IFireSS

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JUNE, 2023

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PROCEEDINGS

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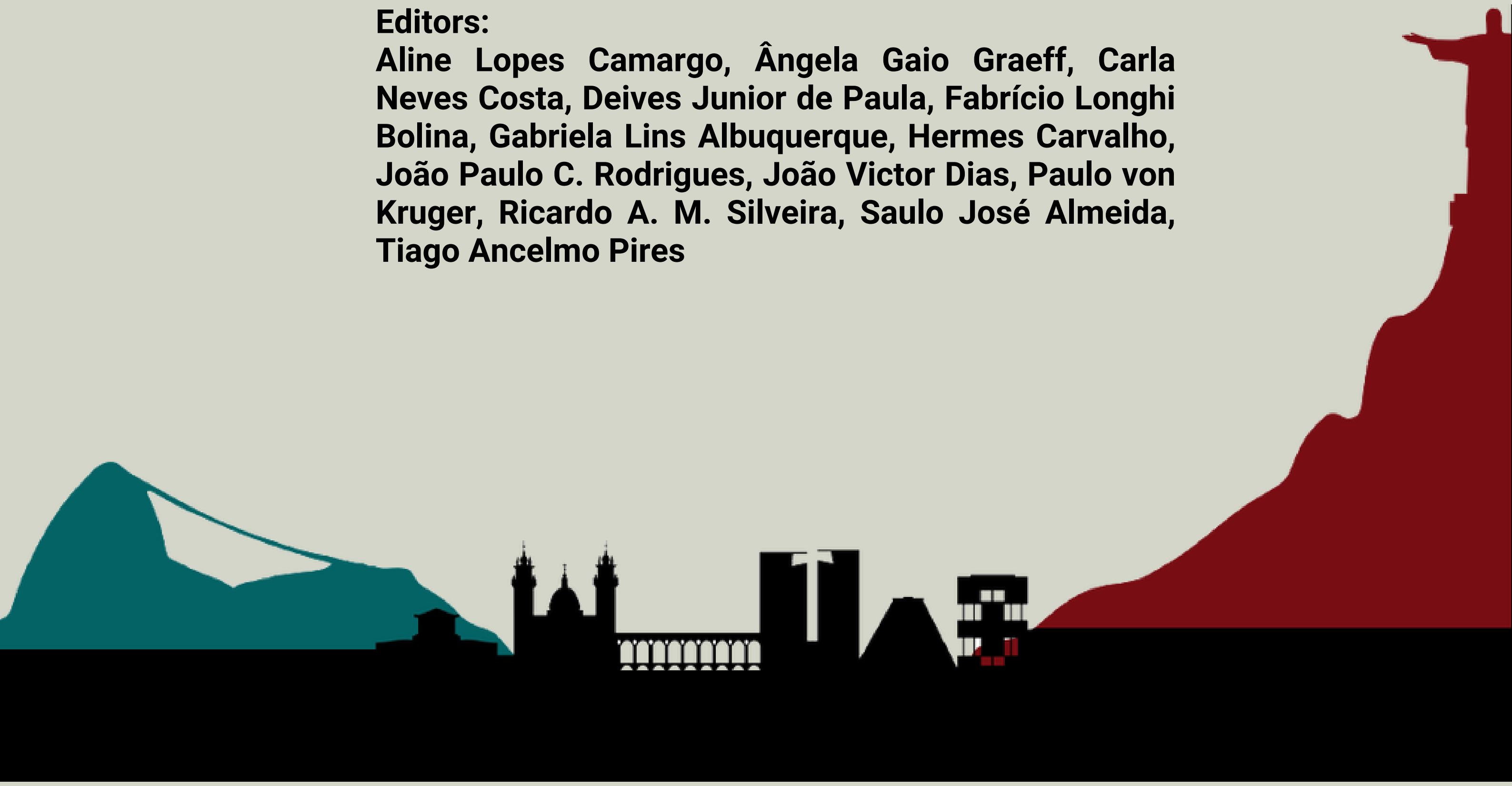

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IFireSS 2023 - International Fire Safety Symposium

Rio de Janeiro - Brazil

June 21st to 23rd, 2023

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Proceedings of IFireSS 2023 - International Fire Safety Symposium

Aline Lopes Camargo, Ângela Gaio Graeff, Carla Neves Costa, Deives Junior de Paula,Fabrício Longhi Bolina, Gabriela Lins Albuquerque, Hermes Carvalho, João Paulo Correia Rodrigues, João Victor Fragoso Dias, Paulo von Kruger, Ricardo A. M. Silveira, Saulo José Almeida, Tiago Ancelmo Pires.

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Preface

The Organising and Scientific committees of IFireSS 2023, as well as CIB W-14 Commission - Fire Safety, would like to thank your participation in the International Fire Safety Symposium – IfireSS – 2023, in Rio de Janeiro, Brazil. The city of Rio de Janeiro allowed the creation of a unique and fantastic environment for the realization of this event.

The Symposium contributed to the exchange of ideas and knowledge in the area of Fire Safety and assisted in planning future research activities for the area.

The Symposium has had participants from different countries around the world and covered a wide variety of research areas including: Structural Fire Safety; Mechanical and Thermal Properties of Materials; Fire Chemistry, Physics and Combustion; Fire Reaction; Fire Safety in Vehicles and Tunnels; Fire Risk Assessment; Smoke Control Systems; Firefighting and Evacuation; and Fire Regulations, Standardization and Construction Trends.

The articles presented at this Symposium were of high quality, in different areas of fire safety, and these proceedings reflect that fact. They will serve as the basis for developments in the field, research projects and technical standards. The in-person or online presentations were superb and resulting in discussions of a high level for the area.

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ANALYSIS OF THE POSSIBILITY OF IGNITION OF VARIOUS MATERIALS BY SHORT-CIRCUIT SPARKS

Kostiantyn A. Afanasenko[a,*]

ABSTRACT

The paper studies the possibility of various substances ignition with an electric ignition source, namely, a short circuit, depending on different parameters. The comparative analysis of fires causes depending on the approach of their conditional classification is given. Among others, ignition sources of electrical origin are highlighted.

An analysis of the fires causes statistical data collection used by various countries is carried out. It has been established that when using different approaches to their collection, the number of electrical ignition sources varies from 15 to 27%. And up to 50% of them are short circuits. The main characteristics of a short circuit and its fire hazard are considered. It has been established that in the event of a short circuit an intense scattering of sparks (drops of molten metal) is observed.

The paper considers the methods for calculating the flight times of a various metals spark in various aggregation states and the possibility of igniting combustible materials by them. Found that a drop of molten copper will be a ignition source for textiles, rubber and fabric with dimensions larger than 2.9 mm; a drop of molten steel will be the ignition source for solid combustible materials with dimensions larger than 2.6 mm.

Keywords: short-cirquit, ignition cource, sparks.

1. ANALYSIS OF THE FIRES CAUSES AND FIRES STATISTICS

Fires at critical infrastructure facilities usually have serious consequences. As a result, people can be injured, and serious damage can be caused to both businesses and the environment.

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At the same time, the causes (ignition sources) of fires at such objects can be divided into 4 groups: open fire, thermal features of mechanical energy, thermal features of chemical reactions, thermal features of electrical energy. The latter, according to statistics, can reach up to 25% of the total.

1.1 Analysis of typical fires causes

Fires causes of can vary in a fairly wide range. The authors [1] identifies the following classification of the fires causes:

1. Arson.
2. Production equipment failure, violation of the technological process: defects in the design, manufacture and installation of production equipment; violation of technological regulations; electrostatic discharge; destruction of moving parts and parts, getting into moving mechanisms of foreign parts; malfunction of the devices cooling system, surfaces friction; malfunction, lack of spark-extinguishing equipment; other malfunctions of production equipment.
3. Violation of fire safety rules during installation and operation of electrical installations: lack of design and production of electrical installations, the electrical network short circuit; violation of the design rules of electrical installations and electrical networks; violation of the rules of electrical installations technical operation; violation of fire safety rules during the operation of electrical household appliances.
4. Violation of fire safety rules during electric gas welding works.
5. Explosion.
6. Self-ignition of substance and materials.
7. Violation of fire safety rules during the installation and operation of furnaces: improper arrangement and malfunction of heating furnaces and chimneys; violation of fire safety rules during the operation of furnaces.
8. Violation of fire safety rules during installation and operation of heat-generating units and installations: lack of design and manufacture of heat-generating units and equipment; violation of the installation rules of heat-generating units and equipment; violation of fire safety rules during the operation of heat-generating units and equipment.
9. Violation of fire safety rules during operating household gas, kerosene, and gasoline appliances.
10. Careless handling of fire: smoking carelessness; carelessness during fire works (heating pipes, engines and other equipment with an open fire); another reason for careless handling of fire.
11. Mischief of children with fire.
12. Lightning discharge.
13. Undetermined cause.
14. Other reasons.

Thus, identifying the main causes of fires (ignition sources) and determining the degree of their danger is an urgent task.

1.2 Statistical data on ignition sources as fires causes

An ignition source is an object that emits thermal energy sufficient for ignition (combustion initiation is an exothermic process that includes redox transformations of substances and materials and is characterized by the presence of volatile products and light radiation) [2].

According to the nature of origin, ignition sources are classified as follows:
– open fire, heated combustion products and surfaces heated by them;
– thermal features of mechanical energy;
– thermal features of electrical energy;
– thermal features of chemical reactions (open fire and combustion products are separated from this group into an independent).

If all fires in Ukraine to be taken for 100%, then fires caused by "violation of fire safety rules during installation and operation of electrical installations" amount to an average of about 25 % annually from the total number of fires; fires due to "electrostatic discharge" and "lightning discharge" account for about 1% of the total number of fires.
Analysis of various statistics shows that the approach to data collection is quite different.

For example, in Canada, during the fires causes data collection, all fires are taken into account, including ecosystems, residential, non-residential buildings, etc. [3]. With this approach, the number of electrical ignition sources can reach 15%. (figure 1).

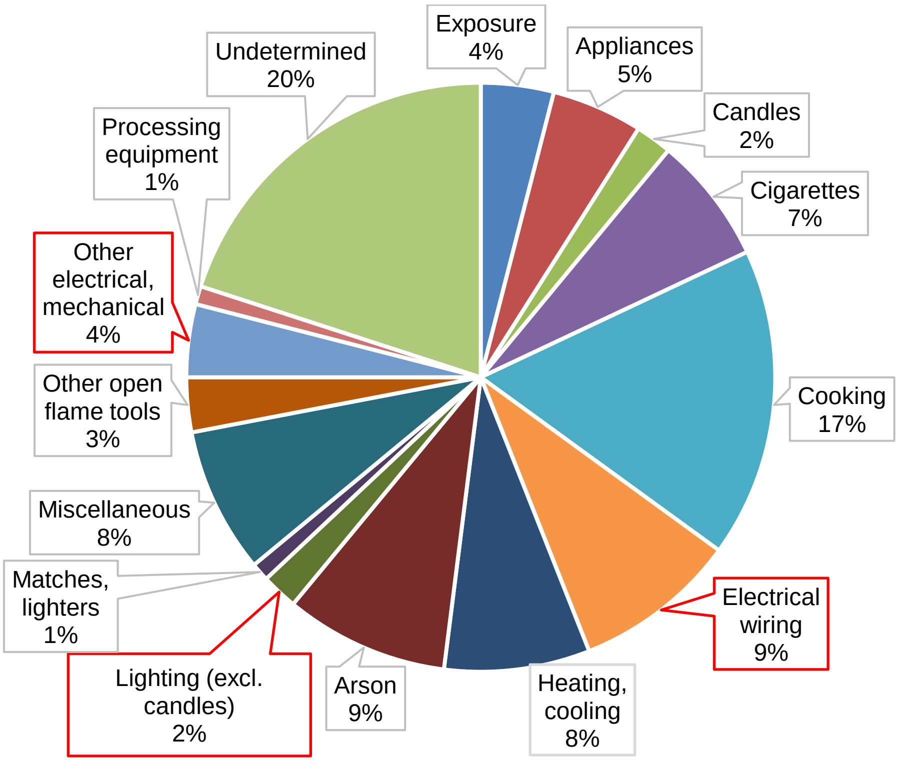


Figure 1: Statistics on the fires causes during 2005-2014 in Canada [3]

However, the statistics of the causes of fires in Great Britain (Table 1) [4] allow us to assess the sources of ignition at industrial enterprises and critical infrastructure facilities. And in this case, the number of electric ignition sources increases to 27%.

Table 1. Average year fire statistics 2010-2020 in England (including Critical Infrastructure Facilities) [4]

		Source of ignition										
Year	**Total**	**Smokers' materials**	**Cigaretts, lighters**	**Matches**	**Cooking appliances**	**Space heating appliances**	**Central and water heating appliances**	**Blowlamps, welding and cutting equipment**	**Electrical distribution**	**Other electrical appliances**	**Candles**	**Other/ Unspecified**
2010/11	20755	1079	726	1295	2742	696	120	380	2613	2720	145	8239
2011/12	20321	1152	737	1321	2491	571	104	401	2432	2585	125	8402
2012/13	16506	852	653	834	2298	547	125	319	2464	2393	142	5879
2013/14	16527	878	619	834	2123	464	135	342	2462	2248	123	6299
2014/15	15562	802	711	762	2136	448	105	334	2288	2177	105	5694
2015/16	16026	949	853	860	2045	415	101	310	2255	2061	113	6064
2016/17	15868	851	919	782	1970	434	104	292	2359	1823	106	6228
2017/18	15616	883	823	703	1943	440	115	267	2186	1820	103	6333
2018/19	15032	922	519	526	1847	379	90	273	2232	1669	90	6485
2019/20	14334	853	517	486	1713	431	98	241	2 223	1628	85	6059
2020/21	11916	735	368	346	1273	376	71	204	1 703	1164	59	5617
Total	178463	9956	7445	8749	22581	5201	1168	3363	**25217**	**2 288**	1196	71299
Persent		5,58	4,17	4,90	12,65	2,91	0,65	1,88	**14,13**	**12,49**	0,67	39,95

The analysis of the given data shows that the number of ignition sources of electrical origin, depending on the method of statistical data collection, can vary within 15-27%. Thus, determining the danger of electrical origin ignition sources is an urgent task.

2. CLASSIFICATION OF THE ELECTRICAL ORIGIN IGNITION SOURCES

Literature analysis shows three groups of electrical origin ignition sources [5, 6, 7]:

1. Electric spark (arc). There are sparks and arcs arising as a result of the thermal action of short-circuit, electric sparks (drops of metal) created during electric welding, arising from the destruction of the bulbs of electric incandescent lamps or as a result of the static electricity charges.
2. Heating of substances, nodes and surfaces of technological equipment.
3. Discharges of atmospheric electricity. There is a difference between a direct lightning strike and secondary lightning strikes.

Also, the power lines heating in case of overvoltage and leakage currents should be attributed to the heat features of electrical energy.

At the same time, a short circuit, as a cause of fires, reaches up to 50% of the total number of electrical ones.

2.1 Thermal action of short-circuit

The danger of short circuits is explained by the thermal effect of electric current, which is quantitatively expressed by the Joule-Lenz law.

According to Ohm's law, as the resistance R decreases, the current I increases in square, so the amount of heat Q released in the conductor when a short-circuit current occurs increases sharply.

A short-circuit, the effect of which is not limited in time, leads to the melting of conductors and the occurrence of sparks and arcs, so it can be a cause of fires of nearest combustible materials.

2.2 Electric sparks (drops of metal)

When a short circuit occurs, sparks occur in 100% of cases. Electric sparks and arcs occur when an electric current passes through the air. Electric sparks (drops of metal) are formed, in the case of short circuits of electrical conductors. The size of the hot particles of metal at short circuit of electric wiring can reach 3 mm. At the same time, when they expand, they are in a molten state, which increases their danger. However, when released into the environment, they gradually cool down.

With a short circuit, sparks fly in all directions, and their speed does not exceed 10 m/s. The area of particle flight in the event of a short-circuit depends on the height of the wire, the initial speed of the particle flight, the angle of departure and is probabilistic in nature (Fig. 2).

For the height of the location of the wire 10 m the probability of hitting particles at a distance 9 m is 0.06; 7 m – 0.45; 5 m – 0.92; for the height of the location 3 m the probability of hitting particles at a distance 8 m is 0.01; 6 m – 0.29; 4 m – 0.96; and for the heights 1 m the probability of scattering of particles on6 m - 0.06; 5 m - 0.24; 4 m – 0.66 and 3 m – 0.99.

It should be noted that during a short-circuit, electric sparks, as a rule, have time to form before the protection devices are triggered, and therefore the probability of ignition of flammable substances and materials during a short-circuit is sufficient.

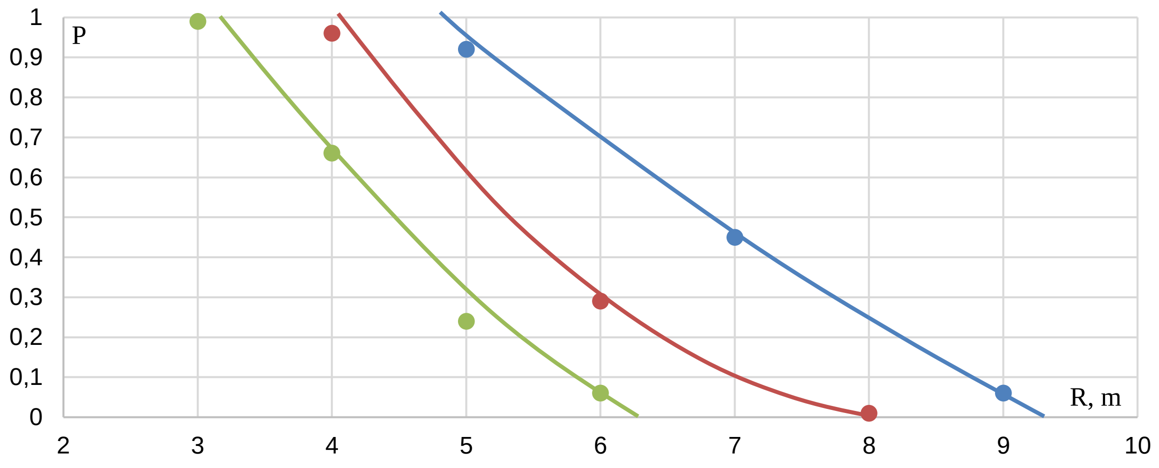


Figure 2. The probability (P) of hitting metal particles depending on the height of their formation and distance to the object (R, m)

Thus, if there is a probability of a drop of metal hitting the surface of a combustible substance, its ignition is possible. Therefore, there is a need to determine the ignition capacity of such a drop depending on the external conditions and physical and chemical properties of the materials of the drop and the combustible substance.

2.3 Calculation of igniting ability of a metal drop

The temperature of the heated particles depends on the type of metal and cannot be lower than its melting temperature. Thus, the temperature of aluminum particles during a short circuit reaches +2500 ºC [8, 9].

The amount of heat that a particle (drop) of metal can give to a combustible environment before reaching its self-ignition temperature is calculated in the following sequence.

The average flight speed of a drop of metal in free fall is calculated by the formula:

$$\omega_{dr} = 0{,}5 \cdot \sqrt{2 \cdot g \cdot H}, [m/s], \quad (1)$$

where g=9.81 – Is the acceleration of free fall;
H – Is the height of the drop.

The volume of a drop of metal is calculated by the formula:

$$V_{dr} = \frac{\pi \cdot d_{dr}^3}{6} = 0{,}524 \cdot d_{dr}^3, [m^3], \quad (2)$$

where d_{dr} – is the diameter of the drop, [m].

The mass of the drop is calculated according to the formula:

$$m_{кр} = V_{dr} \cdot \rho_{dr}, [kg] \quad (3)$$

where ρ_{dr} – Is densityof metal, [kg/m^3].

Further calculations will be made for three metals used in electrical products (including cable products): steel, aluminum and copper [10]. Fig. 3 shows the dependence of the drop mass depending on its diameter and the metal of which it is composed.

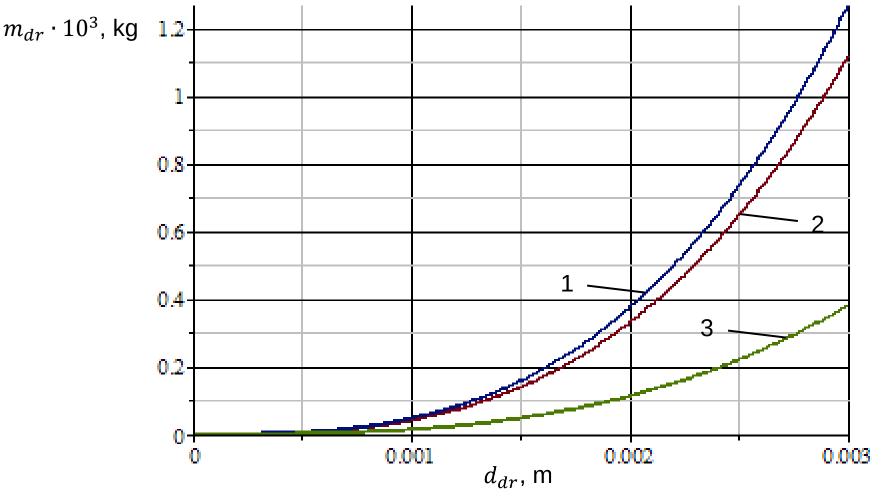


Figure 3. Dependence of the drop mass depending on its diameter and the metal of which it is composed. 1 – copper, 2 –steel, 3 – aluminum.

Depending on the duration of the drop's flight, three states of its aggregate are possible: liquid, crystallization state, and solid.

The flight time of a drop in a liquid state is calculated by the formula:

$$\tau_{liq} = \frac{C_p \cdot m_{dr}}{\alpha \cdot S_{dr}} \cdot ln\frac{T_{start} - T_0}{T_{melt} - T_0}, [s] \tag{4}$$

where C_p –specific heat capacity of the metal melt, [J/(kg·K)]; S_{dr} – surface area of the drop, [m^2]; T_{start} – temperature of the drop at the beginning of the flight, [K]; T_{melt} – metal melting point temperature, [K]; T_0 – ambient temperature, [K]; α –heat transfer coefficient, [W/(m^2·K)].

The drop heat transfer coefficient is calculated in the following sequence:

a) calculate the Reynolds number (the Reynolds number is a dimensionless quantity, is one of the characteristics of the movement of a viscous liquid and determines the ratio of inertial forces to viscous forces) according to the formula:

$$Re = \frac{\omega_{кр} \cdot d_{кр}}{r}, \tag{5}$$

where $r = 15.1 \cdot 10^{-6}\ m^2/s$ – coefficient of kinematic viscosity of air at a temperature of +20 ºC;

b) calculate the Nusselt criterion (the Nusselt criterion characterizes the average intensity of convective heat exchange between the surface of the body and the free or forced flow of liquid or gas) according to the formula:

$$Nu = 0{,}62 \cdot \sqrt{Re}, \tag{6}$$

c) calculate the heat transfer coefficient according to the formula:

$$\alpha = \frac{Nu \cdot \lambda_{air}}{d_{dr}}, [W/(m^2 \cdot K)], \tag{7}$$

where $\lambda_{air} = 0{,}022\ \mathrm{W/(m} \cdot K)$ – air thermal conductivity coefficient.

If $\tau \leq \tau_{liq}$, then the final temperature of the drop is calculated by the formula:

$$T_{final} = \mathrm{T}_0 + (\mathrm{T}_{start} - \mathrm{T}_0) \cdot \exp\left(-\frac{\alpha \cdot S_{dr}}{C_p \cdot m_{dr}}\right), [K]. \quad (8)$$

The drop flight time, during which its crystallization occurs, is determined by the formula:

$$\tau_{cryst} = \frac{m_{dr} \cdot C_{cryst}}{\alpha \cdot S_{dr} \cdot (T_{liq} - \mathrm{T}_0)}, [\mathrm{s}], \quad (9)$$

where C_{cryst} – the specific metal crystallization heat, [J/kg].

With the help of the above formulas, the time of flight of a molten metal drop was calculated depending on external conditions. Graphical interpretation of calculations is shown in Figure 4.

If , then the final temperature of the drop is calculated by the formula:$\tau_{liq} < \tau \leq (\tau_{liq} + \tau_{cryst})$

$$T_{final} = T_{liq}, [\mathrm{K}], \quad (9)$$

To assess the degree of danger in work, the flight time of a drop of metal in a molten state was calculated (Fig. 5) .

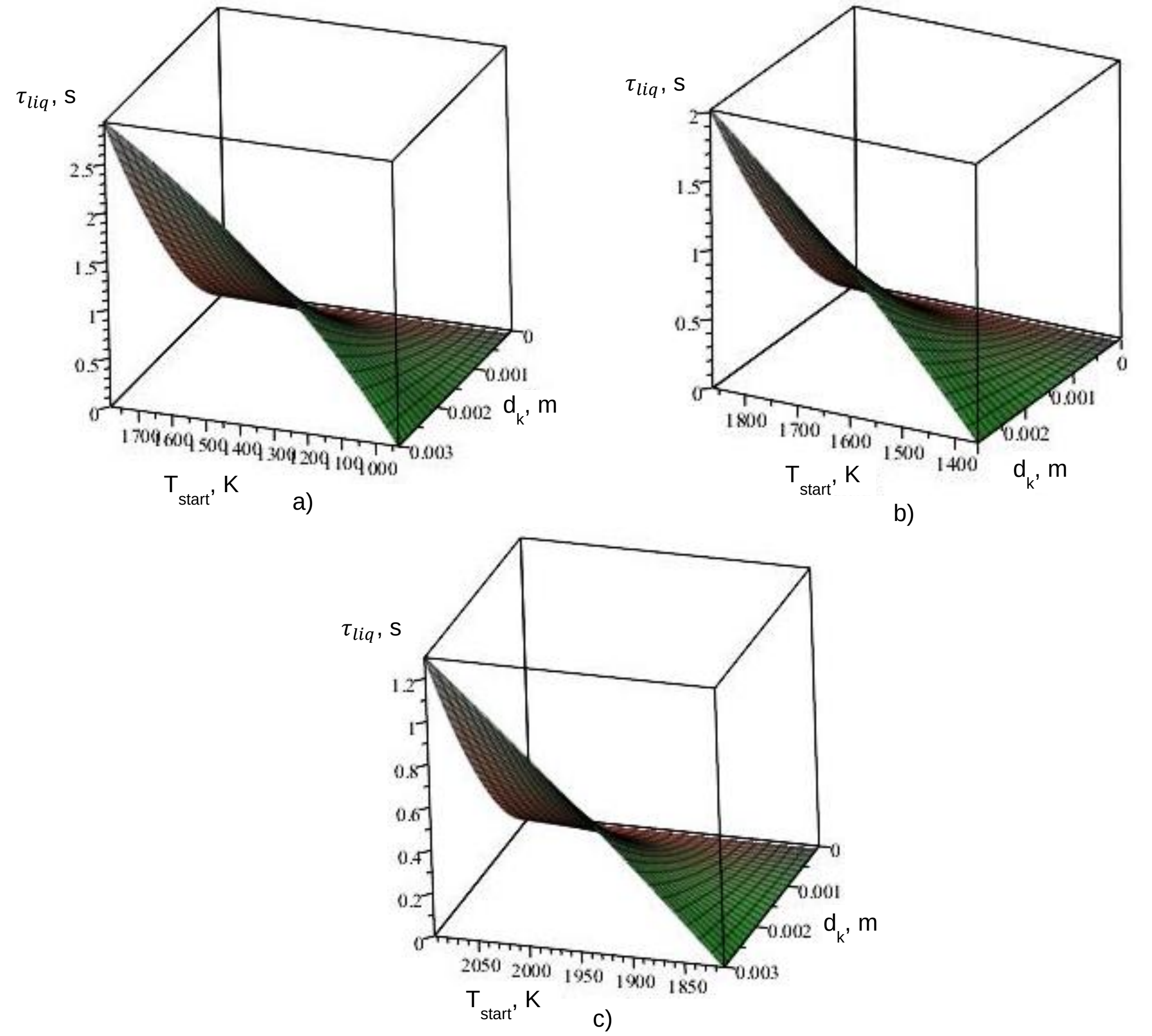


Figure 4. Dependences of the flight time of a metal drop in a molten state on the initial temperature and drop diameter: a) Aluminum; b) Copper; c) Steel.

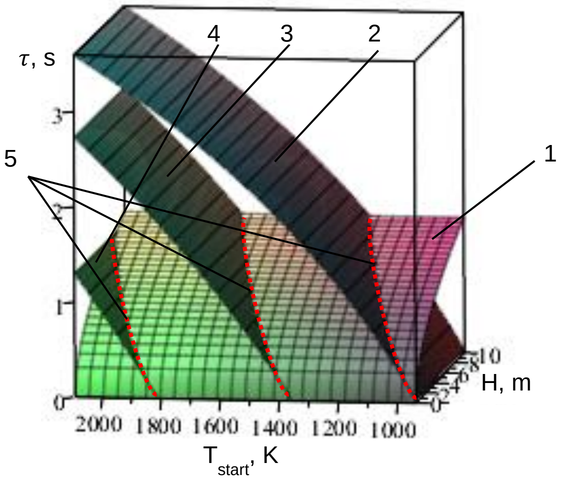


Figure 5. Dependences of the flight time of a metal drop in a molten state on the initial temperature, flight height, and average flight time. 1 – average flight time; 2 – aluminum; 3 – copper; 4 – steel; 5 – the time of the drop falling in the molten state.

Analysis of Fig. 5 shows a comparison of the time the drop remains in the molten state with the flight time of the drop from a certain height. In accordance with the received calculation data, it can be concluded that when falling from a height of up to 8 m, drops of all metals will be in a molten state.

If , then the final temperature of the drop in the solid state is calculated by the formula:$\tau > (\tau_{liq} + \tau_{cryst})$

$$\mathrm{T}_{final} = \mathrm{T}_0 + (\mathrm{T}_{fuse} - \mathrm{T}_0) \cdot \exp\left\{-\frac{\alpha \cdot S_{dr}}{C_{dr} \cdot m_{dr}} \cdot \left[\tau - (\tau_{liq} + \tau_{cryst})\right]\right\}, [K], \tag{9}$$

where C_{dr} – the specific heat capacity of the metal, [J/(kg·K)].

The next stage of the work was to analyze the possibility of ignition from a metal drop in a molten state of various solid combustible materials, such as plastic, wood, textiles and rubber.

The amount of heat that a drop of metal gives off to the solid material on which it fell is calculated by the simplified formula [11, 12, 13]:

$$W = V_{dr} \cdot \rho_{dr} \cdot C_{dr} \cdot (T_{final} - \mathrm{T}_{SI}) \cdot \mathrm{K}, [J], \tag{10}$$

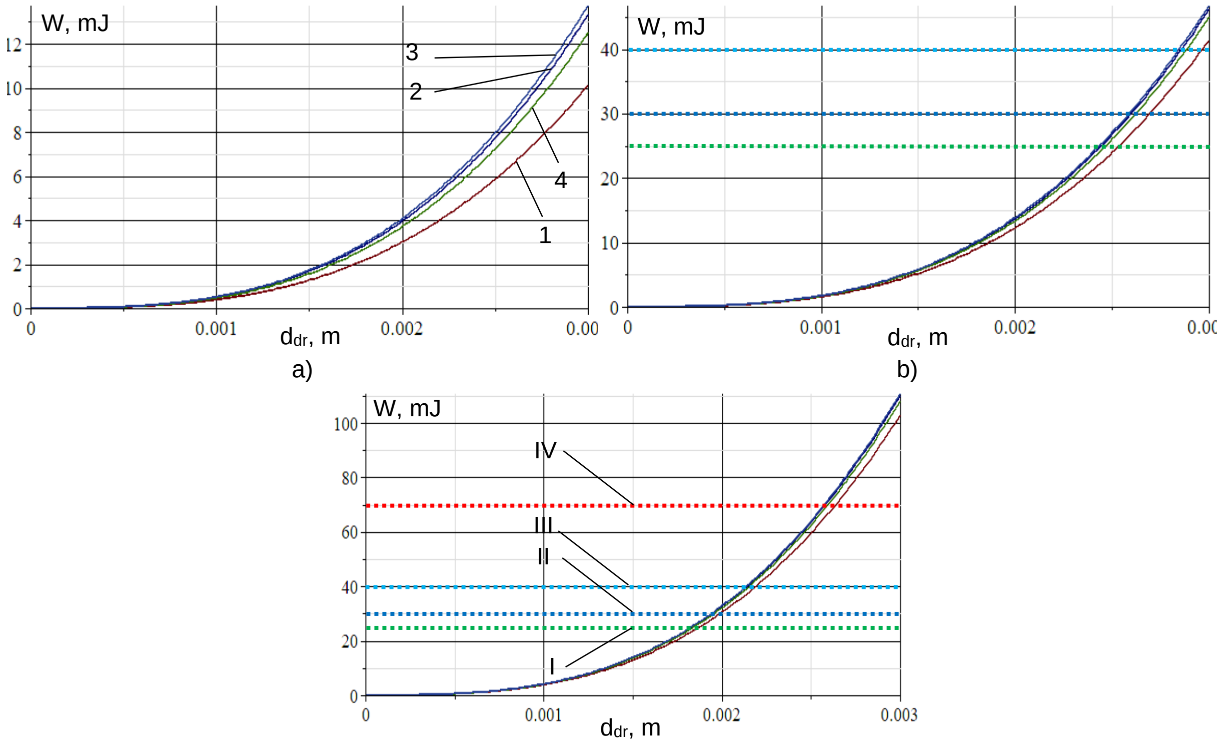
where T_{SI} – the self-ignition temperature of the combustible material, [K]; K – coefficient equal to the ratio of the heat given off to the combustible material to the energy stored in the drop. It is allowed to take K=1.

Some characteristics of the fire hazard of solid combustible materials are given in the table 3.

Table 3. Some fire hazard characteristics of solid combustible materials [14, 15, 16]

Name of the material	**Self-ignition temperature of the substance (T_{SI}), [K]**	**Minimum ignition energy (W_{Ign}), [mJ]**
Polyethylene	690	70
Rubber	613	30
Textile	633	25
Wood	603	40-60

Calculations of the energy transferred by metal drops to combustible materials were carried out according to the above formulas (Fig. 6).



a) b)

c)

Figure 6. Calculated energies of a metal drop in the molten state depending on the diameter of the drop for: a) aluminum, b) copper, c) steel. Transmitted energy: 1 – polyethylene; 2 – rubber; 3 – textiles; 4 - tree. Minimal ignition energy: I – textile; II – rubber; III – wood; IV – polyethylene.

Analysis of the data shown in Fig. 6 allows us to conclude that when drops of molten aluminum fall on combustible materials, ignition will not occur.

At the same time, a drop of molten copper will be a source of ignition for textiles, rubber and fabric with dimensions greater than 2.9 mm.

And a drop of molten steel will be the source of ignition for all listed solid combustible materials with dimensions greater than 2.6 mm.

3. CONCLUSIONS

1. The work examines the statistics of fires in several countries, highlights the peculiarities of statistical data collection. It has been established that the share of electrical ignition sources can be up to 27% at industrial facilities and critical infrastructure facilities.

2. The nature of a short circuit as a source of ignition has been studied. It was established that in the case of a short circuit, drops of molten metal are splashed, which can cause ignition of various materials.

3. The method of calculating the parameters of metal drops when they occur during a short circuit is considered. It has been established that when drops of molten aluminum fall on combustible materials, ignition will not occur. At the same time, a drop of molten copper will be a source of ignition for textiles, rubber and fabric with dimensions larger than 2.9 mm. A drop of molten steel will be the source of ignition for all listed solid combustible materials with dimensions larger than 2.6 mm.

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