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Estimación del tiempo máximo de permanencia de los equipos de intervención en un incendio: temperatura ambiental

Estimation of the maximum time spent by fire intervention teams: room temperature

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Resumen-- **Para poder mejorar los procedimientos de actuación de los equipos de intervención durante un siniestro causado por un incendio, se presenta un modelo mediante la estimación de los tiempos de permanencia a partir de la temperatura ambiental. En la actualidad, la práctica totalidad de los equipos de intervención dispone de cámaras termográficas, que muestran en tiempo real una imagen de la radiación calorífica que está emitiendo un cuerpo, mediante su intensidad de la radiación. A partir de esta temperatura y mediante la aplicación de una ecuación o resolución gráfica, se obtienen los tiempos de permanencia máximos en el área afectada, de forma que se eviten accidentes mortales durante la intervención. Al final, se obtiene que la temperatura máxima admisible en la zona de intervención se sitúa en los 263 °C, siendo el tiempo máximo de permanencia en esas condiciones de 26 segundos.**

Palabras clave— temperatura radiante; distancia de intervención; tiempo de permanencia máximo; análisis de la vulnerabilidad; incendio.

Abstract— **In order to improve the procedures of action of the intervention teams during an incident caused by a fire, a model is presented by estimating the dwell times based on the ambient temperature. Currently, almost all intervention teams have thermographic cameras, which show in real time an image of the heat radiation that a body is emitting, through its radiation intensity. From this temperature and through the application of an equation or graphic resolution, the maximum dwell times in the affected area are obtained, so that fatal accidents are avoided during the intervention. In the end, it is obtained that the maximum permissible temperature in the intervention area is 263 °C, with the maximum time spent in these conditions being 26 seconds.**

Index Terms— radiant temperature; intervention distance; maximum dwell time; vulnerability analysis; fire event.

I. INTRODUCTION

DURING the design process of a building, its behaviour is taken into account in the face of possible accidents that may occur throughout its useful life. An incident that requires the presence of an intervention team can be due to multiple causes, among the most common are fires.

The basic civil protection guideline for the control and planning of the risk of serious accidents establishes the need to determine the distances that delimit the areas of intervention (Ministerio del interior, 2003).

Calculation methods are available, which allow the thermal irradiation caused by the rapid, non-explosive oxidation of combustible substances to be obtained from the characteristics of the fuel that originates it and its distance, both for a stationary fire, considering as such the puddle fire and the fire dart, and for a fireball or progressive flare (Van den Bosch, 1979; CCPS, 2000; Casal et al., 1999).

However, in an intervention these parameters are difficult to estimate, so an alternative method of risk management based on

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temperature is proposed, since practically all the intervention units have thermographic or thermal cameras, which allow the detection of infrared emissions produced by the electromagnetic spectrum.

The temperature reached by the receiver is related to the radiant energy received through the Stefan-Boltzman Law, equating the firefighter with a black body that cannot dissipate the flow of thermal radiation, which causes an increase in its temperature.

This temperature is the parameter from which the maximum dwell time is established, through the application of a vulnerability analysis. To do this, probabilistic methodologies such as Probit Analysis (Probability Unit) are used (Ministerio del Interior, 2003; Van den Bosch, 1979; Casal et al., 1999).

The Probit Analysis method incorporates the concept of radiation dose received by human beings from flames or incandescent bodies in fires, a parameter that is included in the basic civil protection guideline itself, for control and planning in the face of the risk of serious accidents (Ministerio del Interior, 2003; Van den Bosch, 1979; Casal et al., 1999).

II. METHODS

It is considered that, from a certain distance from the source of the fire, the transmission of heat is carried out exclusively by radiation, as defined in the basic civil protection guideline for the control and planning of the risk of serious accidents involving dangerous substances, decreasing its intensity as the distance increases (Ministerio del interior, 2003).

The intensity of the thermal radiation received by a living being or object located in the field of influence of a fire depends on the atmospheric conditions (ambient humidity), the geometry of the fire (diameter of the fire base, height of the flames and distance from the irradiated point) and the physical-chemical characteristics of the product in combustion.

The intensity of irradiation, which a person receives during an intervention, in an accident caused by a fire, is estimated by the following expression:

$$q = d \cdot F \cdot E$$

Where:

- q = Intensity of irradiation at a given distance (kW/m2).
- d = Atmospheric transmission coefficient (dimensionless).
- F = Geometric factor of vision, view or shape (dimensionless).
- E = Average intensity of flame radiation (kW/m2).

The intensity of radiation caused by the flames of a fire is between 40 and 140 kW/m2, depending on the nature of the fire (CCPS, 2000).

The proposed method is based on analysing the consequences of the irradiation caused by the fire on the receiver, instead of analysing the fire and its surroundings.

Since the approval of the basic guideline for the preparation and approval of Special Plans for the Chemical Sector, 5 kW/m2 with a maximum exposure time of 3 minutes and 3 kW/m2 (without indication of the maximum exposure time) (Ministerio del Interior, 1991) have been considered as threshold values for the delimitation of the Intervention Area.

The limit that people can bear is between 4 and 5 kW/m2, while the Dutch Organisation for Scientific Research (TNO) considers a safe space to be one whose irradiation intensity is equal to or less than 1 kW/m2. This reference value is reflected in the expression used to determine the effective exposure time during the development of stationary fires, which allow attempts to escape and seek protection (Van den Bosch, 1979; CCPS, 2000; Casal et al., 1999).

$$t_{ef} = t_r + \frac{3}{5} \cdot \frac{x_0}{\mu}\left[1 - \left(1 + \frac{\mu}{x_0} \cdot t_v\right)^{-5/3}\right]$$

Where:

- tef = Effective exposure time(s).
- tr = Reaction time (5 seconds).
- X0 = Distance to the centre of the fire (m).
- μ = Escape velocity of a person (m/s).
- tv = Time to reach the distance at which the irradiation intensity is 1 kW/m2 (S).

An irradiation intensity of 4.7 kW/m2 is set as a limit value for firefighters and protected persons (Ministerio del Interior, 1991).

The procedure is based on estimating deaths or injuries due to accidents, which occur because of thermal radiation, using vulnerability models.

III. RESULTS

A. Vulnerability models

Among the statistical vulnerability models, the Probit method is one of the most widely used, since it proposes a probability function based on the burden of exposure to a risk. A forecast of damage suffered by exposed persons is established, based on physical variables of the incident.

Vulnerability models propose empirical mathematical expressions, based on experimental studies (Van den Bosch, 1979; CCPS, 2000; Casal et al., 1999), using the following structure as a basis:

$$P_r = a + b \cdot lnV$$

Where:

- Pr = Probability of damage function Probit, compared to the exposed population.
- a = Constant dependent on the type of injury and type of exposure load.
- b = Constant dependent on the type of exposure load.
- V = Variable that represents the exposure load.

Based on the value of the function, the percentage of the exposed population that will be affected by the selected type of lesion is determined, depending on the exposure received. Specific functions are available for different levels of injury or even death caused because of the incident.

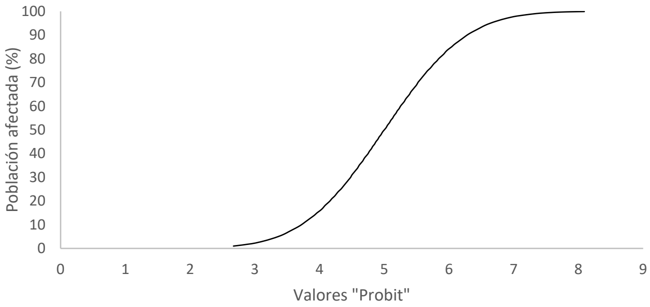

Fig. 1. Equivalence between the "Probit" values and the percentage of the population affected.
(Source: Own elaboration on Van den Bosch, 1979; CCPS, 2000; Casal et al., 1999, 2023)

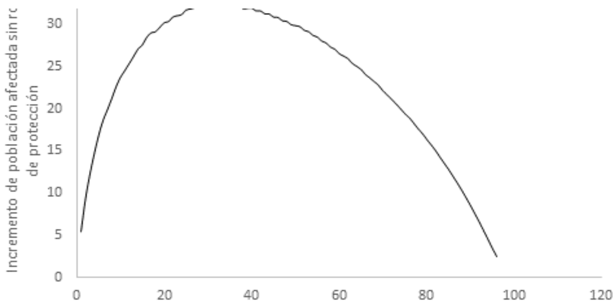

Fig. 2. Comparison of the affected population, depending on the existence of protective clothing. (Source: Authors, 2023)

The value "Probit" is defined as a random variable according to a normal statistical distribution, with a mean value of five and a standard deviation of one. The relationship between this value and the percentage of the population affected is shown in Fig. 1.

The method of vulnerability to thermal radiation considers the intensity of irradiation received as the physical manifestation of the effects of thermal radiation, which determines the percentage of people affected. Irradiation, together with the exposure time, make up the dose of heat radiation received.

The TNO has developed vulnerability functions considering the result of fatal burns, depending on the heat radiation received by a population.

The proposed equations are applicable both for stationary fires (where it is possible to escape), and for short-term fires (flash *fire*), or fireballs generated by a BLEVE and that does not allow time to escape.

If exposed persons are protected by protective clothing (Van den Bosch, 1979; CCPS, 2000; Casal et al., 1999), it proposes the following expression:

$$P_r = -37{,}23 + 2{,}56 \cdot \ln\left(t \cdot W^{4/3}\right)$$

Where:

- t = Effective exposure time in seconds.
- W = Irradiation intensity in W/m2.

In the case of not having protective clothing, the proposed expression (Van den Bosch, 1979; CCPS, 2000; Casal et al., 1999) is as follows:

$$P_r = -36{,}38 + 2{,}56 \cdot \ln\left(t \cdot W^{4/3}\right)$$

Where:

- t = Effective exposure time in seconds.
- W = Irradiation intensity in W/m2.

The increase in the "Probit" value during an intervention, in the case of not having adequate protective clothing, is increased by 0.85 points.

$$P_{r(con\,protección)} + 37{,}23 = P_{r(\sin ropa)} + 36{,}38$$

$$P_{r(con\,protección)} + 0{,}85 = P_{r(\sin ropa)}$$

The same intensity of radiation received leads to an increase in the affected population, the maximum difference of which is 32% (Fig. 2.).

The percentage of mortality due to thermal irradiation can also be evaluated using the mathematical expression developed by Eisenberg (Van den Bosch, 1979; CCPS, 2000; Casal et al., 1999).

$$P_r = -14{,}9 + 2{,}56 \cdot ln\left(\frac{t \cdot W^{4/3}}{10^4}\right)$$

Where:

- t = Exposure time in seconds.

W = Intensity of thermal irradiation in W/m^2.

B. *Development and discussion*

The temperature reached by the receiver is related to the radiant energy received through the Stefan-Boltzman Law, equating the firefighter with a black body that cannot dissipate the flow of thermal radiation, which causes an increase in its temperature.

$$W = \sigma \cdot T^4$$

Where:

- W = Irradiation intensity in W/m2.
- σ = Stefan – Boltzman constant.
    - 5.67037·10-8 W/m2· K
- T = Temperature (in °K).

The black body is an ideal surface that meets the condition of absorbing all the radiation it receives and does not reflect anything, consequently, for a given wavelength, its emitting power is the maximum at a certain temperature. It is important to note that the type of radiation absorbed is diffuse.

The vulnerability model for fatal burns, proposed by the Dutch Organization for Scientific Research, is applied to the radiant energy obtained in this way, if the exposed people are protected, establishing a Probit value of zero.

$$0 = -37{,}23 + 2{,}56 \cdot ln\left(t \cdot\ W^{4/3}\right)$$

Where:

- t = Effective exposure time in seconds.
- W = Irradiation intensity in W/m2.

By applying both expressions, the maximum time of permanence is obtained depending on the temperature to which the firefighter is subjected.

$$e^{\frac{37{,}23}{2{,}56}} = t \cdot \left(5{,}67037 \cdot 10^{-8} \cdot T^4\right)^{4/3}$$

$$t = 9{,}50 \cdot 10^{15} \cdot T^{-16/3}$$

Using the mathematical expression developed by Eisenberg, the function that relates the dwell time to the ambient temperature is as follows:

$$e^{\frac{14{,}9}{2{,}56}} = t \cdot \frac{\left(5{,}67037 \cdot 10^{-8} \cdot T^4\right)^{4/3}}{10^4}$$

$$t = 3{,}39 \cdot 10^{16} \cdot T^{-16/3}$$

Comparing both mathematical expressions, it is observed that, by applying the Heisenberg equation, the dwell times are practically 72% higher than the values offered by the equation developed by the TNO, consequently, the difference is accentuated as the ambient temperature decreases (Fig. 3).

To increase safety during the intervention, the equation obtained from the expressions provided by the Dutch Organization for Scientific Research (TNO) will be used.

This relationship is only applicable in cases in which the ambient temperature is mostly a consequence of radiant energy, as is the case in most fires (Ministerio del interior, 2003).

In addition, it should be noted that only the temperature reached by the receiver (firefighter) is considered, because of the radiant energy received, assuming an ambient temperature, prior to the fire, of 25 °C (Ministerio del interior, 2003).

The ambient temperature offered by the presented method has an application limit, this is obtained from the radiant limit energy received by a firefighter, which, as has been established at 4.7 kW/m^2 (Ministerio del Interior, 1991), with this energy would reach a temperature of 263 °C, estimating a maximum dwell time of 26 seconds.

Although the black body does not exist in nature, this is a reference from which the rest of the surfaces, both radiant and receiving radiation, are defined.

Next, an analysis of the behaviour of a real body is carried out, through the application of the proposed method, for this, the concept of emissivity and absorptivity arises, which is the fraction of radiation emitted and absorbed respectively by a real surface, with respect to a black body subject to the same conditions as the real surface. object of study.

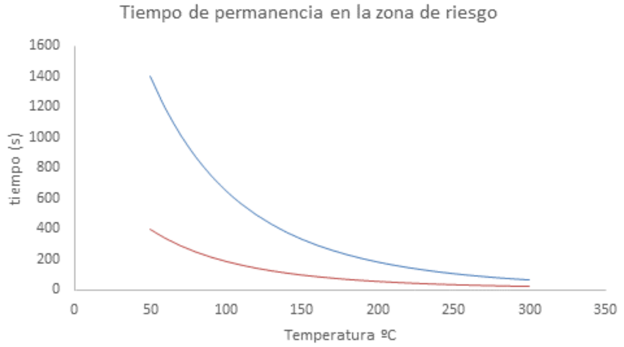

Fig. 3. Comparison of the time spent in the risk area, based on the vulnerability equation used. (Source: Authors, 2023)

Real bodies, the so-called grey surfaces, are characterized in the case of receiving diffuse radiation, by presenting the same emissivity as absorptivity.

The analysis starts from a refractory surface, which are surfaces in which the net flux of radiation is zero, without the need for there to be a thermal equilibrium with the other surfaces, and the absorptivity is increased to unity, the proposed equation is based on the following:

$$0 = -37{,}23 + 2{,}56 \cdot ln[t \cdot (5{,}67037 \cdot 10^{-8} \cdot T^4 \cdot a)]^{4/3}$$

Where:

- t = Time in seconds.
- T = Temperature (in °K).
- a = ε = absorptivity which is equal to emissivity.

Therefore, the expression corresponding to the dwell time for a real body, as a function of the ambient temperature due to radiation, is as follows:

$$t = 9{,}50 \cdot 10^{15} \cdot T^{(-16/3)} \cdot \mathrm{a}^{(-4/3)}$$

Results are shown graphically in **Fig. 4 to 7**.

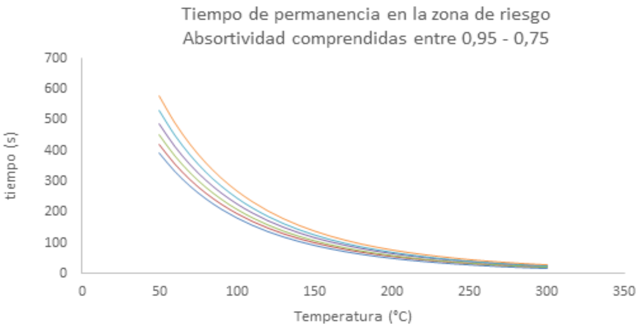

Fig. 4. Time spent in the risk zone for bodies with absorptivities of 0.95, 0.90, 0.85, 0.80 and 0.75. (Source: Authors, 2023)

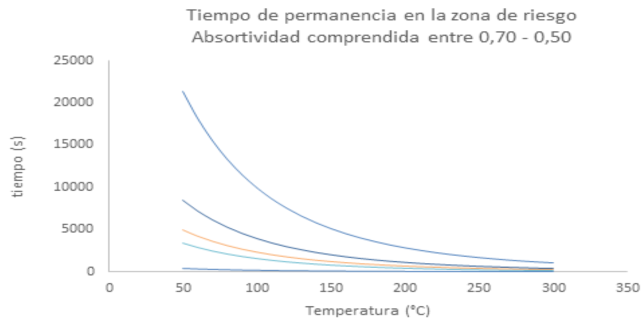

Fig. 5. Time spent in the risk zone for bodies with absorptivities of 0.70, 0.65, 0.60, 0.55 and 0.50. (Source: Authors, 2023)

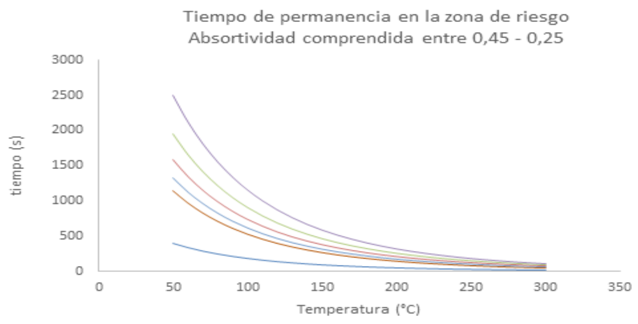

Fig. 6. Time spent in the risk zone for bodies with absorptivities of 0.45, 0.40, 0.35, 0.30 and 0.25. (Source: Authors, 2023)

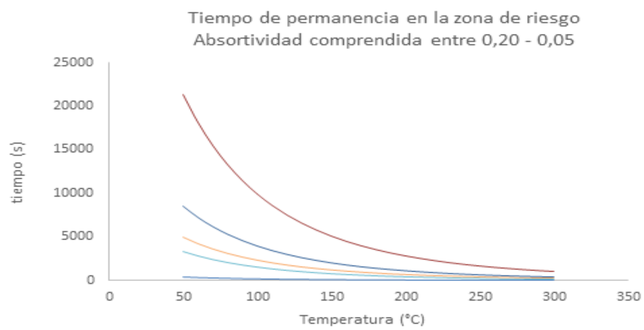

Fig. 7. Time spent in the risk zone for bodies with absorptivities of 0.20, 0.15, 0.10, 0.15 and 0.05. (Source: Authors, 2023)

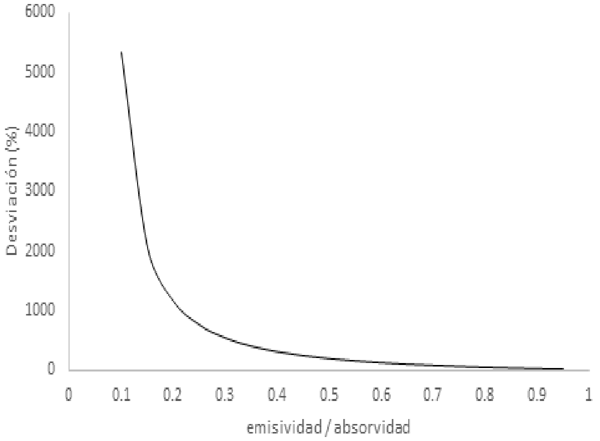

Fig. 8. Deviation of the time spent in the risk zone with respect to the black body, as a function of absorptivity. (Source: Authors, 2023)

As absorptivity increase, a drastic decrease in dwell times is observed. The deviation of the results obtained, with respect to the values taken as a reference, those corresponding to the black body, presents an exponential behaviour, accentuating as the absorptivity decrease (Fig. 8).

However, for absorptivity between 0.8 and 0.95, the behaviour of the deviation becomes linear. So we have a mathematical expression, to be able to adjust the model, in case we know the absorptivity data of the protective suit used during the intervention (Fig. 9).

$$D = 214{,}73 - 210 \cdot a$$

Where:

- D = Deviation from the black body in percentage.
- a = Absorptivity.

The Dutch Organization for Scientific Research also proposes expressions of vulnerability to burns, specifically:

For second-degree burns

$$Pr = -43{,}14 + 3{,}0188 \cdot ln\left(t \cdot W^{4/3}\right)$$

Where:

- t = Exposure time in seconds.
- W = Intensity of thermal irradiation in W/m2.

For first-degree burns

$$Pr = -39{,}83 + 3{,}0186 \cdot ln\left(t \cdot W^{4/3}\right)$$

Where:

- t = Exposure time in seconds.
- W = Intensity of thermal irradiation in W/m2.

By applying the same working method, the residence time is obtained according to the ambient temperature in order to avoid burns.

For second-degree burns,

$$0 = -43{,}14 + 3{,}0188 \cdot ln[t \cdot (5{,}67037 \cdot 10^{-8} \cdot T^4)]^{4/3}$$

$$e^{\frac{43,14}{3,0188}} = t \cdot 2{,}178 \cdot 10^{-10} T^{16/3}$$

The expression that regulates their behaviour is:

$$t = 7{,}38 \cdot 10^{15} \cdot T^{-16/3}$$

Where:

- t = Exposure time in seconds.
- T = Temperature (in °C).

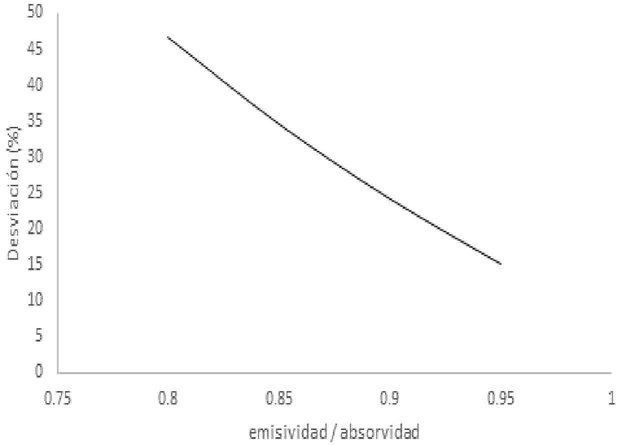

Fig. 9. Deviation of the time spent in the risk zone with respect to the black body, for absorptivity between 0.8 and 0.95. (Source: Authors, 2023)

First-degree burns

$$0 = -39{,}83 + 3{,}0186 \cdot ln[t \cdot (5{,}67037 \cdot 10^{-8} \cdot T^4)]^{4/3}$$

$$e^{\frac{39,83}{3,0186}} = t \cdot 2{,}178 \cdot 10^{-10} T^{16/3}$$

The expression that regulates their behaviour is:

$$t = 2{,}468 \cdot 10^{15} \cdot T^{-16/3}$$

Where:

- t = Exposure time in seconds.
- T = Temperature (in °C).

The behaviour regarding dwell times, to avoid any type of burn, is shown graphically in Fig. 10.

The percentage of the affected population, using the established parameters of temperature and residence time proposed to avoid accidents leading to death, a Probit value of 0.76 is obtained for second-degree burns and 4.069 in the case of first-degree burns, which implies that, with the proposed values, Less than 1% of the affected population will suffer second-degree burns and 18% will suffer first-degree burns.

To avoid these harmful consequences, second- and first-degree burns, it is necessary to reduce the dwell times, specifically, for the estimated maximum temperature limit, 263 °C, the dwell time should be limited from twenty-six seconds to twenty-seven seconds respectively.

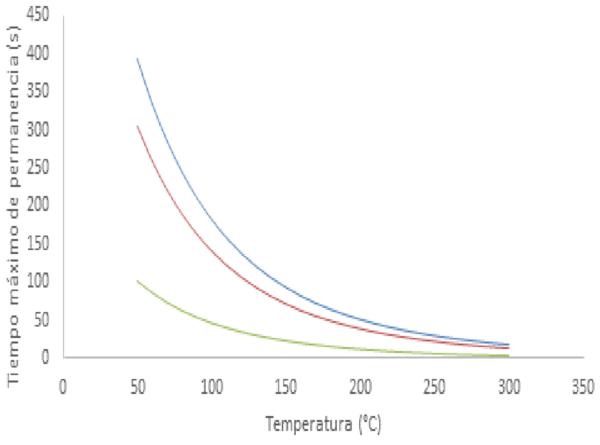

Fig. 10. Time spent in the risk zone to avoid burns, depending on the ambient temperature. (Source: Authors, 2023)

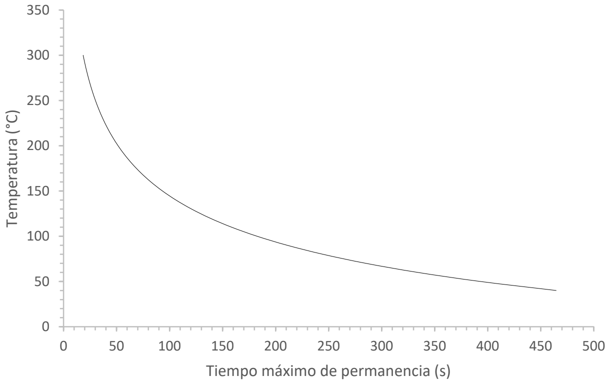

Fig. 10. Maximum time spent during an intervention. (Source: Authors, 2023)

IV. CONCLUSIONS

By applying the vulnerability model for fatal burns proposed by the Dutch Organization for Scientific Research, applied to exposed people protected by appropriate clothing and relating the temperature reached by the receiver as a result of the thermal radiant energy received that cannot be dissipated by the Stefan-Boltzman Law, a mathematical expression is obtained that allows the environmental temperature of the intervention area to be related. with the maximum time of residence, so that fatal accidents can be avoided.

$$t = 9{,}50 \cdot 10^{15} \cdot T^{-16/3}$$

Where:

- t = Effective exposure time in seconds.
- W = Irradiation intensity in W/m2.

This mathematical expression can also be applied graphically (Fig. 11.), being its simple and quick interpretation, so that it is easy to apply during an intervention in an accident caused by a fire.

The maximum thermal radiation flux that can be received by intervention personnel, provided with appropriate clothing, is 4.7 kW/m2 (Ministerio del Interior, 1991; 2003), with this value, the tolerable ambient temperature during an intervention is 263 °C, and its maximum residence time in these circumstances, to avoid accidents resulting in death, is 26 seconds.

These values are significantly lower than those established in the basic guideline for the preparation and approval of Special Plans for the Chemical Sector, where in the alert zone, for a thermal radiation flux greater than 5 kW/m2, regardless of the emission spectrum, the maximum exposure time was established at three minutes (Ministerio del interior, 1991; 2003).

It should be noted that the fabrics with which the intervention suits for firefighters are made have a heat resistance between 250 and 300 °C, values among which is the maximum temperature estimated by the proposed method, in addition, in their design standards, they establish resistance tests in which they must be subjected to thermal radiation of 40 Kw/m^2, almost ten times higher than the one proposed as a limit during an intervention (AENOR, 1994; 2020).

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