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**Fire safety engineering —  
Requirements governing algebraic  
formulae —**

**Part 6:  
Flashover related phenomena**

*Ingénierie de la sécurité incendie — Exigences régissant les formules  
algébriques —*

*Partie 6: Phénomènes liés à l'embrasement généralisé*



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## Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see [www.iso.org/directives](http://www.iso.org/directives)).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see [www.iso.org/patents](http://www.iso.org/patents)).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation on the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see the following URL: [www.iso.org/iso/foreword.html](http://www.iso.org/iso/foreword.html).

The committee responsible for this document is ISO/TC 92, *Fire safety*, Subcommittee SC 4, *Fire safety engineering*.

A list of all parts in the ISO 24678 series can be found on the ISO website.

## Introduction

This document is intended to be used by fire safety practitioners involved with fire safety engineering calculation methods. Examples include fire safety engineers; authorities having jurisdiction such as: territorial authority officials, fire service personnel, code enforcers and code developers. It is expected that users of this document are appropriately qualified and competent in the field of fire safety engineering. It is particularly important that users understand the parameters within which particular methodologies may be used.

Algebraic formulae conforming to the requirements of this document are used with other engineering calculation methods during fire safety design. Such design is preceded by the establishment of a context, including the fire safety goals and objectives to be met, as well as performance criteria when a tentative fire safety design is subject to specified design fire scenarios. Engineering calculation methods are used to determine if these performance criteria will be met by a particular design and if not, how the design must be modified.

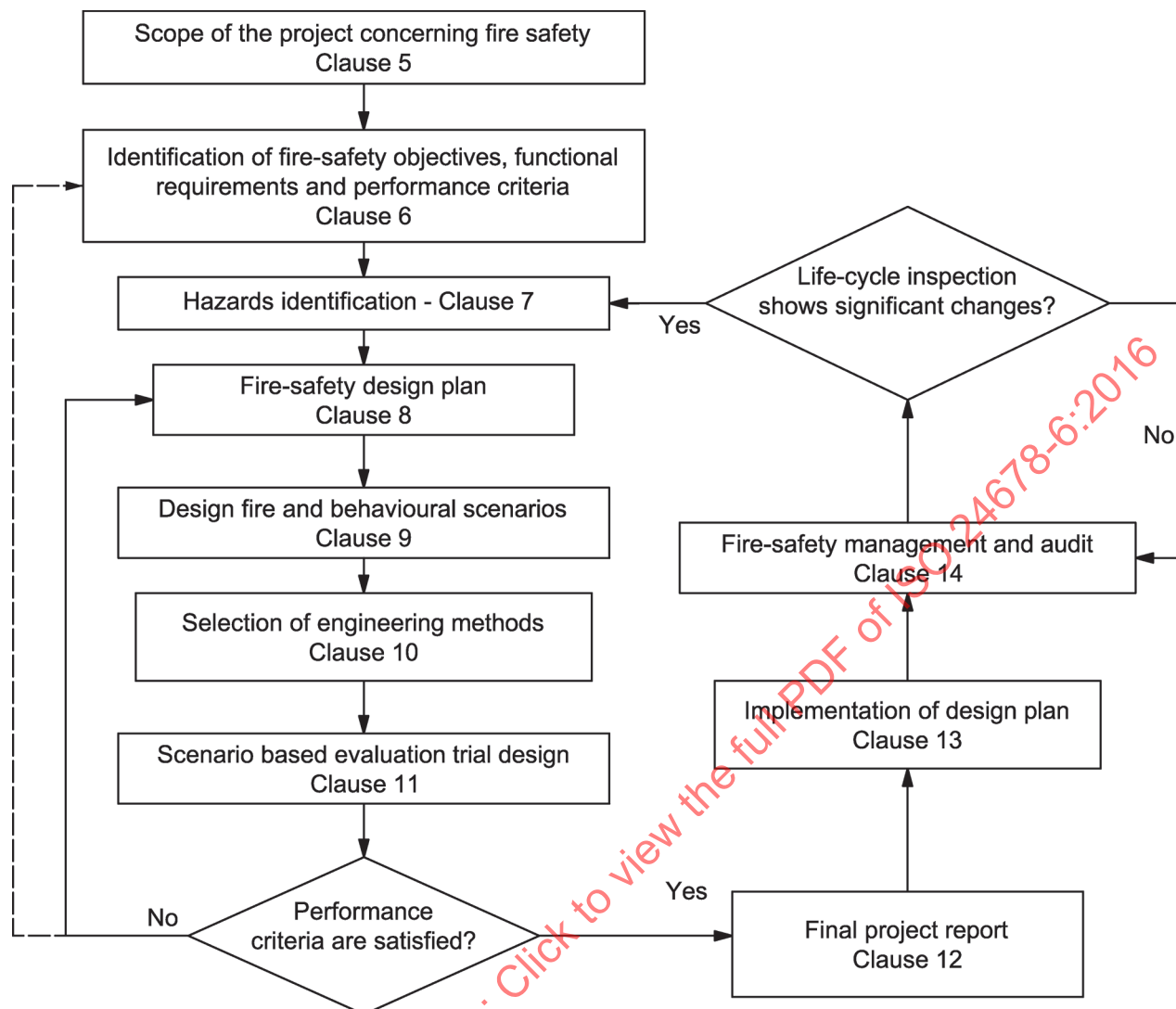
The subjects of engineering calculations include the fire-safe design of entirely new built environments, such as buildings, ships or vehicles as well as the assessment of the fire safety of existing built environments.

The algebraic formulae discussed in this document are very useful for estimating the consequences of design fire scenarios. Such formulae are particularly valuable for allowing the practitioner to quickly determine how a proposed fire safety design should be modified to meet performance criteria. Thus, detailed numerical calculations can be delayed until final design documentation. Examples of areas where algebraic formulae have been applicable include determination of heat transfer, both convective and radiant, from fire plumes, prediction of ceiling jet flow properties governing detector response times, calculation of smoke transport through vent openings and analysis of compartment fire hazards such as smoke filling and flashover.

With respect to flashover phenomena, algebraic formulae are often used to estimate the threshold (minimum) heat release rate required to produce flashover in the space under consideration. These estimates can suggest restrictions on flammable contents or an appropriate fire detection and suppression package to limit the maximum expected heat release rate to below that expected to produce flashover. These formulae are empirically developed from experiments done in relatively small rectilinear enclosures of similar size and with walls and ceilings of similar thermal properties. Thus, the calculated threshold flashover heat release rates do not incorporate the many variables that complicate enclosure fires. Consequently, these calculated values should be considered as preliminary estimates. Ultimately, these estimates can be useful for checking the results of zone and the more comprehensive numerical models that calculate fire growth and its consequences.

ISO 23932 is supported by a set of fire safety engineering documents available on the methods and data needed for the steps in a fire safety engineering design summarized in ISO 23932:2009, Clause 4 and shown in [Figure 1](#) (taken from ISO 23932:2009, Clause 4). This set of documents is referred to as the Global Fire Safety Engineering Analysis and Information System. This global approach and system of documents provides an awareness of the interrelationships between fire evaluations when using the set of fire safety engineering documents. The set includes ISO 16730-1, ISO 16732-1, ISO 16733-1, ISO 16734, ISO 16735, ISO 16736, ISO 16737, ISO/TS 13447, ISO/TS 24679, ISO/TS 29761 and other supporting technical reports that provide examples of and guidance on the application of these documents.

Each document supporting the Global Fire Safety Engineering Analysis and Information System includes language in the introduction to tie said document to the steps in the fire safety engineering design process outlined in ISO 23932. ISO 23932 requires that engineering methods are selected properly to predict the fire consequences of specific scenarios and scenario elements (ISO 23932:2009, Clause 10). Pursuant to the requirements of ISO 23932, this document provides the requirement governing algebraic formulae for fire safety engineering. This step in the fire safety engineering process is shown as a highlighted box in [Figure 1](#) and described in ISO 23932.



NOTE From ISO 23932:2009, Clause 4.

**Figure 1 — Fire-safety engineering process: Design, implementation and maintenance flowchart**

# Fire safety engineering — Requirements governing algebraic formulae —

## Part 6: Flashover related phenomena

### 1 Scope

This document provides requirements to govern the application of explicit algebraic formula sets to the calculation of flashover-related phenomena.

This document is an implementation of the general requirements provided in ISO 16730-1 for the case of fire dynamics calculations involving sets of explicit algebraic formulae.

This document is arranged in the form of a template, where specific information relevant to algebraic flashover formulae are provided to satisfy the following types of general requirements:

- description of physical phenomena addressed by the calculation method;
- documentation of the calculation procedure and its scientific basis;
- limitations of the calculation method;
- input parameters for the calculation method;
- domain of applicability of the calculation method.

[Annex A](#) contains a set of algebraic formulae each of which calculate the minimum heat release rate to cause flashover in residential size enclosures.

### 2 Normative references

The following documents are referred to in text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 16730-1, *Fire safety engineering — Procedures and requirements for verification and validation of calculation methods — Part 1: General*

### 3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 13943 and the following shall apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at <http://www.electropedia.org/>
- ISO Online browsing platform: available at <http://www.iso.org/obp>

### 3.1

#### **critical heat release rate for flashover**

minimum heat release rate of a fire in an enclosure to cause flashover in that enclosure

## 4 Symbols

Symbols for the calculations used to predict flashover onset in [Annex A](#) are listed in [A.2](#).

## 5 Requirements governing description of physical phenomena

**5.1** The onset of flashover is a complex thermo-physical phenomenon that can be highly transient. As a result of burning in an enclosure, hot smoke layer develops in the upper part as stated in ISO 16735. Heat and mass transfer in enclosure takes place. Radiative and convective heat transfer to fuel surface may increase the heat release rate. To calculate the onset of flashover, interactions between phenomena should be considered.

**5.2** Flashover phenomena to be calculated and their useful ranges shall be clearly identified, including those characteristics inferred by association with calculated quantities.

**5.3** Scenario elements (e.g. two-layer environment) to which specific formulae apply shall be clearly identified.

**5.4** Because different formulae describe different flashover characteristics ([5.2](#)) or apply to different scenarios ([5.3](#)), it shall be shown that if there is more than one method to calculate a given quantity, guidance shall be given on the selection of appropriate methods. A descriptive example is given in [Annex A](#).

## 6 Requirements governing documentation

**6.1** The procedure to be followed in performing calculations shall be described through a set of algebraic formulae.

**6.2** Each formula shall be presented in a separate clause containing a phrase that describes the output of the formula, as well as explanatory notes and limitations unique to the formula being presented.

**6.3** Each variable in the formula set shall be clearly defined, along with appropriate SI units, although formula versions with dimensionless coefficients are preferred.

**6.4** The scientific basis for the formula set shall be provided through reference to recognized handbooks, the peer-reviewed scientific literature or through derivations, as appropriate.

**6.5** Examples shall demonstrate how the formula set is evaluated using values for all input parameters consistent with the requirements in [Clause 6](#).

## 7 Requirements governing limitations

**7.1** Quantitative limits on direct application of the algebraic-formula set to calculate output parameters, consistent with the scenarios described in [Clause 6](#), shall be provided.

**7.2** Cautions on the use of the algebraic-formula set within a more general calculation method shall be provided, which shall include checking of consistency with the other relations used in the calculation method and the numerical procedures employed.

## 8 Requirements governing input parameters

**8.1** Input parameters for the set of algebraic-formulae shall be identified clearly, such as; geometric dimensions of enclosure surfaces and vents, special location of vents, special location of fire source, physical properties of boundaries, combustion properties and so on.

**8.2** Sources of data for input parameters shall be identified or provided explicitly within the document.

**8.3** The valid ranges for input parameters shall be listed as specified in ISO 16730-1.

## 9 Requirements governing domain of applicability

**9.1** One or more collections of measurement data shall be identified to establish the domain of applicability of the formula-set. These data shall have certain level of quality [e.g. repeatability and reproducibility; see ISO 5725 (all parts)] assessed through a documented/standardized procedure.

**9.2** The domain of applicability of the algebraic formulae shall be determined through comparison with the measurement data of [9.1](#).

**9.3** Potential sources of error that limit the set of algebraic formulae to the specific scenarios given in [Clause 6](#) shall be identified, for example, the assumption of uniform gas layers in an enclosed space.

## Annex A (informative)

### Algebraic formulae for calculating the minimum heat release rate to cause flashover in residential size enclosures

#### A.1 Description of physical phenomena addressed by the formula set

##### A.1.1 General

The formula sets discussed in Annex A were all empirically derived using temperature and heat flux measurements from tests where different fuels were burned in enclosures of similar size and construction. The tests were generally done to study enclosure fire behaviour including the phenomenon of flashover. Because combustion products from fires have substantially higher temperature than the ambient air, the enclosure gases stratify with the less dense hot combustion products forming a growing hot layer in the ceiling volume of the enclosure. The consensus threshold heat release rate for flashover ( $\dot{Q}_{fo}$ ) is reached when the measured temperature of hot layer exceeds certain values such as 500 °C to 600 °C (approximately 770 K to 870 K) and radiation heat flux to floor surface exceeds 20 kW/m<sup>2</sup> which is enough to ignite common combustible materials in a short time.<sup>[12]</sup>

The range of application is limited by the range in size of the tests from which these formulae were derived; namely, enclosures that have moderate volume. All of these formulae were empirically derived based on small- and residential-sized enclosures. The data sets<sup>[12][13]</sup> analysed show wide variations because they are collected from similar experimental enclosures but using different fuel packages and enclosure lining materials. Note that the majority of algebraic relationships discussed in the following subclauses have been derived from experiments in naturally ventilated enclosures. Only one of the formulae was developed for forced ventilation conditions. To assess uncertainty, it will be necessary to do it for each test article individually.

The formula sets; all normalized by the opening factor  $A\sqrt{H}$ , relate  $\dot{Q}_{fo}$  to the total interior area of the enclosure and a factor proportional to the thermal inertia of the enclosure surfaces. The formula set found to best represent data is identified using the available data and calculations of  $\dot{Q}_{fo}$  using a CFD fire model.<sup>[14]</sup>

##### A.1.2 General description of calculation method

Consider a growing fire in a compartment such as a mattress in a bedroom that has just been ignited by a carelessly discarded cigarette. Sufficient quantities of air are available for combustion in the early stages of fire growth. The burning is said to be fuel-controlled because the combustion, including the resultant heat release rate, is primarily influenced by fuel factors such as fuel type (the mattress) and its configuration (horizontal). Combustion products tend to collect in a layer under the ceiling because they are hotter and therefore less dense than the ambient environment. There is often a fairly sharp demarcation between a hot upper smoke layer and a relatively cool lower layer. As burning continues, the hot layer increases in depth and temperature. This augments the radiative and convective heat transfer to burning items below, which in turn increases their HRR resulting in an increase in the upper layer temperature, further enhancing heat transfer rates to burning items and enclosure surfaces. If sufficient fuel is present and arranged in such a way that the fire does continue to grow, the fire can enter a transitional phase known as flashover.

Flashover is defined as “the rapid transition to a state of total surface involvement in a fire of combustible material within an enclosure”. Essentially, almost all exposed combustible surfaces ignite and burn during flashover. This results in a fully-developed fire. Flashover often represents the

transition from fuel-controlled burning to ventilation-controlled burning where the heat release rate is limited by oxygen availability, which is provided by the flow of fresh air into the compartment. After flashover, there is typically no longer any separation between a hot upper layer and a cool lower layer. Rather, a single well-mixed zone of hot gases exists. The heat release rate has reached a maximum and remains relatively constant until a large fraction of the fuel in the compartment has been consumed. Post-flashover burning represents the most hazardous stage of a compartment fire, and it is therefore of great practical interest to be able to estimate the critical heat release rate at which a fire will show transition to its flashover stage.

While the phenomenon of flashover is universally accepted, the critical conditions defining the threshold for flashover are not. Hot layer temperature between 500 °C and 600 °C, radiative heat flux to the floor of 20 kW/m<sup>2</sup> and appearance of flames exiting vents are all used to signal the event of enclosure flashover. Flashover shall be considered to have occurred when any two of the conditions have been met.<sup>[15]</sup> Because most enclosure fire tests involve extensive temperature measurements, models are designed to predict vertical temperature gradients and the attainment of upper layer temperatures in the above range is most often used to indicate when flashover occurs. Particularly, the algebraic formulae for flashover always use this criterion.

Roughly speaking, the onset of flashover in an enclosure occurs when the radiant heat flux to the floor averages 20 kW/m<sup>2</sup>. This heat flux level corresponds, more or less, to an upper layer temperature of around 500 °C to 600 °C, noting that the radiant flux emitted by a 600 °C black body is about 20 kW/m<sup>2</sup>.

### A.1.3 Scenario elements to which the formula set is applicable

The set of formulae is relevant to the prediction of the minimum heat release rate necessary to cause flashover in a compartment. Except where noted, these formulae apply to naturally ventilated fires, i.e. those where the effect of forced ventilation due to HVAC systems is negligible. In addition, the effect of wind is neglected.

### A.1.4 Self-consistency of the formula sets

The formula set is developed in self-consistent manner.

### A.1.5 Standards and other documents where the formula set is used

None specified.

## A.2 Symbols

|                |                                                                                                                   |
|----------------|-------------------------------------------------------------------------------------------------------------------|
| $A$            | area of ventilation opening (m <sup>2</sup> )                                                                     |
| $A_f$          | area of floor (m <sup>2</sup> )                                                                                   |
| $A_T$          | total interior area of the enclosure excluding opening area (m <sup>2</sup> )                                     |
| $A_{wc}$       | area of walls and ceiling (m <sup>2</sup> )                                                                       |
| $h_T$          | effective heat transfer coefficient (kW·m <sup>-2</sup> ·K <sup>-1</sup> )                                        |
| $(kpc)_f$      | thermal inertia of floor lining (kJ <sup>2</sup> ·m <sup>-4</sup> ·K <sup>-2</sup> ·s <sup>-1</sup> )             |
| $(kpc)_{wc}$   | thermal inertia of wall and ceiling linings (kJ <sup>2</sup> ·m <sup>-4</sup> ·K <sup>-2</sup> ·s <sup>-1</sup> ) |
| $H$            | height of ventilation opening (m)                                                                                 |
| $\dot{m}$      | mechanical ventilation rate (kg·s <sup>-1</sup> )                                                                 |
| $\dot{Q}_{fo}$ | critical (minimum) heat release rate to cause flashover (kW)                                                      |

|                   |                                                                        |
|-------------------|------------------------------------------------------------------------|
| $\dot{Q}$         | heat release rate in an enclosure (kW)                                 |
| $\dot{Q}_0$       | reference heat release rate (=1 000 kW)                                |
| $t_c$             | characteristic time for flashover occurrence (s)                       |
| $t_g$             | characteristic time of fire growth (s)                                 |
| $A\sqrt{H}$       | opening factor ( $\text{m}^{5/2}$ )                                    |
| $A_T / A\sqrt{H}$ | ratio of internal surface area to opening factor ( $\text{m}^{-1/2}$ ) |

### A.3 Formula-set documentation

#### A.3.1 General

The minimum heat release rate required to cause flashover in a compartment is usually predicted by using an energy balance to calculate the upper layer temperature as a function of heat release rate (and sometimes time) and then relating the onset of flashover to the attainment of some critical condition in the compartment. For calculation purposes, flashover is usually assumed to occur when the upper layer temperature rise is between 500 °C and 600 °C or the radiative heat flux to the floor exceeds approximately 20 kW/m<sup>2</sup>.

Empirically and theoretically, the most important factors affecting the minimum heat release rate for flashover ( $\dot{Q}_{fo}$ ) are the area ( $A$ ) and height ( $H$ ) of any compartment vents, the total area of internal surfaces ( $A_T$ ), and the thermal properties of the enclosure lining materials. For this reason, the flashover correlations that have appeared in the literature can be expressed consistently in the form in [Formula \(A.1\)](#):

$$\frac{\dot{Q}_{fo}}{A\sqrt{H}} = f\left(\frac{A_T}{A\sqrt{H}}\right) \quad (\text{A.1})$$

where the total area of internal surfaces ( $A_T$ ) may be determined by net surface area of enclosure boundary walls, floors and ceilings. Some formula includes opening area in the total area of internal surfaces, while some do not. For conservative design calculations, it is recommended to exclude opening area from the total area of internal surfaces.

#### A.3.2 Babrauskas formulae

Using a temperature rise of 575 °C as criterion for onset of flashover, Babrauskas<sup>[13]</sup> proposed the simple expression in [Formula \(A.2\)](#) for estimating the minimum heat release rate to produce flashover:

$$\frac{\dot{Q}_{fo}}{A\sqrt{H}} = 750 \quad (\text{A.2})$$

The coefficient was derived from theoretical assumption that half of the enclosure surface is effective for heat absorption. Comparisons with experiments were carried out for full-scale and model scale experiments conducted in compartments in the range shown in [Table A.1](#). In most of the experiments,

enclosure boundary was made with high density materials. After the comparison, the formula was corrected to [Formula \(A.3\)](#):

$$\frac{\dot{Q}_{fo}}{A\sqrt{H}} = 650 \left( 1 + 0,005 \frac{A_T}{A\sqrt{H}} \right) \quad (\text{A.3})$$

In order to account for the effect of internal surface area, Babrauskas<sup>[16]</sup> also gives a more complicated expression, [Formula \(A.4\)](#), that considers transient heat loss to enclosure surfaces:

$$\frac{\dot{Q}_{fo}}{A\sqrt{H}} = 1 \quad 520 \exp \left( \frac{0,799}{\left( 1 - 0,94 \exp \left( -33 \left( \frac{A_T}{A\sqrt{H}} \right)^{-2/3} \right) \right) \left( 1 - 0,92 \exp \left( -11,9 \left( \frac{A_T}{A\sqrt{H}} \right)^{-0,6} \right) \right)} \right) \quad 1,96 \quad (\text{A.4})$$

[Formula \(A.4\)](#) has been compared with four additional room scale experiments conducted in an enclosure, 2,26 m × 3,94 m × 2,31 m.

**Table A.1 — Range of experimental datasets compared with Babrauskas' formula [[Formula \(A.4\)](#)]**

|                                                    | Internal surface area<br>$A_T$<br>(m <sup>2</sup> ) | Opening factor<br>$A\sqrt{H}$<br>(m <sup>5/2</sup> ) | Ratio of internal surface<br>area and opening factor<br>$A_T / A\sqrt{H}$<br>(m <sup>-1/2</sup> ) |
|----------------------------------------------------|-----------------------------------------------------|------------------------------------------------------|---------------------------------------------------------------------------------------------------|
| Model scale experiments                            | 0,84 to 6,0                                         | 0,06 to 0,68                                         | 9 to 50                                                                                           |
| Full scale experiments                             | 40 to 127                                           | 0,78 to 7,51                                         | 16 to 65                                                                                          |
| Additional room scale<br>experiments <sup>a</sup>  | 43,5 to 44,2                                        | 2,40 to 3,67                                         | 11,8 to 12,0                                                                                      |
| <sup>a</sup> 2,26 m × 3,94 m × 2,31 m (W × L × H). |                                                     |                                                      |                                                                                                   |

### A.3.3 Thomas' formula

Thomas<sup>[17]</sup> used an energy balance that considered heat losses to the bounding surfaces and enthalpy flow through compartment vents. The two adjustable constants were fixed by correlating the model predictions with data from flashover experiments by Hägglund<sup>[18]</sup> in compartments made of concrete and lightweight concrete shown in [Table A.2](#). The resulting expression is as per [Formula \(A.5\)](#):

$$\frac{\dot{Q}_{fo}}{A\sqrt{H}} = 378 + 7,8 \frac{A_T}{A\sqrt{H}} \quad (\text{A.5})$$

**Table A.2 — Range of Hägglund's experimental datasets compared with Thomas' formula [Formula (A.5)]**

|                                                   | Internal surface area<br>$A_T$<br>(m <sup>2</sup> ) | Opening factor<br>$A\sqrt{H}$<br>(m <sup>5/2</sup> ) | Ratio of internal surface<br>area and opening factor<br>$A_T / A\sqrt{H}$<br>(m <sup>-1/2</sup> ) |
|---------------------------------------------------|-----------------------------------------------------|------------------------------------------------------|---------------------------------------------------------------------------------------------------|
| Room scale, series 1<br>(2,9 m × 3,75 m × 2,70 m) | 56,1 to 57,5                                        | 0,22 to 1,78                                         | 31,5 to 258                                                                                       |
| Room scale, series 2<br>(6,0 m × 3,75 m × 2,70 m) | 93,0 to 96,9                                        | 0,89 to 5,34                                         | 17,4 to 109                                                                                       |
| Room scale, series 3<br>(5,9 m × 3,70 m × 2,60 m) | 88,9 to 92,0                                        | 1,78 to 5,34                                         | 16,7 to 51,7                                                                                      |

### A.3.4 McCaffrey's formula

McCaffrey, *et al.* [19] used a regression analysis to develop an empirical correlation to predict the upper layer gas temperature in compartment fires. Assuming that flashover occurs when an upper layer temperature attains 600 °C, the correlation can be used to derive the expression for  $\dot{Q}_{fo}$  shown in Formula (A.6):

$$\frac{\dot{Q}_{fo}}{A\sqrt{H}} = 740\sqrt{h_T} \sqrt{\frac{A_T}{A\sqrt{H}}} \quad (\text{A.6})$$

where the effective heat transfer coefficient to the interior surfaces can be estimated from Formula (A.7):

$$h_T \approx \frac{A_{wc}}{A_T} \sqrt{\frac{(k\rho c)_{wc}}{t_c}} + \frac{A_f}{A_T} \sqrt{\frac{(k\rho c)_f}{t_c}} \quad (\text{A.7})$$

The characteristic time for flashover occurrence  $t_c$  is determined as 1 000 s for typical cases.

The range of enclosure sizes is shown in Table A.3. The thermal inertia of internal linings varied between high (concrete), medium (calcium silicate board, gypsum board) and low values (alumina-silica block, aerated concrete).

**Table A.3 — Range of experimental datasets compared with McCaffrey's formula [Formula (A.6)]**

|                                                   | Internal surface area<br>$A_T$<br>(m <sup>2</sup> ) | Opening factor<br>$A\sqrt{H}$<br>(m <sup>5/2</sup> ) | Ratio of internal surface<br>area and opening factor<br>$A_T / A\sqrt{H}$<br>(m <sup>-1/2</sup> ) |
|---------------------------------------------------|-----------------------------------------------------|------------------------------------------------------|---------------------------------------------------------------------------------------------------|
| Room scale, series 1<br>(2,9 m × 3,75 m × 2,70 m) | 56,1 to 57,5                                        | 0,22 to 1,78                                         | 31,5 to 258                                                                                       |
| Room scale, series 2<br>(6,0 m × 3,75 m × 2,70 m) | 93,0 to 96,9                                        | 0,89 to 5,34                                         | 17,4 to 109                                                                                       |
| Room scale, series 3<br>(5,9 m × 3,70 m × 2,60 m) | 88,9 to 92,0                                        | 1,78 to 5,34                                         | 16,7 to 51,7                                                                                      |

### A.3.5 Hägglund's formula

Hägglund[20] used zone model calculations to develop [Formula \(A.8\)](#):

$$\frac{\dot{Q}_{fo}}{A\sqrt{H}} = 1050 \frac{A_T}{A\sqrt{H}} \left( \frac{1,2}{A_T/A\sqrt{H}} + 0,247 \right)^3 \quad (\text{A.8})$$

The experimental data sets in [Table A.2](#) was utilized for comparison.

### A.3.6 Foote's formula for mechanically ventilated fire

For mechanically ventilated room fires, [Formula \(A.9\)](#), for the minimum heat release rate needed for flashover, is presented by Foote, *et.al.*[21] by assuming that flashover occurs at the upper layer temperature of 600 °C, the initial ambient temperature of 25 °C, and the effective heat transfer coefficient of 0,023 kW/(m<sup>2</sup> K).

$$\dot{Q}_{fo} = 214 \sqrt{A_T \dot{m}} \quad (\text{A.9})$$

[Formula \(A.9\)](#) was derived from mechanically ventilated enclosure fires conducted in a concrete test cell. The test cell dimensions were 4,5 m high, 4,0 m wide and 6,0 m long. The walls and ceiling are 0,1 m thick refractory with a calculated thermal penetration time of 2,5 h. The floor is concrete. Experimental condition is shown in [Table A.4](#). Details of the fuel sources and ventilation variations are contained in Reference [21].

**Table A.4 — Range of experimental datasets compared with Foote's formula [[Formula \(A.9\)](#)]**

|                                       | Internal surface area<br>$A_T$<br>(m <sup>2</sup> ) | Mechanical ventilation rate<br>$\dot{m}$<br>(kg/s) | Ratio of internal surface area and mechanical ventilation rate<br>$A_T / \dot{m}$<br>[m <sup>2</sup> /(kg/s)] |
|---------------------------------------|-----------------------------------------------------|----------------------------------------------------|---------------------------------------------------------------------------------------------------------------|
| Room scale<br>(4,0 m × 6,0 m × 4,5 m) | 138                                                 | 0,11 to 0,325                                      | 115 to 339                                                                                                    |

### A.3.7 Scientific basis for the formula-set

All formulae were all derived using data from experimental fire test cells that were instrumented with thermocouple rakes and gas flow detectors at vent openings. The test cell linings varied from plywood and concrete to polystyrene, where the most common lining was gypsum board. Test cell dimensions were similar in size where the size range averaged close to the dimensions of ISO 9705 testing room. However, some tests were conducted in test articles with vertical dimensions as small as 0,3 m. Indeed, model-scale tests conducted by Hasemi[22] produce data that fall in the same range as data from the larger rooms. There was generally one vent opening for most of the small scale and ISO room scale tests.

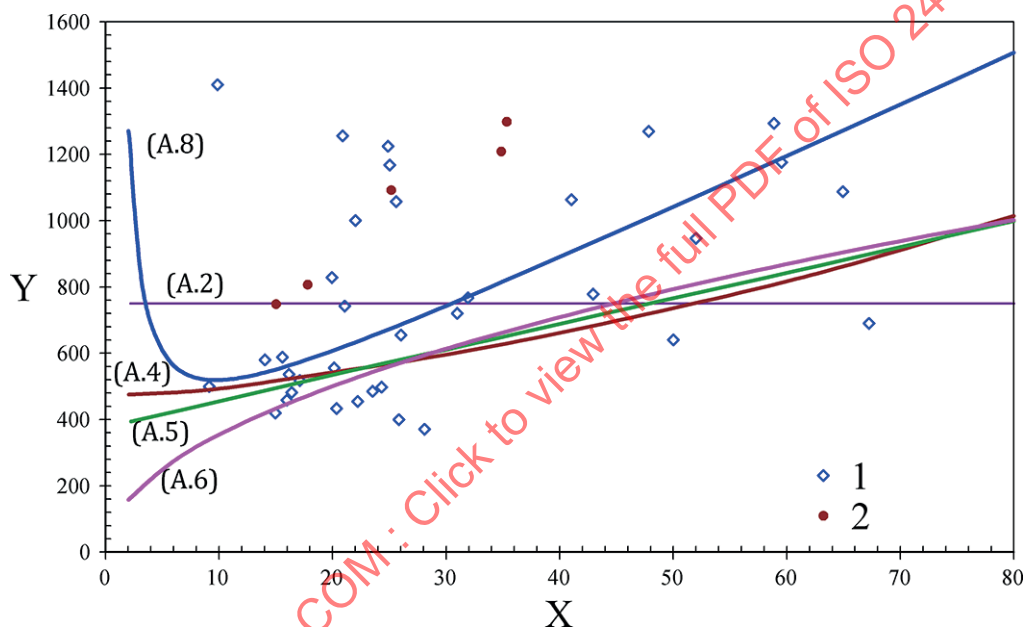
Of these formulae, [Formula \(A.6\)](#) in [A.3.4](#) is recommended to the user because it trends well with the other formulae, and because it contains a term for the effective heat transfer coefficient which accounts for  $A_T$  heat losses resembling the predictions calculated by a CFD fire models as will be demonstrated in [A.3.8](#).

### A.3.8 Comparison with other experimental data

The above expressions have been compared with experimental measurements of the heat release rate at flashover by Babrauskas, *et al.*[12] and Peacock, *et al.*[23] Most of the experiments were carried out in a compartment lined with large thermal inertia materials such as concrete and brick. Internal surface area was in the range of 46,0 m<sup>2</sup> to 127,7 m<sup>2</sup> with an average of 65,3m<sup>2</sup>. Opening factor was in the range of 0,78 m<sup>5/2</sup> to 7,52m<sup>5/2</sup> with an average of 2,52 m<sup>5/2</sup>.

A comparison of the heat release rate at flashover calculated with the above formulae and the experimental data<sup>[12][23]</sup> is given in Figure A.1. For Formula (A.6), it was assumed  $h_T = 0,023 \text{ kW m}^{-2} \text{ K}^{-1}$ . Formula (A.8) does not exhibit a physically correct trend for small values of  $A_T / A\sqrt{H}$ . Formula (A.2), though adequate as a rule of thumb estimate, do not exhibit an increase in  $\dot{Q}_{fo} / A\sqrt{H}$  with  $A_T / A\sqrt{H}$  as is observed experimentally as well as in both zone and CFD simulations. In contrast, Formulae (A.4), (A.5) and (A.6) exhibit very similar estimates of  $\dot{Q}_{fo} / A\sqrt{H}$  for  $20 \text{ m}^{-1/2} < A_T / A\sqrt{H} < 80 \text{ m}^{-1/2}$ . The difference between these three formulae is negligible in comparison to the scatter in the experimental data.

Dimensional analysis [i.e. Formula (A.1)] gives the functional form of the relationship between the critical heat release rate for flashover and the compartment vent areas and height. Correlation with experimental data has been used to postulate several different forms of this function [represented by Formulae (A.4) to (A.6)] and it can be seen from Figure A.1 that the different calculation methods exhibit similar trends and represent the experimental data points fairly well.



#### Key

1 experimental data<sup>[12]</sup>

2 experimental data<sup>[22]</sup>

Y  $\dot{Q}_{fo} / A H^{1/2}$  (kW m<sup>-5/2</sup>)

X  $A_T / A H^{1/2}$  (m<sup>-1/2</sup>)

NOTE See References [12] and [23].

**Figure A.1 — Comparison of predictive methods for critical heat release rate for flashover and experimental data with large thermal inertia walls**

### A.3.9 Discussion on the effect of thermal properties of wall enclosures

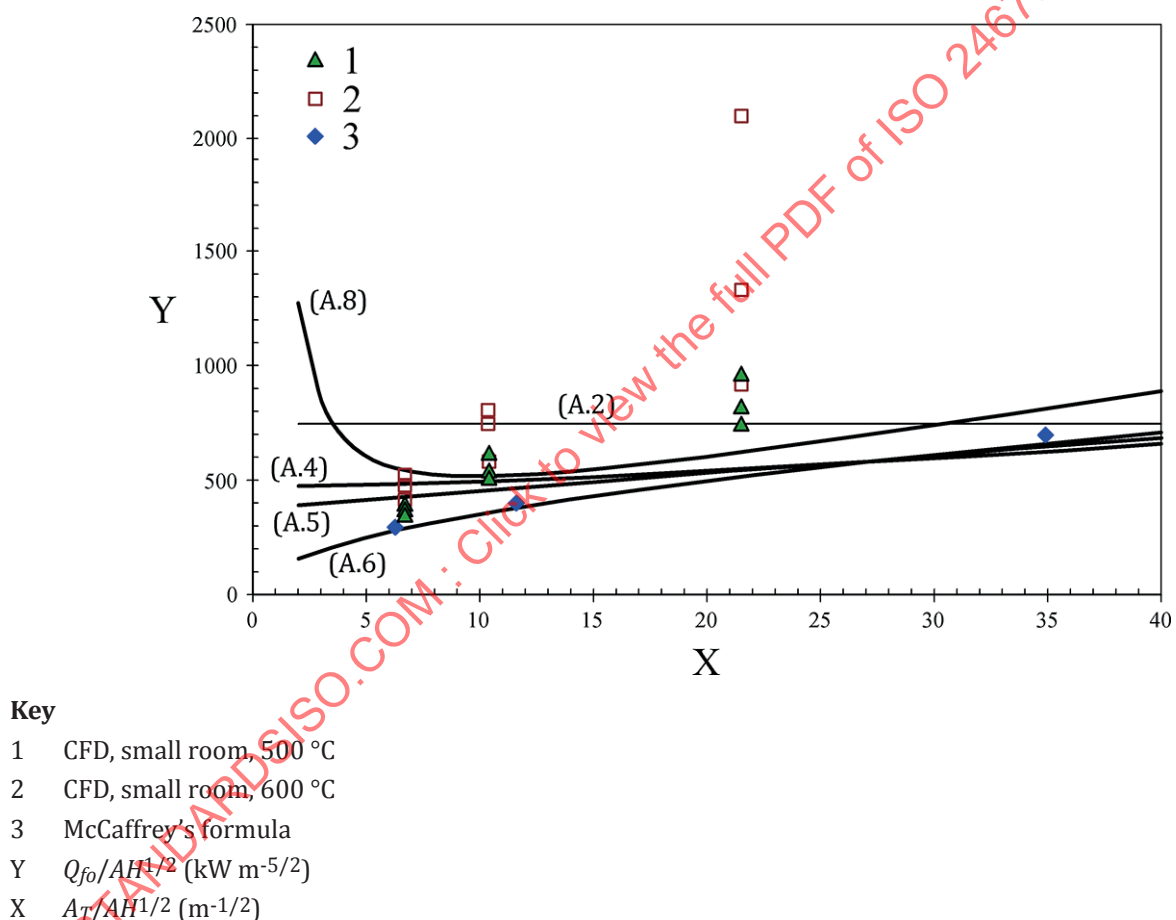
Additional calculations were conducted with a CFD model<sup>[14]</sup> to assess the impact of thermal properties of the wall lining materials on heat release rate at flashover. Simulations were performed for the standard ASTM room (2,42 m × 3,63 m × 2,42 m, with single opening of 0,78 m wide × 2,15 m high) compartment<sup>[15]</sup> lined with three different materials. The compartment had a single ventilation

opening, and the heat release rate was assumed to grow at three different “t-squared” growth rates, as per [Formula \(A.10\)](#).

$$\dot{Q} = \dot{Q}_0 \left( \frac{t}{t_g} \right)^2 \quad (\text{A.10})$$

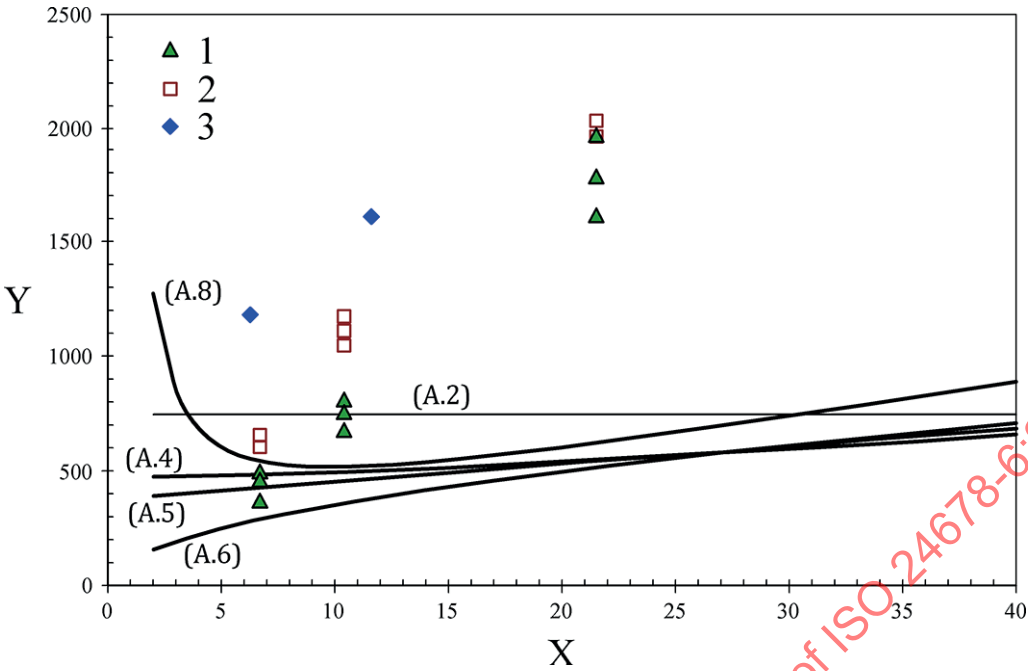
The fire growth rate was set for 1 m × 1 m fire area using the properties of polyurethane and slow ( $t_g = 600$  s), medium ( $t_g = 300$  s) and fast ( $t_g = 150$  s)  $t^2$ -fire growth as defined in ISO 16733-1:2015, Annex C.

The results are summarized in [Figure A.2](#) (gypsum wall lining), [Figure A.3](#) [highly conductive (cold-wall) lining material] and [Figure A.5](#) (highly insulating lining). In addition, [Formula \(A.6\)](#) was applied with appropriate effective heat transfer coefficient ( $h_t$ ) to estimate  $\dot{Q}_{fo} / A\sqrt{H}$  for the same enclosure properties. Since the trends of the estimates are similar to the CFD estimates, [Formula \(A.6\)](#) could be recommended as the best candidate for general application of the formula sets.



NOTE Wall lining for CFD modelling and [Formula \(A.6\)](#) is gypsum.

**Figure A.2 — Comparison of CFD modelling results and estimates (diamonds) with [Formulae \(A.2\)](#) to [\(A.6\)](#) plots for onset of flashover**



Key

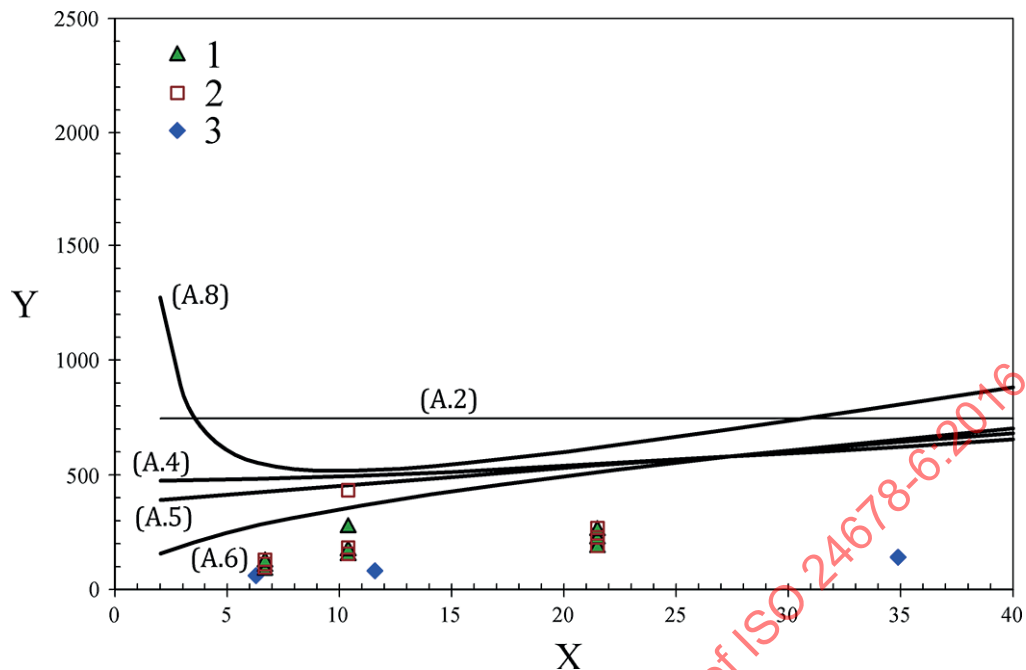
- 1 CFD, small room, 500 °C
- 2 CFD, small room, 600 °C
- 3 McCaffrey's formula
- Y  $Q_{fo}/AH^{1/2}$  (kW m<sup>-5/2</sup>)
- X  $A_T/AH^{1/2}$  (m<sup>-1/2</sup>)

NOTE 1 Wall lining for CFD modelling and [Formula \(A.6\)](#) estimates is cold-wall (ambient) temperature.

NOTE 2 The  $Q_{fo}$  estimate at  $A_T / A\sqrt{H} = 34,8$  is off scale.

NOTE 3 See Reference [\[12\]](#).

Figure A.3 — Comparison of CFD modelling results and [Formula \(A.6\)](#) estimates (diamonds) with [Formulae \(A.2\)](#) to [\(A.6\)](#) plots for onset of flashover



#### Key

- 1 CFD, small room, 500 °C
- 2 CFD, small room, 600 °C
- 3 McCaffrey's formula
- Y  $Q_{fo}/AH^{1/2}$  (kW m<sup>-5/2</sup>)
- X  $A_T/AH^{1/2}$  (m<sup>-1/2</sup>)

NOTE Wall lining for CFD modelling and [Formula \(A.6\)](#) estimate is adiabatic.

**Figure A.4 — Comparison of CFD modelling results and estimates (diamonds) with Formulae (A.2) to (A.6) plots for onset of flashover**

[Figures A.2 to A.4](#) show that the CFD data for the gypsum wall lining material matches the experimental data most closely, and that the experimental data are bracketed by the CFD results and [Formula \(A.6\)](#) estimates for the adiabatic lining and the highly conductive linings. Because  $Q_{fo}$  predictions using CFD modelling and the estimates calculated using [Formula \(A.6\)](#) bracket the experimental data similarly, it appears that [Formula \(A.6\)](#) has the best capability to produce acceptable estimates of  $Q_{fo}$  for preliminary engineering analysis.

## A.4 Formula-set limitations

The application of formula-set is limited to the following situations:

### A.4.1 Normal ambient air

All formulae apply only to normal-air (21 % oxygen by volume), atmospheric pressure environments with ambient temperatures close to “room temperature”. The formulae do not apply directly to environments with oxygen concentrations different from 21 % by volume. Also, the formulae do not apply when ambient temperatures are outside the range of approximately 0 °C to 40 °C.

### A.4.2 Enclosure lining materials

Since the correlations were developed largely from compartment fires having “typical” moderately-conductive wall lining materials, they may not apply to compartments with highly conductive or highly insulating walls. However, [Formula A.7](#) can be used to estimate the heat loss through wall and ceiling

areas with various thermal properties. The CFD does better calculations because this modelling does account for changes in the thermal properties of the lining materials during fire growth.

The correlation does not consider flame spread over wall and ceiling surfaces. Thus the use of formula is limited to rooms with non-combustible or not easily ignitable materials.

### A.4.3 Rectilinear room

The correlations apply to typical rectilinear compartments that do not have large aspect ratios. The algebraic formulae should not be applied to compartments with aspect ratios (the ratio of compartment depth to compartment width as defined in [Figure A.6](#)) greater than approximately 3. The correlations were developed from experimental data for compartments with “normal” ceiling heights (~3 m) so they should not be applied to high-ceiling spaces. The correlations also should not be applied to compartments larger than approximately 4 m by 4 m because few experiments were conducted in compartments larger than this.

## A.5 Formula set input parameters

### A.5.1 Opening factor

Opening factor is calculated from the geometry of opening. For an enclosure with a single opening, opening factor is directly calculated by the height  $H$  and area  $A$  of the opening. For an enclosure with multiple openings as shown in [Figure A.5](#), effective values of the parameters  $A$  and  $H$  can be calculated by [Formulae \(A.11\)](#) and [\(A.12\)](#):<sup>[24]</sup>

$$A = \sum_{i=1}^n A_i \quad (\text{A.11})$$

$$H = \frac{1}{A} \sum_{i=1}^n H_i A_i \quad (\text{A.12})$$

where  $n$  is the number of openings,  $A_i$  and  $H_i$  are the area and height of the  $i$ -th opening.

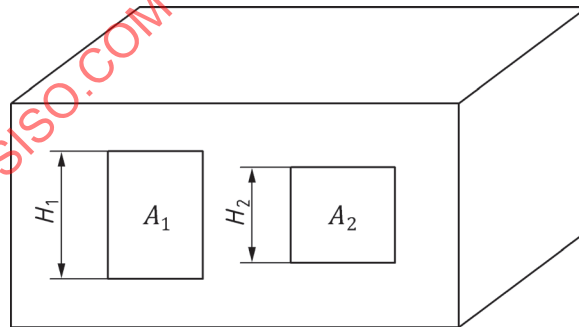


**Figure A.5 — Calculation of effective opening factor for an enclosure with multiple openings**

If the heights of openings above floor are different, mass flow rate of air  $\dot{m}$  incoming to enclosure can be calculated assuming room temperature of 500 °C using the methods in ISO 16737:2012, Annex B. Then the equivalent opening factor is defined by [Formula \(A.13\)](#):

$$A\sqrt{H} = \dot{m} / 0,52 \quad (\text{A.13})$$

which gives the same amount of air flow into compartment.