An integral condition for avoiding damage due to fires in warehouses, or at least minimizing them, is the early detection of fires using fire protection systems, as well as its timely localization. Depending on which fire detectors are selected to protect the relevant premises and where they are installed, the time of operation of all elements of automatic control systems in case of a fire will depend. The review of literary data revealed that at present there is no comprehensive approach to choosing the optimal placement in warehouses. In addition, the optimal placement of fire detectors within the room, taking into consideration the type of fire load, has not been sufficiently studied. Therefore, the purpose of the current study is to establish the dependence of the time of operation of different types of fire detectors on the type of combustible material, namely its mass burnout rate, distance, and height of placement of detectors from a potential fire site. This paper reports a procedure for conducting an experimental study to identify the appropriate dependence for warehouses. The results of the experiments showed that the most effective in warehouses are targeted fire smoke detectors and aspiration systems. Based on the results of a complete factor experiment, nonlinear empirical dependences to determine the time of operation of smoke fire detectors on the above factors were built. The resulting empirical dependences make it possible to choose fire detectors and optimally place them within a room. The average error in these dependences when compared with the experimental data is 6.9 %. The use of the derived dependences makes it possible to reduce the time of operation of fire detectors by 14 s in comparison with their placement in accordance with building codes

Keywords: fire detector, fire development, fire protection system, full-factor experiment, trigger time

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OPTIMIZING THE PROCESS OF FIRE DETECTION IN WAREHOUSES CONSIDERING THE TYPE AND LOCATION OF FIRE DETECTORS

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1. Introduction

Ensuring an acceptable level of fire safety in warehouse buildings and structures is an important task. The number of large warehouse facilities is growing, logistics centers are being built with areas reaching tens of thousands of m^2. Statistics indicate that over the past decade, the number of fires at such facilities has quadrupled. In addition, fires at large warehouse facilities lead to enormous material damage, sometimes to human casualties. Large-scale fires at warehouse sites occur all over the world. Thus, in 2015 in Louisville (Kentucky, USA), there was a fire in warehouse No. 6 in the industrial park of the General Electric plant; the damage reached USD 110 million. In 2020, a fire at Amłazon's logistics center in Redland, Alabama, U.S.A., caused USD 500 million in damage. There are many such examples.

The main task of a fire safety management system at a facility is to organize work to ensure the functioning of the fire protection complex. After all, early detection of a fire, and as a result, its timely localization, minimizes the damage from the fire. One of the main elements of fire protection systems, on which the operation of all other systems (automatic fire extinguishing, smoke removal, alerting people about a fire, etc.) depends, is a fire detector. It is after the fire is detected that the detector transmits a signal to the control panel of other systems. Standards and regulations for the design of fire alarms are strict in terms of placing fire detectors in the premises. There are also no clear recommendations for choosing the type of detector. Thus, the designers do not have the opportunity to control such a parameter as the time of operation of the fire detector in the event of a fire, which directly affects the damage due to the fire.

2. Literature review and problem statement

In building codes, in particular [1], there are recommendations for the choice of fire detectors depending on the purpose of the room but there are no details about their choice depending on the characteristics of the fire load, their optimal placement in the room, etc. Any design requires a flexible object-oriented approach while the legislation on the design of fire alarm systems is quite tough.

The authors of work [2] proposed an engineering method for determining the number of fire detectors in closed premises of warehouses and logistics centers. The simulation results showed that in order to ensure the reliability of fire protection systems, it is necessary to increase the number of fire detectors several times compared to the normative number. However, there remain unresolved questions about what types of detectors to use and at what distance from each other to install, etc. Therefore, experimental studies of the properties or characteristics of fire detectors are an important scientific task.

A method of studying smoke fire detectors is considered in [3]. To simulate smoke due to fire, it is proposed to use an aerosol generator that can change the granulometric composition of the aerosol within the specified limits. This approach is quite interesting but it should be borne in mind that volatile combustion products of the material are characterized not only by dispersion but the combustible material itself is characterized by a linear and mass burnout rate, the optical density of smoke formed, etc. In addition, studies [4] show the effects of aerosols, vapor, sprayers on the false triggering of smoke detectors. Therefore, the more effective way to conduct experiments on the operation of fire detectors is to simulate fires with a real fire load.

The authors of [5] propose using the SDAA algorithm to determine the time of operation of smoke detectors. This algorithm is based on FDS simulation with variable fire parameters. However, this procedure applies only to smoke detectors. Work [6] considers the features of the development of aspiration fire detectors. However, their placement to provide for the efficiency of triggering such detectors is not considered.

Paper [7] considers the impact of air conditioning systems on the time of operation of the fire detector. The main conclusion is that in the presence of a strong airflow, it is necessary to increase the number of fire detectors for timely detection of the fire. However, the cited paper does not consider the impact of the fire load on their number. This problem is considered in [8]; however, the results of that study can be applied only in the design of fire protection of train cars. Work [9] also considers the features of the design of fire protection systems for a smart home. The researchers focused on choosing the type of fire detector but did not take into consideration the required number of them to protect the premises and the placement technique.

Selecting fire detectors depending on their sensitivity in order to reduce the time of detection of the fire is proposed in [10]. Based on the experimental studies and FDS modeling, it is concluded that the lower the sensitivity threshold of the fire detector, the shorter the time of its operation, which is actually an obvious statement. The authors found that for cable tunnels, the best option is an aspiration smoke fire detector. However, to confirm this conclusion for warehouse buildings of large volume and considerable height, additional research should be carried out since the geometry of these objects and cable tunnels differs significantly.

An experimental study of smoke fire detectors is reported in [11]. The results showed that the time of detector operation depends on the distance but there is no dependence on the type of photovoltaic detector. The study was conducted in a room of a small height (4 m), which is not typical for warehouses. In addition, the authors did not process statistics for the construction of empirical formulas that would allow them to choose the optimal placement of detectors.

None of the considered works has an integrated approach; the results of the studies cannot be used to choose the optimal placement in warehouses.

All this allows us to assert that it is expedient to conduct a study on identifying factors that affect the time of operation of the fire detector in case of fires in warehouses. This will be necessary for a further selection of the type of detectors and their optimal placement in a room.

3. The aim and objectives of the study

The purpose of this study is to establish empirical dependences of the time of operation of fire detectors in the case of fire in warehouses, which will make it possible to choose and optimally place fire detectors within a room.

To accomplish the aim, the following tasks have been set:

– to devise a methodology for conducting an experimental study to identify the dependence of the time of operation of various types of fire detectors in case of a fire in warehouses on the type of combustible material, the distance and height of their placement from a potential fire site;

– to conduct experimental studies to identify the dependence of the time of operation of different types of fire detectors;

– to process the results of an experimental study to derive empirical dependences that will make it possible to choose and optimally place fire detectors within a room.

4. The study materials and methods

The object of our study is the process of detecting a fire in warehouses by fire detectors. The hypothesis of the study assumes that there is a high correlation between the time of operation of fire detectors and the height of their placement, the distance from the fire site, and the fire hazard characteristics of combustible materials. At the same time, it is assumed that other factors have a slight impact on the result (room illumination, airflows, etc.). To neutralize these factors, we randomized the experiments, which made it possible to simplify the experiment by reducing the number of experiments.

The purpose of the experiment is to build a dependence of the time of operation of a fire detector τ_{tr} on 3 factors. These include the distance of the vertical axis of the fire site l, m, the height of the fire detector from the floor h, m (Fig. 1), and the rate of burnout of the material in case of fire ψ, kg/m^2·s. To construct empirical dependences, a procedure of a full-factor experiment of type 2^3 was used in this work.

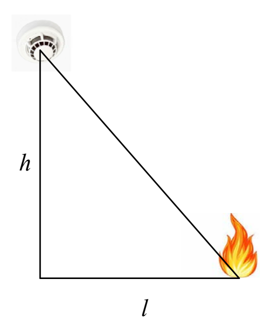
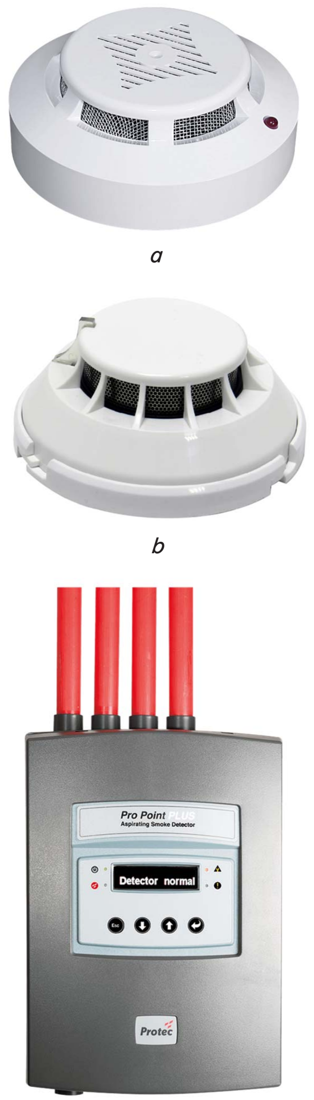


Fig. 1. Location of a fire site relative to the fire detector

It is most expedient to use smoke fire detectors in warehouses and logistics centers since in such premises there is always a large amount of solid combustible material that burns with the release of smoke. In this case, it is necessary to carry out an experiment for different types of fire detectors. To this end, we selected the following fire detectors: a non-targeted point smoke fire detector, a targeted point smoke fire detector, an aspirating smoke fire detector (Fig. 2).



a

b

c

Fig. 2. Fire detectors used in the experiment: *a* – SPD-3; *b* – SPDOTA; *c* – Pro Point Plus

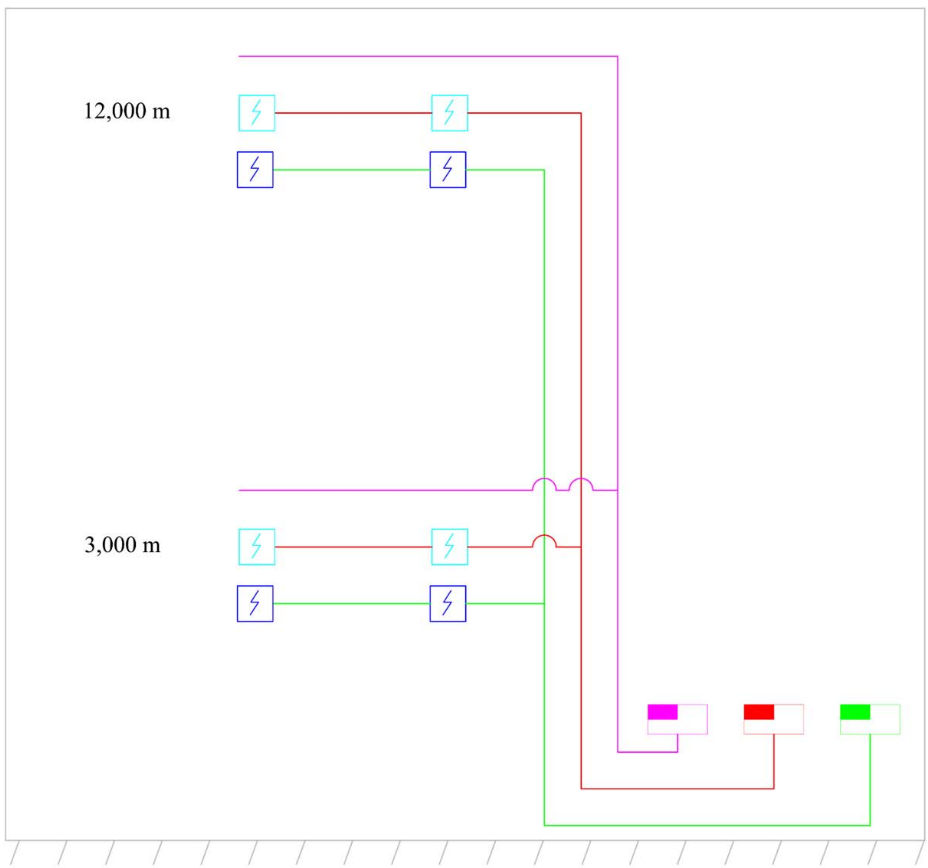
For our study, we used the optical spot smoke fire detector SPD-3 manufactured by PP "ARTON" (Ukraine), the targeted spot smoke optical fire detector SPDOTA manufactured by TzOV "Project AO"(Ukraine), the aspirating smoke fire detector Pro Point Plus manufactured by Protec Fire and Security Group Ltd (UK). These detectors are most often used to protect warehouse facilities.

Experimental studies of fire detection should be carried out in a room of size characteristic of warehouses and logistics centers.

The circuit for connecting detectors to the receiving and control fire devices is shown in Fig. 3.

During experimental studies, we used wood and rubber as combustible materials. These materials are characterized by fire hazard characteristics in a wide range. For example, the smoke-forming capacity of wood is 57 Np·m^2/kg, rubber – 850 Np·m^2/kg, the specific mass rate of wood burn – 0.015 kg/m^2·s, rubber – 0.011 kg/m^2·s, etc. When using wood, a model fire site of type 1A was built, namely: bars with a cross-section of 40×40 mm and a length of 500 mm, which were placed in the form of a lattice of 12 rows of 6 pcs. in each row (Fig. 4, *a*). When using rubber, a fire site is built similar to the model fire site of type 1A but, instead of bars, we used bars made of rubber technoplate (Fig. 4, *b*).

In this case, the mass of wood and rubber at a model fire site should be the same. Under the stack, there is a pallet measuring 400×600 mm, in which gasoline of the A-95 brand with a volume of 0.5 liters is supplied to set fire to the combustible material.



Designations

Item	Name	Designation
1	Protec ProPoint PLUS	
2	Receiving and control fire device Omega (targeted)	
3	Receiving and control fire device Tiras (non-targeted)	
4	Targeted smoke fire detector	
5	Non-targeted smoke fire detector	
6	Mounting cable PSVV 4x0,4	
7	Mounting cable PSVV 2x2x0,8	
8	Aspirating system air inlet channel	

Fig. 3. Connection circuit of detectors and receiving-control fire devices

a

b

Fig. 4. Experimental model fire site: *a* — wood; *b* — rubber

a

b

Fig. 5. Premises in which the experiments were carried out: *a* — arrangement of fire detectors, *b* — receiving and control fire devices

5. Results of studying the trigger time of fire detectors in a warehouse

5. 1. Procedure for conducting an experiment

The research was carried out inside an industrial warehouse with a height of 12.4 m and dimensions of 24×52 m. Two non-targeted fire detectors SPD-3, two targeted fire detectors SPDOTA, and intake air ducts of the aspirating smoke fire detector at a height of 3 and 12 m (Fig. 5, *a*) were mounted in the room. To receive and trigger a signal about a fire, the facility was equipped with devices for receiving and control fire. To connect the SPD-3 detectors, the fire alarm device Tiras was used; the Omega fire alarm device to connect the SPDOTA detectors; for connecting the intake air duct – the fire alarm device Pro Point Plus (Fig. 5, *b*).

During the experiment, it is necessary to change the height of the placement of fire detectors (h), the distance between a fire site (l) and the fire detector, combustible material, and, accordingly, the mass burnout rate (ψ). The levels of factor change are given in Table 1.

Table 1

Levels of factor change

Level of factors	l, m		h, m		ψ, kg/m^2·s	
	$\tilde{x}_1$	$\ln \tilde{x}_1$	$\tilde{x}_2$	$\ln \tilde{x}_2$	$\tilde{x}_3$	$\ln \tilde{x}_3$
Upper (+)	10	2.30	12	2.48	0.015	–4.20
Zero (0)	5.5	1.7	7.5	2.01	0.013	–4.34
Lower (–)	1	0	3	1.1	0.011	–4.51

The levels of factor changes regarding the placement of fire detectors and a fire site were determined by taking into consideration the size of the room and the maximum permissible distance between the detectors. The levels of change in the specific mass burnout rate are explained by the preliminary choice of combustible materials, taking into consideration a wide range of values of their fire hazard characteristics.

For each experiment, it is necessary to conduct 8 experiments with a change in factors. The plan of the experiment is given in Table 2.

Table 2

Levels of factor change

Experiment	(*l*) x_1		(*h*) x_2		(ψ) x_3	
	Code x_1	Value	Code x_2	Value	Code x_3	Value
1	–1	1	–1	3	+1	0.015
2	+1	10	–1	3	+1	0.015
3	–1	1	+1	12	+1	0.015
4	+1	10	+1	12	+1	0.015
5	–1	1	–1	3	–1	0.011
6	+1	10	–1	3	–1	0.011
7	–1	1	+1	12	–1	0.011
8	+1	10	+1	12	–1	0.011

Thus, for each type of detector, 8 experiments should be carried out, that is, 24 experiments. In order to reduce the number of experiments, it is necessary to install all three types of fire detectors at the level of 3 m and 12 m. Only the type of combustible material and the distance of the fire site from the vertical axis of the fire detectors should be changed. In this case, the number of experiments will be reduced to 4:

– experiment 1: the type of combustible material – wood; the distance from the vertical axis of placement of fire detectors – 1 m;

– experiment 2: the type of combustible material – rubber; the distance from the vertical axis of placement of fire detectors – 1 m;

– experiment 3: the type of combustible material – wood; the distance from the vertical axis of placement of fire detectors – 10 m;

– experiment 4: the type of combustible material – rubber; the distance from the vertical axis of placement of fire detectors – 10 m.

For good reproducibility of the experimental results, we take the number of repeated experiments r=2.

5. 2. Results of experimental studies to identify the dependence of trigger time for different types of fire detectors

Our tests were carried out in stages over eight days. Each basic and repeated experiment was performed on a separate day. Fig. 6 depicts the phased conduct of experiments with different types of combustible material.

a *b*

Fig. 6. Conducting experiments with different types of combustible material: *a* – wood; *b* – rubber

The results of studying the trigger time of the targeted smoke fire detector SPDOTA are given in Table 3.

The results of studying the trigger time of the non-targeted smoke fire detector SPD-3 are given in Table 4.

The results of studying the trigger time of an aspirating smoke fire detector are given in Table 5.

Table 3

Investigating the trigger time of a targeted smoke fire detector

Experiment	(*l*) x_1		(*h*) x_2		(ψ) x_3		Experiment 1 τ_{tr}, s	Experiment 2 τ_{tr}, s	Average $\tau_{tr.\,av}$, s	Ln ($\tau_{tr.\,av}$)
	Code x_1	Value	Code x_2	Value	Code x_3	Value	Result	–	Code x_1	Value
1	–1	1	–1	3	+1	0.015	31	32	31.5	3.45
2	+1	10	–1	3	+1	0.015	58	59	58.5	4.07
3	–1	1	+1	12	+1	0.015	18	19	18.5	2.92
4	+1	10	+1	12	+1	0.015	29	30	29.5	3.38
5	–1	1	–1	3	–1	0.011	44	43	43.5	3.77
6	+1	10	–1	3	–1	0.011	86	85	85.5	4.45
7	–1	1	+1	12	–1	0.011	27	26	26.5	3.28
8	+1	10	+1	12	–1	0.011	39	40	39.5	3.68

Table 4

Investigating the trigger time of a non-targeted smoke fire detector

Experiment	(*l*) x_1		(*h*) x_2		(ψ) x_3		Experiment 1 τ_{tr}, s	Experiment 2 τ_{tr}, s	Average $\tau_{tr.\,av}$, s	Ln ($\tau_{tr.\,av}$)
	Code x_1	Value	Code x_2	Value	Code x_3	Value	Result	P Result	Code x_1	Value
1	–1	1	–1	3	+1	0.015	36	34	35	3.56
2	+1	10	–1	3	+1	0.015	66	65	65.5	4.18
3	–1	1	+1	12	+1	0.015	20	21	20.5	3.02
4	+1	10	+1	12	+1	0.015	51	50	50.5	3.92
5	–1	1	–1	3	–1	0.011	46	45	45.5	3.82
6	+1	10	–1	3	–1	0.011	91	89	90	4.50
7	–1	1	+1	12	–1	0.011	29	28	28.5	3.35
8	+1	10	+1	12	–1	0.011	64	61	62.5	4.14

Table 5

Investigating the trigger time of an aspirating smoke fire detector

Experi-ment	$(l)\ x_1$		$(h)\ x_2$		$(\psi)\ x_3$		Experiment 1 τ_{tr}, s	Experiment 2 τ_{tr}, s	Average $\tau_{tr.\,av}$, s	Ln $(\tau_{tr.\,av})$
	Code x_1	Value	Code x_2	Value	Code x_3	Value	Result	P Result	Value	Value
1	–1	1	–1	3	+1	0,015	24	24	24	3,18
2	+1	10	–1	3	+1	0,015	50	49	49,5	3,90
3	–1	1	+1	12	+1	0,015	16	18	17	2,83
4	+1	10	+1	12	+1	0,015	26	28	27	3,30
5	–1	1	–1	3	–1	0,011	39	39	39	3,66
6	+1	10	–1	3	–1	0,011	70	68	69	4,23
7	–1	1	+1	12	–1	0,011	22	24	23	3,14
8	+1	10	+1	12	–1	0,011	58	59	58,5	4,07

The results of our experiments showed that the trigger time of any fire detector is less when reducing the distance from the vertical axis of the detector and when mounting the detector closer to the overlap. The most effective in warehouses, regardless of the type of combustible material, are targeted fire smoke detectors and an aspirating smoke fire detector. At the same time, the intake ducts of the aspirating smoke fire detector when installed closer to the floor are more effective than spot smoke fire detectors.

5. 3. Constructing empirical dependences of trigger time for different types of fire detectors

When planning experiments, a full-factor experiment of type 2^3 was applied. The result of these experiments is to build nonlinear empirical dependences of the following form:

$$y = e^{b_0} \cdot x_1^{b_1} \cdot x_2^{b_2} \cdot x_3^{b_3}. \qquad (1)$$

To construct a nonlinear empirical dependence, the transition from natural factors to dimensionless quantities was executed, given in the standard orthogonal plan-matrix of the experiment (Table 1).

We verified the reproducibility of experiments with the same number of parallel experiments at each combination of factor levels according to the Cochran criterion. In addition, an assessment of the significance of regression coefficients using the Student criterion was carried out.

Based on the results of processing the results of experiments and representing the equation with coded factors in the form of natural variables, the following empirical dependences were built:

– the trigger time of a targeted smoke fire detector:

$$\tau_{tr}^{\text{t.}} = 0.54 \cdot \frac{l^{0.235}}{h^{0.45} \cdot \psi^{1.1}}; \qquad (2)$$

– the trigger time of a non-targeted smoke fire detector:

$$\tau_{tr}^{\text{n.-t.}} = 0.99 \cdot \frac{l^{0.33}}{h^{0.3} \cdot \psi^{0.91}}; \qquad (3)$$

– the trigger time of an aspirating smoke fire detector:

$$\tau_{tr}^{\text{as.}} = 0.04 \cdot \frac{l^{0.3}}{h^{0.28} \cdot \psi^{1.57}}. \qquad (4)$$

Fisher's criterion was used to verify the adequacy of our models.

Table 6 gives the results of comparing the experimental data and those from calculations using dependences (2) to (4) at the values of factors applied during the experiment.

Table 6

Comparing the experimental data on the trigger time of fire detectors with those calculated using dependences (2) to (4)

l, m	h, m	ψ, kg/m^2·s	Experimental value of trigger time, s	Value of trigger time based on dependence (3)	Relative error, %
Targeted smoke fire detector					
1	3	0.015	31.5	33.3	–5.5 %
10	3	0.015	58.5	57.2	2.2 %
1	12	0.015	18.5	17.9	3.6 %
10	12	0.015	29.5	30.7	–3.8 %
1	3	0.011	43.5	46.9	–7.2 %
10	3	0.011	85.5	80.5	6.2 %
1	12	0.011	26.5	25.1	5.5 %
10	12	0.011	39.5	43.2	–8.5 %
Non-targeted smoke fire detector					
1	3	0.015	35	32.7	7.0 %
10	3	0.015	65.5	70.0	–6.4 %
1	12	0.015	20.5	21.6	–5.1 %
10	12	0.015	50.5	46.2	9.4 %
1	3	0.011	45.5	43.4	4.8 %
10	3	0.011	90	92.8	–3.0 %
1	12	0.011	28.5	28.6	–0.5 %
10	12	0.011	62.5	61.2	2.1 %
Aspirating smoke fire detector					
1	3	0.015	24	23.2	3.3 %
10	3	0.015	49.5	46.4	6.7 %
1	12	0.015	17	15.8	7.8 %
10	12	0.015	27	31.5	–14.2 %
1	3	0.011	39	37.8	3.1 %
10	3	0.011	69	75.5	–8.6 %
1	12	0.011	23	25.7	–10.3 %
10	12	0.011	58	51.2	13.3 %

Fig. 7 shows graphical dependences of the trigger time of fire detectors of different types when changing the levels of factors.

The results of our study showed that the strongest relationship exists between the time of operation of fire detectors and the specific mass burnout rate of combustible material. It should also be noted that fire detectors should be placed closer to the ceiling of the room since volatile combustion products in the case of fire are collected in the upper area of the room.

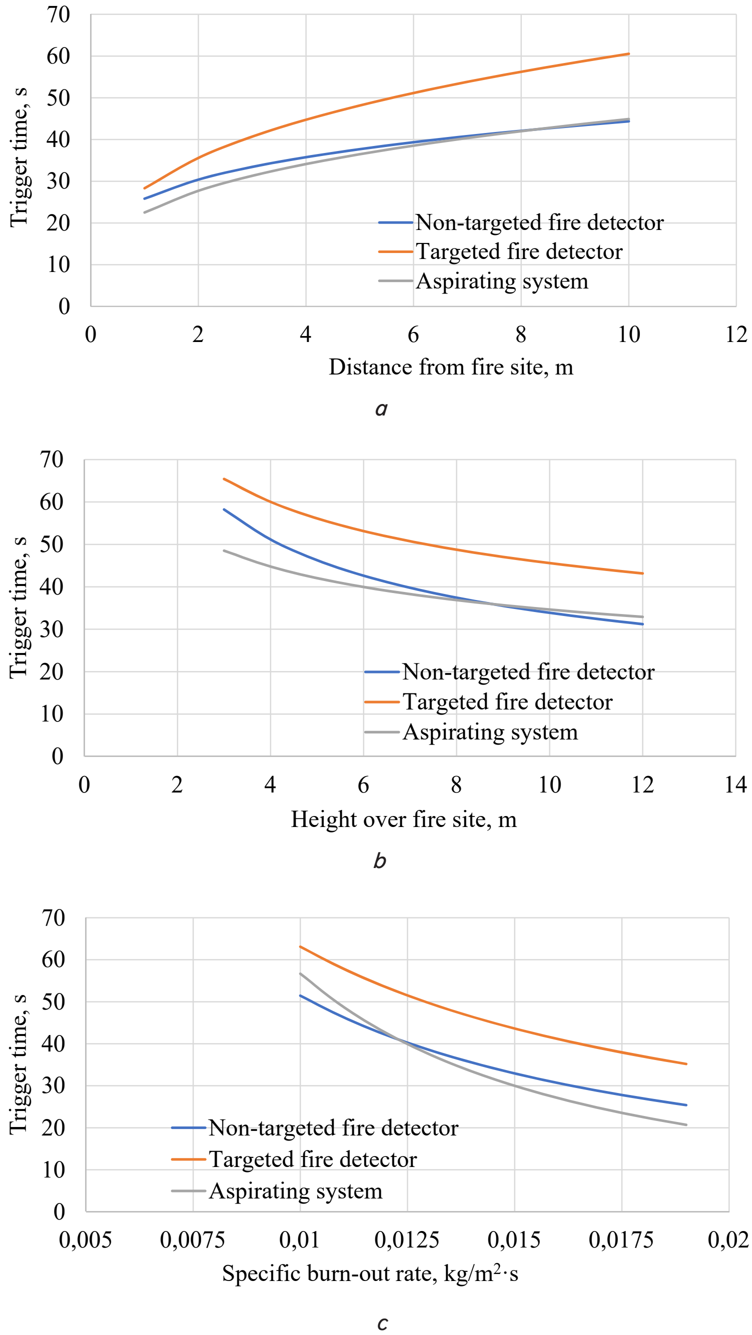


Fig. 7. Dependence of the trigger time of fire detectors: *a* – on the distance from the fire site at a mass burnout rate of 0.013 kg/m^2·s and a height of 7.5 m; *b* – on the height above the fire site at a mass burnout rate of 0.013 kg/m^2·s and a distance of 5.5 m; *c* – on the mass burnout rate of the material at a distance of 5.5 m and a height of 7.5 m

According to state building codes, when placing non-targeted smoke fire detectors in a room with a height of 8 to 11 m, the distance between them should be 7 m. Therefore, the maximum distance from the fire site will be 3.5 m. According to the calculations using depeng dence (3), the trigger time of this detector when burning rubber will be 49 s. The use of a targeted smoke fire detector at a distance of 4 m from each other will reduce the fire detection time to 35 s.

6. Discussion of results of studying the time of operation of different types of fire detectors in the event of a fire in a warehouse

The results of our research make it possible to choose fire detectors and place them indoors in such a way that they are triggered as fast as possible. To select the location and distance between fire detectors, formulas (2), (3), or (4) are to be used, depending on the type of detector selected. Formulas (2) to (4), and Fig. 7, *a–c* indicate that the greatest impact on the time of operation of fire detectors is exerted by combustible material, namely its mass burnout rate.

The study results allow us to devise an object-oriented method for selecting and placing fire detectors inside warehouses, which is aimed at flexible design of fire protection systems, unlike existing design methods. At the same time, we resolved the issue related to choosing the location of fire detectors not only according to strictly established restrictions but taking into consideration the type of combustible material, the type of detector, etc. Reducing fire detection time could reduce fire response time with automatic fire extinguishing systems or by notifying fire and rescue units in a timely manner.

The limitation of the current study is that its results can be applied to warehouses up to 12 m high.

The results of our study showed that the time of operation of smoke fire detectors depends on the specific mass burnout rate: the higher the value of this indicator, the faster the detector is triggered. Thus, for rubber, this figure is lower, so when it burns, the detector is triggered later compared to the burning of wood. However, the optical density of smoke when burning rubber is an order of magnitude higher than when burning wood. Therefore, it is intermediate to conclude that this parameter has no effect on the time of operation of smoke detectors, the confirmation of which requires additional research.

Unlike the results reported in other studies, we have applied an integrated approach when considering the process of detecting fire by fire detectors. Thus, the place, type of fire detector, and fire-hazard properties of combustible material are taken into consideration. This is different from work [5], which takes into consideration only the parameters of the fire, or [10], which took into consideration only the type of fire detector (its sensitivity), etc. In addition, our research addresses fires in warehouses that are present at every production site, in every public building, in the premises of logistics facilities where fires often occur.

In the future, the current study can be advanced by conducting a series of experiments for premises of different heights with a change in combustible material whose parameters of mass burnout rate are in a wider range.

7. Conclusions

1. We have devised a procedure for conducting an experimental study, which makes it possible to establish the empirical dependence of the time of operation of various types of fire detectors in the case of a fire in warehouses. This dependence takes into consideration the type of combustible material, the distance and height of the placement of fire detectors from a potential fire site. To establish such a dependence, it is necessary to conduct a series of 4 experiments, which should be repeated twice.

2. The results of our experiments showed that the trigger time of any fire detector is less when reducing the distance from the vertical axis of the detector and when mounting the detector closer to the overlap. The most effective in warehouses, regardless of the type of combustible material, are targeted fire smoke detectors and aspirating smoke fire detectors. At the same time, the intake ducts of an aspirating smoke fire detector when installed closer to the floor are more effective than spot smoke fire detectors. The optical density of smoke when the material burns has no effect on the time of operation of the smoke detectors or has an inversely proportional dependence.

3. The resulting empirical dependences make it possible to select fire detectors and place them indoors in such a way that they are triggered as fast as possible. The average error of these dependences when compared with the experimental data is 6.9 %. The use of these dependences makes it possible to reduce the time of operation of the fire detector by 14 s compared to placing them in accordance with building codes.

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