2}\right] P_U\right)\right], \quad (3)$$

where $b_{e.pi}$ – fire safety indicator for i-th evacuation path; τ_{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 (compartments 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):

$$P_U = \frac{N_{e(h)}}{N_{overall}}, \quad (4)$$

where $N_{e(h)}$ – 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]

$$P_{e.pi} = 1 - \frac{N_{w.pi}(b_{e.pi} \le 0)}{N_{w.p}}, \quad (5)$$

where $N_{w.pi}$ ($b_{e.p} \le 0$) – quantity of i-th workplaces with exit to i-th evacuation path which do not meet the established fire safety conditions, i.e. $b_{e.p} \le 0$; $N_{w.p}$ – 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 $N_{w.pi}$ ($b_{e.p} \le 0$) in this instance is the quantity of iterations at which $b_{e.p} \le 0$, 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]

$$P_{ei}=\begin{cases}0.999, & \text{if } \prod_{i=1}^{N} b_{\mathrm{e.p}i}>0,\\ 1-\dfrac{N_{\mathrm{e.p}}\left(b_{\mathrm{e.p}}\le 0\right)}{N_{\mathrm{e.p}}}\prod_{i=1}^{n}\left(1-K_{\mathrm{r}i}\right), & \text{if } \prod_{i=1}^{N} b_{\mathrm{e.p}i}\le 0,\end{cases} \quad (6)$$

where $N_{\mathrm{e.p}}(b_{\mathrm{e.p}} \le 0)$ – quantity of evacuation paths that do not meet the established fire safety conditions, i.e. $b_{\mathrm{e.p}} \le 0$; $N_{\mathrm{e.p}}$ – quantity of all evacuation paths in the premise; $K_{\mathrm{r}i}$ – 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 τ_{ob} 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 τ_{ob} 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:

$$d_{ij}=\frac{x(t)_{ij}\left(1+\dfrac{C_x}{\sigma_x\sqrt{2\pi}}\exp\left[\dfrac{-\left(x(t)_{ji}-M_x\right)^2}{2\sigma_x^2}\right]Q_x\right)-x_{\mathrm{allow}}}{x_{\mathrm{allow}}}, \quad (7)$$

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_x – truncation coefficient for truncated normal distribution $x(t)_{ij}$; M_x – mathematical expectation for random value $x(t)_{ij}$; σ_x – mean square deviation for random value $x(t)_{ij}$; Q_x – probability of occurrence for $x(t)_{ij}$; x_{allow} – allowable value for $x(t)_{ij}$.

Table 1

Standard characteristics of $x(t)_{ij}$, Q_x and recommendations for their use in model (7)

Characteristic $x(t)_i$	Parameter $x(t)_l$ *name*	Q_x 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_x is assumed equal to 1. If heating is the result of failure, then Q_x is assumed depending on the reliability law for each type of failure

Values C_x, M_x, σ_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), τ_{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 τ_{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).

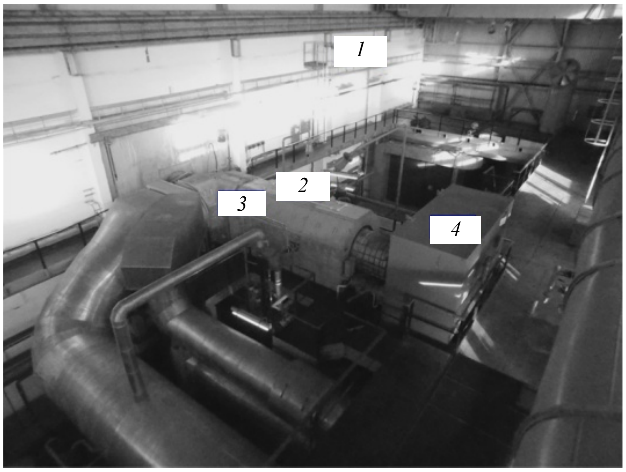

Fig 1. Workplaces of production shop personnel at the gas compression plant maintenance platform: *1* – at the fire annunciators (FA) maintenance platform; *2* – in the GCP right side compartments; *3* – in the GCP left side compartments; *4* – in the air intake chamber

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 $K_{r(EAMS)}$ = 0.953, time $t_{d.m}$ = 8.31 [25, 26], value $t_{h.r}$ = 1.0 s. Then value $\tau_{e.s}$ 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).

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

As U_e, random time of people’s exit to evacuation paths from workplaces was taken. Values M_U and σ_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 σ_U amounted to 10.16 and 4.23 s respectively. For the identical sample M_U and σ_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:

$$b_{e.p(1)} = \frac{1}{\tau_{ob}}\left[\tau_{ob} - 4.2 + 13.81\times \right. \qquad (8)$$

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

$$b_{e.p(2)} = \frac{1}{\tau_{ob}}\left[\tau_{ob} - 2.9 + 13.81\times \right. \qquad (9)$$

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

$$b_{e.p(3)} = \frac{1}{\tau_{ob}}\left[\tau_{ob} - 4.2 + 13.81 \times \right. \tag{10}$$
$$\left. \times\left(1 + \frac{1.028}{10.59}\exp\left[-\frac{\left(U_{e(3)} - 10.16\right)^2}{2\cdot 4.23^2}\right]1\right),\right.$$

$$b_{e.p(4)} = \frac{1}{\tau_{ob}}\left[\tau_{ob} - 6.0 + 13.81 \times \right. \tag{11}$$
$$\left. \times\left(1 + \frac{1.028}{5.23}\exp\left[-\frac{\left(U_{e(4)} - 7.16\right)^2}{8.73}\right]1\right)\right].$$

Obstruction time τ_{ob} is a variable in respect to which $b_{e.p}$ 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: $P_g(t)$ – 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 safety 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_m – probability of occurrence of event $P_m(t) > P_{m(allow)}$; $Q_{s.c}$ – 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

Evaluation results $b_{e.p(1)}$, $b_{e.p(2)}$, $b_{e.p(3)}$, $b_{e.p(4)}$ from workplaces Fig. 1

Workplace 1				Workplace 2			
τ_{ob}, s	$b_{e.p(1)} > 0$	$b_{e.p(1)} \le 0$	$P_{e.p(1)}$	τ_{ob}, s	$b_{e.p(2)} > 0$	$b_{e.p(2)} \le 0$	$P_{e.p(2)}$
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 3				Workplace 4			
τ_{ob}, s	$b_{e.p(3)} > 0$	$b_{e.p(3)} \le 0$	$P_{e.p(3)}$	τ_{ob}, s	$b_{e.p(4)} > 0$	$b_{e.p(4)} \le 0$	$P_{e.p (4)}$
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

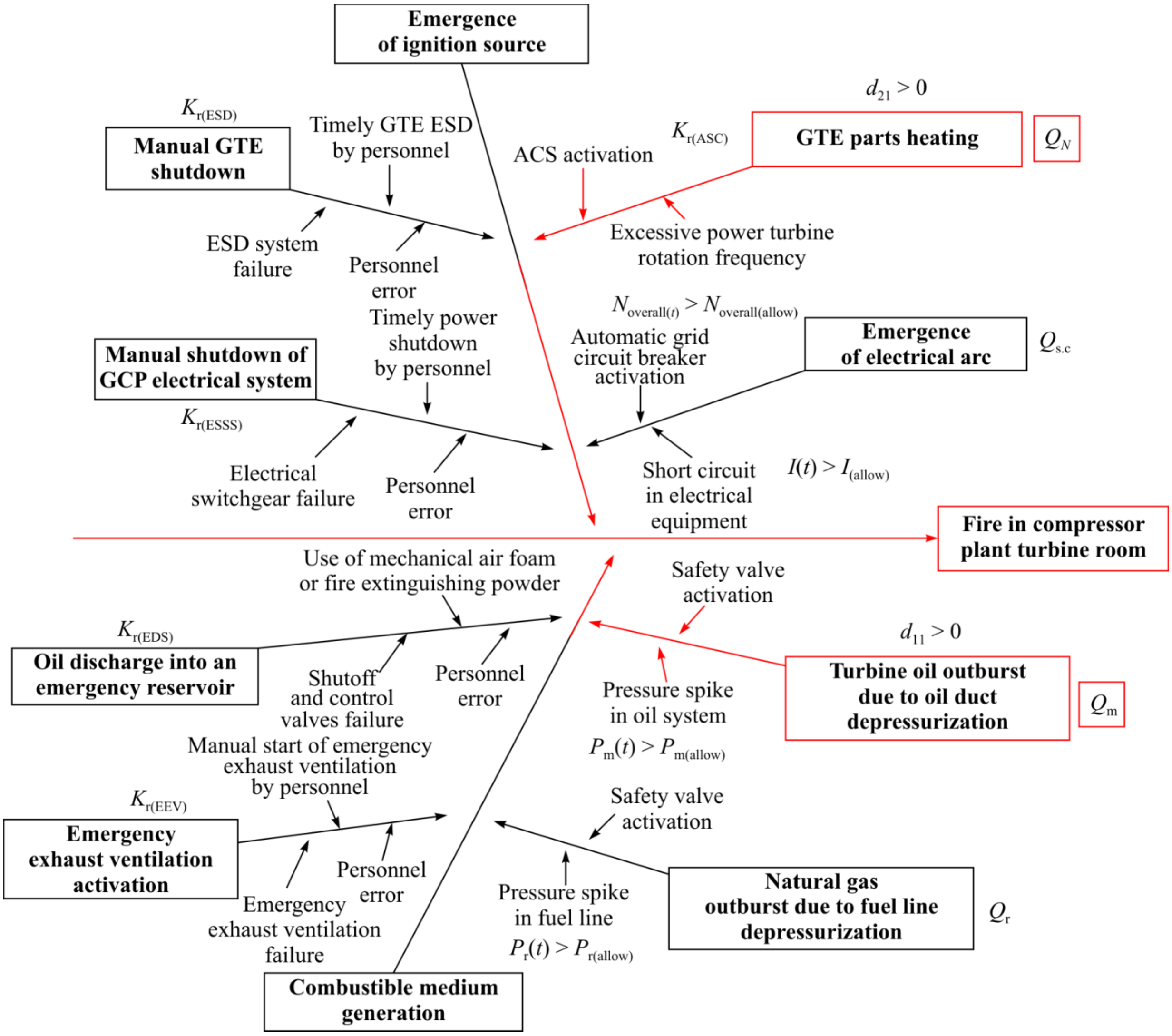

Fig. 2. Fire diagram in compressor plant turbine room. Red arrows signify the fire scenario under analysis

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 $Q_{s.c}$. 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 m^2, 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:

$$d_{11} = \frac{P_{\text{m(allow)}} - P_{\text{m}}(t)\left(1 + \frac{1.0028}{\sigma_P\sqrt{2\pi}}\exp\left[\frac{-(P_{\text{m}}(t) - M_P)^2}{2\sigma_P^2}\right]\right)}{P_{\text{m(allow)}}} \times$$
$$\times Q_{\text{m}}\left(1 - K_{\text{r(EDS)}}\right), \quad (12)$$

$$d_{21} = \frac{N_{\text{overall(allow)}} - N_{\text{overall}}(t)\left(1 + \frac{1.0028}{\sigma_N\sqrt{2\pi}}\exp\left[\frac{-(N_{\text{overall}}(t) - M_N)^2}{2\sigma_N^2}\right]\right)}{N_{\text{overall(allow)}}} \times \quad (13)$$
$$\times\left(1 - K_{\text{r(ACS)}}\right)\left(1 - K_{\text{r(EDS)}}\right).$$

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.

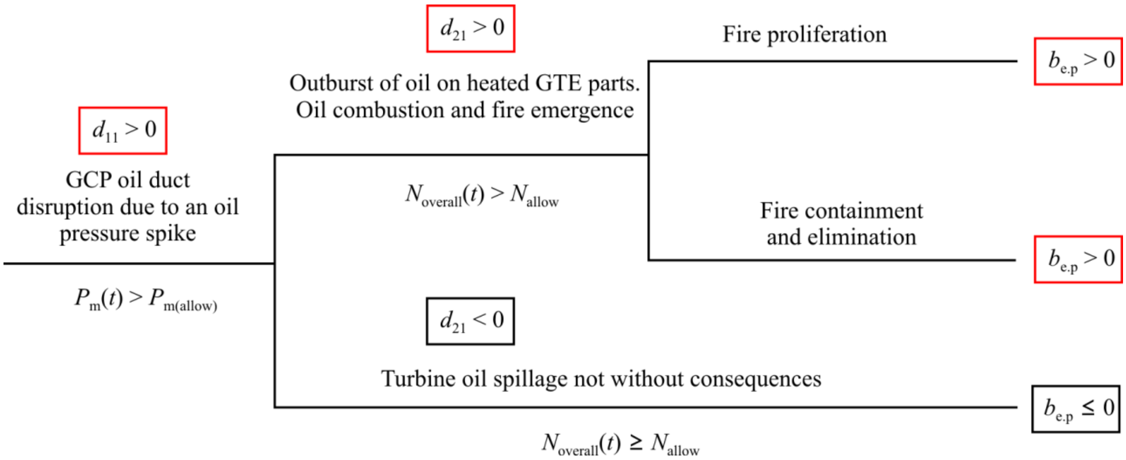

Fig. 3. Event tree for fire scenario emerging as a result of oil combustion from heated GTE parts

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