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Fire Hazards Associated with Vehicle Fire in a Residential Garage

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***Abstract*— The article presents the dangers associated with fires originating in garages integrated into the architecture of single-family homes. Every year, around 500 people lose their lives in residential building fires. Most fire victims, accounting for approximately 60–70% of these cases, are affected by exposure to smoke and toxic combustion products. The article outlines the potential causes of such significant fatalities and proposes solutions that can significantly enhance the safety of residents.**

Keywords— safety, risk, hazard, fire, explosion

I. INTRODUCTION

Fire has accompanied humanity since the dawn of time. It provides warmth and a sense of security, but when uncontrolled, it brings death and destruction. When the combustion process of flammable materials is not under control, a fire occurs. Fires tend to ignite at the most unfavourable time and place for the person or entity affected. Therefore, fire safety measures and solutions increase with the fire category of a building, which is also related to the building's height. In residential buildings, due to their structure and height, chimney effects may occur, potentially leading to faster fire development and a significant rise in temperature. Escape routes (the only way out) may become filled with smoke, making evacuation impossible for the occupants. In Poland, dozens of people die in building fires each year, with approximately 60-70% of fatalities caused by exposure to smoke and toxic combustion products. The direct cause of death is often highly toxic combustion and thermal decomposition products: carbon monoxide, hydrogen chloride, and hydrogen cyanide. Fires occur despite changes in fire protection regulations, advancements in residential construction technology, and improvements in the safety of technical devices.

This article attempts to illustrate the level of risk in the event of an uncontrolled fire in vehicles located inside a garage directly adjacent to the residential section of a single-family house. To this end, an analysis of legal requirements for fire resistance classifications of buildings was conducted, along with an assessment of the threat posed by the potential migration of carbon monoxide generated in a fire environment, which has a destructive impact on individuals inside the building.

II. FIRE SAFETY AS A SUBJECT OF RESEARCH – CONCEPTS RELATED TO THE PHENOMENON OF FIRE

Fire safety is a complex concept. Its definition as a scientific concept can, among other things, be based on the theory of "safety" developed by Professor Leszek Korzeniowski, which constitutes an inseparable element of the proper functioning of fire protection understood as a system and a set of actions with a defined synergy. Thus, "Fire safety is an objective state that is a function of the level of threats and defensive potential." In this regard, the state—understood as a situation, level, or property—can be described considering the following assumptions:

- There is always a time frame marking the beginning and end of the state.
- Each entity within a given time frame possesses a certain property.
- In reality, every state is defined between extreme values.

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- A specific relationship exists between entities.

An objective state – existing independently of the consciousness of the observing entity. A threat, on the other hand, is a situation dangerous to life or health, synonymous with danger. Based on the cause-and-effect relationship, threats can be categorized as causal or consequential. A system, considering fire protection conditions, should be understood as a set of interrelated elements functioning as a single whole. Therefore, a fire protection system is any internally coordinated system with a specific structure, consisting of elements and a set of interactions between them that collectively determine the features of the whole.

In this context, the system is an organized entity operating within a defined environment and composed of smaller components—subsystems. Subsystems, in turn, are systems within a broader system, interconnected through numerous cooperative relationships in such a way that each of them achieves the main goal and contributes to the success of the whole. A system can also be described as a configuration of certain elements interconnected by various relationships, created to fulfill specific functions.

Therefore, fire safety in a building is determined not only by its basic structure and main components. A crucial role is also played by the training of residents, access to and proper use of portable firefighting equipment, as well as finishing elements that can enhance fire resistance, such as cladding and protective coatings. These are among the fundamental elements included in the definition of defensive potential. The aim of limiting the spread of fire and smoke beyond the room where the fire originated—which is directly specified in fire protection regulations is the implementation of appropriate technical measures such as fire partitions, fire closures, the construction of extinguishing systems, or the installation of smoke barriers. For single-family residential buildings, the relevant provisions include the Regulation of the Minister of Infrastructure of April 12, 2002, on the technical conditions that buildings and their location must meet (Journal of Laws 2022, item 1225). This regulation defines the fire resistance class of a building as specified in §§ 212, 214, and 216, applicable to buildings classified under the ZL IV category of human hazard, i.e., residential buildings. Limiting the spread of fire to adjacent buildings part of the requirements catalog for both residential ZL IV buildings and other structures can be achieved through passive protection measures such as maintaining a buffer zone that reduces radiation, as well as additional elements of the analyzed protection system. These include the properties of facade materials, the fire resistance of walls, reducing the flammability of roof coverings, preventing fire penetration into the building's interior, minimizing the risk of roof ignition on a structure being destroyed by fire, and thus preventing the fire from spreading to the exterior.

A fire is defined depending on the field of life that uses this concept for its purposes. Among firefighters and individuals involved in fire safety, a fire is defined as an uncontrolled combustion process occurring in a location not intended for it, spreading uncontrollably, posing a threat to human life and health, and causing material losses. An analysis of numerous court rulings also reveals that in specialized professional literature, T. Sawicki, B. Sygit, and P. Guzewski noted that "not every fire is a fire," and not every fire is penalized under Article 163 § 1 point 1 of the Act of June 6, 1997, Penal Code (Journal of Laws 2024, items 37, 1222, 1248). Fire, therefore, is merely a phenomenon involving the release of heat and light accompanying the burning of materials, perceived in the form of flames and glow. A fire, however, refers to a large-scale (extensive) fire that causes significant property damage. On the other hand, a commonly dangerous fire, as analyzed under Article 163 § 1 point 1 of the Penal Code, is defined as "a large-scale fire (extensive fire) that caused property damage and, additionally, poses a threat to the life or health of many people or to further property on a large scale."

Years of full-scale fire research and observations of real fires have allowed for a generalization of their description by identifying the relationship between changes in the average temperature of combustion gases over time, distinguishing three main phases of this phenomenon. Although the phases of a fire generally describe the hazard concerning the course of fire temperature in a room as a function of time, they can serve as a useful reference for assessing fire hazards in relation to other event circumstances, including the analyzed case.

- Phase I – Also known as the growth or development phase of a fire, or the pre-flashover phase.
- Phase II – The fully developed fire, also referred to as the post-flashover phase, during which flammable materials undergo combustion.
- Phase III – The decay (cooling) phase. Transition to this phase usually occurs after the depletion of flammable materials, leading to a decrease in temperature and other fire parameters. It is generally accepted that the beginning of this stage is marked by a temperature drop to 80% of the maximum value.

For a proper understanding of "fire" within the context of the Penal Code, the doctrine suggests that a "fire," based on the analysis of available court rulings in similar cases, should be considered an event causing a first-degree consequence. Meanwhile, the feature "threatens the life or health of many people or property on a large scale" constitutes a second-degree consequence. Whether a particular event constitutes a "fire" can be determined by referring to rulings of the Supreme Court adjudicating in similar cases. "A fire is not just any flame but one spreading with elemental force and on such a large scale that it creates specific, real, and immediate danger to the life or health of many people or to property on a large scale. This threat cannot be distant in time or dependent on the occurrence of certain conditions in the future; it must exist currently." – Supreme Court ruling of December 11, 1978, II KR 269/78, OSNKW 1979, no. 5, item 55.

"A fire is characterized by suddenness, violence, and the potential for a large scale. Igniting a small fire under conditions where there was a real possibility of its immediate spread and threat to the life or health of many people or to property on a large scale—if the fire had not been extinguished—is already considered a fire. It must be a fire of significant size, one that has engulfed objects to such an extent that controlling it requires considerable effort." – Supreme Court ruling of May 13, 1971, IV KR 68/71, OSPiKA 1972.

"Such a fire corresponds to the concept of fire even when it affects multiple objects (buildings, forests, warehouses, materials), as well as when it involves a single object, creating a state of threat to property on a large scale. For the concept of fire, the risk of the fire spreading to other objects (e.g., other buildings) is not crucial. Setting fire to an isolated building, the burning of which created a threat to the lives of many people or property on a large scale, meets the criteria for this offense, even if—due to the location of the building—the spread of the fire beyond its boundaries was impossible." – Supreme Court ruling of February 13, 1978, IV KR 18/78, OSNPG 1978, no. 7, item 80. "A fire must be of such a large scale that the danger to the life or health of many people or to property on a large scale is concrete, real, and immediate, not merely potential. A fire extinguished at its inception does not constitute a fire; however, depending on the circumstances, it may indicate an attempt to cause a fire." – Supreme Court ruling of December 14, 1976, III KR 316/76, OSNKW 1977, no. 3, item 20.

Nevertheless, for a proper understanding of the fire mechanism, it is essential to first define the combustion process. Below, the main elements of combustion, which constitute the interactions within a fire, are presented, such as:

- fuel – any substance capable of burning
- oxidizer – oxygen from the air
- heat – playing a dual role in initiating and sustaining the process,
- free radicals – unpaired inter-molecular bonds (without pairing) formed as a result of chemical reactions, facilitating the branching chain reaction of decomposition and oxidation (combustion). Thermal inertia is the ratio of three properties of a given material:
- thermal conductivity (k),
- density of the material (ρ) – Greek letter "rho",
- heat capacity (c)

At the beginning of the combustion process with the potential to become a fire (i.e., combustion that, without intervention, will escalate into a fire), we can speak of a "fuel-controlled fire" (FCF). This means that the dynamics of combustion are influenced solely by the characteristics of the fuel (quantity, flammability, degree of fragmentation, arrangement, and heat of combustion) and not by the availability of air. As the combustion zone expands, the amount of incoming air becomes insufficient to sustain the ever-increasing dynamics of fire development and the growing release of heat. At a certain point, the fire's development becomes entirely governed by the amount of incoming air. This is referred to as a "ventilation-controlled fire" (VCF). During this phase, the lack of oxygen is caused by the high demand for it due to the release of significant amounts of heat, bringing the fire closer to the phenomenon of flashover. This occurs alongside the intense outflow of fire gases from the combustion zone, resulting in a turbulent gas exchange and visible turbulence at the neutral plane, which is the horizontal boundary between the smoke-filled zone and the smoke-free zone. This characteristic behavior of smoke (the neutral plane) can serve as one of the indicators of a fire, helping identify fire conditions and its phase. It should also be noted that there exists an extreme state of a ventilation-controlled fire, known as an "under-ventilated fire" or "oxygen-deficient fire." This state promotes the occurrence of the "backdraft" phenomenon, also referred to as the "reverse flame flow"Since a fire is a dynamic phenomenon, progressing through successive stages of development and occurring over time, the heat released should also be expressed as a function of time.

The heat released at a given moment represents its power. In fires, heat transfer occurs through three main mechanisms:

conduction – the transfer of heat through solids via molecular vibrations. Thermal conductivity in solids is accompanied by the phenomenon of thermal expansion. This can be classified into volumetric expansion, which increases dimensions in all directions, and linear expansion, which characterizes elongated objects. Some materials exhibit high thermal expansion values, often corresponding to high thermal conductivity

convection – the transfer of heat along with mass, occurring in liquids and gases (in physics, liquids and gases are treated as fluids with different densities due to their similar mechanical behavior). It typically results from density differences caused by temperature gradients. There is also forced heat transfer with mass, driven by an external factor.

-radiation – the transfer of thermal energy through electromagnetic waves.

Depending on their behavior in a fire, substances are generally classified into different "fire groups." Regardless of this classification, from the perspective of combustion and fire processes, every heated substance must transition to a gaseous state before undergoing flaming combustion. A flame is a highly heated gaseous space where gaseous fuel mixes (or is pre-mixed) with air, including oxygen. Solids that do not melt undergo a stage called pyrolysis during a fire. Pyrolysis, or thermal decomposition, is the irreversible chemical breakdown of a substance under the influence of heat.

For most substances, the autoignition temperature parameter can also be determined. When a sufficient amount of heat accumulates, the substance begins to combust automatically—this can occur without the presence of an ignition flame or spark. The ignition energy has been reached, and the substance burns. This applies to both solids and gases (most flammable liquids exist as gases at this temperature due to exceeding their boiling point). Apartments in buildings, due to the risks associated with fire progression, should constitute a specific type of fire zone that fire cannot penetrate. However, in practice, analyzing multi-family residential buildings reveals that fires, depending on the type of structure in which they originate, exhibit varying dynamics in terms of temperature rise and the amount of fire gases produced. The development and spread of a fire largely depend on the construction method and the materials used. One significant threat in this context is carbon monoxide, which easily mixes and spreads in the air. Carbon monoxide (commonly known as "CO") enters the body through the respiratory system and is then absorbed into the bloodstream. In the human respiratory system, carbon monoxide binds to hemoglobin 210 times faster than oxygen, blocking the flow of oxygen into the body. This poses a serious threat to human health and life. It prevents the proper distribution of oxygen in the blood and causes damage to the brain and other organs. Acute carbon monoxide poisoning can result in irreversible damage to the central nervous system, coronary insufficiency, a heart attack, or even death.

Symptoms of carbon monoxide poisoning were likely known from the moment the first fire was lit, long before the discovery of gases. To this day, carbon monoxide remains one of the most dangerous poisons. Every year, dozens of people die due to carbon monoxide poisoning, commonly referred to as "CO poisoning." The most frequent sources of carbon monoxide poisoning in spaces intended for human occupancy are fires, and in areas where gas other than natural gas is used, faulty household gas installations (e.g., coal gas contains about 10–15% CO). This substance can also be released due to the improper functioning of heating devices caused by one or more factors. For instance, a gas heater installed in a small bathroom without proper exhaust ventilation (lacking a chimney, having a clogged exhaust duct, or experiencing a reverse draft in the chimney) can produce a lethal dose of carbon monoxide within one minute. Carbon monoxide (commonly called "CO," systematically named carbon monoxide (II)) easily mixes with air. It is a gas that poses a threat at any concentration – at lower concentrations, it causes a loss of motor coordination, while at higher concentrations, it leads to sudden death. It affects the central nervous system and the cardiovascular system. Carbon monoxide is absorbed into the body through the respiratory system. The rate of absorption increases with factors such as physical exertion or high temperature, which enhance lung ventilation. The toxic effects of carbon monoxide result from its strong affinity (about 250–300 times greater than oxygen) for hemoglobin in red blood cells (erythrocytes). Carbon monoxide binds to hemoglobin, forming a compound called carboxyhemoglobin (HbCO), which is more stable than oxyhemoglobin (a combination of oxygen and hemoglobin) and can no longer serve as an oxygen carrier in the body. As a result, oxygen levels in the blood drop, leading to hypoxia. Carbon monoxide is toxic to cells, disrupting respiratory processes in mitochondria. While the bond with carboxyhemoglobin is reversible, the damage caused by carboxyhemoglobin affects organs that are highly sensitive to oxygen deprivation, such as the central nervous system and the cardiovascular system,which are vital for human survival.

III. ANALYSIS OF A FIRE ORIGINATING IN A GARAGE ADJACENT TO A RESIDENTIAL BUILDING

The analysis focused on Audi A3 and Mazda 3 vehicles parked in a garage adjacent to a residential building. For the purposes of vehicle fire characteristics, the technical parameters of the Audi A3 were used for calculations:

- Length: 4292 mm
- Width: 1765 mm
- Width with side mirrors: 1995 mm
- Height: 1423 mm
- Weight: Approximately 1370 kg

Based on the analysis of the Audi A3 vehicle, an average heat of combustion value of 35.72 MJ/kg was assumed for calculations, considering that approximately 25% of the vehicle's weight consists of combustible materials, i.e., 342 kg. The total heat of combustion for combustible materials is therefore approximately 12,216 MJ. The heat release rate (HRR) during the combustion of combustible materials in the analyzed vehicle, as referenced in G. E. Gorbett, Fire Dynamics, Pearson Education Inc., New Jersey 2011, pp. 132-140, is used for further calculations (1):

Q = X □ mn □ Af □ ΔHc, (1)

X – coefficient of incomplete combustion (<1.0),

mn – mass loss rate (g/m²·s),

Af – surface area of combustible material (m²),

ΔHc – heat of combustion of the volatile phase (kJ/g).

- For the calculations, the following values were assumed:
- X = 0,8
- mn – 29,5 g/m2s (average value for PP, PE, PS, PVC),
- Af – 7.5 m2
- ΔHc – 35,72 kJ/g (average value for PP, PE, PS, PVC).

After calculation: Q = X □ mn □ Af □ ΔHc = 0,8 □ 29,5 □ 7,5 □ 35,72 = 6320 kW (moc energii dla uszkodzeń pojazdu)

Based on the estimated amount of identified combustible materials, the assumed value of thermal damage, and the adopted mass loss rate during the combustion of combustible materials in the Audi A3 vehicle, calculations were performed using the empirical formula for determining the approximate time required for the complete combustion of combustible materials, as shown in the formula below (2):

$$t = \frac{M}{A_f \cdot m^n} \qquad (2)$$

where:

- t – total combustion time (s),
- M mass of combustible material (kg),
- Af surface area of combustible material (m2),
- mn – mass loss rate (g/m2s).

For the calculations, the following values were assumed:

- M = 342 000 g,
- Af = 7,5 m2,
- mn – 29,5 g/m2s (average value for PP, PE, PS, PCV).
- After calculation: t = 342 000: (7,5 □ 29,5) = ok. 1546 s = ok. 26 min (total estimated time for complete vehicle combustion)

For the characterization of the occurred fire, the technical parameters of the Mazda 3 vehicle were assumed for calculations, as it was parked next to the Audi A3 at the time of the fire.

- Length: 4465 mm
- Width: 1796 mm
- Width with side mirrors:2053 mm
- Height: 1450 mm
- Weight: ok 1280 kg

Based on the analysis of the Mazda 3 vehicle, an average heat of combustion value of 35.72 MJ/kg was assumed for calculations. The total heat of combustion of the combustible materials is approximately 11,430 MJ. The heat release rate (HRR) during the combustion of combustible materials in the analyzed vehicle, based on formula (1), is 6743 kW.

Based on the estimated amount of recognized combustible materials, the assumed value of thermal damage, and the adopted mass loss rate during the combustion of the combustible materials in the Mazda 3 vehicle, calculations were performed using the empirical formula for determining the approximate time required for the complete combustion of combustible materials, as shown in formula (2). After calculation, the total estimated time for complete combustion of the vehicle is 23 minutes.

At the same time, the calculated potential heat release in the garage from the Audi A3, relative to the adjacent parked Mazda, may significantly affect the combustible wooden elements of the building. These elements are located at a distance of approximately 0.92 meters from the side window of the garage in the northern wall and the wooden entrance. The measured distance of 1.5 meters from the side door of the garage to the wooden entrance door of the residential building will favor further fire development and uncontrolled fire migration deep into the inner part of the building. Fire load density is the thermal energy, expressed in megajoules, that may be generated by the combustion of flammable materials located in a room or fire zone per unit area of the facility, expressed in square meters. The fire load density is calculated in accordance with the Polish Standard PN - B-02852 according to the formula:

$$Q_d = \frac{\sum_{i=1}^{i=n} \left(Q_{cl} \cdot G_1\right)}{F} \quad (3)$$

- Qd – fire load density, in [MJ/m²],
- n – number of combustible materials stored in the building,
- F – net horizontal projection area of the building, in [m²],
- ni – mass of individual combustible materials stored in the building, in [kg],
- qcl – heat of combustion of individual combustible materials stored in the building, in [MJ/kg].

For the fire in the garage with Audi A3 and Mazda 3 vehicles, Qd is approximately 850 MJ/m² plus additional combustible materials in the garage (furniture, tires, etc.). The relative duration of the fire in an unfavorable fire scenario, with two passenger vehicles on fire along with other combustible materials, based on the estimated fire load density [Qd] and calculated from the PN-B-02852:2001 standard chart, is approximately 51 minutes.

Years of full-scale fire research and observations of real fires in buildings have allowed for the generalization of their description by providing the relationship between changes in the average temperature of combustion gases over time, distinguishing three main phases of the phenomenon. The individual phases can be described as follows:

- Phase I – also called the growth or development phase, or the pre-flashover phase. It is characterized by a relatively low average gas temperature, and the rate of thermal decomposition and combustion depends on the exposed surface area of combustible materials. The fire is "fuel-controlled."
- Phase II – the fully developed fire, also known as the post-flashover phase, during which the temperature reaches its maximum value (800 - 1000°C), and all combustible materials are burned. During this phase, flames fill the entire room, and the fire becomes "ventilation-controlled" due to the reduced O2 concentration.
- Phase III – the decay (cooling) phase. Transition to phase III usually occurs after the depletion of combustible materials, which leads to a decrease in temperature and other fire parameters.

In the analyzed fire event, the flammability properties of materials and their impact on the dynamics of fire development must also be taken into account. Phase I of the fire is directly related to the safety of the building structure affected by the fire. Its progression depends on the flammability properties of the materials present in the building, among which the most important parameters can be considered as follows:

- Flammability of the material,
- Heat generation kinetics,
- Rate of smoke and toxic product generation during decomposition and combustion,
- Smoke density,
- Flame spread rate.

The fire property of a material is its fire value, determined empirically. The parameter characterizing each fire property is a specific numerical value, which is a function of the measurement system parameters. The listed flammability properties are consistent with the scope of testing and evaluation of building products according to the European Fire Reaction Classes defined in the PN EN 13501-1:2008 standard, Fire classification of construction products and building elements. Part 1. Classification based on fire performance tests.

- Amount of heat released and rate of energy release,
- Time to ignition,
- Flame spread,
- Smoke production,
- Presence of burning droplets and debris.

From the perspective of fire protection, the most significant influence on the dynamics of the combustion process is the heat release rate (HRR) and the total amount of heat released (THR). The potential for heat release from the vehicle, taking into account the fire load density with parameters of approximately 850 MJ/m², significantly impacts, as shown by the conducted analysis, the building's structural elements, including its combustible elements, due to the influence from the interior of the garage where the fire originated. The required fire resistance class for the analyzed residential building (ZL IV) is defined in the Regulation of the Minister of Infrastructure of April 12, 2002, on technical conditions buildings and their location should meet (Journal of Laws 2022, item 1225), specifically in §212, which specifies fire resistance class "D." According to Table 2 of the regulation, related to the fire resistance class of building elements, there are no specific requirements, in comparison with other buildings, regarding interior walls between individual rooms in single-family residential buildings, such as in the analyzed case.

IV. CONCLUSION

The actions and solutions undertaken to improve the safety of the building's operation should be implemented in the following areas: - organizational and legal measures – conducting periodic inspections of technical installations, limiting the presence of combustible materials in unauthorized areas. - construction investments – limiting the spread of fire (so-called passive fire protection), constructing the building with non-combustible materials, equipping the building with materials resistant to ignition, and creating fire-separated rooms (e.g., fire doors with EI30 class). - investments in fire protection systems – so-called active fire protection, such as fire alarm systems (autonomous detectors or systems with control panels) and portable firefighting equipment.

An important issue in this case is the fact that the predicted fire load density for the garage should not exceed 500 MJ/m². Exceeding this limit significantly contributed, due to the lack of passive fire protection (such as the construction of building walls and the lack of window opening protection), to the degradation of the residential building adjacent to the garage. Regarding equipping residential buildings with portable fire protection equipment, the author of the publication has repeatedly emphasized, after studying the causes and circumstances of fire occurrences, that possessing portable fire equipment, such as smoke detectors, would significantly lead to earlier detection of the fire and attempts to extinguish it.

Smoke detectors are being purchased in many countries around the world. This is due to the awareness that in the event of a fire, the risk of losing life increases dramatically. Studies in the UK and the USA have confirmed that the use of fire early warning devices reduces the risk of death by about 40%. In Poland, the law does not require building or apartment owners to equip their properties with portable firefighting equipment or a fire alarm system.

Despite the lack of an obligation to install such devices in homes, individually installed devices of this type are now more commonly found in Poland than in previous years. Not without significance is the project carried out by the Ministry of the Interior and Administration aimed at making smoke detectors mandatory in homes and buildings, as well as public information campaigns run by the State Fire Service, such as "Carbon Monoxide and Fire. Raise Awareness." These actions, in the authors' opinion, should, however, serve as a first step towards further barriers that form active safety systems. Experience shows that the original design assumptions, which constitute passive fire protection for the building and the rooms associated with it, due to unauthorized changes in the use of rooms, the accumulation of combustible materials above the assumed design limits, over time, significantly deviate from the original assumptions.

As a result, the fire safety aspects of the building become outdated during the use of the residential buildingA major factor influencing the current number of fatalities and injuries within society is the low level of awareness regarding fire safety. When talking about awareness, it refers to the knowledge area that allows for the detection of potential hazards that could contribute to the outbreak of a fire. The lack of knowledge about basic fire safety neglects, such as a loose socket or storing cardboard or other combustible materials near heat sources, can be a source of fire. While the occurrence of fire in residential buildings in a global context is not questioned by society, when it comes to one's own apartment, the possibility of a fire is often dismissed, justified in various ways.

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