

## On the application field of OZone V2

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### Abstract

The computer code OZone V2 has been developed to help engineers in designing structural elements submitted to compartment fires. The code is based on several recent developments, in compartment fire modelling on one hand and on the effect of localised fires on structures on the other hand. It includes a single compartment fire model that combines a two zone model and a one zone model. It takes into account the localised effect of a fire with the help of the Hasemi's model. It is thus a pre- and post-flashover model. It calculates the temperature of a steel section submitted to that compartment fire and, finally, evaluates the fire resistance of simple steel elements, according to EC3.

The methodology implemented in the tool OZone V2 to design steel elements submitted to compartment fires is first briefly presented. Some important sub-models are also describe (combustion model, wall model).

Some limitations of the code inherent in the zone model approach are first quoted.

Comparisons of the code with full scale fire tests are then presented. These comparisons enable to find some limits of application of the code. A particular emphasis will be given on large compartments with large openings and on the effect of the effect of thermal properties of partition materials.

### 1 Introduction

OZone V2 is a tool which has been developed to help engineers in designing structural elements submitted to compartment fires. It has been made in the scope of two European researches “Competitive Steel Buildings through Natural Fire Safety Concept” [1] and “Natural Fire Safety Concept- Full Scale Tests, Implementation in the Eurocodes and Development of an User Friendly design tool” [2]. It is described in [3], [4] and [5].

One of the most important thing concerning fire models is its application range. Unfortunately it is very difficult to define clear limits of application of models. Moreover users of fire models must be conscious of the fact that each fire is unique and that many important phenomena, such as flashover, are very difficult to predict.

This paper is an attempt to find some limits in which the compartment fire model implemented in the code is applicable and on the assessment of the shape of the design fire proposed in the tool.

The comparison with two full scale fire test series is presented. Some design rules are proposed.

## Notation

$1ZM:$		One zone model
$2ZM:$		Two zone model
$\xi_{ox}$	[ ]	concentration of oxygen in the gas inside the compartment
$\lambda$	[W/m K]	Thermal conductivity of partition material
$\rho$	[kg/m <sup>3</sup> ]	Density of partition material
$A_f:$	[m <sup>2</sup> ]	Floor area of a compartment
$A_{fi}:$	[m <sup>2</sup> ]	horizontal burning area of fuel
$A_{fi,max}:$	[m <sup>2</sup> ]	maximum horizontal burning area of fuel
$A_t:$	[m <sup>2</sup> ]	total area of partitions of the compartment
$A_w:$	[m <sup>2</sup> ]	area of vertical opening
$c$	[J/kg K]	Specific heat of partition material
$H:$	[m]	height of the compartment
$H_{c,net}:$	[J/kg]	complete combustion heat of fuel (obtained in bomb calorimeter)
$H_{c,eff}:$	[J/kg]	effective combustion heat of fuel (in real fire)
$h_w$	[m]	height of windows
$i,$	[ ]	indicia equal to $U$ for upper layer, to $L$ for lower layer and $g$ for 1ZM
$m:$	[ ]	combustion efficiency factor
$\dot{m}_{fi}:$	[kg/s]	pyrolysis rate
$m_{fi}:$	[kg]	total mass of fuel
$M_{fi,c}:$	[kg]	total mass of fuel in the compartment
$m_g,$	[kg]	mass of the gas in the compartment (1ZM)
$m_{ox}:$	[kg]	mass of oxygen in the compartment
$m_{ox,ini}:$	[kg]	mass of oxygen in the compartment at initial time
$m_{ox,in}:$	[kg]	mass of oxygen coming in the compartment through vents
$m_{ox,out}:$	[kg]	mass of oxygen going out of the compartment through vents
$m_U \& m_L,$	[kg]	mass of the gas of, respectively, the upper and lower layer (2ZM)
$\dot{m}_{VV,in}:$	[kg/s]	mass of gas coming in the compartment through vertical vents
$\dot{m}_{VV,out}:$	[kg/s]	mass of gas going out of the compartment through vertical vents
$\dot{m}_{VV,U,in}:$	[kg/s]	mass of gas coming in the upper layer through vertical vents
$\dot{m}_{VV,U,out}:$	[kg/s]	mass of gas going out of the upper layer through vertical vents
$RHR:$	[W]	Heat release rate
$RHR_f:$	[W/m <sup>2</sup> ]	Heat release rate per unit floor area of compartment
$t_s:$	[s]	Time of switch from the 2ZM to the 1ZM
$T_g,$	[K]	temperature of the gas (1ZM)
$T_{out},$	[K]	temperature of the gas outside the compartment
$T_U \& T_L,$	[K]	temperatures of the gas of, respectively, the upper and lower layer (2ZM)
$V,$	[m <sup>3</sup> ]	volume of the compartment (constant)
$V_U \& V_L,$	[m <sup>3</sup> ]	volumes of, respectively, the upper and lower layer (2ZM)
$V_f$	[m <sup>5</sup> /2]	ventilation factor ( $=A_w h_w^{1/2}$ )
$W$	[m]	width of windows
$Z_s$	[m]	lower layer thickness

## 2 Compartment fire model

The code includes a two zone model and a one zone model. An automatic procedure is define to choose which model is more appropriated. A complete description of the compartment fire model is given in [3] and [4] These models are briefly presented in this section. A short description of the vertical vent submodel is given.

### 2.1 Two zone model

Figure 1 shows a schematic view of the two zone model and its sub-models.

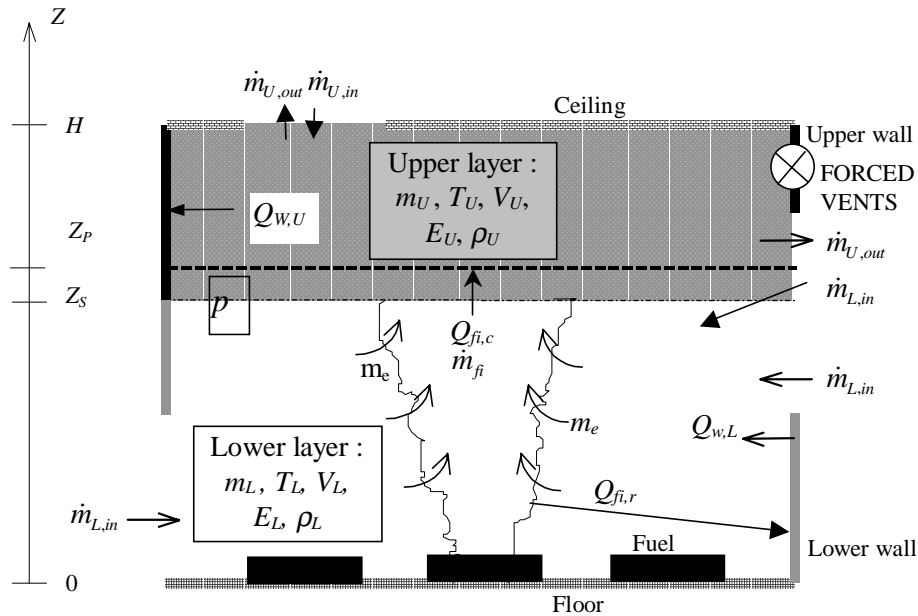


Figure 1 Schematic view of two zone model and associated sub-models

### 2.2 One zone model

Figure 2 shows a schematic view of the one zone model and its sub-models.

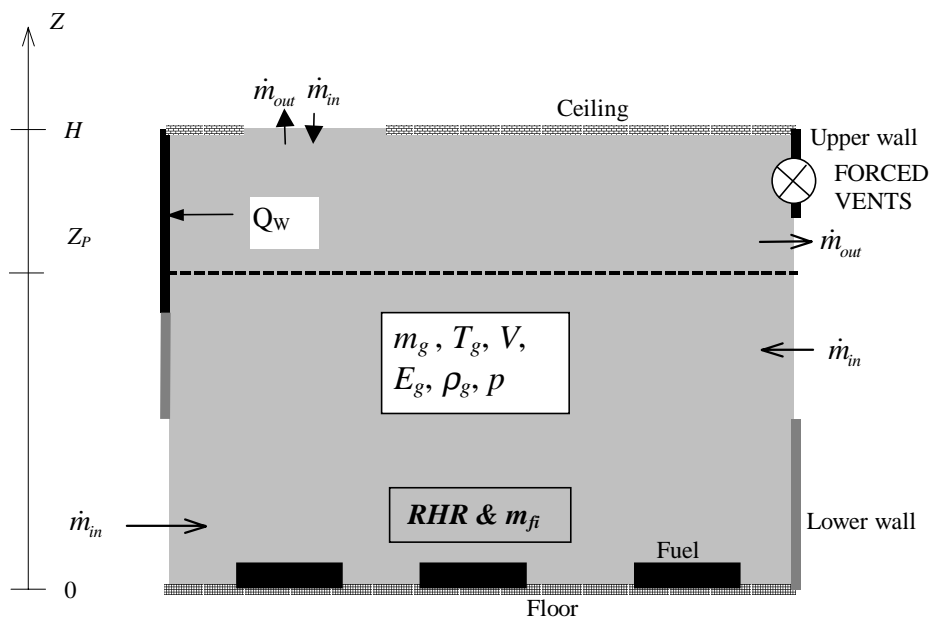


Figure 2 Schematic view of one zone model and associated sub-models

### 2.3 Switch from two zone to one zone model

If some criteria are encountered during a two zone simulation, the code will automatically switch to a one zone simulation, which better suits the situation inside the compartment at that moment. The simulation will continue until the end of the fire under the hypothesis of a one zone model. A complete description of the criteria and of their effect on the simulation process is given in [4].

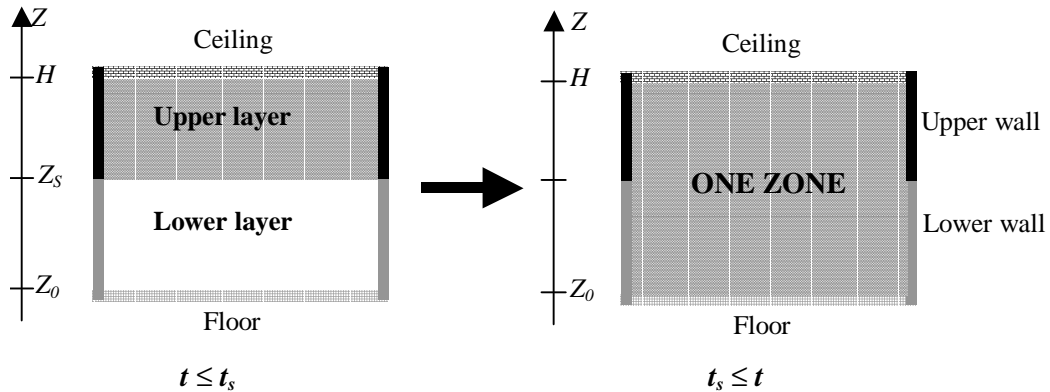


Figure 3 Switch from the two to the one zone model

### 2.4 Vertical vents submodel (vv indicia)

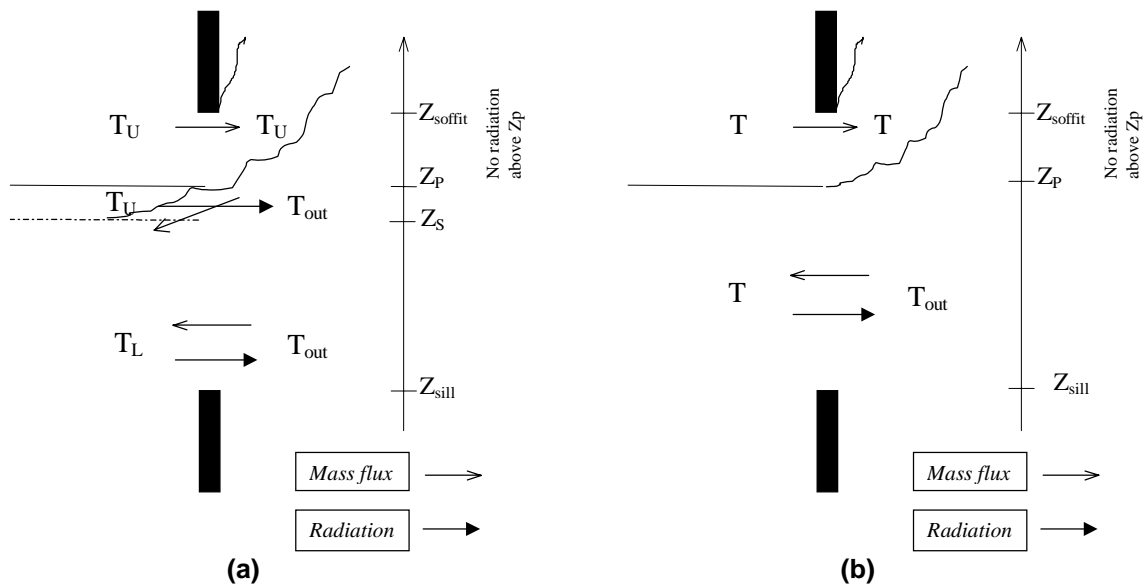


Figure 4 Exchanges through vertical vents in (a) 2ZM and (b) 1ZM

The mass flow through vents is calculated by integrating the Bernoulli law on each opening, Eq. (1).

$$\dot{m}_{i,vv,\beta} = \text{sign } K b (T \text{ or } t) \int_{Z'}^{Z''} \frac{p_A(z)}{R T_A} \sqrt{2 R T_A \left( 1 - \frac{p_B(z)}{p_A(z)} \right)} dz \quad (1)$$

- With
- $A$  : variable at origin of the flux
  - $B$  : variable at destination of the flux
  - $Z'$  &  $Z''$ : bounds of integration on altitude  $Z$
  - $b$  : width of vertical vent
  - $t$  :  $U$  if the integration is made in the upper layer,  $L$  if the integration is made in the lower layer and  $g$  in case of one zone model.
  - $\beta$  :  $in$  if gas goes in the compartment,  $out$  if gas goes out of the compartment
  - $sign$  : (+1) if gas goes in the compartment, (-1) if gas goes out of the compartment

### 3 Fire source - Input of heat and of combustion products in the compartment

To represent the fire, the basic inputs are the heat release rate  $RHR(t)$  [W], the pyrolysis rate  $\dot{m}_{fi}(t)$  [kg/s] and the fire area  $A_{fi}(t)$  function of time. The pyrolysis rate is taken into account in mass balances and the heat release rate in energy balances. The fire area is used in Heskestad and Thomas air entrained models. This section explains the physical parameters used to define the fire source, how they are related and how OZone deals with them in function of the oxygen available in the compartment. The strategy of calculations may also influence these inputs as explained in [4].

#### 3.1 Basic parameters

##### *Heat release rate - RHR*

The heat release rate is the quantity of energy that is released by the fire per second. The  $RHR$  depends on the type and quantity of fuel present in the compartment, on the quantity of oxygen available in the compartment, on phase of the fire (rising, stationary, decreasing)...

##### *Heat release rate density - $RHR_f$*

The heat release rate density is the quantity of energy that is released by one square metre of fire per second.

##### *Pyrolysis Rate - $\dot{m}_{fi}$*

The pyrolysis rate  $\dot{m}_{fi}$  is the quantity of mass of solid fuel that is transformed into combustible gases per second. It is indeed the mass loss rate of fuel.

##### *Combustion Heat of Fuel - $H_c$*

The energy released by the combustion of one unit of mass of fuel in an oxygen bomb calorimeter under high pressure and in pure oxygen is  $H_{c,net}$ , the complete (or net) combustion heat of the fuel. Under these conditions nearly all the fuel is burnt, leaving no residue and releasing all its potential energy. In real fires the energy that the same unity of mass is able to release is lower than  $H_{c,net}$ . Usually about 80% of the complete combustion heat is released. A part of the combustible is not pyrolysed leaving some soot and not all of the volatile produced by pyrolysis is converted in heat. The effective combustion heat of fuel is defined as the ratio between the heat release rate during a real fire and the rate of mass of fuel loss during this real fire.

$$H_{c,eff}(t) = \frac{RHR(t)}{\dot{m}_{fi}(t)} \quad (2)$$

The efficiency of the combustion is represented by the combustion efficiency factor  $m$ , ratio between the effective and the complete combustion heat of the fuel:

$$m(t) = \frac{H_{c,eff}(t)}{H_{c,net}} \quad (3)$$

The values of the effective combustion heat and therefore of the combustion efficiency factor depend on many parameters, the temperature in the compartment, the way of storage of fuel... and are actually varying with time. Nevertheless, in most cases the combustion efficiency factor is assumed to be constant.

##### *Fire Area - $A_f(t)$*

The fire area is the burning area of fuel. In real fires, it is usually varying with time. In some cases (ex. pool fire tests), the fire area can be constant. The maximum fire area in a compartment is the floor area on which combustible is present. The pyrolysis rate and the heat release rate are of

course linked to the fire area (see next paragraphs). Moreover, some air entrained models [4] depend on the fire diameter and therefore on the fire area.

$$RHR(t) = A_{fi}(t) RHR_f \quad (4)$$

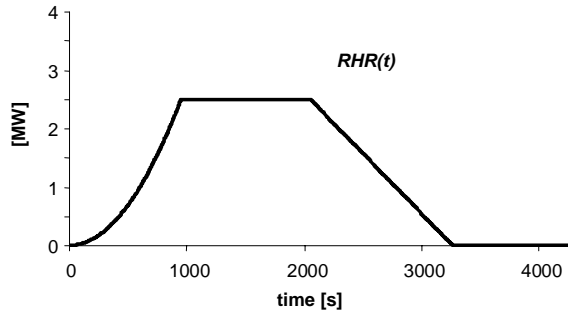


Figure 5 Input Heat release rate Curve

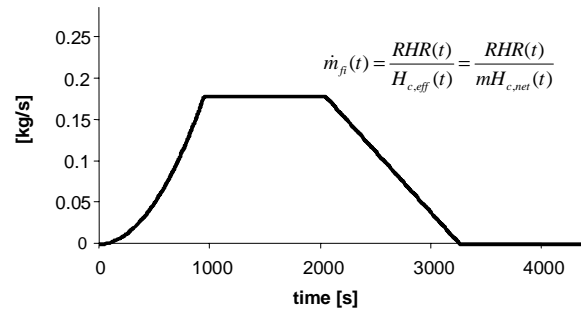
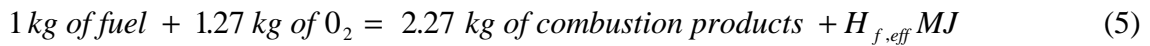


Figure 6 Input Pyrolysis Rate Curve

The fire source is defined by three parameters, the pyrolysis rate, the heat release rate and the fire area. They can be linked (for instance the heat release rate and the pyrolysis rate can be linked as shown on Figure 5 and Figure 6) or defined independently ones of the others.

### 3.2 Combustion chemistry

The following chemical reaction is considered :



### 3.3 Oxygen balance

The mass of oxygen in the compartment is calculated at each time by integrating the oxygen balance:

$$\dot{m}_{ox} = \dot{m}_{ox,in} + \dot{m}_{ox,out} - 1.27\dot{m}_{fi} \quad (6)$$

The initial mass of oxygen in the compartment is considered to be 23% of the initial mass of gas, supposed to be fresh air. The mass of oxygen coming in the compartment is considered to be 23% of the mass of gas coming in the compartment through vents. The mass of oxygen going out of the compartment is considered to be  $\xi_{ox}$  % of the mass of gas going out of the compartment.  $\xi_{ox}$  is the concentration of oxygen in the gas inside the compartment and is calculated by Eqs. (7).

$$\xi_{ox} = \frac{m_{ox}}{m_U + m_L} \quad (2ZM) \quad (7)$$

$$\xi_{ox} = \frac{m_{ox}}{m_g} \quad (1ZM)$$

The concentration of oxygen in the compartment is supposed to be uniform in the compartment.

### 3.4 Combustion models

Users have to choose between three different combustion models. Each of them has been designed to represent a different situation of utilisation of the code.

- With "no combustion model", the presence of oxygen in the compartment does not influence the heat release rate.
- When no more oxygen is available inside the compartment, the "external flaming" combustion model limits the amount of energy release inside the compartment.
- In the same case, the "extended fire duration" combustion model limits the amount of energy release inside the compartment and all the fire load is burned in the compartment by extending the initial fire duration.

### 3.4.1 No combustion model

With this model, the pyrolysis rate and the heat release rate set in the data are used in the mass and energy balances without any modification regarding to the oxygen concentration in the compartment. No control by the ventilation will be made. At each time, Eqs. (8) will be satisfied.

$$\begin{aligned} \dot{m}_f(t) &= \dot{m}_{f,data}(t) \\ RHR(t) &= RHR_{data}(t) \end{aligned} \quad (8)$$

This model is used for the simulation of experimental tests where the mass loss and the heat release rate have been measured independently. It suits also to situations where the pyrolysis rate is known and where the fire is assumed to be fuel controlled.

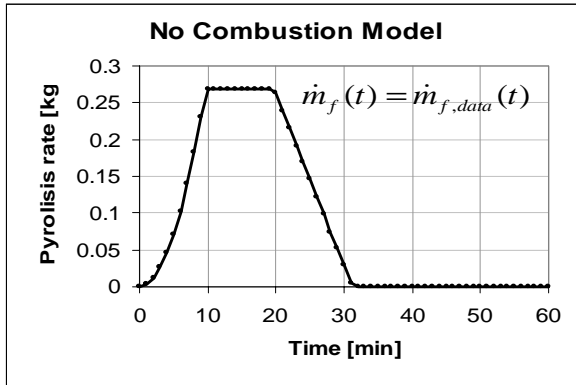


Figure 7 Heat release rate Curve

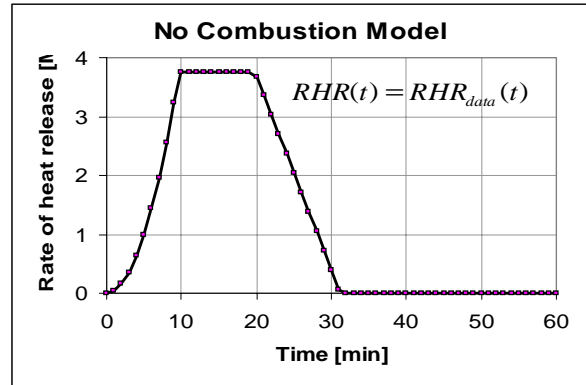


Figure 8 Pyrolysis Rate Curve

### 3.4.2 External flaming Combustion model

In this model external combustion is assumed, all the fire load is transformed into gases in the compartment but only a part of it delivers energy in the compartment. The heat release rate may be limited by the quantity of oxygen available in the compartment but the pyrolysis rate remains unchanged.

When oxygen is still present in the compartment, the fire is fuel controlled and all the mass loss of fuel delivers energy inside the compartment.

$$\begin{aligned} \dot{m}_f(t) &= \dot{m}_{f,data}(t) \\ RHR(t) &= RHR_{data}(t) = \dot{m}_f(t)H_{f,eff} \end{aligned} \quad (9)$$

If all the oxygen in the compartment has been consumed, the fire is ventilation controlled and the combustion is not complete. The energy released is governed by the mass of oxygen coming in the compartment through vents:

$$\begin{aligned} \dot{m}_f(t) &= \dot{m}_{f,data}(t) \\ RHR(t) &= \frac{\dot{m}_{ox,in}(t)}{1.27} H_{f,eff} \end{aligned} \quad (10)$$

When oxygen is again available, for example during the decreasing phase of the fire, in the compartment, the fire is coming back to fuel controlled regime and Eqs. (9) governs the pyrolysis and the heat release rates.

This model is used for the simulation of experimental tests where the mass loss or the heat release rate has been measured.

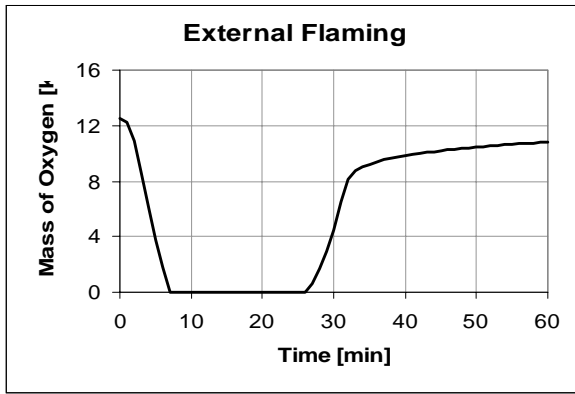


Figure 9 Oxygen mass curve

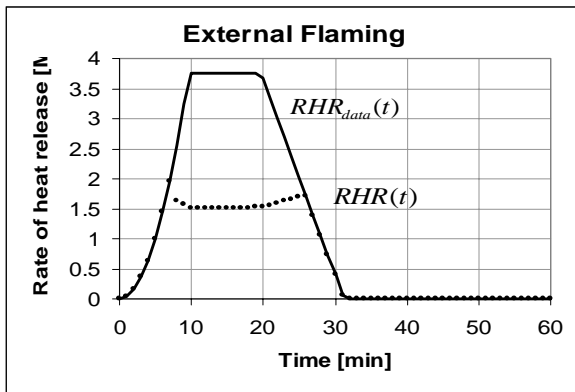


Figure 10 Heat release rate Curve

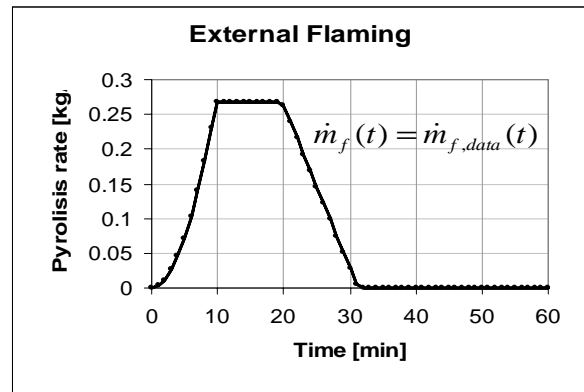


Figure 11 Pyrolysis Rate Curve

### 3.4.3 Extended fire duration combustion model

In this model, the release of mass may be limited by the quantity of oxygen available in the compartment. The total mass of fuel is burnt inside the compartment and the fire duration is increased compared to the input one.

When there is still oxygen in the compartment, the fire is fuel controlled and all the mass loss of fuel delivers energy into the compartment.

$$\begin{aligned} \dot{m}_f(t) &= \dot{m}_{f,data}(t) \\ RHR(t) &= RHR_{data}(t) = \dot{m}_f(t)H_{f,eff} \end{aligned} \quad (11)$$

If the oxygen in the compartment has been consumed, the fire is ventilation controlled. In this case, the mass lost by the fire is governed by the mass of oxygen coming in the compartment and all the pyrolysed mass is transformed into energy:

$$\begin{aligned} \dot{m}_f(t) &= \frac{\dot{m}_{ox,in}(t)}{1.27} \\ RHR(t) &= \dot{m}_f(t)H_{f,eff} = \frac{\dot{m}_{ox,in}(t)}{1.27}H_{f,eff} \end{aligned} \quad (12)$$

The linear decreasing phase begins when 70% of the total fire load is consumed.

In this model no external combustion is assumed, all the fire load delivers its energy into the compartment. If the fire is ventilation controlled, the pyrolysis rate is proportional to the oxygen coming in the compartment.

This model is not a physical model because pyrolysis is not directly dependent on oxygen concentration. It has been established for design purpose, in order to avoid uncertainties on the maximum pyrolysis rate and therefore to be on the safe side concerning the fire duration.

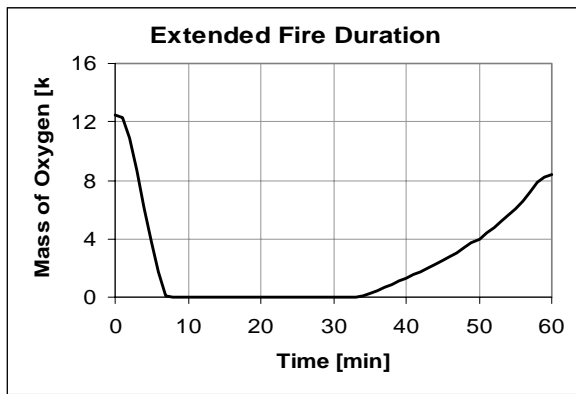


Figure 12 Oxygen mass curve

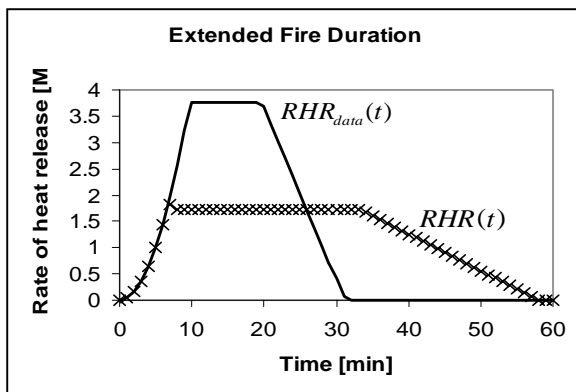


Figure 13 Heat release rate Curve

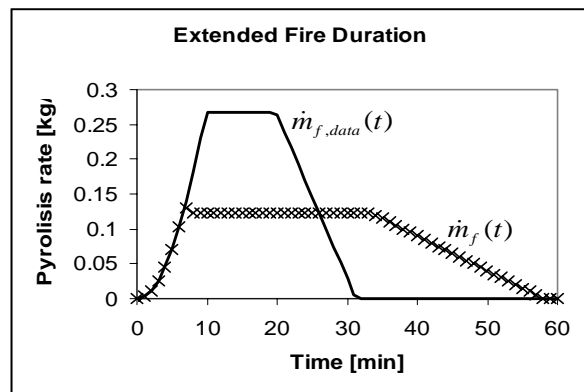


Figure 14 Pyrolysis Rate Curve

## 4 Overview of the design methodology implemented in OZone

The methodology of the design can be divided in 6 main steps that are described in detail in [5]. The steps are:

- 1 description of the compartment.
- 2 definition of design fire.
- 3 calculation of the temperatures in the compartment.
- 4 a. definition of the thermal and mechanical section properties, of the thermal properties of the insulation material if the section is protected and of the thermal boundary conditions.  
b. calculation of the temperature of steel elements, taking into account if necessary, the localised effect of the fire with the help of Hasemi's model.
- 5 a. definition of the dimensions, the solicitations, and static boundary conditions of the member.  
b. calculation of the fire resistance of the steel element.
- 6 acceptance or not of the fire resistance obtained in step 5. If the fire resistance is not accepted, the section or the thermal resistance of the insulation has to be increased and the process must be restarted from step 4.

## 5 Some limitations of the models

The models implemented in code limits the use of the tool to :

- A single compartment with quite simple shape suitable for zone modelling;
- A single fire source;
- In case of localised fire, fire resistance of beams at ceiling level. (see [5])

- The conditions covered by the empirical submodels used (plume models...), and of the empirical parameters used in some models (discharge coefficient used in vent models, convection coefficient and emissivity of partition model...).

## 6 Comparisons with full scale fire tests

### 6.1 Objectives of comparisons with tests.

There are two main aims of the comparison with full scale fire test.

The first one is to investigate whether the main model formulations (zone equations and partition model) and the sub models formulation are able to represent the course of a fire. This first objective includes the assessment of the parameter values which have been set by default in the code.

The second objective is to see whether the design fire curve (defined in [5]) is able to represent a real fire source.

#### *A priori, Blind and open comparisons*

In publication concerning comparison of fire model with experiments, it is often difficult to know which procedure has been used in the comparison. It is particularly important to know whether data measured during the experiment have been used. To clarify the descriptions of comparisons with tests, Beard [6] has proposed to subdivide comparisons into three categories : a priori, blind and open comparisons.

The conditions that a comparison has to fulfil to be classified in a category are listed hereafter for the three categories.

#### **'A priori'**

An a priori comparison between theory and experiment may be characterized by the three conditions:

- The test results of the variable being used for the comparison have not been used in the modelling. As temperature is the variable being used for this comparison, the temperatures resulting from the tests have not been used.
- No data from the experiment have been used; in this case, only the mass loss rate has been used.
- No adjustment of input parameter values has taken place. All the default values of parameters have been used.

#### **“Blind”.**

A blind comparison between theory and experiment may be characterized by the three conditions:

- The test results of the variable being used for the comparison have not been used in the modelling. As temperature is the variable being used for this comparison, the temperatures resulting from the tests have not been used.
- Data from the experiment have been used; in this work, the mass loss rate or the heat release rate is used.
- No adjustment of input parameter values has taken place. All the default values of parameters have been used.

#### **“Open”**

An open comparison between theory and experiment may be characterized by the following conditions :

- The test results of the variable being used for the comparison are used in the modeling. The temperatures resulting from the tests can be used in the comparison.
- Some data from the experiment can be used.

- Adjustments of input parameter values can taken place. Any modification in the input parameters can be done to improve the agreement between the calculations and the experiment results.

The choice between the type of comparison depend on the objective the modeller has:

- An a priori comparison will enable to investigate whether the design procedure proposed in the code gives safe results.
- A blind comparison can assess the basic model and the sub models and the choice of the empirical parameters.
- An open comparison is used when there is disagreement between the model and experiments in an a priori or a blind comparison. By adapting input data or parameters of the code, it can be shown that these parameters did not suit to the situation or that a physical phenomenon is not taken into account by the model.

## 6.2 Comparison with Natural Fire Tests in Large Compartment

The comparison of OZone V2.1.6 with 9 tests performed at Cardington, UK, by the British Steel Technical in collaboration with BRE is presented. The tests where performed in 1993 and described in reference [7]. These tests are in the database of the NFSC1 research [1] with numbers NFSC7 to NFSC15.

The tests were originally aimed at investigating whether the relationship for time equivalent of fire severity presented in Eurocode 1 can be safely applied to buildings with large compartments.

### 6.2.1 Tests Data

The compartment has a length  $L_1$  of 22.86 m, a width of 5.6m and a height of 2.75m for 7 tests (tests 1 to 6 and 9) and slightly different dimensions for one test (test 8 : some centimetres of difference due to additional lining on partitions). One test (test 7) was performed in a small compartment with a length  $L_2$  of 5.6 m, a width of 5.6m and a height of 2.75m. (Figure 15).

For all tests but test 8, the walls and ceiling are made of concrete blocks insulated, on the inside surface, by ceramic fibre blanket. In test 8, an additional layer of fireline plasterboard has been set on the inside surface of partitions. The floor is a concrete slab covered by fluid sand.

The thermal properties of partition materials are given in the test report and reported in Table 1.

**Table 1 Thermal properties of partition material**

<i>material type</i>	Density $\rho$ [kg/m <sup>3</sup> ]	Specific heat $c$ [J/kg K]	Thermal conductivity $\lambda$ [W/m K]	$b = \sqrt{c\rho\lambda}$
concrete	1375	753	0.42	659
ceramic fibre	128	1130	0.02	54
fireline plasterboard	900	1250	0.24	520
Fluid sand	1750	900	1.0	1255

The fire load, made of uniformly distributed wood cribs, is 20 kg of wood/m<sup>2</sup> or 40 kg of wood/m<sup>2</sup>. The net combustion heat of wood is reported to be 19MJ/kg.

Vertical openings are made in only one of the short wall. Four tests are made with the wall completely open; Two tests with an opening of half of the front wall surface; two test with one fourth and one test with one eights.

Thus the compartment is large (about 128m<sup>2</sup> of floor area) and has the particularity to be much longer than larger and to have opening(s) in a single short wall.

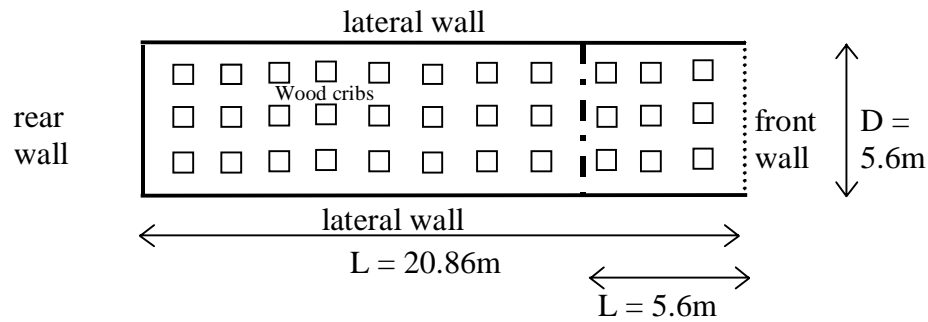


Figure 15 Schematic plan view of the compartment

In tests 1 to 8, the rear line of wood cribs has been ignited. In test 9, all the wood cribs have been ignited simultaneously. During the tests with the rear line ignition, a flame front with higher temperature than in the rest of the compartment started on the rear of the compartment, went quite quickly to the front and went back slowly to the rear and finally finished (see Figure 16).

Three thermocouples were placed in the compartment, figure XX shows the mean temperature of each thermocouple in function of time for test n°XX. The crossing of the three curves is due to the progression of the flame front from the back to the front and then to the back of the compartment.

Figure XX shows the maximum, minimum and mean temperatures curves used in the latter comparisons.

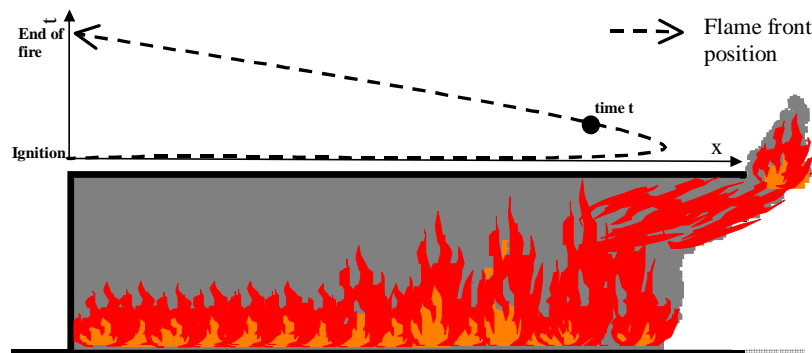


Figure 16 Schematic view of the front flame progression in the compartment

Table 2 Summary of the main data of the tests

Test	$D$	$L$	$H$	$A_f$	$A_t$	$V$	$W$	$h$	$A_w$	$A_{t,net}$	$A_w h^{1/2}$	$A_w h^{1/2}/A_{t,net}$	$q_f$	$q_f$
n°	m	m	m	m <sup>2</sup>	m <sup>2</sup>	m <sup>3</sup>	m	m	m <sup>2</sup>	m <sup>2</sup>	m <sup>5/2</sup>	m <sup>1/2</sup>	kg/m <sup>2</sup>	MJ/m <sup>2</sup>
1	5.595	22.855	2.75	127.87	412.22	351.65	5.6	2.75	15.386	396.836	25.515	0.064	40	700
2	5.595	22.855	2.75	127.87	412.22	351.65	5.6	2.75	15.386	396.836	25.515	0.064	20	350
3	5.595	22.855	2.75	127.87	412.22	351.65	5.6	1.47	7.638	404.584	9.261	0.023	20	350
4	5.595	22.855	2.75	127.87	412.22	351.65	5.2	1.47	7.638	404.584	9.261	0.023	40	700
5	5.595	22.855	2.75	127.87	412.22	351.65	2.1	1.73	3.702	408.520	4.869	0.012	20	350
6	5.595	22.855	2.75	127.87	412.22	351.65	5.2	0.375	1.949	410.274	1.193	0.003	20	350
7	5.595	5.595	2.75	31.30	124.15	86.09	1.4	2.75	3.768	120.386	6.248	0.052	20	350
8	5.465	22.78	2.68	124.49	400.38	333.64	5.6	2.68	14.995	385.384	24.547	0.064	20	360.5
9	5.595	22.855	2.75	127.87	412.22	351.65	5.6	2.75	15.386	396.836	25.515	0.064	20	350

### 6.2.2 'A priori' comparison

The geometry (compartment size and opening dimensions) and the partitions characteristics are defined as described in the tests report. The net combustion heat of wood is set to 17.5MJ/kg with a combustion efficiency factor of 0.8, both value are the default value in the code. The extended

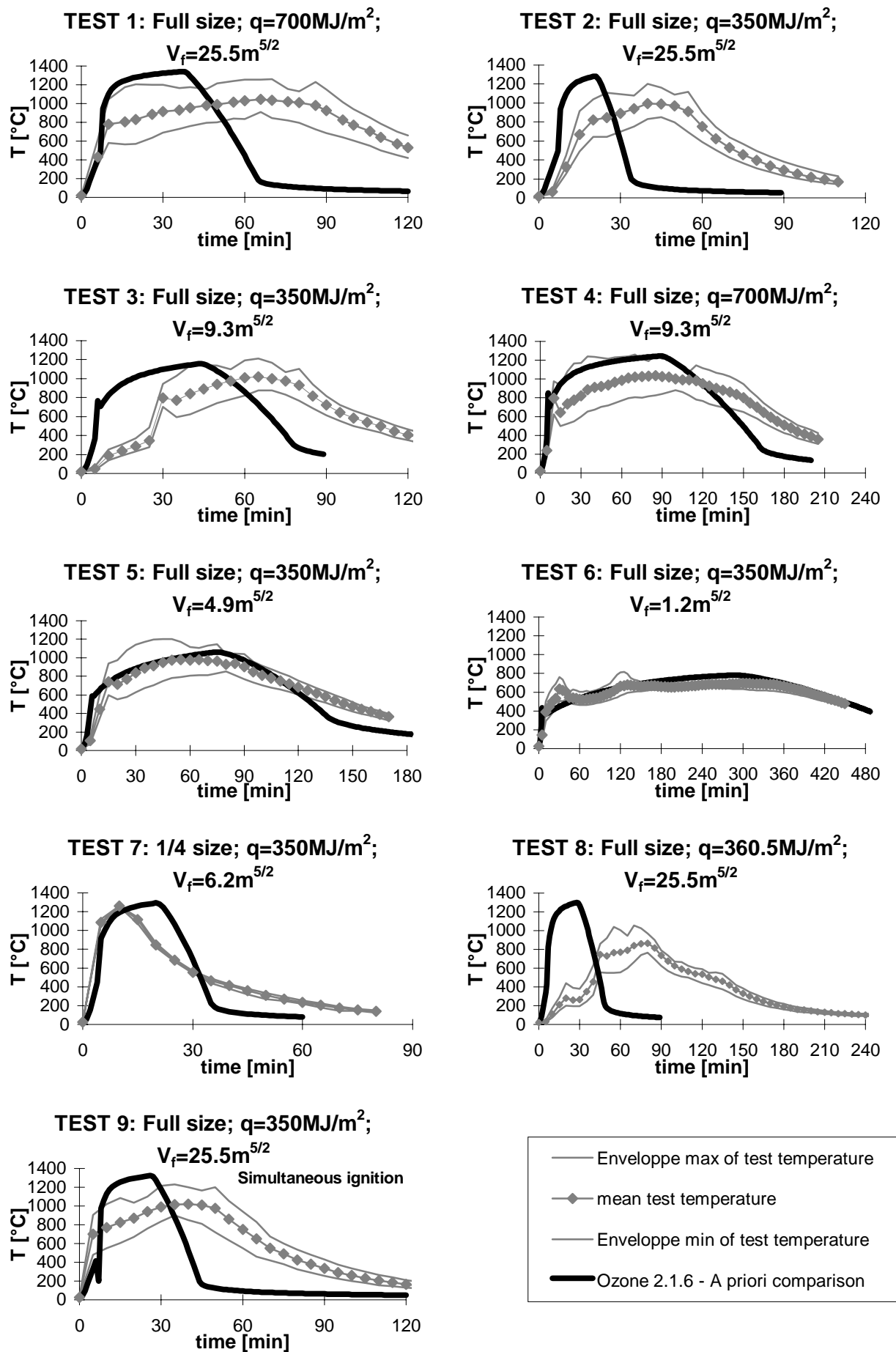


Figure 17 "A priori" comparison of temperatures histories

fire duration combustion model is used. The discharge coefficient  $C_f$  is 0.7. A fast fire is defined and the flashover temperature  $T_{fl}$  is 500°C. These values are the default ones in OZone.

Observing the "a priori" comparison results, it can be noticed that :

- During the rising phase, a fast fire gives a good correlation for 5 of the 9 tests (n°1, 4, 5, 6 and 7); a reasonable correlation for 2 tests (n°2 and 9) and a poor correlation for 2 tests (n°3 and 8).
- The calculated temperatures and fire durations are really close to the measured ones, in case of opening area equal to one fourths and one eights of the front wall area. This comparison is very good either in terms of maximum temperature and of fire duration.
- The calculated temperature are too high for test with a large opening. This is in a reasonable proportion for opening area equal to the half of the front wall area but unacceptable with the front wall completely open.
- When the temperatures are too high, the fire duration is too short.

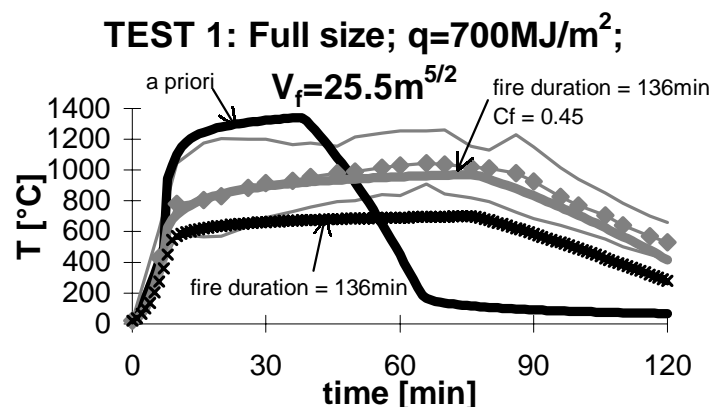
In summary, the calculations give very good estimation of the mean temperature histories for opening areas up to the half of the front wall area. For higher opening area, the code is not able to predict the fire course.

### 6.2.3 'Open' comparison

In test 3, although the rising phase is not well modelled, the post-flashover phase modelling is quite good. Thus the calculation is improved by setting  $t_\alpha$  to 900s (ultra slow), all other parameters being unchanged.

In test 1, the fire duration is too small, thus the heat release rate is set in the data so that the fire duration is the one obtained during the test. The end of the plateau is defined to be at 76min. That leads to a maximum heat release of 14.5MW. In other words, the fire load was burned in the "a priori" procedure in 65min, in this procedure it is imposed to burn the fire load slower, i.e. in 136min.

The calculated temperatures obtained with this RHR are too low. That means that the cooling of the gas in the compartment by the gas flow through the vent is overestimated. The discharge coefficient  $C_f$  is thus reduced from 0.7 to 0.45. Leading to a very good estimation of the fire course.



**Figure 18 Modification of the fire duration and of the discharge coefficient to improve the modelisation of test 1**

The other open simulations (tests 2, 8 and 9) are made with the modified parameters obtained in test 1, i.e. a maximum RHR of 14.5MW and a reduced value of  $C_f$  of 0.45. In these 3 tests, the rising phase is also modified:  $t_\alpha$  is set to 300s for tests 2, to 900s for test 8 and to 75s for tests 9. The results (Figure 19) are quite good for the five tests.

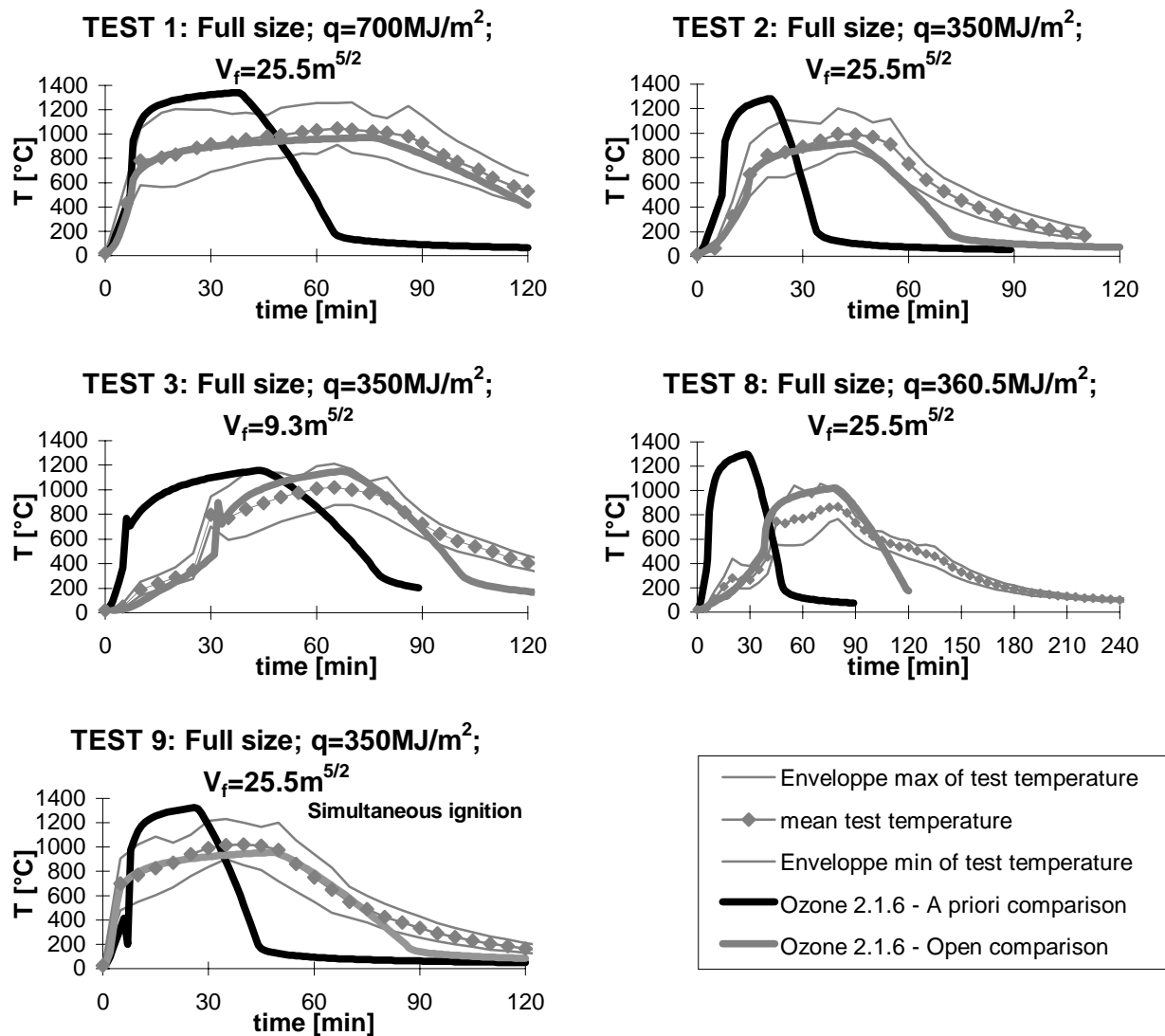
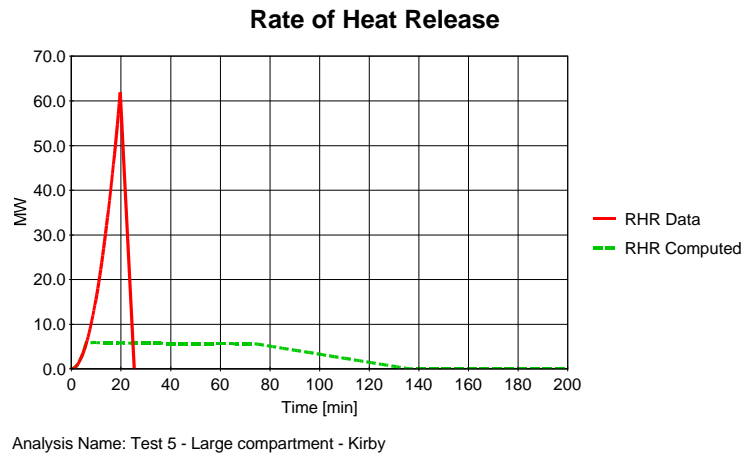


Figure 19 "Open" comparison of temperatures histories

#### 6.2.4 Rate of Heat Release

The rates of heat release set in the data and computed by the code for the 'a priori' simulation of test n°5 are shown on Figure 20. The maximum RHR set in the data is about 62MW while the maximum RHR computed is about 6MW. It is here evident that the external flaming combustion model would have been unrealistic and unsafe. With this model the heat release rate computed would have decrease after a time of 22min, time at which the computed RHR would have been equal to the RHR set in the data. This comparison shows that the extended fire duration combustion model must be used in design procedure. This combustion model is based on the hypothesis that the incoming airflow limits the rate of mass loss (cf. [4]).



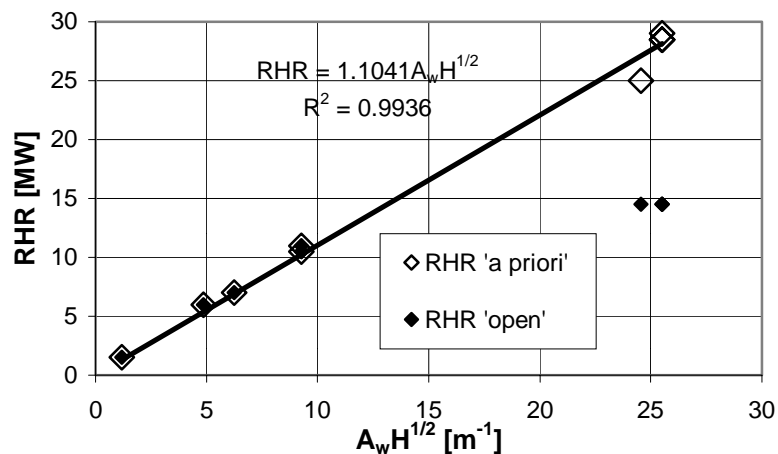
**Figure 20 Heat release rate set in the data and calculated**

Table 3 is a summary of the rate of heat release calculated in the 'a priori' comparison and set in the 'open' one for the 9 tests. Figure 21 is a plot of the heat release rates function of the ventilation factors of the different tests.

**Table 3 Heat release rate obtained from the a priori comparison and set in the open comparison**

Test n°	$A_w h^{1/2}$ $m^{5/2}$	$A_w h^{1/2}/A_{t,net}$ $m^{1/2}$	$q_f$ $MJ/m^2$	RHR 'a priori' [MW]	RHR 'open' [MW]
1	25.515	0.064	700	28.5	14.5*
2	25.515	0.064	350	29	14.5*
3	9.261	0.023	350	10.5	10.5
4	9.261	0.023	700	11	11
5	4.869	0.012	350	6	6
6	1.193	0.003	350	1.5	1.5
7	6.248	0.052	350	7	7
8	24.547	0.064	360.5	25	14.5*
9	25.515	0.064	350	28.5	14.5*

\* values set in the data



**Figure 21 Heat release rate function of ventilation factor**

A linear regression, Eq. (13) on the 'a priori' RHR value function of the ventilation factor shows a very good correlation of these two parameters.

$$RHR \approx 1.1 A_w \sqrt{h_w} \quad [MW] \quad (13)$$

Considering an effective combustion heat of 14MJ/kg, Eq. (13) can be transformed into Eq. (14).

$$\dot{m}_f = \frac{RHR}{H_{c,eff}} = \frac{1.1A_w\sqrt{h_w}}{14} = 0.08A_w\sqrt{h_w} \quad [kg/s] \quad (14)$$

The Kawagoe law, Eq.(15), obtained from tests measurements, links the mass loss rate and the ventilation factor :

$$\dot{m}_{fi} \approx 0.09 A_w\sqrt{h_w} \quad [kg / s] \quad (15)$$

A remarkable agreement is found between OZone's results and Kawagoe's correlation.

A similar agreement has already been found by Drysdale who has used a simple analytical model to determine the air inflow in a compartment and has consider an overall chemical reaction similar to the one considered in OZone. The fact that the rate of burning is directly coupled to the air inflow is surprising. Drysdale concludes that this agreement is fortuitous and should only be valid in case of wood cribs fires, in which the burning surfaces are largely shielded from radiative heat feed back from surroundings which is known to have an important influence on burning rate.

In the particular condition of this test series, it is probable that another phenomenon is also present: The quantity of combustible gases produced by pyrolysis can be higher than the one predicted by Eq.(15). This correlation gives only the part of it which burns instantaneously, the rest is accumulated in the compartment. Only a negligible quantity of combustible gases is going out through the opening, leading to few external flaming.

### 6.2.5 Conclusion

The results obtained with the open simulation are quite good but show that the rising phase and the mass exchange through a large vertical vent is difficult to model.

No reason are stated in the test report for having different rising phase during the different tests, except test 9 during which a simultaneous ignition of the wood cribs has been made. We can thus conclude that it is very difficult to be confident in the rising phase prediction.

The procedure used to improve the simulation results shows that the vertical vent model implemented in OZone is not applicable anymore. With this model it can be observed that the neutral level is always at the third of the total height of the opening. Looking on the picture taken during the tests XX coming from the test report, it is clear that the neutral level is much higher or that some cold air is going out of the compartment as shown on Figure 22. A part of the cold gases coming in the compartment go directly out without any mixing with the inside gases.

It shows also that the quantity of air

The tests with opening areas up to the half of the front wall area were clearly ventilation controlled. The other tests are also ventilation controlled but the influence of the geometry is high. Fires are usually classified either in "ventilation controlled" either in "fuel controlled". A third category is here clearly present which could be called "geometry controlled" fires.



Figure 22 Schematic view of the gas flow through the opening

### Design proposal

In this test configuration, the application of the simple rule of Eq. (16) give satisfactory results for the four tests with an opening area equal to the front wall area. The rule limit the height of large opening to the half of the height of the compartment. Anyway this formula has to be confirmed/improved with other tests. Among other things, the distance between the fuel and the opening ( $D_{fuel-opening}$  on Figure 22) should influence this phenomenon.

$$\text{If } V_f \geq 9.3m^{5/2} \text{ then } h_{w,model} = \min\left(h_w, \frac{1}{2}H\right) \quad (16)$$

Figure 23 present the simulation of test 1 with the application of the rule of Eq. (16).

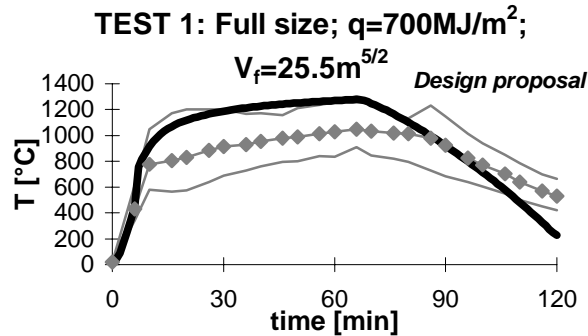


Figure 23 Application of the design proposal to test 1.

### 6.3 Small room tests – furniture and paper fires

The comparison of 10 compartment fire tests is now presented. These tests have been performed in 1974 at CTICM [8]. The compartment was 3.13m high, with a rectangular floor of 3.38m by 3.68m.

Three walls are made of bricks, covered by vermiculite mortar. The ceiling and the fourth wall are made of cellular concrete. The opening is made in the cellular concrete wall. The thermal properties of partition materials are given in the test series reports and a summarized in Table 4.

Table 4 Thermal properties of partition material

<i>material type</i>	Density $\rho$ [kg/m <sup>3</sup> ]	Specific heat $c$ [J/kg K]	Thermal conductivity $\lambda$ [W/m K]	$b = \sqrt{c\rho\lambda}$
Normal brick	1600	840	0.69	963
Vermiculite	200	1850	0.2	272
Cellular concrete	450	1000	0.3	367
Refractory concrete	2300	1000	1.6	1918

The opening area is 0.954m<sup>2</sup> for the first test, 4.251m<sup>2</sup> for the last test and 2.572m<sup>2</sup> for all other tests. The opening factors ( $A_v \cdot (h)^{0.5} / A_{t,net}$ ) is thus 0.015 m<sup>0.5</sup> for the first test, 0.099 m<sup>0.5</sup> for the last test and 0.058 m<sup>0.5</sup> for other tests.

The fire load was made of different percentage of wood, furniture and paper. The fire load density was between 15 and 45 kg per m<sup>2</sup> of floor area. The mass of fuel has been measured during these tests.

An overview of the geometry of the compartment and of the fire load is given for each test in Table 5

Table 5

Test	$D$	$L$	$H$	$W_w$	$h_w$	$A_f$	$A_{t,net}$	$V$	$A_w$	$A_{t,eff}$	$O_f$	%wall	$V_f$	$q_{f,m}$	$q_{f,net}$	$q_{f,eff}$
NFSC	$m$	$m$	$m$	$m$	$m$	$m^2$	$m^2$	$m^3$	$m^2$	$m^2$	$m^{1/2}$		$m^{5/2}$	$kg/m^2$	$MJ/m^2$	$MJ/m^2$
54	3.36	3.6	3.13	0.90	1.06	12.10	67.76	37.86	0.954	66.81	0.015	10	0.98	30	525	420
55	3.36	3.6	3.13	1.18	2.18	12.10	67.76	37.86	2.572	65.19	0.058	25	3.80	15	262.5	210
56	3.36	3.6	3.13	1.18	2.18	12.10	67.76	37.86	2.572	65.19	0.058	25	3.80	20	350	280
57	3.36	3.6	3.13	1.18	2.18	12.10	67.76	37.86	2.572	65.19	0.058	25	3.80	22	385	308
58	3.36	3.6	3.13	1.18	2.18	12.10	67.76	37.86	2.572	65.19	0.058	25	3.80	30	525	420
59	3.36	3.6	3.13	1.18	2.18	12.10	67.76	37.86	2.572	65.19	0.058	25	3.80	30	525	420
60	3.36	3.6	3.13	1.18	2.18	12.10	67.76	37.86	2.572	65.19	0.058	25	3.80	30	525	420
61	3.36	3.6	3.13	1.18	2.18	12.10	67.76	37.86	2.572	65.19	0.058	25	3.80	45	787.5	630
62	3.36	3.6	3.13	1.18	2.18	12.10	67.76	37.86	2.572	65.19	0.058	25	3.80	45	787.5	630
63	3.36	3.6	3.13	1.95	2.18	12.10	67.76	37.86	4.251	63.51	0.099	40	6.28	30	525	420

TEST NFSC 54 to 63 - Mean test temperature

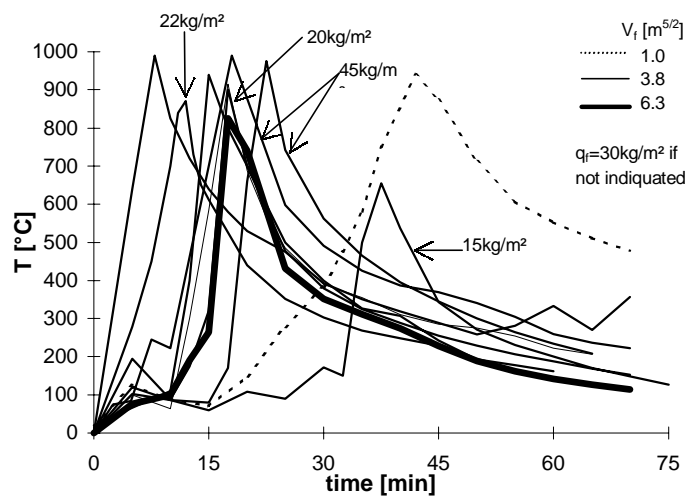


Figure 24 Overview of the mean temperatures measured in the 10 tests

### 6.3.1 A. Blind comparison

The mass loss rate is calculated by deriving the mass measurements and is introduced in the simulation. The “external flaming” combustion model was activated.

A good agreement is generally found on the maximum temperature and on the shape of the temperature time curve.

In test 54, a poor correspondence of maximum temperature is obtained while a good estimation of the rising phase and decreasing phase is found. The maximum temperature is limited to 732°C in the calculation although in the measured one reaches 940°C. The calculation lead to a ventilation controlled fire. The poor correlation of the maximum temperature is the result of a poor estimation of the maximum rate of heat release by the combustion model. Unfortunately, test 54 is the only one of the series with a ventilation factor of  $1m^{5/2}$ .

Tests 55 to 58 and 60 to 62 are also ventilation controlled. In these tests a very good agreement between measurements and calculations is obtained.

In test 59, the peak in the temperature curve is not well predicted. This is due to the absence of peak in the measured mass loss rate. In this case, the calculation lead to a fuel controlled fire. As this test is very similar to tests 58 and 60, it seems that the mass loss measurements are not fully reliable in this case.

In test 63, the ventilation factor is  $6.3m^{5/2}$ . The calculation lead to a fuel controlled fire, which is physically consistent as the opening is large. A very good agreement is found between the experiment and the calculation.

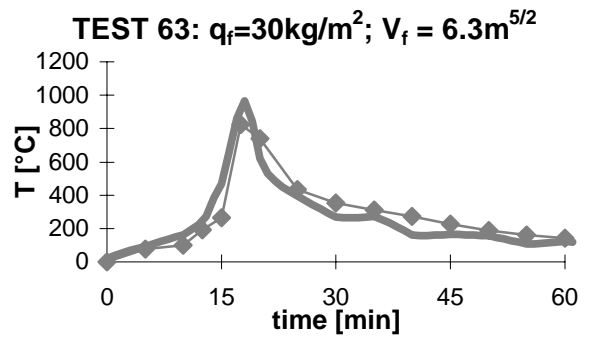
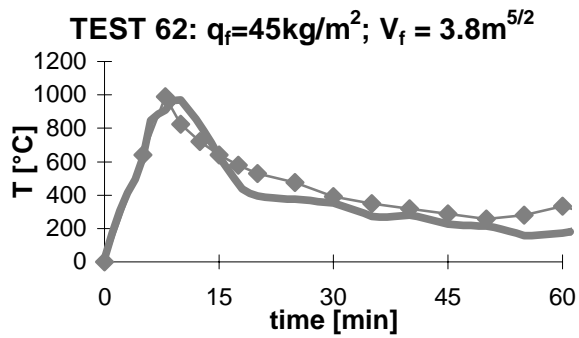
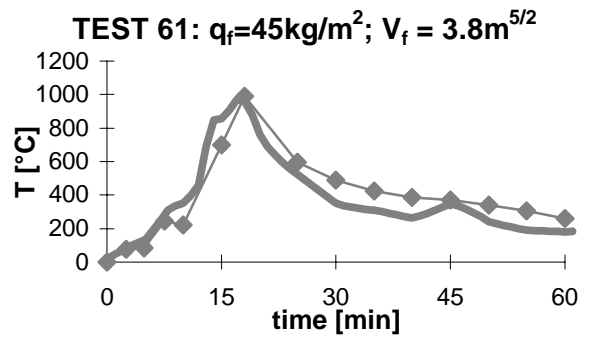
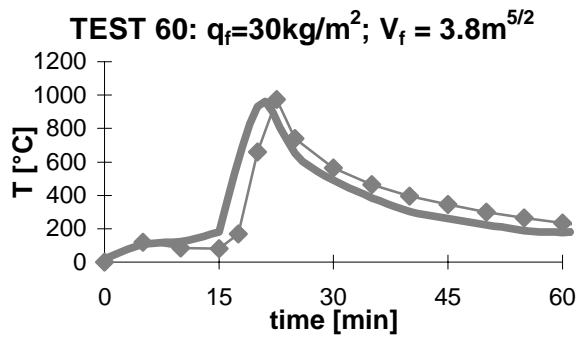
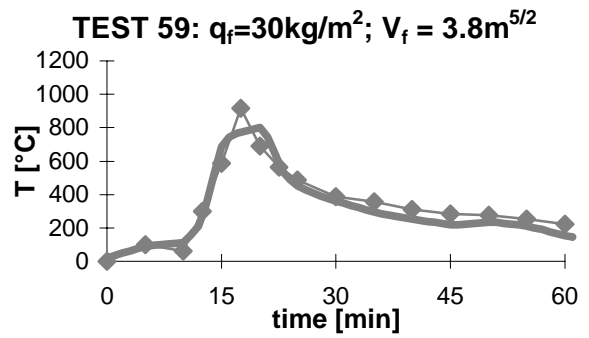
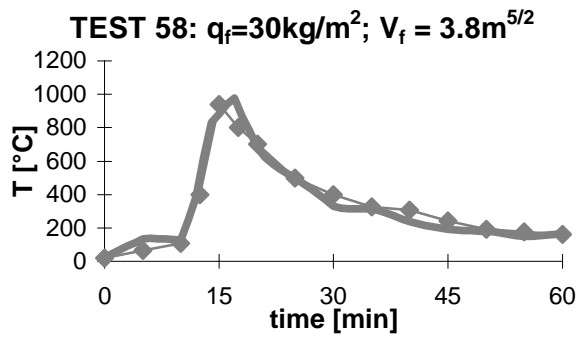
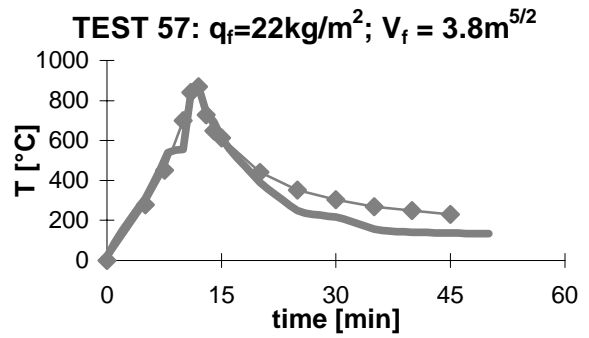
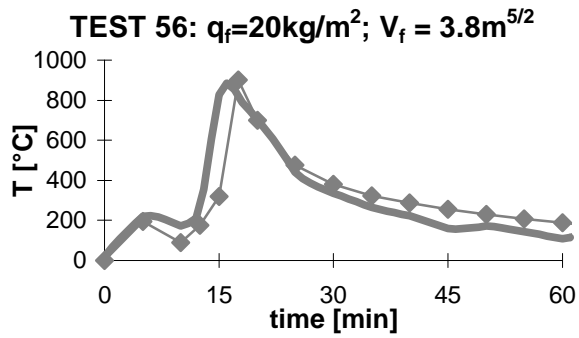
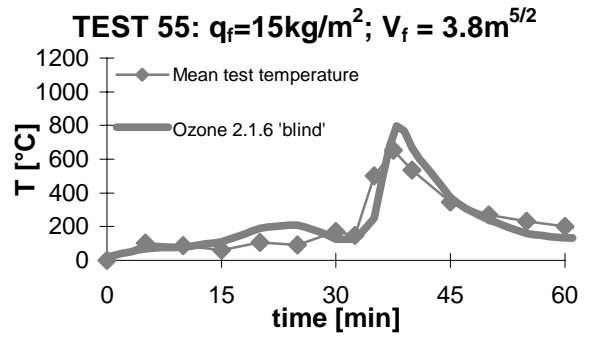
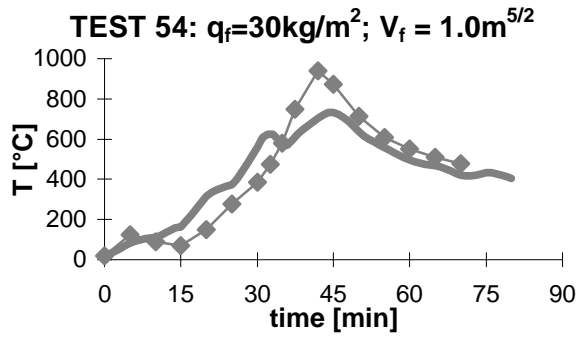


Figure 25 Blind comparison

### 6.3.2 "A priori" comparison

Ignoring the mass loss measurement, an 'a priori' comparison is made. The objective is now to investigate whether OZone is able to predict the behaviour of the fire source.

The design fire is the Office NFSC design fire. It is defined by a medium fire growth rate ( $t_a = 300s$ ) and a rate of heat release density of  $250MJ/m^2$ . The design fire load is the fire load set in the compartment during the tests (given in the test report and summarized in Table 5).

The results are presented on Figure 27.

For test 54, the calculation lead to a ventilation controlled fire. The maximum temperature of the gas is quite well estimated but the temperature are too high during the rising and the decreasing phases. The calculated fire is much more severe than the experimental one. This is due to the fact that in the 'extended fire duration' combustion model all the fire load is forced to burn in the compartment. The hypothesis that no external flaming exists is very safe in this case.

All other calculations lead to fuel controlled fire. It is thus not consistent with the results obtained in the blind comparison. It is due to the fact that the plateau of the design fire curve is not existing in the experiment (as an example RHR in tests 57 and 63 are shown on Figure 26). Nevertheless the calculated curves are relatively close to the experimental ones and on the safe side in all case.

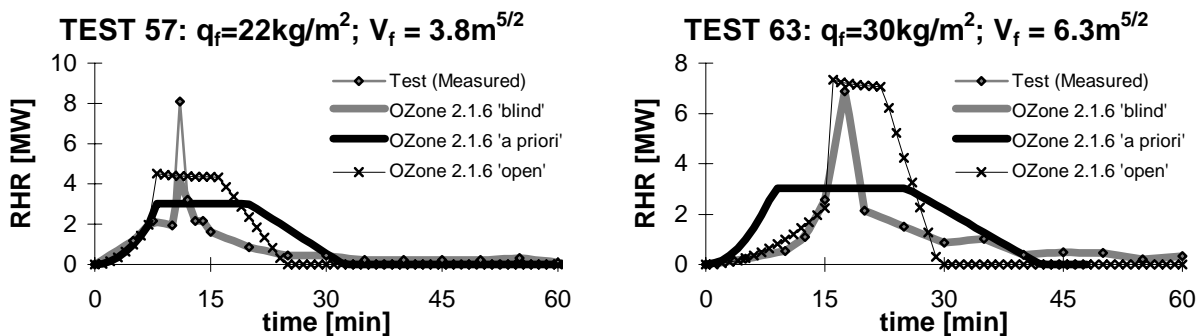


Figure 26 Measured and Calculated Rate of heat release in test 57 and 63.

Although the blind comparison seems to give safe results, the maximum temperature obtained in the simulation of test 63 is too low. This can lead to unsafe results in case of unprotected steel member design.

This study shows that the calculated fire source behaviour is quite different than the experimental one but that the design procedure is safe in all but one case. The value of the rate of heat release density is questionable. Thus an open comparison is made to better understand the influence of this parameter.

Table 6

Test	$q_{f,m}$	$V_f$	Ventilation controlled ?			$T_{max}$	$T_{max}$	$T_{max}$
			blind	a priori	open	Test	Blind	A priori
NFSC	$kg/m^2$	$m^{5/2}$				[°C]	[°C]	[°C]
54	30	0.98	yes	yes	yes	940	733	895
55	15	3.80	no	no	yes	655	798	821
56	20	3.80	yes	no	yes	900	886	848
57	22	3.80	yes	no	yes	870	870	860
58	30	3.80	yes	no	yes	940	977	886
59	30	3.80	no	no	yes	915	803	886
60	30	3.80	yes	no	yes	975	962	886
61	45	3.80	yes	no	yes	990	972	917
62	45	3.80	yes	no	yes	990	971	917
63	30	6.28	no	no	yes	825	965	629

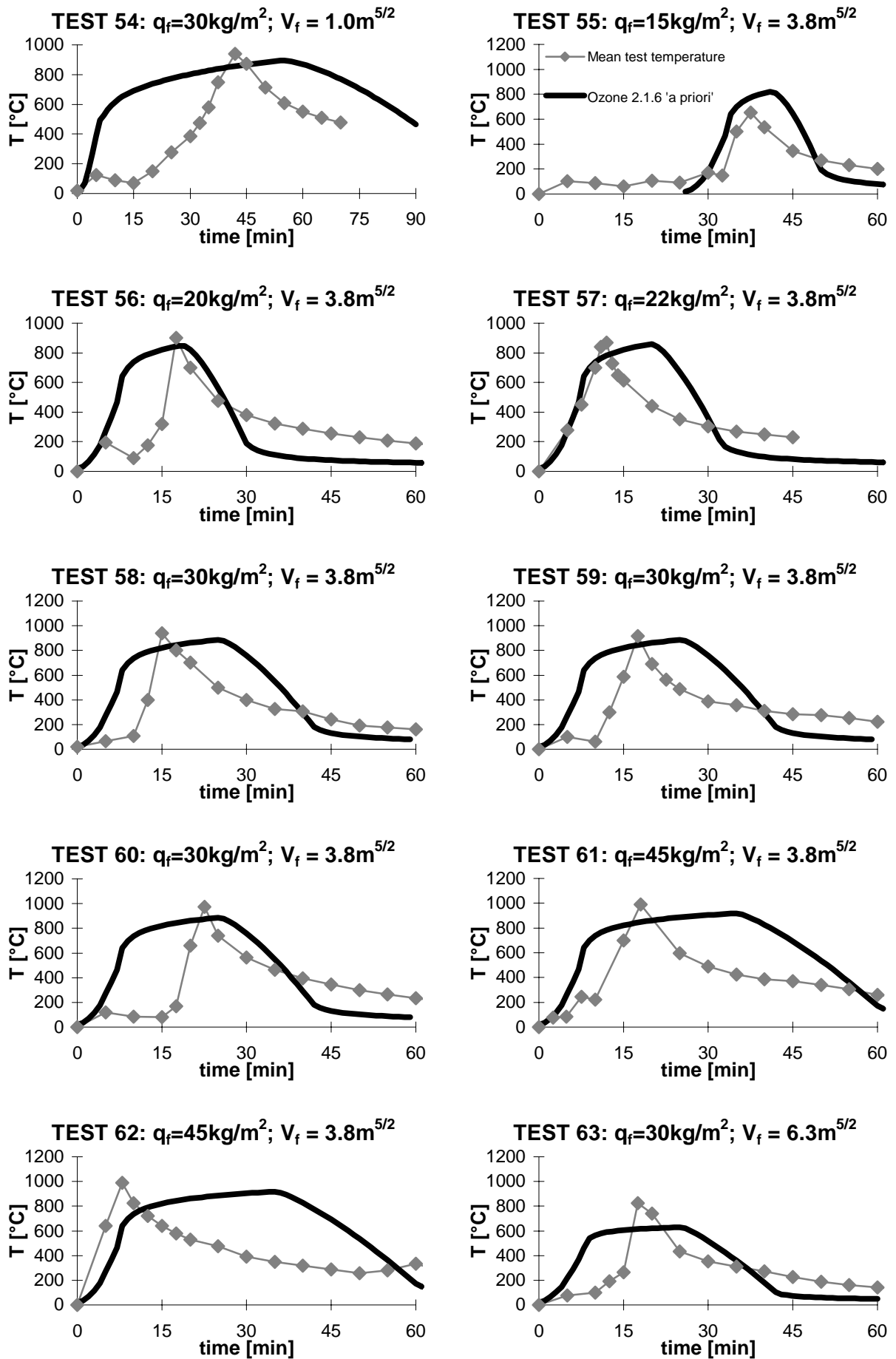


Figure 27 A priori comparison

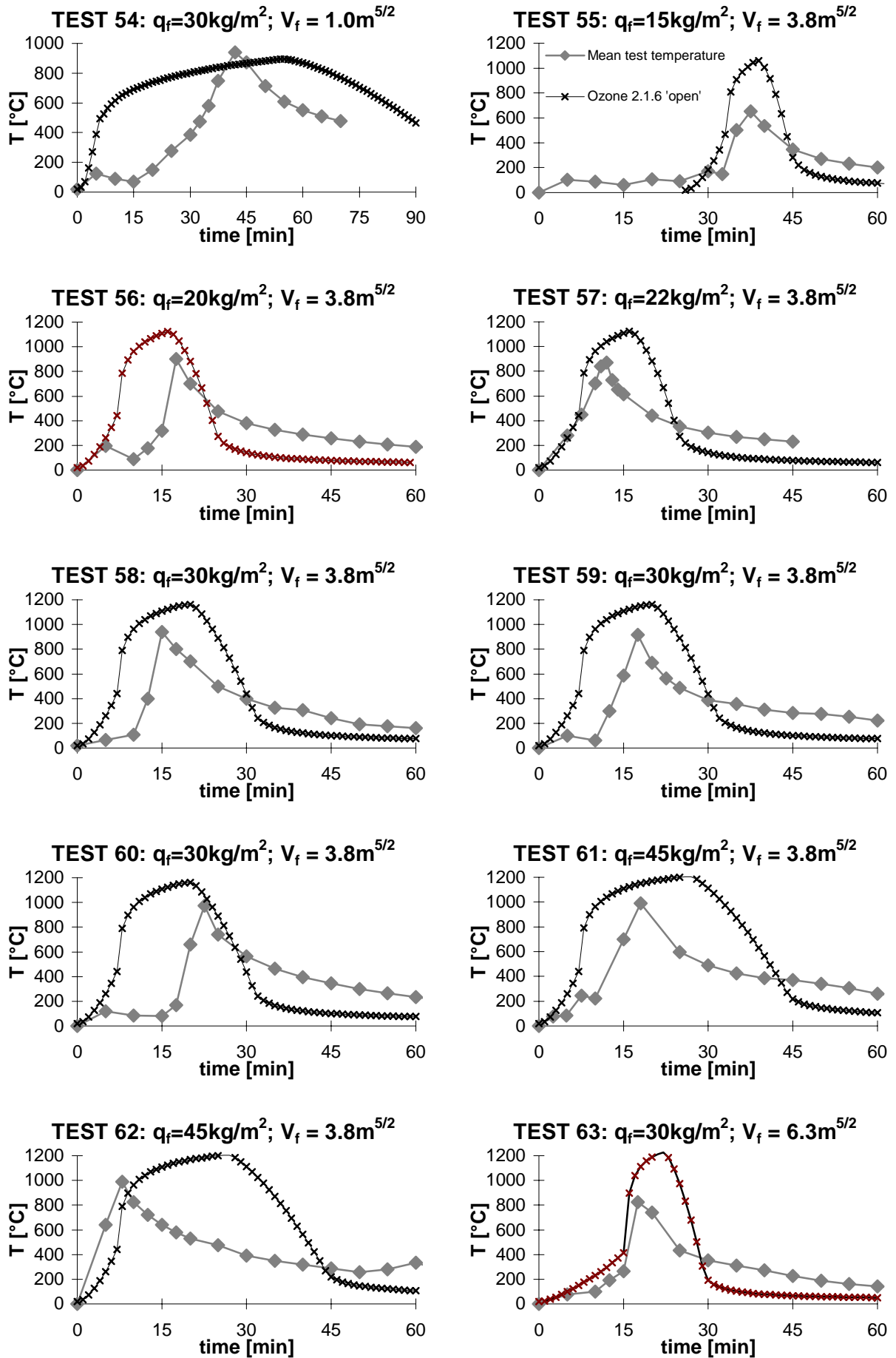


Figure 28 Open comparison

### 6.3.3 "Open" comparison

In case of fuel controlled fire, the plateau of the design fire curve is of primary importance to predict the temperature in a fire compartment. In the a priori comparison, the fires were fuel controlled in all tests but one, while in the blind simulation these tests were ventilation controlled.

In this comparison the rate of heat release density is increased so that all the fires are ventilation controlled (see Figure 26 for tests 57 and 63).

The results are presented on Figure 28.

In this case, all the calculations give safe results.

### 6.3.4 Conclusion

A summary of the different comparisons between OZone and the test series is given on Figure 29.

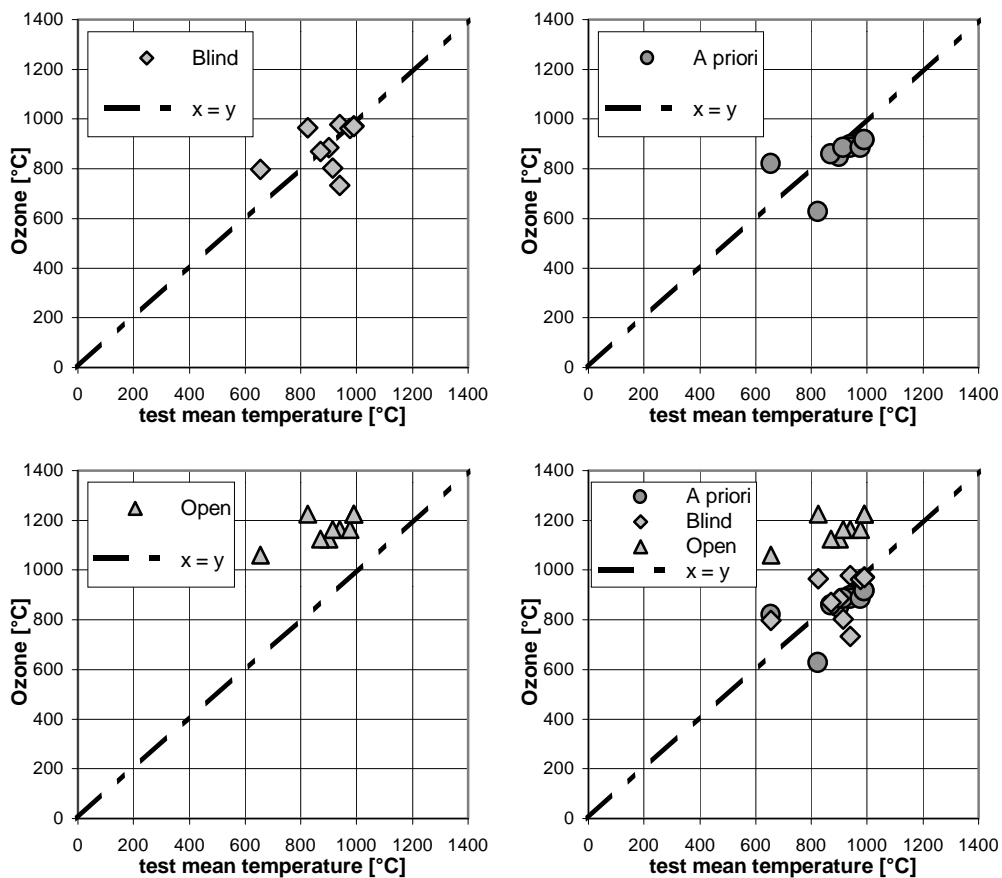


Figure 29 Comparison of the maximum calculated and measured mean temperatures

The blind comparison has shown that, in a small fire room with ventilation factor up to  $6.3\text{m}^{5/2}$ , OZone give a very good estimation of the fire course if the mass loss rate is known.

The a priori comparison has shown that the NFSC design fire give a safe prediction of the fire course in all but one tests. Nevertheless some restriction are made on the rate of heat release density defined in NFSC for office buildings.

The open comparison has shown that the simulations can be safe in all cases by increasing the rate of heat release density so that the fire becomes ventilation controlled.

## 7 Conclusions

The comparison with the Large Compartment series shows that the design procedure implemented in OZone is very good for ventilation factor up to  $9.3\text{m}^{5/2}$ . For higher ventilation

factor, OZone is not able to give a good prediction of the fire course. A proposal of design rule is given. This rule must be confirmed/improved.

The comparison with the Small Compartment series shows that OZone is able to give a good prediction the fire course if the mass loss rate is known. The NFSC design fire give safe results in all but one tests. The simulations can be safe in all cases by increasing the rate of heat release density so that the fire becomes ventilation controlled.

## 8 Download informations

OZone V2.1 is a freeware. It can be downloaded from the FTP site :

FTP address: CHAGAL.SPEC.GCIV.ULG.AC.BE  
USERID: choose anonymous login  
PASSWORD: type your e-mail address

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