FACTA UNIVERSITATIS
Series: **Working and Living Environmental Protection** Vol. 21, Nº 2, 2024, pp. 109 - 117
https://doi.org/10.22190/FUWLEP240830010S

Original Scientific Paper

FIRE RISK ASSESSMENT IN HAZARDOUS MATERIALS WAREHOUSES

UDC 614.841.47:620.26

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Abstract. *Fire protection in hazardous materials warehouses is based on a complex analysis of calculations and the current state to determine appropriate protection measures. This paper explores the fire hazards associated with storing hazardous materials in a warehouse setting. It provides a detailed assessment of potential risks, focusing on the unique challenges posed by the nature of the materials stored. The study examines various factors that contribute to fire risk, including the flammability of materials, storage conditions, and existing fire prevention measures. The objective is to identify critical vulnerabilities and propose strategies for enhancing safety and reducing the likelihood of fire incidents. The findings aim to inform best practices for managing fire risks in hazardous material storage facilities.*

Key words: *fire risks, assessment, warehouse, hazardous materials.*

1. INTRODUCTION

Fire and explosion protection, as a set of preventive and repressive measures and activities, aims to prevent the outbreak and spread of fires, minimize their consequences to the lowest possible level, ensure efficient fire extinguishing, determine the causes and origins of fires and explosions, and assess potential responsibility for failure to take prescribed or required fire and explosion protection measures, as well as detect possible elements of criminal offenses. The ultimate goal is to protect human lives and material

Received August 30, 2024 / Accepted October 11, 2024
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assets [1]. Fire protection refers to measures taken to reduce the likelihood of damage to material assets or injuries to employees [2,3,4,5]. Preventive measures are crucial for preventing the occurrence of fires and minimizing the consequences they cause [6,7,8]. Due to the concept of prevention, the global fire management paradigm is shifting from damage mitigation to proactive action [9]. Accordingly, fire protection management can be divided into four phases: prevention (mitigation), preparedness, response, and recovery [10]. Prevention methods include continuous education of all stakeholders, fire risk assessment, and improvement of fire response infrastructure [11,12,13]. On the other hand, fire risk assessment involves developing prevention plans considering the likelihood and effects of fire occurrence, prevention costs, and the efficiency and availability of resources [14].

There are various methods and procedures for fire risk assessment [15]. The first group of fire risk assessment procedures originated from the research of Swiss engineer Max Gretenar, conducted between 1961 and 1968. Based on the data obtained, Gretenar formulated a fire risk assessment procedure and defined recommendations for implementing minimum preventive fire protection measures, depending on the fire risk. Gretenar's procedure has been modified in several ways. One version was standardized by the Swiss Association of Insurance Companies in collaboration with the Swiss Association of Engineers and Architects under the name SIA 81, with its latest version, SIA 2007, published in 2007. Another version was developed by the Austrian Fire Brigade Association under the name Technical Recommendation TRVB 100. A modification that differs significantly in its calculation procedure from the previous two was also developed by the European Fire Alarm Manufacturers Association. In Belgium, a fourth modification known as FRAME (Fire Risk Assessment Method for Engineering) was developed in 1988. Its new versions were defined in 1999 and 2008. The latest version of FRAME is aligned with the methodology on which the European norms defining machine safety EN 954-1 and EN 14121-1:2007 are based, which were revised and published in 2010 as ISO 12100:2010.

The second group of procedures aims to assess the minimum necessary fire resistance of building structures. The first was developed by Gellinger in 1950 for industrial buildings with metal structures. His procedure was expanded by German engineer Halpap for other industrial buildings. Halpap's procedure was standardized in 1964 in the form of the DIN18230 standard. In our country, this standard was translated as SRPS TR19:1997. New versions of the DIN18230 standard (with expanded tables) were published in 1998 and 2010. In 2012, the SRPS-EN199 1-1-2:2012 standard was adopted, in which Halpap's calculation procedure was modified. The PURT-EUROALARM method was applied to assess the fire risk for a hazardous materials warehouse and define protection measures to proactively improve the fire protection system.

2. METHODS

The fire risk assessment was carried out using the PURT-EUROALARM method, which pertains to the calculation of the fire risk of the building and the fire risk of the building's contents. The PURT-EUROALARM method, though named after its creator, is occasionally referred to by the name of the institution where he was employed—the European Association of Fire Alarm Manufacturers. This method evaluates fire risk by assessing 10 Fire Vulnerability Components, which consider factors such as the susceptibility of structural materials, the impact of smoke, the occupants' vulnerability, and the effectiveness of fire suppression systems [16].

The data related to the fire risk calculation for the hazardous materials warehouse are approximate and based on empirical knowledge.

3. RESULTS AND DISCUSSIONS

The raw materials used in the technological process are stored in a hazardous materials warehouse and are then pumped through a closed pipe system into production. The materials used are mainly organic solvents (Petroleum benzine 60-95, Phenol/Cressol and others). Accordingly, a fire risk assessment for the hazardous materials warehouse has been carried out, based on the intensity and duration of the fire, as well as on the structural characteristics of the building's load-bearing elements, according to Equation 1.

$$R_0 = \frac{(P_0 \times C + P_k) \times B \times L \times S}{W \times R_i} \quad (1)$$

Where is:
R_0 - fire risk of the warehouse;
P_0 - fire load coefficient of the warehouse contents;
C - combustibility coefficient of the warehouse contents;
P_k - fire load coefficient of the materials used in the warehouse construction;
B - size and position coefficient of the fire sector;
L - delay coefficient of the firefighting start;
S - width coefficient of the fire sector;
W - fire resistance coefficient of the warehouse's load-bearing structure;
R_i - risk reduction coefficient.

The fire load coefficient of the warehouse contents (P_0) is determined based on the heat value of all combustible materials in the warehouse in MJ/m², as shown in the following Table 1.

Table 1 Fire load coefficient of warehouse contents (P_0)

MJ/m²	0 - 251	252 - 502	503 - 1004	1005 - 2009	2010 - 4019	4020 - 8038	8039 - 16077	16078 - 32154	32155 - 64309	≥64310
P_0	1	1.2	1.4	1.6	2.0	2.4	2.8	3.4	3.9	4.0

If the calculated total heat value of all combustible materials in the warehouse is 4500 MJ/m², it follows from Table 1 that the coefficient P_0 is 2.4.

The combustibility coefficient (C) is determined according to the fire hazard class, as shown in Table 2.

Table 2 Combustibility coefficient of the warehouse contents (C)

Fire hazard class	VI	V	IV	III	II	I
Combustibility coefficient (C)	1.0	1.0	1.0	1.2	1.4	1.6

The hazardous materials warehouse falls into fire hazard class III. From Table 2, it follows that the combustibility coefficient (C) is 1.2.

The fire load coefficient of the warehouse construction (P_k) is determined based on the heat value of all combustible materials in the building in MJ/m², as shown in Table 3.

Table 3 Fire load coefficient (P_k)

MJ/m²	0-419	420-837	838-1675	1676-4187	≥4188
P_k	0	0.2	0.4	0.6	0.8

The calculated total heat value of all combustible materials in the warehouse is 2500 MJ/m². From Table 3, it follows that the fire load coefficient of the warehouse construction (P_k) is 0.6.

The coefficient of the size and position of the fire sector (B) is determined according to the descriptive characteristics of the warehouse, as shown in Table 4.

Table 4 Size and position coefficient of the fire sector (B)

Characteristics of the building	Fire sector up to 1500 m², room height up to 10 m, a maximum of 3 floors	Fire sector from 1500 to 3000 m², room height from 10 to 25 m, one floor in the basement	Fire sector from 3000 to 10,000 m², room height over 25 m, 2 or more floors in the basement	Fire sector over 10,000 m²
B	1.0	1.3	1.6	2.0

According to the description of the warehouse characteristics from Table 4, the coefficient B is 1.

The delay coefficient for the start of the intervention (L) depends on the equipment and type of fire brigade intervening, as well as its distance from the building, as shown in Table 5.

Table 5 Delay coefficient of the firefighting start (L)

Time until the start of firefighting Distance of the fire brigade		10' 1 km	10'-20' 1-6 km	20'-30' 1 km	≥30' 1-6 km
Type of fire brigade	Professional industrial fire brigade	1.0	1.1	1.3	1.5
	Volunteer industrial fire brigade	1.1	1.2	1.4	1.6
	Territorial professional fire brigade	1.0	1.1	1.2	1.4
	Territorial volunteer fire brigade with permanent duty	1.1	1.2	1.3	1.5
	Territorial volunteer fire brigade without permanent duty	1.3	1.4	1.6	1.8

Based on the optimal time to start firefighting and the distance of the fire brigade from the building, Table 5 indicates that the coefficient L is 1.

The width coefficient (S) depends on the width of the fire sector, as shown in Table 6.

Table 6 Width coefficient of the fire sector (S)

Minimum width of the fire sector [m]	< 20	20-40	40-60	≥60
S	1	1.1	1.2	1.3

Based on the width of the fire sector, Table 6 indicates that the coefficient S is 1.

The fire resistance coefficient (W) of the load-bearing structure depends on the structural characteristics of the building, as shown in Table 7.

Table 7 Fire resistance coefficient of the warehouse's load-bearing structure (W)

Fire resistance in minutes	< 30	30	60	90	120	180	240
Fire resistance coefficient (W)	1.0	1.3	1.5	1.6	1.8	1.9	2.0

Based on the structural characteristics of the building, Table 7 indicates that the fire resistance coefficient W is 1.8.

The risk factor coefficient (Ri) is calculated considering the type of combustible material, storage method, burning rate, and other influencing factors. The fire risk of the building can be reduced depending on the risk factor coefficient, with values provided in Table 8.

Table 8 Risk reduction coefficient (R_i)

Risk	Circumstances affecting the risk assessment	Ri
Maximum	High flammability of materials and storage with larger clearances; expected rapid spread of fire; presence of a higher number of potential ignition sources in the technological process or during storage	1.0
Normal	Flammability is not excessively high, and storage has sufficient clearances for handling; normal rate of fire spread is expected; normal ignition sources are present in the technological process or during storage	1.3
Less than normal	Lower flammability due to partial storage (20-25%) of combustible goods in non-combustible packaging; storage of combustible goods without clearances; rapid spread of fire is not expected; for ground-level halls with an area less than 3000 m²; for buildings where smoke and heat extraction is adequately managed	1.6
Negligible	Low probability of ignition due to goods stored in metal crates or similar materials, as well as very dense storage; very slow fire development is expected	2.0

Based on the type, storage method, and combustion rate of combustible materials, it follows from Table 8 that the coefficient R_i is 1.

Considering the parameters that have been presented the fire risk calculation for the hazardous materials warehouse is:

$$R_0 = \frac{(2.4\times 1.2 + 0.6)\times 1\times 1\times 1.2}{1.8\times 1} = 2.32 \tag{2}$$

The fire risk of the building's contents depends on the potential danger to people, equipment, furniture, stored goods, etc., and is calculated using the following formula:

$$R_s = H \times D \times F \tag{3}$$

Explanation of the formula:
R_s - Fire risk of the building's contents;
H - Coefficient of danger to people;
D - Property risk coefficient;
F - Smoke impact coefficient.

The coefficient of danger to people (H) depends on the possibility of timely evacuation of people from the building and is determined as shown in Table 9.

Table 9 Coefficient of danger to people (H)

Degree of threat	Coefficient of danger to people (H)
There is no danger to the person	1.0
There is danger for people, but they can save themselves	2.0
There is a danger to people, and evacuation is difficult (heavy smoke, a large number of people present, a multi-storey building, rapid fire development, the presence of immobile persons - sick, children, elderly)	3.0

Based on the level of threat and the possibility of timely evacuation of people from the building, it follows from Table 9 that the coefficient H is 2.

The property risk coefficient (D) depends on the concentration of value within a single fire sector, as well as the possibility of replacing the destroyed property, as shown in Table 10.

Table 10 Property risk coefficient (D)

Concentration of value	Property risk coefficient (D)
The contents of the building do not represent significant value or are not highly susceptible to destruction	1.0
The contents of the building have value and are susceptible to destruction	2.0
The destruction of value is definitive and the loss is irreplaceable (such as cultural assets, etc.), or the destruction indirectly threatens the livelihood of the population	3.0

Based on the concentration of value and the possibility of replacing the destroyed property of the building, it follows from the table that the coefficient D is 2.

The presence of a large amount of smoke increases the risk to people and property (due to its toxic and corrosive nature) and is taken into account through the smoke impact coefficient (F), as shown in Table 11.

Table 11 Smoke impact coefficient (F)

Circumstances leading to smoke inhalation	F
There is no particular risk of fumes and corrosion	1.0
More than 20% of the total weight of all fuels causes smoke or emit toxic combustion products	1.5
More than 50% of the substances present generate smoke or emit toxic combustion products or more than 20% consist of substances present that emit highly corrosive gases	2.0

Based on the description of circumstances leading to smoke and/or corrosion, it follows from Table 11 that the coefficient F is 1.5.

According to the adopted values, the fire risk of the building's contents is calculated using the formula:

$$R_s = 2 \times 2 \times 1.5 = 6 \quad (4)$$

Since all circumstances and data about the building have been considered for calculating R_0 and R_S through the coefficients, the required type of protection for the hazardous materials warehouse can be determined according to the decision diagram. By applying the obtained values of R_0 and R_S to the diagram, it is possible to determine what type of protection should be implemented for the building, as illustrated in Figure 1.

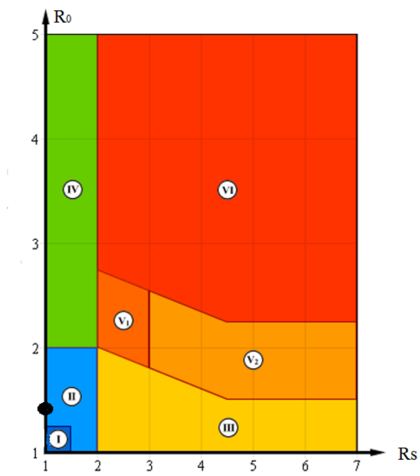

Fig. 1 Decision diagram

Explanatory diagram:
I preventive measures are sufficient
II fire alarm and extinguishing systems are not required
III alarm system is required but not a fire extinguishing system
IV extinguishing system is required but not a fire alarm system
V_1 fire extinguishing system is required
V_2 fire alarm system is required
VI fire extinguishing and warning systems are needed

Considering that the value of R_0 is 2.32 and the value of R_S is 6, the fire risk in the hazardous materials warehouse falls into group V_2, which necessitates the installation of a fire alarm system.

Hazardous chemical leaks from storage equipment can lead to fire and explosion accidents if the chemicals come into contact with an ignition source. To enhance risk control measures and prevent the escalation of such accidents, researchers globally have studied the occurrence, progression, and characteristics of fires at different stages. Wu et al. introduced an innovative fire detection method using video cameras, where a machine-learning algorithm creates a fire detection model. This system can detect fires and export the coordinates of the fire area upon capture [17]. Cheng and Hadjisophocleous developed a dynamic model that accounts for both horizontal and vertical fire spread, applicable to all building types and beneficial for fire risk assessment in building safety design [18]. Additionally, a model for analyzing the probability of fire accidents was proposed, emphasizing the significance of time-dependent fire scenarios, which was utilized for time-based fire probability analysis and system optimization [19]. Ding et al. created a comprehensive framework for the quantitative risk management of warehouse fires by examining past incidents and suggesting specific safety measures [20]. Accordingly, a fire protection system based on fire detection predicts the development of a fire and the implementation of the best preventive technical and organizational protection measures.

4. Conclusion

The assessment of fire risks in a warehouse that stores hazardous materials has been conducted thoroughly by evaluating the fire risk coefficients R_0 and R_S based on the specific circumstances and data related to the building. The analysis revealed that the value of R_0 is 2.32 and R_S is 6, which places the fire risk in the warehouse within group V_2. This classification indicates a high level of fire risk due to the nature of the stored materials and the potential impact on safety. As a result, it is evident that the warehouse requires a robust fire protection system. Specifically, the implementation of a fire alarm system is necessary to ensure timely detection and response in the event of a fire. This measure will significantly enhance the safety of the facility, mitigate potential damage, and protect both personnel and property from fire hazards. In conclusion, addressing the identified fire risks with appropriate protective measures will contribute to a safer working environment and ensure compliance with fire safety regulations. It is recommended that the warehouse management prioritize the installation and maintenance of the recommended fire protection systems to effectively manage and reduce fire risks.

Acknowledgement: *This paper is a part of the research funded by the Ministry of Education, Science and Technological Development of the Republic of Serbia pursuant to agreement No. 451-03-66/2024-03/ 200148.*

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PROCENA POŽARNOG RIZIKA SKLADIŠTA OPASNIH MATERIJA

Zaštita od požara u skladištima opasnih materija temelji se na detaljnoj analizi relevantnih parametara koji se odnose na požarni rizik objekta i uskladištenog materijala kako bi se utvrdile odgovarajuće mere zaštite od požara. Ovaj rad analizira potencijalne opasnosti koje se javljaju pri skladištenju opasnih materija i procenjuje rizik nastanka požara. Analizirani su faktori koji doprinose povećavanju rizika od požara, kao što su zapaljivost materijala, uslovi skladištenja i postojeće mere zaštite. Cilj rada je identifikovati ključne parametre koji mogu uticati na nastanak požara u skladištima opasnih materija i u skladu sa tim definisati stepen zaštite od požara.

Ključne reči: *rizik nastanka požara, procena rizika, skladište opasnih materija.*