Determination method of sprinklers with electrical activation in case of internal fire

I Babikov¹, A Tanklevskiy¹, A Arakcheev¹, A Tarantsev²
¹ Peter the Great St. Petersburg Polytechnic University, Fire Safety Department, Saint-Petersburg, Russia
² Saint Petersburg University of State fire Service of Emercom of Russia
E-mail: tanklevskij_lt@spbstu.ru

Abstract
The issues of determination of sprinklers with electrical activation of a sprinkler automatic fire extinguishing system with electrical activation in case of fire source occurring in a compartment and activation of one of the sprinklers are investigated. The problem of preventive activation of sprinklers is formulated; its solution will allow determining the minimal quantity of sprinklers and their coordinates which will ensure localization and even extinguishing using much less water, as if activation of sprinklers was implemented in a traditional way – by heating their bulbs with ignition products. Examples are given.

1 Introduction
One of the most important tasks in the situation when fire occurs in a compartment protected by sprinkler automatic fire extinguishing system [1,4,15] is the fast extinguishing by preventive electrical activation of sprinklers before the fire area becomes too large. The solution of this problem depends on fast detection of the fire source based on the information from one of the sprinklers; after that control device of the fire extinguishing system can make a decision on activation of particular sprinklers – one of them or the group [11-13].

2 Formulation of the problem
Generally, the task can be formulated the following way. If sprinklers are located in a compartment by «square-breeding» method (figure 1a) and one of them was activated (in this case it is sprinkler №5 with coordinates (xᵢ, yᵢ)), it is needed to detect which 3 of the neighboring sprinklers (1, 2, 3, 4, 6, 7, 8, 9) and in what quadrant (I-IV) should be activated, when the coordinates of sprinklers (x, y) and temperatures in their locations {T} are known. If all 8 neighboring sprinklers are activated, the unreasonably big amount of fire extinguishing agent (water) is released; it also becomes a concomitant hazardous factor [2,5,14].

Specific tasks can also be formulated. For example – if the sprinkler №3 near the wall actuated (figure 1b), which group of sprinklers should be activated – 1, 2 and 4 (quadrant I) or 4, 5 and 6 (quadrant II) – in case when fire occurs in one of these quadrants. Or will it be sufficient to activate sprinkler №1 (the fire source is near the wall between sprinklers 1 and 3), or the sprinkler №4 should be activated (the fire source is near the wall between sprinklers 3 and 4).

If fire occurs in a corridor or a tunnel (figure 1d) and if sprinkler i (№2) activates, it is also important to detect between which sprinklers – i-1 and i, or i and i+1 –the fire source is located. In the first case i-1 (№1) sprinkler should be activated, in the second case – i+1 (№3).
When solving the task on preventive sprinkler activation, it is also important to determine coordinates of the fire source in a fast and objective way.

Express-method

The problem of express-method of determining the group of sprinklers which should be preventively activated if one of them is actuated is to make it without determining the coordinates of the fire source.

3.1 With regard to the case in fig. 1a the task is to make a decision which sprinklers – 1, 2 and 4 (quadrant I), 2, 3 and 6 (quadrant II), 6, 8 and 9 (quadrant III) or 4, 7 and 8 (quadrant IV) should be activated if the temperatures $T_1$–$T_9$ are known and the sprinkler №5 is activated. This means that the fire source may be located in one of the quadrants. Firstly, it is needed to calculate average temperatures in quadrants:

\[ T_I = \left( T_1 + T_2 + T_4 \right) / 3, \]  
\[ T_{II} = \left( T_2 + T_3 + T_6 \right) / 3, \]  
\[ T_{III} = \left( T_5 + T_6 + T_9 \right) / 3, \]  
\[ T_{IV} = \left( T_4 + T_7 + T_8 \right) / 3, \]  

Quadrant of activating sprinklers is determined from the condition: max ($T_I$, $T_{II}$, $T_{III}$, $T_{IV}$)

It should be considered that the possibility of fire source to be situated under sprinkler 5, or between sprinklers 2 and 5, or between sprinklers 4 and 5, or between sprinklers 5 and 6, or between sprinklers 5 and 8, is negligible.
Example 1. $T_1 = 30^\circ C$, $T_2 = 50^\circ C$, $T_3 = 20^\circ C$, $T_4 = 40^\circ C$, $T_5 \geq 60^\circ C$, $T_6 = 30^\circ C$, $T_7 = 20^\circ C$, $T_8 = 30^\circ C$, $T_9 = 20^\circ C$. According to (1)-(4): $T_I = (30^\circ + 50^\circ + 40^\circ)/3 = 40^\circ C$, $T_{II} = (50^\circ + 20^\circ + 30^\circ)/3 = 33.33^\circ C$, $T_{III} = (30^\circ + 30^\circ + 20^\circ)/3 = 26.67^\circ C$, $T_{IV} = (40^\circ + 20^\circ + 30^\circ)/3 = 30^\circ C$. Then the statement max ($T_I = 40^\circ; T_{II} = 33.33^\circ; T_{III} = 26.67^\circ; T_{IV} = 30^\circ$) says that the group of sprinklers in quadrant I should be activated because the fire source is situated between sprinklers 1, 2, 4 and 5.

3.2 With regard to the case in fig. 1b (sprinkler 3 near the wall was activated) it should be decided which sprinklers – 1, 2 and 4 (quadrant I) or 4, 5 and 6 (quadrant II) should be activated (the fire source may be located in quadrant I or II), or will it be sufficient to activate sprinkler 1 (the fire source is near the wall between sprinklers 1 and 3), or only sprinkler 5 (when the fire source is near the wall between sprinklers 3 and 5).

Calculating average temperatures in quadrants:

$$T_I = \frac{(T_1 + T_2 + T_4)}{3},$$

$$T_{II} = \frac{(T_4 + T_5 + T_6)}{3},$$

after that, according to the condition max ($T_I, T_{II}, T_2, T_5$), it is needed to determine which sprinkler or group of sprinklers should be preventively activated.

Example 2. $T_1 = 30^\circ C$, $T_2 = 40^\circ C$, $T_3 \geq 60^\circ C$, $T_4 = 20^\circ C$. According to (5) -(6): $T_I = (30^\circ + 20^\circ + 40^\circ)/3 = 30^\circ C$, $T_{II} = (40^\circ + 20^\circ + 30^\circ)/3 = 30^\circ C$. Then the condition max ($T_I = 30^\circ; T_{II} = 40^\circ; T_2 = 20^\circ; T_5 = 50^\circ$) says that the sprinkler 5 should be activated because the fire is located near the wall between sprinklers 3 and 5.

3.3 According to the case in fig. 1c, if the sprinkler 3 in the corner was activated it should be decided which sprinklers – 1, 2 and 4 (the fire source is between sprinklers 1, 2, 3 and 4), or sprinkler 1 (the fire source is near the wall between sprinklers 1 and 3), or sprinkler 4 (the fire source is near the wall between sprinklers 3 and 4), should be activated. Temperatures $T_1$, $T_4$ and average $T_I = (T_1 + T_2 + T_4)/3$ are compared, and the decision of sprinkler activation is made according to the highest of them.

Example 3. $T_1 = 30^\circ C$, $T_2 \geq 60^\circ C$, $T_3 = 40^\circ C$. Then $T_I = (30^\circ + 40^\circ + 20^\circ)/3 = 30^\circ C$. The statement max($T_1 = 30^\circ; T_4 = 20^\circ; T_3 = 40^\circ$) is uncertain because $T_1 = T_I = 30^\circ C$. But all three sprinklers should be preventively activated (1, 2 and 4) because sprinkler 2 is heated the most which means that the ignition center is located between these four sprinklers.

3.4 And finally, according to the case on figure 1d when the sprinkler 2 went off, it should be decided which sprinklers – 1 (ignition center is between sprinklers 1 and 2) or 3 (ignition center is between sprinklers 2 and 3) should be activated. Then, if $T_1 > T_3$ sprinkler 1 should be activated, if $T_1 < T_3$, sprinkler 3 should be activated.

Example 4. $T_1 = 30^\circ C$, $T_2 \geq 60^\circ C$, $T_3 = 40^\circ C$. Since $T_1 < T_3$, sprinkler 3 should be activated preventively, because the center of ignition is located between sprinklers 2 and 3.

4 Specified estimation of fire source coordinates

Nevertheless, it is also important to determine the coordinates of ignition center which leads to more balanced decisions in fire extinguishing. This problem can be solved using approximation methods.

4.1 For example, in the case described in fig. 1d (ignition in a corridor) if temperatures $T_1$, $T_2$ and $T_3$ are known, their temperature profile $T(x)$ can be described using square polynomial:

$$T(x) = a_0 + a_1 x + a_2 x^2,$$

coefficients $a_0$, $a_1$ and $a_2$ can be calculated using following formulas [3,10]:

$$a_0 = T_1, a_1 = T_2 - T_3, a_2 = T_3 - T_1.$$
Coordinate of fire source \( x_f \) and conditional maximum of temperatures \( T_f \) can be calculated in the following way:

\[
\begin{align*}
a_0 &= T_3 - \frac{T_2 - T_3}{x_2 - x_3} x_3 + \frac{T_1 - T_3 + \frac{T_2 - T_3}{x_2 - x_3} (x_3 - x_1)}{x_2 x_3 - x_1 x_2 - x_1 x_3 + x_1^2} x_2, \\
a_1 &= T_2 - T_3 - \frac{T_1 - T_3 + \frac{T_2 - T_3}{x_2 - x_3} (x_3 - x_1)}{x_2 x_3 - x_1 x_2 - x_1 x_3 + x_1^2} (x_2 + x_3), \\
a_2 &= \frac{T_1 - T_3 + \frac{T_2 - T_3}{x_2 - x_3} (x_3 - x_1)}{x_2 x_3 - x_1 x_2 - x_1 x_3 + x_1^2}.
\end{align*}
\]

(8)

If the distance between sprinklers is constant and equal to \( \Delta \), and the coordinate system is altered so that \( x_2 = 0 \), formulas (8) can be simplified:

\[
\begin{align*}
x_f &= -\frac{a_1}{2a_2}, \\
T_f &= a_0 - \frac{a_1^2}{4a_2}.
\end{align*}
\]

(10)

Example 5. \( T_1=30^\circ C \), \( T_2=60^\circ C \), \( T_3=40^\circ C \) (as in Example 4), and the sprinklers are located evenly on the distances \( \Delta=3 \) m. Due to (11) polynomial coefficients are calculated (7): \( a_0=60 \), \( a_1=5/3 \) and \( a_2=-25/9 \). Then the coordinate of ignition is calculated from (9) \( x_f=0.3 \) m, and the maximum temperature from (10) \( -T_f=60,25^\circ C \).

4.2 The outlined approach may be used in general case which was observed in 1.1 and described in fig. 1a.

The temperature profile of «vertical» lines – left (sprinklers 1, 4, 7), middle (sprinklers 2, 5, 8) and right (sprinklers 3, 6, 9) can be described as square polynomials:

\[
\begin{align*}T_1 &= a_{10} + a_{11} y + a_{12} y^2, \\
T_c &= a_{c0} + a_{c1} y + a_{c2} y^2, \\
T_7 &= a_{70} + a_{71} y + a_{72} y^2.
\end{align*}
\]

(12)

from where at \( (T_1, T_7)<T_4 \), \( (T_2, T_8)<T_5 \) and \( (T_3, T_9)<T_6 \) the coordinates of maximal temperatures of vertical lines are found:
\[
\begin{bmatrix}
y_1 \\
y'_c \\
y'_r
\end{bmatrix} = -0.5 \begin{bmatrix}
a_{10} & a_{11} & a_{12} \\
a_{20} & a_{21} & a_{22} \\
a_{30} & a_{31} & a_{32}
\end{bmatrix}^T \tag{13}
\]

Coefficients \{a\} are calculated from generalized equations:

\[
\begin{align*}
a_{10x0,0,0} &= T_{4,5,6}; \\
a_{11x1,1,1} &= T_{1,2,3} - T_{7,8,9} / 2\Delta; \\
a_{12x2,2,2} &= T_{7,8,9} + T_{1,2,3} - 2T_{4,5,6} / 2\Delta^2. \tag{14}
\end{align*}
\]

If the coordinate system is chosen in such way that \(y_4=y_5=y_6=0\), and the distance between sprinklers is equal to \(\Delta\), equations (14) can be simplified:

\[
\begin{align*}
a_{10x0,0,0} &= T_{4,5,6}; \\
a_{11x1,1,1} &= T_{1,2,3} - T_{7,8,9} / 2\Delta; \\
a_{12x2,2,2} &= T_{7,8,9} + T_{1,2,3} - 2T_{4,5,6} / 2\Delta^2. \tag{15}
\end{align*}
\]

According to the calculated coordinates of maximums, the angled line \(y_l\leftrightarrow y_c\leftrightarrow y_r\) is drawn and applied to the scheme (fig. 1a).

Temperature profiles for «horizontal» lines are calculated in the same way – for the upper (sprinklers 1, 2, 3), middle (sprinklers 4, 5, 6) and lower (sprinklers 7, 8, 9) – using square polynomials:

\[
\begin{bmatrix}
T_u \\
T_c \\
T_d
\end{bmatrix} = \begin{bmatrix}
a_{u0} & a_{u1} & a_{u2} \\
a_{c0} & a_{c1} & a_{c2} \\
a_{d0} & a_{d1} & a_{d2}
\end{bmatrix} \begin{bmatrix}
x \\
x^2
\end{bmatrix} \tag{16}
\]

from where at \((T1,T3)<T2\), \((T4,T6)<T5\) and \((T7,T9)<T8\) the coordinates of maximal temperatures of horizontal lines are found:

\[
\begin{bmatrix}
x_u \\
x'_c \\
x'_d
\end{bmatrix} = -0.5 \begin{bmatrix}
a_{u1} & a_{u1} & a_{u1} \\
a_{d1} & a_{d2} & a_{d2}
\end{bmatrix}^T \tag{17}
\]

Assuming that the coordinate system is chosen so that \(x_2=x_5=x_8=0\), and the distance between sprinklers is equal to \(\Delta\), simplified equations for coefficients \{a\} of polynomials (16) are obtained:
According to the calculated values of \(x_u, x_c \) and \( x_d \) the angled line \( x_u \leftrightarrow x_c \leftrightarrow x_d \) is drawn. Its crossing with the horizontal line \( y_l \leftrightarrow y_c \leftrightarrow y_r \) can be a spot of the fire source.

Example 6. \( T_1=30\, ^\circ C, T_2=50\, ^\circ C, T_3=20\, ^\circ C, T_4=40\, ^\circ C, T_5 \geq 60\, ^\circ C, T_6=30\, ^\circ C, T_7=20\, ^\circ C, \) \( T_8=30\, ^\circ C, T_9=20\, ^\circ C. \) It is not only the quadrant where ignition started that should be found, but also the coordinates of the fire source (if the distance between sprinklers is constant \( \Delta=3 \) m and the coordinate system is chosen in the way that the activated sprinkler 5 is located in the center \( (x_5=0, \, y_5=0) \)).

Firstly, the angled line \( y_l \leftrightarrow y_c \leftrightarrow y_r \) should be drawn according to (15):

\[
\begin{align*}
    a_{u_1,c_1,d_1} &= \left( T_1 - T_3 \right) / 6 = 5/3; \\
    a_{u_1,c_1,d_1} &= \left( T_2 - T_4 \right) / 6 = 10/3; \\
    a_{u_1,c_1,d_1} &= \left( T_5 - T_7 \right) / 6 = 0; \\
    a_{u_2,c_2,d_2} &= \left( T_3 + T_5 - 2T_4 \right) / 18 = -5/3; \\
    a_{u_2,c_2,d_2} &= \left( T_4 + T_6 - 2T_5 \right) / 18 = -10/9. \\
\end{align*}
\]

Then, according to (13): \( y_l=0.5 \) m; \( y_c=0.75 \) m; \( y_r=0 \). The line \( 0.5 \leftrightarrow 0.75 \leftrightarrow 0 \) is applied in fig. 2.

Firstly, the angled line \( y_l \leftrightarrow y_c \leftrightarrow y_r \) should be drawn according to (15):

\[
\begin{align*}
    a_{u_1,c_1,d_1} &= \left( T_1 - T_3 \right) / 6 = 5/3; \\
    a_{u_1,c_1,d_1} &= \left( T_2 - T_4 \right) / 6 = 10/3; \\
    a_{u_1,c_1,d_1} &= \left( T_5 - T_7 \right) / 6 = 0; \\
    a_{u_1,c_1,d_1} &= \left( T_3 + T_5 - 2T_4 \right) / 18 = -5/3; \\
    a_{u_2,c_2,d_2} &= \left( T_4 + T_6 - 2T_5 \right) / 18 = -10/9. \\
\end{align*}
\]

Then, according to (17): \( x_u=-0.5 \) m; \( x_c=-0.3 \) m; \( x_d=0 \). The line \( -0.5 \leftrightarrow -0.3 \leftrightarrow 0 \) is applied in fig. 2.

Crossing of these lines allows determining the coordinates of the fire source (\( x_f \approx -0.4 \) m; \( y_f \approx 0.72 \) m). This result correlates with the results from Example 1 – the fire source is located in quadrant I.

\[
\begin{align*}
    a_{u_0,c_0,d_0} &= T_{2,5,8}; \\
    a_{u_1,c_1,d_1} &= \frac{T_{3,6,9} - T_{1,4,7}}{2\Delta}; \\
    a_{u_2,c_2,d_2} &= \frac{T_{1,4,7} + T_{3,6,9} - 2T_{2,5,8}}{2\Delta}. \\
\end{align*}
\]

(18)
Conclusion

Results of this research work show the possibility of determination of a group of sprinklers or a certain sprinkler which should be preventively activated, if one sprinkler has already been actuated. Information about coordinates of sprinklers and the data obtained from their heat sensors can help to solve that task and also to determine coordinates of the fire source. Preventive activation of sprinklers allows fast extinguishing of the fire source using minimal amount of water or another extinguishing agent.

References

[1] Set of rules 5.13130.2009. Fire protection systems. Automatic fire alarm and extinguishing units. Design rules and regulations.
[2] Federal law №123 «Technical regulations of fire safety requirements».
[3] Korn G, Korn T. Maths reference book for scientific workers and engineers. Publication 4, M.:Science, 1978, 881.
[4] Burlov V, Popov N 2017 Management of the application of the space geoinformation system in the interests of ensuring the environmental safety of the region Advances in the Astronautical Sciences
[5] Bardin A, Korotkov A, Kazarnovskij V 2017 Limit of fire resistance of a steel transport structures. Simplified calculation methods IOP Conference Series: Earth and Environmental Science DOI: 10.1088/1755-1315/90/1/012207
[6] Zybina O, Gravit M, Stein Y 2017 Influence of carbon additives on operational properties of the intumescent coatings for the fire protection of building constructions IOP Conference Series: Earth and Environmental Science 90 (1) DOI: 10.1088/1755-1315/90/1/012227
[7] Bolgov I, Kaverzneva T, Kolesova S, Stolyarov O, Tarkhov D 2016 Neural network model of rupture conditions for elastic material sample based on measurements at static loading under different strain rates Journal of Physics: Conference Series DOI: 10.1088/1742-6596/772/1/012032
[8] Gravit M, Gumerova E, Bardin A, Lukinov V 2018 Increase of Fire Resistance Limits of Building Structures of Oil-and-Gas Complex Under Hydrocarbon Fire Advances in Intelligent Systems and Computing, 692 pp 818-829 DOI: 10.1007/978-3-319-70987-1_87
[9] Burlov V, Andreev A, Gomazov F 2018 Mathematical model of human decision - A methodological basis for the realization of the human factor in safety management Procedia Computer Science
[10] Pykhtin K, Simankina T, Shamarin V, Kopytova A 2017 Risk-based approach in valuation of workplace injury rate for transportation and construction industry IOP Conference Series: Earth and Environmental Science 90 (1) DOI: 10.1088/1755-1315/90/1/01206
[11] Dubov, S., Babikov, I., Vasilyev, M., & Tanklevsky, L. (2018). Methods of instrument testing of smoke detectors performance. Paper presented at the MATEC Web of Conferences, 245 doi:10.1051/matecconf/201824511005
[12] Gravit M & Golub E 2018 Increase of fire resistance of reinforced concrete structures with polypropylene microfiber. Paper presented at the MATEC Web of Conferences, 245 doi:10.1051/matecconf/201824503005
[13] Gravit M V, Golub E V & Antonov S P 2018 Fire protective dry plaster composition for structures in hydrocarbon fire. Magazine of Civil Engineering, 79(3), 86-94. doi:10.18720/MCE.79.9
[14] Gravit M V, Terekh M D, Lyulikov V A & Svintsov S A 2018 Software packages for calculation of fire resistance of building construction, including fire protection. Paper presented at the IOP Conference Series: Materials Science and Engineering, 456(1) doi:10.1088/1757-899X/456/1/012016
[15] Nedryshkin O, Gravit M & Mukhamedzhanova O 2017 Use of intumescent compounds in fire curtains. Paper presented at the IOP Conference Series: Earth and Environmental Science, 90(1) doi:10.1088/1755-1315/90/1/012186
[16] Nikitina M, Ustinov A, Kiseleva V Babikov I 2018 New fire retardant compositions for fire-resistant automatic curtains. Paper presented at the MATEC Web of Conferences, , 245 doi:10.1051/matecconf/201824511004