No fire without smoke.

Prediction models for heat release
and smoke production
in the SBI test and the Room Corner test
based on Cone Calorimeter test results.

Anne Elise Steen Hansen

Department of Building and Construction Engineering
Faculty of Engineering Science and Technology
Norwegian University of Science and Technology
Trondheim, Norway

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Summary

Smoke production in fire represents a threat because fire smoke reduces visibility and because fire smoke is toxic. One way to reduce the risk of persons being overcome by smoke during evacuation is by setting requirements to the building materials' ability to contribute to the smoke production in a fire. By regulating the use of building products based on their contribution to the optical smoke production in a fire, the toxicity aspects of the smoke will be covered to a high degree as well.

In this work prediction models for optical smoke production in the Single Burning Item test (SBI) and in the Room Corner test have been developed. The models are of two kinds; *classification models* based on multivariate statistical analysis of Cone Calorimeter test results, and *dynamic calculation models* where empirically developed equations are combined with multivariate statistical classification models. The basic idea behind the dynamic smoke prediction models is that the smoke production rate is closely linked to the heat release rate. Prediction models for heat release rate in the two larger-scale methods were therefore a necessary starting point for the modelling of smoke production. Existing models simulating heat release in the SBI test and in the Room Corner test were modified to suit these needs; and were assessed to have high predictability after the modifications.

My work comprise the following prediction models:

- A modified version of the Wickström/Göransson model for prediction of heat release rate in the Room Corner test.
- A statistical model for predicting time to flashover in the Room Corner test using the concept of FO-categories.
- A model for predicting smoke production rate in the Room Corner test.
- A statistical model predicting the level of maximum and average smoke production rate in the Room Corner test.
- A modified version of the model by Messerschmidt et. al. for prediction of heat release rate in the Single Burning Item test.
- A model for predicting smoke production rate in the Single Burning Item test.
- A statistical model predicting the level of SMOGRA and the smoke classification in the Single Burning Item test.

All models, both for prediction of heat release and smoke production, use results from Cone Calorimeter tests at heat flux level 50 kW/m^2 as input data. The empirical basis for the models is test data from a total of 65 different products. 32 of the products are tested both in the SBI test and in the Cone Calorimeter test; 56 are tested both in the Room Corner test and in the Cone Calorimeter test. Data from a total of 194 Cone Calorimeter tests have been analysed.

Both the statistical classification models and the dynamic calculation models can easily be implemented in a PC worksheet, and the prediction results are readily achieved.

The models’ predictability has been evaluated by comparing the predicted results to results from “real“ larger-scale tests, and by comparing predicted classification to the classification actually obtained. The actual and predicted classifications have been calculated according to the new European system for classification of building products based on reaction to fire test results, and according to the existing classification system based on the EUREFIC-programme.

The results show that both heat release and smoke production are possible to predict with these models. The predictions of the Single Burning Item test results are more precise than the Room Corner test results, this is probably because the ventilation conditions in the Cone Calorimeter test are more similar to the Single Burning Item test than to the conditions in the Room Corner test. The large-scale fire behaviour is found difficult to predict for some types of products where the fire behaviour depends on certain mechanical or chemical changes during the fire exposure. Such events are obviously not easily predicted from small-scale tests in the Cone Calorimeter, and will need more detailed modelling.

This thesis presents a generic method of designing prediction models where test results from small-scale methods are used to predict fire behaviour in larger scale. The main feature of this kind of models is the integration of multivariate statistical models in the calculations. Statistical information makes it possible to discriminate between different kinds of products and fire behaviour, and thereby to choose calculation algorithms specially designed for different product groups. Products with high flame-spread ability, products with low heat release, products with high smoke production and wood-based products are examples of product types that require special treatment in the modelling of fire behaviour in the Room Corner test and in the SBI test. Modelling of other large-scale test methods may need the option of discriminating between other kinds of groups, based on e.g. product type, geometrical considerations etc.

Preface

This thesis presents the results from the work carried out during my dr.ing. study at the Norwegian University of Science and Technology (NTNU), Department of Building and Construction Engineering.

The work was started in 1998, and has been financed by a scholarship from the Norwegian insurance company Vesta AS. The work has also been financially supported by Norges branntekniske laboratorium as, SINTEF. Some of the work has also been a part of a Nordic project financed by NORDTEST.

I wish to thank my supervisor, Professor Per Jostein Hovde, for his support and encouragement during my work.

The management at NBL deserves acknowledgement for making it possible for me to carry out this study; both through financial and moral support, and by giving me office accommodation during these four years.

I will thank my colleagues at NBL for being there and for their encouraging attitude.

I also owe a debt of gratitude to my family for letting me work at this project at hours not always as family-friendly as one would wish.

I have really enjoyed working with this thesis, despite some periods when the work was less fun. The dr.ing. study has given me a broader theoretical base for my future work, it has given me insight to the process of research and scientific writing, and I have also found new friends through the work.

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Anne Steen Hansen

List of papers

This thesis consists of a summary of my work (Part I) and a collection of the following papers (Part II):

Paper I	Hansen, A S. Heskestad A W. **Assessment of smoke atmospheres where loss of visibility is the limiting hazard.** Conference Proceedings 2nd International Symposium on Human Behaviour in Fire, 26/28 March 2001. Massachusetts Institute of Technology, USA, pp. 97-308. Interscience Communications Ltd, London UK, 2001. ISBN 0 9 5 3 2312 6 7
Paper II	Hansen, A S. Hovde P J. **Prediction of Smoke Production in Large and Intermediate Scale Tests based on Bench Scale Test Results. A Multivariate Statistical Analysis.** Proceedings of Fire and Materials 2001 Conference, January 22-24 2001, San Francisco, USA, pp 363-374.
Paper III	Hansen, A S. Hovde P J. **Prediction of time to flashover in the ISO 9705 Room Corner test based on Cone Calorimeter test results.** Submitted to *Fire and Materials*, May 2001. Revised January 2002.
Paper IV	Hansen, A S. **Prediction of heat release in the Single Burning Item test.** Submitted to *Fire and Materials*, July 2001. Revised February 2002.
Paper V	Hansen, A S. Hovde P J. **Prediction of smoke production based on statistical analyses and mathematical modelling.** Conference Proceedings Interflam 2001, Edinburgh, UK, September 17-19, 2001. Volume 1, pp 113-124.
Paper VI	Hansen, A S. Hovde P J. **Simulation of smoke production in large-scale fire tests based on small-scale test results using multivariate statistical analysis to enhance predictability.** Accepted as a poster to be presented at the 7th International Symposium on Fire Safety Science, Worcester, Massachusetts, USA, 16-21 June 2002 (IAFSS 2002).

Terms and definitions

$A_{HRR,eff}$	Effective heat releasing area [m^2].
$A_{SPR,eff}$	Effective smoke producing area [m^2].
$A_{max,HRR}$	A constant used in calculation of the effective heat releasing area in the Single Burning Item test [-].
$A_{max,SPR}$	A constant used in calculation of the effective smoke producing area in the Single Burning Item test [-].
asphyxiant[1]	A toxicant causing narcosis, resulting in central nervous system depression with loss of consciousness and ultimately death.
CO	Carbon monoxide.
COHb	Carboxyhaemoglobine; i.e. the complex of CO bound to haemoglobine in the blood.
FED	Fractional effective exposure dose.
FIGRA	**FI**re **G**rowth **RA**te index (calculated in the SBI test) [kW/s].
fire effluent[1]	Total gaseous, particulate and aerosol effluent from combustion or pyrolysis.
FR	Fire retardant or fire retardant agent
HCN	Hydrogen cyanide.
HRR	Heat release rate [kW] (SBI test and Room Corner test) or [kW/m^2] (Cone Calorimeter test).
I_{HRR}	Index parameter indicating the route of development for the effective heat releasing area in the Single Burning Item test.
I_λ^0	The light intensity for a beam of parallel light rays of wavelength λ measured in a smoke free environment.

[1] As defined in ISO Guide 52 Glossary of fire terms and definitions (ISO/IEC 1990)

I_λ	The light intensity for a beam of parallel light rays of wavelength λ having traversed a certain length (L) of smoky environment.
incapacitation[1]	A state of physical inability to accomplish a specific task, e.g., safe escape from a fire.
irritation, sensory/upper respiratory[1]	The stimulation of nerve receptors in the eyes, nose, mouth, throat and respiratory tract, causing varying degrees of discomfort and pain along with the initiation of numerous physiological defence responses.
k	Light extinction coefficient [m^{-1}].
$\mathbf{k_{SPR}}$	The ratio $A_{SPR,eff}/A_{HRR,eff}$ [-].
L	Pathlength of lightbeam through smoke [m].
$\dot{q}''_{CC}$	Heat release rate per m^2 in the Cone Calorimeter [kW/m^2].
$\dot{s}''_{CC}$	Smoke production rate per m^2 in the Cone Calorimeter [1/s].
ρ	Density [kg/m^3].
ρ_{eff}	Effective density, i.e. the density averaged over a depth of one cm from the exposed surface [kg/m^3].
smoke[1]	A visible suspension of solid and/or liquid particles in gases resulting from combustion or pyrolysis.
SBI	Single Burning Item (EN 13823:2002).
SMOGRA	**SMO**ke **G**rowth **RA**te index (calculated in the SBI test) [m^2/s^2].
SPR	Smoke production rate [m^2/s].
t	Time [s].
$\mathbf{t_{ign}}$	Time to ignition in the Cone Calorimeter [s].
$\mathbf{t_{FO}}$	Time to flashover in the Room Corner test [s].
$\mathbf{t_{SPR}}$	Time to start of smoke production in the Cone Calorimeter [s].
THR	Total heat release [MJ] (SBI test and Room Corner test) or [MJ/m^2] (Cone Calorimeter test).

THR_{300s}	Total heat release during 300 s after ignition in the Cone Calorimeter test [MJ/m^2].
THR_{600s}	Total heat release during 600 s after ignition of the burner in the SBI test [MJ].
toxic hazard[1]	The potential for harm resulting from exposure to toxic products of combustion.
TSP	Total smoke production [m^2] (SBI test and Room Corner test) or [-] (Cone Calorimeter test).
TSP_{600s}	Total smoke production during the first 600 s of testing time in the SBI test [m^2].
$\dot{V}$	Volume flow [m^3/s].

Subscripts

avg	average, averaged
CC	Cone Calorimeter
eff	effective
FO	flashover
ign	ignition
λ	wavelength
max	maximum value
0	initial value

Table of contents

PART I: MAIN REPORT

If you will enjoy the fire you must put up with the smoke. (Latin proverb)

1. Introduction

1.1 Structure of this thesis

This thesis is built on the set of six publications listed on page v. The thesis is divided into two parts. **Part I**, which this section belongs to, gives an overview of the papers together with the strategy for my work and the main results. **Part II** is a collection of the six papers presented in the version they were either published or submitted in revised version for publishing.

Section 2 briefly presents the problem with smoke in fires, both in a historical view and with respect to the present situation. A simple method for assessing the toxicity in a smoke-filled atmosphere where loss of visibility is a crucial factor, is presented.

In **Section 3** the tested materials that the simulation models are built on are presented.

Section 4 gives a brief overview of the methods applied; both fire test methods and the statistical approach are presented. The classification systems used for evaluating the results from the prediction models are also described here.

The models for simulation of heat release in the Single Burning Item test and in the Room Corner test are presented in **Section 5**, while the smoke simulation models are described in **Section 6**. The development of these models is described in Papers II through VI. I have chosen to give a detailed description of the smoke prediction models in Part I of the thesis, because the final models are results of a long process of analyses and assessments. The original models proposed in the papers have to some degree been adjusted when I achieved new insight to the topic during the process, and when more test results became available during the work. The calculation models represent the core of my project, and I believe they can be valuable tools for both fire scientists and practicians in fire engineering. A complete overview of the prediction models will therefore facilitate the understanding and make the application of the models easier for other fire safety engineers.

Section 7 contains conclusions, a discussion of the prediction models and an assessment of their validity. Suggestions for further work are also given.

Appendices I-IV contain graphical and tabulated results from application of the simulation models on test results for the different analysed products in my work. These appendices are included because I found it convenient to collect all these results together with the thesis.

1.2 Objectives and scope

The objectives for my study were in the beginning expressed as *"Building products' reaction to fire, with emphasis on smoke production"*, which is a very broad and little definite statement. Later on the scope was defined more precisely:

- *prediction of smoke production in the Single Burning Item test and in the Room Corner test*
- *further understanding of smoke toxicity and human response*

The first part of this scope is presented as the substantial result of my thesis, i.e. models that are ready to be applied in fire engineering contexts. This work is presented in papers II-VI. The latter part of the scope is treated through studies of relevant literature in this field, and through presentation of a simple assessment tool published in paper I.

1.3 Delimitation of the work

The prediction models are limited to cover one narrow part of the branch *reaction-to-fire testing*. The models are designed to predict heat release and optical smoke production in the larger-scale Single Burning Item test and Room Corner test based on input data from the small-scale Cone Calorimeter test. I have chosen to concentrate on the philosophy used in the model presented by Wickström and Göransson (1992), the so-called Cone Tools model. The reason for this choice, is that there is a long experience in using this model for predicting the heat release rate in the Room Corner test in the Nordic countries. The philosophy behind the model has later been used to develop a model predicting heat release rate in the SBI test as well. If a smoke prediction model could be included in the model, this would mean a great improvement to an already efficient tool.

The models are designed empirically, which means that they are results of the sets of test data that were available. The models are not able to predict fire behaviour that is caused by mechanical or chemical changes late in the fire. Such changes can be burn-through of seals and joints, breakdown because of weakened mechanical strength, or chemical processes that make fire retardant systems overcome by the fire conditions.

However, the applicability of the work is less limited in the sense that it presents a generic method for designing new prediction models for other kinds of test methods - only fantasy and available test data would restrict such further work.

2. Fire and the smoke problem

2.1 Safe escape through smoke?

Fire leads to production of smoke, and smoke represents a threat in two ways. It contains toxic substances that may be dangerous to inhale, and it may contain substances that irritate eyes and upper airways. Smoke obscures the environment, and the visibility is thereby reduced. Loss of visibility is in many fire situations the condition that is determining whether a person will be able to escape or not. Modest loss of visibility can slow down the movement speed during egress and prevent evacuating people from finding the closest exit, which in turn leads to prolonged exposure to toxic gases and thereby to higher exposure doses. The final result may be fatal.

2.2 How is smoke production regulated?

Legislation is one of the areas where smoke production and toxic effects come into consideration. The very first attempt to regulate smoke production from burning materials in Europe was made by the English king Edward I. In the 1280's he tried to get control over burning of sea-coal in London; the burning led to the air being "*infected and corrupted to the peril of those frequenting and dwelling in those parts*" (Calendar of the Patent rolls 1893). In 1307 he issued an order to the Sheriffs of London and Southwark where they were told to prohibit the burning while the Queen was in residence in the Tower of London. Breaking of this order should cause "*pain of heavy forfeiture*" (Calendar of the Close rolls 1908). The demand is based both on the annoyance created by the smoke ("*an intolerable smell*") and on human safety aspects ("*injury of their bodily health*").

Smoke inhalation is the main cause of death for the majority of victims in building fires. This has been concluded through studies of fatal fires in the US (Harwood and Hall 1989), Denmark (Leth 1998) and in Norway (Lundberg and Pedersen 1982, Hansen 1995).

In this millennium there are many nations in the world where the use of building products is restricted based on the products' ability to produce smoke in a fire. Such regulations may cover either optical smoke density or smoke toxicity of building materials or both issues. In the new European system for reaction-to-fire testing and classification, measurement of optical smoke production forms the base for a ranking of building products (EN 13501-1: 2002). The authorities in each of the different EU- and EFTA member countries decide whether documentation of smoke production will be a part of their building regulations or not.

In the 1970's and –80's a huge amount of research was done to get to know more about the toxicity of fire effluents (Kaplan et. al. 1984, Hartzell 1989, Hall 1996). One of the aims of studying smoke toxicity was to get knowledge that could support ranking and classification of materials for buildings and interior appliances according to their smoke toxicity. Different materials were burnt under varying combustion conditions in several fire test apparatuses. The toxicity of the produced smoke was assessed in several ways, both by chemical analysis and by bioassays. Different animal species were exposed to the smoke, and the animal response was assessed. Several research groups in laboratories performed such work all over the world, and the outcome was a vast amount of data on smoke and toxicity. Among other findings, the results showed that a burning material can be the source of several toxic species in the effluents, and that the toxicity of different gas species and different gas mixtures can vary significantly. The search for a so called “super toxicant” gave no unique result (Hall 1996), and today there is a common understanding that smoke toxicity is caused by a small number of toxic gases (Purser 1999). Smoke toxicity is still an important topic in international fire research.

2.3 Flashover fires are dangerous fires

There is no doubt that flashover fires represent a serious threat to life. US fire statistics show that more than half of all fire deaths are associated with post-flashover fires, and slightly more than half of the victims are located outside the room of fire origin (Hall 1996). According to the Norwegian studies (Lundberg and Pedersen 1982, Hansen 1995), approximately 2/3 of the victims were found outside the room of fire origin. About half of the fires had developed beyond flashover when the fire brigades arrived, either flashover in the room of origin, or flashover in the total or parts of the building. Danish data show, however, that only 25% of the fires in the analysis developed to flashover fires (Leth 1998). This is also the case in the UK, where the fatal fires are more likely to be confined to the room of fire origin (Hall 1996). However, in disasters where several people are killed, the fire development will be expected to have reached flashover.

The risk connected to flashover fires is reflected in the new European system for classification based on reaction to fire tests. The newly developed *Single Burning Item test*, or SBI for short (EN 13823:2002) is a central part of this system. The method is based on the *Room Corner test* (ISO 9705:1993), which has been given the status as the reference scenario for the SBI test. Time to flashover is an important test result in the Room Corner test.

2.4 Toxic substances in fire smoke

Fire smoke may contain several toxic substances in different phases; both solid particles (soot, fibres), liquid droplets (aerosols) and gaseous components.

One single material may produce hundreds of different gas species during combustion depending on the burning conditions, and several of these gases may act as toxicants when concentrations become high enough. According to Purser (1999), only four asphyxiant gases are found to be important in fires, namely carbon monoxide (CO), carbon dioxide (CO_2), hydrogen cyanide (HCN) and reduced oxygen concentration (O_2). Among these, the dominating asphyxiant gas in fires is known to be CO. CO will always be found in smoke from a real fire, while other toxic substances will depend more on the chemical composition of the burning fuel. The majority of fire victims are found to have lethal concentrations of COHb in the blood (Lundberg and Pedersen 1982, Locatelli et. al. 1994, Hansen 1995, Leth 1998). Elevated concentrations of COHb can indicate poisoning by HCN as well, and it is reasonable to assume that a person is poisoned by HCN after inhalation of fire smoke (Nelson 1998).

So far only a few authorities have regulations on smoke toxicity, like the state of New York in the US, Germany and Japan (Hartzell 1989), as well as the International Maritime Organization (IMO 1998). Other regulators recommend that the smoke production and smoke toxicity for building materials should be assessed, without stating any definite criteria (Norwegian Petroleum Directorate 1998, National Office of Building Technology and Administration 1997).

There is a recognised opinion among several fire researchers that products for buildings and interiors should not be ranked or classified according to their performance in fire toxicity tests (Hartzell 1989). Other reaction-to-fire parameters are more determining for human fire safety. Among these the rate of heat release is governed as the most important one, as smoke production is closely linked to the size of the fire. The importance of smoke production in fire, both with regard to optical smoke density and concentration of toxic gases shall, however, not be underestimated. In hazard analyses of building fires there is clearly a need for tools capable of predicting available time to incapacitation for people exposed to smoke, and such tools must take both optical smoke density and smoke toxicity into account.

2.5 Assessment of loss of visibility

There have been several different attempts on measuring optical smoke production from a burning material, and different philosophies regarding what to measure and how to measure it. One common way is to measure how much the smoke attenuates the light from a light source; this is often called *smoke obscuration*. Smoke production can be measured as a dynamic quantity where the attenuation of light is measured in a flow-through system, or it can be measured as a static quantity, where the attenuation is measured after a fixed volume has been filled with smoke. Gravimetric measurement of smoke means filtering of the smoke followed by determination of the mass of smoke particles retained in the filter. Smoke production rate (SPR) is measured as a dynamic value in the three test methods analysed in my work. SPR is here defined in the same way as it is calculated according to the standards ISO 9705 : 1993 and EN 13823 : 2002 :

$$SPR = k \cdot \dot{V} = \frac{1}{L} \cdot \ln \frac{I_\lambda^0}{I_\lambda} \cdot \dot{V} \qquad [\mathrm{m^2/s}] \tag{2-1}$$

Where

k:	light extinction coefficient [m^{-1}]
$\dot{V}$:	the volume flow rate in the exhaust duct [m^3/s]
L :	pathlength of lightbeam through smoke [m]
I_λ^0:	the light intensity for a beam of parallel light rays of wavelength λ measured in a smoke free environment.
I_λ :	the light intensity for a beam of parallel light rays of wavelength λ having traversed a certain length (L) of smoky environment

SPR can also be expressed relatively to the area of the burning material (in units [1/s]), it can be expressed relatively to the mass loss of the burning material (in units [m^2 /kg·s]), or relatively to both area and mass loss (in units [1/kg·s]).

Jin did some extensive work in the 1970's and -80's where he related the smoke obscuration to movement speed through the smoke, and to visibility of exit signs (Jin 1971, 1976, 1981, 1986). For "non-irritating" smoke, a light extinction coefficient below 1.2 m^{-1} (i.e. a visibility of 1.67 m) is necessary for people familiar with the building to be able to escape. For irritating smoke, the limiting value will be lower. Jin proposed a value of 0.5 m^{-1}, which corresponds to a visibility of 4 meters. Jin's conclusions on limiting values for smoke density have later been adopted by several researchers as benchmarks of the hazard represented by smoke (Babrauskas 1977, Purser 1995).

2.6 Assessment of smoke toxicity

Several methods for assessment of fire smoke toxicity have been published during the last decades. The N-gas model (Babrauskas et.al. 1991) assumes that toxicity of combustion products can be approximated by a small number N of fire gases, and is commonly applied to data from measurements of the four gases CO, CO_2, HCN and O_2. The hazard related to exposure to fire environments could also be assessed by applying the concept of Fractional Effective Dose (FED) (Hartzell and Emmons 1988). FED is later redefined to Fractional Effective Exposure Dose, as the exposure dose is the measurable quantity in a fire situation (Huggett 1989, Babrauskas et. al. 1991). The original FED model is based on rat lethality data from experiments on exposure to a selection of important toxic gases (CO, HCN, HCl), and the idea is to add up effects from several toxicants to a single value, the FED. Effect of irritant gases to the total lethality is not included in the model. This model has later been expanded to take effects from heat exposure and low oxygen concentration into account.

A similar concept of a fractional incapacitating dose for narcosis has also been published (Purser 1995, BS ISO/TR 9122-5:1996). The aim of this model is to predict at what time the occupants exposed to the fire effluents will be incapacitated, i.e. when they become unable to escape from the fire because of toxic effects.

2.7 Is there any link between smoke density and toxicity?

In paper I we demonstrate how the principles of calculated fractions of incapacitating units can be used in a very simplified hazard analysis of how toxicity and loss of visibility can be assessed in combination. This method is very rough, however, we believe that it can be a useful engineering tool when designing efficient escape routes. Our method is built on Purser's model mentioned above (Purser 1995), and uses data from large-scale fire tests as input parameters. The smoke toxicity is then assessed at a point far from the origin of fire, when the smoke is diluted and cooled down by fresh air, but still affects the visibility to a high degree. The model was found to be sensitive to the concentration of HCN, and we therefore recommend that different sets of input values are used before any conclusions are drawn.

Heat release rate is often regarded as a product's most important reaction-to-fire property. Restricting a product's ability to release heat would also (normally) restrict the smoke production, as these qualities are closely linked. However, there are products where rate of smoke production can be large compared to heat release rate, e.g. some fire retarded products. Fire smoke is toxic and should therefore always be regarded as dangerous. By limiting the use of products with high smoke production in a building, the probability that escape routes are rapidly filled with dense and toxic smoke is automatically reduced. Longer time with acceptable visibility means longer time for evacuation. Following this logic I believe that regulations on production of optical smoke will cover the toxicity aspects of smoke to a high degree. This is reflected in the core part of my work, where prediction of optical smoke production is the objective.

3. Tested products used in the model development

The 65 products included in the analyses are collected from several research programmes. All products are tested with horizontal specimen orientation in the Cone Calorimeter apparatus. Most products are tested at heat flux density 50 kW/m^2 while some are also tested at other heat flux density levels. The same products are tested either according to the Room Corner test method or the SBI test method, or according to both. The tested materials cover a range from products with very low combustibility, like gypsum board, via wood-based products to highly combustible materials like foamed plastics.

The **first group** of test materials used in this study consisted of the products selected for the European SBI Round Robin in 1997. Six of the products tested in the Round Robin are excluded from this analysis, these are the FR Extruded polystyrene board (M03), FR polycarbonate panel (M07), PVC water pipe (M17), plastic electric cables (M18), unfaced rockwool (M19) and steel clad polystyrene sandwich panel (M21). M03 was melting in the SBI test and formed a burning pool on the floor (Messerschmidt et. al 1999). M07 was omitted because it was heavily melting in the Room Corner test, and the burning was limited and took place in the melted material on the floor (Sundström et.al. 1997). M19 did not ignite in the Cone Calorimeter test, and gave thereby no input values to the model development. M21 was discarded because this is a product where the fire protection may be damaged by structural changes during large-scale fire exposure, and such effects are difficult to simulate in the small-scale Cone Calorimeter. M17 and M18 are excluded because they represent product groups not intended for testing in the standard Room Corner test or in the SBI test.

All the SBI Round Robin products were tested once according to the Room Corner test, more than 20 times in the SBI test and at least three times in the Cone Calorimeter. The tests were performed by different laboratories (Sundström et. al. 1997, Messerschmidt et. al. 1999).

The **second group** contains 11 products tested in the EUREFIC programme (Wickström et. al. 1991). EUREFIC (European Reaction to Fire Classification) was a research programme designed to improve the system for fire testing and classification of wall and ceiling linings in the Nordic countries. The programme was completed in 1991.

The products in the **third group** are 4 products tested in an inter-laboratory trial between 4 laboratories within the EUREFIC programme (Mangs et. al.1991).

The **fourth group** contains test results from 13 products tested in a Swedish test programme in the 1980's (Sundström 1986).

The 4 products in **group five** were tested in a Norwegian test programme sponsored by the offshore industry and the Norwegian Petroleum Directorate (Hansen and Hovde 1993).

Group six consists of three products tested by the Norwegian Fire Research Laboratory, SINTEF (unpublished results) and 6 wood-based products tested by the Swedish Institute for Wood Technology Research (Östman 2001).

A brief description of the 65 products is given in Tables 3-1 to 3-6.

Table 3-1 Description of the materials from the SBI Round Robin programme used in the analyses (Sundström et. al. 1997).

Material ID	Material description	Thickness [mm]	Density [kg/m^3]
M01	Paper-faced gypsum plasterboard	13	700
M02	FR[1)] PVC	3	1180
M04	PUR[2)] foam panel with Al-foil faces	40	PUR:40
M05	Mass timber (pine), varnished	10	450
M06	FR[1)] chip board	12	780
M08	Painted paper-faced gypsum plasterboard	13	700
M09	Paper wallcovering on gypsum board	13	700
M10	PVC wallcarpet on gypsum plasterboard	13	700
M11	Plastic-faced steel sheet on mineral wool	0.15+1+50	m.wool:160
M12	Mass timber (spruce) unvarnished	10	450
M13	Gypsum plasterboard on polystyrene	13+100	700/20
M14	Phenolic foam	40	58
M15	Intumescent coating on particle board	12	700
M16	Melamine-faced MDF[3)] board	12	MDF:750
M20	Melamine-faced particle board	12	695
M22	Ordinary particle board	12	700
M23	Ordinary plywood (birch)	12	650
M24	Paper wallcovering on particle board	12	700
M25	Medium density fibreboard	12	700
M26	Low density fibreboard	12	250
M27	Gypsum plasterboard/PUR[2)]	13 + 87	PUR:38
M28	Acoustic mineral fibre tiles	18	m.wool:220
M29	Textile wallpaper on CaSi-board	CaSi:10	CaSi:875
M30	Paper-faced glass wool.	100	18

[1)] FR: Fire retarded
[2)] PUR: polyurethane
[3)] MDF: medium density fibreboard

Table 3-2 Description of the materials from the EUREFIC programme used in the analyses (Wickström et. al. 1991).

Material ID	Material description	Thickness [mm]	Density [kg/m^3]
E01	Painted paper-faced gypsum board	12	800
E02	Ordinary plywood (birch)	12	600
E03	Textile wallcovering on gypsum board	1+12	800
E04	Melamine-faced non-combustible board	12,5	1055
E05	Plastic-faced steel sheet on mineral wool	0.15+0.7+23	640
E06	FR[1)] particle board type B1	16	630
E07	Combustible faced mineral wool	30	87
E08	FR[1)] particle board	12	750
E09	Plastic faced steel sheet on PUR[2)] foam	80+0.1+1	160
E10	PVC wallcarpet on gypsum board	0.9+12	800
E11	FR[1)] polystyrene foam	25	37

[1)] FR: Fire retarded
[2)] PUR: polyurethane

Table 3-3 Description of the materials from the inter-laboratory trial within the EUREFIC programme used in the analyses (Mangs et. al. 1991).

Material ID	Material description	Thickness [mm]	Density [kg/m^3]
EI-1	Ordinary plywood (birch)	12	650
EI-2	FR[1)] plywood	9	620
EI-3	Melamine faced particle board	12	700
EI-4	FR[1)] polystyrene foam	25	30

[1)] FR: Fire retarded

Table 3-4 Description of the materials from the Swedish research programme used in the analyses (Sundström 1986).

Material ID	Material description	Thickness [mm]	Density [kg/m^3]
S01	Ordinary particle board	10	670
S02	Insulating wood fibre board	13	250
S03	Medium density wood fibre board	12	655
S04	Wood panel, spruce	11	450
S05	Melamine-faced particle board	12+1	870
S06	PVC wallcovering on gypsum board	13+0.7	725
S07	Textile wallcovering on gypsum board	13+0.5	725
S08	Textile wallcovering on mineral wool	42+0.5	150
S09	Paper wallcovering on particle board	10+0.5	670
S10	Polyurethane foam	30	32
S11	Polystyrene foam	49	18
S12	Paper wallcovering on gypsum board	13+0.5	725
S13	Paper-faced gypsum board	13	700

Table 3-5 Description of the materials from the Norwegian research programme used in the analyses (Hansen and Hovde1993).

Material ID	Material description	Thickness [mm]	Density [kg/m^3]
N01	PVC on steel sheets /rockwool (rw)	0.7+150μ+50	150 (rw)
N02	1.4 mm phenolic laminate on CaSi	1.4+19	-
N03	0.8 mm phenolic laminate on CaSi	0.8+19	-
N04	Painted steel sheets	145μ+0.7	450

Table 3-6 Description of the additional materials used in the analyses.

Material ID	Material description[1)]	Thickness [mm]	Density [kg/m^3]
A01	Paper-faced gypsum board	12.5	756
A02	Ordinary particle board	13	654
A03	FR[2)] Spruce panel, 100-130 l FR/m^3	19	507
O	Spruce panel, untreated	19	500
ZA	FR Spruce panel, 170 kg FR/m^3	22	690
ZB	FR Spruce panel, 105 kg FR/m^3	11	690
ZC	FR Spruce panel, 65 kg FR/m^3	12	690
X	FR Spruce panel, 35 kg FR/m^3	18	540
Y	FR Spruce panel, 55 kg FR/m^3	18	510

1) The products A01-A03 were tested by the Norwegian Fire Research Laboratory, SINTEF (unpublished results) while the last 6 products were tested by the Swedish Institute for Wood Technology Research (Östman 2001).

2) FR: Fire retarded or Fire retardant chemical agent

4. Modelling smoke production – means and methods

4.1 Scientific approach

One of the fire engineer's dreams is the possibility of predicting how smoke is produced in a certain fire scenario. How much smoke is produced, how fast is it produced, how toxic is the smoke? My goal in this project has been a moderate version of this vision: to predict a material's optical smoke production in a larger-scale fire test from test results obtained through small-scale testing. Thereby a prediction of the product's smoke classification obtained through large-scale testing can be given.

My work towards this goal has included analyses of results from fire tests of several products in three scales. The analyses include statistical methods and application of existing empirical mathematical models. This exploration of test data gave a strong indication that smoke prediction will have to involve some sort of prediction of heat release to be efficient.

The Cone Tools model by Wickström and Göransson (1992) has been focused in my work, because it has been used for many years in the Nordic countries, and has proven to be both stable and efficient. To extend the applicability of this model would therefore be of great practical interest, both regarding product development and product control. The theory behind the model has later been used to develop a model for predicting heat release rate in the Single Burning Item test (Messerschmidt et al, 1999). Myllymäki and Baroudi (1999) have investigated if the same approach could be used to predict smoke production in large-scale tests, and their conclusions were promising. I therefore found it interesting to follow their track to see if there was a practical solution to the problem of predicting the production of optical smoke.

Through this work a set of models predicting heat release and smoke production in the larger-scale methods has been developed. These methods combine statistical analyses and empirical calculation models; an approach that is not commonly used in the field of modelling reaction-to-fire tests. To evaluate the models the predicted classification according to the new European classification system and according to the system proposed in the EUREFIC programme have been compared with the actual obtained classifications for each analysed product. Validation of the models and assessment of limits of applicability have also been necessary parts of this work.

4.2 Test methods in three different scales

I have used results from three test methods for the correlation studies of smoke production and rate of heat release. These methods are the Cone Calorimeter test (ISO 5660-1:1993, ISO/DIS 5660-2:1999), the Single Burning Item test – or SBI for short (EN 13823:2002), and the Room Corner test (ISO 9705:1993). All methods are based on the same principles for measurement of rate of heat release and rate of smoke production.

These three methods represent three levels of scale. The Cone Calorimeter method is a small-scale fire test where the test sample has an area of 0.01 m^2, the SBI test is an intermediate-scale test with an exposed area of 2.25 m^2, while the Room Corner test is in large scale, where 32 m^2 of the product is tested.

ISO 9705, the Room Corner test, is defined as the reference scenario for the SBI test.

4.3 The European classification system for SBI test results

The new European system for testing and classification of reaction-to-fire properties, also called the system of *Euroclasses*, has been developed through thorough correlation analyses of data from the Room Corner test and the SBI test. Results from the SBI test are used as a base for the classes A2, B, C and D, with additional classes s1, s2 and s3 for smoke production (EN 13501-1:2002). In specific cases results from the SBI test can be used for classification into class A1 as well. The criteria to the parameters FIGRA and THR_{600s} for classes B through D are presented in Table 4-1.

Table 4-1 Criteria to parameters related to heat release measured in the SBI test in the European classification system (EN13501-1).

Classification	FIGRA [W/s]	THR_{600s} [MJ]
A1	20*)	4.0
A2/B	120*)	7.5
C	250**)	15
D	750**)	-
E/F	No criterion	No criterion

*) For classification A1, A2 and B, FIGRA = $FIGRA_{0,2\ MJ}$.
**) For classification C and D, FIGRA = $FIGRA_{0,4\ MJ}$.

In the analyses of the FIGRA value, I have solely concentrated on $FIGRA_{0,2MJ}$ (EN 13823:2002). The decision of how the threshold values 0.2 MJ and 0.4 MJ used in FIGRA calculations should be applied for the different classes was only recently published (EN13501-1:2002). However, none of the analysed products change class when the classification is based on $FIGRA_{0.4MJ}$ instead of $FIGRA_{0.2\ MJ}$.

Lateral flame spread and observations of flaming droplets or particles are also parameters that are used in the classification. These are not included in my analyses.

Products are categorised into 3 subclasses according to their smoke production in the SBI test. The criteria for the additional classifications s1, s2 and s3 are based on the SMOGRA index and on TSP_{600s} as presented in Table 4-2.

Table 4-2 Criteria to parameters related to smoke production in the SBI test in the European classification system (EN13501-1:2002).

Smoke class	SMOGRA [m^2/s^2]	TSP_{600s} [m^2]
s1	30	50
s2	180	200
s3	-	-

4.4 The EUREFIC classification system for Room Corner test results

A product's performance in the Room Corner test apparatus can be evaluated according to the classification system proposed through the EUREFIC programme. Time to flashover, maximum heat release rate (HRR_{max}) and average heat release rate (HRR_{avg}) form the basis for the EUREFIC-classes, while the classification of smoke production is based on maximum smoke production rate (SPR_{max}) and average smoke production rate (SPR_{avg}).

The EUREFIC-classes and requirements for heat release- and smoke production parameters are shown in Table 4-3 below.

Table 4-3 Classification criteria for smoke production, together with the corresponding EUREFIC-classes and requirements for heat release parameters (Wickström et. al. 1991).

EUREFIC class	Minimum t_{FO} [1] [s]	HRR_{max} [2] [kW]	HRR_{avg} [2] [kW]	SPR_{max} [3] [m^2/s]	SPR_{avg} [3] [m^2/s]
A	1200	300	50	2.3	0.7
B	1200	700	100	16.1	1.2
C	720	700	100	16.1	1.2
D	600	900	100	16.1	1.2
E	120	900	No requirement	16.1	No requirement

[1] t_{FO} : time to flashover
[2] Heat release rate from burner not included
[3] Smoke production rate from burner not included

4.5 Multivariate statistical analysis

4.5.1 General considerations

Fire is a highly multivariate phenomenon including a large number of variables. Variables may be parameters describing the burning materials, parameters describing the geometry of the fire scenario, and parameters related to the fire conditions, like ventilation conditions, temperatures, ignition details, smoke production etc. In standardised fire testing, most of the parameters describing the fire scenario are well defined, and many varying fire parameters can be measured and recorded during the test. It is obvious that some variables related to fire depend on each other, while the connection between other variables may be less clear.

Prediction of smoke production in large-scale test methods based on small-scale test results is one field in fire research where simple correlations are difficult to find, and where an advanced analysis including several variables may give better results (ISO/TR 11696-1:1999). Analysis based on multivariate statistical models may be an effective tool to solve this problem.

One goal is to be able to predict the smoke classification a certain product will obtain in a large-scale test method, using test results from a small-scale test as input. This could be obtained through application of a multivariate statistical classification model, and I have investigated one possible way of doing this in my work.

Another goal is to predict the time-dependent rate of smoke production in a large-scale test, by using a dynamic calculation model. In the simple prediction model developed in this study, there was a need to identify different groups of products based on their smoke production ability. When the most suitable group membership was determined, the most proper calculation algorithm to be used for each of these product groups could be chosen. Discrimination between different groups of smoke producers and prediction of the most probable group membership were made by applying the same multivariate statistical classification model as for predicting smoke classification. The method chosen was Multivariate Discriminant Analysis, abbreviated MDA.

4.5.2 Multivariate Discriminant Analysis, MDA

The multivariate statistical method applied in this work is Multiple Discriminant Analysis (MDA) (Garson 2000, Kinnear and Gray 2000) which is a classification method that represents a way of revealing "hidden" information in a set of data. MDA is briefly described in papers II to VI, but a closer description of the method will be given below.

Purpose of discriminant function analysis

Multiple discriminant function analysis, abbreviated MDA, is used to classify cases into groups. The groups are determined based on a categorical dependent variable, i.e. a variable that shows discrete values that can be assigned to discrete classes.

Discriminant function analysis can be used to

- classify cases into groups
- investigate differences between groups
- detect variables that are important for distinguishing between groups
- discard variables that are irrelevant for group distinctions

When a relation between groups and variables exist, MDA will find the simplest way of assigning cases to a set of predetermined groups. The classification is then governed by functions, which include only the variables that are most strongly related to the group distinction.

The canonical discriminant functions

A canonical discriminant function is analogous to multiple regression in that it creates a linear function between the latent variable F_i and the n different independent variables $x_1, x_2,\ldots,x_n$ that are found to be relevant for distinguishing between groups:

$$F_i = b_1x_1 + b_2x_2 + \ldots + b_nx_n + c_i \qquad \textbf{(4-1)}$$

where c_i is a constant. However, the coefficients $b_1, b_2, \ldots,b_n$ in this expression are maximising the distance between the means of the dependent variable (the criterion for which class a case should be assigned to). If there are k different predetermined groups and p different discriminating variables, a set of the lesser of (k-1) or p functions will be evaluated. Each function is orthogonal to the others, i.e. all functions are independent of the other functions. Normally the first two canonical functions (F_1 and F_2) will account for the major part of the variance in the data set. Plotting each case's scores of F_1 and F_2 in a diagram will then give a visual presentation of how well the method is able to discriminate between the different groups. Examples of such diagrams can be found in paper III showing the discrimination between different groups of time to flashover in the Room Corner test. In chapter 6.3.4.3 and 6.3.4.4 similar diagrams show the discrimination between the different smoke classification levels in the SBI test.

Data and assumptions

The theory behind discriminant functions assumes that each of k populations with p variables have a multivariate normal distribution with the same covariance matrix. Before performing a discriminant analysis, these assumptions must be validated through statistical examination of the data. Do the variables follow a multivariate normal distribution? Are within-group distributions symmetric? Do different populations have about equal spread of variance for each variable? Transformation of variables may be necessary to improve normality, stabilise variance and make distributions more symmetric. However, multiple discriminant analysis is relatively robust against modest violations of the assumptions of multivariate normality and equal covariance matrix. Discriminant analysis is highly sensitive to outliers, and outliers should therefore be carefully sought and eliminated from the analysis.

Other assumptions that should be met are that population sizes should not differ too much, and all cases should be independent. Residuals are assumed to be randomly distributed.

4.5.3 Classification

Based on the results from MDA, classification rules can be found. These rules are combinations of relevant parameters that best describe differences between different groups (or classes).

SPSS 9.0 gives the option to choose Fisher's linear discriminant function for classification of cases. The result of this analysis is a set of k linear functions, one for each of the k groups. A new case will be predicted as belonging to the group where the associated classification function obtains the highest value.

Another possibility for classification would be to compute the statistical distance from a new case to the different groups' centroids. The case is then predicted as a member of the group which distance from the centroid to the co-ordinates for the new case is shortest. Statistical distance is interpreted as a measure of distance which takes account of differences in variance and the presence of correlation, and is thus differing from the ordinary Euclidean distance. Statistical distance is fundamental to multivariate analysis (Johnson and Wickern, 1998, p 29), and is calculated by weighing highly variable co-ordinates less than co-ordinates with little variation.

4.5.4 Evaluation and validation of classification functions

Classification functions are constructed to be able to predict the group membership of future samples. A simple presentation of the predictability can be given through a confusion matrix, where actual and predicted group membership are presented, see Figure below.

		Predicted membership		
		π_1	π_2	
Actual membership	π_1	n_{1C}	$n_{1M} = n_1 - n_{1C}$	n_1
	π_2	$n_{2M} = n_2 - n_{2C}$	n_{2C}	n_2

Figure 4-1 Confusion matrix.
n_{1C} = number of items in group π_1 correctly classified as π_1 items
n_{1M} = number of items in group π_1 misclassified as π_2 items
n_{2C} = number of items in group π_2 correctly classified as π_2 items
n_{2M} = number of items in group π_2 misclassified as π_1 items

Validation of classification functions can be performed by analysing how well a set of observations not used in building the classification functions are grouped. These cases belong to the *validation set*, while the cases used for building the classification functions belong to the so-called *test set*. The proportion of correctly classified cases of the validation set will normally be lower than the proportion of correctly classified cases from the test set.

There are several ways of separating data into a test set and a validation set, and there are several ways to perform cross validation. One attempt is called Lachenbruchs hold-out procedure[2] (Johnson and Wickern 1998, p 654) where all but one case is used in designing the classification functions, and the last case is classified using the computed functions. The number of misclassified cases are then summarised after repeating this procedure, leaving each case out one at a time.

Another attempt is the so called 10-fold cross-validation. The data set is divided into 10 equally sized groups, where 9 groups are used in the test set, and the last group is defined as the validation set. The analysis is then repeated 9 more times, each time using a different group as the validation set and the other 9 as the test sample. Each step gives a different set of classification functions; however, the important variables for distinguishing between groups of observations can be evaluated.

A third possibility is to randomly select a specific percentage of the data set to be held back as the validation set, and then perform the analysis on the remaining cases resembling the test set. The procedure can then be repeated several times, each time with different test- and validation samples.

Splitting the data into two groups like this requires large numbers of observations to give reliable results. When not all data is used building the functions, valuable information may be lost which results in less useful classification functions. By applying the Lachenbruch hold-out procedure and the 10-fold cross-validation to the data set, this problem is avoided, but as earlier mentioned, the evaluation of the classification functions may have some positive bias.

Practical approach

I have applied the statistical software package SPSS 9.0 in my work (SPSS 1999).

The data sets used for building and validating the different classification models were for each statistical prediction model divided into two parts before the analysis was performed. One part was defined as the test set and was used to develop the prediction model. Lachenbruchs hold-out procedure was used in each analysis to cross validate the classification functions. The other part of the data set was defined as the validation set, and was used to validate the prediction models afterwards.

[2] This procedure may also be called ”leave-one-out cross-validation”, or ”jackknifing”.

4.5.5 Alternative statistical classification methods

Other multivariate statistical methods could also be applied to investigate the problem of predicting smoke production. One approach could be by performing a principal component analysis (PCA) on the data set. The concept behind PCA is to explain the variance-covariance structure of a set of variables through a few linear combinations of these variables (Johnson and Wichern, 1998, pp 458-513). The main objectives of PCA are data reduction and interpretation. Classification could then be based on the principal components derived from the PCA. As the statistical approach in PCA (analysing variance - covariance) is different from MDA (analysing variable means), it could give different results to the same analysed problem. The use of PCA is not addressed in my work, but could be investigated in a future study.

4.6 Implementation of the prediction models

All predictions of heat release and smoke production in this project have been calculated on an ordinary PC. The statistical classification models have been implemented as simple calculation formulas in an Excel worksheet, and the dynamic models have been programmed using Visual Basic in Excel. A simulation of heat release rate or smoke production rate in the SBI test or the Room Corner needs a few seconds before the results are calculated.

Where there is smoke, there is fire.
(Old international proverb)

5. Prediction of heat release

5.1 How can heat release in large-scale tests be predicted?

One of the assumptions I made, was that it would be difficult to simulate smoke production in the larger-scale SBI test and the Room Corner test without taking the heat release from the burning product into account. The development history of the burning area is also a necessary input to the way smoke production is modelled following the ideas of Myllymäki and Baroudi (1999). The hypothesis is that heat release and smoke production in a fire are closely linked, and that the relation between these two properties may be different for different product families. This hypothesis was the result from the exploration of the available data set of the 65 products described in Section 3. Thus, to be able to predict the time-dependent smoke production rate, a model able to predict the history of heat release in the two test apparatuses would be essential.

Many different strategies for predicting heat release rate in larger scale based on input from Cone Calorimeter tests have been reported in the literature, some of them are mentioned here. Because the SBI test is still a very young method, the majority of the reported work is performed on finding predictions of Room Corner test results.

Karlsson and Magnusson (1991) proposed an expression where time to flashover in the Room Corner test can be predicted through a combination of bench-scale test results, and where the Cone Calorimeter is one of the applied tests.

Wickström and Göransson (1992) have developed the so-called Cone Tools model, where time to ignition and the array of heat release rate measured in the Cone Calorimeter at heat flux 25 kW/m^2 are used as input. The output of the Cone Tools model is the predicted curve of HRR in the Room Corner test. Messerschmidt et. al. (1999) have used the philosophy of the Cone Tools model to develop a model for prediction of HRR in the SBI test.

Through dimensional analysis Kokkala (1993) developed an ignitability index and a heat release index. These indices were able to predict in which time interval time to flashover in the Room Corner test would occur with good accuracy. Hakkarainen (1991) has later used the concept of heat release- and ignitability indices to predict the value of FIGRA in the SBI test, and this approach worked well for products with a time to ignition between 5 s and 60 s at 50 kW/m^2 in the Cone Calorimeter test.

In Quintiere's model (1993) calculations of temperature development, burning area and energy balance in the Room Corner test result in the time dependent curve of HRR. Material properties obtained through different bench-scale test methods, including the Cone Calorimeter, are used as input to the model. Grenier et. al. (2001) presented a modified version of Quintiere's model. The modifications included some simplifications of the original model, an improvement of the HRR simulation, and an approach to estimate smoke production rate.

The model by Östman and Tsantaridis (1994) is a simple correlation where input of the product's density, time to ignition in the Cone Calorimeter test at 50 kW/m^2, and the total heat released during the first 300 s after ignition results in a predicted value of time to flashover.

Opstad (1995) has presented a way of modelling thermal flame spread in the Room Corner test, where the material properties applied in the model are obtained from the Cone Calorimeter test, and are used as input to a CFD model.

Hakkarainen and Kokkala (2001) applied a one-dimensional thermal flame spread model to predict the HRR in the SBI test, using Cone Calorimeter test results obtained at a heat flux level of 50 kW/m^2 as input. The calculated FIGRA value was in the correct class for 90 % of the 33 building products studied.

As mentioned earlier, I have chosen to concentrate on the two models reported by Wickström and Göransson, and by Messerschmidt et. al., where HRR is predicted in the Room Corner test and in the SBI test respectively.

I have also used the model for prediction of time to flashover in the Room Corner test presented by Östman and Tsantaridis (1994) as a calculation tool in the work reported in paper III.

5.2 Modelling heat release rate in the Room Corner test

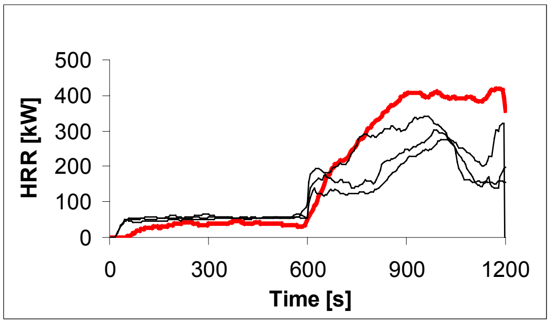
The model developed by Wickström and Göransson (1992) where HRR in the Room Corner test is predicted is simple, but though found to be both efficient and stable.

I started to explore how the simulated results for the Room Corner test agreed with results from real tests. The model was good at predicting time to flashover before 10 minutes of testing time. This is not surprising, because the model is to a great extent based on data from testing of wood products. A normal wooden panel reaches flashover during a few minutes in the Room Corner test. For products where flashover was reached after 10 minutes, or where the event of flashover was not reached at all, the model performed poorer. The model and my modifications of it are described in detail in Paper III.

Results from simulation of HRR in the Room Corner test

Results from the Room Corner HRR simulations using the modified version of the Wickström/Göransson model are collected in Appendix I. In Figure 5-1 below, two simulation examples are shown to demonstrate the model's predictability for these products.

FR chipboard (M06)



Ordinary particle board (M22)

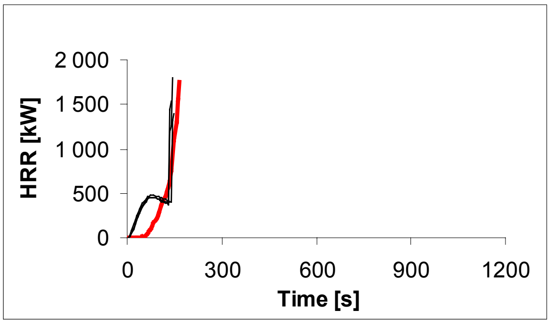


Figure 5-1 Simulation of HRR in the Room Corner test for the modified Wickström/Göransson model. The thin black lines show simulated values based on Cone Calorimeter tests at 50 kW/m^2, while the thicker lines show results from real Room Corner tests.

The predictability with respect to FO-category for the modified version of the Wickström/Göransson model was as follows:

82 % of cases in FO-category 1 were correctly classified

61 % of cases in FO-category 2 were correctly classified

93 % of cases in FO-category 3 were correctly classified

78 % of cases in FO-category 4 were correctly classified

5.3 Modelling heat release rate in the SBI test

The Wickström/Göransson-model has recently been used as a basis for development of an HRR prediction model for the SBI test (Messerschmidt et. al. 1999). As this strategy looked promising, I wanted to explore the HRR model for the SBI to find possible modifications that would enhance the predictability. The original Messerschmidt model had some limitations with regard to predicting HRR for products with high flame spread ability. The errors in the HRR predictions after 600 s of testing time in the SBI were also large.

Details of my work with modifications of the Messerschmidt model are given in Paper IV.

Results from simulation of HRR in the SBI test

Some results from the modified Messerschmidt simulation model for HRR in the SBI test are presented in Paper IV and all results are collected in Appendix III. In Figure 5-2 below, two simulation examples are shown to demonstrate the model's predictability for these products.

Paper-faced gypsum board (M01) **Low density fibreboard (M26)**

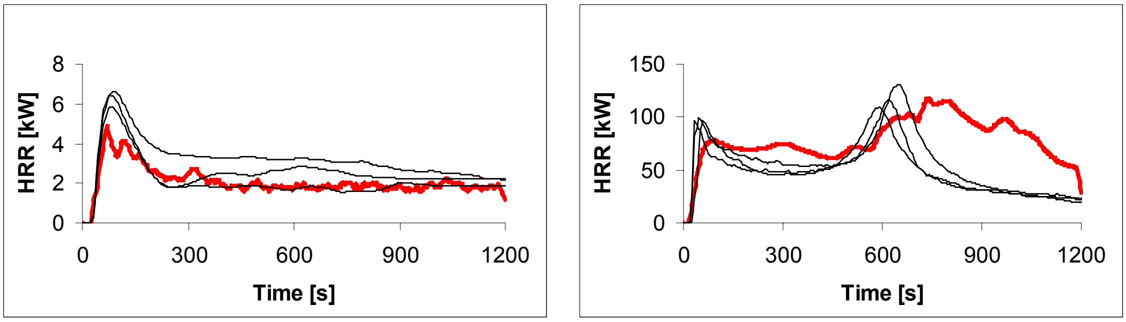


Figure 5-2 Simulation of HRR in the SBI test for the modified Messerschmidt model. The thin black lines show simulated values based on Cone Calorimeter tests at 50 kW/m^2, while the thicker lines show results from real SBI tests.

$FIGRA_{0.2}$ calculated from the predicted results was in the correct class in 92 % of the analysed cases. The classification based on the predicted THR_{600s} value was correct in 87 % of the cases. All in all, the model was able to predict the final reaction-to-fire classification with about 90 % certainty.

An overview over average values for FIGRA and THR_{600s} ± 2 standard deviations for repeatability, s_r, for the SBI Round Robin products from the test programme is given in Figure 5-3. The average values ± 2 standard deviations for the simulated results for the same group of products are also presented in the figure.

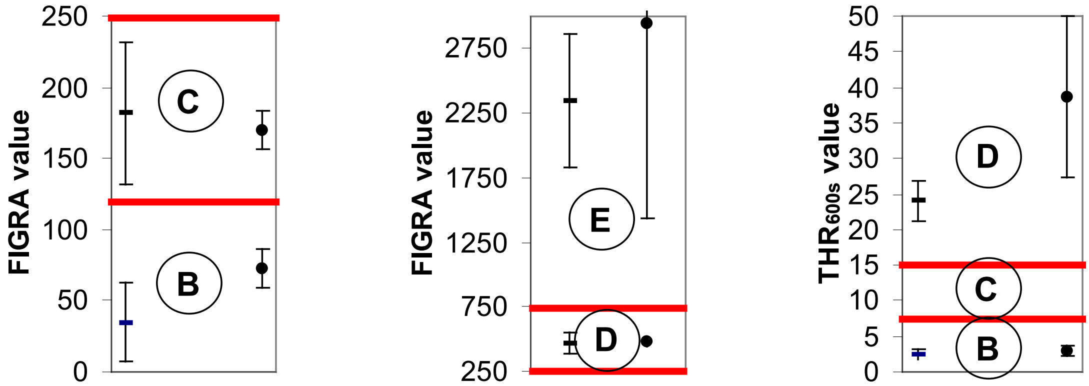


Figure 5-3 Average values (horizontal bars) for FIGRA and THR_{600s} ± 2 standard deviations for repeatability, s_r, for SBI test results from 24 of the SBI Round Robin products are presented on the left-hand side of each diagram (EN 13823:2002). The average values (dots) ± 2 standard deviations from simulations for the same products are presented on the right-hand side in the same diagrams. The letters in circles indicate the different classes, while the horizontal lines indicate the class limits. The FIGRA values are presented in two separate diagrams because of the large span in results. There were no products in the data set that were in class C with respect to THR_{600s}.

The figure shows that the averaged values for FIGRA and THR_{600s} calculated from the simulated results are of the correct order of magnitude. The standard deviations for each class are also comparable with the standard deviations for repeatability, s_r. For both the measured and simulated values for FIGRA and THR_{600s} the classification is unchanged within an interval of the average value ± 2 standard deviations. These results show that the HRR simulation model for the SBI test is stable, and that the variation in the input values from the Cone Calorimeter does not introduce larger variations in the simulated results than in the measured results from the SBI test.

6. Prediction of smoke production

6.1 Some attempts on correlating small- and large-scale smoke production rate

Many different attempts on prediction of smoke production have been presented in the literature. Babrauskas (1981) reported that specific smoke extinction area, combined with heat release rate, seemed as a promising solution for prediction of large scale smoke production. In the Nordic EUREFIC programme a correlation study between smoke production in the Cone Calorimeter and the Room Corner test was performed (Östman et. al. 1992). In that study, several parameters describing the smoke production from 28 different surface products were investigated. The best correlations in the project were obtained when the test material was divided into two groups, depending on whether flashover occurred within 10 minutes of testing time or not.

Heskestad and Hovde (1993) performed a study of possible correlations between several smoke parameters from measurements in the Cone Calorimeter and from tests in the Room Corner apparatus. The best correlation was obtained for total smoke production (TSP) for products not reaching flashover in the Room Corner test within 10 minutes of testing time. No simple correlation was found for smoke production from the products that went to flashover during the first 10 minutes.

An investigation of the 30 SBI Round Robin materials regarding possible correlations between the SMOGRA indices calculated from data from the Room Corner test, the SBI test and the Cone Calorimeter test was performed by Trätek in Sweden (Tsantaridis and Östman 1999). Through this work no simple correlation between the calculated SMOGRA indices from the three test methods was found.

It has not yet been shown that large-scale smoke production can be predicted from smoke measurements in small-scale tests alone (ISO/TR 11696-1:1999). Through combination of different small-scale test results related to e.g. heat release, flame spread, ignitability, production of CO and CO_2, it is assumed that large-scale smoke production can be predicted with far better precision than previous attempts have been able to.

An interesting solution to the complicated task of predicting smoke is therefore to include several parameters in the model, and to apply advanced multivariate statistical techniques. One attempt was made by Heskestad and Hovde (1999), who developed an empirical correlation model based on logistic linear multiple regression. In their model the SPR at 400 kW in the Room Corner test was predicted based on input from the Cone Calorimeter test. The idea behind the model is to be able to sort out products that produce large amounts of smoke without reaching flashover. The model is based on the assumption that full-scale smoke production is governed by the tested material when the total heat release is below 400-600 kW. The parameters that were used as input to the model were total CO production, total heat released, the time elapsed between ignition and maximum rate of heat release, and a variable indicating whether the tested product is a plastic material or not.

The simulation models for HRR in the SBI test and the Room Corner test presented in Section 5 form the basis of the SPR prediction models I have developed. The assumption behind the smoke prediction model is that the smoke is released from an area, and the development of this area throughout the test procedure is possible to predict. I chose to use the concept of *an effective smoke producing area*, $A_{SPR,eff}$. This expression was first presented in a Nordtest project (Myllymäki and Baroudi 1999), to point out that the effective area may contain information about other factors than just the physical burning area (e.g. ventilation and geometrical properties may be intrinsic parts of $A_{SPR,eff}$). The development of the model is described in Paper VI.

6.2 Modelling of smoke production

In the following sections I present different ways of predicting smoke production in the Room Corner test and the SBI test. The principles behind the models are the same as presented in papers II, V and VI. Some calculation details may however be different from the models in the papers. I regard the models below as the final results from my thesis work on smoke predictions.

6.2.1 Parameters used in the prediction models

Below the different parameters used in the SPR prediction models are described. Parameters that are identical to those used in the HRR model are not described here, see papers III and IV.

Effective smoke producing area, $A_{SPR,eff}$

As for the prediction of heat release rate, the basic idea is that the history of smoke production rate for each unit area in large scale will be the same as in small scale. The initial level of SPR for the products in the data set could roughly be divided into two groups. Multivariate statistical analysis of the data set was used to sort out which variables from the Cone Calorimeter that were able to distinguish products with high initial smoke production from modest smoke producers. These variables were then used to build a set of two Fisher's linear discriminant functions. This set of classification functions was then built into the model.

Time to ignition, t_{ign}, and time to start of smoke production, t_{SPR}

The same way of calculating time to ignition as used in the HRR model has been used for the SPR model. Exceptions from this are products with long times to ignition, but where the onset of smoke production appears early in the Cone Calorimeter test (e.g. FR wood products). Then t_{ign} in the calculations is replaced with time to start of smoke production, $t_{SPR,}$ which I have defined as the time when SPR in the Cone Calorimeter test exceeds 0.01 m^2/s. This limit is empirically chosen through analysis of the set of Cone Calorimeter test results.

Necessary testing time in the Cone Calorimeter

The array of the first 600 s of testing time in the Cone Calorimeter is used as input to the SPR model modified in the same way as described for the HRR model. The parameters for the statistical parts of the model (equation 6-1) are calculated over a period of 900 s from start of the test. If the test was terminated before 900 s, the period between start and end of test was used for the calculations.

Parameters used in the statistical classification rules in the models

Parameters calculated from Cone Calorimeter test results are used in different classification rules in the models, and an overview over the different parameters is therefore presented in equation (6-1) below.

$$\left.\begin{aligned}
z_1 &= \rho_{eff} \\
z_2 &= THR_{300s} \\
z_3 &= \ln(HRR_{\max}) \\
z_4 &= \ln(SPR_{\max}) \\
z_5 &= \ln(SMOGRA_{CC}) \\
z_6 &= t_{ign} \text{ (or alternatively } t_{SPR}) \\
z_7 &= I_{HRR}
\end{aligned}\right\} \quad \textbf{(6-1)}$$

where

ρ_{eff} :	Effective density, i.e. the density averaged over a depth of one cm from the exposed surface [kg/m^3].
THR_{300s} :	Total heat release during 300 s after ignition in the Cone Calorimeter test [MJ/m^2].
HRR_{max} :	Maximum value of HRR in the Cone Calorimeter test [kW/m^2].
SPR_{max} :	Maximum value of SPR in the Cone Calorimeter test [m^2/s].
$SMOGRA_{CC}$:	The maximum value of the ratio of SPR measured in the Cone Calorimeter test and the time when the SPR was measured [m^2/s^2].
t_{ign} :	Time to ignition in the Cone Calorimeter.
t_{SPR} :	Time to start of smoke production in the Cone Calorimeter, found as described in 6.2.1.
I_{HRR} :	Index variable describing the applied route for development of $A_{HRR,eff}$ in the SBI HRR prediction model (see paper IV). I_{HRR} takes the values 1, 2 or 3 if HRR-route I, II or III are applied, respectively.

6.2.2 A general smoke production model

A hypothesis is that SPR from a burning product in a larger-scale test, as the Room Corner test or the SBI test, can be described by

$$SPR_{product}(t) = \sum_{i=1}^{N} \Delta A_{SPR,eff,i} \cdot \dot{s}''^{N-i}_{CC} \qquad \textbf{(6-2)}$$

where

N :	total number of time increments after t_{ign} (or alternatively after t_{SPR}).
$\Delta A_{SPR,eff,i}$:	increment in the effective smoke producing area at time step i
$\dot{s}''^{N-i}_{CC}$:	SPR per unit area [1/s] measured in the Cone Calorimeter at time step N-i.

The smoke produced by the burner in the large-scale test is assumed to be negligible.

Smoke measurements from Cone Calorimeter tests performed at other heat flux levels than 50 kW/m^2 are used directly in the model. I have not introduced any corrections for possible dependence between heat flux level and smoke production.

The effective heat releasing area and the effective smoke producing area are assumed to be connected through a constant k_{SPR}:

$$A_{SPR,eff} = k_{SPR} \cdot A_{HRR,eff} \qquad \textbf{(6-3)}$$

The value of k_{SPR} is dependent on the burning product. The different values presented in the sections below are empirically chosen after analyses of SPR measurements in the SBI and in the Room Corner test.

6.2.3 Modelling smoke production rate in the Room Corner test

Equation (6-3) is of course a large simplification of a complicated reality, but works well for the group of products we are concerned with – non-flashover products or products with a long time to flashover in the Room Corner test. The value of k_{SPR} is determined through the following set of Fisher's discriminant functions found through Multiple Discriminant Analysis (MDA) of the data set:

$$\left.\begin{aligned} F_{k\text{-}0.5} &= z_1 \cdot 0.01897 + z_5 \cdot 7.956 - 27.306 \\ F_{k\text{-}1.0} &= z_1 \cdot 0.0003307 + z_5 \cdot 13.768 - 49.01 \end{aligned}\right\} \qquad \textbf{(6-4)}$$

If $F_{k-0.5}$ gives the largest result, k_{SPR} is set to 0.5; otherwise k_{SPR} = 1.0. After 10 minutes of simulated testing time in the Room Corner test, k_{SPR} = 2.0 for all products.

Equation (6-4) shows that the density of the tested product (z_1) and the SMOGRA value in the Cone Calorimeter test (z_5) are important parameters that determine the initial level of smoke production in the Room Corner test.

6.2.4 Results from simulations of SPR in the Room Corner test

Some results from the Room Corner simulation model for SPR are presented in Paper VI and all simulation results are collected in Appendix III. In Figure 6-1 below, two simulation examples are shown to demonstrate the model's predictability for these products.

Paper-faced gypsum board (M01) **FR chipboard (M06)**

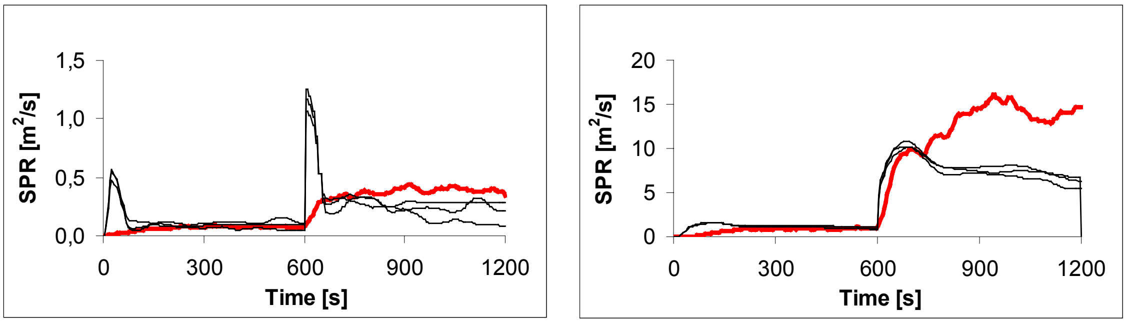


Figure 6-1 Simulation of SPR in the Room Corner test. The thin black lines show simulated values based on Cone Calorimeter tests at 50 kW/m^2, while the thicker lines show results from real Room Corner tests.

From the predicted SPR results the maximum average SPR were calculated. SPR_{max} was predicted in the correct EUREFIC class for 48 % of the cases, while the classification based on SPR_{avg} was correctly predicted in 71 % of the cases. The resulting EUREFIC classification was correctly predicted in only 42 % of all the analysed cases.

When the group of products not reaching flashover in the ISO Room Corner test during the first 300 s was analysed alone (i.e. results from 55 single Cone Calorimeter tests), 69 % were correctly classified based on SPR_{max} and 75 % were correctly classified based on SPR_{avg}. For this group, the correct EUREFIC classification was predicted in 58 % of the analysed cases.

6.2.5 Modelling smoke production rate in the SBI test

The development of the model is described in Paper V and Paper VI, and the final model is summarised below.

The development of the effective smoke producing area can be grouped according to the following criteria:

A) Products with a similar shape of the effective heat releasing area and the effective smoke-producing area, where equation (6-3) applies.

- **A1)** Products with low smoke production, $k_{SPR} = 0.3$
- **A2)** Products with medium smoke production, $k_{SPR} = 1.0$
- **A3)** Products with high smoke production, $k_{SPR} = 2.5$

B) Products where the shape of the two area-describing functions are significantly different.

- **B1)** Products with high smoke production
- **B2)** Products with low smoke production

The distinction between group A and group B products are made through calculation of the set of Fisher's discriminant functions in equation (6-5). The product's density (z_1) and the total heat released 300 s after ignition in the Cone Calorimeter test (z_2) are the important parameters in these functions:

$$\left.\begin{aligned} F_A &= z_1 \cdot 0.006712 + z_2 \cdot 0.216 - 3.421 \\ F_B &= z_1 \cdot 0.003662 + z_2 \cdot 1.406 - 30.483 \end{aligned}\right\} \qquad \textbf{(6-5)}$$

If the calculated result for function F_A is larger than the F_B result, the product is treated as a group A member and vice versa.

For **group A products** the value of k_{SPR} is determined through a set of three Fisher's discriminant functions corresponding to the three groups A1, A2 and A3:

$$\left.\begin{aligned} F_{A1} &= -z_2 \cdot 0.583 + z_3 \cdot 31.986 + z_4 \cdot 2.810 + z_6 \cdot 0.003424 + z_7 \cdot 15.035 - 98.974 \\ F_{A2} &= -z_2 \cdot 0.603 + z_3 \cdot 26.800 + z_4 \cdot 2.511 + z_6 \cdot 0.01991 + z_7 \cdot 14.373 - 72.318 \\ F_{A3} &= -z_2 \cdot 0.885 + z_3 \cdot 32.428 - z_4 \cdot 1.653 - z_6 \cdot 0.01048 + z_7 \cdot 5.302 - 67.779 \end{aligned}\right\} \qquad \textbf{(6-6)}$$

The determination the level of k_{SPR} is based on a combination of 5 different variables connected to heat release and smoke production in the Cone Calorimeter. The development route for the effective heat releasing area in the SBI test is also important input here.

The effective smoke producing area is then calculated through equation (6-3).

For **group B products** the effective heat releasing area is not directly used to find the smoke producing area as for products in group A. The effective smoke producing area is instead initially calculated according to equation (6-7). This expression is equivalent to the equation describing the initial development of the effective heat releasing area, see paper IV.

$$A_{SPR,eff}(t) = A_{\max,SPR}\left[1-\left(1+\frac{t-\frac{t_0}{2}}{t_0}\right)\cdot\exp\left(-\frac{t-\frac{t_0}{2}}{t_0}\right)\right] \qquad \textbf{(6-7)}$$

where t_0 is based on the apparent time to ignition as explained in paper III, or alternatively based on the value of t_{SPR} for products where smoke production is significant before ignition in the Cone Calorimeter test. $A_{max,SPR}$ is a parameter that determines the maximum level of the effective smoke producing area. $A_{max,SPR}$ takes the initial values 0.02 or 0.1 depending on the product's performance in the Cone Calorimeter test. The level of $A_{max,SPR}$ is determined based on the maximum HRR in the Cone Calorimeter test (z_3) through application of the following two Fisher's discriminant functions:

$$\left.\begin{aligned} F_{0.02} &= z_3 \cdot 41.358 - 113.870 \\ F_{0.1} &= z_3 \cdot 44.126 - 129.522 \end{aligned}\right\} \qquad \textbf{(6-8)}$$

An $A_{max,SPR}$ of 0.02 is changing to 0.2 if the predicted SPR exceeds 0.04 m^2/s. If the initial $A_{max,SPR}$ is 0.1, it is increased to 0.5 if the predicted SPR exceeds 0.3 m^2/s. After

one of these criteria has been reached, $A_{SPR,eff}$ is described by

$$A_{SPR,eff}(t) = A_{\max,SPR}\left[1-\left(1+\frac{t+\frac{t_0}{2}}{t_0}\right)\cdot\exp\left(-\frac{t+\frac{t_0}{2}}{t_0}\right)\right] \qquad \textbf{(6-9)}$$

The SPR in the SBI test is calculated using equation (6-2) for products of both type A and type B.

6.2.6 Results from simulations of SPR in the SBI test

Some results from the SBI simulation model for SPR are presented in Paper V and in Paper VI, and all simulation results are collected in Appendix IV. In Figure 6-2 below, two simulation examples are shown to demonstrate the model's predictability for these products.

PUR foam panel with Al-foil faces (M04) **Low density fibreboard (M26)**

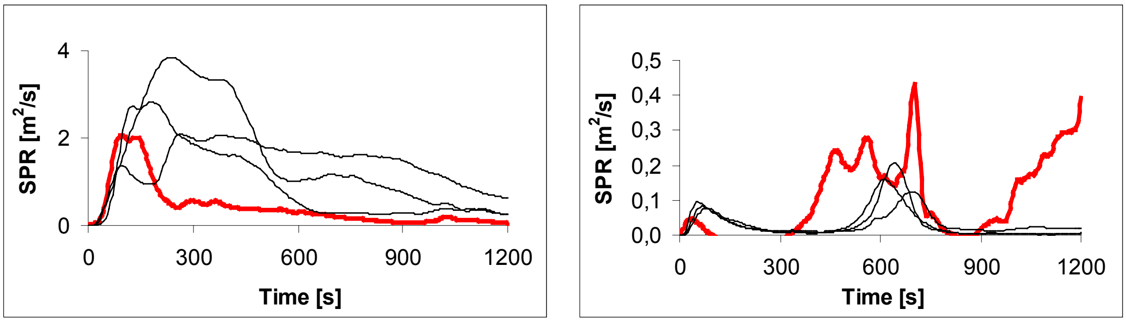


Figure 6-2 Simulation of SPR in the SBI test. The thin black lines show simulated values based on Cone Calorimeter tests at 50 kW/m^2, while the thicker lines show results from real SBI tests.

The parameters SMOGRA and TSP_{600s} were calculated from the predicted SPR. The classification based on SMOGRA was correct in 93 % of the cases, while classification based on TSP_{600s} was correctly predicted in 91 %. The smoke classification within the new European system was predicted correctly in 91 % of the analysed cases.

An overview over average values for SMOGRA and TSP_{600s} ± 2 standard deviations for repeatability, s_r, for the SBI Round Robin products from the test programme is given in Figure 6-3. The average values ± 2 standard deviations for the simulated results for the same group of products are also presented in the figure.

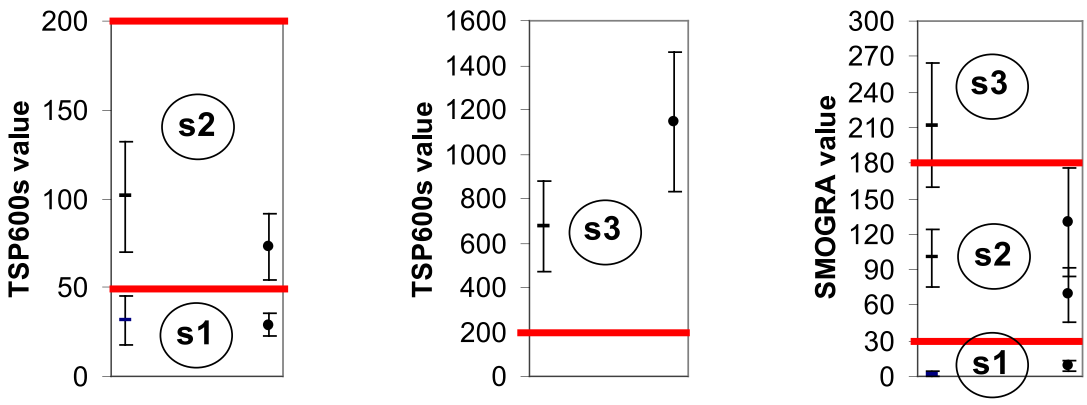


Figure 6-3 Average values (horizontal bars) for TSP_{600s} and SMOGRA ± 2 standard deviations for repeatability, s_r, for SBI test results from 24 of the SBI Round Robin products are presented on the left-hand side of each diagram (EN 13823:2002). The average values (dots) ± 2 standard deviations from simulations for the same products are presented on the right-hand side in the same diagrams. The letters in circles indicate the different classes, while the horizontal lines indicate the class limits. The values for TSP_{600s} are presented in two separate diagrams because of the large span in results.

The figure shows that the averaged values for SMOGRA and TSP_{600s} calculated from the simulated results are of the correct order of magnitude. The standard deviations, s, are also comparable with the standard deviations for repeatability, s_r. For both the measured and simulated values for SMOGRA and TSP_{600s} the classification is unchanged within an interval of the average value ± 2 standard deviations; except for SMOGRA in class s3 that is outside the expected interval for the simulated values. The Round Robin results are also outside class s3 in the lower part of the interval [average value - 2 standard deviations of repeatability]. The smoke classification for all of the products tested in the SBI Round Robin was governed by the value of TSP_{600s}. This means that the prediction of smoke classification based on TSP_{600s} alone is a reliable indicator of the final smoke classification, where SMOGRA also has to be considered.

These results show that the variation in the input values from the Cone Calorimeter does not introduce larger variations in the simulated results than in the measured test results, and that the model is relatively stable.

6.3 Statistical models for prediction of smoke classification

6.3.1 General

This part of my work is described more in detail in Paper II.

6.3.2Prediction of EUREFIC smoke classification

The EUREFIC classification system is described in Section 4.4. I realised early in this analysis that the event of flashover was crucial to the final smoke classification based on Room Corner test results. This supports the conclusions of Östman et. al. (1992) and of Heskestad and Hovde (1993) referred to in section 6.1. I therefore chose to group the products according to FO-categories (see Paper III) before performing MDA on each group. Each of these groups of data were then divided into a test set and a validation set.

Different rules have to be applied dependent on which of the FO-categories 1, 2, 3 or 4 the analysed product is predicted to belong to. The prediction model for classification based on SPR measured in the Room Corner test therefore requires a model able to predict the correct FO-category with a high degree of certainty. The models described in Section 5.2 and in Paper III can be applied for this purpose.

The variables used in the smoke classification rules are:

$$\left.\begin{aligned} w_1 &= \ln(FIGRA_{CC}) \\ w_2 &= \sqrt{TSP_{CC}} \\ w_3 &= \ln(\frac{SPR_{\max}}{HRR_{\max}}) \end{aligned}\right\} \qquad \textbf{(6-10)}$$

where the parameters are defined in Section 6.2 and below.

$FIGRA_{CC}$:	The maximum value of the ratio of HRR measured in the Cone Calorimeter test and the time when the HRR was measured [kW/m^{2}s]
TSP_{CC} :	Total smoke production in the Cone Calorimeter test [m^2]

The variables w_1, w_2 and w_3 are then used to build sets of Fisher's discrimination functions, one set for each Classification rule. To avoid confusion, I have chosen to name the functions $F_{i\text{-}avg\_k}$ and $F_{i\text{-}max\_k}$. i is a reference to the level of smoke performance (1, 2 or 3), avg and max refer to prediction of either average or maximum SPR and k is a reference to the FO-category, and thereby to the corresponding classification rule (1, 2 or 3). The resulting classification rules are presented in Tables 6-1 and 6-2 below.

Table 6-1 Classification rules for maximum smoke production rate, SPR_{max}, in the Room Corner test.

SPR_{max} – Classification rule 1
$F_{1\text{-}max1} = w_1 \cdot 5.580 + w_2 \cdot 12.797 - w_3 \cdot 25.224 - 126.897$ $F_{2\text{-}max1} = w_1 \cdot 2.742 + w_2 \cdot 11.848 - w_3 \cdot 22.889 - 104.753$ No products in FO-category 1 in the test set belonged to smoke category 3 with respect to SPR_{max}.
SPR_{max} – Classification rule 2
No products in FO-category 2 in the test set belonged to smoke category 1 with respect to SPR_{max}. $F_{2\text{-}max2} = w_1 \cdot 0.753 + w_2 \cdot 41.382 - w_3 \cdot 29.851 - 153.726$ $F_{3\text{-}max2} = - w_1 \cdot 1.106 + w_2 \cdot 43.884 - w_3 \cdot 32.566 - 178.942$
SPR_{max} – Classification rule 3
No products in FO-category 3 in the test set belonged to smoke category 1 with respect to SPR_{max}. $F_{2\text{-}max3} = - w_1 \cdot 74.324 + w_2 \cdot 51.400 - w_3 \cdot 130.771 - 616.808$ $F_{3\text{-}max3} = -w_1 \cdot 74.171 + w_2 \cdot 52.469 - w_3 \cdot 129.462 - 607.353$

Table 6-2 Classification rules for average smoke production rate, SPR_{avg}, in the Room Corner test.

SPR_{avg} – Classification rule 1
$F_{1\text{-}avg1} = w_1 \cdot 9.887 + w_2 \cdot 10.197 - w_3 \cdot 30.173 - 151.056$ $F_{2\text{-}avg1} = w_1 \cdot 8.602 + w_2 \cdot 12.041 - w_3 \cdot 28.519 - 138.898$ $F_{3\text{-}avg1} = w_1 \cdot 5.311 + w_2 \cdot 10.232 - w_3 \cdot 25.580 - 110.999$
SPR_{avg} – Classification rule 2
$F_{1\text{-}avg2} = w_1 \cdot 11.032 + w_2 \cdot 27.397 - w_3 \cdot 28.953 - 156.755$ No products in FO-category 2 in the test set belonged to smoke category 2 with respect to SPR_{avg}. $F_{3\text{-}avg2} = w_1 \cdot 5.604 + w_2 \cdot 38.266 - w_3 \cdot 26.649 – 145.549$
SPR_{avg} – Classification rule 3
All products in FO-category 3 in the test set belonged to smoke category 3 with respect to SPR_{avg}.

In Paper II, a system of classification rules for the final EUREFIC smoke classes is presented, as well as a system for predicting the Room Corner SMOGRA value. As the final EUREFIC classification is a combination of both the level of SPR_{max} and the level of SPR_{avg} I do not see any reason for introducing a specific model for prediction of the EUREFIC class here. The validity of the Room Corner SMOGRA value is not yet clear in the European system, and a prediction model will therefore not have much value at this stage. This parameter is further discussed in Section 7.

6.3.3 Prediction of smoke classification s1, s2 or s3 and SMOGRA level

The classification functions for the SBI predictions were developed from a test set containing results from 59 Cone Calorimeter tests. Cone calorimeter results from 34 additional tests were used as a validation set for the prediction models. The Prediction rules for smoke classification s1, s2 or s3, and for the level of SMOGRA are presented in Table 6-3. The rules for predicting the level of TSP_{600s} are identical to the rules for predicting the final smoke class.

The variables used in the smoke classification rules are:

$$\left.\begin{aligned} y_1 &= \ln\left(\frac{SPR_{\max}}{HRR_{\max}}\right) \\ y_2 &= \sqrt{TSP_{CC}} \\ y_3 &= \ln(SMOGRA_{CC}) \\ y_4 &= \rho_{eff} \\ y_5 &= \ln(t_{ign}) \text{ [or alternatively } \ln(t_{SPR})] \end{aligned}\right\} \qquad \textbf{(6-11)}$$

where the parameters are defined in Section 6.2.1.

Table 6-3 Rules for prediction of smoke classification in the SBI test.

Prediction of classification s1, s2 or s3
$F_{s1} = -y_1 \cdot 51.668 + y_2 \cdot 20.817 - y_3 \cdot 18.952 + y_4 \cdot 0.0269 - y_5 \cdot 15.735 - 320.829$ $F_{s2} = -y_1 \cdot 42.981 + y_2 \cdot 17.487 - y_3 \cdot 14.393 + y_4 \cdot 0.0215 - y_5 \cdot 10.240 - 202.707$ $F_{s3} = -y_1 \cdot 42.462 + y_2 \cdot 25.508 - y_3 \cdot 21.506 + y_4 \cdot 0.0157 - y_5 \cdot 14.022 - 271.147$
Prediction of SMOGRA level
$F_{SMOGRA1} = -y_1 \cdot 61.979 + y_2 \cdot 7.251 - y_3 \cdot 4.893 - y_4 \cdot 0.0579 + y_5 \cdot 23.626 - 338.193$ $F_{SMOGRA2} = -y_1 \cdot 48.016 + y_2 \cdot 7.773 - y_3 \cdot 3.797 - y_4 \cdot 0.0360 + y_5 \cdot 17.488 - 211.420$ $F_{SMOGRA3} = -y_1 \cdot 56.989 + y_2 \cdot 11.632 - y_3 \cdot 11.969 - y_4 \cdot 0.0849 + y_5 \cdot 23.588 - 350.784$
Prediction of TSP_{600s} level
The prediction rules for TSP_{600s} are identical to the prediction rules for classification s1, s2 or s3.

6.3.4 Predicted results from the statistical models

6.3.4.1 Prediction of the Room Corner test level of SPR_{max}

In Figure 6-4 the predictability of the levels of SPR_{max} from Classification rules 1, 2 and 3 for cases in the test sets and cases in the validation sets are presented.

FO-category =1:

Test set (n=32, cross validated)

Actual level \ Predicted level	1	2	3
1	**20 (91%)**	2	
2	3	**7 (70%)**	
3	0	0	

Validation set (n=14)

Actual level \ Predicted level	1	2	3
1	**4 (100%)**	0	
2	1	**5 (83%)**	
3	3	1	

FO-category =2:

Test set (n=15, cross validated)

Actual level \ Predicted level	1	2	3
1		0	0
2		**7 (100%)**	0
3		1	**7 (88%)**

Validation set (n=5)

Actual level \ Predicted level	1	2	3
1			
2		**3 (100%)**	0
3		2	**0 (0%)**

FO-category =3:

Test set (n=28, cross validated)

Actual level \ Predicted level	1	2	3
1		0	0
2		**18 (78%)**	5
3		4	**1 (20%)**

Validation set (n=8)

Actual level \ Predicted level	1	2	3
1		0	0
2		**3 (100%)**	0
3		3	**2 (40%)**

Figure 6-4 Confusion tables for Classification rules 1, 2 and 3 for prediction of SPR_{max} level in the Room Corner test. The grey shaded areas indicate the levels where no classification rules apply.

Figure 6-4 shows that the level of SPR_{max} is predicted with good accuracy for products in FO-category 1 and 2. The worst level of SPR_{max}, level 3, is difficult to predict for products in FO-category 3, where a large share of the cases are misclassified into level 2. The classification functions for these cases, given in Table 6-1 do not differ much, and this will lead to misclassification if there is large inaccuracy in the input values from the Cone Calorimeter test. However, it is clear from the data set that products in FO-category 3 most probably will have an SPR_{max} at level 2 or 3.

6.3.4.2 Prediction of the Room Corner test level of SPR_{avg}

In Figure 6-5 the predictability of the levels of SPR_{avg} from classification rules 1, 2 and 3 for cases in the test sets and cases in the validation sets are presented.

FO-category =1:

Test set (n=32, cross validated)

Actual level	Predicted level 1	Predicted level 2	Predicted level 3
1	**19 (100%)**	0	0
2	3	**3 (50%)**	0
3	0	0	**7 (100%)**

Validation set (n=14)

Actual level	Predicted level 1	Predicted level 2	Predicted level 3
1	**4 (100%)**	0	0
2	0	**0**	4
3	1	3	**2 (33%)**

FO-category =2:

Test set (n=15, cross validated)

Actual level	Predicted level 1	Predicted level 2	Predicted level 3
1	**6 (86%)**		1
2	0		0
3	1		**7 (88%)**

Validation set (n=6)

Actual level	Predicted level 1	Predicted level 2	Predicted level 3
1	**2 (100%)**		0
2	1		0
3	0		**3 (100%)**

FO-category =3:

All 35 cases in FO-category 3 in both the test set and the validation set were predicted to be in level 3 with respect to $SPR_{avg.}$

Figure 6-5 Confusion tables for classification rules 1, 2 and 3 for prediction of SPR_{avg} level in the Room Corner test. The grey shaded areas indicate the levels where no classification rules apply.

Figure 6-5 shows that levels 1 and 3 of SPR_{avg} is predicted with good accuracy for products in all FO-categories. Level 2 of SPR_{max} is difficult to predict for products in FO-category 1, and this level of average smoke production was not found for FO-categories 2 and 3. The data set shows that products in FO-category 3 most probably will have an SPR_{avg} at the worst level, i.e. level 3.

6.3.4.3 Prediction of the SMOGRA level in the SBI test

How well the statistical model in the middle of Table 6-3 is able to discriminate between the three different levels of SMOGRA in the SBI test is demonstrated in Figure 6-6.

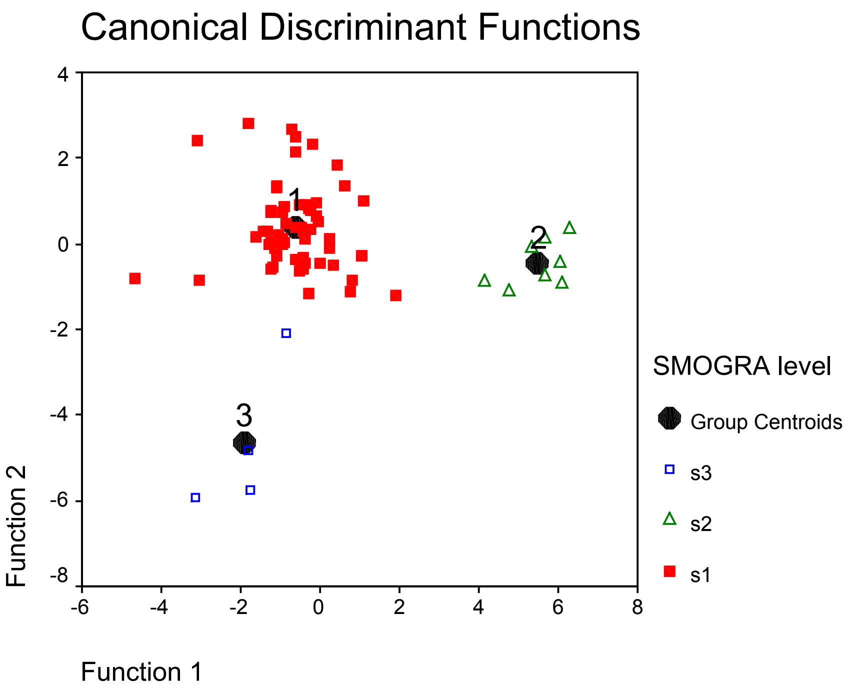


Figure 6-6 The statistical classification model's ability to separate cases belonging to different levels of SMOGRA measured in the SBI test. The diagram shows the scores for each of the 69 cases in the test set for the two canonical discriminant functions. The circular dark spots show the group centroids, i.e. the centre of gravity for each cluster.

In Figure 6-7 the predictability for the different levels of SMOGRA for cases in the test set and cases in the validation set are presented in confusion tables.

Test set (n=69, cross validated)

		Predicted level		
		s1	**s2**	**s3**
Actual level	**s1**	**57 (100%)**	0	0
	s2	0	**8 (100%)**	0
	s3	1	0	**3 (75%)**

Validation set (n=22)

		Predicted level		
		s1	**s2**	**s3**
Actual level	**s1**	**19 (95%)**	1	0
	s2	0	**2 (100%)**	0
	s3	-	-	-

Figure 6-7 Confusion tables for prediction of SMOGRA level in the SBI test.

6.3.4.4 Prediction of additional smoke classification s1, s2 or s3

How well the statistical model in the upper part of Table 6-3 is able to discriminate between the three smoke classifications s1, s2 and s3 is demonstrated in Figure 6-8.

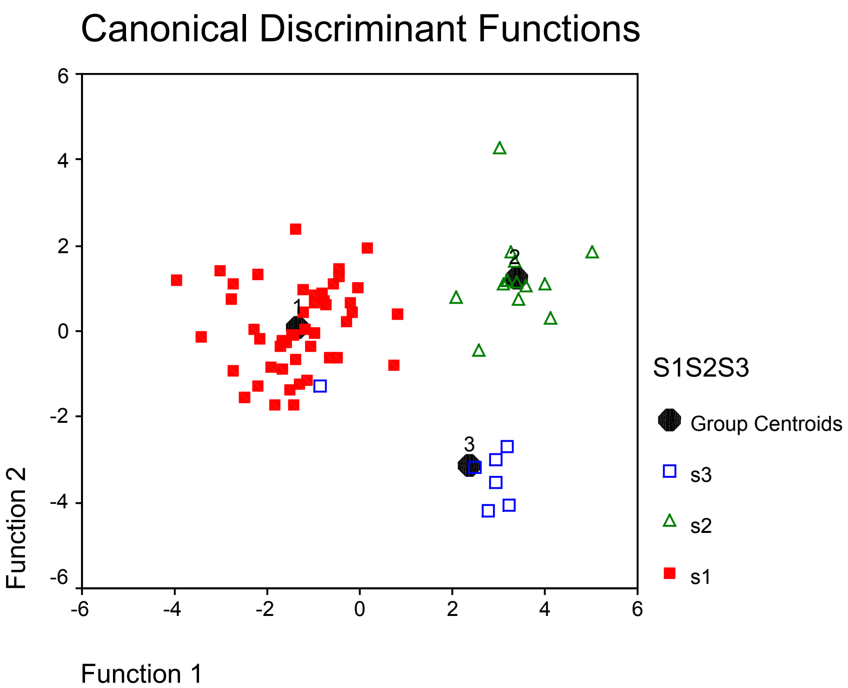


Figure 6-8 The statistical classification model's ability to separate cases belonging to either smoke class s1, s2 or s3. The diagram shows the scores for each of the 69 cases in the test set scores for the two canonical discriminant functions. The circular dark spots show the group centroids, i.e. the centre of gravity for each cluster.

In Figure 6-9 the predictability for the different smoke classes s1, s2 and s3 for cases in the test set and cases in the validation set are presented in confusion tables.

Test set (n=69, cross validated)

		Predicted class		
		s1	**s2**	**s3**
Actual class	**s1**	**48 (100%)**	0	0
	s2	0	**14 (100%)**	0
	s3	1	0	**6 (86%)**

Validation set (n=22)

		Predicted class		
		s1	**s2**	**s3**
Actual class	**s1**	**14 (100%)**	0	0
	s2	0	**8 (100%)**	0
	s3	-	-	**-**

Figure 6-9 Confusion tables for prediction of additional smoke classification s1, s2 or s3.

7. Discussion and conclusions

Overview of the developed prediction models

The preceding sections show that modelling of fire performance of most products in the SBI test and in the Room Corner test based on Cone Calorimeter test results is possible. My work comprise the following prediction models:

- A modified version of the Wickström/Göransson model for prediction of HRR in the Room Corner test.
- A statistical model for predicting time to flashover in the Room Corner test using the concept of FO-categories.
- A model for predicting SPR in the Room Corner test.
- A statistical model predicting the level of SPR_{max} and SPR_{avg} in the Room Corner test.
- A modified version of the model by Messerschmidt et. al. for prediction of HRR in the SBI test.
- A model for predicting SPR in the SBI test.
- A statistical model predicting the level of SMOGRA and the smoke classification in the SBI test.

All these models can easily be implemented in a PC worksheet, and the prediction results are then readily achieved. The statistical models have been implemented as calculation formulas in an Excel worksheet, and the dynamic models have been programmed using Visual Basic in Excel.

The results from these models can be used to predict the resulting reaction-to-fire classification with a relatively high degree of certainty, both for heat release and smoke production. Using statistical models for predicting which heat- and smoke classification a product most probably will obtain in larger-scale tests has also proven to be a powerful method. The SBI test results are more correctly predicted than the Room Corner test results, and the most probable reason for this is that the ventilation conditions in the Cone Calorimeter test are more similar to the conditions in the SBI test than in the Room Corner test. However, there are some considerations to be taken both about the applicability of the models and about the quality of input- and output data. These objectives have been discussed in the papers in Part II, but I will summarise some of the main points here.

The Room Corner SMOGRA value

That the Room Corner test has status as the *reference scenario* for the SBI test implies that ranking of materials according to test results from the two methods should be more or less equivalent. A good correlation between ranking order has been found for heat release results, using FIGRA from the SBI test and FIGRA from the Room Corner test. No obvious and simple correlation has been found between SMOGRA values from the two methods, and the ranking based on smoke production is very different from ranking based on heat release. As far as I know, there has not yet been presented a classification system based on SMOGRA calculated from Room Corner test results. There have been discussions about defining a limiting heat release rate, e.g. 400 kW, below which SMOGRA is not to be calculated, but no conclusions are yet drawn to solve this problem.

When looking at smoke production in these two methods, the totally different test conditions with respect to ventilation have to be considered. It is not very likely that the history of smoke production from a specific product will follow the same path in the SBI test and in the Room Corner apparatus. The tested product experiences unrestricted air supply in the SBI during the whole test period, while the fire environment in the Room Corner apparatus may become severely underventilated, which in turn results in incomplete combustion and large amounts of soot and CO. A higher production of soot means more optically dense smoke, and implicitly a higher level of smoke production. The rate of smoke production is dependent of the oxygen availability, which again is a result of the combustion conditions and the material's burning behaviour. Peaks in SPR may appear at different times in the Room Corner test than in the SBI test, resulting in different SMOGRA values. This may lead to a totally different ranking order of products in the two methods if the ranking criteria are based on the SMOGRA parameter only.

When SMOGRA is calculated from Room Corner test results for the products included in my study, the values cover a broad range, from values near zero to values in the order of magnitude 10^2. Smoke production during the very first minutes of the test will be determining for the final SMOGRA value. I therefore suggest that, like in the SMOGRA calculations from SBI test results, threshold values should be applied in the Room Corner calculations. Threshold values could be defined to prevent calculation of SMOGRA before SPR exceeds a predefined value and the total smoke production is above a certain level. Because of the uncertainty with regard to the calculation and applicability of the Room Corner SMOGRA value, all results from analysis and prediction of this parameter are omitted from my thesis. Room Corner SMOGRA values are, however, included in Appendix II.

Limitations of the prediction models

I have assumed that it would be difficult to predict large-scale test results for products where the fire behaviour depends on the fire resistance of fixing details, joints and seals using the simple approach I have presented in this thesis. Breakdown of such details may cause escalation in the fire, but this kind of behaviour is not possible to read from the small-scale Cone Calorimeter test. Some fire retardant treated wood products (FR wood products) may also be problematic, because the fire retardant system may be overcome late in the fire test by chemical and physical changes in the material. Because FR wood products tend to behave in a special way in the Room Corner test, with a late onset of flashover (if any), one possibility would be to let the prediction models treat this kind of products specially. This problem could be solved by performing a multivariate statistical analysis of the products where FR wood products are defined as members of a group with specific properties in the data set. The classification rules based on this analysis can then be built into the prediction model. When a product is defined as FR wood by the model, it is routed to a specific calculation algorithm made especially for such cases. This work requires that a sufficient amount of test results from FR wood products is available.

For some products the heat flux density level applied in the Cone Calorimeter test may give misleading conclusions when the test results are used as input values to the prediction models. Some products do not ignite at 50 kW/m^2 in the Cone Calorimeter, but may, however, obtain flashover in the Room Corner test. A Room Corner prediction based on a Cone Calorimeter test with no ignition would certainly give *no flashover* as result. Such products should be modelled based on Cone Calorimeter test results from higher flux density levels as well. Other products may show high heat release and smoke production in the Cone Calorimeter test at 50 kW/m^2, but low HRR and SPR in the SBI test and in the Room Corner test. The reason for this may be that the product's fire retardant system is overcome by the fire conditions in the Cone Calorimeter, but not in the larger-scale tests. For such products input values from a lower level of heat flux density to the prediction model would be more appropriate. The proper heat flux density level for modelling of fire behaviour for different types of products should be investigated closer to avoid unnecessary testing and incorrect assessments.

Limitations of the available data sets

The models are empirically developed, and as such they are results of analyses on the available data set. For the SBI smoke prediction, a limitation was the skewed distribution of products on the different smoke classes. The vast majority of the data were in the best categories with respect to parameters describing the smoke production, and this has of course affected the statistical parts of the models. I will therefore recommend that the models should be further verified by analysing input values from s2 and s3 products. When a larger amount of test data is available, these data should be used to create new and more robust sets of discriminant functions to replace the ones presented in this thesis. The same is also the case for the Room Corner SPR prediction models, where especially the number of cases in FO-categories 2 and 3 ideally should have been larger.

Another point to be mentioned is the smoke measurement system used in the SBI Round Robin. The smoke measurement system was modified after the Round Robin was finished. This was done to avoid problems with sooting of the lenses. A possible result of the sooting may have been that a higher smoke density than actually present in the exhaust system was measured. The improvement in the smoke measurement system may lead to a change in the obtained smoke classification for some products, most likely an improved result. Future work with validation and refinement of the models will take account of the possible effects the modifications may have had on the products' smoke performance in the SBI apparatus. With reference to the skewed distribution of smoke performance in the available data set, with the majority of products in class s1, my suggestion is that the changes in the SBI apparatus will have negligible effect on the smoke prediction models presented in this thesis.

Limited repeatability and reproducibility in fire testing

A common problem in fire testing is the relatively low repeatability and reproducibility for certain products. This applies to both the input data and the results from the SBI test and the Room Corner test that are used as the "true answers" in the development of the prediction models. This problem would affect borderline products at most; i.e. products that are difficult to classify because the variation in test results may be large from one test to another. The repeatability and reproducibility are worse for smoke measurements than for measurements of heat release, which complicates the prediction of smoke production to a high degree.

Final conclusions

Based on this discussion and the papers in Part II, the main conclusions can be summarised in the following points:

- Multivariate statistical analysis can be a valuable tool when results from reaction-to–fire tests are analysed. A multivariate statistical analysis may give more information than by investigating different test results and parameters one at a time. The results from such an analysis can e.g. be used to predict classification, to identify groups or to identify group membership. By implementing this sort of statistical information into fire modelling, predictability may be enhanced.
- A set of prediction models for HRR and SPR in the SBI test and the Room Corner test has been developed. The models are based on the Cone Tools model by Wickström and Göransson, and use Cone Calorimeter test results obtained at 50 kW/m^2 as input. The prediction models are efficient and easy to implement on a normal computer.
- The presented dynamic prediction models for HRR and SPR in the SBI test were able to predict the correct class within the European system of Euroclasses as follows:
  - 90 of 100 analysed cases were predicted to belong to the correct Euroclass.
  - 89 of 98 analysed cases were correctly predicted with respect to smoke classification.
- The presented multivariate statistic classification model for SPR in the SBI test was able to predict the correct smoke classification within the European system of Euroclasses in 90 of 91 analysed cases.
- The presented dynamic prediction model for HRR in the Room Corner test was able to predict the correct FO-category as follows:
  - 82 % of 67 analysed cases in FO-category 1 were correctly classified.
  - 61 % of 32 analysed cases in FO-category 2 were correctly classified.
  - 93 % of 28 analysed cases in FO-category 3 were correctly classified.
  - 78 % of 19 analysed cases in FO-category 4 were correctly classified.
- The presented dynamic prediction model for SPR in the Room Corner test was able to predict the correct smoke classification within the EUREFIC system as follows:
  - 75 % of 55 analysed cases in FO-category 1 were correctly classified with respect to SPR_{avg}, while 69 % of the same cases were correctly classified with respect to SPR_{max}.
  - Prediction of SPR for cases in the other FO-categories was not successful using this model.
- The presented multivariate statistic classification model for the Room Corner test was able to predict the correct FO-category as follows:

  - 90 % of the analysed cases in FO-category 1 were correctly classified.
  - 71 % of the analysed cases in FO-category 2 were correctly classified.
  - 90 % of the analysed cases in FO-category 3 were correctly classified.
  - 75 % of the analysed cases in FO-category 4 were correctly classified.
- The Room Corner prediction models presented here are not applicable for certain product families where mechanical details are determining for the large-scale fire behaviour.
- The Room Corner prediction models have to be revised to be applicable for FR treated wood products.

Proposal for further work

The models developed are specifically designed for predicting heat release and smoke production in the SBI- and Room Corner tests. However, the methods presented are generic in the sense that the same strategy may be applicable for predicting results from other fire test methods as well. The only requirement is that a data set containing test results from products tested both in the Cone Calorimeter and according to the test method in question exists. One possible application could be prediction of fire behaviour of upholstered furniture. In the CBUF project (1995) a model predicting the heat release in full-scale tests of upholstered furniture from Cone Calorimeter test results was developed. In a project in New Zealand (Enright 2001) the CBUF model was found to give insufficient prediction of fire behaviour for the tested samples of furniture. To improve the model's predictability, a multivariate statistical analysis on the set of Cone Calorimeter test results could be performed. Such an analysis may give valuable information about parameter correlations that are hidden to the analyst; information that could be built into the calculations and thereby improve the model's precision. Upholstered furniture is only one field of application, developing prediction models for other types of product tests using this methodology is equally possible. Other areas are prediction of heat release and smoke production in large-scale testing of electrical cables and plastic pipes.

Only creativity sets the limits.

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APPENDIX I:
Room Corner HRR simulation results

Structure of Appendix I

Results from Room Corner HRR simulations are listed in this appendix in the following order:

M01-M30 (see Table 3-1)

E01-E11 (see Table 3-2)

EI-01 – EI-04 (see Table 3-3)

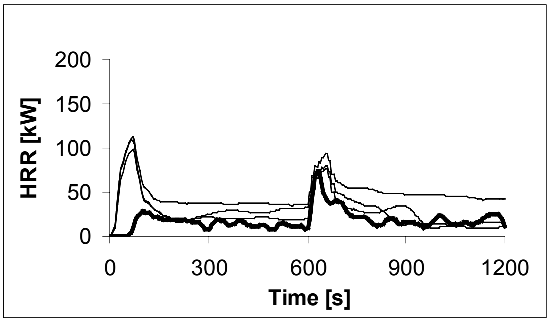
N01-N04 (see Table 3-5)

A03 (see Table 3-6)

For each product a graphical presentation of the HRR measured in one single Room Corner test is shown with a bold line, and the simulated results are shown with thinner lines. Observe that the scale on the ordinate differ from figure to figure. Values for time to flashover (t_{FO}), HRR_{max}, HRR_{avg} and FIGRA are tabulated below each figure. The values calculated based on the real Room Corner test are shown in bold types, and the test is designated r/c. The Cone Calorimeter tests used for simulations are designated cc1, cc2 and cc3, and the simulated values are printed in normal types.

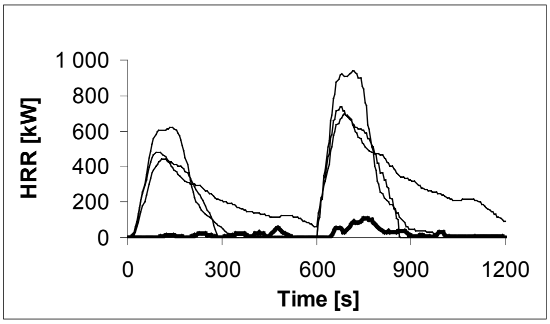
HRR_{avg} and FIGRA have not been calculated for cases where time to flashover is below 300 s. In these cases the tables are shaded with a grey colour.

Paper-faced gypsum board (M01)



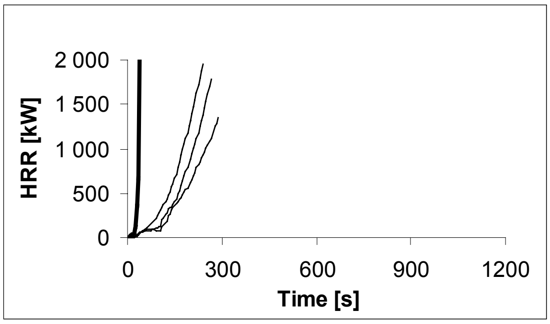
Test	t_{FO}	HRR_{max}	HRR_{avg}	FIGRA
r/c	**NFO**	**73.8**	**18.2**	**0.29**
cc1	NFO	108.9	27.0	2.19
cc2	NFO	98.0	29.6	1.85
cc3	NFO	111.8	47.1	2.13

FR PVC (M02)



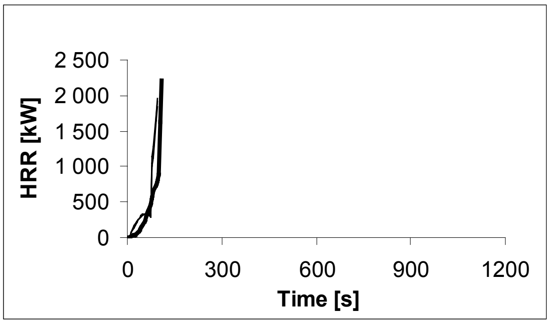
Test	t_{FO}	HRR_{max}	HRR_{avg}	FIGRA
r/c	**NFO**	**111.1**	**19.4**	**0.15**
cc1	665	700	167.1	5.71
cc2	655	700	190.9	6.62
cc3	NFO	695.7	272.4	4.51

PUR foam panel with Al-foil faces (M04)



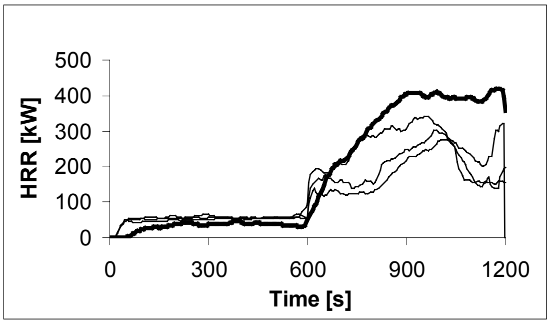
Test	t_{FO}	HRR_{max}	HRR_{avg}	FIGRA
r/c	**41**			
cc1	170			
cc2	205			
cc3	240			

Mass timber (pine). varnished (M05)



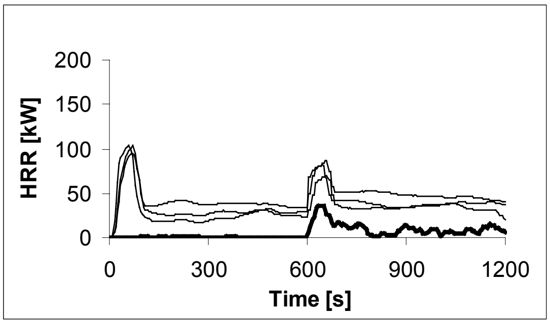
Test	t_{FO}	HRR_{max}	HRR_{avg}	FIGRA
r/c	**106**			
cc1	80			
cc2	80			
cc3	80			

FR chipboard (M06)



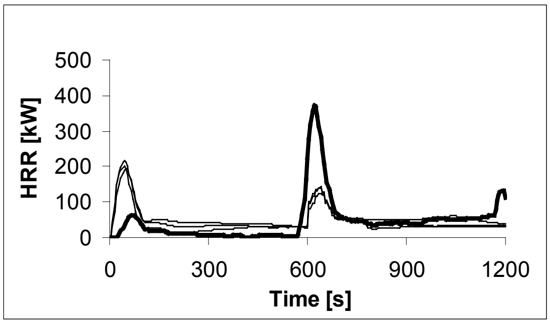
Test	t_{FO}	HRR_{max}	HRR_{avg}	FIGRA
r/c	**NFO**	**418.5**	**180.1**	**0.45**
cc1	NFO	276.2	110.7	1.04
cc2	NFO	303.0	125.1	1.13
cc3	NFO	341.3	156.8	1.13

Painted paper-faced gypsum board (M08)



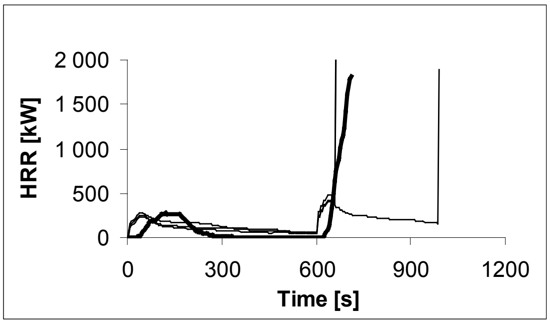
Test	t_{FO}	HRR_{max}	HRR_{avg}	FIGRA
r/c	**NFO**	**35.9**	**5.5**	**0.06**
cc1	NFO	103.7	35.5	2.81
cc2	NFO	95.2	34.1	1.76
cc3	NFO	103.3	45.8	1.98

Paper wallcovering on gypsum (M09)



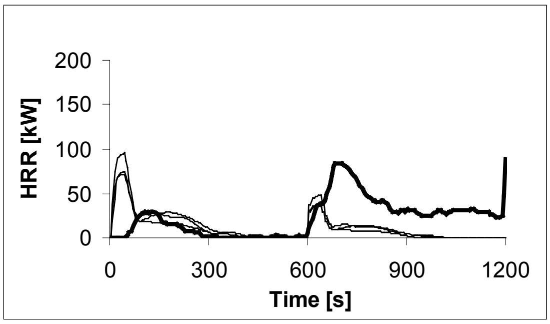
Test	t_{FO}	HRR_{max}	HRR_{avg}	FIGRA
r/c	**NFO**	**372.9**	**47.6**	**0.95**
cc1	NFO	202.3	41.4	7.40
cc2	NFO	195.3	46.3	5.79
cc3	NFO	217.2	56.9	7.27

PVC wallcarpet on gypsum board (M10)



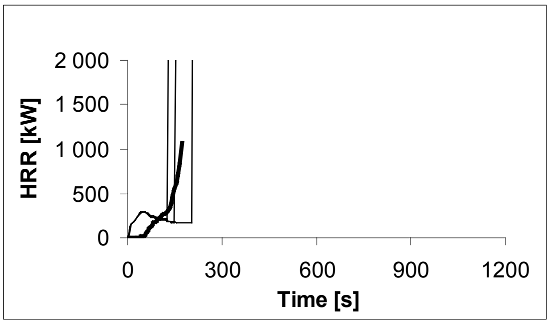
Test	t_{FO}	HRR_{max}	HRR_{avg}	FIGRA
r/c	**675**	**700**	**84.4**	**2.42**
cc1	665	700	117.2	13.25
cc2	990	700	158.9	10.72
cc3	665	700	158.0	15.57

Plastic-faced steel sheet on mineral wool (M11)



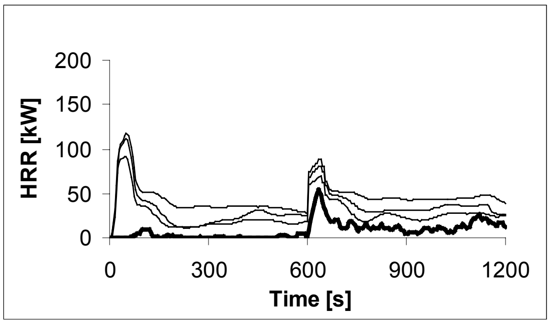
Test	t_{FO}	HRR_{max}	HRR_{avg}	FIGRA
r/c	**NFO**	**88.4**	**23.0**	**0.27**
cc1	NFO	71.2	11.2	3.87
cc2	1070	700	11.5	5.00
cc3	NFO	74.5	11.8	3.26

Mass timber (spruce) unvarnished (M12)



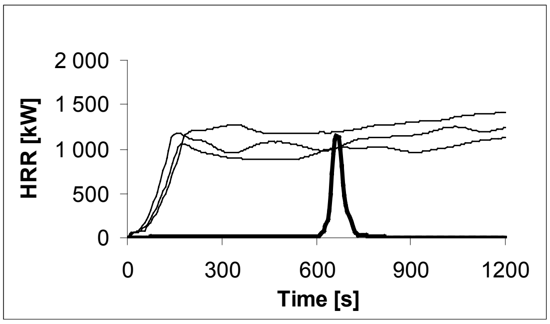
Test	t_{FO}	HRR_{max}	HRR_{avg}	FIGRA
r/c	**170**			
cc1	155			
cc2	210			
cc3	130			

Gypsum board on polystyrene (M13)



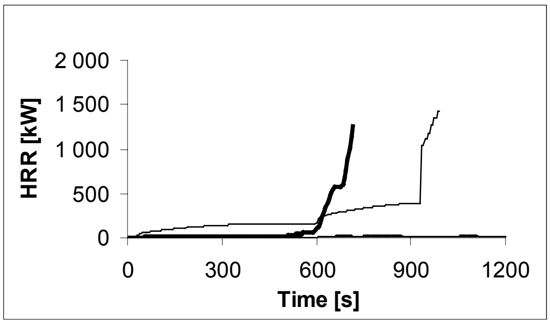
Test	t_{FO}	HRR_{max}	HRR_{avg}	FIGRA
r/c	**NFO**	**53.9**	**8.2**	**0.10**
cc1	NFO	91.9	26.5	3.11
cc2	NFO	111.7	34.0	3.49
cc3	NFO	117.9	45.1	3.33

Phenolic foam (M14)



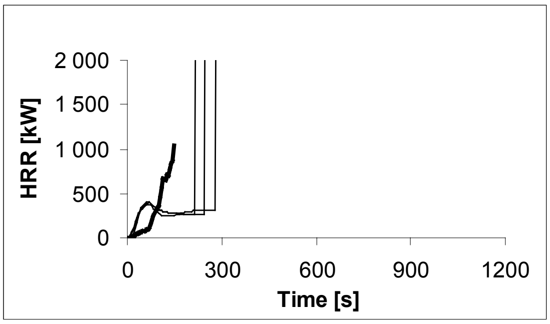
Test	t_{FO}	HRR_{max}	HRR_{avg}	FIGRA
r/c	**640**	**700**	**22.6**	**0.74**
cc1	125	900		
cc2	150	900		
cc3	165	900		

Intumescent coating on particle board (M15)



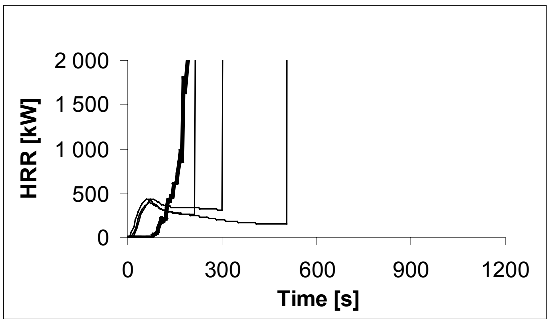
Test	t_{FO}	HRR_{max}	HRR_{avg}	FIGRA
r/c	**700**	**700**	**80.2**	**1.10**
cc1	NFO	29.2	14.3	0.16
cc2	NFO	23.8	10.4	0.11
cc3	935	700	196.4	1.19

Melamine-faced MDF board (M16)



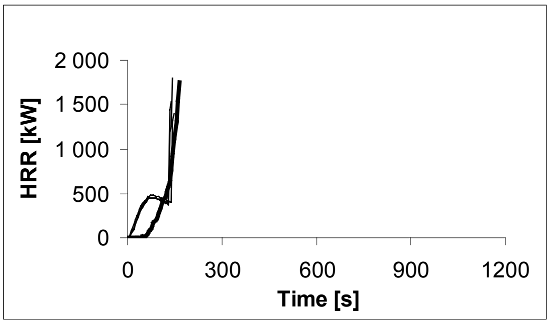
Test	t_{FO}	HRR_{max}	HRR_{avg}	FIGRA
r/c	**150**			
cc1	220			
cc2	250			
cc3	285			

Melamine-faced particle board (M20)



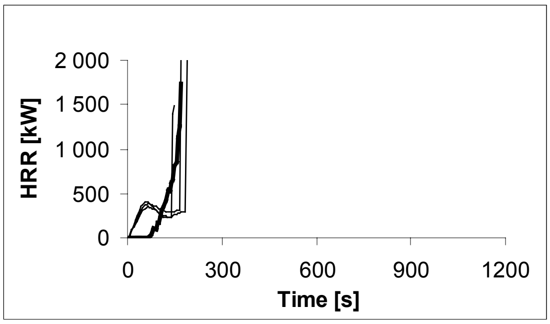
Test	t_{FO}	HRR_{max}	HRR_{avg}	FIGRA
r/c	**165**			
cc1	220			
cc2	510			
cc3	305			

Ordinary particle board (M22)



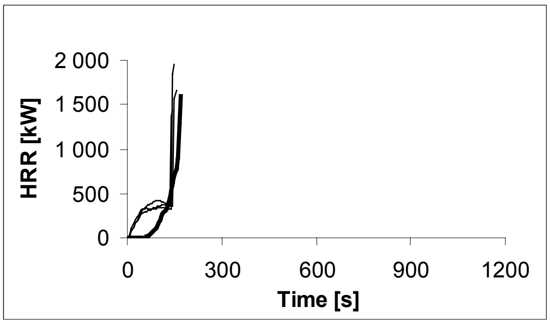
Test	t_{FO}	HRR_{max}	HRR_{avg}	FIGRA
r/c	**155**			
cc1	135			
cc2	135			
cc3	145			

Ordinary plywood (birch) (M23)



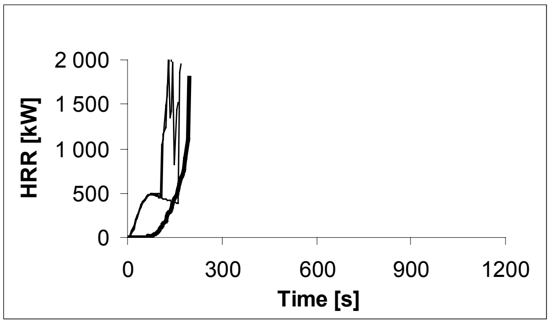
Test	t_{FO}	HRR_{max}	HRR_{avg}	FIGRA
r/c	**160**			
cc1	145			
cc2	190			
cc3	170			

Paper wallcovering on particle board (M24)



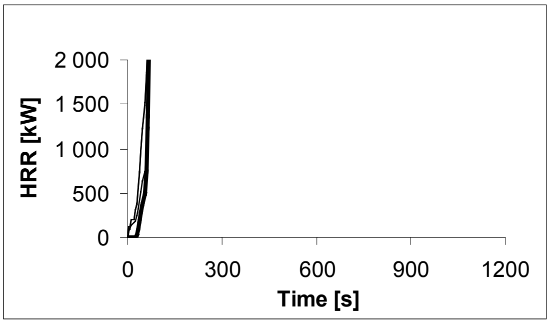
Test	t_{FO}	HRR_{max}	HRR_{avg}	FIGRA
r/c	**165**			
cc1	140			
cc2	145			
cc3	150			

Medium density fibreboard (M25)



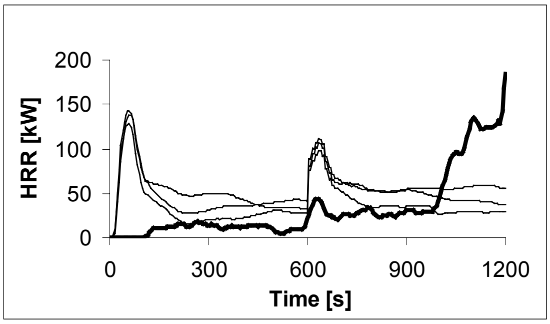
Test	t_{FO}	HRR_{max}	HRR_{avg}	FIGRA
r/c	**190**			
cc1	165			
cc2	115			
cc3	110			

Low density fibreboard (M26)



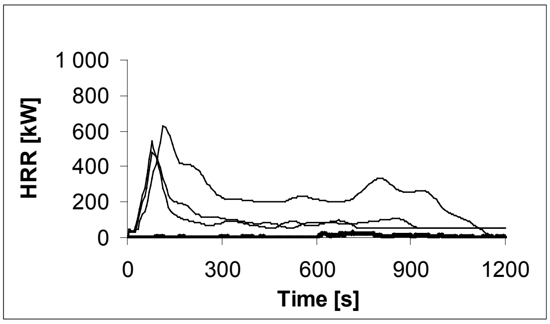
Test	t_{FO}	HRR_{max}	HRR_{avg}	FIGRA
r/c	**58**			
cc1	60			
cc2	45			
cc3	45			

Gypsum board/PUR (M27)



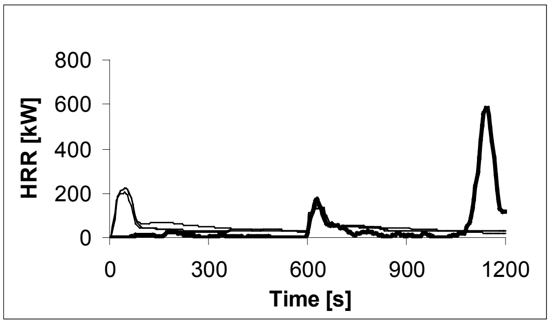
Test	t_{FO}	HRR_{max}	HRR_{avg}	FIGRA
r/c	**NFO**	**184.9**	**33.2**	**0.15**
cc1	NFO	138.1	52.9	2.75
cc2	NFO	128.0	37.2	2.80
cc3	NFO	143.4	52.9	3.03

Acoustic mineral fibre tiles (M28)



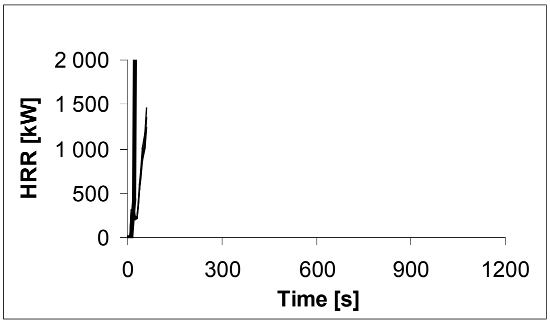
Test	t_{FO}	HRR_{max}	HRR_{avg}	FIGRA
r/c	**NFO**	**27.2**	**7.6**	**0.06**
cc1	NFO	480.7	104.3	6.10
cc2	NFO	546.4	91.2	9.34
cc3	NFO	630.5	230.6	5.48

Textile wallpaper on CaSi board (M29)



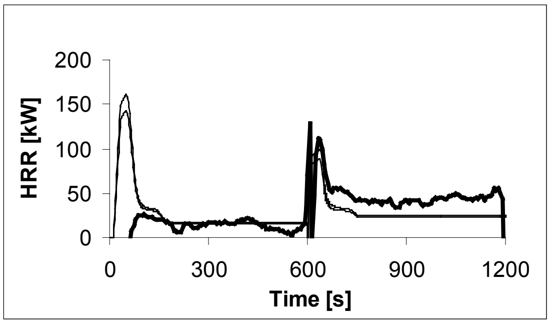
Test	t_{FO}	HRR_{max}	HRR_{avg}	FIGRA
r/c	**NFO**	**585.8**	**44.6**	**0.51**
cc1	NFO	223.0	47.8	7.38
cc2	NFO	202.3	45.6	8.31
cc3	NFO	223.1	53.0	7.43

Paper-faced glass wool (M30)



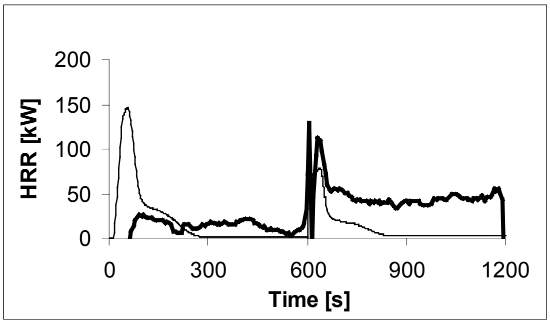
Test	t_{FO}	HRR_{max}	HRR_{avg}	FIGRA
r/c	**18**			
cc1	50			
cc2	55			
cc3	50			

Painted paper-faced gypsum board (E01) heat flux 50 kW/m²



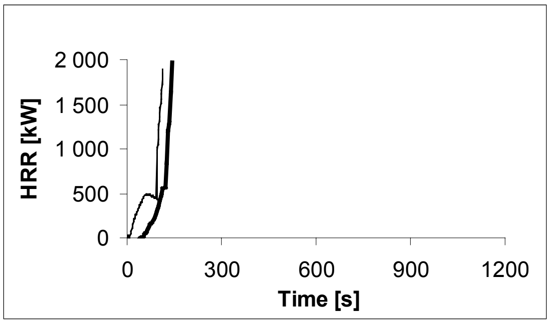
Test	t_{FO}	HRR_{max}	HRR_{avg}	FIGRA
r/c	**NFO**	**128.8**	**25.8**	**0.29**
cc1	NFO	160.8	30.6	4.61
cc2	NFO	142.6	27.3	3.93

Painted paper-faced gypsum board (E01) heat flux 75 kW/m²



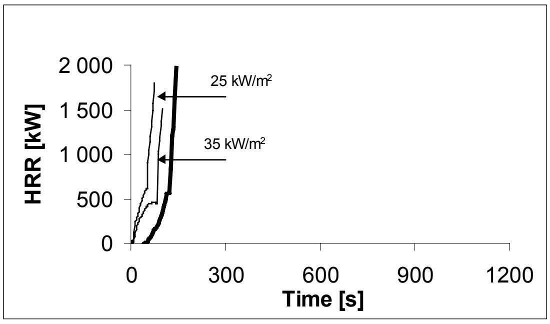
Test	t_{FO}	HRR_{max}	HRR_{avg}	FIGRA
r/c	**NFO**	**128.8**	**25.8**	**0.29**
cc1	NFO	146.4	15.9	3.35

Ordinary plywood (birch) (E02) heat flux 50 kW/m²



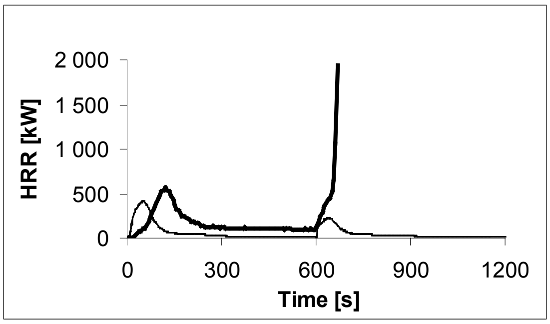
Test	t_{FO}	HRR_{max}	HRR_{avg}	FIGRA
r/c	**150**			
cc1	94			
cc2	92			

Ordinary plywood (birch) (E02) heat flux 25 and 35 kW/m²



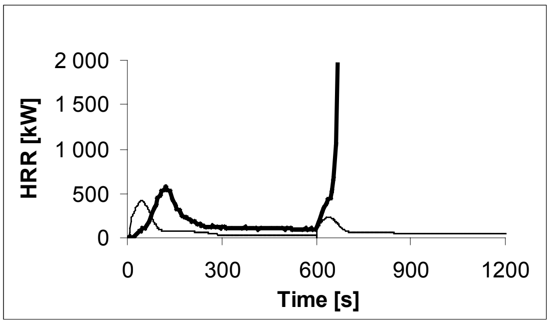
Test	t_{FO}	HRR_{max}	HRR_{avg}	FIGRA
r/c	**150**			
cc1	52			
cc2	84			

Textile wallcovering on gypsum paper plasterboard (E03) - heat flux 50 kW/m²



Test	t_{FO}	HRR_{max}	HRR_{avg}	FIGRA
r/c	**660**	**665.4**	**183.0**	**4.77**
cc1	NFO	411.7	58.9	13.20
cc2	NFO	416.8	58.4	12.87

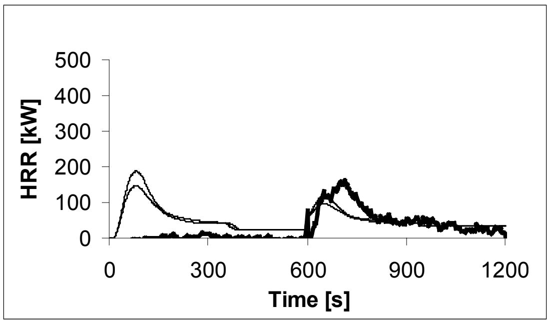
Textile wallcovering on gypsum paper plasterboard (E03) - heat flux 25 kW/m²



Test	t_{FO}	HRR_{max}	HRR_{avg}	FIGRA
r/c	**660**	**665.4**	**183.0**	**4.77**
cc1	NFO	419.2	72.6	16.07

Melamine faced high density non-combustible board (E04) -

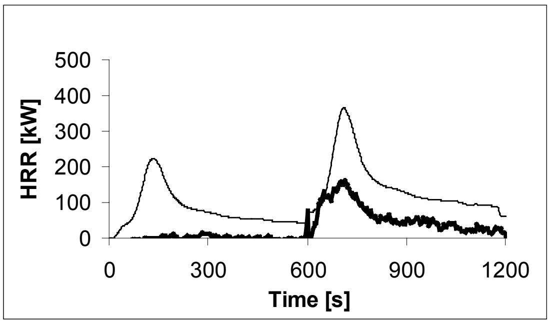
heat flux 50 kW/m²



Test	t_{FO}	HRR_{max}	HRR_{avg}	FIGRA
r/c	**NFO**	**129.5**	**5.3**	**0.20**
cc1	NFO	187.4	53.8	2.64
cc2	NFO	145.9	48.9	2.18

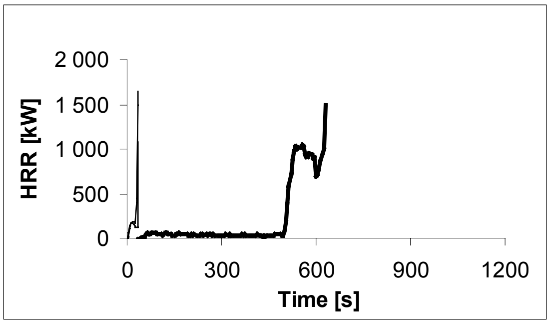
Melamine faced high density non-combustible board (E04) -

heat flux 75 kW/m²



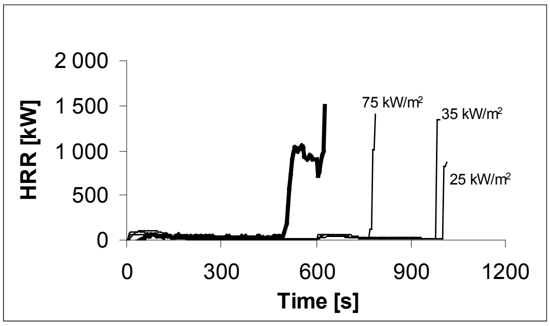
Test	t_{FO}	HRR_{max}	HRR_{avg}	FIGRA
r/c	**NFO**	**129.5**	**5.3**	**0.20**
cc1	NFO	365.5	110.2	1.73

FR particle board type B1 (E06) – heat flux 50 kW/m^2



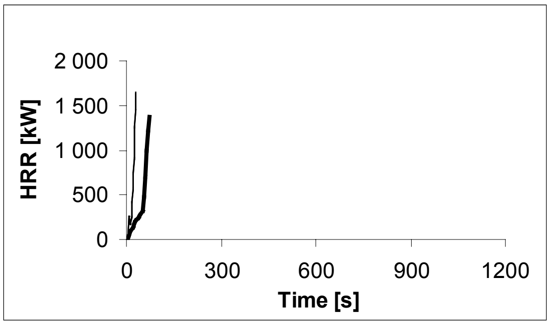
Test	t_{FO}	HRR_{max}	HRR_{avg}	FIGRA
r/c	**630**	**700**	**333.1**	**2.85**
cc1	80			
cc2	85			

FR particle board type B1 (E06) – heat flux 25, 35 and 75 kW/m^2



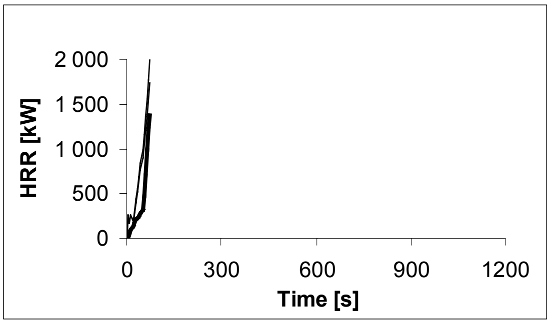
Test	t_{FO}	HRR_{max}	HRR_{avg}	FIGRA
r/c	**630**	**700**	**61.7**	**1.93**
cc1	1005	700	18.8	4.68
cc2	985	700	36.2	7.86
cc3	780	700	25.3	3.41

Combustible faced mineral wool (E07) - heat flux 50 kW/m^2



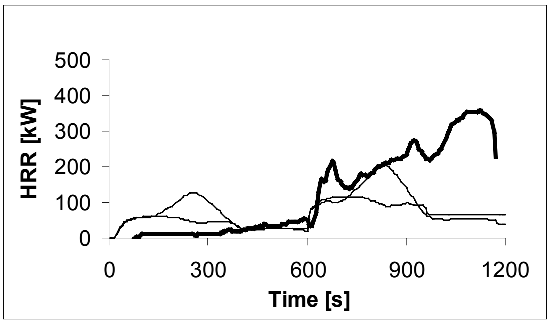
Test	t_{FO}	HRR_{max}	HRR_{avg}	FIGRA
r/c	**70**			
cc1	24			
cc2	24			

Combustible faced mineral wool (E07) - heat flux 25 kW/m^2



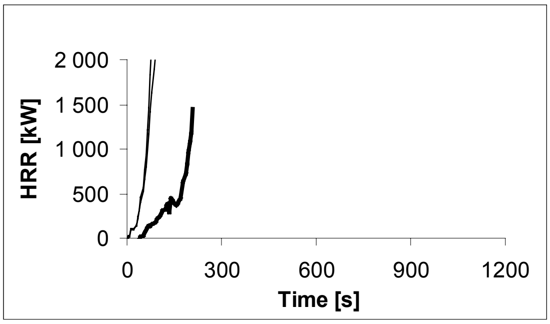
Test	t_{FO}	HRR_{max}	HRR_{avg}	FIGRA
r/c	**70**			
cc1	50			

FR Particle board (E08) - heat flux 50 kW/m²



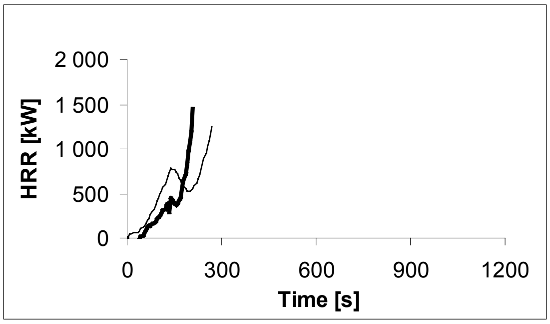
Test	t_{FO}	HRR_{max}	HRR_{avg}	FIGRA
r/c	**NFO**	**356.9**	**118.7**	**0.33**
cc1	NFO	207.8	77.6	1.02
cc2	NFO	117.1	62.6	0.93

Plastic-faced steel sheet on PUR foam (E09) - heat flux 50 kW/m²



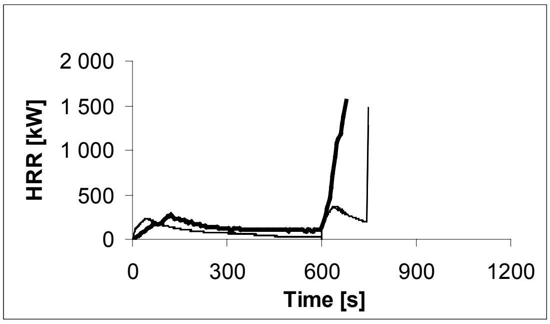
Test	t_{FO}	HRR_{max}	HRR_{avg}	FIGRA
r/c	**195**			
cc1	65			
cc2	60			

Plastic-faced steel sheet on PUR foam (E09) - heat flux 35 kW/m²



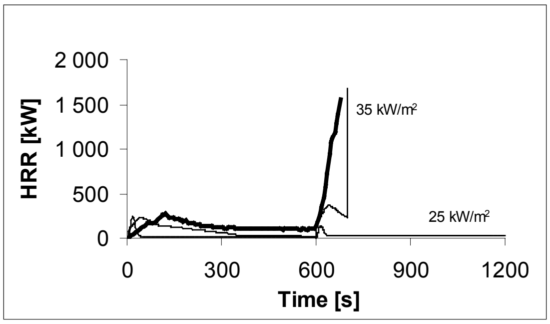
Test	t_{FO}	HRR_{max}	HRR_{avg}	FIGRA
r/c	**195**			
cc1	250			

PVC wallcarpet on gypsum plasterboard (E10) - heat flux 50 kW/m²



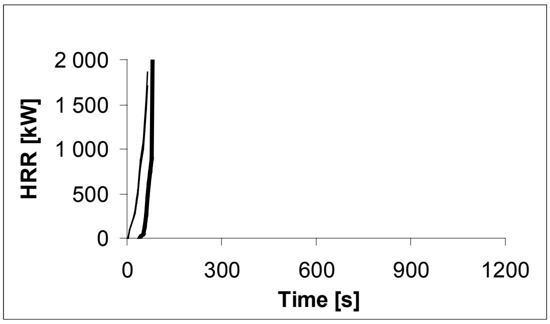
Test	t_{FO}	HRR_{max}	HRR_{avg}	FIGRA
r/c	**655**	**935.9**	**155.8**	**2.67**
cc1	746	359.3	119.2	12.94
cc2	746	376.0	121.5	11.25

PVC wallcarpet on gypsum plasterboard (E10) - heat flux 25 and 35 kW/m²



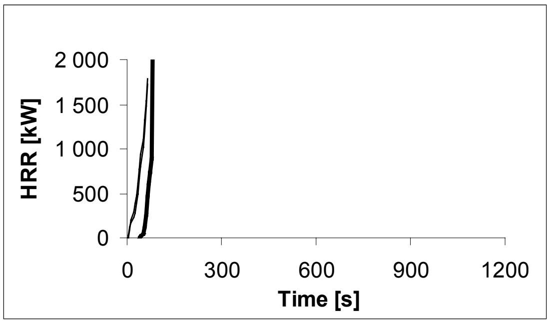
Test	t_{FO}	HRR_{max}	HRR_{avg}	FIGRA
r/c	**655**	**700**	**155.8**	**2.67**
cc1	NFO	250.1	24.6	14.22
cc2	700	700	108.4	13.98

FR extruded polystyrene foam (E11) - heat flux 50 kW/m²



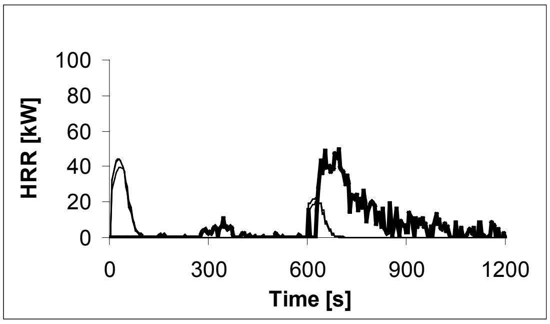
Test	t_{FO}	HRR_{max}	HRR_{avg}	FIGRA
r/c	**80**			
cc1	50			
cc2	50			

FR extruded polystyrene foam (E11) - heat flux 25 and 35 kW/m²



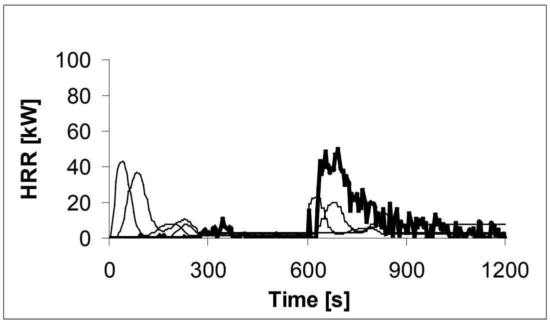
Test	t_{FO}	HRR_{max}	HRR_{avg}	FIGRA
r/c	**80**			
cc1	50			
cc2	45			

PVC on steel sheets /rockwool (N01) - heat flux 25 kW/m²



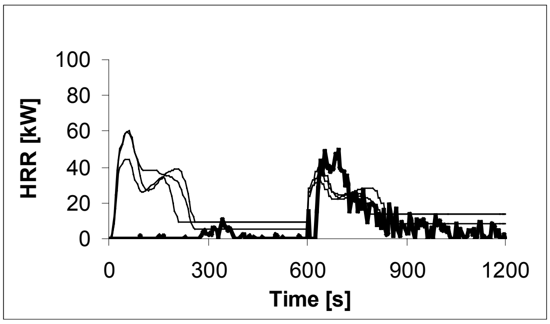
Test	t_{FO}	HRR_{max}	HRR_{avg}	FIGRA
r/c	**NFO**	**49.7**	**6.7**	**0.07**
cc1	NFO	39.7	2.3	2.70
cc2	NFO	44.4	2.3	3.29
cc3	NFO	43.8	2.5	3.26

PVC on steel sheets /rockwool (N01) - heat flux 35 kW/m²



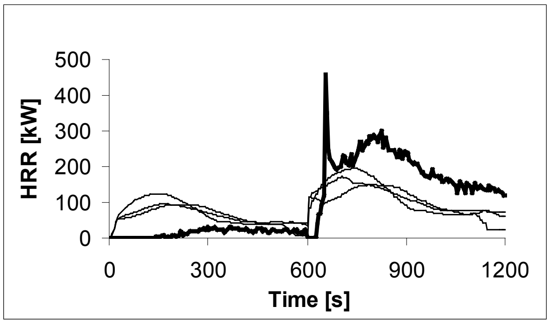
Test	t_{FO}	HRR_{max}	HRR_{avg}	FIGRA
r/c	**NFO**	**49.7**	**6.7**	**0.07**
cc1	NFO	42.7	4.8	1.57
cc2	NFO	36.6	5.5	2.00
cc3	NFO	14.7	4.2	3.00

PVC on steel sheets /rockwool (N01) - heat flux 50 kW/m²



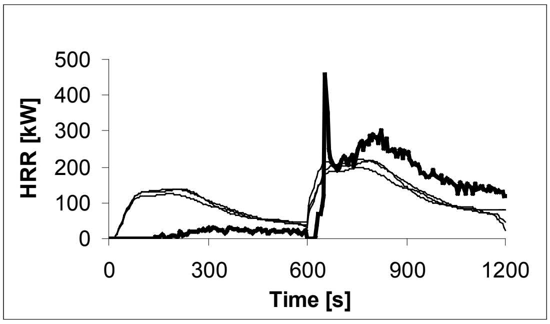
Test	t_{FO}	HRR_{max}	HRR_{avg}	FIGRA
r/c	**NFO**	**49.7**	**6.7**	**0.07**
cc1	NFO	44.6	16.2	4.00
cc2	NFO	59.5	16.1	5.00
cc3	NFO	60.3	18.9	6.00

1.4 mm phenolic laminate on CaSi (N02) - heat flux 25 kW/m²



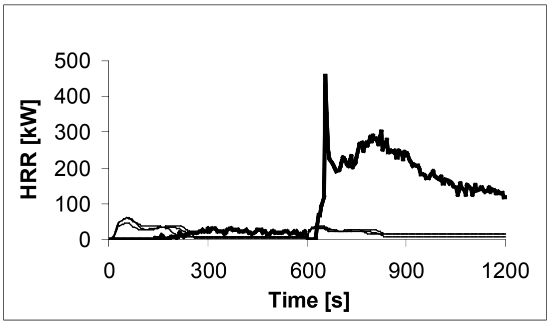
Test	t_{FO}	HRR_{max}	HRR_{avg}	FIGRA
r/c	**NFO**	**458.4**	**96.3**	**0.69**
cc1	NFO	195.9	85.3	2.28
cc2	NFO	172.2	86.9	2.17
cc3	NFO	150.4	83.8	2.30

1.4 mm phenolic laminate on CaSi (N02) - heat flux 35 kW/m²



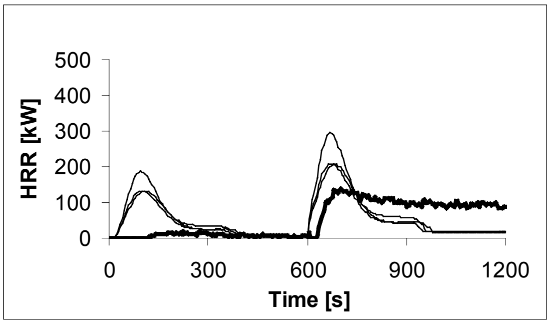
Test	t_{FO}	HRR_{max}	HRR_{avg}	FIGRA
r/c	**NFO**	**458.4**	**96.3**	**0.69**
cc1	NFO	219.7	116.5	1.52
cc2	NFO	216.2	109.6	2.00
cc3	NFO	198.6	104.2	3.00

1.4 mm phenolic laminate on CaSi (N02) - heat flux 50 kW/m²



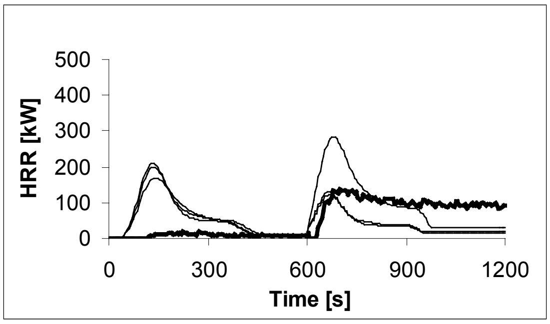
Test	t_{FO}	HRR_{max}	HRR_{avg}	FIGRA
r/c	**NFO**	**458.4**	**96.3**	**0.69**
cc1	NFO	44.6	16.2	4.00
cc2	NFO	59.5	16.1	5.00
cc3	NFO	60.3	18.9	6.00

0.8 mm phenolic laminate on CaSi (N03) - heat flux 25 kW/m²



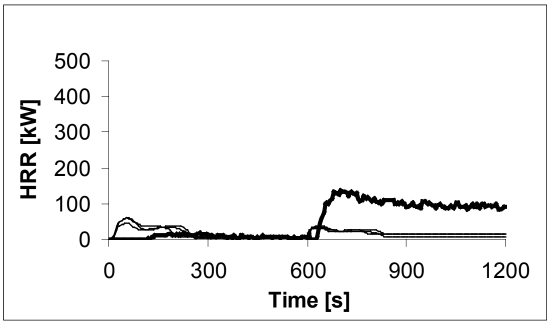
Test	t_{FO}	HRR_{max}	HRR_{avg}	FIGRA
r/c	**NFO**	**137.5**	**47.4**	**0.20**
cc1	NFO	207.4	51.1	1.41
cc2	NFO	208.0	49.8	1.57
cc3	NFO	295.7	64.4	2.20

0.8 mm phenolic laminate on CaSi (N03) - heat flux 35 kW/m²



Test	t_{FO}	HRR_{max}	HRR_{avg}	FIGRA
r/c	**NFO**	**137.5**	**47.4**	**0.20**
cc1	NFO	284.0	76.5	1.28
cc2	NFO	209.2	50.3	2.00
cc3	NFO	199.4	46.5	3.00

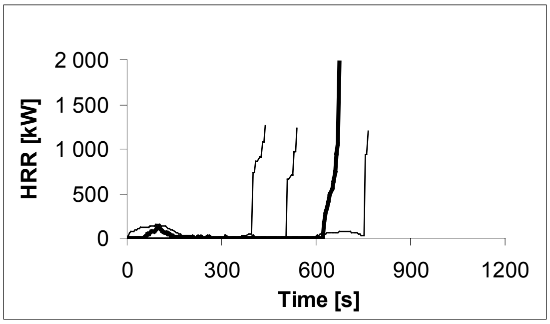
0.8 mm phenolic laminate on CaSi (N03) - heat flux 50 kW/m²



Test	t_{FO}	HRR_{max}	HRR_{avg}	FIGRA
r/c	**NFO**	**137.5**	**47.4**	**0.20**
cc1	NFO	44.6	16.2	4.00
cc2	NFO	59.5	16.1	5.00
cc3	NFO	60.3	18.9	6.00

Painted steel sheets (N04)

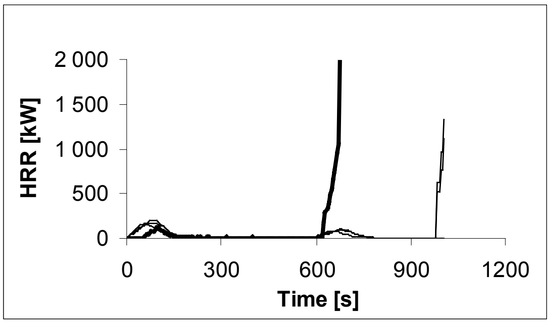
- heat flux 25 kW/m²



Test	t_{FO}	HRR_{max}	HRR_{avg}	FIGRA
r/c	**665**	**745.7**	**40.5**	**1.26**
cc1	755	149.4	37.0	6.32
cc2	420	861.6	43.1	2.09
cc3	530	708.4	27.4	1.36

Painted steel sheets (N04)

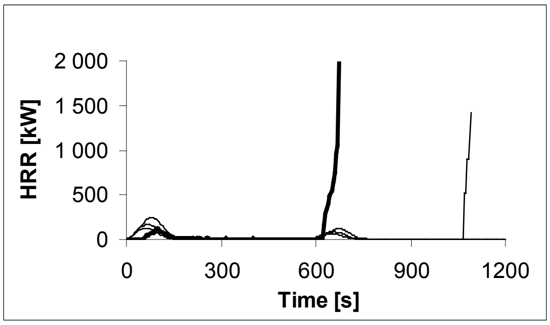
- heat flux 35 kW/m²



Test	t_{FO}	HRR_{max}	HRR_{avg}	FIGRA
r/c	**665**	**745.7**	**40.5**	**1.26**
cc1	995	963.0	38.5	3.75
cc2	NFO	163.9	17.9	4.09
cc3	995	767.1	36.8	3.12

Painted steel sheets (N04)

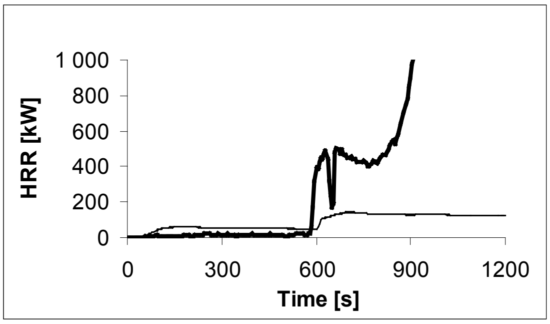
- heat flux 50 kW/m²



Test	t_{FO}	HRR_{max}	HRR_{avg}	FIGRA
r/c	**665**	**745.7**	**40.5**	**1.26**
cc1	NFO	126.0	12.1	4.00
cc2	NFO	166.7	16.9	5.00
cc3	1080	901.9	37.3	6.00

FR spruce panel (A03)

- heat flux 75 kW/m²



Test	t_{FO}	HRR_{max}	HRR_{avg}	FIGRA
r/c	**910**	**700**	**178.2**	**1.08**
cc1	NFO	139.2	86.4	0.45
cc2	NFO	144.6	87.0	0.47

APPENDIX II:
Room Corner SPR simulation results

Structure of Appendix II

Results from Room Corner SPR simulations are listed in this appendix in the following order:

M01-M30 (see Table 3-1)

E01-E11 (see Table 3-2)

EI-01 – EI-04 (see Table 3-3)

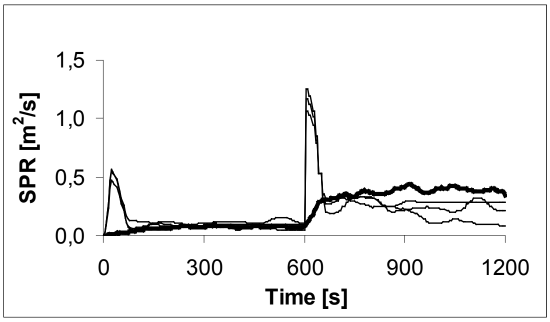
N01-N04 (see Table 3-5)

A03 (see Table 3-6)

For each product a graphical presentation of the SPR measured in one single Room Corner test is shown with a bold line, and the simulated results are shown with thinner lines. Observe that the scale on the ordinate differ from figure to figure. Values for SPR_{max} and SPR_{avg} and SMOGRA are tabulated below each figure. The values calculated based on the real Room Corner test are shown in bold types, and the test is designated r/c. The Cone Calorimeter tests used for simulations are designated cc1, cc2 and cc3, and the simulated values are printed in normal types.

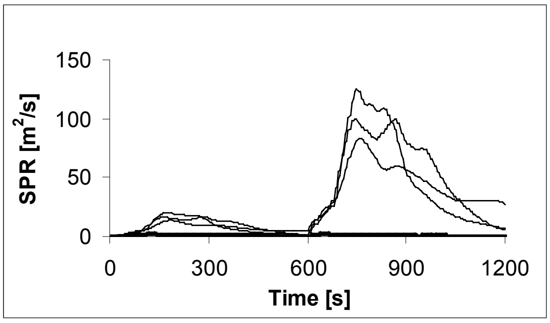
SPR_{max}, SPR_{avg} and SMOGRA have not been calculated for cases where time to flashover is below 300 s. Such cases are therefore omitted from this appendix.

Paper-faced gypsum board (M01)



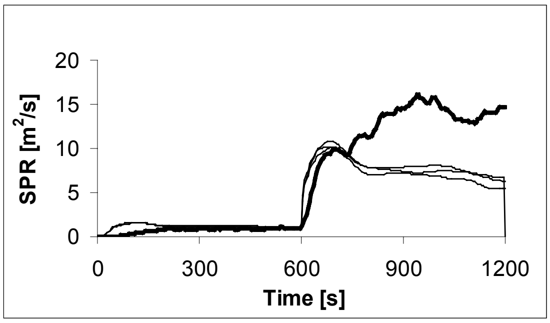
Test	SPR_{max}	SPR_{avg}	SMOGRA
r/c	0.43	0.21	0.00
cc1	1.17	0.18	1.93
cc2	1.06	0.22	1.76
cc3	1.25	0.23	2.06

FR PVC (M02)



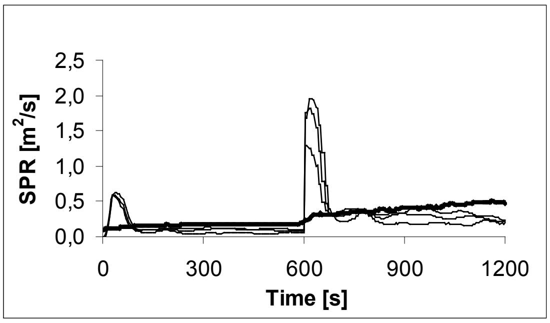
Test	SPR_{max}	SPR_{avg}	SMOGRA
r/c	2.01	0.92	12.65
cc1	26.35	9.59	103.37
cc2	21.09	8.15	120.54
cc3	83.53	25.29	109.91

FR chipboard (M06)



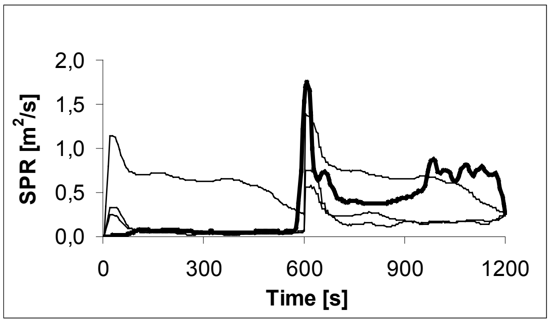
Test	SPR_{max}	SPR_{avg}	SMOGRA
r/c	16.07	6.49	15.24
cc1	10.12	4.52	21.49
cc2	10.20	4.15	22.99
cc3	10.84	4.47	23.98

Painted paper-faced gypsum board (M08)



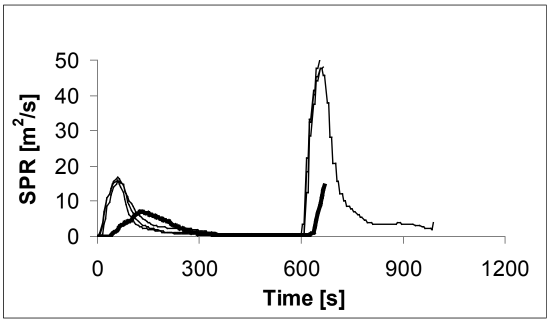
Test	SPR_{max}	SPR_{avg}	SMOGRA
r/c	0.50	0.28	0.00
cc1	1.30	0.25	2.14
cc2	1.95	0.30	3.17
cc3	1.82	0.23	2.95

Paper wallcovering on gypsum (M09)



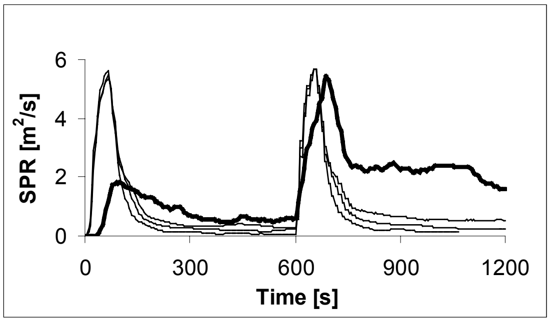
Test	SPR_{max}	SPR_{avg}	SMOGRA
r/c	**1.75**	**0.34**	**1.70**
cc1	1.39	0.65	57.40
cc2	0.75	0.14	0.00
cc3	0.57	0.15	0.00

PVC wallcarpet on gypsum board (M10)



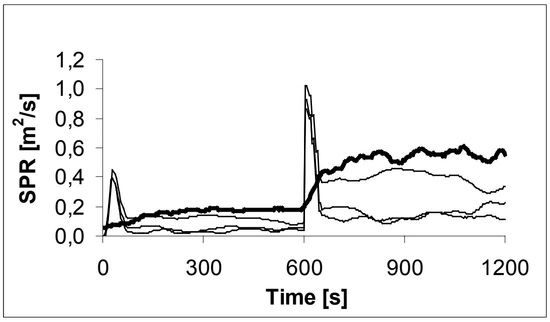
Test	SPR_{max}	SPR_{avg}	SMOGRA
r/c	**14.62**	**2.16**	**47.38**
cc1	47.56	4.88	359.95
cc2	47.56	6.05	296.84
cc3	50.92	6.05	362.96

Plastic-faced steel sheet on mineral wool (M11)



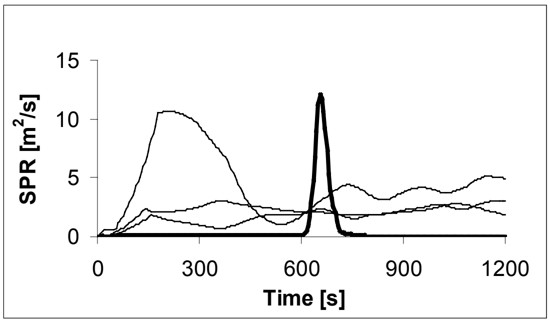
Test	SPR_{max}	SPR_{avg}	SMOGRA
r/c	**5.43**	**1.67**	**16.85**
cc1	5.67	0.95	110.51
cc2	5.69	0.87	117.15
cc3	5.69	1.13	110.31

Gypsum board on polystyrene (M13)



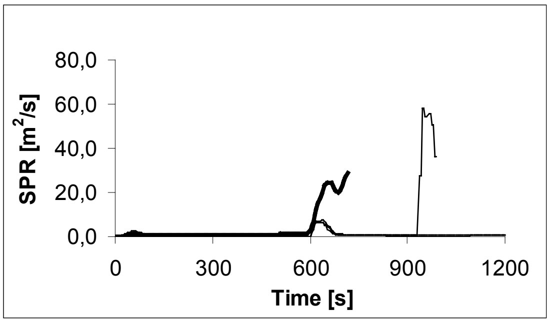
Test	SPR_{max}	SPR_{avg}	SMOGRA
r/c	**0.61**	**0.34**	**0.00**
cc1	0.93	0.12	0.00
cc2	0.87	0.12	0.00
cc3	1.02	0.28	1.69

Phenolic foam (M14)



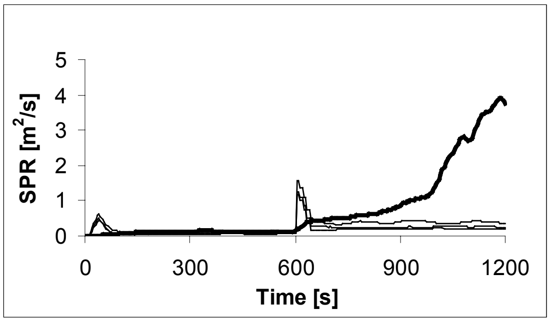
Test	SPR_{max}	SPR_{avg}	SMOGRA
r/c	**9.06**	**0.29**	**1.90**
cc1	1.79	0.65	12.19
cc2	1.56	0.57	9.26
cc3	8.32	2.86	43.94

Intumescent coating on particle board (M15)



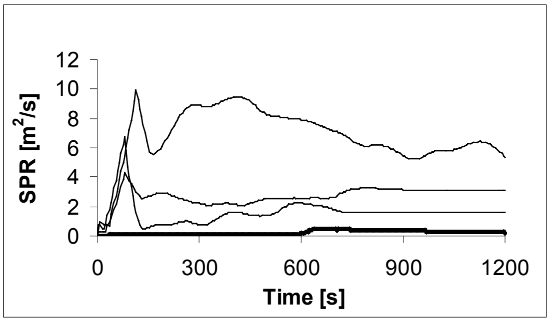
Test	SPR_{max}	SPR_{avg}	SMOGRA
r/c	**24.58**	**3.15**	**32.09**
cc1	6.47	0.67	44.85
cc2	7.21	0.62	47.99
cc3	6.51	0.77	38.03

Gypsum board/PUR (M27)



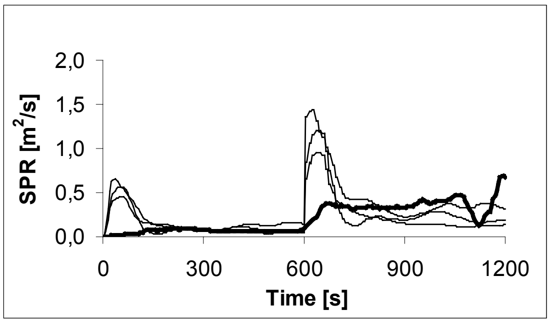
Test	SPR_{max}	SPR_{avg}	SMOGRA
r/c	**3.89**	**0.76**	**3.23**
cc1	1.18	0.15	1.95
cc2	1.27	0.19	2.09
cc3	1.57	0.29	2.59

Acoustic mineral fibre tiles (M28)



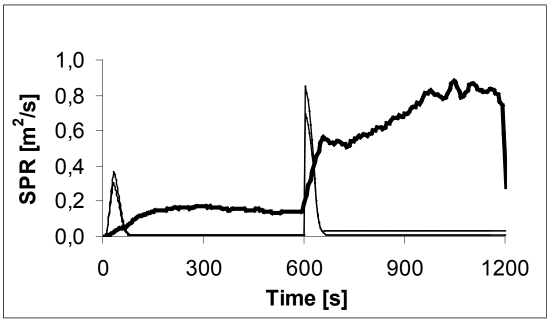
Test	SPR_{max}	SPR_{avg}	SMOGRA
r/c	**0.47**	**0.22**	**0.00**
cc1	4.31	2.70	53.83
cc2	6.75	1.63	84.38
cc3	9.89	6.80	86.02

Textile wallpaper on CaSi board (M29)



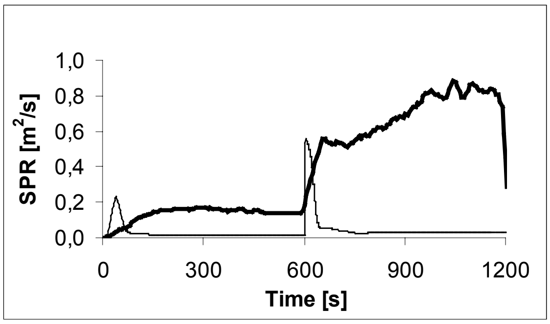
Test	SPR_{max}	SPR_{avg}	SMOGRA
r/c	**0.69**	**0.20**	**0.00**
cc1	1.20	0.23	1.89
cc2	0.95	0.19	0.00
cc3	1.44	0.33	2.32

Painted paper-faced gypsum board (E01) heat flux 50 kW/m^2



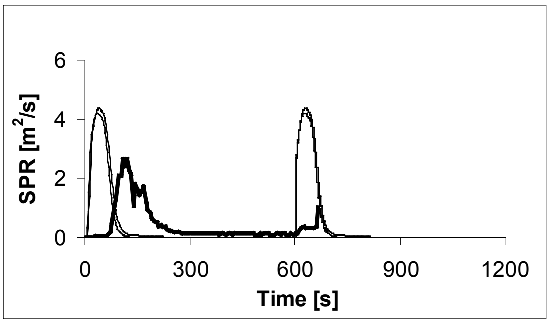
Test	SPR_{max}	SPR_{avg}	SMOGRA
r/c	**0.88**	**0.40**	**0.00**
cc1	0.70	0.04	0.00
cc2	0.85	0.03	0.00

Painted paper-faced gypsum board (E01) heat flux 75 kW/m^2



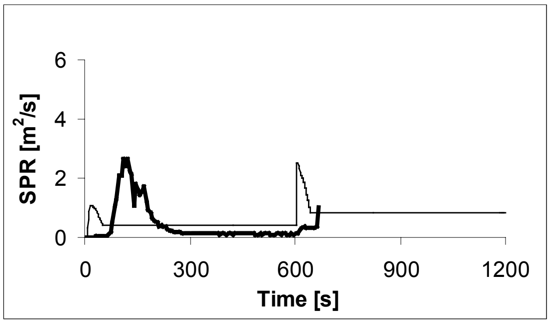
Test	SPR_{max}	SPR_{avg}	SMOGRA
r/c	**0.88**	**0.40**	**0.99**
cc1	0.56	0.04	5.96

Textile wallcovering on gypsum paper plasterboard (E03) - heat flux 50 kW/m^2



Test	SPR_{max}	SPR_{avg}	SMOGRA
r/c	**2.65**	**0.42**	**14.97**
cc1	4.19	0.41	181.59
cc2	4.38	0.46	157.24

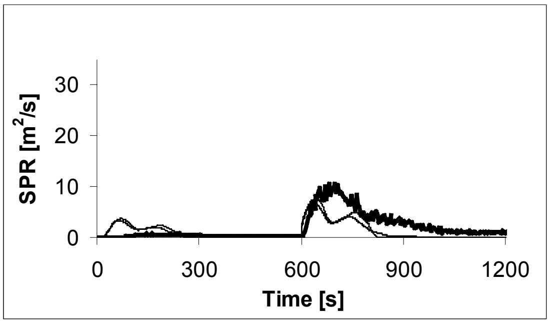
Textile wallcovering on gypsum paper plasterboard (E03) - heat flux 25 kW/m²



Test	SPR_{max}	SPR_{avg}	SMOGRA
r/c	**2.65**	**0.42**	**14.97**
cc1	2.52	0.67	75.45

Melamine faced high density non-combustible board (E04) -

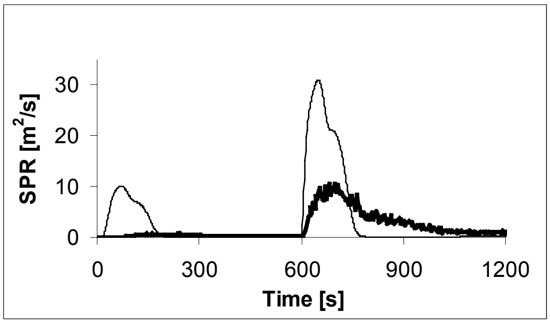
heat flux 50 kW/m²



Test	SPR_{max}	SPR_{avg}	SMOGRA
r/c	**10.03**	**0.97**	**12.60**
cc1	6.99	1.09	59.26
cc2	7.56	1.15	58.21

Melamine faced high density non-combustible board (E04) -

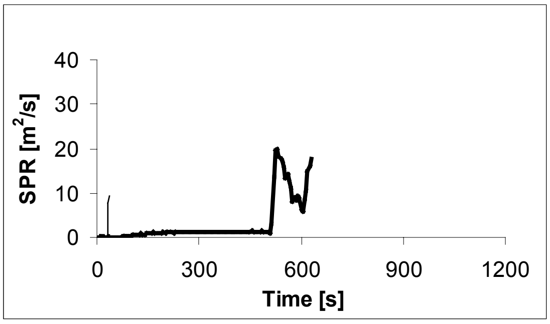
heat flux 75 kW/m²



Test	SPR_{max}	SPR_{avg}	SMOGRA
r/c	**10.03**	**0.97**	**0.65**
cc1	31.01	3.38	173.58

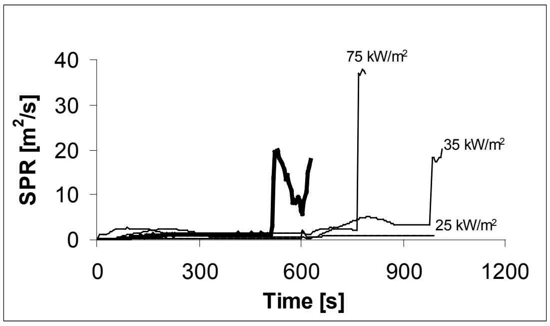
FR particle board type B1 (E06) –

heat flux 50 kW/m²



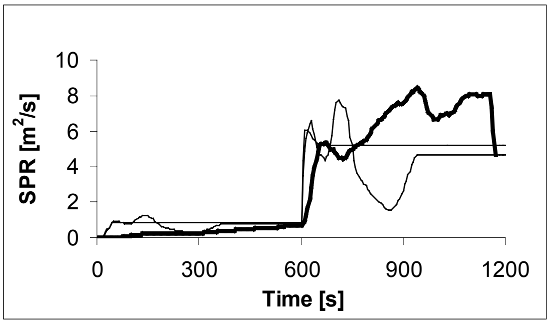
Test	SPR_{max}	SPR_{avg}	SMOGRA
r/c	**19.89**	**3.35**	**56.57**
cc1			
cc2			

FR particle board type B1 (E06) – heat flux 25. 35 and 75 kW/m²



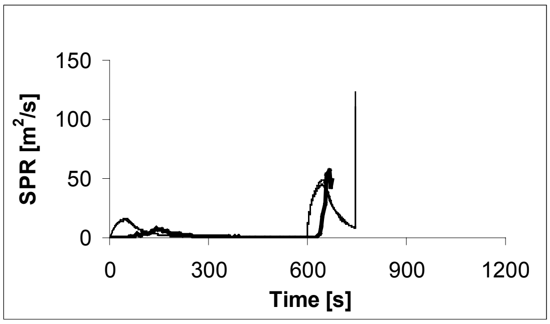
Test	SPR_{max}	SPR_{avg}	SMOGRA
r/c	**19.89**	**3.35**	**56.57**
cc1	26.04	1.66	6.05
cc2	5.04	2.20	22.16
cc3	36.96	1.89	120.42

FR Particle board (E08) - heat flux 50 kW/m²



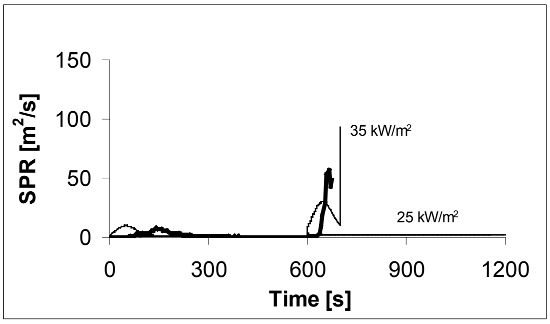
Test	SPR_{max}	SPR_{avg}	SMOGRA
r/c	**8.42**	**3.24**	**8.02**
cc1	7.77	2.50	10.94
cc2	6.05	3.01	9.91

PVC wallcarpet on gypsum plasterboard (E10) - heat flux 50 kW/m²



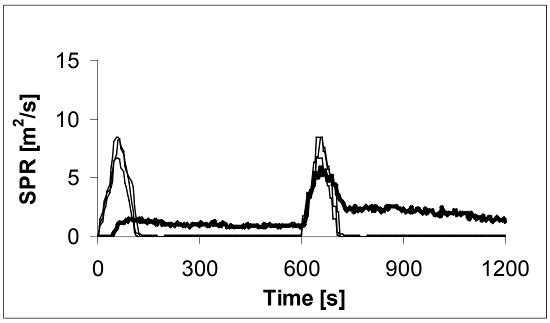
Test	SPR_{max}	SPR_{avg}	SMOGRA
r/c	**9.29**	**1.66**	**36.90**
cc1	44.93	6.97	648.82
cc2	49.08	7.25	613.25

PVC wallcarpet on gypsum plasterboard (E10) - heat flux 25 and 35 kW/m²



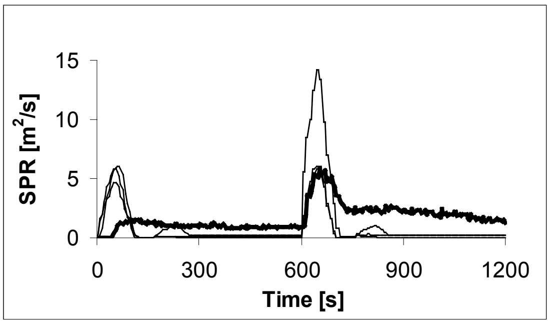
Test	SPR_{max}	SPR_{avg}	SMOGRA
r/c	**9.29**	**1.66**	**57.47**
cc1	3.32	1.32	169.75
cc2	30.15	4.47	420.93

PVC on steel sheets /rockwool (N01) - heat flux 25 kW/m²



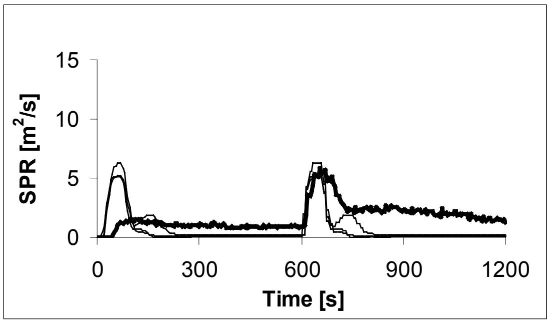
Test	SPR_{max}	SPR_{avg}	SMOGRA
r/c	**5.84**	**1.71**	**17.56**
cc1	6.71	0.70	129.34
cc2	8.49	0.87	151.98
cc3	8.41	0.95	161.38

PVC on steel sheets /rockwool (N01) - heat flux 35 kW/m²



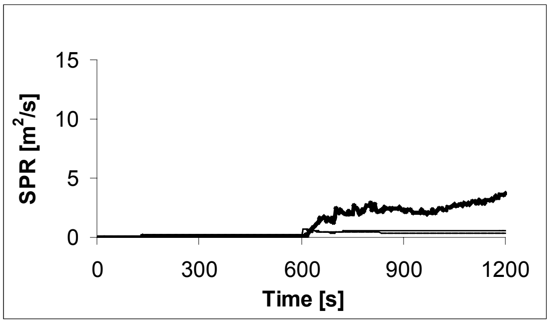
Test	SPR_{max}	SPR_{avg}	SMOGRA
r/c	**5.84**	**1.71**	**17.56**
cc1	6.07	0.88	129.34
cc2	5.84	0.63	153.21
cc3	14.15	1.12	158.96

PVC on steel sheets /rockwool (N01) - heat flux 50 kW/m²



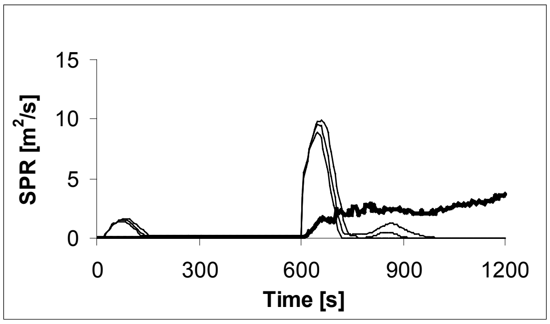
Test	SPR_{max}	SPR_{avg}	SMOGRA
r/c	**5.84**	**1.71**	**17.56**
cc1	6.32	0.71	122.39
cc2	5.20	0.59	120.42
cc3	5.27	0.92	109.45

1.4 mm phenolic laminate on CaSi (N02) - heat flux 25 kW/m²



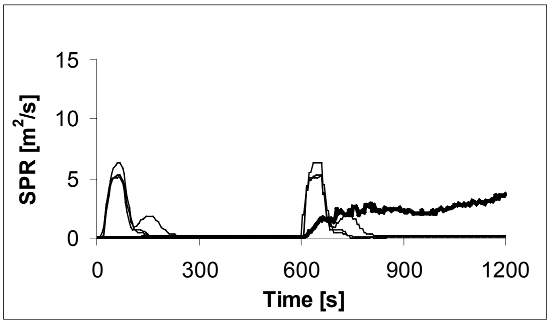
Test	SPR_{max}	SPR_{avg}	SMOGRA
r/c	**3.72**	**1.18**	**3.61**
cc1	0.00	-0.05	0.00
cc2	0.72	0.25	4.63
cc3	0.73	0.32	4.47

1.4 mm phenolic laminate on CaSi (N02) - heat flux 35 kW/m²



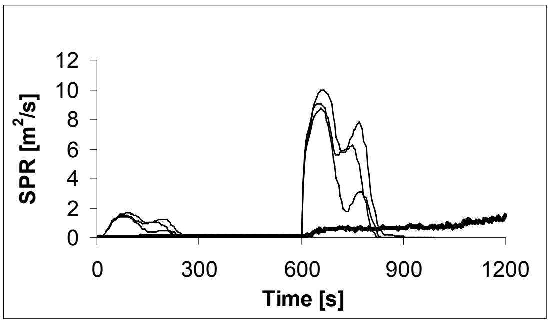
Test	SPR_{max}	SPR_{avg}	SMOGRA
r/c	**3.72**	**1.18**	**3.61**
cc1	9.55	0.86	0.00
cc2	9.89	0.85	24.34
cc3	8.93	0.64	25.29

1.4 mm phenolic laminate on CaSi (N02) - heat flux 50 kW/m²



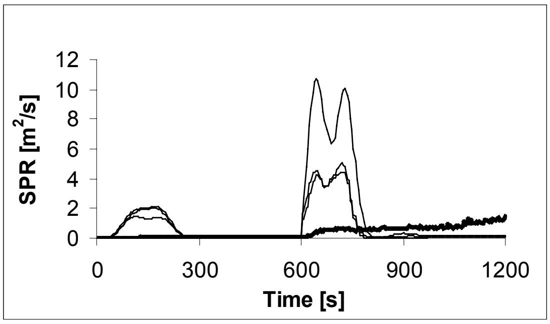
Test	SPR_{max}	SPR_{avg}	SMOGRA
r/c	**3.72**	**1.18**	**3.61**
cc1	8.93	0.71	122.39
cc2	5.20	0.59	120.42
cc3	5.27	0.92	109.45

0.8 mm phenolic laminate on CaSi (N03) - heat flux 25 kW/m²



Test	SPR_{max}	SPR_{avg}	SMOGRA
r/c	**1.46**	**0.40**	**1.22**
cc1	8.72	0.90	23.67
cc2	9.06	1.15	25.67
cc3	9.93	1.46	24.14

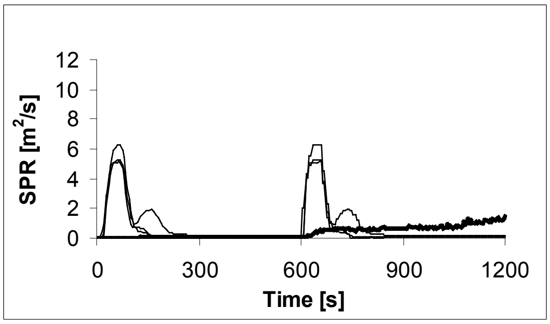
0.8 mm phenolic laminate on CaSi (N03) - heat flux 35 kW/m²



Test	SPR_{max}	SPR_{avg}	SMOGRA
r/c	**1.46**	**0.40**	**1.22**
cc1	10.67	1.34	23.67
cc2	4.47	0.70	15.45
cc3	5.03	0.80	17.22

0.8 mm phenolic laminate on CaSi (N03)

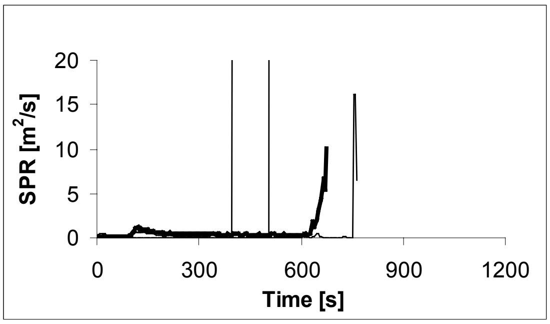
- heat flux 50 kW/m²



Test	SPR_{max}	SPR_{avg}	SMOGRA
r/c	**1.46**	**0.40**	**1.22**
cc1	6.32	0.71	122.39
cc2	5.20	0.59	120.42
cc3	5.27	0.92	109.45

Painted steel sheets (N04)

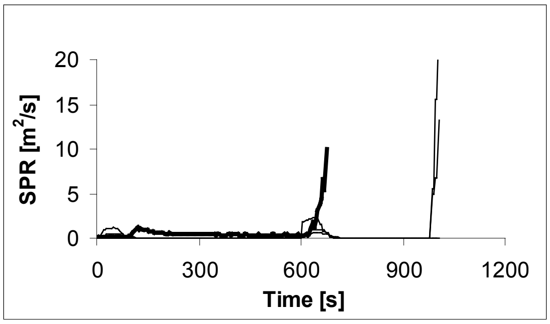
- heat flux 25 kW/m²



Test	SPR_{max}	SPR_{avg}	SMOGRA
r/c	**4.41**	**0.53**	**15.57**
cc1	0.55	0.04	2405.07
cc2	67.10	32.52	167.74
cc3	196.07	7.52	377.05

Painted steel sheets (N04)

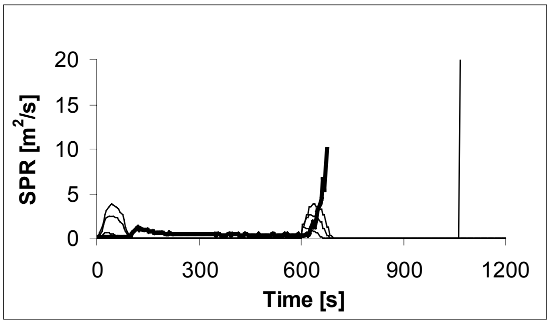
- heat flux 35 kW/m²



Test	SPR_{max}	SPR_{avg}	SMOGRA
r/c	**4.41**	**0.53**	**15.57**
cc1	6.79	0.16	27.64
cc2	2.32	0.21	46.61
cc3	15.60	0.24	15.68

Painted steel sheets (N04)

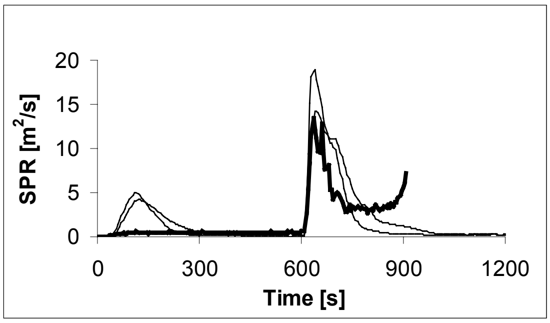
- heat flux 50 kW/m²



Test	SPR_{max}	SPR_{avg}	SMOGRA
r/c	**4.41**	**0.53**	**15.57**
cc1	1.29	0.03	26.84
cc2	2.56	0.22	78.92
cc3	73.78	1.06	102.73

FR spruce panel (A03)

- heat flux 75 kW/m^2



Test	SPR_{max}	SPR_{avg}	SMOGRA
r/c	**13.39**	**1.92**	**14.25**
cc1	18.86	1.83	45.65
cc2	14.22	2.09	36.26

APPENDIX III:
SBI HRR simulation results

Structure of Appendix III

Results from SBI HRR simulations are listed in this appendix in the following order:

M01-M30 (see Table 3-1)

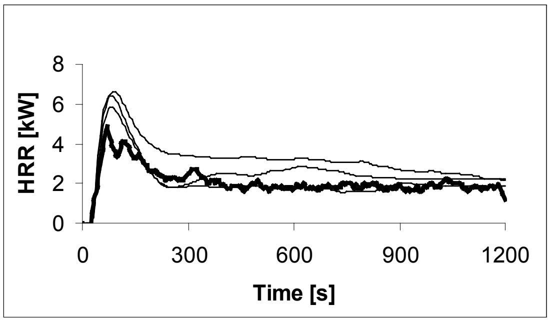
O, ZA, ZB, ZC, X, Y, A01, A02 (see Table 3-6)

For each product a graphical presentation of the HRR measured in one single representative SBI test is shown with a bold line, and the simulated results are shown with thinner lines. Observe that the scale on the ordinate differ from figure to figure.

Values for FIGRA and THR_{600s} are tabulated below each figure together with the obtained classification. The FIGRA values are calculated with threshold values HRR>3 kW and THR> 0.2 MJ according to prEN 13823.

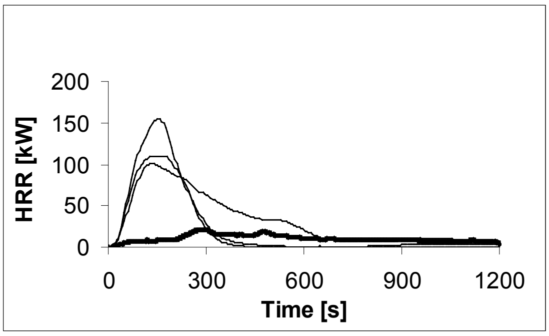
The values calculated based on the real SBI test are shown in bold types, and the test is designated SBI. For the products M01-M30 the bold values are the resulting averaged values from the SBI round robin programme as published in prEN13823:2001. The Cone Calorimeter tests used for simulations are designated cc1, cc2 and cc3, and the simulated values are printed in normal types.

Paper-faced gypsum board (M01)



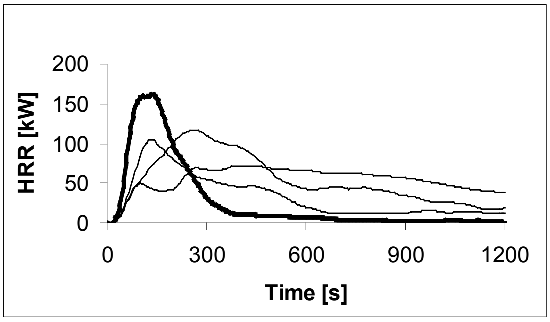
Test	FIGRA	THR_{600s}	Class
SBI	**21**	**1.0**	**B**
cc1	85.1	1.5	B
cc2	72.6	1.6	B
cc3	84.6	2.2	B

FR PVC (M02)



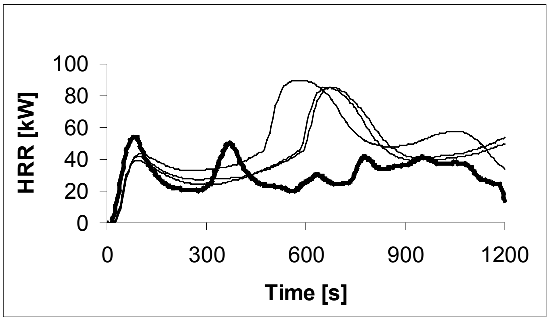
Test	FIGRA	THR_{600s}	Class
SBI	**81**	**5.9**	**B**
cc1	1023.9	220	D
cc2	1228.5	27.1	D
cc3	893.3	32.6	D

PUR foam panel with Al-foil faces (M04)



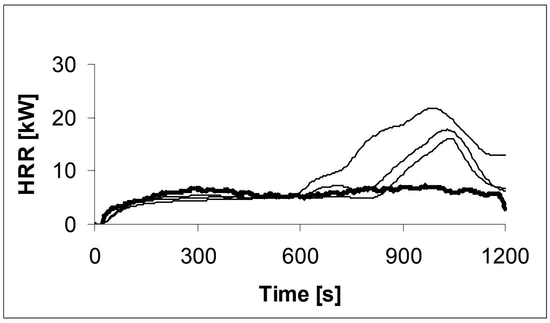
Test	FIGRA	THR_{600s}	Class
SBI	**1869**	**28.6**	**E**
cc1	859.0	31.1	E
cc2	539.1	44.4	D
cc3	546.6	33.2	D

Mass timber (pine). varnished (M05)



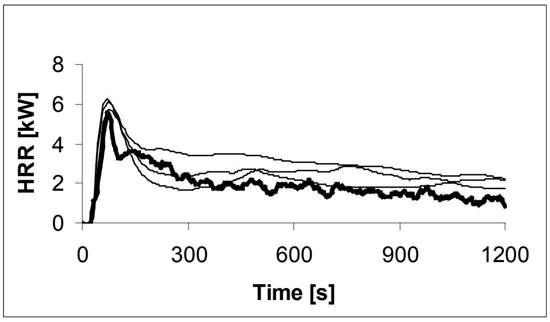
Test	FIGRA	THR_{600s}	Class
SBI	**681**	**15.1**	**D**
cc1	512.2	17.9	D
cc2	517.1	18.5	D
cc3	510.4	25.9	D

FR chipboard (M06)



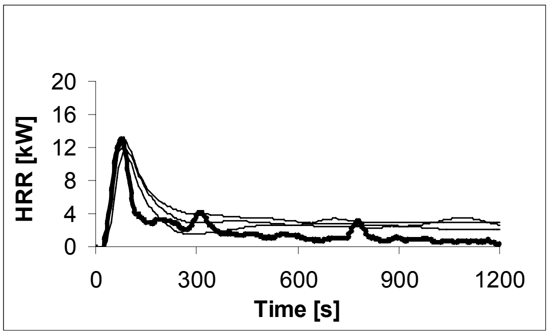
Test	FIGRA	THR_{600s}	Class
SBI	**25**	**2.3**	**B**
cc1	29.1	2.4	B
cc2	35.5	2.6	B
cc3	34.6	2.7	B

Painted paper-faced gypsum board (M08)



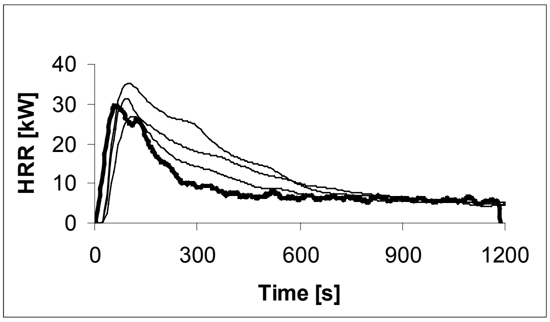
Test	FIGRA	THR_{600s}	Class
SBI	**16**	**0.8**	**B**
cc1	82.8	1.5	B
cc2	71.4	1.7	B
cc3	81.2	2.1	B

Paper wallcovering on gypsum (M09)



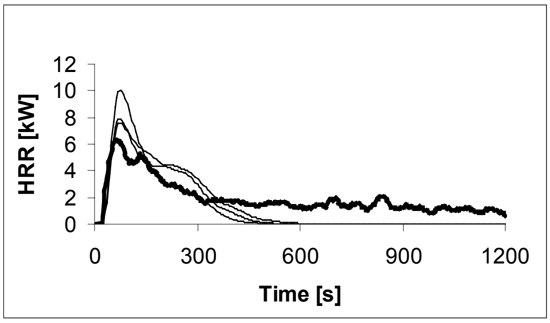
Test	FIGRA	THR_{600s}	Class
SBI	**202**	**1.4**	**C**
cc1	162.8	2.1	C
cc2	141.6	2.5	C
cc3	165.5	2.9	C

PVC wallcarpet on gypsum board (M10)



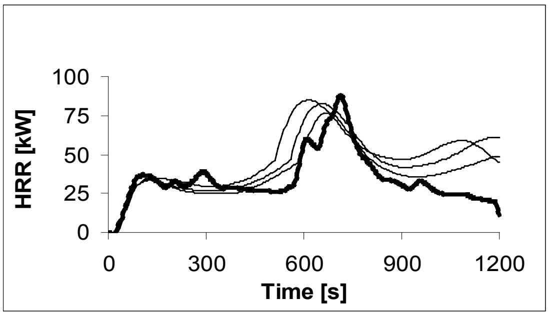
Test	FIGRA	THR_{600s}	Class
SBI	**380**	**6.5**	**D**
cc1	402.4	8.7	D
cc2	287.7	9.8	D
cc3	447.5	12.3	D

Plastic-faced steel sheet on mineral wool (M11)



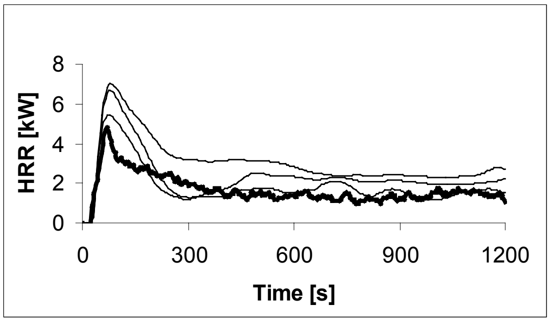
Test	FIGRA	THR_{600s}	Class
SBI	**78**	**1.2**	**B**
cc1	107.3	1.6	B
cc2	146.9	1.4	C
cc3	112.2	1.6	B

Mass timber (spruce) unvarnished (M12)



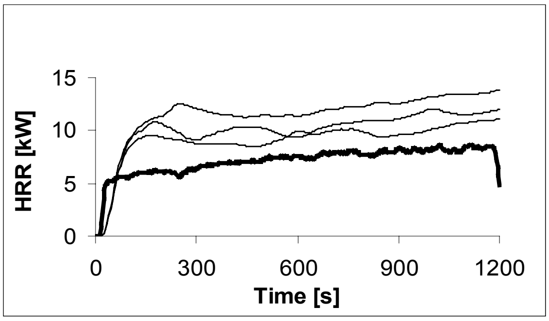
Test	FIGRA	THR_{600s}	Class
SBI	**440**	**15.7**	**D**
cc1	344.2	16.9	D
cc2	345.7	18.5	D
cc3	340.4	21.7	D

Gypsum board on polystyrene (M13)



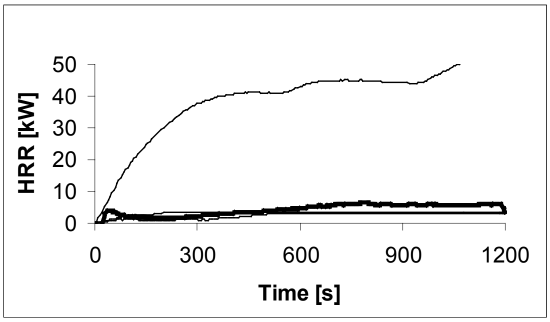
Test	FIGRA	THR_{600s}	Class
SBI	**9**	**0.8**	**B**
cc1	67.8	1.3	B
cc2	88.6	1.6	B
cc3	92.7	2.2	B

Phenolic foam (M14)



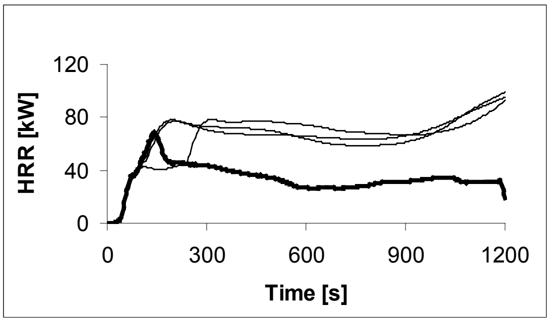
Test	FIGRA	THR_{600s}	Class
SBI	**82**	**3.2**	**B**
cc1	97.2	5.4	B
cc2	89.6	4.9	B
cc3	91.6	6.1	B

Intumescent coating on particle board (M15)



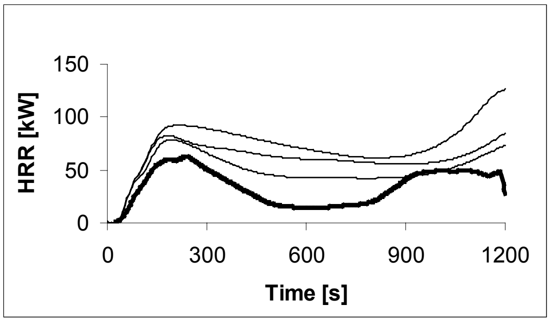
Test	FIGRA	THR_{600s}	Class
SBI	**16**	**1.9**	**B**
cc1	16.7	1.8	B
cc2	5.4	1.0	B
cc3	192.0	19.1	D

Melamine-faced MDF board (M16)



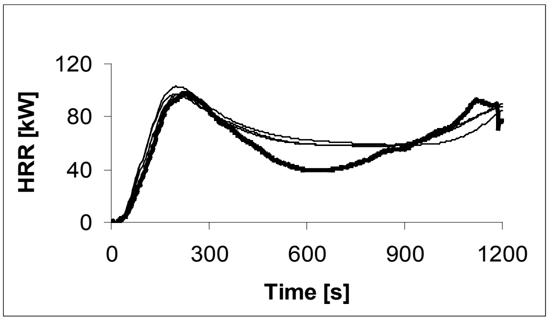
Test	FIGRA	THR_{600s}	Class
SBI	**601**	**24.0**	**D**
cc1	463.10	36.06	D
cc2	455.47	36.72	D
cc3	470.69	34.71	D

Melamine-faced particle board (M20)



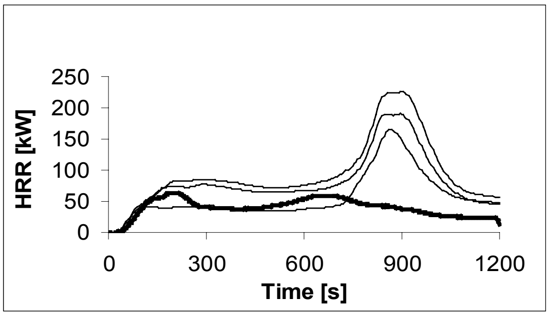
Test	FIGRA	THR_{600s}	Class
SBI	**381**	**20.1**	**D**
cc1	525.0	36.5	D
cc2	470.7	30.9	D
cc3	542.9	42.6	D

Ordinary particle board (M22)



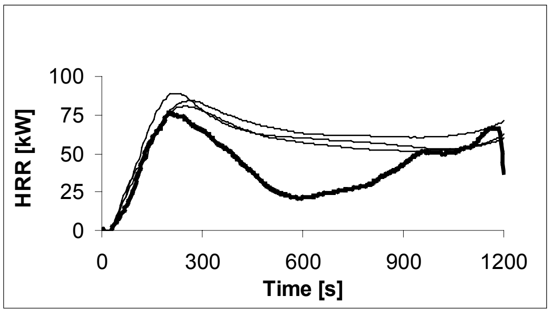
Test	FIGRA	THR_{600s}	Class
SBI	**404**	**26.9**	**D**
cc1	536.1	38.7	D
cc2	573.0	39.6	D
cc3	591.5	41.3	D

Ordinary plywood (birch) (M23)



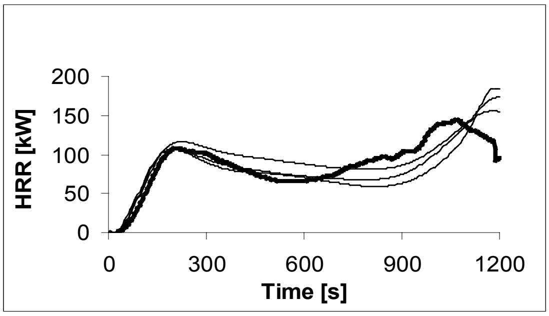
Test	FIGRA	THR_{600s}	Class
SBI	**399**	**21.7**	**D**
cc1	361.5	20.3	D
cc2	466.2	36.1	D
cc3	428.5	39.4	D

Paper wallcovering on particle board (M24)



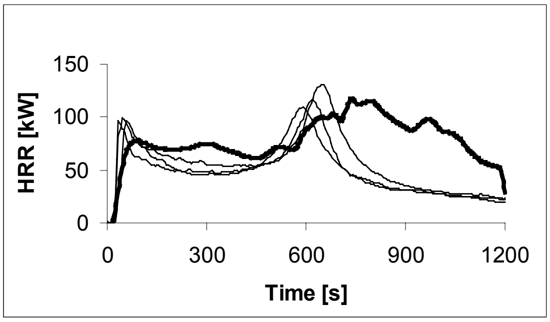
Test	FIGRA	THR_{600s}	Class
SBI	**479**	**26.7**	**D**
cc1	470.2	36.5	D
cc2	391.3	34.7	D
cc3	394.3	36.6	D

Medium density fibreboard (M25)



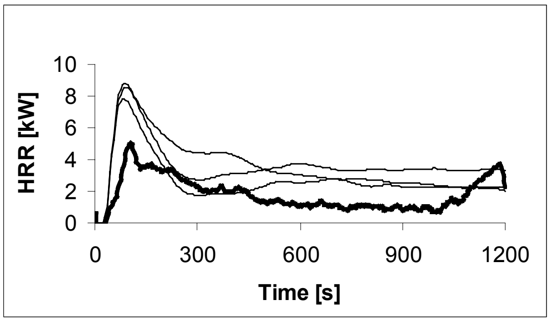
Test	FIGRA	THR_{600s}	Class
SBI	**436**	**33.4**	**D**
cc1	643.6	44.5	D
cc2	635.4	45.4	D
cc3	624.4	51.2	D

Low density fibreboard (M26)



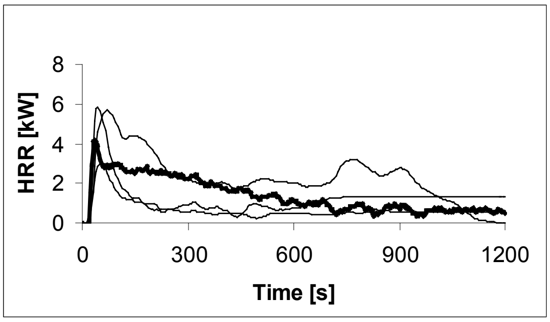
Test	FIGRA	THR_{600s}	Class
SBI	**1103**	**39.7**	**E**
cc1	1715.8	35.5	E
cc2	2741.1	33.9	E
cc3	2349.9	37.0	E

Gypsum board/PUR (M27)



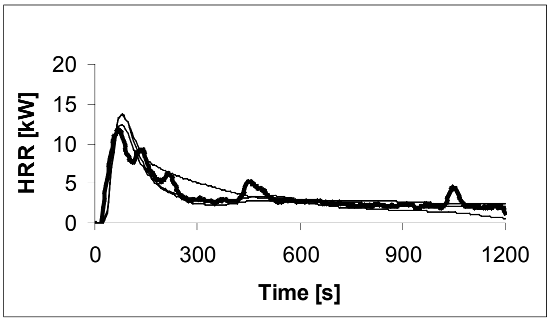
Test	FIGRA	THR_{600s}	Class
SBI	**17**	**0.7**	**B**
cc1	108.2	2.4	B
cc2	102.5	1.8	B
cc3	112.8	2.8	B

Acoustic mineral fibre tiles (M28)



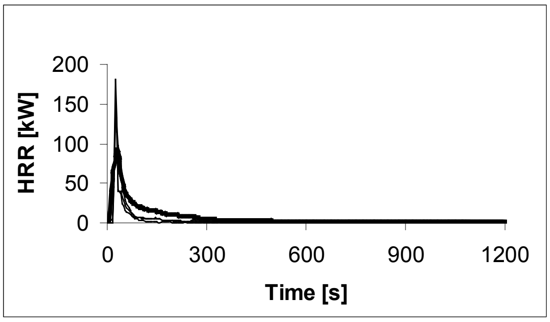
Test	FIGRA	THR_{600s}	Class
SBI	**0**	**0.7**	**B**
cc1	0.0	0.5	B
cc2	71.7	0.7	B
cc3	81.2	1.7	B

Textile wallpaper on CaSi board (M29)



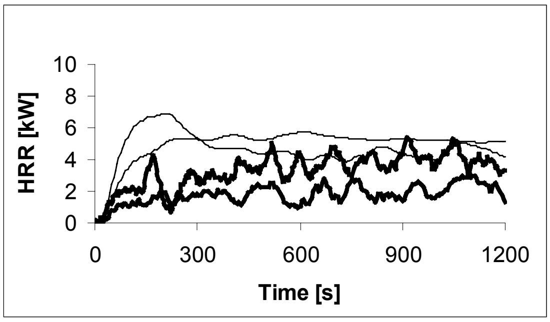
Test	FIGRA	THR_{600s}	Class
SBI	**162**	**1.9**	**C**
cc1	189.01	2.69	C
cc2	176.39	2.42	C
cc3	189.58	3.22	C

Paper-faced glass wool (M30)



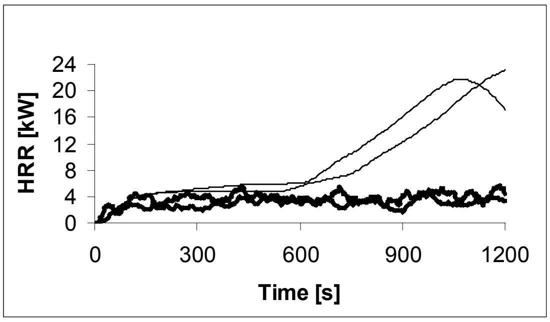
Test	FIGRA	THR_{600s}	Class
SBI	**4073**	**6.7**	**E**
cc1	7210.2	4.0	E
cc2	6141.1	3.5	E
cc3	5344.3	3.6	E

FR Spruce panel. 170 kg FR/m^3 (ZA)



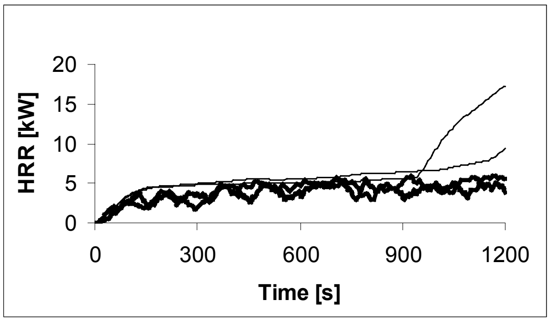
Test	FIGRA	THR_{600s}	Class
SBI-1	**26**	**1.6**	**B**
SBI-2	**0**	**0.9**	**B**
cc1	33.7	2.7	B
cc2	57.6	2.9	B

FR Spruce panel. 105 kg FR/m^3 (ZB)



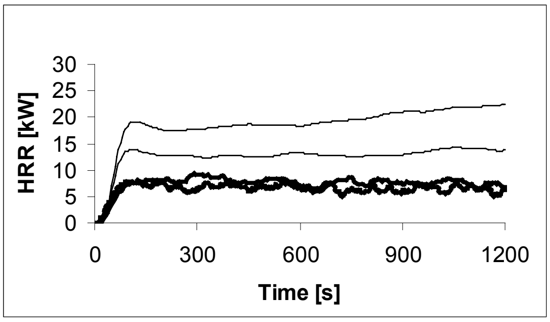
Test	FIGRA	THR_{600s}	Class
SBI-1	**38**	**2.1**	**B**
SBI-2	**15**	**1.7**	**B**
cc1	32.5	2.5	B
cc2	32.2	2.8	B

FR Spruce panel. 65 kg FR/m^3 (ZC)



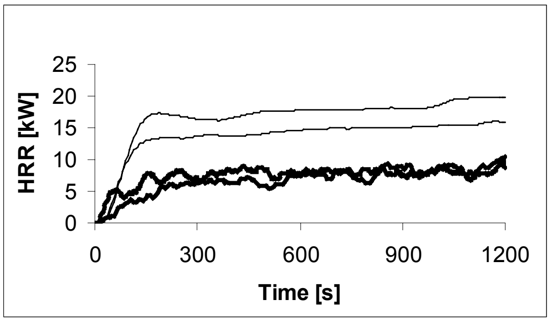
Test	FIGRA	THR_{600s}	Class
SBI-1	**29**	**1.9**	**B**
SBI-2	**34**	**2.3**	**B**
cc1	32.4	2.5	B
cc2	33.8	2.7	B

FR Spruce panel. 35 kg FR/m^3 (X)



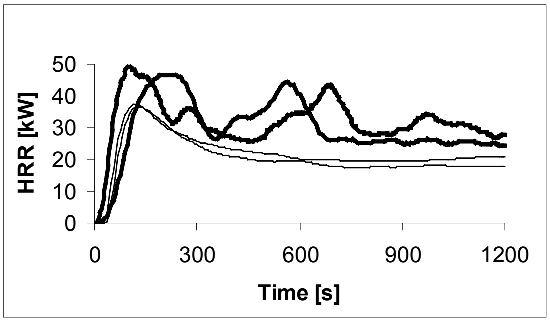
Test	FIGRA	THR_{600s}	Class
SBI-1	**94**	**3.9**	**B**
SBI-2	**123**	**4.4**	**C**
cc1	203.6	9.9	C
cc2	159.3	7.1	C

FR Spruce panel. 55 kg FR/m^3 (Y)



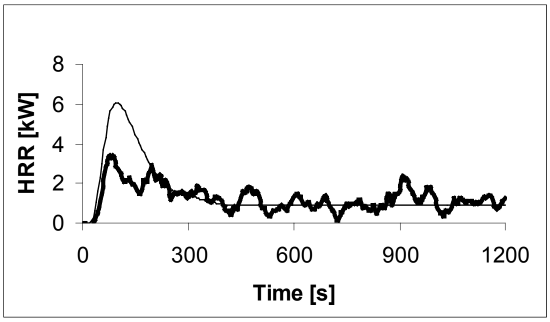
Test	FIGRA	THR_{600s}	Class
SBI-1	**77**	**4.1**	**B**
SBI-2	**48**	**3.8**	**B**
cc1	118.1	8.8	C
cc2	103.2	7.2	B

Spruce panel. untreated (O)



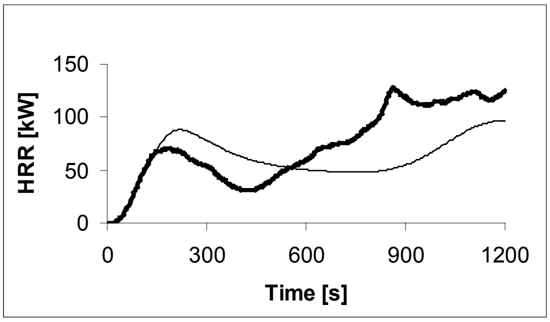
Test	FIGRA	THR_{600s}	Class
SBI-1	**595**	**19.3**	**D**
SBI-2	**494**	**18.4**	**D**
cc1	343.9	13.7	D
cc2	387.2	14.7	D

Paper-faced gypsum board (A01)



Test	FIGRA	THR_{600s}	Class
SBI	**0**	**0.9**	**B**
cc1	66.4	1.2	B

Ordinary particle board (A02)



Test	FIGRA	THR_{600s}	Class
SBI	**470**	**26.6**	**D**
cc1	463.1	34.8	D

APPENDIX IV:
SBI SPR simulation results

Structure of Appendix IV

Results from SBI SPR simulations are listed in this appendix in the following order:

M01-M30 (see Table 3-1)

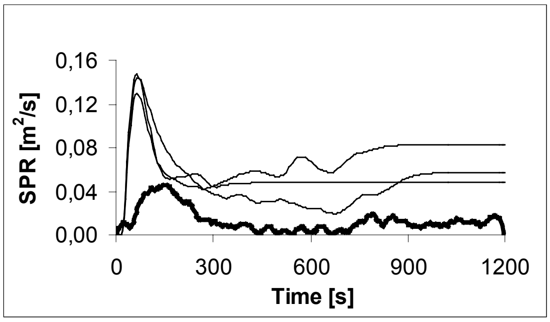
O, ZA, ZB, ZC, X, Y, A01, A02 (see Table 3-6)

For each product a graphical presentation of the SPR measured in one single (or two) representative SBI test is shown with a bold line, and the simulated results are shown with thinner lines. Observe that the scale on the ordinate differ from figure to figure.

Values for SMOGRA and TSP_{600s} are tabulated below each figure together with the obtained classification. The SMOGRA values are calculated with threshold values SPR> 0.1 m^2/s and TSP> 6 m^2 according to prEN 13823.

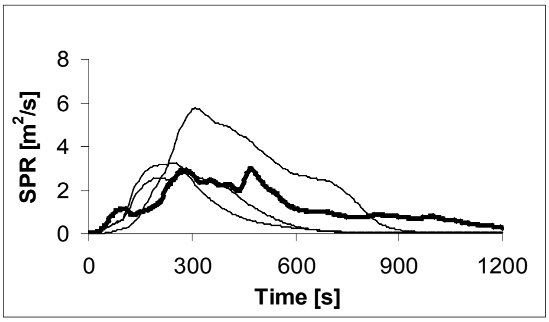
The values calculated based on the real SBI test are shown in bold types, and the test is designated *SBI*. For the products M01-M30 the bold values are the resulting averaged values from the SBI round robin programme as published in prEN13823:2001. The Cone Calorimeter tests used for simulations are designated cc1, cc2 and cc3, and the simulated values are printed in normal types.

Paper-faced gypsum board (M01)



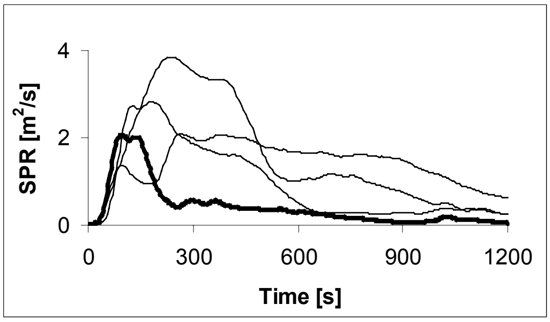
Test	SMOGRA	TSP_{600s}	Class
SBI	**0**	**29**	**s1**
cc1	17.3	31.5	s1
cc2	13.6	35.7	s1
cc3	16.9	34.5	s1

FR PVC (M02)



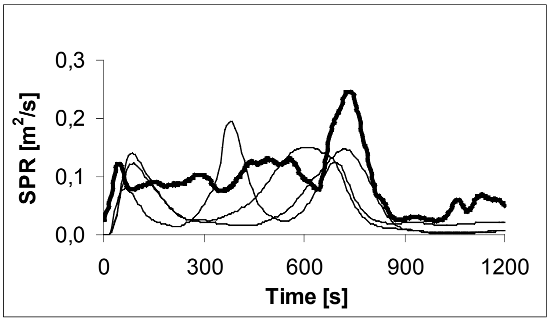
Test	SMOGRA	TSP_{600s}	Class
SBI	**120**	**937**	**s3**
cc1	138.7	942.2	s3
cc2	171.6	841.8	s3
cc3	190.7	1818.2	s3

PUR foam panel with Al-foil faces (M04)



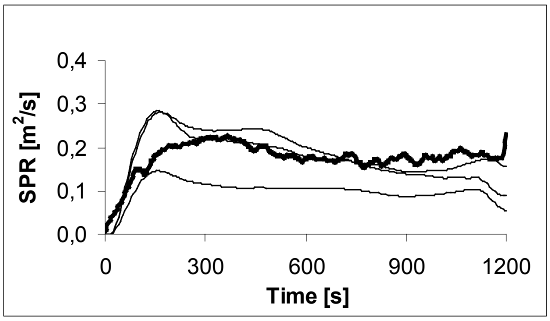
Test	SMOGRA	TSP_{600s}	Class
SBI	**212**	**410**	**s3**
cc1	69.3	949.0	s3
cc2	55.2	1409.3	s3
cc3	156.1	919.8	s3

Mass timber (pine). varnished (M05)



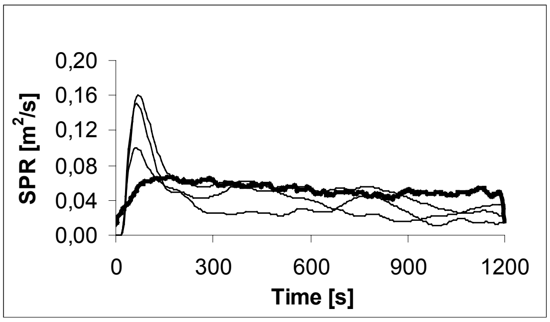
Test	SMOGRA	TSP_{600s}	Class
SBI	**2**	**45**	**s1**
cc1	5.2	34.5	s1
cc2	14.4	27.2	s1
cc3	11.9	40.3	s1

FR chipboard (M06)



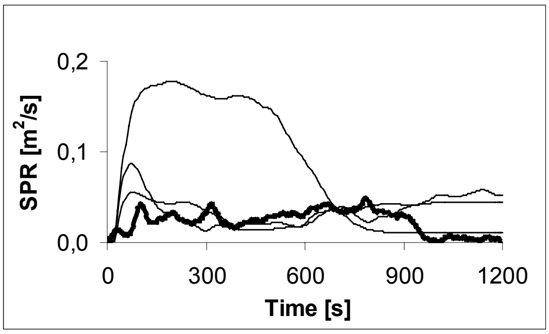
Test	SMOGRA	TSP_{600s}	Class
SBI	**12**	**101**	**s2**
cc1	20.8	129.9	s2
cc2	22.2	120.7	s2
cc3	11.2	63.1	s2

Painted paper-faced gypsum board (M08)



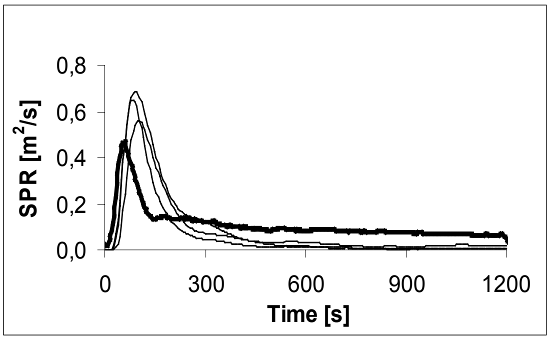
Test	SMOGRA	TSP_{600s}	Class
SBI	**0**	**29**	**s1**
cc1	21.1	41.1	s1
cc2	19.3	35.1	s1
cc3	0.0	23.5	s1

Paper wallcovering on gypsum (M09)



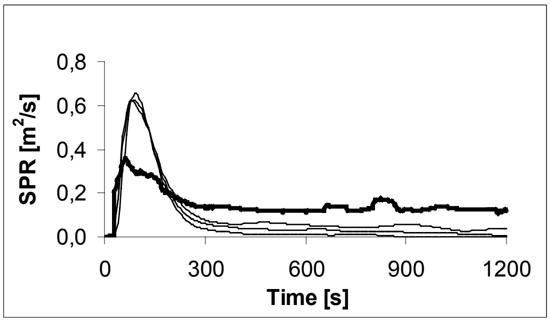
Test	SMOGRA	TSP_{600s}	Class
SBI	**0**	**30**	**s1**
cc1	18.3	86.5	s2
cc2	0.0	17.9	s1
cc3	0.0	18.0	s1

PVC wallcarpet on gypsum board (M10)



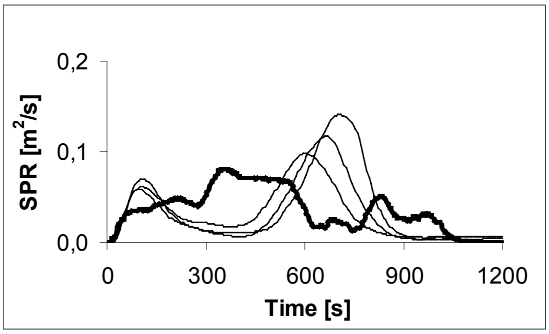
Test	SMOGRA	TSP_{600s}	Class
SBI	**114**	**164**	**s2**
cc1	84.7	75.1	s2
cc2	60.6	81.8	s2
cc3	84.3	107.2	s2

Plastic-faced steel sheet on mineral wool (M11)



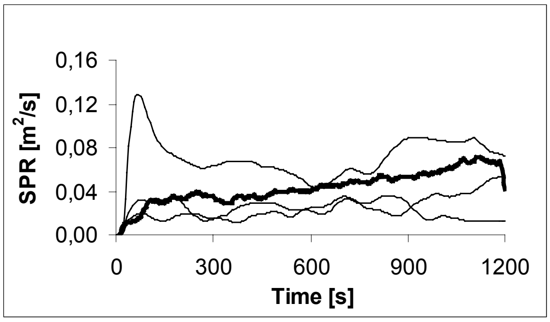
Test	SMOGRA	TSP_{600s}	Class
SBI	**67**	**108**	**s2**
cc1	82.6	93.4	s2
cc2	78.2	80.5	s2
cc3	87.5	104.2	s2

Mass timber (spruce) unvarnished (M12)



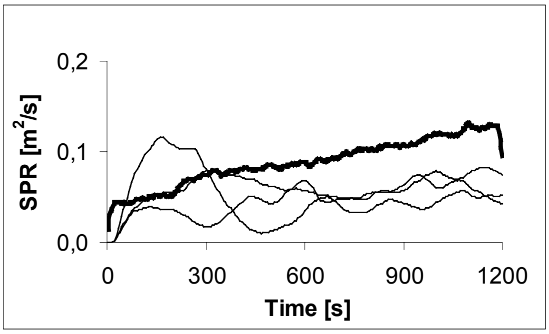
Test	SMOGRA	TSP_{600s}	Class
SBI	**3**	**47**	**s1**
cc1	1.8	17.1	s1
cc2	2.0	17.0	s1
cc3	0.0	23.3	s1

Gypsum board on polystyrene (M13)



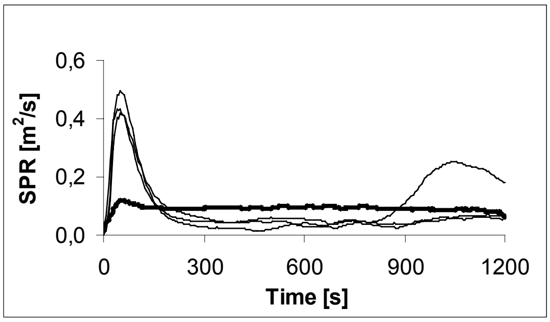
Test	SMOGRA	TSP_{600s}	Class
SBI	**0**	**34**	**s1**
cc1	0.0	9.8	s1
cc2	0.0	14.4	s1
cc3	14.2	40.9	s1

Phenolic foam (M14)



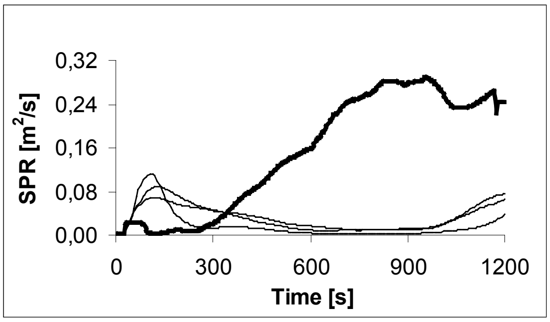
Test	SMOGRA	TSP_{600s}	Class
SBI	**1**	**43**	**s1**
cc1	0.0	34.2	s1
cc2	0.0	21.3	s1
cc3	8.1	33.2	s1

Intumescent coating on particle board (M15)



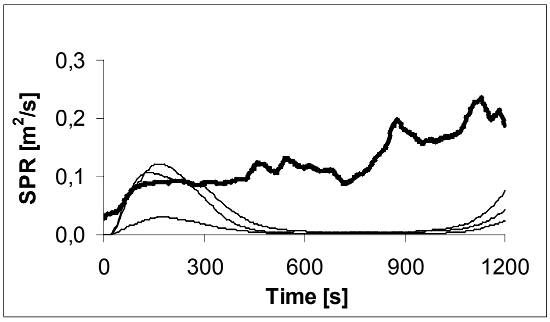
Test	SMOGRA	TSP_{600s}	Class
SBI	**1**	**55**	**s2**
cc1	131.5	64.4	s2
cc2	120.1	58.6	s2
cc3	100.6	64.9	s2

Melamine-faced MDF board (M16)



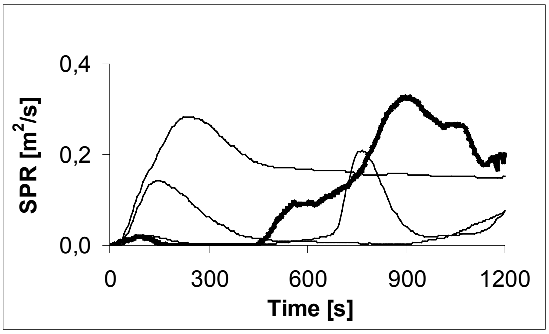
Test	SMOGRA	TSP_{600s}	Class
SBI	**1**	**24**	**s1**
cc1	0.0	24.9	s1
cc2	0.0	23.9	s1
cc3	10.2	16.9	s1

Melamine-faced particle board (M20)



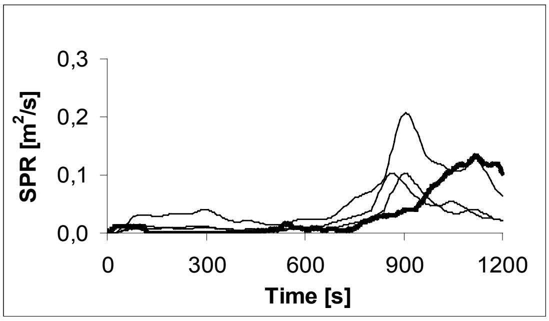
Test	SMOGRA	TSP_{600s}	Class
SBI	**2**	**39**	**s1**
cc1	8.5	31.9	s1
cc2	8.5	29.4	s1
cc3	0.0	8.0	s1

Ordinary particle board (M22)



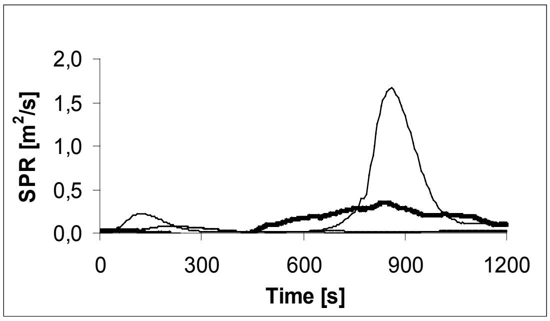
Test	SMOGRA	TSP_{600s}	Class
SBI	**3**	**29**	**s1**
cc1	2.7	4.2	s1
cc2	11.0	32.7	s1
cc3	14.0	112.4	s2

Ordinary plywood (birch) (M23)



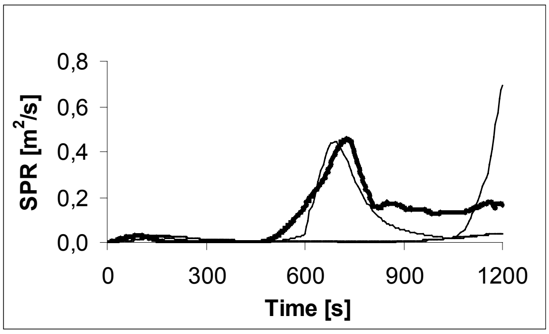
Test	SMOGRA	TSP_{600s}	Class
SBI	**1**	**19**	**s1**
cc1	2.3	14.4	s1
cc2	1.1	4.5	s1
cc3	1.2	4.1	s1

Paper wallcovering on particle board (M24)



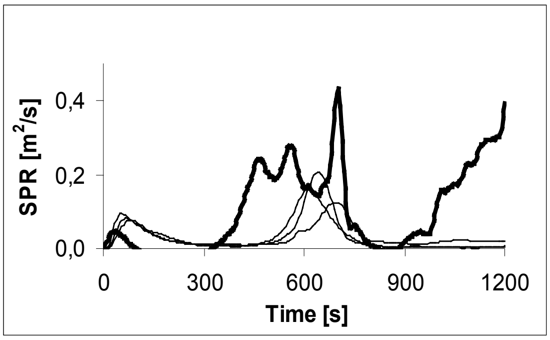
Test	SMOGRA	TSP_{600s}	Class
SBI	**2**	**18**	**s1**
cc1	20.4	35.5	s1
cc2	0.0	20.7	s1
cc3	0.0	21.3	s1

Medium density fibreboard (M25)



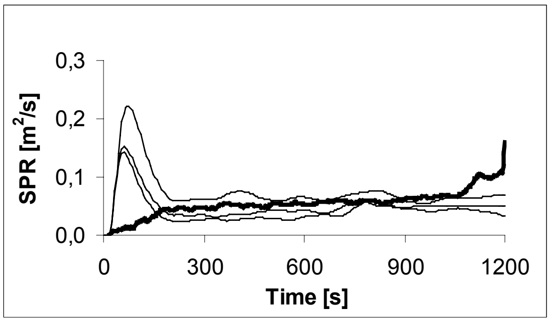
Test	SMOGRA	TSP_{600s}	Class
SBI	**1**	**20**	**s1**
cc1	6.4	7.1	s1
cc2	0.0	7.7	s1
cc3	0.0	6.8	s1

Low density fibreboard (M26)



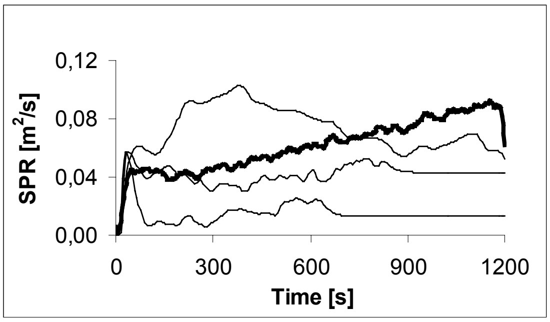
Test	SMOGRA	TSP_{600s}	Class
SBI	**9**	**79**	**s2**
cc1	2.6	20.1	s1
cc2	3.2	18.3	s1
cc3	1.8	16.4	s1

Gypsum board/PUR (M27)



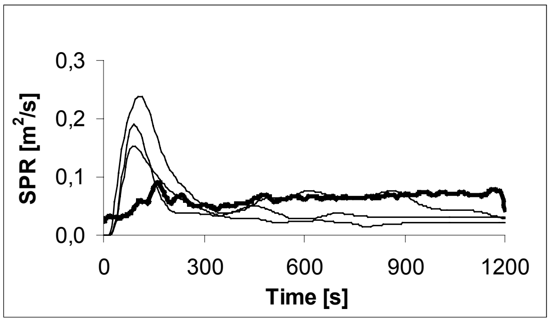
Test	SMOGRA	TSP_{600s}	Class
SBI	**0**	**30**	**s1**
cc1	15.5	24.3	s1
cc2	19.2	30.7	s1
cc3	31.7	50.2	s2

Acoustic mineral fibre tiles (M28)



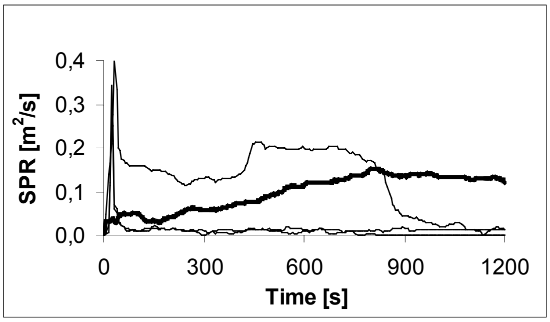
Test	SMOGRA	TSP_{600s}	Class
SBI	**0**	**31**	**s1**
cc1	0.0	23.1	s1
cc2	0.0	9.8	s1
cc3	2.8	47.4	s1

Textile wallpaper on CaSi board (M29)



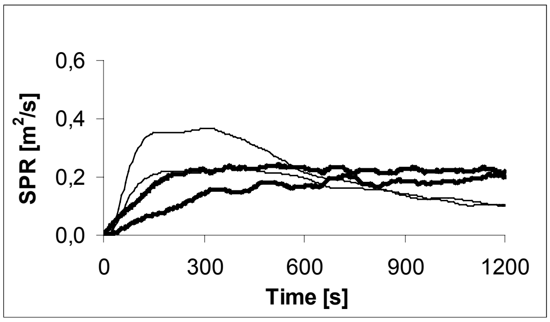
Test	SMOGRA	TSP_{600s}	Class
SBI	**0**	**31**	**s1**
cc1	22.03	34.68	s1
cc2	16.04	32.37	s1
cc3	26.93	54.09	s2

Paper-faced glass wool (M30)



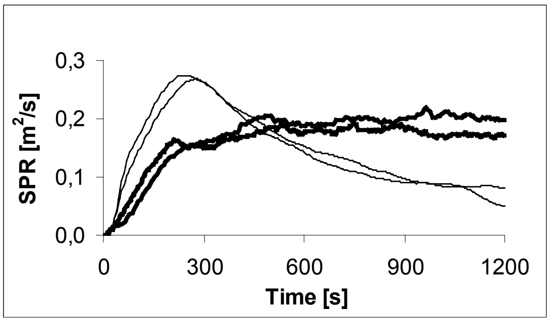
Test	SMOGRA	TSP_{600s}	Class
SBI	**3**	**43**	**s1**
cc1	0.0	10.8	s1
cc2	0.0	10.4	s1
cc3	114.1	97.2	s1

FR Spruce panel. 170 kg FR/m³ (ZA)



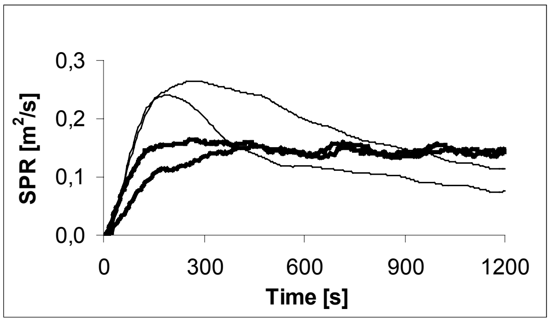
Test	SMOGRA	TSP_{600s}	Class
SBI-1	**11.7**	**114.3**	**s2**
SBI-2	**8.1**	**85.9**	**s2**
cc1	17.0	115.7	s2
cc2	29.7	173.8	s2

FR Spruce panel. 105 kg FR/m³ (ZB)



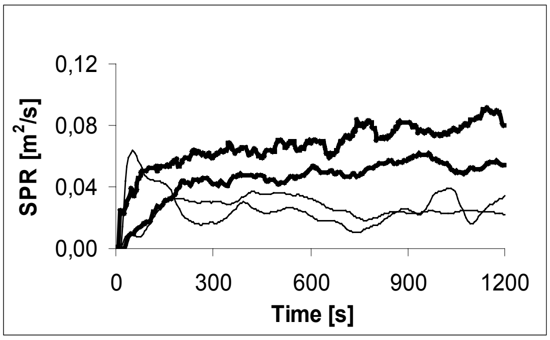
Test	SMOGRA	TSP_{600s}	Class
SBI-1	**8.4**	**82.8**	**s2**
SBI-2	**11.4**	**97.7**	**s2**
cc1	17.2	115.0	s2
cc2	13.9	111.9	s2

FR Spruce panel. 65 kg FR/m³ (ZC)



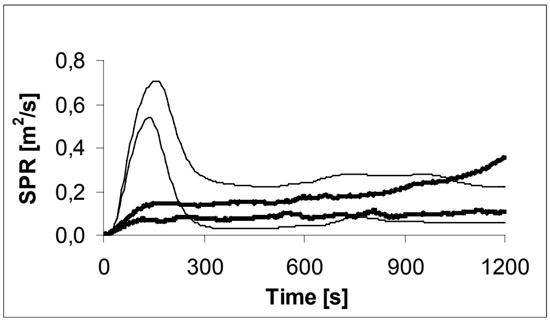
Test	SMOGRA	TSP_{600s}	Class
SBI-1	**12.2**	**82.7**	**s2**
SBI-2	**11.0**	**75.7**	**s2**
cc1	16.7	126.9	s2
cc2	17.8	95.8	s2

FR Spruce panel. 35 kg FR/m³ (X)



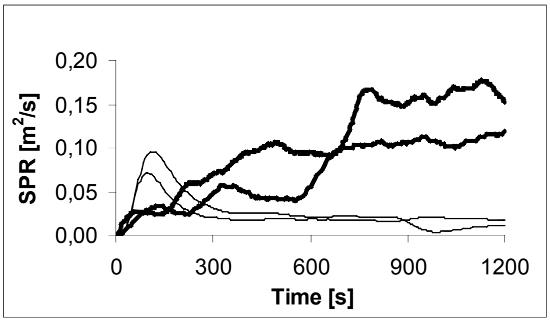
Test	SMOGRA	TSP_{600s}	Class
SBI-1	**0.0**	**34.4**	**s1**
SBI-2	**0.0**	**26.2**	**s1**
cc1	0.0	17.2	s1
cc2	0.0	16.6	s1

FR Spruce panel. 55 kg FR/m^3 (Y)



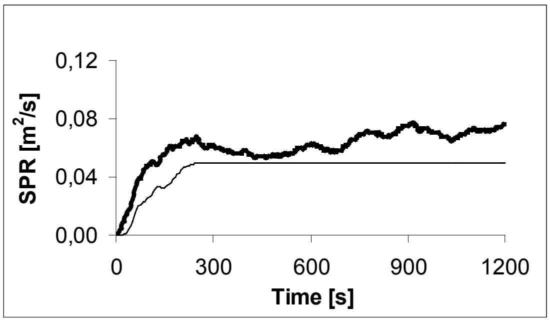
Test	SMOGRA	TSP$_{600s}$	Class
SBI-1	**1.9**	**43.1**	**s1**
SBI-2	**16.8**	**95.2**	**s2**
cc1	55.2	194.1	s2
cc2	44.8	84.4	s2

Spruce panel. untreated (O)



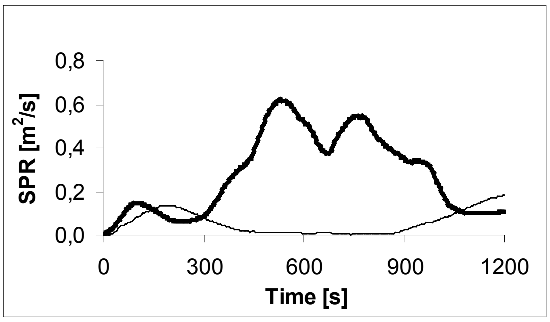
Test	SMOGRA	TSP$_{600s}$	Class
SBI-1	**2.2**	**39.1**	**s1**
SBI-2	**2.4**	**37.2**	**s1**
cc1	0.0	23.5	s1
cc2	0.0	16.5	s1

Paper-faced gypsum board (A01)



Test	SMOGRA	TSP$_{600s}$	Class
SBI	**0.0**	**31.5**	**s1**
cc1	0.0	24.4	s1

Ordinary particle board (A02)



Test	SMOGRA	TSP$_{600s}$	Class
SBI	**16.0**	**144.7**	**s2**
cc1	8.2	33.9	s1

PART II: PAPERS

This part is a collection of the following papers:

Paper I Hansen. A S. Heskestad A W. **Assessment of smoke atmospheres where loss of visibility is the limiting hazard.** Conference Proceedings 2nd International Symposium on Human Behaviour in Fire. 26/28 March 2001. Massachusetts Institute of Technology. USA. pp. 97-308. Interscience Communications Ltd. London UK. 2001. ISBN 0 9 5 3 2312 6 7

Paper II Hansen. A S. Hovde P J. **Prediction of Smoke Production in Large and Intermediate Scale Tests based on Bench Scale Test Results. A Multivariate Statistical Analysis.** Proceedings of Fire and Materials 2001 Conference. January 22-24 2001. San Francisco. USA. pp 363-374.

Paper III Hansen. A S. Hovde P J. **Prediction of time to flashover in the ISO 9705 Room Corner test based on Cone Calorimeter test results.** Submitted to *Fire and Materials*. May 2001. Revised January 2002.

Paper IV Hansen. A S. **Prediction of heat release in the Single Burning Item test.** Submitted to *Fire and Materials*. July 2001. Revised February 2002.

Paper V Hansen. A S. Hovde P J. **Prediction of smoke production based on statistical analyses and mathematical modelling.** Conference Proceedings Interflam 2001. Edinburgh. UK. September 17-19. 2001. Volume 1. pp 113-124.

Paper VI Hansen. A S. Hovde P J. **Simulation of smoke production in large-scale fire tests based on small-scale test results using multivariate statistical analysis to enhance predictability.** Submitted to The 7th International Symposium on Fire Safety Science (IAFSS 2002) October 2001.

ASSESSMENT OF SMOKE ATMOSPHERES WHERE LOSS OF VISIBILITY IS THE LIMITING HAZARD

Anne Steen Hansen[*] and Atle William Heskestad[**]
[*]Norwegian University of Science and Technology, Norway
[**] InterConsult Group ASA (ICG), Norway

ABSTRACT

Statistics on victims of fire show that the major threat for people in a building on fire is exposure to toxic gases in the smoke. As most fatal fires start as enclosure fires that develop to flashover and fully developed fires, this scenario should be focused in fire hazard analyses considering humans exposed to toxic and dense smoke atmospheres. A simple method for comparing hazards related to toxicity and optical density of a smoke filled atmosphere is presented. The toxicity is assessed when the smoke has spread some distance away from the fire room, and has been diluted and cooled by entrainment of ambient air. At this location the smoke density has been decreased sufficiently to make escape possible, which means that it has reached the point where loss of visibility is recognised not to be the limiting hazard. Through analyses of data from flashover fire experiments, we suggest a set of sensible input values for toxic gas concentrations and smoke production to be used in hazard analyses. The results are presented graphically and show the fraction of incapacitating unit as a function of light extinction coefficient.

1. INTRODUCTION

Fire represents threat to people in several ways. Exposure to flames, heat and toxic gases can affect people in such a way that they are unable to escape from the fire; they are *incapacitated*. Fire statistics from Norway[1] and USA[2] show that in fires with more than one fatality, the victims can be found quite a distance from the room of fire origin, and that the majority of fatal fires are flashover fires. The same statistical material also shows that most victims are overcome by smoke, and that carbon monoxide (CO) is responsible for the vast majority of these deaths. More than 60% of the victims die because of CO intoxication. The conclusion to be drawn from this material is that smoke inhalation from post-flashover fires is responsible for the majority of fire fatalities, and should be focussed for analyses of smoke hazard[3].

Loss of visibility is in many fire situations the condition that is determining for whether a person will be able to escape or not. Modest loss of visibility can slow down the movement speed during egress and prevent evacuating people from finding the closest exit[4], which in turn leads to prolonged exposure to toxic gases and thereby to higher exposure doses.

Through this paper we want to present a simple way of assessing the smoke hazard, both with respect to toxicity and with respect to visibility. Our assessment is based on data from several large-scale fire tests where flashover conditions were obtained. High smoke production is found to be closely connected to the event of flashover[5]. We want to focus on smoke atmospheres far away from the fire origin, and consider the concentrations of toxic gases and smoke density when the smoke has been mixed with entrained air. This atmosphere contains lower concentrations of toxic gases and soot than smoke close to the fire, and the temperature will be decreased to nearby ambient temperature. The aim of this study is to find a method to evaluate the conditions with focus on evacuation through smoke. When can escape through smoke be accepted, and which sort of aids (low leading lights, illuminated signs, tactile handrails etc) are necessary to increase way-finding effectiveness through smoke-filled atmospheres?

2. HAZARD ASSESSMENT OF EXPOSURE TO SMOKE

Assessment of loss of visibility

Jin did some extensive work in the 1970's where he related the smoke obscuration to movement speed through the smoke, and to visibility of exit signs[6, 7, 8]. The relation between visibility V and extinction coefficient k was found to be approximated by $V \cdot k = 2$. He concluded that for "non-irritating" smoke a light extinction coefficient below 1.2 m^{-1} (i.e. a visibility of 1.67 m) was necessary for people familiar with the building to be able to escape. An atmosphere filled with smoke with this density will be experienced as very difficult to move through. For irritating smoke, the limiting value will be lower, and Jin proposed 0.5 m^{-1}, which corresponds to a visibility of 4 meters. These limiting values have later been adopted by several researchers as benchmarks of the hazard represented by smoke[9,10]. Smoke with light extinction coefficient of 1.2 m^{-1} can be assumed to be highly irritant, although differences in irritancy are experienced between smoke with the same optical density[10].

Purser has introduced a specific parameter named FIC, for assessment of the loss of visibility hazard[11]. The parameter is simply the ratio between the measured extinction coefficient k and the extinction coefficient found to represent the limiting level for incapacitation.

Assessment of smoke toxicity

The hazard related to exposure to fire environments could be assessed by applying the concept of Fractional Effective Dose (FED)[12]. The original FED model is based on rat lethality data from experiments on exposure to a selection of important toxic gases (CO, HCN, HCl), and the idea is to add up effects from several toxicants to a single value, the FED. Effect of irritant gases to the total lethality is not included in the model. This model has later been expanded to take effects from heat exposure and low oxygen concentration into account. A similar concept of a fractional incapacitating dose for narcosis has also been published[10,13] and we have chosen to apply this concept to our fire test data presented in this paper. The aim of the referred model is to predict at what time the occupants exposed to the fire effluents will be incapacitated, i.e. when they become unable to escape from the fire because of toxic effects. The referred model is based on some assumptions:

1) CO and HCN are directly additive
2) CO_2 increases the rate of uptake of CO and HCN by increasing the respiratory rate. This is implemented in the model by use of a multiplication factor V_{CO2}.
3) Effect of low oxygen concentration is considered to be directly additive to the effects of CO and HCN.
4) The narcotic effect of CO_2 is acting independently of the other narcotic gases. If the concentration of CO_2 is 11.9%, the fractional incapacitating dose because of CO_2 equals 1.

The fractional incapacitating dose per minute for narcosis, F'_{IN}, is calculated by

Total $F'_{IN} = [(F'_{ICO} + F'_{ICN}) \times V_{CO2} + F'_{IO}]$ **or** F'_{ICO2} **Equation 1**

where

F'_{ICO} = fraction of an incapacitating dose of CO
F'_{ICN} = fraction of an incapacitating dose of HCN
VCO_2 = multiplication factor for CO_2 induced hyperventilation
F'_{IO} = fraction of an incapacitating dose of low oxygen concentration
F'_{ICO2} = fraction of an incapacitating dose of CO_2

The fractions of incapacitating dose per minute are calculated according to Equations 2 to 6.

$$F'_{ICO} = 8.2925 \cdot 10^{-4} \cdot \frac{\left(ppmCO^{\,1.036}\right)}{30}$$ **Equation 2**

$$F'_{ICN} = \frac{1}{\exp(5.396 - 0.023 \cdot ppmHCN)}$$ **Equation 3**

$$VCO_2 = \frac{\exp(0.1903 \cdot \%CO_2 + 2.0004)}{7.1}$$ **Equation 4**

$$F'_{IO} = \frac{1}{\left[\exp(8.13 - 0.54 \cdot (20.9 - \%O_2)\right]}$$ **Equation 5**

$$F'_{ICO2} = \frac{1}{\exp(6.1623 - 0.5189 \cdot \%CO_2)}$$ **Equation 6**

A Total F_{IN} value of 0.1, 0.5, 1 and 2 imply times to incapacitation of 10 minutes, 2 minutes, 1 minute and 0.5 minute respectively

Effects of exposure to heat from the fire can also be included in the model, but have been disregarded in our analysis. According to Purser, exposure to radiant and convective heat can be regarded as a separate threat, not directly affecting the uptake of toxic gases.

3. PARAMETERS DESCRIBING FIRE ATMOSPHERES

Smoke obscuration – the light extinction coefficient k

Exposure to smoke atmospheres will irritate eyes and mucous membranes, and thereby utterly decrease a person's ability to see, move and orientate through the smoke. Loss of visibility can indirectly be measured by determining the smoke obscuration. Smoke obscuration is measured in several fire tests, by determining attenuation of a light beam by the smoke. The parameter derived from such measurements is the light extinction coefficient k defined by Bouguer's law

$$\frac{I_\lambda}{I_\lambda^0} = e^{-k \cdot L}$$ **Equation 7**

where I_λ^0 is the initial light intensity and I_λ is the light intensity measured after the light beam has traversed a smoke filled path of length L. k is expressed in units of m^{-1}.

Generation of smoke and toxic gases

We assume here that for most materials smoke generation will be proportional to heat release[14]. This will be an appropriate assumption for most materials, exceptions are materials with high smoke production and low heat release, which will have to be considered separately. We define the smoke to heat ratio, S_Q, as

$$S_Q = \frac{SP}{HR} = \frac{SEA}{\Delta h_{c,eff}} \quad \mathbf{[m^2/MJ]}$$ **Equation 8**

where SP is the smoke production ([m^2/s] or [m^2]) and HR is the heat release ([MW] or [MJ]). SEA is the specific extinction area [m^2/kg] and $\Delta h_{c,eff}$ is the effective heat of combustion [MJ/kg]. The parameters can be expressed as instant or averaged values.

The yield of toxic gases produced in a fire can be expressed in relation to mass loss of combustible material. The yield is then expressed in units of g/g, i.e. mass of species produced divided with total mass loss of combusted material. The yield of species ***i*** is expressed as

$$Y_{species\ i} = \frac{mass\ produced_{species\ i}}{total\ massloss} \quad [g/g]$$ **Equation 9**

The yield can be normalised to the maximum obtainable yield of species i, $k_{species\ i}$, as calculated from the chemical reactions taking place in the fire. The normalised yield $f_{species\ i}$ is expressed as

$$f_{species\ i} = \frac{Y_{species\ i}}{k_{species\ i}}$$ **Equation 10**

Due to practical reasons, mass loss is not measured in full and real-scale fire tests and experiments. Alternatively, generation of fire effluents may be related to heat release[15]. The yield of species ***i*** is then calculated according to Equation 11 below. The index *Q* indicates the relation to total heat release.

$$species\ i_Q = \frac{mass_{species\ i}}{total\ heat\ released}\ \text{[g/MJ]} \qquad \textbf{Equation 11}$$

This is equivalent with normalising the yield of the species to the effective heat of combustion ($h_{c,eff}$) as shown in Equation 12.

$$species\ i_Q = \frac{mass_{species\ i}}{total\,heat\,released} = \frac{mass_{species\ i}\,/\,total\,mass\,loss}{total\,heat\,released\,/\,total\,mass\,loss} = \frac{Y_{species\ i}}{h_{c,eff}} \qquad \textbf{Equation 12}$$

$h_{c,eff}$ will to a certain degree depend on the fire conditions. In an intensely burning fire, the combustion of a product will be more complete than in a smaller fire, and this will affect the calculation of effective heat of combustion. This has to be taken into consideration when using this parameter in a hazard assessment. Another way of using this concept is to start with a proper value for $h_{c,eff}$, either as a value measured in a small-scale test, or a value based on scientific considerations.

We assume that the yields of CO_2 and HCN are scale independent, while the CO yield in small-scale tests is significantly less than in real scale room fires[16]. This is also the case for medium-scale well-ventilated fires. The yield of CO is closely connected to burning conditions, and a ratio between CO yield and heat release may be too inaccurate to be used in hazard assessments. In early stages of a fire, the CO yield will depend on the chemical composition of the burning fuel. When the fire has grown larger in size and the combustion is more intense, CO yield tends to be independent of material properties. A value of 0.2 g CO per grams of fuel burnt is reported as valid for underventilated fires with a high temperature in the upper layer[17], and this value is also recommended as a sensible value for use in hazard analyses[16].

The concentration of CO_2 will also depend on the fire conditions. In a well-ventilated fire, the yield of CO_2 is assumed to be near the maximal obtainable yield based on consideration of chemical reactions in the fire. When the fire becomes underventilated, the CO_2 yield will drop because of an increase in the amount of products from incomplete combustion, CO included.

The yield of HCN is also dependent of fire conditions, but may be more connected to the burning materials' chemical composition. HCN is expected to be present in smoke from all real building fires, because there will most probably always be nitrogen-containing products involved in the fire that are capable of producing HCN.

4. DATA FROM FIRE EXPERIMENTS

One of our interests here is to evaluate large fires, i.e. fires that lead to flashover, and spread large amounts of smoke and toxic species to a larger volume than the room of origin. To cover this scenario, we have studied large-scale test fires that developed to flashover conditions. Also fires of single pieces of furniture were studied, to cover the scenario of a furniture fire in a compartment not leading to flashover, however capable of spreading significant amounts of smoke and toxic gases to adjacent areas. A more extensive study of data from the furniture calorimeter should be performed to get valid and useful input data for hazard analyses.

Presented here are analyses using experimental data from the following tests:

- the Room/Corner test for 15 surface products, ISO 9705
- the furniture calorimeter, NT FIRE 032
- test results from modelling of the fire on the passenger ferry "Scandinavian Star" in 1990.

The selection of tested products covers a range of materials with "normal" combustibility (like wood products) to highly combustible products (like polyurethane foam).

Calculations of smoke density and gas concentrations

We have chosen to calculate the different parameters for the hazard analysis over the periods with the highest rates of heat release, i.e. post-flashover conditions. In practice, this means that for the results from the Room/Corner tests, the values selected for our calculations were averaged over the period with heat release rate above 1 MW, which is defined as the point of flashover. For the "Scandinavian Star" experiment, the values were averaged over a period of about 7 minutes when heat release rate increased from 1 MW to about 15 MW and until the fire was extinguished. For the furniture tests, we calculated averaged values over the periods of highest heat release rates, typically above 200-400 kW.

There are many considerations to be taken when selecting values to be used in a fire hazard analysis. In the "Scandinavian Star" experiment, a corridor section connected to a two-floor staircase was resembled to simulate the real geometry onboard the ferry. The fire in the surface laminate in the corridor was so intense, that flames emerged into the exhaust duct where gas samples were taken for analysis. This affected the measurement of different gas species, and a high degree of critical sense was required to select the proper values for our analysis.

Smoke production

It has been shown in a previous work[18] that the parameter S_Q were scattered over a range between 10 and 40 m^2/MJ for a range of tested products, but with the majority of S_Q results close to 10 m^2/MJ. These considerations are also supported by our recent data analyses, and we assume that a value of S_Q equal to 10 m^2/MJ will be a sensible choice for use in simple approximations of smoke production at flashover conditions. Products known to produce exceptional high amounts of smoke must, of course, be considered separately, using a higher value for S_Q.

Production of HCN

Looking at our test data material, we find that HCN yield normalised to heat release is spread over the range between 0 and 0.3 g/MJ. In the Scandinavian Star experiment, the ratio reached a level of about 0.3 g/MJ for heat release rates between 10 and 15 MW. We choose to apply a preliminary value for HCN_Q of 0.15 g/MJ, and rather evaluate the possibility of high HCN production from case to case. Such considerations could be based on results from small-scale testing of the materials under consideration.

Production of CO_2

An analysis of our data set shows that the CO_2 production cannot be normalised to the heat release. Such normalised values are scattered from 12 to 540 g/MJ in our limited data material. However, the effect of CO_2 on people exposed to fire smoke, is that breathing rate is increased, the result being a larger uptake of toxic gases. A CO_2 concentration of 3-4 vol% will result in a doubling in breathing rate.

In our data set, the CO_2 concentration in the smoke at flashover is above 5 %. In the Scandinavian Star experiment, the CO_2 concentration reached a value of 12 vol%. We have chosen a value of 6 vol% CO_2 to represent flashover fires. Looking at CO_2 production relative to heat release rate, we find a large spread in the test results. Excluding the extreme values, we find that an average value of 75 g/MJ could be used as a representative value for CO_2 production for fires at flashover and post-flashover conditions.

The calculated results for S_Q, CO_Q, HCN_Q and $CO2_Q$ are shown graphically in Figure 1 below.

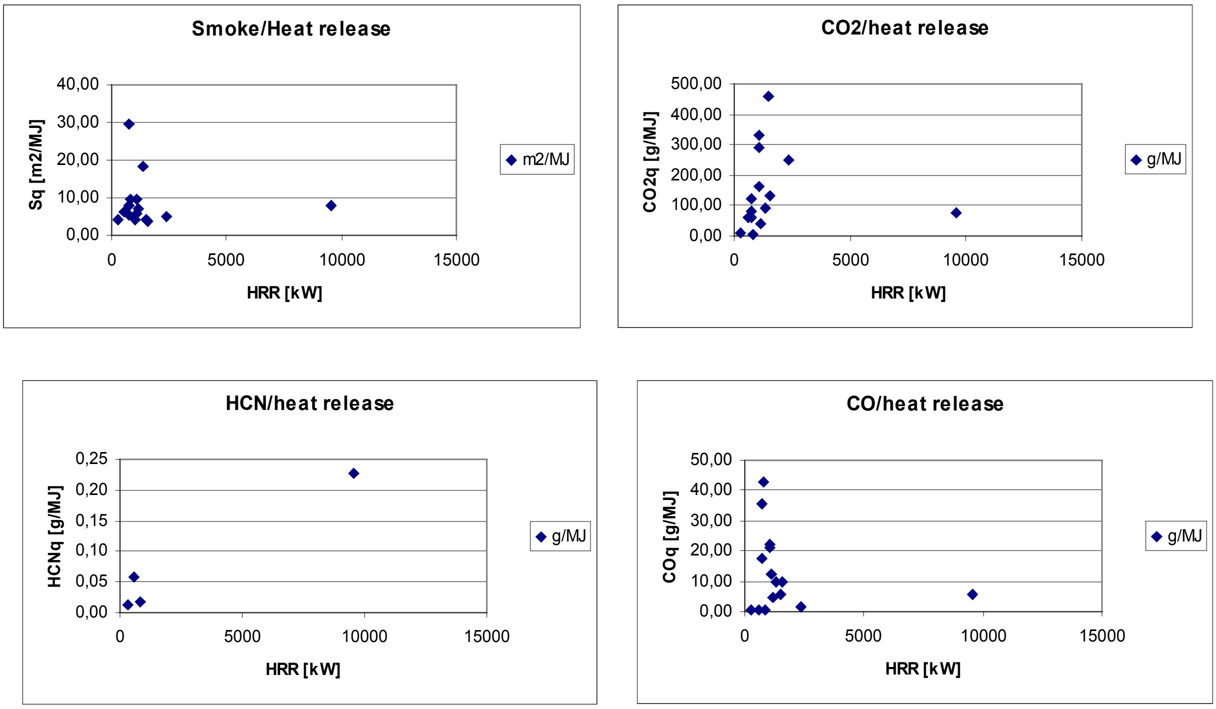


Figure 1 S_Q, CO_Q, HCN_Q and $CO2_Q$ calculated from the test data set described in the text. The values on the abscissa are averaged maximum heat release rate for the different single tests.

Based on the discussion in paragraph 3 in conjunction with analysis of data from the fire experiments mentioned above, we have chosen the following values to represent generation of specific fire effluents in a fire at flashover conditions:

- $[O_2]$: the concentration of O_2 will be near ambient concentration when smoke is transported away from the fire room and diluted by ambient air. The narcotic effect of low O_2 can therefore be excluded from the analysis.
- $[CO_2]$ = 3 vol% or 75 g/MJ

- CO-generation = 0.2 g/g fuel burnt
- HCN-generation = HCN_Q = 0.15 g/MJ
- Smoke generation = S_Q = 10 m^2/MJ

Assessment of toxicity

After the values for O_2 concentration and production of CO, CO_2, HCN and smoke were selected, the values for fraction of incapacitating dose were calculated according to Equations 2 to 6. These calculated values then represent the toxicity of the smoke as measured in a specific volume directly outside the room on fire. We then assumed that this original volume is spread outside the room, and where it is diluted by entrainment of ambient air. The resulting concentrations of visible smoke and the different gas species are calculated in this new atmosphere, and these values are used as input to the equations for fraction of incapacitating dose. Our objective is to study the toxicity of a smoky atmosphere when visibility is reaching the limit for incapacitation, i.e. when the extinction coefficient k gets close to a value of 1.2 m^{-1}.

5. RESULTS

The fractions of incapacitating dose were calculated using the measured concentrations of CO, CO_2, O_2, HCN and smoke density in the simulation of the fire on the passenger ferry "Scandinavian Star". The values used in this analysis are measured values averaged over a period of 7 minutes in the stage of flashover, where heat release rates as high as 15 MW were measured. The input values were as follows:

Smoke production:	77 m^2/s
S_Q:	8.1 m^2/MJ
Extinction coefficient, k:	7.4 m^{-1}
[CO]	11306 ppm
[CO_2]	9.4 %
[HCN]	451 ppm
[O_2] =	8.8 vol%
Exhaust gas temperature:	634 K
Volume flow, V_{298}:	4.4 m^3/s
Heat release rate:	9.6 MW

We then simulated dilution of this initial volume with ambient air, and we assumed that the temperature in this diluted volume is at room temperature, i.e. 298 K. The resulting curves for Fraction of incapacitating units for CO, HCN and the combinations of CO, HCN, O_2 and CO_2, are shown in Figure 2 below.

As can be seen from Figure 2, the combined fraction of incapacitating units is calculated to be about 0.13 min^{-1} when k=1.2 m^{-1}. This implies a time to incapacitation of $(0.13)^{-1}$ min = 7.7 min for people trying to escape when the smoke has been diluted to an optical density that make egress possible.

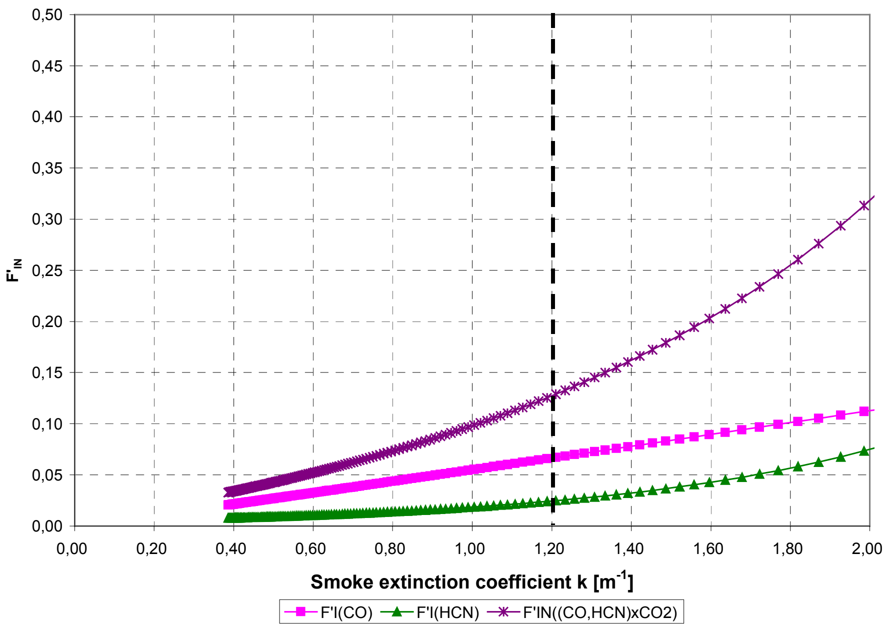


Figure 2 Fractions of incapacitating units for each single gas CO, HCN and O_2, and the combined effect of all gases including increased breathing rate caused by CO_2. The figure shows the toxicity expressed as fraction of incapacitating dose per minute related to smoke extinction coefficient k. The value of k= 1.2 m^{-1} is representing the limiting smoke density where escape is being hindered.

In our second calculation example, we want to show how a simple hazard assessment of toxicity related to smoke density can be made using a set of sensible input parameters for the analysis. We assume that a fire in an enclosure develops to flashover, and reaches a heat release rate of 2 MW. The developed fire is underventilated, and the fire effluents leave the enclosure at a rate of 4 m^3/s (at T=298 K), and the temperature of the effluents is 700 K. Effective heat of combustion for the materials in the enclosure is set to 17 MJ/kg. Using the values suggested in paragraph 4, we get the following characterisation of the smoke from this fire:

Smoke production = $S_Q \cdot$ HRR = 10 m^2/MJ · 2MW = 20 m^2/s

$$k = \frac{SEA}{V_T} = \frac{20}{4 \cdot \frac{700}{298}} \; m^{-1} = 2{,}13\, m^{-1}$$

$$CO\ production = \frac{HRR}{\Delta h_{c,eff}} \cdot 0{,}2 gCO / gfuel = \frac{2}{17} \cdot 0{,}2 kg\ CO / s = 23{,}5 g\, CO / s$$

$$[CO] = \frac{23{,}5 \cdot 10^{-3} kg / s \cdot 0{,}877 m^3 / kg}{4 m^3 / s} = 5159\, ppm$$

$[CO_2] = 3$ vol%

$$HCN\ production = \frac{0{,}3g/MJ}{2MW} = 0{,}15\,g\,HCN/s$$

$$[HCN] = \frac{0{,}15 \cdot 10^{-3}\,kg/s \cdot 0{,}909m^3/kg}{4m^3/s} = 34\,ppm$$

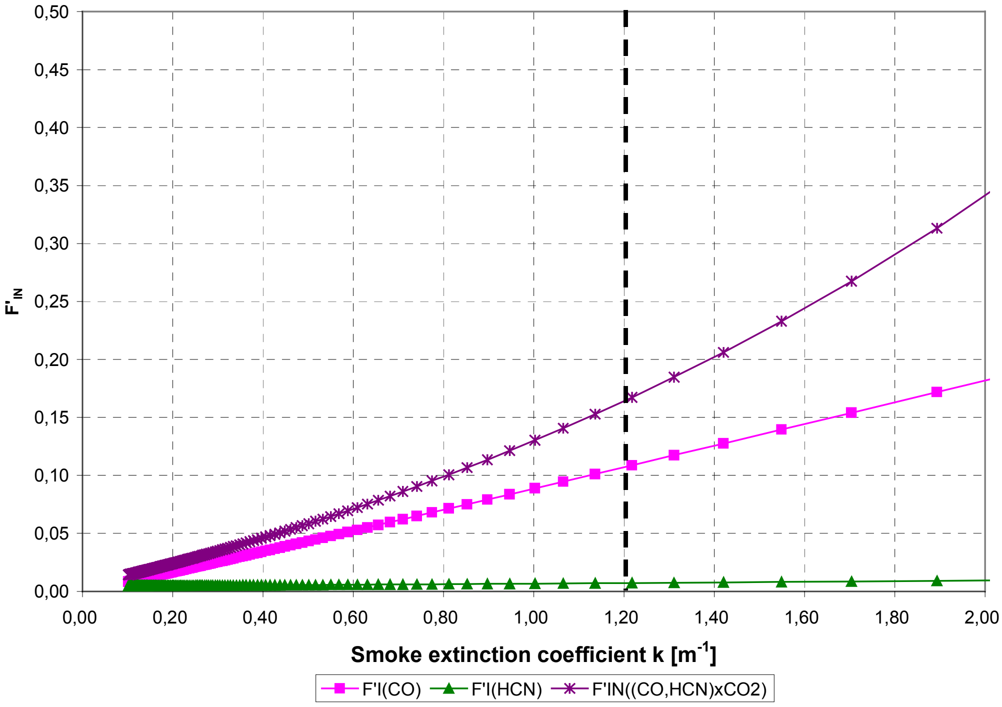


Figure 3 Fractions of incapacitating dose for each single gas CO and HCN, and the combined effect of them including increased breathing rate caused by CO_2. The figure shows the toxicity expressed as fraction of incapacitating dose per minute related to smoke extinction coefficient k. The value of k= 1.2 m^{-1} is representing the limiting smoke density where escape is being hindered.

As Figure 3 shows, the fraction of incapacitating unit for the combination of CO, HCN and CO_2 is about 0.16 min^{-1} when k reaches the value of 1.2 m^{-1}, which means a time to incapacitation of 6.3 minutes. The toxicity of CO combined with hyperventilation caused by elevated CO_2 concentration is responsible for incapacitation in this example. The concentration of HCN is too low to represent any hazard. According to Equation 3, the time to incapacitation when breathing in air containing 34 ppm HCN is more than 1½ hours. Other input values in this analysis would give different results. A doubling of the rate of CO_2 production would increase the breathing rate, and thereby decrease the available time to about 4.5 minutes before an evacuee is incapacitated. A twofold increase of the CO generation rate would result in a time to incapacitation of about two minutes, and would thus have a greater effect on the toxicity of the smoke filled atmosphere.

It should be emphasised that the presented results are sensitive to the production of HCN. Consideration of the data set used in Figure 2 (from the Scandinavian Star simulation) shows a ratio between concentrations of HCN and CO of 1:20. However, other sets of data present values as high as 1:5 [i]. An increase of the HCN concentration used in Figure 2 of 2 or 3 times, increases the F'_{ICN} value 5 or 28 times respectively.

6. DISCUSSION AND CONCLUSIONS

The point of the examples in paragraph 5 is not to present absolute values for toxicity of optically dense smoke filled atmospheres. Our intention is rather to demonstrate how the principles of calculated fractions of incapacitating units can be used in a very simplified hazard analysis of how toxicity and loss of visibility can be assessed in combination.

The generation rates for the different toxic components will affect the results, especially will the analysis be sensitive to the concentration of HCN. A selection of input values should be assessed carefully before any conclusions on toxic hazard are drawn. Main objectives to consider is effective heat of combustion for the materials involved in the fire, expected heat release at flashover and shortly after, ventilation conditions and the burning materials' propensity to produce HCN and smoke. The calculations should cover a range of different toxic gas concentrations.

In our work, we have disregarded effects of irritating smoke. High concentrations of irritating gases in the atmosphere will reduce a person's ability to escape, because of irritation of eyes, nose and mucous membranes. These effects should not be forgotten in a complete assessment of exposure to toxic gases in a fire.

Used together with a model for simulation of smoke spread, this method might be a useful tool for evaluation of escape routes where loss of visibility caused by smoke can be a problem. Using this method, available time to escape in case of a compartment flashover fire can be estimated, and serve as a basisi for consideration of the proper aids facilitating egress in a fire situation.

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PREDICTION OF SMOKE PRODUCTION IN LARGE AND INTERMEDIATE SCALE TESTS BASED ON BENCH SCALE TEST RESULTS. A MULTIVARIATE STATISTICAL ANALYSIS.

Anne Steen Hansen and Per Jostein Hovde
Department of Building and Construction Engineering,
Norwegian University of Science and Technology, Trondheim, Norway

ABSTRACT

Data from 28 different building products tested in the Cone Calorimeter at an incident heat flux level of 50 kW/m^2 have been analysed together with data for the same products tested in the SBI test and in the Room/Corner test. The analyses also include data from 24 products tested in the Cone Calorimeter and the Room/Corner test in two Nordic projects.

Multivariate statistical methods have been used to reveal correlations between results obtained through testing according to the three different methods. Multiple Discriminant Analysis (MDA) applied to the Cone Calorimeter data has been used to predict which smoke classification these materials would obtain in the new system of Euroclasses. Based on a limited selection of variables measured in the Cone Calorimeter, the classification can be predicted with a high level of confidence. MDA was also used to predict the level of smoke production in the Room/Corner test, and good models for smoke prediction were obtained. The success of these models, however, depends on reliable prediction of time to flashover in the Room/Corner test. A mathematical model is available, but need refinement to give a satisfactory level of prediction reliability. Development of prediction models based on statistical methods seems promising, and will be investigated further.

These simple classification models can be useful engineering tools in development of new building products, and will also be applicable for quality assurance and product control.

1. INTRODUCTION

One of the key test methods in the new European classification system is prEN 13823, the Single Burning Item (SBI) test[1]. ISO 9705, the Room/Corner test[2], is the reference scenario for the SBI test. Products that for some reason cannot be tested in the SBI apparatus will be tested according to the Room/Corner test. Both methods use the same principles for measurement of smoke production and heat release rate as the small scale Cone Calorimeter (ISO 5660)[3, 4, 5].

The purpose of this analysis is to find a tool with the ability to predict which smoke classification a certain product most probably will obtain in the new European system. The prediction shall be based on small scale testing in the Cone Calorimeter. Classification systems based on testing in the Room/Corner apparatus and in the SBI test are of interest. Smoke production is known to be a very complex phenomenon, dependent on parameters like material, burning conditions, geometry, fire intensity etc, and where the ventilation conditions may be the most important parameter. Differences in both geometry and ventilation in the three test methods in our project suggest that a simple correlation between single smoke variables cannot be expected, and therefore a multivariate attempt seems to be sensible. In this work, we have chosen to perform a Multiple Discriminant Analysis (MDA) on the variables calculated from the Cone Calorimeter tests.

2. STATISTICAL METHOD

Multiple discriminant function analysis, abbreviated MDA, is used to classify cases into groups. The groups are determined based on a categorically dependent variable, i.e. a variable that shows discrete values that can be assigned to discrete classes[6].

Discriminant function analysis can be used to
- classify cases into groups
- investigate differences between groups
- detect variables that are important for distinguishing between groups
- discard variables that are irrelevant for group distinctions

When a relation between groups and variables exist, MDA will find the simplest way of assigning cases to a set of predetermined groups. The classification is then governed by linear functions, which include only the variables that are most strongly related to the group distinction. The software system SPSS 9.0[7] gives the option to choose Fisher's linear discriminant function for classification of cases. The result of this analysis is a set of k linear functions, one for each of the k groups. A new case will be associated to the group which classification function obtains the highest value.

The theory behind discriminant functions assumes that each of k populations with p variables have a multivariate normal distribution with the same covariance matrix. Transformation of variables may be necessary to improve normality, stabilise variance and make distributions more symmetric. However, MDA is relatively robust against modest violations of the assumptions of multivariate normality and equal covariance matrix[6]. Other assumptions that should be met are that population sizes should not differ too much, and all cases should be independent. Residuals are assumed to be randomly distributed.

The results of MDA will be highly discrete, and will not give any predictions of the dynamics in smoke production in the larger test apparatuses. Interpretations of physical phenomena may, however, be apparent through examination of which combinations of variables that give good classification rules, and which weights these variables are given in the mathematical expressions.

Evaluation and validation of classification functions

Classification functions are constructed to be able to predict the group membership of future samples. Validation of classification functions can be performed by analysing how well a set of observations not used in building the classification functions are grouped. These cases belong to the *test set*, while the cases used for building the classification functions belong to the so-called *training set*. The proportion of correctly classified cases of the test set will normally be lower than the proportion of correctly classified cases from the training set. A simple measure of misclassification is the apparent error rate (APER), which is defined as the fraction of observations in the training set that are misclassified by the classification functions calculated from the very same training set[8]. The APER is easily calculated, but may give a too optimistic evaluation of the classification functions, because the same observations used to build the function are also used to evaluate it. The actual error rate (AER), is a measure of how well the functions perform when classifying future observations. For very large samples, the APER will be a good estimate of the AER. For smaller samples, alternative validation procedures should be applied.

There are several ways of separating data into a test set and a training set, and there are several ways to perform cross validation. We have used the method called *leave-one-out cross-validation*, where all but one case is used in designing the classification functions, and the last case is classified using the computed functions. Another attempt we have used is the so called *10-fold cross-validation*. The data set is then divided into 10 equally sized groups, where 9 groups resemble the training set, and the last group is the test set. In both methods, the validation procedure is repeated several times.

A third possibility is to randomly select a specific percentage of the data set to be held back as the test set, and then perform the analysis on the remaining cases resembling the training set. Splitting the data into two groups like this requires large numbers of observations to give reliable results. When not all data are used in building the functions, valuable information may be lost and the result may be less useful classification functions. By applying the leave-one-out cross-validation and the 10-fold cross-validation to the data set, this problem is avoided. However, the evaluation of the classification functions may have some positive bias using these procedures, which should be paid attention to.

3. EXPERIMENTAL STUDIES

Fire Test Methods

The test methods included in this analysis are the bench scale *Cone Calorimeter* test, the intermediate scale Single Burning Item test (*SBI*) and the large scale *Room/Corner* test. All methods use the oxygen consumption theory for calculating heat release based on measurements of O_2 and CO_2 in the exhaust gases. Smoke production is calculated based on measurements of attenuation of a light beam by smoke in the exhaust duct.

In the Cone Calorimeter, products are tested as horizontal specimens with a surface area of 0,01 m^2. The specimens are exposed to a constant incident heat flux density, and a spark igniter is the ignition source. The ventilation is unrestricted during the test period, which can vary between a few minutes to an hour, dependent on how well the specimen is burning. In the tests included in this study, all specimens were tested at a heat flux level of 50 kW/m^2.

The intermediate scale SBI requires a corner shaped specimen with a total area of 2,25 m^2. A propane burner placed in the corner exposes the specimen to 30 kW during the 20 minutes of test duration, and the fire is freely ventilated.

Next step on the test scale is the Room/Corner test where about 32 m^2 of the material is tested in a room configuration. A propane burner in the corner exposes the specimen to 100 kW during the first 10 minutes of testing time, and if no flashover is obtained, to 300 kW for the last 10 minutes. The ventilation of the test room is governed by the intensity of the fire; a product reaching flashover may lead to significantly underventilated fire conditions.

Tested Products

The products included in this analysis are 28 of the products tested in the European SBI Round Robin programme[9], 11 products tested in the Nordic EUREFIC programme[10] and 13 products tested in a Swedish research programme[11]. The tested products cover a range from products with very low combustibility (e.g. paper-faced gypsum plasterboard) via products with “normal” combustibility (e.g. wood products) to highly combustible products (e.g. expanded polystyrene foam). Non-homogeneous products, like thin surface materials attached to a backing material, are also included. References 9, 10 and 11 give detailed descriptions of these products.

The SBI Round Robin products are comprehensively tested in the SBI apparatus, where 15 different European laboratories performed 3 single tests of each product. In the round robin programme, each product was also tested once in the Room/Corner test. Additionally, these products were tested in the Cone Calorimeter at heat flux level 50 kW/m^2. Three different laboratories participated in this task, resulting in about 6 single tests per product.

The EUREFIC products are all tested once in the Room/Corner test, and twice in the Cone Calorimeter at heat flux level 50 kW/m^2. No SBI test results are available for these products. The Swedish products are tested once in the Room/Corner test and 2 or 3 times in the Cone Calorimeter. These products are not tested in the SBI apparatus.

Calculation of Variables from Experimental Results

When presenting variables calculated from test results, we have added a subscript (CC, R/C or SBI) to clarify which test each variable refers to. A large number of different variables calculated from the Cone Calorimeter tests were included in the analysis. The variables investigated are describing the fire development in the Cone Calorimeter with regard to

- how fast the fire starts and develops
- how much heat the material releases
- how much smoke the fire produces, and how fast it is released
- how much CO the fire produces, and how fast it is released
- ratios of different variables

The total testing time for the Cone Calorimeter tests varied from 90 seconds to 30 minutes, which raised the question for how long period the different investigated variables should be evaluated. Should for instance total smoke production be integrated over the total time of testing irrespective of the length of test, or should another, more "universal" period be chosen? To solve this problem, all variables of interest were calculated over test periods of *15 minutes* (measured from start of test) and over *total testing time*, to investigate how the results from the statistical analysis were affected. In cases where total testing time was below 15 minutes, *total testing time* was the only period used. Calculation for the first 10 minutes of testing was also considered, but we found this could eliminate important data for products with long burning times or low ignitability.

By exploring the different variables using the statistical computer software SPSS Base 9.0, it was shown that very few of the variables were satisfactorily close to a multivariate normal distribution. Common transformations used for enhancing normality of data sets are power transformations and logarithmic transformations, and the data set was prepared using such transformations.

After a thorough analysis of the variables, both with regard to statistical properties and with regard to which variables that worked best in the classification models, a set of 5 variables were chosen. These variables are transformations of the original variables calculated from the data set, and are described in Table 1 below. The original variables are multiplied by appropriate factors to give more conveniently scaled values. We have chosen to give the variables names that reflect their meaning. A "new" parameter, the COGRA, was invented, and the name is an acronym for CO Growth Rate. COGRA is calculated based on the same principles as calculation of FIGRA and SMOGRA from SBI test results[1].

Table 1 Investigated test results and calculated variables from fire tests in the Cone Calorimeter. The selected transformations result in variables that approximately follow a multivariate normal distribution.

Original variable, x	Transformation, f(x)	Transformed variable, z
Max HRR divided by time to max HRR, 30s sliding average, [$kW/s\cdot m^2$]	$\ln((x)^{-1/2})$	$z_1 = FIGRA_{CC}$
Total smoke produced, multiplied by 10^2, [m^2]	$x^{1/2}$	$z_2 = TSP_{CC}$
Max SPR divided by max HRR, 30s sliding average, multiplied by 10^6, [m^4/kJ]	$\ln(x)$	$z_3 = SP/HR_{CC}$
Total CO produced, multiplied by 10^3, [g]	$\ln(x)$	$z_4 = TCO_{CC}$
Max CO divided by time to max CO, 30s sliding average, multiplied by 10^6, [g/s^2]	$\ln((x)^{-1/2})$	$z_5 = COGRA_{CC}$

4. CORRELATING SMOKE PRODUCTION IN SMALL, INTERMEDIATE AND LARGE SCALE

There are two different strategies on how to choose the starting point of the multiple discriminant function analysis of the data from the Cone Calorimeter:

1. The first, and also the simplest strategy, is to perform the MDA on the data set without taking any notice of the history of heat release rate for each material in the large scale test. For prediction of smoke production in the SBI test, this means that the Euroclass system is not taken into consideration when the classification functions are designed. When predicting the smoke class for new cases, the same set of classification functions is used, and eventually the correct class is determined based on the function scores.

2. The second way is to first select important variables of the heat release development in large scale, and group the cases according to these variables. Each group will then consist of more or less "equally" behaving products with respect to heat release, and a specific set of classification functions is then designed for each group. For prediction of smoke production in the Room/Corner test, grouping can be based on different approaches where time to flashover is believed to be an important parameter. This alternative requires a separate calculation model or classification rule to be able to predict membership of the most probable "heat release group".

For prediction of smoke production in the SBI test, the first alternative is our first choice, because the test specimens in both the Cone Calorimeter and in the SBI test are freely ventilated.

When smoke production in the Room/Corner test is to be predicted, we assume that finding a model covering all products regardless of whether flashover is reached or not, will be very difficult. We have therefore chosen the second alternative solution for this case. A model that has been found to predict time to flashover in the Room/Corner test fairly well was presented within the EUREFIC project[12], and can be used to "pre-group" results from testing in the Cone Calorimeter. A refinement of this method is also under work[13]. Yet another model has been proposed by Östman[14]. A model based on multivariate statistical methods seems promising, and this attempt will be further investigated.

5. PREDICTION OF SMOKE PRODUCTION IN THE SBI TEST

The additional smoke classification in the Euroclass system is based on the $SMOGRA_{SBI}$ value (SMOke Growth RAte) combined with the total smoke produced during the first 600 s of the test, TSP_{600s}[1]. The classification criteria for the three smoke classes s1, s2 and s3 are shown in Table 2 below.

Table 2 The Euroclass system for additional smoke classification[15].

Euroclass smoke classification	**Criteria for $SMOGRA_{SBI}$**	**Criteria for TSP_{600s}**
s1	SMOGRA ≤ 30 m^2/s^2	TSP_{600s} ≤ 50 m^2
s2	SMOGRA ≤ 180 m^2/s^2	TSP_{600s} ≤ 200 m^2
s3	No requirements	No requirements

In our analyses we want to predict the levels of TSP_{600s} and $SMOGRA_{SBI}$ as well as the resulting smoke classification.

An assumption of equal prior probability of all groups was made before starting the analyses. That means that we assume that the probability of observing an object in s1 is equal to the probability of observing an object being a member of s2, or to the probability that an object belongs to s3. As long as we have no other information, this assumption can be justified. However, this assumption will have a significant impact on the outcome from the analysis.

Predicting SBI Smoke Class Membership

The data from single tests in the Cone Calorimeter (one test = one case) used in the analysis are distributed into the three smoke classes with 105 in class s1, 22 in s2 and 15 in s3. The five variables were combined in two functions that distinctly separate the cases into three groups according to smoke classification. The constants of these functions are given in Table 3.

Table 3 Constants of the two unstandardized canonical discriminant functions that separate the data from the Cone Calorimeter into three groups according to the materials' smoke classification in the system of Euroclasses.

Variable	Variable name	Function 1	Function 2
z_1	SP/HR_{CC}	1,041	1,115
z_2	TCO_{CC}	-0,126	0,912
z_3	$FIGRA_{CC}$	0,293	-0,610
z_4	$COGRA_{CC}$	-0,630	0,227
z_5	TSP_{CC}	0,118	-0,146
Constant	Constant	-7,129	-7,549

The function scores for each case are calculated by the equations

$$F1\,(z) = z_1 \cdot 1{,}041 - z_2 \cdot 0{,}126 + z_3 \cdot 0{,}293 - z_4 \cdot 0{,}630 + z_5 \cdot 0{,}118 - 7{,}129 \qquad \textbf{Equation 1}$$

$$F2(z) = z_1 \cdot 1{,}115 + z_2 \cdot 0{,}912 - z_3 \cdot 0{,}610 + z_4 \cdot 0{,}227 - z_5 \cdot 0{,}146 - 7{,}549 \qquad \textbf{Equation 2}$$

A scatter plot of scores of Function 1 and Function 2 for the analysed data is shown in Figure 1.

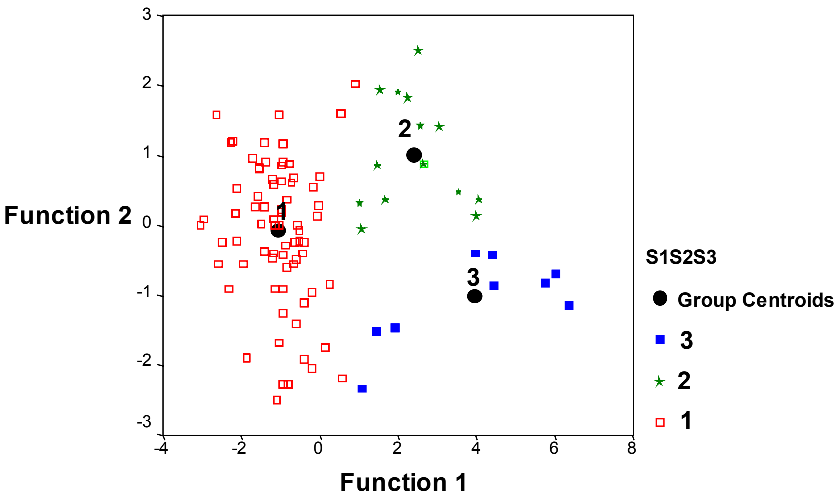

Figure 1 Scatter diagram of cases belonging to smoke classes s1 (=group 1), s2(=group 2) and s3 (=group 3). The markers in the diagram show the scores of each single Cone Calorimeter test calculated by using the canonical discriminant functions 1 and 2 resulting from the MDA.

Results from the MDA including the constants for the three Fisher's discriminant functions from this analysis are summarised in Table 4.

Table 4 Results from MDA for prediction of smoke class in the Euroclass system.

No. of cases in smoke class			Fisher's Linear Discriminant Functions for predicting membership in additional smoke class					% correctly classified
s1	**s2**	**s3**	**Variable**		**F1**	**F2**	**F3**	
105	22	15	z_1	**SP/HR$_{CC}$**	16,776	21,573	20,951	>90%
			z_2	**TCO$_{CC}$**	7,684	8,232	6,181	
			z_3	**FIGRA$_{CC}$**	-6,337	-5,982	-4,283	
			z_4	**COGRA$_{CC}$**	2,603	0,672	-0,781	
			z_5	**TSP$_{CC}$**	-0,466	-0,217	0,265	
			Constant		-53,612	-89,170	-90,104	

The Fisher's Linear Discriminant Functions are expressed mathematically as

$$F1(z) = z_1 \cdot 16{,}776 + z_2 \cdot 7{,}684 - z_3 \cdot 6{,}337 + z_4 \cdot 2{,}603 - z_5 \cdot 0{,}466 - 53{,}612$$
Equation 3

$$F2(z) = z_1 \cdot 21{,}573 + z_2 \cdot 8{,}232 - z_3 \cdot 5{,}982 + z_4 \cdot 0{,}672 - z_5 \cdot 0{,}217 - 89{,}170$$ **Equation 4**

$$F3(z) = z_1 \cdot 20{,}951 + z_2 \cdot 6{,}181 - z_3 \cdot 4{,}283 - z_4 \cdot 0{,}781 + z_5 \cdot 0{,}265 - 90{,}104$$
Equation 5

A case will be assigned to the group, which associated Fisher's discriminant function, F_i, gets the highest score. A 10-fold cross-validation analysis combined with leave-one-out cross-validation gave very positive results regarding the choice of variables in the discriminating functions. The validation analysis gave an average value above 90% correct classification of the members of the training set, the test set and the cases from the hold-out procedure for a set of 10 validation exercises. Membership of subclass s1 is predicted most correctly, while subclass s2 is more difficult to separate from the two others.

Predicting SMOGRA$_{SBI}$

The same variables used for predicting smoke classification were chosen in the MDA to build functions for predicting the level of SMOGRA$_{SBI}$ value. According to the Euroclass system, products can be separated into three groups depending on their SMOGRA$_{SBI}$ value, as shown in Table 2. As in the prediction of smoke classification, the separation of the three groups was very good, although the number of products in SMOGRA$_{SBI}$ level 3 was too small to give a reliable prediction model. The results from this MDA are shown in Table 5 below.

Table 5 Results from MDA for predicting level of SMOGRA$_{SBI}$ in the Euroclass system.

Number of cases in SMOGRA level			Fisher's Linear Discriminant Functions for predicting membership of SMOGRA$_{SBI}$ level					% correctly classified
1	**2**	**3**	**Variable**		**F1**	**F2**	**F3**	
114	21	5	z_1	**SP/HR$_{CC}$**	16,776	21,573	20,951	> 89%
			z_2	**TCO$_{CC}$**	7,684	8,232	6,181	
			z_3	**FIGRA$_{CC}$**	-6,337	-5,982	-4,283	
			z_4	**COGRA$_{CC}$**	2,603	0,672	-0,781	
			z_5	**TSP$_{CC}$**	-0,466	-0,217	0,265	
			Constant		-53,612	-89,170	-90,104	

Predicting TSP_{600}

An analysis where the aim was to predict the TSP_{600} was also performed. Not surprisingly, the outcome of the analysis was identical to the results from the analysis above where the intention was to predict the smoke classification. A quick look at the results from the tested products used in this analysis showed that TSP_{600} was determining the final class for all the products. SMOGRA was not overriding the TSP_{600} value in any of the observations. This means that prediction of smoke class membership is equivalent to prediction of the level of total smoke production during the first 600 s of testing.

6. PREDICTION OF SMOKE PRODUCTION IN THE ROOM/CORNER TEST

We have chosen to group the products according to time to flashover, t_{FO}, before performing MDA on each group. One set of separation criteria found to be both sensible and to work well were

- Group 1: products not reaching flashover during 1200 s testing time
- Group 2: 600 s $\le t_{FO} <$1200 s
- Group 3: 120 s $< t_{FO} <$ 600 s
- Group 4: $t_{FO} <$ 120 s

Different rules have to be applied dependent on predicted time to flashover in the Room/Corner test. A general flowchart showing the system for prediction of smoke variables based on this philosophy is shown in Figure 2.

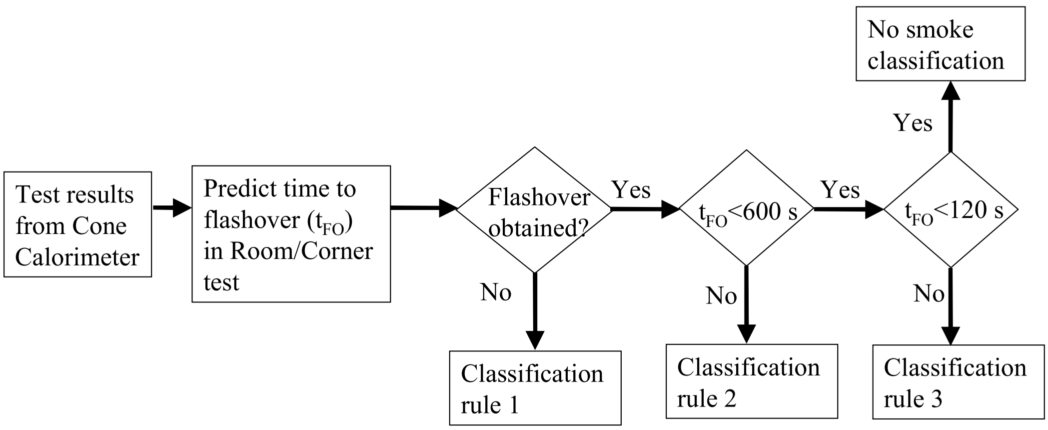

Figure 2 General flowchart showing how the classification rules can be used in prediction of different Room/Corner smoke classification variables.

The MDA groups are established according to the smoke classification system proposed in the EUREFIC programme. This system classifies smoke performance based on two variables, maximum (SPR_{max}) and average smoke production rate (SPR_{avg}), and each variable has three possible levels. Combinations of these variables result in four different categories which products can be grouped into, as shown in Table 6 below.

Table 6 The EUREFIC smoke classification system, also showing the requirements to minimum time to flashover. Criteria for heat release rate are not shown here.

EUREFIC class	t_{FO}	SPR_{max}	SPR_{avg}	Smoke category
A	> 20 min	≤ 2,3 m^2/s	≤ 0,7 m^2/s	1
B	> 20 min	≤ 16,1 m^2/s	≤ 1,2 m^2/s	2
C	> 12 min	≤ 16,1 m^2/s	≤ 1,2 m^2/s	2
D	> 10 min	≤ 16,1 m^2/s	≤ 1,2 m^2/s	2
E	> 2 min	≤ 16,1 m^2/s	No requirements	3
Unclassified	-	-	-	4

When analysing data from Room/Corner tests, we have chosen to separate the products into three groups depending on their Room/Corner SMOGRA value:

- Category 1: $SMOGRA_{R/C} \leq 25$ m^2/s^2
- Category 2: 25 m^2/s^2 < $SMOGRA_{R/C} \leq 60$ m^2/s^2
- Category 3: $SMOGRA_{R/C} > 60$ m^2/s^2

As in the analysis for SBI-prediction, we assume equal prior probability of all smoke categories. The results from these MDA are summarised in Table 7 to Table 11.

Table 7 Results from MDA for prediction of RSP_{max} level in the Room/Corner test.

t_{FO}	No. of cases in smoke category			Fisher's Linear Discriminant Functions for predicting membership in RSP_{max} level					% correctly classified
	1	2	3	Variable		F1	F2	F3	
NFO	50	22	0	z_1	**SP/HR_{CC}**	18,242	21,473		> 80%
				z_2	**TCO_{CC}**	13,668	15,447		
				z_3	**$FIGRA_{CC}$**	-10,712	-9,365		
				z_4	**$COGRA_{CC}$**	9,914	12,096		
				z_5	**TSP_{CC}**	-1,778	-2,007		
				Constant		-59,869	-79,951		
>600s	0	15	20	z_1	**SP/HR_{CC}**		14,978	14,334	> 85%
				z_2	**TCO_{CC}**		7,834	9,216	
				z_3	**$FIGRA_{CC}$**		6,010	8,436	
				z_4	**$COGRA_{CC}$**		-2,496	,655	
				z_5	**TSP_{CC}**		-,676	-,331	
				Constant			-60,398	-64,916	
>120s	0	37	10	z_1	**SP/HR_{CC}**		23,602	26,234	> 80%
				z_2	**TCO_{CC}**		7,671	7,861	
				z_3	**$FIGRA_{CC}$**		-3,535	-5,866	
				z_4	**$COGRA_{CC}$**		13,351	13,001	
				z_5	**TSP_{CC}**		-1,048	-1,274	
				Constant			-60,063	-69,356	

Table 8 Results from MDA for prediction of RSP_{avg} level in the Room/Corner test.

t_{FO}	No. of cases in smoke category			Fisher's Linear Discriminant Functions for predicting membership in RSP_{avg} level					% correctly classified
	1	2	3	Variable		F1	F2	F3	
NFO	40	15	17	z_1	**SP/HR_{CC}**	31,406	32,701	40,345	> 90%
				z_2	**TCO_{CC}**	22,110	21,983	27,415	
				z_3	**$FIGRA_{CC}$**	-8,771	-9,919	-7,198	
				z_4	**$COGRA_{CC}$**	18,406	17,947	23,935	
				z_5	**TSP_{CC}**	-2,611	-2,325	-3,114	
				Constant		-99,170	-111,825	-160,886	
>600s	9	5	21	z_1	**SP/HR_{CC}**	19,340	20,487	22,926	> 75%
				z_2	**TCO_{CC}**	10,085	8,677	10,391	
				z_3	**$FIGRA_{CC}$**	7,912	7,864	8,976	
				z_4	**$COGRA_{CC}$**	0,0318	-0,617	0,830	
				z_5	**TSP_{CC}**	-0,221	-0,204	0,0259	
				Constant		-76,157	-75,430	-99,208	
>120s	0	0	47	**Not applicable**					

Table 9 Results from MDA for prediction of the smoke classification according to the EUREFIC system.

t_{FO}	No. of cases in smoke category				Fisher's Discriminant Function for predicting membership of smoke category					% correctly classified
	1	2	3	4	Variable		F1	F2	F3	F4
NFO	40	15	17	0	Identical to prediction of RSP_{avg}					
>600s	0	7	8	20	z_1	SP/HR_{CC}		46,344	59,782	54,073
					z_2	TCO_{CC}		20,381	25,779	25,076
					z_3	$FIGRA_{CC}$		29,133	38,975	37,604
					z_4	$COGRA_{CC}$		-15,953	-21,667	-16,449
					z_5	TSP_{CC}		-0,947	-1,071	-0,690
					Constant			-163,81	-272,57	-232,39
>120s	0	0	37	10	Identical to prediction of RSP_{max}					

Note: % correctly classified for >600s: >80%.

Table 10 Results from MDA for prediction of SMOGRA level in the Room/Corner test.

t_{FO}	No. of cases in smoke category			Fisher's Linear Discriminant Functions for predicting membership in SMOGRA level					% correctly classified
	1	2	3	Parameter		F1	F2	F3	
NFO	72	0	0	Not applicable					
>600s	20	10	5	z_1	SP/HR_{CC}	29,740	33,653	20,473	> 80%
				z_2	TCO_{CC}	16,256	18,878	12,109	
				z_3	$FIGRA_{CC}$	6,572	6,957	6,782	
				z_4	$COGRA_{CC}$	0,989	4,750	6,496	
				z_5	TSP_{CC}	-3,064	-3,216	-0,388	
				Constant		-104,070	-134,449	-83,515	
>120s	0	31	16	z_1	SP/HR_{CC}		20,826	21,627	> 67%
				z_2	TCO_{CC}		8,438	7,228	
				z_3	$FIGRA_{CC}$		-0,926	-1,832	
				z_4	$COGRA_{CC}$		14,269	13,443	
				z_5	TSP_{CC}		-0,836	-0,871	
				Constant			-59,034	-56,649	

7. DISCUSSION AND CONCLUSIONS

Multiple Discriminant Analysis (MDA) has proved to be a powerful tool for prediction of large-scale smoke classification based on test results from the Cone Calorimeter. The different sets of classification functions found through this project can be used to predict parameters connected to smoke production in the SBI test and in the Room/Corner test with a high degree of certainty. The variables selected as input to the MDA describe the burning behaviour in the Cone Calorimeter with respect to heat release, smoke production and production of CO. Excluding CO related variables from the analyses resulted in high uncertainty connected to the smoke prediction. We also believe that MDA will be useful for prediction of classification based on other criteria than used in this analysis.

Prediction of Smoke Production in the SBI test

This work has shown that MDA is well suited to predict important parameters connected to smoke production in the SBI test from Cone Calorimeter data. The parameter $SMOGRA_{SBI}$, as well as the additional smoke classification based on these parameters, was predicted with a confidence of about 90%. Based on our test data, prediction of TSP_{600} was found to be identical to predicting smoke class. Further refinement and verification of this model is required. Especially are data from products with smoke production belonging to the additional classes s2 and s3 in the SBI test needed as input to the MDA to make the classification prediction more reliable for these classes.

Prediction of Smoke Production in the Room/Corner Test

The different statistical analyses designed to find rules for predicting group membership based on values of EUREFIC smoke category, RSP_{max}, RSP_{avg} and $SMOGRA_{R/C}$, revealed some fundamental, well-known physical connections between smoke production and fire conditions.

For the group of products not reaching flashover, we find that the sets of Fisher's Linear Discriminant functions are identical for prediction of EUREFIC smoke class and RSP_{avg}. For this group of products, the averaged rate of smoke production will determine which smoke class the product belongs to, and smoke production is never so high that maximum SPR will determine the classification.

Products reaching flashover after 600 s are not very likely to obtain the EUREFIC smoke category 1, because the level of RSP_{max} will be too high.

Smoke classification of products with time to flashover less than 600 s is completely governed by the value of maximum smoke production, as the averaged smoke production will most probably be in the group with the worst performance.

These observations clearly show that smoke production is a phenomenon highly controlled by the ventilation conditions. Especially will the maximum rate of smoke production be closely connected to the history of burning, and reaching flashover implies that smoke is produced at a high rate. Test results on how much and how fast smoke is produced in the Room/Corner test are not meaningful if they are disconnected from information about the history of heat release. Of special importance is information about if and when flashover occurred. For products not reaching flashover within the 20 minutes of testing time, the Room/Corner test will be able to identify products with relatively high smoke production and low heat release.

Further Work

Further work will include refinement and verification of the classification rules, by applying the functions on Cone Calorimeter data from products with known performance in the SBI test and in the Room/Corner test.

It is also of interest to explore if there can be found any links between the intermediate and the large-scale tests. Can smoke production in the SBI test be translated into smoke production in the Room/Corner test and vice versa? Other multivariate methods, like principal component analysis (PCA), will also be applied to the data set, to see if this enhances the predictability further.

The existing model for prediction of Room/Corner heat release history will need adjustment to make it able to predict time to flashover with a better precision than at present. This work is now in progress. We will also put effort into finding a model based on multivariable statistics that can predict time to flashover with a low level of uncertainty.

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PREDICTION OF SMOKE PRODUCTION BASED ON STATISTICAL ANALYSES AND MATHEMATICAL MODELLING.

Anne Steen Hansen and Per Jostein Hovde
Department of Building and Construction Engineering,
Norwegian University of Science and Technology, Trondheim, Norway

SUMMARY

This paper presents the development of a mathematical model that uses Cone Calorimeter test results to predict smoke production in the Single Burning Item (SBI) test. A method for classification of cases based on multivariate statistical analysis is incorporated in the model. This makes it possible to distinguish products with heavy smoke production from products that produce relatively little smoke compared to the rate of heat release. The model is based on a similar model for prediction of heat release rate in the SBI test. We have assumed that the shape of the function describing the effective smoke producing area in the SBI test is equivalent to the shape of the effective heat releasing area. This may be a too great simplification of the reality, and will be improved through further work. However, the smoke prediction model presented here is working well for a wide range of products. The model has been applied to 99 data files with Cone Calorimeter test results from 33 different products and was able to predict the correct additional smoke classification within the system of Euroclasses in more than 75 % of the cases.

INTRODUCTION

In the new harmonised European system for testing and classification of materials' reaction-to-fire, the classification of smoke production is optional, but will, however, be required by several authorities. An important test method in this system is the medium-scale Single Burning Item test (SBI), which is used for assessment of both heat release, smoke production and burning droplets. The reference scenario for the SBI test method is the large-scale Room/Corner test, which will be used for testing products that for some reason cannot be tested according to the SBI method. The small-scale Cone Calorimeter test will also play an important role as an efficient tool to be used in product development and product control in Europe, although it has no official status as a classification test method. All these three test methods are based on the same principles for measurement of heat release rate (HRR) and smoke production rate (SPR).

The aim of our work is to predict the smoke classification that a product will obtain from the SBI test based on test results from the Cone Calorimeter. Earlier work has shown that the smoke production from a burning product is to some extent dependent on the heat the product releases during the fire. Therefore a model capable of predicting the rate of smoke production would most likely be linked to a model capable of predicting the rate of heat release. We have started by looking for a model where HRR in the SBI test can be predicted based on test results from the Cone Calorimeter, and found that the model presented by Messerschmidt et. al.[1] is a sound basis for our further work. We have improved this HRR prediction model by introducing certain modifications that will be described in detail in a later paper[2]. A new approach in this sort of simple fire modelling is the application of multivariate statistical analysis as a part of the calculations. The introduction of multivariate statistics in the model is based on the assumption that some of the important information we need from the

Cone Calorimeter test results may be hidden in the interaction between different parameters, and this information needs advanced tools to be revealed.

A parameter for smoke classification in the new European system is SMOGRA. SMOGRA is an acronym for SMOke Growth RAte Index, and it is based on measurements of smoke production in the SBI test. It is calculated as the maximum value of the ratio between SPR and the time when the SPR is measured; and is reported in units of m^2/s^2. Threshold values are introduced to avoid misclassification of products with low SPR peaks occurring early in the test. Another parameter used in the classification system is the total smoke produced during the first 600 seconds of the test; TSP_{600s}. The criteria for SMOGRA and TSP_{600s} in the system of Euroclasses are shown in Table 1.

Table 1 The criteria for SMOGRA and TSP_{600s} in the system of Euroclasses[3]

Class	SMOGRA	TSP_{600s}
s1	< 30 m^2/s^2	< 50 m^2
s2	< 180 m^2/s^2	< 200 m^2
s3	No criterion	No criterion

PRODUCTS

The development of a smoke prediction model is based on a test set containing 62 data files with Cone Calorimeter test results from 23 of the 30 products tested in the SBI Round Robin programme[4,6]. A separate set of data containing 20 data files with Cone Calorimeter tests results from 13 of the SBI Round Robin products and 14 test results from 8 additional products, was used for validating the model. The analysed data and covers a range from products with low combustibility to highly combustible products. The products that were omitted from the original SBI Round Robin data set gave diverging results due to differences in mounting, melting behaviour, and fire behaviour in the SBI test that are not easily predicted through small scale testing in the Cone Calorimeter. These products were the PVC water pipes (M17), the PVC covered electric cables (M18), Steel clad expanded polystyrene sandwich panel (M21), the FR extruded polystyrene board (M03) and the 3-layered FR polycarbonate panel (M07). The products are briefly described in Table 2.

METHODS

Multivariate Statistical Analysis

Smoke production is a very complex phenomenon, depending on several parameters connected to physical properties and chemical composition of the burning products, as well as on fire conditions like temperature and ventilation. The SBI and the Cone Calorimeter tests are similar in one important point; there are no restrictions on the ventilation to the specimen, and thus the combustion is assumed to be fuel controlled in both cases. It is, however, not very likely that a simple correlation between smoke production measured in different test apparatuses exists, not even between the Cone Calorimeter and the SBI. By applying multivariate statistical methods on the data set containing Cone Calorimeter test results, we may sort out parameters that are crucial for predicting a product's ability to produce smoke when tested in the SBI.

Table 2 A brief description of the products used for developing and validating the smoke prediction model[4, 5,6]

Product ID	Product description	T or V*)	SMOGRA $[m^2/s^2]$**)	TSP_{600} $[m^2]$**)	Smoke class
M01	Paper-faced gypsum plasterboard	T/V	0	29	s1
M02	FR PVC	V	120	937	s3
M04	PUR foam panel with Al-foil faces	T/V	212	410	s3
M05	Mass timber (pine), varnished	T	2	45	s1
M06	FR chip board	T/V	12	101	s2
M08	Painted paper-faced gypsum board	T/V	0	29	s1
M09	Paper wallcovering on gypsum	T/V	0	30	s1
M10	PVC wallcarpet on gypsum plasterboard	T	114	164	s2
M11	Plastic-faced steel sheet on mineral wool	T	67	108	s2
M12	Mass timber (spruce) unvarnished	T	3	47	s1
M13	Gypsum plasterboard on polystyrene	T	0	34	s1
M14	Phenolic foam	T	1	43	s1
M15	Intumescent coating on particle board	V	1	55	s1
M16	Melamine-faced MDF board	T	1	24	s1
M19	Unfaced rockwool	V	0	26	s1
M20	Melamine-faced particle board	T	2	39	s1
M22	Ordinary particle board	T/V	3	29	s1
M23	Ordinary plywood (birch)	T/V	1	19	s1
M24	Paper wallcovering on particle board	T/V	2	18	s1
M25	Medium density fibreboard	T	1	20	s1
M26	Low density fibreboard	T/V	9	79	s2
M27	Gypsum plasterboard/PUR	T	0	30	s1
M28	Acoustic mineral fibre tiles	T	0	31	s1
M29	Textile wallpaper on CaSi-board	T/V	0	31	s1
M30	Paper-faced glass wool.	T	3	43	s1
N01	Paper-faced gypsum plasterboard	V	0	31	s1
N02	Ordinary particle board	V	14	117	s2
O	Spruce panel, untreated	V	2	38	s1
ZA	FR Spruce panel, 170 kg FR/m^3	V	10	100	s2
ZB	FR Spruce panel, 105 kg FR/m^3	V	10	90	s2
ZC	FR Spruce panel, 65 kg FR/m^3	V	12	79	s2
X	FR Spruce panel, 35 kg FR/m^3	V	0	30	s1
Y	FR Spruce panel, 55 kg FR/m^3	V	9	69	s2

*) T = test set, V = validation set, T/V = some Cone Calorimeter data files used in the test set, others used for validation
**) The values of SMOGRA and TSP_{600} for the SBI Round Robin products (M01-M30) in Table 2 are taken from the SBI draft test standard prEN 13823[6], and are the average values from mainly more than 20 single SBI tests from several laboratories. The values for the rest of the products are average values from 2 single SBI tests per product.

The statistical method applied is Multiple Discriminant Analysis (MDA)[7] which represents a way of revealing "hidden" information in a set of data. The MDA is found to be a powerful tool in predicting smoke production and heat release in the Room/Corner test and in the SBI test[8,9].

MDA is used to classify cases into groups. The groups are determined based on a variable that shows discrete values that can be assigned to discrete classes. When a relation between groups and variables exists, MDA will find the simplest way of assigning cases to a set of predetermined groups. The classification is then governed by linear functions, which include only the variables that are most strongly related to the group distinction. The software system SPSS 9.0[10] gives the option to choose Fisher's linear discriminant functions for classification of cases. The result of this analysis is a set of k linear functions, one for each of the k groups. A new case will be associated to the group which classification function obtains the highest value. The theory behind discriminant functions assumes that each of k populations with p variables have a multivariate normal distribution with the same covariance matrix. Transformation of variables may be necessary to improve normality, stabilise variance and make distributions more symmetric. However, MDA is relatively robust against modest violations of the assumptions of multivariate normality and equal covariance matrix[7]. Other assumptions that should be met are that population sizes should not differ too much, and all cases should be independent. Residuals are assumed to be randomly distributed.

Mathematical modelling of smoke production

The starting point of our smoke production model is a modified version of the model for prediction of heat release in the SBI test proposed by Messerschmidt et al[1,2] and the development is based on results from a Nordtest project[11] performed at VTT in Finland.

Products do not necessarily produce smoke at the same rate and amount relatively to the heat release in small- and large-scale fires. When looking at the ratio between SPR and HRR, some products will produce more smoke per heat released in the Cone Calorimeter than in the SBI test, while some produce more smoke in the SBI compared with in the Cone Calorimeter test. Other products may have approximately the same ratio between SPR and HRR in both test methods. To be able to model the dynamic smoke production in the SBI test, a connection between smoke production in the two scales of testing should be estimated.

The origin of the smoke production can be assumed to be an area. It may not necessarily be a geometrically well-defined area, but can be regarded more like an *effective smoke producing area*[11]. This effective area, which we have called $A_{SPR,eff}$, may be different from the *effective heat releasing area,* $A_{HRR,eff}$, found in the models where heat release rate is simulated in the SBI and in the Room/Corner test[1,2,12.] Observe that we have chosen to regard also the heat releasing area as an *effective* area.

To investigate the development of the effective heat releasing and smoke producing areas, the test results from the SBI and the Cone Calorimeter were analysed using a "backwards calculation procedure". The procedure for finding the effective smoke producing area is described below, but the principles for analysing the development of the effective heat releasing area are identical.

It is assumed that smoke production in the SBI test can be predicted from Cone Calorimeter test data in the same way as heat release. The instant smoke production rate at time t, $SPR_{SBI}(t)$, can be calculated by

$$SPR_{SBI}(t) = \int_{t_{ign}}^{t} \dot{A}_s(\tau) \cdot \dot{s}''_{CC}(t-\tau)d\tau \qquad [1]$$

where $\dot{A}_s(\tau) =$ the time derivative of the effective smoke producing area at time (τ) after ignition.

$\dot{s}''_{CC}(t-\tau) =$ the smoke production rate per unit area [1/s] measured in the Cone Calorimeter at time (t-τ) after ignition.

Equation 1 can be approximated by the summation formula

$$SPR_{SBI}(t) = \sum_{i=1}^{N} \Delta A_{s,i} \cdot \dot{s}''^{N-i}_{CC} \qquad [2]$$

where

N =	the total number of time increments after ignition
$\Delta A_{s,i}$ =	the effective smoke producing area increment at time step i
$\dot{s}''^{N-i}_{CC}$ =	the smoke production rate per unit area [1/s] measured in the Cone Calorimeter at time step N-i.

The smoke production rate after the first time interval $1 \cdot \Delta t$ has elapsed, $SPR_{SBI}(t=\Delta t)$, is then expressed as

$$SPR_{SBI}(\Delta t) = \Delta A_{s,1} \cdot \dot{s}''^{1}_{cc} \qquad [3]$$

and the first increment of the effective smoke producing area, $\Delta A_{s,1}$, can accordingly be expressed as

$$\Delta A_{s,1} = \frac{SPR_{SBI}(\Delta t)}{\dot{s}''^{1}_{cc}} \qquad [4]$$

As $\Delta A_{SPR,eff,1}$ is now found by Equation 4, the second area increment can be found by

$$\Delta A_{SPR,eff,2} = \frac{SPR_{SBI}(2\Delta t) - \Delta A_{SPR,eff,1} \cdot \dot{s}''^{2}_{cc}}{\dot{s}''^{1}_{cc}} \qquad [5]$$

Following this procedure, the i[th] effective smoke producing area increment can be determined according to

$$\Delta A_{s,i} = \frac{SPR_{SBI}(i \cdot \Delta t) - \Delta A_{s,1} \cdot \dot{s}''^{(i-1)}_{cc} - \Delta A_{s,2} \cdot \dot{s}''^{(i-2)}_{cc} - \ldots\ldots - \Delta A_{s,(i-1)} \cdot \dot{s}''^{2}_{cc}}{\dot{s}''^{1}_{cc}} \qquad [6]$$

The result is an array of incremental values of the effective smoke producing area, which can be used to make a graphical presentation of the area development. The results for the determination of $A_{SPR,eff}$ and $A_{HRR,eff}$ for some of the products are shown in Figure 1 below.

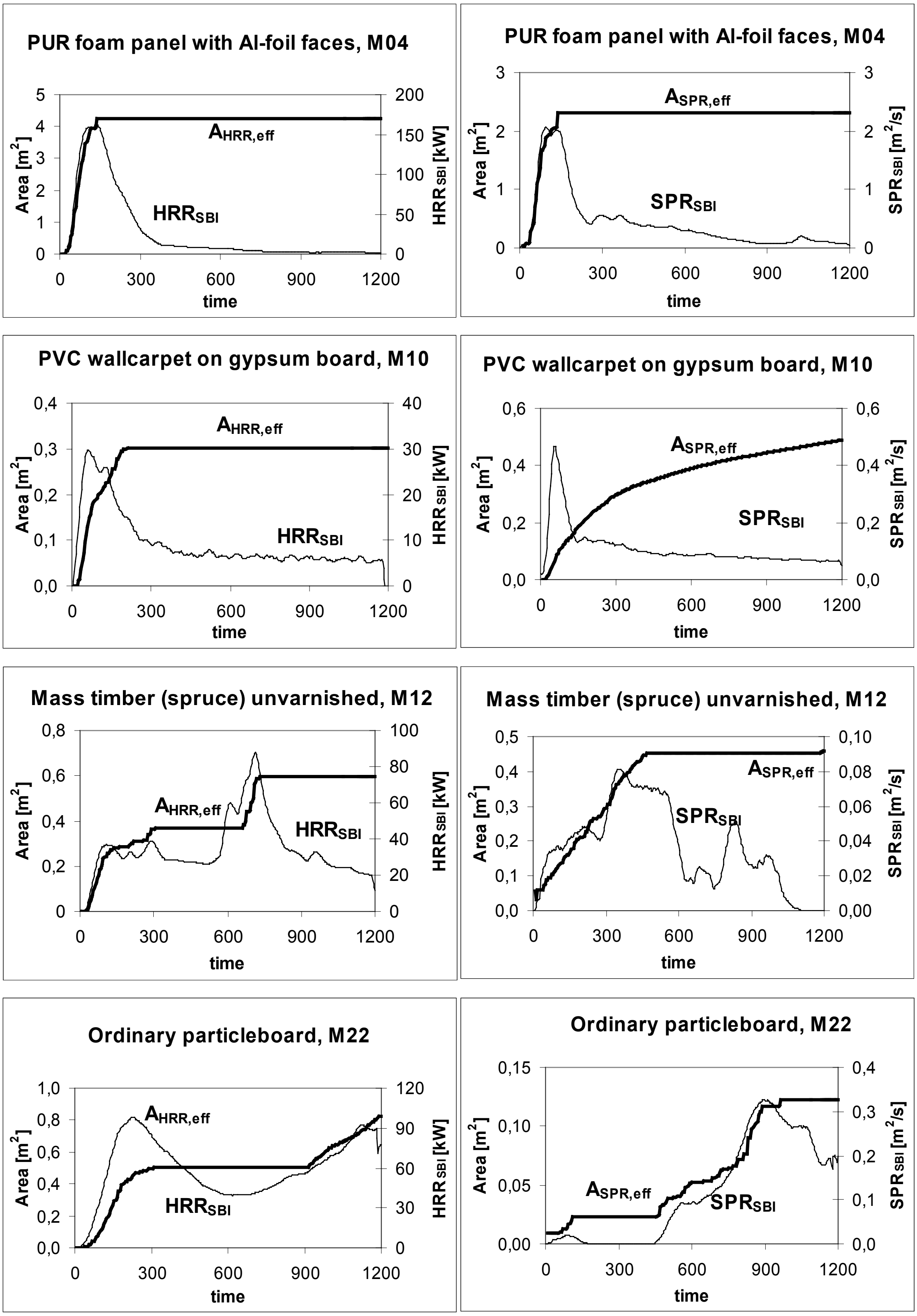

Figure 1 Calculated effective heat releasing and smoke producing areas, $A_{HRR,eff}$ (left figures) and $A_{SPR,eff}$ (right figures) for some of the products. The thin lines show the measured HRR and SPR from one single SBI test for each product. The black heavy lines represent the development of the effective heat releasing and smoke producing areas respectively, as calculated based on results from one Cone Calorimeter test. The results from both the SBI tests and the Cone Calorimeter tests used for calculations in this example are typical for these products.

In development of the prediction model for HRR in the SBI test[2], we discovered that the development of $A_{HRR,eff}$ may follow three different routes, as shown in Figure 2:

I. An exponential route with a rather low maximum value. This development is typical for products with low combustibility, like paper faced gypsum board.
II. A stepwise function with two plateau levels. This development is seen in e.g. wood based products.
III. An exponential route with a steep initial slope and a rather high maximum value. Products with a high ability of surface spread of flame, e.g. low density fibre board and paper faced mineral wool will follow this route.

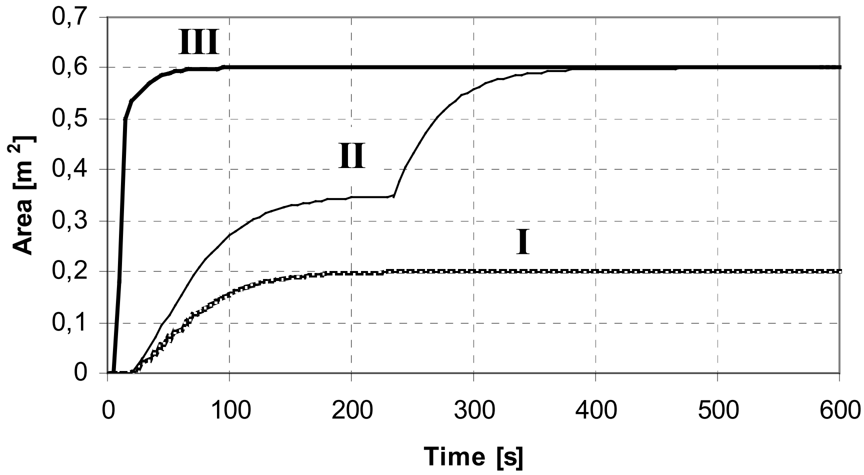

Figure 2 The different possible routes for development of the effective heat releasing area in the SBI test[2].

Effective smoke producing area
The shape of the function for the effective smoke producing area may differ somewhat from the function for the effective heat releasing area. This is clearly seen in the examples shown in Figure 1. For the product mass timber (M12), $A_{HRR,eff}$ follows a two-step function with a steep initial slope while $A_{SPR,eff}$ follows an exponential function with a low initial slope. For other products the effective heat releasing area may follow a function with the same shape as for the smoke producing area; this is the case for the PUR foam panel (M04). Some products follow completely different functions, like e.g. PVC wallcarpet on gypsum board (M10), where no plateau level is reached at all.

We assume that there is a connection between the heat released from a burning product and the smoke it produces. Therefore, as a first attempt, we have chosen to approximate the development of $A_{SPR,eff}$ to follow a route with the same shape as for $A_{HRR,eff}$. Effectively, this means to multiply the values of $A_{HRR,eff}$ by a predetermined constant factor k_{SPR} to find the $A_{SPR,eff}$.

The effective smoke producing area is then found by

$$\Delta A_{SPR,eff,i} = k_{SPR} \cdot \Delta A_{HRR,eff,i} \qquad [7]$$

By applying Equation 2 and replacing $\Delta A_{SPR,i}$ with $\Delta A_{SPR,eff,i}$ from Equation 7 the result will be the predicted rate of smoke production in the SBI test.

The expression in Equation 7 may be a great simplification of the problem but we think, however, that it may lead to reasonable results. The maximum levels of $A_{SPR,eff}$ will depend on properties of the product under consideration. To investigate the difference in development of the two kinds of effective areas, the ratio between the maximum levels of the areas $A_{SPR,eff}$ and $A_{HRR,eff}$ found through the backwards procedure were calculated. As a simplification, we have chosen to divide the analysed products into three groups according to how much smoke they produce relatively to their heat release:

1) Products that release small amounts of smoke compared to their heat release. In this group we typically find non-FR wood based products.
2) Products with a ratio between heat releasing area and smoke producing area of about unity.
3) Products with high smoke production compared to the heat release. This group contains products with limited heat release, like paper faced gypsum board and FR chip board.

The data set was analysed through MDA to find the classification rules that place each case (one case = one Cone Calorimeter test) in the correct group regarding the level of the multiplication factor k_{SPR}. The parameters which were able to classify the cases into groups 1, 2 or 3 according to their level of k_{SPR} were

- z_1 = time to ignition (t_{ign}) calculated from the HRR measurements[2,9]
- z_2 = the total heat release 300 s after time to ignition (THR_{300})
- a parameter indicating the route for development of $A_{HRR,eff}$
  (z_3 = 1 for route I, 2 for route II and 3 for route III)
- mathematical transformations of
  - the maximum rate of heat release; $z_4 = \ln(1/\sqrt{HRR_{\max}})$
  - maximum rate of smoke production; $z_5 = \ln(1/\sqrt{1000 \cdot SPR_{\max}})$

The classification model based on these parameters was able to group the products correctly in 86 % of the cases with regard to the level of k_{SPR}.

Time to start of smoke production

When exposed to external heat, some products will start to produce smoke before they ignite. This may be the case for FR treated products, where time to ignition may be rather long but the smoke production before any flames are observed can be significant. For such products it will give misleading results to define time to ignition as the starting point of the array of recorded smoke values to be used in the calculations. The time to start of smoke production has therefore been determined empirically as the moment when the SPR exceeds 0.01 m^2/s. For products where SPR never exceeds this value the time to start of smoke production is set equal to the time to ignition.

As in the model for prediction of HRR in the SBI test[2] we have chosen to use only Cone Calorimeter test results from the first 10 minutes after ignition as input values. The philosophy behind this is that the small scale fire behaviour of most products that will be relevant for predicting large scale fire behaviour will appear early in the burning history in the Cone Calorimeter. Some of the large scale fire behaviour including the smoke production is caused by events that cannot be simulated in the Cone Calorimeter, such as when a product loses strength and breaks down because of thermal degradation.

RESULTS

The prediction model was applied to the Cone Calorimeter test results from both the test set and the validation set, which means a total of 96 data files containing test results from the 32 different products in the analysis. The history of smoke production for each case was calculated, and formed the basis for calculation of SMOGRA and TSP_{600} and thereby prediction of the smoke classification within the system of Euroclasses.

Some of the predicted smoke production curves are presented in Figure 3.

In Figure 4 the results from the comparison between the SMOGRA values calculated from the SBI test results and the predicted SMOGRA values are shown.

In Figure 5 the results from the TSP_{600s} values calculated from the SBI test results and the predicted TSP_{600s} values are shown.

The model's ability to predict the final additional smoke classification s1, s2 or s3 is presented in a confusion matrix[13] in Figure 6.

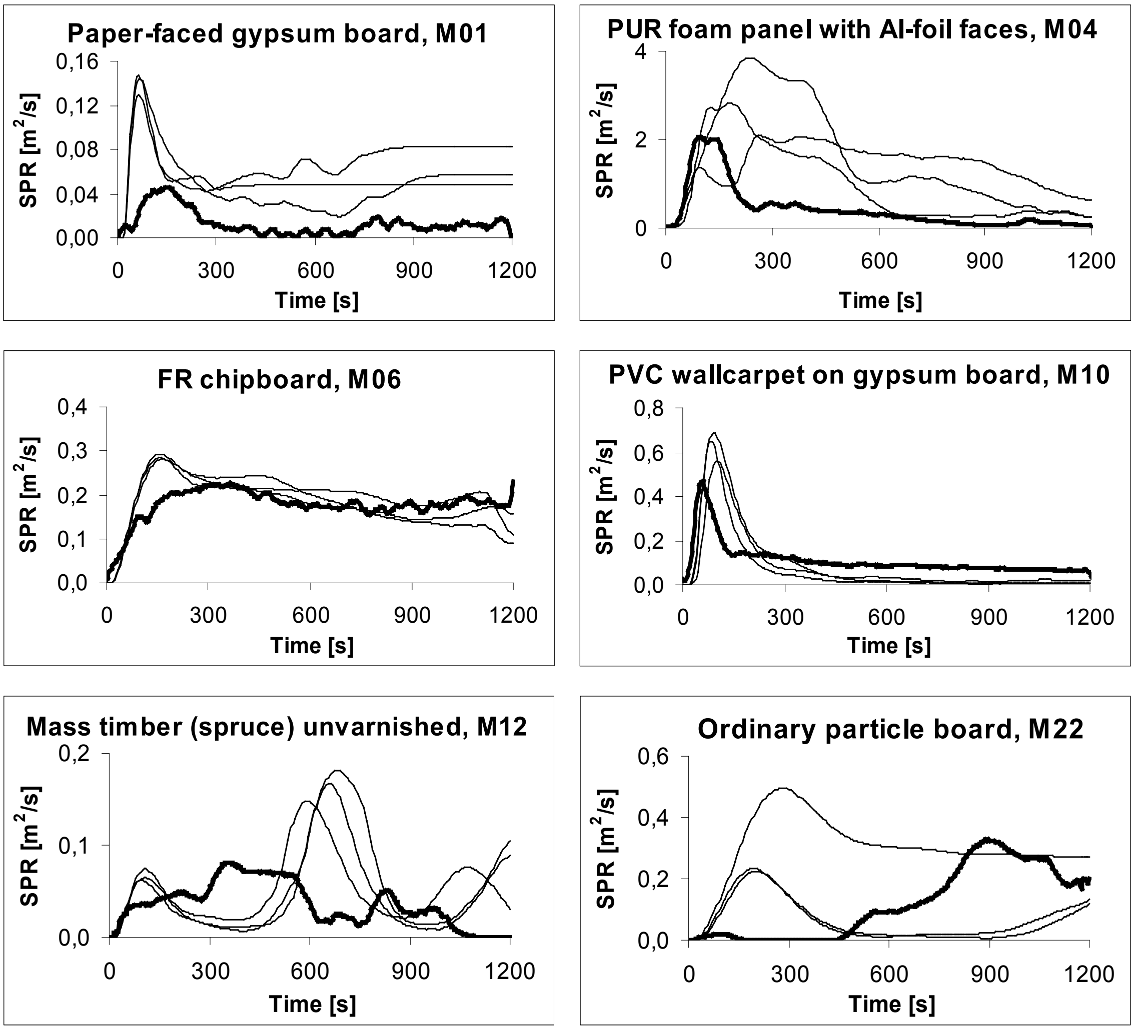

Figure 3 Predicted rate of smoke production curves for 6 different products with varying level of smoke production. The black solid lines show the SPR measured in a single SBI-test, while the three grey lines show the SPR predicted from results from three different Cone Calorimeter tests**.**

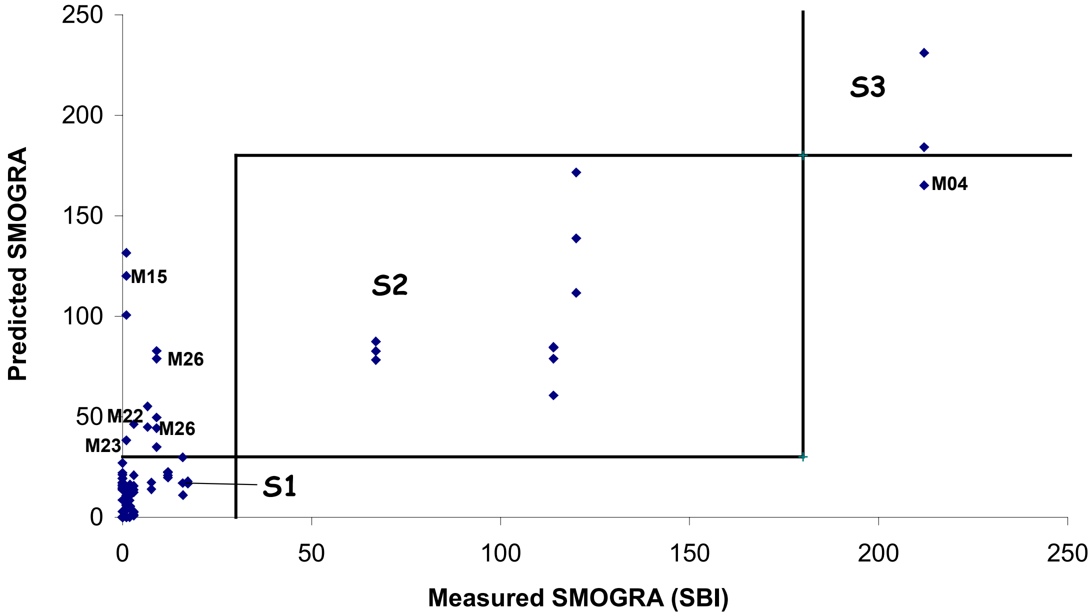

Figure 4 Predicted SMOGRA values for the SBI test based on Cone Calorimeter tests versus SMOGRA values calculated from SBI test results for 32 different products. The heavy solid lines show the SMOGRA criteria limits for smoke classifications s1, s2 and s3. A data point inside the square formed by the borders is correctly predicted by the model.

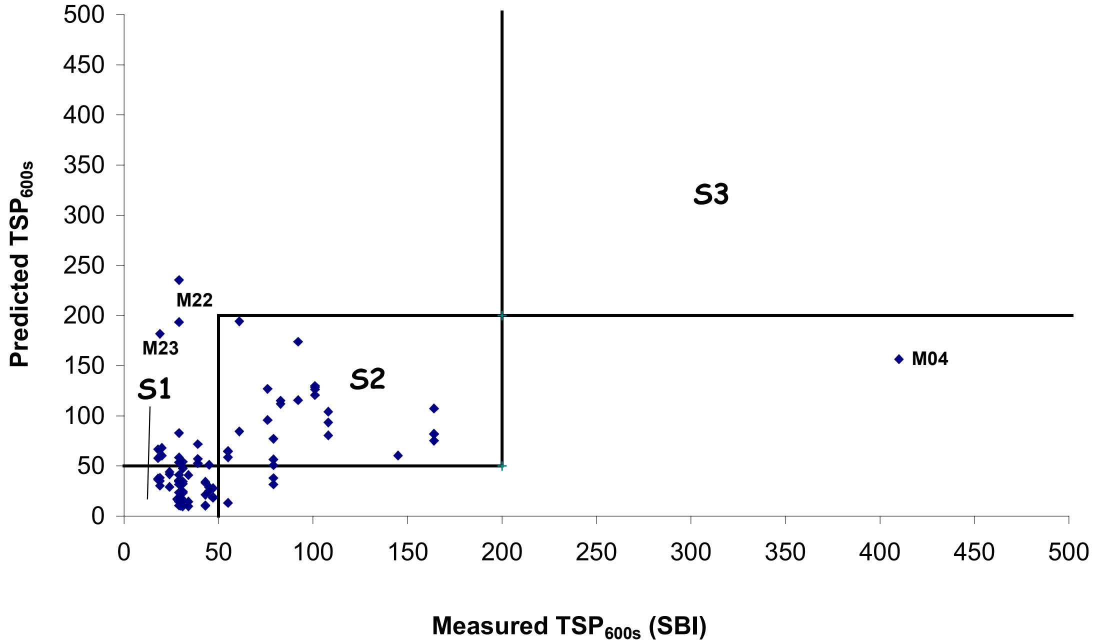

Figure 5 Predicted TSP_{600s} values for the SBI test based onCone Calorimeter tests versus TSP_{600s} values calculated from SBI test results for 32 different products. The solid lines show the criteria limits for TSP_{600s} for smoke classifications s1, s2 and s3. A data point inside the square formed by the borders is correctly predicted by the model.

the test set (N=62)

%		Actual smoke class s1	s2	s3
	s1	75	0	0
Predicted	s2	25	100	0
smoke class	s3	0	0	100

the validation set (N=34)

%		Actual Euroclass s1	s2	s3
	s1	69.2	5.9	0
Predicted	s2	23.1	94.1	25
smoke class	s3	7.7	0	75

Figure 6 The model's ability to predict membership of the correct additional smoke classification within the system of Euroclasses presented as confusion matrices. The numbers presented in squares with heavy borderlines are the shares of correctly classified cases, the other numbers represent misclassifications.

DISCUSSION AND CONCLUSIONS

Predicting the smoke classification

The model is based on test results from 22 different products, and the validation is based on test results from 21 different products. However, as Table 2 shows, 22 of these products are classified in smoke class s1, 9 are s2 products and only 2 are s3 products. As the results in our work show, the model is able to predict the correct smoke class membership for all three options with good certainty. There is, however, a need for more data from products with large smoke production to validate the model further. The results presented in figures 3-6 show that products in class s1 may be difficult to distinguish from s2 products with regard to values for both SMOGRA and TSP_{600s}. Still about 70 % of s1 products are correctly classified. Generally, with three optional classes, prediction by a classification model is better than a random guess if more than a third of the cases are correctly classified. A guess will, however, not be made on a completely random basis but will more or less be a qualified guess based on previous knowledge. We still regard a predictability of 70 % for our model as a good result, which shows that this way of modelling the smoke production in the SBI test should be of practical interest for fire laboratories. The model should, however, be refined to be able to handle smoke production from all products under evaluation.

Predicting the shape and level of the rate of smoke production curve

The wood based products are difficult to predict correctly both with regard to SMOGRA and TSP_{600s}. As the results in Figure 3 show, the predicted shape of the smoke production curve does not always fit with the shape of the smoke production curve as measured in the SBI test. This is clearly demonstrated for the products M12 and M22 in Figure 3, and from Figure 1 we see that the shapes of the effective heat releasing area and the effective smoke producing area are significantly different for these products. For prediction of SMOGRA and TSP_{600s} it is important that the first part of the smoke production curve is correct both regarding shape and level. However, the criteria intervals for SMOGRA and TSP_{600s} in the Euroclass system are wide enough to allow for some inaccuracy in the predicted values and still result in the correct classification. Looking at the results in Figure 3, we observe that even though the shape of the predicted curves may be incorrect for some of the products, the level of smoke production is mainly in the proper range. This means that the model is able to distinguish between heavily smoke producing products and products with little smoke production.

A major source of uncertainty is that smoke measurements tend to have very low repeatability and reproducibility; especially for some products. This means that it may be difficult to define what the "correct" answer is; i.e. the correct smoke curve from the SBI test, and it may be difficult to judge how a "typical" smoke measurement curve in the Cone Calorimeter looks like for some products. For other products there are just minor variances in smoke measurements from one test to another; both in the SBI test and in the Cone Calorimeter test. When assessing the output from the smoke prediction model, this problem must be born in mind. A way to avoid false conclusions is to base the prediction on results from more than one Cone Calorimeter test and to include knowledge of smoke performance in the SBI test for similar products when assessing the predicted results.

The presented model is able to predict smoke production in the SBI test with a satisfactory level of accuracy. However, we believe that the model can be further improved through better definition of the development of the effective smoke producing area. This will be aimed at in our further work.

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Paper VI

Simulation of smoke production in large-scale fire tests based on small-scale test results using multivariate statistical analysis to enhance predictability.

Anne Steen Hansen and Per Jostein Hovde
Department of Building and Construction Engineering,
Norwegian University of Science and Technology,
N-7491 Trondheim, Norway

ABSTRACT

This paper presents the development and the results of a mathematical model for prediction of smoke production rate in a large- and an intermediate-scale fire test. The smoke prediction is based on modified versions of two existing models for prediction of heat release rate. The model uses input from small-scale fire tests in the Cone Calorimeter, and predicts the smoke production in the ISO Room/Corner test and in the Single Burning Item test (SBI). To make it possible to distinguish between products with different levels of smoke production we have implemented a multivariate statistical model in the model. Both the model's qualitative and quantitative prediction of smoke production in the two test methods are quite good. The Euroclass smoke classification based on SBI test results is predicted with a certainty of 91 %. Maximum and averaged smoke production in the ISO Room/Corner test can be predicted with about 70 % accuracy for products that do not reach flashover within the first 5 minutes of the test. For products reaching flashover earlier in the Room/Corner test smoke prediction will be of little relevance.

INTRODUCTION

In many connections information about how different products and materials will behave in a real fire is required. Because the expression "real fire" is a diffuse term meaning anything between a small well defined fire to a large uncontrolled fire scenario, the most relevant information may describe the fire behaviour of the product in question in a medium- or large-scale fire test. Also in connection with development of products where specific large-scale reaction-to-fire behaviour is required, some sort of screening method would be useful to avoid unnecessary spending of time and materials.

Smoke production is one of the important fire properties of a product. Smoke may hinder people from evacuating a building on fire in two ways; through physical impairment caused by toxic and irritating effects of the smoke and by decreasing visibility in escape routes. Optical smoke density is a parameter that is measured in several fire test methods and several nationalities have requirements regarding smoke production from building products. The large-scale smoke production of products is therefore of great interest in many fire safety engineering analyses.

In our work we have aimed at predicting the smoke production in large- and intermediate-scale tests based on test results from the ISO 5660 Cone Calorimeter[1]. We wanted to predict the smoke production in the new medium-scale Single Burning Item test (SBI)[2] and in the large-scale ISO 9705 Room/Corner test[3] because these methods will be important in the new harmonised system for fire testing and classification of building products in Europe. However, the strategy and theoretical methods we have used will certainly also be applicable for development of prediction models for other large-scale test methods.

The Cone Calorimeter-, the SBI- and the ISO Room/Corner tests are all based on the same principles for measuring heat release rate (HRR) and smoke production rate (SPR) and it is therefore not unlikely that correlations between these methods exist. The specimens in both the Cone Calorimeter test and the SBI test are freely ventilated, while the fire conditions may become underventilated for well-burning products in the ISO Room/Corner test.

In a single Cone Calorimeter test of a product several variables are recorded, like time to ignition, smoke gas concentrations, heat release rate, specimen mass loss and smoke density. Other parameters are used to describe the product before testing, like density and thickness. Since a test in the Cone Calorimeter clearly is a multivariate phenomenon, the test results should be well suited for a multivariate statistical analysis. Through application of statistical tools we may sort out parameters that are crucial for predicting a product's ability to produce both heat and smoke in the SBI test and in the ISO Room/Corner test.

PRODUCTS IN THE ANALYSIS

The products included in our analysis are collected from several research programmes and cover a wide range of combustibility; from gypsum board, via wood based products to highly combustible materials like foamed plastics.

The products analysed in this study were 25 of the products selected for the European SBI Round Robin in 1997, 11 products tested in the Nordic EUREFIC-programme[4] and 9 additional products tested in the Cone Calorimeter and in the SBI in Nordic projects. All the SBI Round Robin products were tested mainly more than 30 times in the SBI apparatus, once according to the ISO Room/Corner test, and at least three times in the Cone Calorimeter[5,6]. The Cone Calorimeter tests were performed with a horizontal specimen orientation and at heat flux density 50 kW/m^2. To check the model's validity for input data from Cone Calorimeter tests performed at other heat flux levels than 50 kW/m^2, 17 Cone Calorimeter results from testing of 10 of the products at heat flux levels 25, 35 and 75 kW/m^2 were used as input data to the model. All in all 45 different products have been analysed in this project.

Before applying the multivariate statistical analysis the data set was divided into two parts: a test set for development of the statistical parts of the prediction model, and a validation set used for checking the validity of the model. We did not have results from both the SBI test and the ISO

Room/Corner test for all the available products used in our analysis. We therefore decided to use 61 of the Cone Calorimeter test results from the SBI round robin products as a common test set for development of both the SBI- and the ISO Room/Corner parts of the model, while the two validation sets were partly different. For validation of the SBI prediction results, the validation set contained results from 37 single Cone Calorimeter tests of 23 different products. The validation set for the ISO Room/Corner prediction results contained 28 Cone Calorimeter data files from 14 different products.

STATISTICAL METHOD

The multivariate statistical method applied is Multiple Discriminant Analysis (MDA)[7] which represent a way of revealing "hidden" information in a set of data. The MDA is found to be a powerful tool in predicting smoke production in the ISO Room/Corner test and in the SBI test[8,9] and it has also been able to predict time to flashover in the ISO Room/Corner test with good accuracy[10].

MDA can be used to

- classify cases into groups
- investigate differences between groups
- detect variables that are important for distinguishing between groups
- discard variables that are irrelevant for group distinctions

When a relation between groups and variables exists, MDA will find the simplest way of assigning cases to the most probable group. The classification is then governed by a set of functions, which include only the variables that are most strongly related to the group distinction.

The theory behind discriminant functions assumes that each of g populations with p variables have a multivariate normal distribution with the same covariance matrix[11]. Before performing a discriminant analysis, these assumptions must be validated through statistical examination of the data. The variables should be explored for normality, shape of within-group distributions and spread of variance. Transformation of variables may be necessary to improve normality, stabilise variance and make distributions more symmetric. However, multiple discriminant analysis is relatively robust against modest violations of these requirements. Population sizes, i.e. the number of cases belonging to each predetermined group, should not differ too much and all cases should be independent. Residuals should be randomly distributed.

We have used the software program SPSS 9.0[11] to perform the MDA in our project, and chose the option of calculating Fisher's linear discriminant functions for classification of cases. If there are 3 groups, the result of this analysis will be a set of 3 linear functions, one for each group. The functions are expressed in the following way

$$F_i = a_{1,i} \cdot z_1 + a_{2,i} \cdot z_2 + \ldots + a_{n,i} \cdot z_n + \text{constant}_i \quad (i = 1, 2, 3) \qquad (1)$$

where $a_{1,i},\ldots,a_{n,i}$ are coefficients to be multiplied with variables $z_1,\ldots,z_n$ in function no. i. The number of variables in the functions can be determined by the analyst or can be found automatically by the computer program. A new case will be associated to the group which classification function obtains the highest value. An example: if the value calculated from F_1 is larger than the values from both F_2 and F_3 the analysed case is predicted to be in group 1.

PREDICTION OF SMOKE DEVELOPMENT

Smoke production is a very complex phenomenon, and may therefore be difficult to predict. Several parameters will influence the smoke production of a burning material; like the chemical and physical composition of the material, material properties like density, heat capacity and heat conduction; ventilation conditions, geometry and fire intensity. The involved factors may be interrelated in ways not immediately evident.

Our first assumption is that there is a strong link between the smoke production and the heat release of a product. Therefore a model able to simulate HRR with sufficient precision is required before the SPR can be predicted. The model originally developed by Wickström and Göransson[12] to predict HRR in the ISO Room/Corner test has been the basis for our work. Later on the same philosophy was applied by Messerschmidt et. al. to develop a HRR prediction model for the SBI test[5]. We have modified these original models to make them more precise and give them a higher predictability. One of the modifications was to include a method for multivariate statistical analysis of Cone Calorimeter variables in the models. The development of our HRR prediction models is described in detail in two separate papers[10,13].

The ISO Room/Corner HRR-model computes the increase of the burning area in the room, using a surface temperature criterion when deciding whether flame spread on the surface occurs or not. Flames are assumed to spread on the surface when the surface temperature exceeds 335 ^{o}C. The assumption is that the history of heat release rate for each unit area in large scale will be the same as in small scale and the growth rate of the heat releasing area and the heat release rate are decoupled. The development of the heat releasing area follows a function which shape is empirically determined. In our work we have chosen to use the term *effective heat releasing area* to point out that the area development function may not describe a physical area. Parameters that are essential for prediction of heat release, like factors connected to ventilation conditions and geometry, may be implicit parts of the function. Following the same philosophy as for the heat released, the smoke originates from *an effective smoke producing area*, which cannot be regarded as a simple geometrically well-defined area. The shape of the functions describing the development of the heat releasing and smoke producing areas will not be the same for all products, simply because different types of products produce different amounts of heat and smoke at different times during the fire tests. The functions are developed based on empirical analyses.

A common model for predicting HRR in the SBI test and in the ISO Room/Corner test:
In the simulation models for both the SBI test and the ISO Room/Corner test the HRR from the burning product at time t is described by

$$HRR_{product}(t) = \sum_{i=1}^{N} \Delta A_{HRR,eff,i} \cdot \dot{q}''^{\,N-i}_{CC} \qquad (2)$$

where

N = total number of time increments after ignition

$\Delta A_{HRR,eff,i}$ = increment in the effective heat releasing area at time step i

$\dot{q}''^{N-i}_{CC}$ = HRR [kW/m^2] measured in the Cone Calorimeter at time step N-i.

Calculating the effective heat releasing area in the Room/Corner test:
The effective heat releasing area in the ISO Room/Corner test, $A_{HRR,eff}(t)$, initially follows the function

$$A_{HRR,eff}(t) = 4 \cdot (\frac{t}{t_{ign}}) - 1 \tag{3}$$

Where t_{ign} is the calculated time to ignition in the Cone Calorimeter at heat flux level 50 kW/m^2, here defined as the time when $\dot{q}''_{CC}$ exceeds 25 kW/m^2. If the Cone Calorimeter test is performed at an other heat flux level density than 50 kW/m^2, the time to ignition used in the calculations is found by

$$t_{ign} = t_{ign,meas} \cdot \left(\frac{50}{\dot{q}''}\right)^2 \tag{4}$$

where $t_{ign,meas}$ is the actual time to ignition measured at heat flux density level $\dot{q}''$. If the surface temperature criterion is exceeded, the area growth function is written as

$$A_{HRR,eff}(t) = A_0 \left[1 + a \cdot \frac{(t - t_x)^2}{t_{ign}}\right] \tag{5}$$

Where

t_x = the time when the surface temperature criterion is exceeded

A_0= the area behind the burner (chosen as 2 m^2)

a = empirical constant of 0.025 s^{-1}

If no flashover is obtained during the first 10 minutes with burner output 100 kW the burner effect is raised to
300 kW. Then the burning area initially will follow the expression

$$A_{HRR,eff}(t) = 2 + \frac{24}{t_{ign}} \cdot (t - 600) \tag{6}$$

If the surface temperature criterion is reached, the burning area will increase according to equation (5), with $A_o = 5$ m^2 and $a = 0.1$ s^{-1}.

Calculating the effective heat releasing area in the SBI test:

The effective heat releasing area in the SBI is initially expressed as

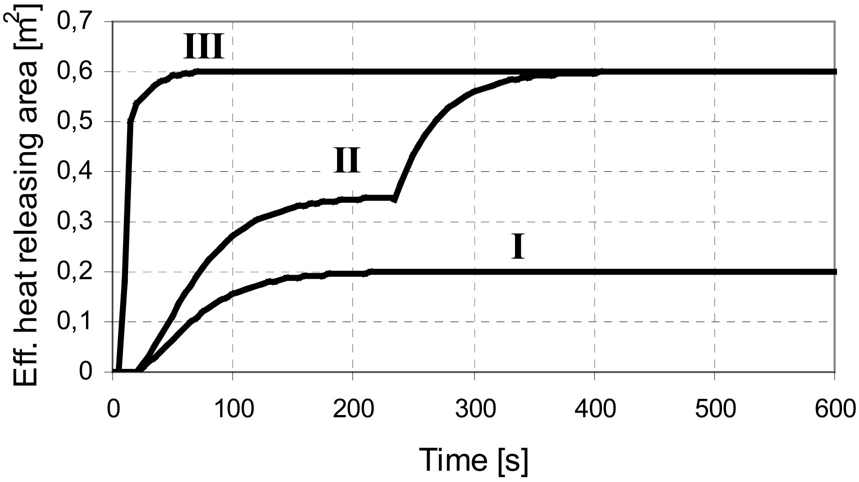
$$A_{HRR,eff}(t) = A_{\max,HRR}\left[1 - \left(1 + \frac{t - \frac{t_{ign}}{2}}{t_{ign}}\right) \cdot \exp\left(-\frac{t - \frac{t_{ign}}{2}}{t_{ign}}\right)\right] \tag{7}$$

where $A_{max,HRR}$ is a parameter that determines the maximum level of the effective heat releasing area. $A_{max,HRR}$ takes the initial values 0.2 or 0.35 depending on the product's performance in the Cone Calorimeter test. $A_{HRR,eff}$ is changing to 0.6 when the total heat release rate (product + burner) exceeds 75 kW. After this criterion has been reached $A_{HRR,eff}$ is described by

$$A_{HRR,eff}(t) = A_{\max,HRR}\left[1 - \left(1 + \frac{t + \frac{t_{ign}}{2}}{t_{ign}}\right) \cdot \exp\left(-\frac{t + \frac{t_{ign}}{2}}{t_{ign}}\right)\right] \tag{8}$$

The development of the effective heat releasing area in the ISO Room/Corner test and in the SBI test are shown in Figure 1 [10,13].

A)



B)

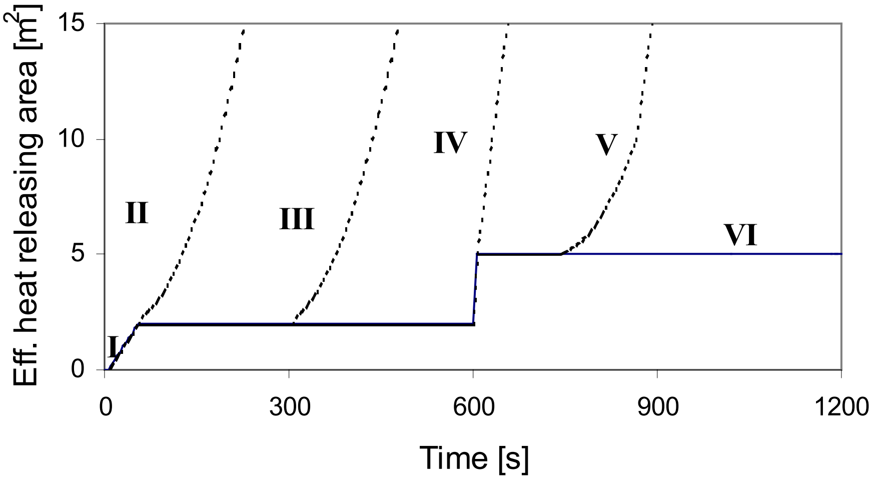


Figure 1 **A)** The different possible routes for development of the effective heat releasing area in the SBI. Route I: slow and low heat release rate, route II: normal combustibility, route III: high flame spread ability.
B) Schematic visualisation of the possible routes of burning area growth in the ISO Room/Corner test[10,12]. The route labelled VI represents non-flashover products, while the routes II to V indicate the occurrence of flashover at different times in the test.

A common model for predicting SPR in the SBI test and in the ISO Room/Corner test:

We assume that the smoke production rate for both the SBI test and the ISO Room/Corner test can be calculated by

$$SPR_{product}(t) = \sum_{i=1}^{N} \Delta A_{SPR,eff,i} \cdot \dot{s}''^{N-i}_{CC} \tag{9}$$

where

$\Delta A_{SPR,eff,,i}$ = increment in the effective smoke producing area at time step i

$\dot{s}''^{N-i}_{CC}$ = the smoke production rate per unit area [1/s] measured in the Cone Calorimeter at time step N-i.

The function describing the development and level of the effective smoke producing area will be specific for each of the two test methods, and will be outlined below.

PREDICTING SMOKE PRODUCTION IN THE SBI TEST

Our first approach was to assume that the effective smoke producing area in the SBI test follows the same function as the effective heat releasing area. As a first approximation the effective smoke producing area is described by

$$A_{SPR,eff} = k_{SPR} \cdot A_{HRR,eff} \tag{10}$$

This was found to be a satisfactory estimate for most of the analysed products with the exception of not fire retardant treated wood based materials[9]. The products included in our analysis could be separated into two distinct groups, each with subgroups:

A) Products with a similar shape of the effective heat releasing area and the effective smoke producing area.
   A1) Products with high smoke production, k_{SPR} = 0.3
   A2) Products with medium smoke production, k_{SPR} = 1.0
   A3) Products with low smoke production, k_{SPR} = 2.5

B) Products where the shape of the two area-describing functions are significantly different.
   B1) Products with high smoke production
   B2) Products with low smoke production

The functions given in equations (7) and (8) that are describing the effective heat releasing area can also be used to describe the effective smoke producing area for group B products. $A_{HRR,eff}$ and $A_{HRR,max}$ are then replaced by $A_{SPR,eff}$ and $A_{SPR,max}$ respectively. For B1 products $A_{SPR,max}$ takes the initial value 0.1m^2 in eq. (7). Transition to eq. (8), with an $A_{SPR,max}$ of 0.5 m^2 is applied after the predicted SPR has exceeded a value of 0.3 m^2/s^2. For B2 products $A_{SPR,max}$ takes the initial value 0.02 m^2 in eq. (7) and eq. (8) applies with $A_{SPR,max}$ =0.2 m^2 after SPR has reached a value of 0.04 m^2/s^2.

Through a multiple discriminant analysis a combination of Cone Calorimeter variables able to distinguish between the groups above was found. Two parameters that were able to distinguish between products in group A and B were the product's effective density ρ and the total heat released in the period 300 seconds after ignition in the Cone Calorimeter (THR_{300CC}).

The separation into high-, medium- and low smoke producing products in group A was based on combinations of the parameters THR_{300CC}, time to ignition (t_{ign}) and variables representing the maximum heat release rate and the maximum smoke production rate in the Cone Calorimeter test. In addition a discrete parameter representing the level of heat release rate (high, medium or low HRR) found through the HRR simulation was used in the calculations.

If a product is found to belong to group B the distinction between subgroups B1 and B2 is made by a single variable representing the maximum heat release rate.
A flowchart showing the algorithm in the smoke prediction model for the SBI test is shown in Figure 2. The steps where MDA is applied in the model are outlined in the figure.

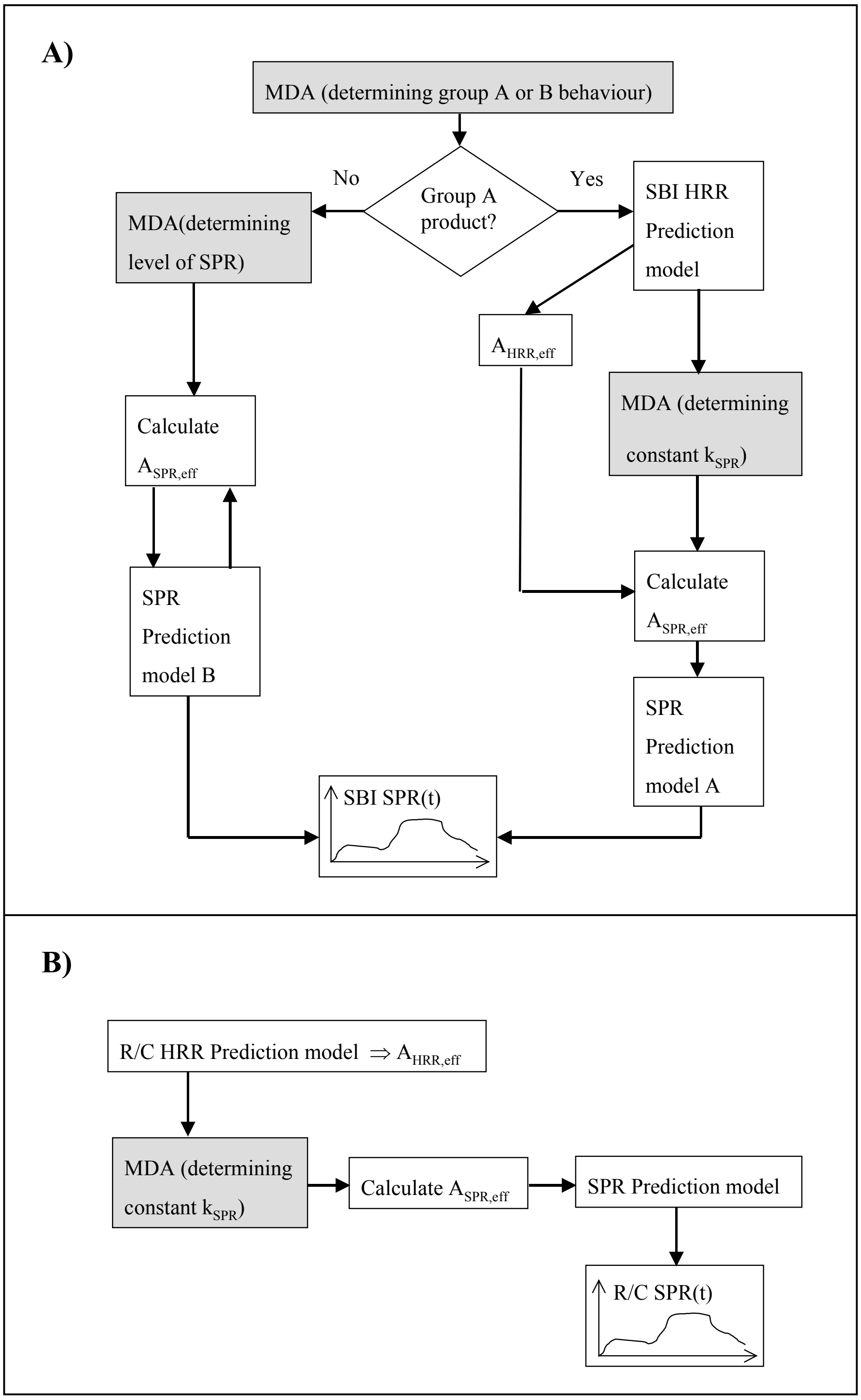


Figure 2 Flow charts for the SBI smoke prediction part of the model (A) and the Room/Corner smoke prediction part of the model (B). The boxes with grey shading show the steps where MDA is applied.

PREDICTING SMOKE PRODUCTION IN THE ISO ROOM/CORNER TEST

The analysis of the ISO Room/Corner test data showed that the tested products roughly can be separated into two groups; products with low and products with high initial smoke production. We also found that equation (10) could give a good approximation of the development of $A_{SPR,eff}$ for a lot of products. The constant k_{SPR} will then be specific for the product; either indicating a low (k_{SPR}=0.5) or a high (k_{SPR}=1.0) initial smoke production, i.e. when $t \leq 600$ s. When $t > 600$ s k_{SPR}=2.0 for all products. The initial value for k_{SPR} is found through calculations of Fisher's discriminant functions determined through MDA of the Cone Calorimeter data in the test set. The analysed variables that were most efficient in separating the initial smoke levels were the product's density and the maximum ratio between SPR and time in the Cone Calorimeter test. A flowchart showing the algorithm in the smoke prediction model for the ISO Room/Corner test is shown in Figure 2. The step where MDA is applied in the model is outlined in the figure.

HOW SHOULD THE QUALITY OF THE SMOKE SIMULATION BE EVALUATED?

An important question is how the quality of the calculated results should be evaluated in a relevant way. How good is the model in simulating the qualitative smoke production with respect to level and shape of the SPR curve? Are the results precise enough to predict quantitative measures with good accuracy? A qualitative evaluation will be useful for assessing the applied methods, but will necessarily include more subjectivity than will be used in a quantitative assessment.

For the quantitative evaluation of the predicted SBI results, we have chosen to look at the total smoke production during the first 600 seconds of testing (TSP_{600s}), and at the maximum value of the ratio between the SPR and time (known as the *SMOGRA value*). The European classification of smoke production within the system of Euroclasses is based on these two parameters. For the ISO Room/Corner test results we have chosen to evaluate the maximum and average smoke production rate (SPR_{max} and SPR_{avg}), which the classification criteria proposed in the EUREFIC programme were linked to. The evaluation will explore how well the simulated results place the products in the correct smoke classes with respect to the different quantitative parameters. The smoke classification criteria applied are as shown in Table 1.

Table 1 The Euroclass system[14] and the EUREFIC smoke classification system[4]. Classification criteria for heat release rate are not shown here, except for the time to flashover (t_{fo}) in the EUREFIC-system.

Euroclass smoke classification	**Criteria for $SMOGRA_{SBI}$**		**Criteria for TSP_{600s}**
s1	SMOGRA ≤ 30 m^2/s^2		$TSP_{600s} \leq 50\ m^2$
s2	SMOGRA ≤ 180 m^2/s^2		$TSP_{600s} \leq 200\ m^2$
s3	No requirements		No requirements
EUREFIC class	t_{FO}	SPR_{max}	SPR_{avg}
A	> 20 min	≤ 2,3 m^2/s	≤ 0,7 m^2/s
B	> 20 min	≤ 16,1 m^2/s	≤ 1,2 m^2/s
C	> 12 min	≤ 16,1 m^2/s	≤ 1,2 m^2/s
D	> 10 min	≤ 16,1 m^2/s	≤ 1,2 m^2/s
E	> 2 min	≤ 16,1 m^2/s	No requirements
Unclassified	-	-	-

RESULTS

A total of 98 cases with Cone Calorimeter test results from 33 different products was used for the SBI prediction and results from totally 89 Cone Calorimeter tests of 32 different products were used for the ISO Room/Corner smoke prediction. The smoke production rate in the SBI test and in the ISO Room/Corner test for each case was calculated.

In Figure 3 we have shown the predicted SPR curves for six selected products with different levels of smoke production.

Prediction of qualitative smoke production

As the curves in Figure 3 show, the simulated SPR more or less follows the same development as the SPR measured in the large-scale test methods. The level of smoke production is also predicted with good precision; with an exception of some simulated peak values that are too high. However, the smoke level is in the correct range, which means that it is possible to distinguish a heavily smoke producing material from one that releases less smoke. This is true for most of the analysed products, while some cases do not fit into this pattern. Examples of products found difficult to predict by our model are a quality of FR PVC, a panel consisting of intumescent coating on particle board, and some qualities of sandwich panels. The smoke production from a phenolic foam was simulated very well for the SBI test, while the ISO Room/Corner prediction results were far from reality.

Prediction of parameters describing the quantitative smoke production

The parameters SMOGRA and TSP_{600s} were calculated from the predicted SPR in the SBI test. The classification based on SMOGRA was correct in 93 % of the cases, while classification based on TSP_{600s} was correctly predicted in 91 %. The smoke classification within the system of Euroclasses was predicted correctly in 91 % of the analysed cases.

From the predicted SPR results in the ISO Room/Corner test the maximum and average SPR were calculated. The SPR_{max} was predicted in the correct EUREFIC-class for 48 % of the cases, while the classification based on SPR_{avg} was correctly predicted in 71 % of the cases. The resulting EUREFIC classification was correctly predicted in only 42 % of all the analysed cases

When the group of products not reaching flashover in the ISO Room/Corner test during the first 300 s was analysed alone (i.e. 55 single Cone Calorimeter data files), 69 % were correctly classified based on SPR_{max} and 75 % were correctly classified based on SPR_{avg}. For this group, the correct EUREFIC classification was predicted in 58 % of the analysed cases.

DISCUSSION AND CONCLUSIONS

The assumption that smoke production is closely linked to the heat release rate is the basis for our smoke production simulation model. Our strategy for developing a smoke prediction model requires that a model for prediction of the heat release rate is available and that this HRR model has sufficiently good predictability. Because products have very different behaviour in fire with regard to how heat release and smoke production develop over time, the 45 products used in our analysis have been categorised with regard to these properties. Multivariate statistical methods are frequently used in other scientific areas like chemistry and social sciences while such methods seldom are used in the area of fire research. Because statistical methods are universal and usually not designed for a specific field of science, our idea was to include these recognised methods into the area of reaction to fire. By application of MDA to the data set containing test results from the Cone Calorimeter we have been able to sort building products into different categories depending on their smoke production in the intermediate-scale SBI test and the large-scale ISO Room/Corner test. In this way the simulation model decides the most appropriate calculation algorithm and applies the most appropriate calculation factors to model the expected SPR. This has been a valuable and necessary step towards the final prediction models for smoke production in these two methods.

The simulation of SPR in the SBI has been very successful, with a correctly predicted smoke classification in more than 90 % of the analysed cases. The shape and level of the predicted SPR curve is close to measured results for the vast majority of the tested products.

The simulation of the smoke production in the ISO Room/Corner test is less successful, but still we regard the model as good.

Physical and chemical deterioration of the burning material during the fire will affect smoke production. Increase in smoke production late in a fire may occur when parts of a burning panel falls down, when a protective layer is burnt through and the core material is exposed to the fire, or when the fire protective action of a fire retardant is overcome by the fire conditions. For some products this will be the normal behaviour and should therefore be predictable based on small-scale test results. For other products the fire development will be more dependent on the fire resistance of mechanical details like fixing systems, seals and joints and such breakdown will more or less be impossible to simulate based on small scale fire testing. Another source of error could be the heat flux level applied in the Cone Calorimeter test. For some fire-retarded products the fire protective mechanism may be overcome by the fire conditions in the Cone Calorimeter while the fire retardant system works as intended in the ISO Room/Corner test. For other products the horizontal configuration of the test specimen in the Cone Calorimeter may give misleading results with respect to the large-scale fire behaviour. This was the case with a PUR foam covered with aluminium foil. Time to ignition in the Cone Calorimeter was in the order of 70 seconds while the time to flashover in the ISO Room/Corner test was 41 seconds, i.e. much shorter than predicted by our model.
For the smoke production in the ISO Room/Corner test we discovered that the event of flashover was determining for the eventual level of smoke production[8]. If the HRR prediction shows that a product will reach flashover within the first few minutes of the ISO Room/Corner test, there will be a large inaccuracy in the simulated smoke production because the calculations are made over a very reduced time interval. However, both the ISO Room/Corner test results and the simulations show that the event of flashover automatically leads to a large smoke production rate.

On the other hand it is not very likely that a product with a short time to flashover will be a realistic candidate for smoke classification. We have therefore chosen to omit these products from the final evaluation of our prediction model. Products that reach flashover later in the test are included in the analysis, like the PVC wallcarpet on gypsum board (see Figure 3) that reached flashover after 675 seconds. The predictability of the model is then about 70 % for both maximum and averaged SPR.

Another error is introduced by using only one surface temperature criterion of 335 ^{o}C for the transition to a more rapid growing effective heat releasing area. For some products use of another temperature criterion in the simulations give predicted results for heat release rate that are more in agreement with the results measured in the ISO Room/Corner test; this is also what we would expect based on general knowledge of products' wide range of ignitability. A simple method able to determine the proper surface temperature criterion for individual products based on Cone Calorimeter data has been proposed by Opstad[15], and may be applied in conjunction with our model.

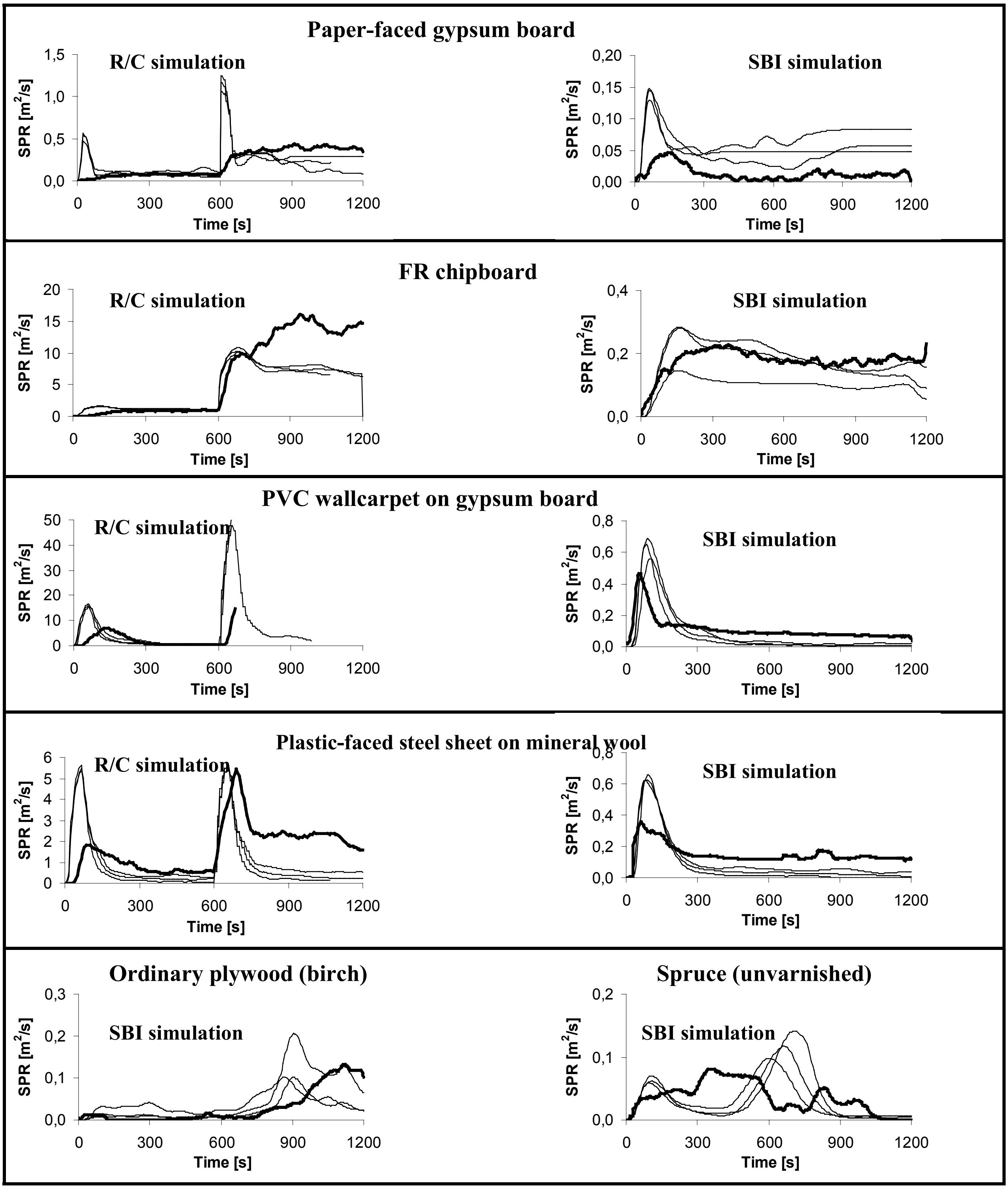


Figure 3 Predicted rate of smoke production curves for 4 different products with varying level of smoke production. The black heavy lines show the SPR measured in a single SBI-test or ISO Room/Corner test (abbreviated R/C) respectively, while the three thinner lines show the SPR predicted from results from three different Cone Calorimeter tests**.** The last two products were only predicted in the SBI because of their short time to flashover in the ISO Room/Corner test.

Through our results we have shown that our model is able to predict the qualitative smoke production in the ISO Room/Corner test and in the SBI test; i.e. we are able to tell if a material will produce little or much smoke, and to predict a good approximation to the actual shape of the SPR curve. Of course, the “actual shape” is far from an exact expression, because the uncertainty in smoke production measurements is large for the two test methods[16] and the repeatability and the reproducibility are low for a lot of products[2]. Still we regard our model as a helpful tool in assessment of a product’s ability to produce smoke.

The prediction of smoke production in real fire scenarios based on small scale fire test results may seem as an unreachable goal. However, the possibility of predicting smoke production in large-scale and intermediate-scale standardised fire test has brought us one step closer to the solution. We have shown that both qualitative and quantitative predictions of smoke production are possible by using advanced statistical tools combined with simple mathematical models, and we believe that the philosophy will be applicable when searching for correlations between other test regimes than the ones our model is built on.

NOMENCLATURE

$A_{HRR,eff}$	effective heat releasing area [m^2]
$A_{SPR,eff}$	effective smoke producing area [m^2]
$A_{max,HRR}$	constant used in calculation of the effective heat releasing area in the ISO Room/Corner test
$A_{max,SPR}$	constant used in calculation of the effective smoke producing area in the ISO Room/Corner test
CC	Cone Calorimeter
HRR	heat release rate [kW/m^2]
k_{SPR}	the ratio $A_{SPR,eff}/A_{HRR,eff}$
MDA	multiple discriminant analysis
$\dot{q}''_{CC}$	heat release rate in the Cone Calorimeter [kW/m^2]
ρ	density [kg/m^3]
R/C	Room/Corner
$\dot{s}''_{CC}$	smoke production rate in the Cone Calorimeter [1/s]
SBI	Single Burning Item
SPR	smoke production rate [m^2/s]
t	time [s]
t_{ign}	time to ignition in the Cone Calorimeter [s]
t_x	time to a specific criterion is fulfilled [s]
THR_{300CC}	total heat release during 300 s after ignition in the Cone Calorimeter [MJ/m^2]
TSP	total smoke production [m^2]
TSP_{600s}	total smoke production during the first 600 s of testing time in the SBI [m^2]

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