DOI: http://doi.org/10.25728/cs.2022.1.1

PROBLEMS OF MANAGING THE FIRE SAFETY SYSTEM OF A FACILITY. PART I: ASSESSMENT METHODS

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Abstract. The scope and capabilities of managing the fire safety system of a facility from the position of its representative (head) are overviewed. Part I of the survey is devoted to the general problem statement and methods to assess the fire safety of a facility and the safety of people inside a building. As shown, fires and deaths of people testify to certain problems either in the facility's fire safety system or in the management of such a system. The existing methods for assessing the fire safety of a facility cannot be applied by its head: they require deep knowledge of the subject matter as well as the corresponding qualifications and tools (computer programs). In the current situation, the head (decision-maker) has no formalized objective assessment of the fire safety of his or her organization at a particular time, which significantly complicates (or even disables) rational decision-making.

Keywords: fire safety, management, facility assessment, fire safety system, fire risk.

INTRODUCTION

Each facility must have a fire safety system (FSS) to prevent fire, ensure people's safety, and protect property in the event of a fire.

Based on the purpose of this system, it is reasonable to choose the prevented fire and the absence of deaths (injuries) of people as assessment criteria. However, as shown by analysis, despite the general trend of reducing the number of fires, they still cause many deaths (at least 7000 people annually) and significant damage, exceeding 15 billion rubles annually [1]. At least 90% of people die in fires due to violations of fire safety codes and careless handling of fire. These factors generally determine the managerial aspect of the problem.

According to qualitative analysis of large fires, the main causes of fires resulting in mass deaths are violations of fire safety codes (careless handling of fire, smoking in unauthorized places, fireworks, etc.) or electrical wiring malfunction. One way or another, these problems are related to organizing fire safety at facilities.

The main causes of deaths and injuries are either the absence (disabling) of fire alarm and warning or the lack of necessary evacuation measures (mechanical blocking of evacuation exits and poorly organized evacuation). Like fire, death and injury have causes in organizing and managing the fire safety of facilities.

Thus, there are specific problems either with the fire safety system of facilities or with the management of this system.

A retrospective survey of the existing fire safety system of facilities, its operation specifics, and organizational and managerial aspects [1] showed that this system developed very slowly, and management areas were not considered for it (reduced to specifying organizational and technical measures). At the same time, there is no document regulating the management of this system, criteria for assessing the current state of the system, or its management mechanisms. Presently, the concept of a fire safety system as a controlled object is absent: this procedure is not described, there are no criteria for assessing the efficiency of fire safety systems, and the heads of organizations do not understand what they need to manage.

This paper overviews the scope and capabilities of managing a facility's fire safety system from the position of its representative (head). The survey consists of two interrelated parts. Part I is devoted to methods for assessing the fire safety of a facility and the safety of people inside it. We begin by describing the fire safety system of a facility.

1. THE FIRE SAFETY SYSTEM OF A FACILITY

Russia's current legislation[1] requirements determine the need for a fire safety system for each facility. Figure 1 presents the structure of a fire safety system.

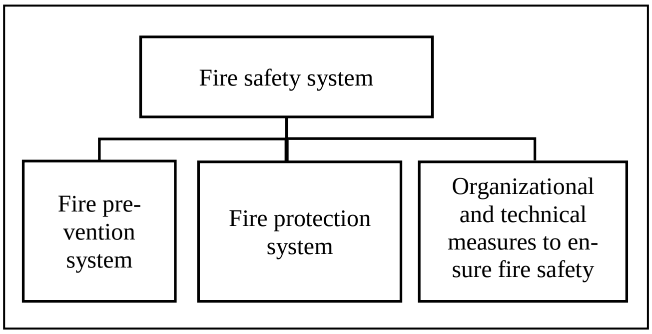

Fig. 1. Structure of the fire safety system of a facility.

An FSS consists of three main subsystems: a fire prevention system, a fire protection system, and organizational and technical measures to ensure the facility's fire safety. Let us consider them in detail.

The purpose of fire prevention systems is to exclude the conditions of fire occurrence by excluding the conditions for forming a combustible environment and (or) excluding the conditions for forming inflammation sources[1] in the combustible environment (or introducing such sources into it).

Conditions for forming a combustible environment are excluded by the following methods:

– using non-combustibles;

– limiting the mass and (or) volume of combustibles;

– using the safest methods to arrange combustibles and materials whose interaction may form a combustible environment;

– isolating a combustible environment from inflammation sources (using insulated compartments, chambers, or cabins);

– maintaining a safe concentration of oxidizers and (or) combustibles in the environment;

– reducing the concentration of oxidizers in the combustible environment in the protected volume;

– maintaining the temperature and pressure of the environment under which flame propagation is excluded;

– mechanizing and automating technological processes related to the handling of combustibles;

– installing fire-potential equipment in separate premises or open areas;

– using protective devices for production equipment that prevent combustibles from escaping into the premises or devices that prevent the formation of a combustible environment in the premises;

– removing fire-potential industrial waste, dust, and fluff from the premises, process equipment, and communications.

Conditions for forming inflammation sources in a combustible environment (or introducing such sources into it) are excluded by the following methods:

– using electrical equipment corresponding to the class of fire and (or) explosive zone and the category and group of an explosive mixture;

– using fast-response protective cutout devices for power plants or other devices that exclude the appearance of inflammable sources;

– using equipment and technological process modes with protection against static electricity;

– designing the lightning protection of buildings, facilities, and equipment;

– maintaining a safe heating temperature for substances, materials, and surfaces that come into contact with a combustible environment;

– using means and devices to limit the spark energy in the combustible environment to safe values;

– using spark foolproof tool ware when working with flammable liquids and combustible gases;

– eliminating conditions for thermal, chemical, and (or) spontaneous microbiological inflammation of circulating substances, materials, and products;

– excluding contact of pyrophoric substances with the air;

– using devices that exclude the possibility of flame propagation between adjacent volumes.

The purpose of fire protection systems is *to secure people and property against fire hazards and (or) limit the consequences of fire*. This purpose is achieved by the following methods:

– using space-planning solutions and means to limit the spread of fire beyond the hearth;

[1] Federal Law of the Russian Federation of July 22, 2008, No. 123-FZ "Technical Regulations on Fire Safety Codes."

– arranging evacuation routes that meet the requirements of the safe evacuation of people in the event of a fire;

– arranging fire detection systems (fire alarm devices and systems), warning and evacuation control in the event of a fire;

– using collective protection systems (including smoke protection) and personal protective equipment against fire hazards;

– using basic building structures with fire resistance limits and fire hazard classes corresponding to the required degree of fire resistance and structural fire hazard class of buildings and facilities; limiting the fire hazard of surface layers (finishes, facings, and fire protection means) of building structures on the evacuation routes;

– using fire retardants and building materials (facings) to increase the fire resistance limits of building structures;

– arranging the emergency drainage of flammable liquids and emergency bleeding of combustible gases from the equipment;

– arranging anti-explosion protection systems on the technological equipment;

– using primary fire extinguishing equipment;

– using automatic and (or) autonomous fire extinguishing systems;

– organizing the activities of fire protection units.

Generalizing these subsystems, we form a tree of FSS goals (Fig. 2).

According to the presented structure of the FSS, the goals of all subsystems, and methods for achieving them, the initial task is to prevent fire (assigned to a fire prevention system). If this task is not solved (a fire occurs), a fire protection system is activated. At the same time, the goals of organizational and technical measures to ensure fire safety and ways to achieve them are established (Fig. 2). However, such methods

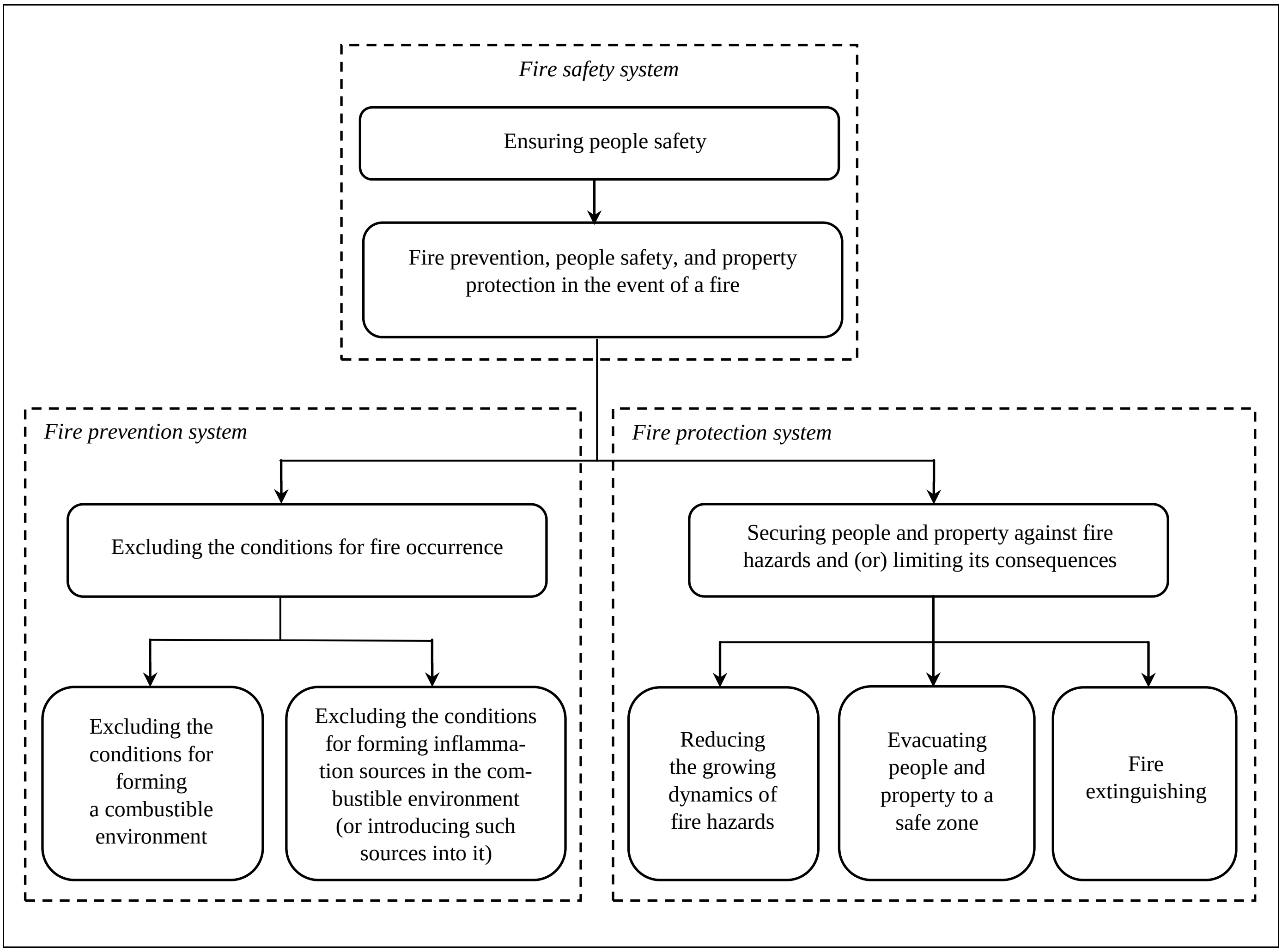

Fig. 2. The fire safety system of a facility: the tree of goals.

were previously formulated in several documents.[2,3] They included:

– developing an action plan for the administration, workers, employees, and population in the event of a fire (particularly evacuation of the people);

– making and using visual aids for fire safety;

– rationing the number of facility's employees based on safety conditions in the event of a fire;

– and others.

Note that similar requirements are now contained in the rules of the fire protection regime in the Russian Federation.[4] They are presented as a list of fire safety codes defining people's behavior, the order of production organization, and (or) maintenance of territories, buildings, facilities, premises, and other objects of organizations to ensure fire safety. Nevertheless, the goals of this set of codes are not formulated. The fire safety system was first introduced in 1977, and its structure has undergone no significant changes since then.[5] Requirements for the subsystems were refined from edition to edition. Very little attention was paid to organizational and technical activities within the system. There were changes in the criteria for assessing the system's operation, but the quantitative value of the assessment criteria was not changed and amounted to $1 \cdot 10^{-6}$. The facility's head manages the system and has the personal responsibility for observing the fire safety codes. Therefore, it is necessary to consider the entire process of state fire safety regulation and the organizational scheme of management.

Generalizing the analysis results and the facility's fire safety management system (the structural scheme in Fig. 3) [1], we make the following conclusions. In the form of requirements of federal legislation, supervisory authorities, etc., the environment obliges the facility's head to manage its fire safety system. The controlled system is the facility's fire safety system.

At the same time, in the classical statement of a control problem [2], the facility's head must carry out appropriate control actions based on the controlled system state (the facility's fire safety). From the legislative point of view, the controlled system state is characterized by obligatory fulfillment of fire safety codes and individual fire risk value or full compliance with all fire safety codes. In other words, at any time (the system is dynamic), the facility's head must monitor

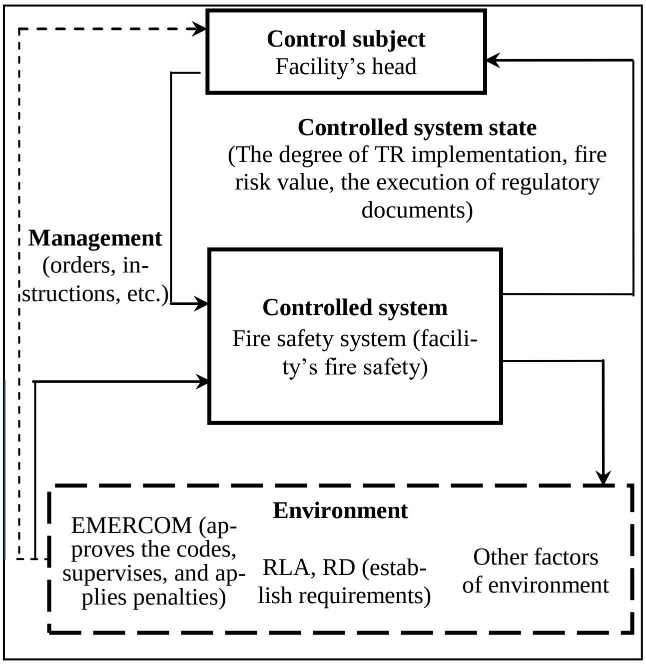

Fig. 3. The existing structure of the facility's fire safety management system: TR—technical regulations, RLA—regulatory legal acts, and RD—regulatory documentation.

the controlled system state and, if necessary, make managerial decisions to bring it to an appropriate state.

In addition, note that the facility's head has the right to appoint persons responsible for fire safety in the organization.[4] In this case, an organizational structure is formed; see an example in Fig. 4.

One way or another, being responsible for ensuring fire safety, the facility's head deals with the need to have extensive knowledge in fire safety. In Russia, the State Fire Supervision Service of EMERCOM is traditionally believed to be responsible for ensuring fire safety. However, it is not the case. The Service only controls (supervises) how the fire safety codes are observed. Thus, the facility's head is personally responsible for fire safety in the organization. Several large, high-profile fires in the last decade have shown that if people die or get injured in a fire, the facility's head bears criminal liability. As a rule, the facility's head or the person responsible for fire safety has only a superficial knowledge of fire safety, worsening the situation. However, note that qualification requirements[6] are currently being established for personnel responsible for fire safety (including a degree in fire safety), which would improve the situation.

At the same time, a profile education does not guarantee the result. The paper [3] assessed the reliability of specialists with experience from three to five years with a profile education in fire safety. Reliability

[2] GOST (State Standard) 12.1.004-85: The System of Labor Safety Standards. Fire Safety. General Requirements.

[3] GOST (State Standard) 12.1.004-91: The System of Labor Safety Standards. Fire Safety. General Requirements.

[4] Decree of the Government of the Russian Federation of September 16, 2020, No. 1479 "On Approval of the Rules of the Fire Protection Regime in the Russian Federation."

[5] GOST (State Standard) 12.1.004-76: The System of Labor Safety Standards. Fire Safety. General Requirements.

[6] Draft law No. 1188754-7 "On Amendments to Articles 24 and 37 of the Federal Law 'On Fire Safety.'"

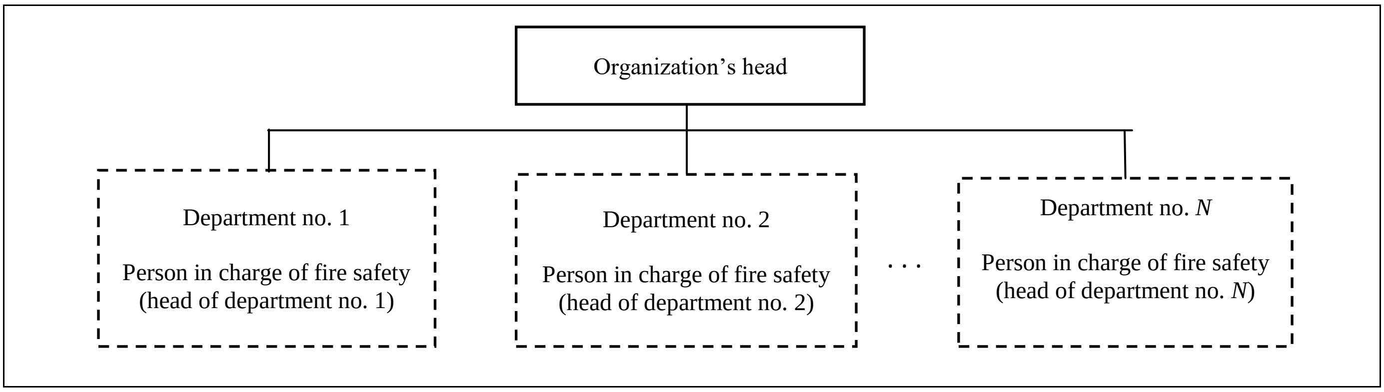

Fig. 4. The organizational structure of an enterprise in terms of fire safety (*N* is the number of departments in the organization).

was determined by the difference between the detected number of violations of fire safety codes and their total number on the example of a particular facility. The results showed that such a specialist could identify only 16–20% of the total number of violations.

In the current practice of fire safety, the situation develops as follows. After commissioning or when taking its office, the head receives a facility with an already defined set and structure of fire protection systems. Being responsible, he or she controls fire protection systems and organizes evacuation drills, periodic training, and briefings. With an irresponsible approach, he or she does not. It seems that the reason lies not even in the unwillingness of the head to manage the fire safety of the facility but rather in the impossibility of assessing the state of fire safety to make appropriate decisions. We consider the existing methods for assessing the facility's fire safety to verify this assertion.

2. METHODS FOR ASSESSING THE FIRE SAFETY OF A FACILITY AND THE SAFETY OF PEOPLE INSIDE THE BUILDING

2.1. Fire safety assessment based on Russian legislation

At present, several approaches exist to assess the compliance of facilities with fire safety codes in Russia. Strictly speaking, it is necessary to separate the fire safety of the building and the safety of people in case of a fire as its most important component. The legislation establishes forms for assessing the compliance of facilities with fire safety codes, which include:

– independent fire risk assessment (fire safety audit),

– the Federal State Fire Supervision,

– fire safety declaration,

– acceptance and commissioning of the facility and fire safety systems.

The forms mentioned above are chosen only for facilities and not products. The facility's head can initiate only independent fire risk assessment (fire safety audit). Moreover, it is a commercial service: the fire safety of a facility is confirmed by a specialized organization.

Regardless of the form of confirmation for the building, there exist two conditions for compliance with the fire safety codes:

– the fire safety codes of technical regulations are fully met, and the fire risk does not exceed the feasible value (for public facilities, $1 \cdot 10^{-6}$),

or

– the fire safety codes of technical regulations and regulatory documents on fire safety are fully met.

If one of the conditions is satisfied, the facility (in terms of legislation) is considered safe against fires. All conditions include compliance with the requirements of technical regulations, which establish general compulsory fire safety codes for fire distances, evacuation routes, evacuation and emergency exits, fire resistance of the building, etc. Usually, these are general requirements without specific statements (like, e.g., the value of a parameter *X* for a group of facilities *Y* must be at least *Z*): they just establish the need for something (e.g., buildings of class *X* must have a system of type *Y*). Thus, these conditions are prescriptive and imply that the facility is safe concerning the factor in question if they are met. This form of assessment is directive. The second part of the conditions is variable and also directive. It establishes that if all standards are met, then the facility is safe. However, an advanced tool in this area is the second part of the first condition, which establishes that only general requirements can be met, while the fire risk should not exceed $1 \cdot 10^{-6}$.

Fire risk assessment in domestic practice is carried out based on the corresponding methodology[7] for calculating the fire risk in buildings, constructions, and structures of different classes of functional fire hazard (further called the Methodology), approved by EMERCOM. As a rule, the Methodology involves computer programs.

The Methodology for calculating the fire risk is a set of procedures and their sequence, including the stages shown in Fig. 5.

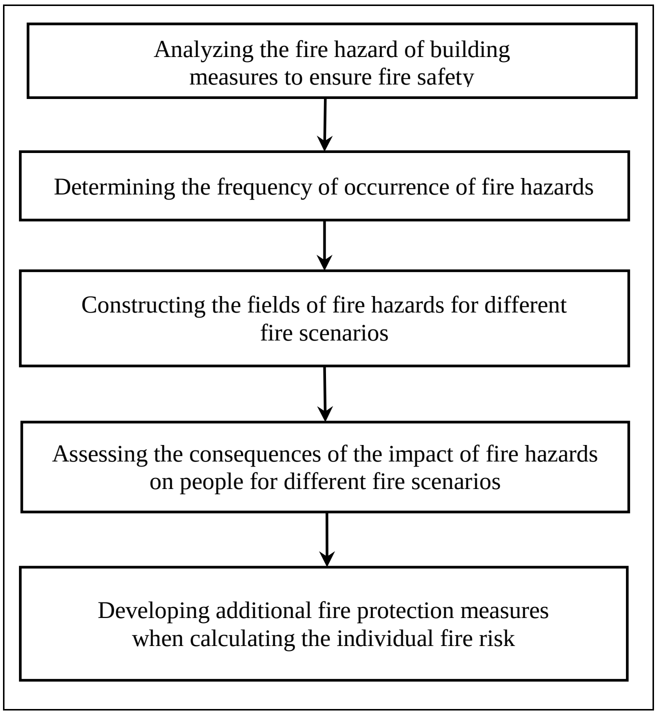

Fig. 5. Fire risk assessment stages.

The safety condition is given by the inequality

$$Q_{\text{risk}} \le Q_{\text{risk}}^{\text{norm}}, \quad (1)$$

where Q_{risk} is the calculated individual fire risk, and $Q_{\text{risk}}^{\text{norm}}$ is the individual fire risk norm.

The risk value is calculated by the formula

$$Q_{\text{risk},i} = Q_{\text{fire},i} \cdot \left(1 - K_{\text{fire-fight},i}\right) \cdot P_{\text{people},i} \cdot \left(1 - P_{\text{evac},i}\right) \cdot \left(1 - K_{\text{fire prot},i}\right)$$

with the following notations: $Q_{\text{risk},i}$ is the individual fire risk in the *i*th fire scenario; $Q_{\text{fire},i}$ is the frequency of fires in the building during the year; $K_{\text{fire-fight},i}$ is the coefficient describing the compliance of automatic fire-fighting systems with the requirements of the fire safety regulations; $P_{\text{people},i}$ is the probability of people's presence in the building; $P_{\text{evac},i}$ is the probability of people's evacuation; $K_{\text{fire prot},i}$ is the coefficient describing the compliance of the fire protection system, aimed to ensure the safe evacuation of people in a fire, with the requirements of the fire safety regulations.

Then, the maximum value among all $Q_{\text{risk},i}$ is taken and compared with the norm (the expression (1)).

The Methodology provisions were discussed many times. Therefore, we consider only some of them.

According to several researchers, the Methodology requires substantial revision [4] due to the following drawbacks:

– The probability of fire is not determined for some buildings, and there are no recommendations on its choice.

– There are contradictions in the choice of the parameter P_{people}.

– There are no data and conditions for choosing the type of human clothing (this determines the projection area in the calculations) and fire load (including the criteria for choosing this load).

– It is unclear how many scenarios to consider and under what conditions to select the blocking of the evacuation exit.

– Several parameters are not considered (fire passages, fire distances, drencher curtains, outdoor water supply, personal protective equipment, etc.).

As determined, the Methodology should be improved by developing an indicator of the quality of fire protection systems and differentiated values of fire risk. According to the Law,[8] the risk value should confirm the fire safety of the facility, people, and property. However, the indicators in the calculation formula indirectly determine the risk value for people and property. The fire community (experts and supervising bodies) believes [4] that the fire risk is a tool of justification of deviations concerning the parameters of evacuation ways, and it is not an indicator of the facility's safety.

There is evidence [5] that Russia's individual fire risk norm is significantly underestimated and requires revision. The variables figuring in the expression (1) and their values and determination methods are ques-

[7] Order the Ministry of the Russian Federation for Civil Defense, Emergencies and Elimination of Consequences of Natural Disasters of June 30, 2009, No. 382 "On Approving the Methodology for Calculating Fire Risk in Buildings, Facilities, and Constructions of Different Classes of Functional Fire Hazard."

[8] Federal Law of the Russian Federation of July 22, 2008, No. 123-FZ "Technical Regulations on Fire Safety Codes."

tioned. The acceptable (normative) risk level is debatable. As mentioned earlier [6], fire risk is too abstract for life and, therefore, difficult to express understandably and acceptably for society.

Generally speaking, the Russian approach to assessing the safety of people has been repeatedly criticized (particularly in the paper [7], where proposals to improve the procedure for assessing the safety of people inside the building were presented). As described therein, the reaction time significantly affects the total evacuation time; the factors affecting the time to start evacuation were listed. According to some evidence, the facility's personnel (constantly trained) do not always behave adequately when the fire alarm system is triggered, looking for confirmation information, not starting the evacuation, etc. In addition, the person's decision to evacuate is made by perceiving incoming information about the presence of fire signs and comparing a set of factors determining the probability of fire and the truthfulness of this information. In other words, a person to decide must overcome a certain threshold ("really happened fire" vs. "false alarm"). Then the evacuation management problem reduces to bringing this threshold closer by any means as soon as possible. The following idea was proposed in the paper: correction factors can be applied to the fire risk value, e.g., if the personnel are familiar with the evacuation plan. As also argued, the methodology for determining the fire safety level overestimates the time to evacuate people in a fire.

Thus, the state-level approaches to assess the fire safety of a building consist in either fulfilling all the requirements of fire safety codes or fulfilling the compulsory codes and calculating the fire risk (assessing the individual risk of death in a fire). At the same time, the procedure of calculating this risk has been repeatedly criticized and objectively requires improvement.

2.2. Domestic approaches to fire risk assessment

Consider the approaches to assessing fire safety developed by domestic researchers.

One approach under development is express fire risk assessment [8–12]. It reduces mathematical models describing a fire hazard to a simpler form (many indicators are generalized to three or four ones). As a result, they can be calculated by any specialist of basic qualification without special software. In other words, calculations can be performed when examining the facility using simple technical devices (cell phone, calculator, etc.).

Another way to assess the facility's safety is the scenario approach: baseline scenarios of a particular emergency are studied [13]. For each baseline scenario, safety aspects associated with it are identified, and each aspect is assigned a certain number of factors affecting this scenario. Then an operator multigraph is used to construct the relationship of successive events of an emergency, and its consequences are assessed and predicted by simulation methods. This approach was tested for a station of the Moscow subway [14].

A disadvantage of this approach (in terms of fire safety) is a significant simplification of the processes occurring during fire growth. For example, the scenario approach does not consider the dynamics of fire hazards directly: calculations require preliminary modeling of fire hazards (FHs) and an array of critical values of FHs at each calculation point. The data on the evacuation of people are also taken incorrectly. For example, evacuation speed is defined as 3 persons per second (healthy people) and 2 persons per second (injured people), linearly on the entire segment [15]. In contrast, the fundamental law in the evacuation of people is a logarithmic dependence of evacuation speed on the human flow density [16, 17]; this density is determined by the geometric dimensions of evacuation routes, which are not considered within the scenario approach. Hence, this approach is appropriate for forming development scenarios and not assessing their consequences (at least in terms of fire safety).

Note the mechanisms for assessing the safety of potentially dangerous facilities [18, 19] based on the theory of active systems [20]. For its implementation, decision trees and bottom-up aggregation are used. The main stages include selecting directions that characterize the facility's state, assessing the facility by these directions, performing convolution, and obtaining a comprehensive assessment of the facility's state. In general, this approach is promising for fire state assessment due to its simplicity, efficiency, and wide approbation in various areas [21–23].

Several studies [24, 25] were devoted to index methods for fire risk assessment, particularly the Gretener method. The cited authors adapted the method to the Russian conditions (preliminary fire safety assessment, analysis of the probability of fire, etc.) However, the method was not systematically described to evaluate its efficiency. This method will be considered in detail in subsection 2.3 below.

Another fire risk assessment method involves the classical definition: the fire risk is defined as the probability of event occurrence multiplied by the expected damage [26–29]. In particular, the following typification is considered: the risk of encountering a fire, the risk of dying in a fire, the risk of destroying a structure, etc. Thus, fire risk is generalized, often at the strategic level (scale), using mathematical statistics methods. Considering such assessment directly for the facility, we obtain the expected risk of fire or damage (but not its quantitative estimate) based on the facility's characteristics.

2.3. Foreign approaches to assessing fire safety

Fire safety assessment methods in the foreign scientific literature are analyzed much wider and deeper. There are different requirements, guidelines, and approaches to assessing fire risk.

The regulation of fire safety (in general) and risk calculations (in particular) considerably varies abroad. Only the basic part of fire safety codes is established and regulated at the state level. Another feature is the approach called *performance-based design*. It is defined [30] as "an engineering approach to fire protection design based on agreed upon fire safety goals, loss objectives and performance objectives, deterministic and probabilistic evaluation of fire initiation, growth and development, the physical and chemical properties of fire and fire effluents, and quantitative assessment of design alternatives against loss and performance objectives."

Consider the regulated methods for assessing fire safety through fire risk analysis.

The Society of Fire Protection Engineers (SFPE) Guide [31] establishes general requirements for fire risk assessment. This guide is intended for professionals in construction and process design. In particular, it provides a recommended assessment procedure, hazard identification methods, data sources, and risk modeling and calculation methods.

In the US, *the National Fire Protection Association* (NFPA) developed a fire risk assessment guide [32] containing a sequence of steps to be followed by a professional. The guide provides well-developed risk assessment and analysis methods with input and output data, model assumptions and constraints, scenario selection methods, etc.

In the UK, a fire risk assessment standard was developed [33]. Like the guides discussed above, it provides a methodological framework for the professional to analyze and assess risk. In contrast to the standards mentioned above, this document establishes risk acceptance criteria and describes methods for assessing financial losses.

The International Organization for Standardization (ISO) also developed a standard conceptually describing the risk assessment procedure [34]. The document describes the risk assessment procedure, the principles of risk assessment, and uncertainty analysis methods. An essential difference of this standard is recommendations to interpret the risk assessment results.

Interestingly, in Germany, the procedure for regulating risk assessment at the legislative level is just emerging, and a corresponding standard is being developed [35].

Now we discuss methods and approaches developed for fire risk assessment.

Hazard and Operability Study (HAZOP) is a risk analysis method to identify situations entailing the failure of any elements or the entire system and assess the consequences of such failures [36]. Generally speaking, it is not intended for fire risk assessment but can be used to identify potential fire elements of a building or fire potential processes.

Failure modes and effects analysis (FMEA) and *Failure mode, effects and criticality analysis* (FMECA) are methods for analyzing failures (usually, technical elements without human factors) and the consequences of such failures and determining their criticality [36]. These methods are rarely used within the fire risk assessment procedure. Nevertheless, attempts were made [37] to adapt FMEA to fire risk assessment by synthesizing this method with fuzzy logic theory on the example of a railway tunnel. As a result, two types of risks contributing to fire and causing tragic consequences were established.

Event tree analysis (ETA) and *Fault tree analysis* (FTA) are methods to identify hazard and failure scenarios. For their application, it is necessary to construct trees with the probabilities of transition to downstream events. The probability of the resulting event is defined as the product of the probabilities preceding the given branch. The approaches mentioned above can be referred to as quantitative or qualitative risk assessment methods, depending on whether the probabilities of transition between events are assigned or not. They are often used for fire risk assessment, usually at the stage of identifying potential causes of an accident or constructing fire growth scenarios [38–42]. In addition, note that these methods are often used to assess the fire risk at production facilities.

FN-curves describe risk analysis results (frequency and consequences): a risk curve shows the probability of N or more deaths per year as a function of the event frequency F on a double logarithmic scale [43]. This value is often used to assess collective risk, mainly at production facilities [44, 45].

As low as reasonably practicable (ALARP) is a fundamental principle rather than a method to minimize risk. This principle was originally formulated in 1954 by the International Commission on Radiological Protection and was actively used to ensure the safety of nuclear power plants. Indeed, many experts [46–50] agree that achieving zero risk is not practicable due to various uncertainties, the interrelation of risks, etc. For fire risk assessment, this principle was rarely applied. Note the recent paper [49], where the ALARP principle was applied to fire risk assessment and tested on selecting an automatic water fire-fighting system and determining the size of the evacuation exit.

Fire Safety Concept Tree (FSCT) is a concept for assessing fire hazards and their consequences [51] based on two obligatory basic components, namely, fire prevention and consequence management. Like in ETA and FTA, a tree structure is used, but the probabilities of transition are not specified.

Simple Analysis Fire Risk Evaluation (SAFRE) is an approach based on the construction of failure and event trees, intended to assess the fire risk of cultural heritage buildings. It identifies possible fire growth scenarios and examines probable consequences [52].

The Gretener method [53, 54] is an index fire risk assessment method widely used in practice. It has undergone many changes and variations [55–60]. Initially, the fire risk measure was the product of the probability of an event and the degree of its hazard; the hazard was defined as the ratio of the potential hazard to the protective measures [53].

In this method, the fire risk is calculated as

$$R = A \times B,$$

where A is the probability of a fire, and B is the fire hazard (its level or the degree of consequences).

The fire hazard is given by

$$B = P / (N \times S \times F),$$

where: P is the potential fire hazard; N, S, and F are the aggregate indicators characterizing standard fire safety measures, special fire safety measures, and the fire resistance of the building, respectively.

The Carleton University model [61] is a quantitative fire risk assessment method implemented in the computer program CUrisk. This approach was developed mainly for buildings with wooden frames. The approach estimates the following parameters:

– fire growth scenarios (based on event trees),

– the dynamics of FH development (based on the *CFAST* model [62]),

– the stability of wooden structures (estimated during fire exposure based on the *WALL2D* model [63]),

– the evacuation of people (no model specified),

– the actions of fire units (no model specified),

– economic damage (no model specified).

The computer program calculates *the expected risk to life* (ERL) [64] and *the expected risk of injury* (ERI) [61] in case of deaths and disabilities.

The Edinburgh Risk Assessment Model is a matrix concept for assessing fire safety developed at the University of Edinburgh for hospitals [65]. It represents a hierarchy of matrices at the following levels:

1. the facility's fire safety policy,
2. the goals (tasks) of the facility's fire safety,
3. the strategy of ensuring the facility's fire safety,
4. the facility's fire safety components.

As stated, this approach assesses the fire safety of any facility; if necessary, additional levels of the hierarchy can be introduced to detail any component. At each level of the hierarchy, a matrix of comparisons of fire safety factors at each level is compiled. Then a relationship between the levels is established. As a result, the relationship between the components is traced at the system level. Currently, this method is developing [66, 67].

As a rule, the risk assessment approaches discussed above are particular and have a fundamental component affecting the resulting risk value. Let us consider complex approaches combining several methods.

The Australian Centre for Environmental Safety and Risk Engineering developed CESARE-Risk, a fire risk assessment method extending Australian building codes [68]. This method is intended for officials and engineers to select cost-efficient fire safety measures at an acceptable level of risk. It includes the following steps.

1. Forming an event tree for developing fire scenarios. Note that the current state of the building, the probability of a fire, the characteristics of people in the building, the availability of fire protection, and other factors are considered.

2. Fire growth modeling. An original fire growth model was used [69].

3. Evacuation modeling, including the people's reaction to a fire warning, a routing model (people can change their direction if there is smoke or open flame on their way), and the presence of people under alcohol or drugs.

4. Fire-fighting modeling: the arrival of fire crews to a building and the deployment of resources are simulated using event trees. Depending on prevailing conditions, fire extinguishing, people's search and rescue missions, and fire localization and elimination are also simulated.

5. Building stability modeling. The service time of building structures and the emergence of a limit state for fire resistance are predicted. See the publication [70] for a detailed description of this method.

FiRECAM was designed to quantify the fire risk in residential buildings and offices in accordance with Canadian fire safety codes [71]. This approach calculates the expected risk to human life and the expected fire damage for each fire scenario; based on these values, the fire safety concept is accepted or revised. It includes the following steps.

• Six fire types for each floor are considered fire growth scenarios: three types of combustion (smoldering combustion, flame combustion inside the premises, and flame combustion going outside the premises) and two door states (open or closed). The probabilities of different fire types are assigned using statistical data.

For example, according to the data presented in [72], fires in buildings have the following dynamics: 22% of fires are smoldering combustion without further growth, 54% of fires are flame combustion inside the premises, and 24% of fires are flame combustion going outside the premises.

- The probability of fire occurrence is estimated if the building is not typical and there are no data on the frequency of fires. In this case, the probability of fire occurrence is estimated based on several factors (the type and combustibility of materials, potential sources of fire, maintenance of fire protection systems, etc.).
- Fire growth is modeled to estimate the time of occurrence of fire hazards.
- The stability of building elements is modeled based on thermal effects to estimate the probability of fire spreading inside the building considering the operability of the automatic fire-fighting system.
- People's evacuation is described by the model [73], which considers the reaction time, situations when people are blocked inside the building, etc.
- The actions of the fire-fighting crews are modeled considering the movement time and response time and the possibility of rescuing people blocked inside the building.
- The fire safety costs are assessed for each fire scenario as its probability multiplied by the expected amount of damage.
- The probability of people's death is estimated by comparing the FH spread and their movement routes. The presence of a balcony nearby or a fire-safe zone is considered. See the publication [74] for a detailed description.

CRISP is a fire risk assessment approach based on simulation and the Monte Carlo method. It determines the conditions of safe evacuation by comparing the blocking time of evacuation routes and evacuation time. This approach is less comprehensive than the previous ones but advanced compared to Russia's current Methodology. In particular, much attention is paid to the stochasticity of processes (random processes and random initial conditions). In the course of multiple modeling, the probabilities of death and injury are calculated through the *fractional effective dose* (FED) [75]. This method was considered in detail in the paper [76].

Lund QRA is another risk assessment method developed at Lund University. It has two versions: standard and extended. Their principal difference consists in considering the random nature of the variables: in the extended version, the risk is calculated by the standard method with Monte Carlo simulations. The event tree is used to construct the fire growth scenarios. Each outcome in the event tree has a set of probabilities and consequences, called the Kaplan and Garrick triplet. The risk assessment results are presented in FN-diagrams or a risk profile on a logarithmic diagram. Human risk is generally defined as a "safety margin" (the conditions for safe evacuation). This method was described well in the publication [77].

We draw several conclusions based on the analysis of various methods for assessing the facility's fire safety and the safety of people inside the building in a fire.

- Under the form established by the legislation of the Russian Federation, the facility's compliance with fire safety codes (over 100 000 in total [3]) is assessed. As a result, the fire risk can be assessed, but the corresponding Methodology needs significant revision.
- As shown by the survey, foreign fire and human safety assessment approaches are strongly developed and deeply elaborated. Most likely, this is due to the absence of "tough" state regulation in fire safety.
- All approaches considered are probabilistic. Strictly speaking, the calculation results are relevant only for the conditions accepted and neglect the dynamically changing environment.
- Despite many approaches to fire safety assessment, they are difficult to implement for the facility's head: he or she needs deep knowledge of the subject matter and the availability of appropriate qualifications and tools (computer programs).

CONCLUSIONS

Concluding part I of the survey, we note the following.

- As shown by the statistical data on fires in the Russian Federation, the number of deaths is high, and the damage from fires exceeds 15 billion rubles annually. The majority (90%) of people die in fires due to violations of fire safety rules and careless handling of fire. Hence, there are problems in managing the facility's fire safety. Qualitative analysis of fires with mass death confirms this conclusion since the main causes of fire, mass death, and injuries are violations in the facility's fire safety organization and management.
- Currently, the fire safety system as a controlled object is absent at the conceptual level. The corresponding procedure is not described, there are no criteria for assessing the efficiency of the fire safety system, and the facility's head does not understand what he or she needs to manage.
- Despite numerous approaches to fire safety assessment, their application requires deep knowledge of the subject matter and appropriate qualifications and tools (computer programs). Thus, the facility's head

cannot assess the security of his or her organization (facility) without qualified specialists.

Part II of the survey will consider methods to monitor the facility's fire safety and assess the state of socio-economic systems in fire safety. The existing contradictions in the fire safety management system will be shown, and some ways to resolve them will be presented.

Acknowledgments. *The author is grateful to the reviewers for careful reading of the manuscript and helpful remarks.*

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This paper was recommended for publication by V.V. Kul'ba, a member of the Editorial Board.

Received July 19, 2021, and revised November 1, 2021.
Accepted November 22, 2021.

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Cite this paper

Shikhalev, D.V. Problems of Managing the Fire Safety System of a Facility. Part I: Assessment Methods. *Control Sciences* **1,** 2–14 (2022). http://doi.org/10.25728/cs.2022.1.1

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