# BACKGROUND AND LIMITATIONS OF THE EUROCODE PARAMETRIC FIRE CURVES, INCLUDING THE FIRE DECAY PHASE

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**Abstract**
The research study investigates the background and assumptions behind the definition of the Eurocode Parametric Fire Curves (EPFC), the most adopted methodology to replicate natural fire exposures on structural elements. The analysis explores the fire heating phase, as well as the fire decay phase. Particularly, a numerical analysis is carried out to explicitly quantify the maximum temperature, the cooling rate and the duration of the fire decay phase for a reference compartment. Results show that, for both ventilation- and fuel-controlled conditions, the fire decay phase can largely vary in function of the opening factor and fuel load density. Also, comparing empirical temperature-time curves from large-scale fire tests (BRE Cardington 1999-2000) and the calculated EPFC evidences that the EPFC constant cooling rates are not appropriate to correctly characterise the thermal exposure to structural elements during the fire decay phase.

**Keywords:** parametric fire curve, fire decay phase, cooling phase, natural fire, compartment fire dynamics

## 1 INTRODUCTION

Recent research (e.g. Gernay and Franssen, 2015, and Thienpont *et al.,* 2021) has highlighted the relevance of adopting holistic performance-based methodologies for the design of fire-safe structures that ensure structural integrity and stability until complete fuel burnout. These approaches do not only consider the growing and fully-developed phases of fires (e.g. standard fire curve), but also investigate the structural behaviour during the fire decay phase. Indeed, delayed failure may occur during or after the fire decay phase and a few cases have been reported (Gernay, 2019).
The most adopted methodology to replicate natural fire exposures on structures is represented by the Eurocode Parametric Fire Curves (EPFC) (EN 1991-1-2:2002). This method offers analytical equations to generate the temperature-time history of a natural fire as a function of a few input parameters related to the fuel load and compartment characteristics.
However, the background and assumptions behind the definition of the EPFC have not been comprehensively stated during its development, especially with respect to the fire decay phase. Furthermore, the goodness-of-fit of the EPFC relative to experimental data is not always clear to the new generation of structural fire engineers.
To help alleviate the limits to the readily available state-of-knowledge within the profession, the following review provides background to the EPFC, as well as a critical evaluation relative to experimental data, particularly focusing on the fire decay phase.

## 2 EUROCODE PARAMETRIC FIRE CURVES: BACKGROUND

### 2.1 Importance and interpretation of the Eurocode parametric fire curve

The EPFC have been the most popular parametrized approximation for one-zone compartment fires since its implementation in Annex A of EN 1991-1-2:2002. This methodology provides analytical (i.e. parametric) equations to estimate the temporal evolution of a uniform "gas temperature" in a post-flashover fire compartment. The EPFC are calculated as a function of the fuel load density, compartment geometry and characteristics (i.e. floor area, ventilation conditions and thermal effusivity of the lining materials) with specific limits of applicability: (i) compartments with a floor area up to 500 $m^2$ and height up to 4 m; (ii) vertical openings only (walls, not ceiling); (iii) thermal effusivity of the compartment lining materials in the range 100-2200 $J/m^2s^{0.5}K$. The resulting temperature-time curves are adopted to quantify the thermal exposure to structural elements during all the typical phases of a natural fire in an enclosure (refer to Fig.2). The convective heat transfer is specified with respect to this "gas temperature", considering a convection coefficient of 35 $W/m^2K$. Also, the radiative heat transfer is specified with respect to this "gas temperature", and EN 1991-1-2:2002 states that the configuration (view factor) can be taken as unity and the material emissivity as 0.8 (except where stated otherwise in the material-specific Eurocodes). In a real compartment fire, however, the convective heat transfer coefficient depends on the flow conditions of the hot gas near the structure, while the radiative heat transfer results from an interaction with the surroundings. In this regard, the "gas temperature" defined by the EPFC is more correctly described as an adiabatic surface temperature and it should be treated accordingly.

### 2.2 Background: origins of the heating phase formulation

The EPFC are commonly considered to have been derived from the "Swedish fire curves" (Magnusson and Thelandersson, 1970, and Petterson *et al.*, 1976) through energy balance considerations for ventilation-controlled compartment fires. However, Wickström (Wickström, 1981, and Wickström, 1985) derived the formulation of the EPFC heating phase from first principles, building on the concepts underlying the "Swedish fire curves", and validated his approach against those curves. In his derivation, Wickström made the following assumptions: (i) uniform gas temperature in the fire compartment; (ii) total fuel burnout inside the compartment; (iii) ventilation-controlled fire; (iv) natural ventilation. The temperature-time curve is then obtained through energy-balance equations, additionally assuming that (i) the compartment linings can be approximated as semi-infinite solids with constant thermal properties, and (ii) the linings surface temperature equals the compartment gas temperature. This assumption results in an overestimation of heat losses and thus lower fire compartment temperatures, notably early in the fire.

Considering the time-dependent temperature in the compartment, Wickström obtained a convolution equation for the heat losses to the walls. At this point, the concept of scaled time $t^* = \Gamma \cdot t$ was introduced. This allowed to express post-flashover fires as a single time-temperature curve, for which time is scaled to account for the ventilation conditions and linings properties. The scaling factor $\Gamma$ is defined by Eq. (1), where $O_{ref}$ is the reference opening factor (0.04 $m^{0.5}$) and $b_{ref}$ the reference thermal effusivity (1160 $J/m^2s^{0.5}K$). This is explained in more detail by Hopkin *et al.* (2021), where also the heat balance equations themselves are outlined. The obtained curve was named the "general natural fire curve". If the radiation contribution is fully neglected, a closed form solution is obtained (Wickström, 1984). Also, an analytical formulation for this general natural fire curve was obtained by curve fitting (Wickström, 1981). The curve is of the general format of Eq. (2), with coefficients as listed in Table 1. The obtained heating curve is close to the ISO 834:1975 standard heating regime for reasonable fire durations, e.g. up to $t^* = 3$ hours (ISO 834:1975). Arguably considering this small discrepancy between the curve-fit and the ISO 834 heating regime, the coefficients applied by Wickström (1984) are those listed in the Swedish building code at that time as approximations for the ISO 834 standard heating regime. The general format of Eq. (2) applies to the EPFC as well, considering an ambient temperature of 20°C. It is clear from Table 1 that the listed coefficients proposed by Wickström (1984) have been adopted in EN 1991-1-2:2002. In this formulation, the duration of the heating phase is governed by the assumptions of ventilation-controlled fire and full combustion inside the compartment. This results in a heating phase duration proportional to the fire load density and inversely proportional to the ventilation factor. While the method is a major improvement over the consideration of a standard heating regime, Wickström (1984) highlights that the method is very approximate and should be used with care.

$$\Gamma = \left( \frac{O/O_{ref}}{b/b_{ref}} \right)^2 \tag{1}$$

$$\theta_f\left(t^*\right) = B_0 + \sum_{i=1}^{3} B_i\, \boldsymbol{exp}\left(-\beta_i t^*\right) \tag{2}$$

Table 1. Coefficients for the “generalized natural fire curve” (heating regime).

| | $B_0$ [ºC] | $B_1$ [ºC] | $\beta_1$ [h$^{-1}$] | $B_2$ [ºC] | $\beta_2$ [h$^{-1}$] | $B_3$ [ºC] | $\beta_3$ [h$^{-1}$] |
|---|---|---|---|---|---|---|---|
| **Wickström, 1981** | 1110 | -369.7 | 0.61 | -200.4 | 4.94 | -539.9 | 23.1 |
| **Wickström, 1984** | 1325 | -430.0 | 0.20 | -270.0 | 1.70 | -625.0 | 19.0 |
| **EN 1991-1-2:2002** | 1325 | -429.3 | 0.20 | -270.3 | 1.70 | -625.4 | 19.0 |

Comparing the above with the current heating phase formulation of EN 1991-1-2:2002 evidences that the generalized natural fire curve obtained by Wickström has been adopted in the Eurocode. Nevertheless, there are some important changes/specifications: (i) the time $t_{max}$ of maximum temperature is defined both for ventilation-controlled fires and fuel-controlled fires (for the fuel-controlled fires a distinction is made based on occupancy type); (ii) equations are introduced for the thermal effusivity of multi-layered walls, following proposals by Franssen (2000). The final modifications to the EPFC proposal, however, resulted in a discontinuity in the calculation of the maximum temperature for ventilation-controlled and fuel-controlled fires. Reitgrüber *et al.* (2006) highlighted how the maximum compartment temperature discretely jumps over a hundred degrees at the transition. Furthermore, Reitgrüber *et al.* (2006) state that the EPFC calibration for $t_{max}$ considers an effective heat of combustion of 18 MJ/kg (wood), which is at odds with the recommended value for the effective heat of combustion within Annex E of EN 1991-1-2:2002, where a value of 14 MJ/kg is recommended (taking into account a combustion factor of 0.8). This results in an underestimation of compartment fire temperatures within the EPFC. Additional background to the modifications made during the adoption can be found in Hopkin *et al.* (2021).

## 2.3 Background: origins of the fire decay phase formulation

The fire decay phase description of the EPFC is a direct remnant of a simplifying assumption made by Wickström (1981, 1985). In his seminal work, Wickström adopted the linear cooling rates specified in the at that time current ISO 834 standard (ISO 834:1975): 625°C per hour for a heating duration up to 0.5 hours, 250°C per hour for a heating duration of 2 hours or more, and an interpolated value for intermediate heating durations. The ISO standard specified these cooling rates “when an element of building construction has to fulfil certain functions during the heating period and during the subsequent cooling period” up to the point where the furnace temperature has decreased to 200°C. No further justification for the cooling rates in ISO 834:1975 could be determined. Wickström himself stated that the ISO 834 cooling rates “cannot be derived from the physical aspects of a compartment”.

EN 1991-1-2:2002 has adopted these linear cooling rates, while maintaining the ventilation-controlled time scaling factor $\Gamma$ applied in the heating phase definition. This scaling results in EPFC cooling rates that can be much faster or slower than those originally listed in ISO 834:1975. In conclusion, the above implies that (i) the cooling rate of the EPFC is not based on clear physical considerations; (ii) application the heating phase time scaling to the decay phase definition results in EPFC cooling rates which differ strongly from the cooling rates listed in the original background.

# 3 EUROCODE PARAMETRIC FIRE CURVES: ANALYSIS ON THE DECAY PHASE

The previous section has evidenced the background behind the derivation of the heating and decay phases of the EPFC. Differently to the heating phase, the fire decay phase has been formulated including significant simplifications (i.e., linear cooling rates) and applying analogous concepts to the ones originally derived for the heating phase (e.g., time scaling factor). Consequently, the resulting representation of the fire decay phase is noticeably inaccurate and the EPFC cooling rates can be unrealistically high or low for certain combinations (Feasey and Buchanan, 2002).

According to the current formulation, the EPFC constant cooling rates are directly related to the scaled time of maximum temperature $t^*_{max}$, the product of the time of maximum temperature $t_{max}$ and the (ventilation-controlled) scaling factor $\Gamma$. As a result, the cooling rate of the EPFC is directly influenced by the compartment opening factor, linings thermal effusivity, fuel load density and type (fire growth rate). However, due to its implicit formulation, it is difficult to understand how the different compartment and fuel characteristics affect the estimation of the EPFC cooling rate. To clarify these dependencies, a numerical analysis was carried out to explicitly quantify the maximum temperature, the cooling rate and the decay phase duration for a reasonable range of opening factors (0-0.4 $m^{1/2}$) and fuel load densities (0-2000 $MJ/m^2$). This evaluation was performed according to previous research outcomes, which highlighted that the EPFC has two real degrees of freedom and they can be studied using a reference compartment with a floor area of 10 x 10 $m^2$, a height of 3 m, and linings thermal effusivity of 1450 $J/m^2s^{0.5}K$ (Thienpont *et al.* 2020). Note that the fuel load and opening factor limits of applicability when using the EPFC methodology do not apply to the reference compartment evaluation (see Thienpont *et al.* 2020).

As regards the heating phase, Fig. 1 shows how the compartment maximum temperature is affected by the fuel load density and opening factor. For ventilation-controlled conditions, the higher these values, the higher maximum compartment temperature. On the contrary, for fuel-controlled conditions, low temperatures are obtained for low fuel loads, but the maximum temperature is independent of the opening factor. Fig. 1 confirms the discrete shift in maximum temperature at the ventilation- and fuel-controlled transition, already underlined by Reitgrüber *et al.* (2006).

As regards the fire decay phase, the constant cooling rates and decay phase durations are closely related, but also influenced by the maximum compartment temperature. In the case of fuel-controlled conditions, the cooling rate is largely affected by the opening factor and the fuel load density, but the decay phase is typically short (below 30 min). On the other hand, for ventilation-controlled conditions, the opening factor strongly influences the decay phase, which can register a wide range of cooling rates and decay phase durations.

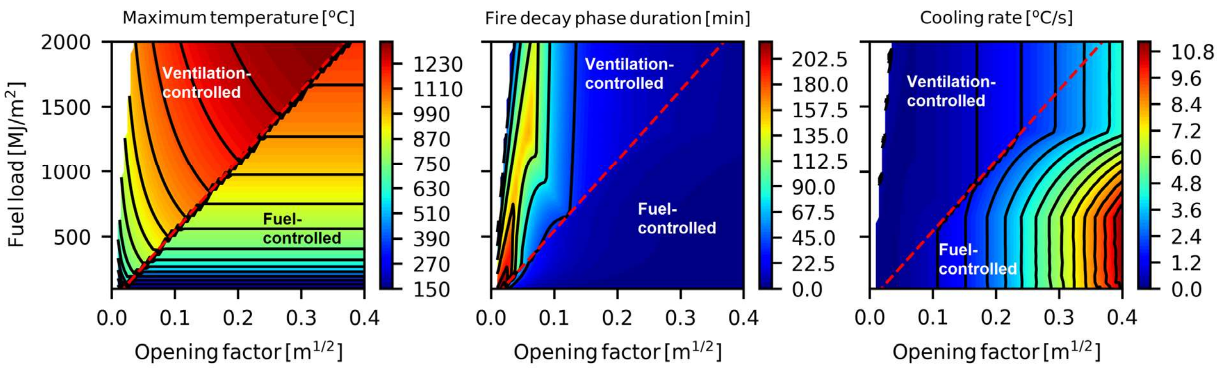


Fig. 1. Maximum temperature, cooling rate and decay phase duration estimated according to the EPFC as a function of opening factor and fuel load density, for ventilation- and fuel-controlled conditions.

In general, according to the EPFC methodology, an enclosure can experience a vast variety of thermal exposures during the fire decay phase based on its characteristics (e.g. ventilation- *vs.* fuel-controlled). In particular, the fire decay phase can last for less than 30 minutes in the case of well-ventilated compartments, but it can also register very low cooling rates (below 0.1 ºC/s) and last for more than 200 minutes in the case of under-ventilated compartments. As highlighted in the introduction, the thermal exposure during the fire decay phase can have significant consequences on the structural stability and integrity of load-bearing members. As a consequence, there is a need to comprehend if the EPFC methodology represents an appropriate design tool to predict the natural fire exposures to structural elements during the fire decay phase.

## 4 COMPARISON TO LARGE-SCALE FIRE EXPERIMENTS

To understand if the EPFC methodology is able to accurately predict the decay phase of natural fire exposures, the existing literature was reviewed to provide experimental evidence and a series of large-scale fire tests was chosen for comparison. The selected experimental programme was carried out in 1999-2000 at the BRE Cardington facilities within the scope of the *"Natural Fire Safety Concept 2 (NFSC2)"* series of fire tests. The experimental campaign investigated full-scale post-flashover fires performed in a large compartment measuring 12 x 12 m in plan, 3 m in height, and involved a total of eight scenarios, which differed for opening position, fuel load composition and the thermal insulation of the compartment boundaries. A detailed description of the experimental campaign has been provided by Lennon and Moore (2003). In accordance with the tested compartment and fuel characteristics, the corresponding EPFC were estimated for the eight tested scenarios by defining the following input parameters (Lennon and Moore 2003):

- Test 2 & Test 3: $O = 0.10$ m$^{0.5}$, $q_f = 680$ MJ/m$^2$, $b = 720$ J/m$^2$s$^{0.5}$K
- Test 1 & Test 8: $O = 0.10$ m$^{0.5}$, $q_f = 680$ MJ/m$^2$, $b = 1600$ J/m$^2$s$^{0.5}$K
- Test 4 & Test 5: $O = 0.07$ m$^{0.5}$, $q_f = 680$ MJ/m$^2$, $b = 720$ J/m$^2$s$^{0.5}$K
- Test 6 & Test 7: $O = 0.07$ m$^{0.5}$, $q_f = 680$ MJ/m$^2$, $b = 160$ J/m$^2$s$^{0.5}$K

The experimental temperature-time curves and the estimated EPFC are shown in Fig. 2. In their manuscript, Lennon and Moore (2003) highlighted a few shortcomings of the EPFC methodology as regards to the fire heating phase. On the contrary, this research study aims at understanding the limitations and potential improvements of EPFC related to the fire decay phase.

Fig. 2 underlines the different nature of the experimentally-measured temperature-time curves and the ones obtained according to the EPFC methodology. All the experimental curves follow a similar trend, which can be directly associated with the specific characteristics of the tested compartment and fuel. On the other hand, the linear EPFC cooling rates often under-estimate the thermal exposure during the fire decay phase. In addition, a linear relationship is certainly not a correct approximation, considering that the experimental temperature-time curves decrease following specific curved trends, much like power or exponential functions (with negative exponent). This aspect becomes more evident when the cooling rates are compared, as shown in Fig. 3. The EPFC methodology estimates constant cooling rates that are either largely overestimated or are not able to describe the typical temperature decay. The empirical curves are characterised by higher cooling rates at high temperatures, and they gradually decrease for lower temperatures. In this specific experimental campaign, the cooling rates vary roughly between 0.1 and 0.6 ºC/s.

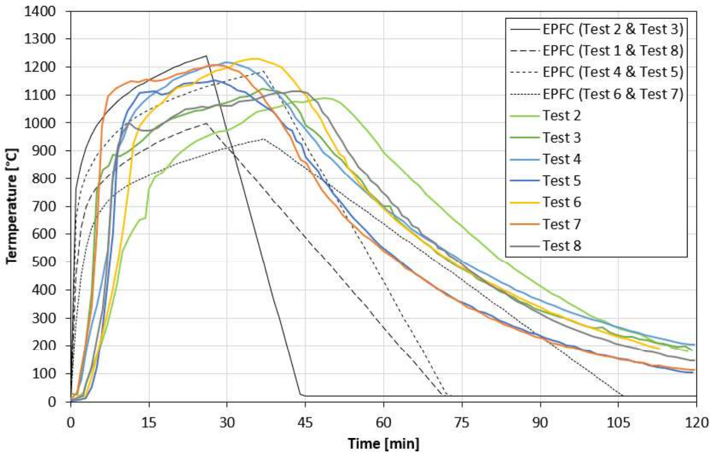


Fig. 2. Temperature-time curves comparison between the EPFC and the Cardington fire tests.

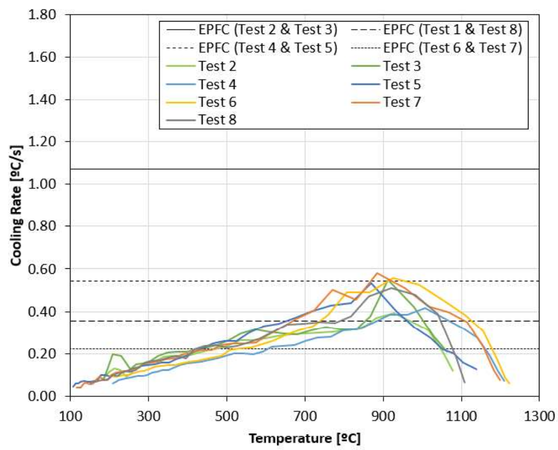


Fig. 3. Cooling rates comparison between the EPFC and the Cardington fire tests.

## 5 CONCLUDING REMARKS

The Eurocode Parametric Fire Curves (EPFC) currently represent the most adopted methodology to replicate natural fire exposures on structural elements. In the current research study, the background and assumptions of the present analytical formulation of the EPFC have been presented. Starting from the simplifications and assumptions made by Wickström to define the "general natural fire curve", the literature review presents the background behind the formulation of both the heating and decay phase. Particular interest has been paid on the definition of the fire decay phase: in its current formulation, the fire decay phase is substantially simplified into a linear relationship, following constant cooling rates prescribed in the ISO 834:1975 standard. Furthermore, the time-scaling applied in the EPFC heating phase formulation has been applied to the decay phase without clear justification.

A numerical analysis aimed at explicitly quantifying the maximum temperature, the cooling rate and the duration of the fire decay phase according to the EPFC methodology has been presented. Results highlight how these values vary significantly as a function of the opening factor and fuel load density, for a given reference compartment. This investigation also shows that, for both ventilation- and fuel-controlled conditions, an enclosure can experience a vast variety of thermal exposures during the fire decay phase: this phase can last for less than 30 minutes and up to more than 200 minutes according to the EPFC, depending on the compartment and fuel characteristics.

Comparing the temperature-time curves measured during large-scale fire tests (BRE Cardington 1999-2000) and the calculated EPFC evidences the incapacity of the methodology to correctly characterise the thermal exposure during the fire decay phase. To accurately predict the decay phase of natural fires, future research should focus on defining a better approximation and analytical expressions. This will allow to correctly study the behaviour of structural elements exposed to natural fires, considering all their typical phases, including the fire decay phase.

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