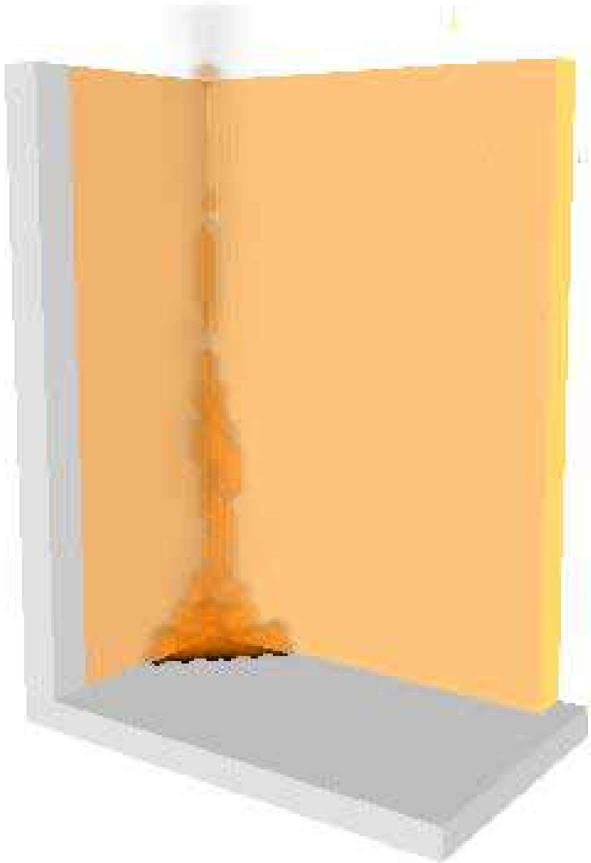
Flame spread modelling of textile materials

Maria Hjohlman, Petra Andersson

FlexiFunBar
Multifunctional barriers for flexible structures
textile, leather and paper



SP Technical Research Institute of Sweden

Fire Technology

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Abstract

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Flame spread in textile material was modelled using two different simulation programs: the semi-empirical area-based code, Conetools, and the CFD-code, FDS. Two textile products developed within the EU-project Flexifunbar were selected for study. The two products show a large difference in composition and application area, and represent material for which fire test results indicate a classification on either end of the rating scale for wall materials according to EN 13501.

Two FDS-models were developed for the simulations. The first FDS model was a relatively simple model of the small scale cone calorimeter test (ISO 5660) which served the purpose of a first preliminary validation of the pyrolysis of the material model. In the second FDS model, a model of the intermediate scale SBI test method (EN 13823), the fire scenario was expanded to simulate flame spread over a surface. The work included determination of the necessary material properties. In Conetools, the option to predict an SBI test was used.

The results from the two simulation methods were compared to real SBI tests. Neither model was able to fully predict the heat release rate for these complex products. However, the results from both codes were accurate enough to give a correct fire rating for wall linings according to EN13501.

Key words: Flame spread, textiles, Conetools, FDS, Euroclasses

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Preface

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1 Introduction

Simulation of fires is an important tool when evaluating a building's fire safety. There are a number of different computer codes available for this application. The computer codes can be divided in two major groups, i.e. two-zone models in which a room is divided in one cold layer with air and one hot layer with smoke, and computational fluid dynamics (CFD) codes where the room is divide into several small volumes for which an appropriate form of the Navier-Stokes equations are solved. Independent of the code, it is common that the fire is a predefined input parameter expressed, e.g., the Heat Release Rate as a function of time. This approach has a disadvantage in not taking into account the influence of the surroundings on the fire unless fire tests in similar environments on each item likely to start burning are conducted. Further, it is not possible to take full account of extinguishing systems and changes in material configuration with this approach. It is therefore desirable that models be developed to predict flame spread on any material to be able to fully evaluate the fire safety of a building and to reliably predict the emission of gases in a fire.

Flame spread is a complicated phenomenon controlled by several factors, such as heat transfer by radiation (from surrounding surfaces, flames and soot particles), convection and conduction, chemical reactions in the material induced by the elevated temperature, cooling by vaporisation of water, pyrolysis of fuel gases and combustion of fuel gases controlled by temperature and the access of oxygen. To accurately model flame spread numerically in a CFD code, requires sub-models in the code that represents all of these phenomena.

Flame spread models to date are quite simple in their approach. Many take their starting point in that a certain area is heated by the flame through convection and radiation and when the surface reaches a certain temperature it is ignited, as described by Saito, Quintere and Williams[1]. This approach is used in anything from semi-empirical models like Conetools[2] through two-zone models like Branzfire[3] to CFD codes like FDS[4].

There are different approaches in determining the size of the area that is heated and how much heat is transferred to the material over that area. Many methods are based on a correlation of flame size depending on the scenario, e.g. the heated area is larger for an upward spread than for a downward spread. The heat transfer from the flame to the material is set to a constant value in some models (a value between 25 and 35 kW/m^2)[5] while the CFD codes can calculate this value based on the local conditions in each cell. Some models use ignition temperature as a criteria for ignition, others use critical mass flux from the material surface ($g/m^2/s$), this critical mass flux value depends then on the scenario[5].

The burning rate per unit area as a function of time can then be calculated from a heat release vs. time curve obtained e.g. in a cone calorimeter test. This approach can be used in several codes e.g. Sofie[6], Conetools and FDS. Another approach, used by FDS, is to specify the pyrolysis as an Arrhenius function depending on the material temperature.

In this project pyrolysis from textile materials was modelled. To date most flame spread simulations have been made on different wooden materials like particle board and fibre board, or polymers like PMMA, PVC and PUR. A few examples of modelling textile materials used as linings on different boards using Conetools and the semi-empirical model developed by Karlsson[7] are given in Sundström[5] . This report present results for different textile materials using Conetools and also the CFD code FDS.

Textile materials are commonly used in furniture, but can also be found in building materials, such as wallpaper or insulation. Textile products are often relatively thin or consists of several layers of material. In end use applications textiles are often mounted on another material such as a foam or board material. When modelling pyrolysis and flame spread in such a material the outer surface temperature will be effected by the conduction of heat from the surface through the layers and into the backing material. Further, pyrolysis may occur from several of the layers simultaneously. When modelling pyrolysis and flame spread in such material it may be convenient to specify the material properties of each layer separately instead of calculating some kind of weighted average of the material properties. A multi-layered model which has been introduced in FDS ver 5 therefore has the potential to be a useful feature when modelling flame spread in textiles.

2 Technical Approach

Two textile products developed in the Flexifunbar project were selected for the study. The two products were examples of products with a large difference in thickness, structure and fire performance.

The flame spread in the textile products in an SBI test (EN 13823) were simulated using two different programs, the semi-empirical code Conetools and the CFD code Fire Dynamics Simulator, FDS, version 5.

The work included developing a model in FDS of the SBI test, validating the model regarding radiation, and determining the necessary material properties of the materials. A model of the small scale cone calorimeter test was also developed to serve as a preliminary investigation of the pyrolysis model. A sensitivity study was also conducted for some important parameters.

The results from the simulations were compared to the results from real SBI tests.

3 Materials

The objective of the study was to develop a numerical model for the pyrolysis of textiles developed in the EU Flexifunbar project. A large amount of material has been tested in the cone calorimeter within Flexifunbar, but the large challenge when modelling pyrolysis is to model flamespread in a larger scale than the cone calorimeter. Therefore two materials developed within Flexifunbar which have also been exposed to the SBI test were selected for the study. The two products had a very different structure, fire behaviour and end-use application. One material was a non-woven 35 mm thick insulation material of wool and flax fibres. This product was mounted on a non-combustible board in the flame spread test. The second material consisted of a thin cotton fabric coated with an intumescing graphite product. The function of the product is to improve the fire behaviour of an underlying substrate. The product was therefore glued onto a particle board in the tests. To build a model of this multilayered structure the particle board itself had to be modelled and the board is included in the study as a third material. The three materials are described below and their properties summarised in Table 1.

INF/Isoflax W1
A non-woven insulation material in 35 mm thick flexible sheets. Its main components were flax and wool fibres.

INCA-XO 300 and 320
A cotton woven fabric coated with an intumescent graphite product. When tested, this material was glued (Bostik Golv-Vägglim 300 g/m^2) to a particle board.

Particle Board
The particle board had a thickness of thickness 12 mm. The particle board fulfilled the requirements in EN 13238:2001[8].

Table 1. Materials

Material	Density (kg/m^3)	Thickness (mm)
Isoflax	24	35
INCA XO 300	43	0.8
Particle board	640	12

4 Conetools

The Conetools software is an area-based semi-empirical model developed to predict the fire behaviour of building products in the SBI and Room Corner test. The model has been shown to be able to predict the fire performance of a large number of building products[9] in these applications. Conetools uses the heat release curve as well as time to ignition determined from the cone calorimeter at heat flux level 50 kW/m^2 as input.

Three major assumptions have been made in the prediction model of heat release rate in the SBI test:

1) The burning area growth rate and the heat release rate are decoupled.
2) The burning area growth rate is proportional to the ease of ignition, i.e. the inverse of the time to ignition in small scale.
3) The history of the heat release rate per unit area at each location in the SBI test is the same as in the cone calorimeter.

The area growth rate is described using the following function:

$$A(t) = A_{max} \cdot \left[1 - \left(1 + \frac{t - \frac{t_{ign}}{2}}{t_{ign}} \right) \cdot \exp\left(\frac{t - \frac{t_{ign}}{2}}{t_{ign}} \right) \right] \qquad [1]$$

where A_{max} is the maximum area involved and t_{ign} is time to ignition in the Cone Calorimeter.

In the beginning of the test, all products are assumed to follow the same area growth function. However, if the sustained flame height reaches the top of the test specimen, which is 1.5 m, the maximum area in the area growth function changes. This is the only parameter that is changed when changing from one flame spread regime to another. The sustained flame height is a function of the calculated total heat release in the test as explained below.

The area growth function and the different values for the maximum area are empirically chosen based on an SBI round robin test series at both SP and the Danish Institute of Fire Technology (DIFT). The maximum area is assumed to be 0.35 m^2 for those products which do not have a sustained flame height of 1.5 m. This area is roughly equal to the area behind the burner flames. For products where the sustained flame height exceeds 1.5 m the maximum area is 0.60 m^2.

The flame height, H, in a wall corner geometry is given as[10]:

$$\frac{H}{D} = 3 \cdot \dot{Q}^{*2/3} \qquad [2]$$

where

$$\dot{Q}^{*} = \dot{Q}_{total} \cdot (D^{5/3} \cdot 1110) \qquad [3]$$

D is the diameter of the burner, which was assumed to be 150 mm considering that the burner is triangular.

The results given as output from a Conetools SBI simulation is the total heat released during the first 600 seconds after ignition of the burner, THR_{600}, the FIGRA and the heat release curve during 600 seconds.

5 FDS

Fire Dynamics Simulator, FDS, is a computational fluid dynamics, CFD, code developed by the National Institute of Standards and Technology, NIST, in the USA. The program was developed with an emphasis on flows typically occurring during a fire, i.e. low-speed and thermally-driven flows and models turbulence using the Large Eddy Simulation, LES, technique[4].

The program includes several sub-models for modelling phenomena such as combustion, radiation, water droplet trajectories, heat transfer, and pyrolysis. The program is under constant development and the latest version, version 5, released in October 2007, includes new features of the solid surface model such as a possibility to model a material that undergoes several reactions during decomposition, and surfaces consisting of several layers of materials.

5.1 Modelling flame spread in FDS v.5

There are two methods for modelling pyrolysis of solid materials using FDS. i.e.:

1. Specifying a heat release rate per unit area as a function of time that will be activated when a user specified surface temperature is reached.
2. Control of the pyrolysis using the heat balance for the surface, and an Arrhenius function:

$$r = \frac{\partial}{\partial t}\left(\frac{\rho}{\rho_0}\right) = \left(\frac{\rho}{\rho_0}\right)^n A \exp\left(-\frac{E}{RT}\right) \qquad [4]$$

where,

r = the reaction rate
ρ =density
ρ_0 =density
A = pre-exponential factor
E = activation energy
R = Stefan-Boltzmann constant
Ts = temperature of the material
n = reaction order

The second method in which the burning rate depends on the heat feedback to the surface has been used in this project. The reaction process may produce fuel which is released into the gas phase, residue which may consist of char, water vapour or another material that may undergo a second reaction.

The parameters A and E may be specified by the user or calculated by FDS based on a default value for A of $1.0\text{x}10^{13}$ 1/s and a user specified mass loss rate at a user specified reference temperature (could be regarded as the ignition temperature).

The temperature of the surface is effected by heat transfer through radiation, convection and conduction and the energy consumed by the reaction process described above. The conduction of heat into the surface is calculated using a one-dimensional model with the direction perpendicular to the surface. The boundary condition on the backside of the material is specified by the user as insulated or opened to an air gap. The surface may be specified as consisting of several layers of material.

Combustion is often modelled as a single step chemical reaction for which its products are tracked by a mixture fraction model. A multi-step finite rate model is also available. Parameters of importance to the flame spread include the heat of combustion, energy released per unit mass of oxygen consumed, soot yield and radiative fraction.

Radiative heat transfer is modelled using a gray-gas or a wide-band model. Several parameters may be controlled by the user but are outside the scope of this project. The most important parameter is the fraction of heat released as radiation during combustion.

The material parameters are further described in section 5.2 below.

5.2 FDS material parameters

Two material models were developed for the Isoflax material. The difference being how the A end E parameters in the Arrhenius equation were determined. For Isoflax1, A and E values were determined from TGA measurements. For Isoflax2, A and E were calculated by FDS based on additional input, see below.

The model of the particle board included vaporization of water and production of an insulating char layer.

When modelling INCA glued on particle board the option of specifying a surface consisting of two layers was used. The heat release generated by the INCA material only (including glue) in the cone calorimeter tests as presented in Figure 5 was considered negligible. The material was assumed not to generate any fuel in the model and therefore A, E and heat of reaction are not specified.

The material parameters are listed below with the name of the relevant FDS parameter in brackets in bold. Summaries of the values of the parameters for each material are presented in Table 2 to Table 5. The methods used for determination are further described in section 6. Experiments. The material models in FDS input format are presented in Appendix B and Appendix C.

Thickness (THICKNESS [m])
The thickness of the material. FDS will use this value for the heat conduction and pyrolysis calculations, it will not use the actual geometries specified for the object to which the surface is attached.

Density (DENSITY [kg/m^3])
The density of the material.

Emissivity (EMISSIVITY [-])
The emissivity of the surface. The default value of 0.9 was used.

Arrhenius function parameters A and E, Reference Temperature and Reference Mass Flux Rate (A [1/s], E [kJ/kmol], REFERENCE_TEMPERATURE [°C], REFERENCE_RATE [1/s])
The pre-exponential factor A and the activation energy E may be specified by the user or calculated by FDS based on a default value for A of 1.0×10^{13} 1/s and a user specified mass loss rate at a user specified temperature (usually close to ignition). The default value of the reference rate is 0.1 1/s.

A and E for the particle board were previously determined from thermogravimetric analysis, TGA, results[11] using the isothermal method as described by Svensson[12] .

For Isoflax two methods were used. For the material model Isoflax1, A and E were determined from TGA results measured with the dynamic heating rate method[13] at N_2 atmosphere and an average heating rate of 2 ºC/min. The several peaks in the derived weight curve in Figure 2 indicate a composite material that undergoes several reactions during decomposition. Only one reaction was included in the model and the A and E values determined by the TGA software at the maximum weight loss rate was used.

For material model Isoflax2, A and E were calculated by FDS, based on the specified REFERENCE_TEMPERATURE = 220 ºC and the default values of A = 1.0×10^{13} 1/s and REFERENCE_RATE = 0.1 1/s. The REFERENCE_TEMPERATURE for Isoflax2 was determined from the TGA results as the temperature at which a mass loss of 5%, excluding the mass loss due to vaporization of water, had occurred.

All material models used a reaction order n=1. For comparison reasons the reaction rate calculated from the A and E values of the different materials, using equation [4] and assuming $\rho/\rho_0=1$, are plotted in Figure 1.

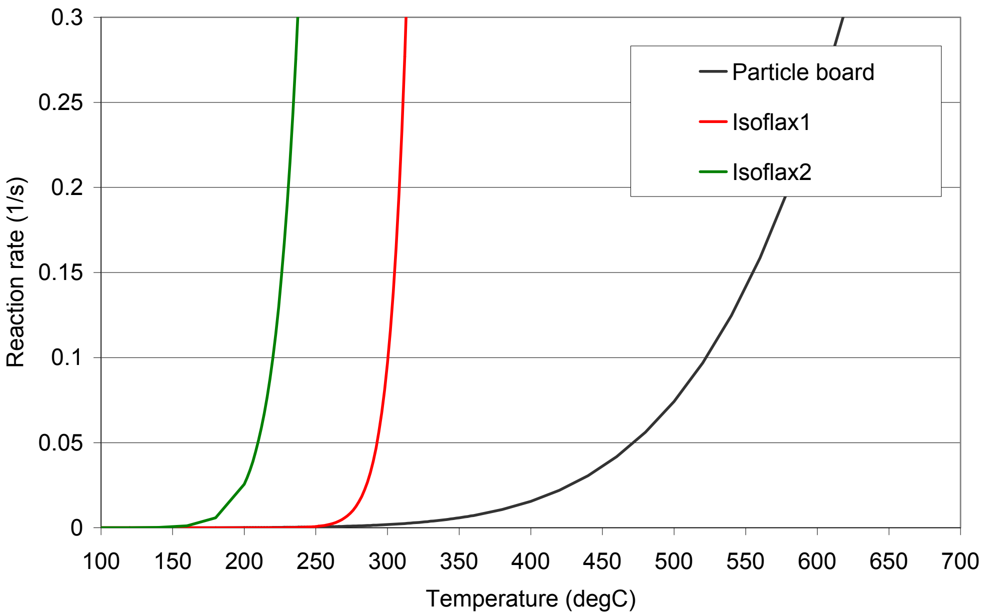

Figure 1. Reaction rate vs temperature, calculated for the different A and E, using equation [4] and assuming ρ/ρ_0=1.

Heat of Combustion (HEAT_OF_COMBUSTION [kJ/kg])
Energy generated per unit weight of material consumed. The heat of combustion was determined based on the cone calorimeter tests.

Heat of Reaction (HEAT_OF_REACTION [kJ/kg])
The heat of reaction is the energy required to convert the material into the reactant. Applied to a pyrolysis process where a solid is totally converted into a gas, it is the heat of vaporisation or the enthalpy difference between the fuel as a solid and as a gas. The pyrolysis rate in the model is very sensitive to the value of the heat of reaction and since it is not easily determined for complex products, the value was determined empirically by a parameter study in the simple radiated surface model. The heat release rate and mass loss rate were compared with cone calorimeter results at 35 and 50 kW/m^2.

Specific Heat and Thermal Conductivity (SPECIFIC_HEAT [kJ/kg/K], CONDUCTIVITY [W/m/K])
The conductivity and specific heat were measured using the Transient Plane Source, TPS, method[14,15]. For particle boards, measurements were conducted at multiple temperatures. Temperature dependant properties were specified for these materials using SPECIFIC_HEAT_RAMP and CONDUCTIVITY_RAMP.

For the INCA material, the material typically was fully expanded after 10 seconds in a 50 kW/m^2 cone-calorimeter test. Measurements were therefore conducted on expanded material since this is the form of the material during the major period of the tests.

Soot yield (SOOT_YIELD [kg/kg])
The soot yield is the mass fraction of the fuel being converted into soot.
The soot yield where calculated from the cone calorimeter results as follows[16]:

$$SOOT\_YIELD = \frac{SEA}{8700} \qquad [5]$$

where,

SEA = specific extinction cross section area determined in the cone calorimeter [m^2/kg]

Yield of Fuel, Water and Residue (NU_FUEL [kg/kg], NU_WATER [kg/kg], NU_RESIDUE [kg/kg])
The fuel, water and residue yield is the mass fraction of the material being converted into fuel, water and residue respectively. The residue was determined from the cone calorimeter tests as the remaining mass after the tests.

For particle board the water content was determined by weighing a sample material before and after conditioning in a furnace until no reduction in mass was reached (2 days).

The fuel yield was then calculated as:

$$NU\_FUEL = 1 - NU\_WATER - NU\_RESIDUE \qquad [6]$$

Combustion reaction in the gas phase (REAC)
In FDS the stoichiometry of the fuel involved in the predominant reaction must be specified or the stoichiometry of propane will be used as default. In the simple radiated surface model (i.e. the cone model) the stoichiometry of cellulose[17] was used for the particleboard, INCA and Isoflax. In the SBI model, the stoichiometry of propane, the fuel of the burner, was used for all materials.

Backside of surface (BACKING)
The backing parameter specifies the conditions on the backside of the surface. The boundary condition is used in the convective heat transfer calculation. The user can chose between ‘VOID’, ‘INSULATED’ or ‘EXPOSED’.

In the cone calorimeter tests the samples were resting on insulating fibres. Consequently the backing parameter ‘INSULATED’ was used in the model. In the SBI tests ‘VOID’ was used for particle board and for Isoflax where the samples were mounted on non-combustible calcium silicate boards ‘INSULATED’ was used.

Table 2. Material and surface parameters for particle board.

Parameter	Unit	Value		Method
A	1/s	2.38E+06		TGA
E	kJ/kmol	1.05E+05		TGA
HEAT_OF_COMBUSTION	kJ/kg	1.33E+04		Cone Calorimeter
DENSITY	kg/m3	640		Calliper and balance
HEAT_OF_REACTION	kJ/kg	500		Parameter study in cone calorimeter model
SPECIFIC_HEAT_RAMP; T		T (C)	kJ/kg/K	
		20	1.66	TPS
		75	2.07	TPS
		105	2.25	TPS
		149	2.74	TPS
CONDUCTIVITY_RAMP;T		T (C)	W/mK	
		20	0.164	TPS
		75	0.186	TPS
		105	0.191	TPS
		149	0.184	TPS
EMISSIVITY	-	default=0.9		default
SOOT_YIELD	kg/kg	0.0053		Calculated from Cone calorimeter results
DENSITY_CHAR	kg/m3	129		Calliper and balance
SPECIFIC_HEAT of CHAR	kJ/kg/K	2.5		Hietenamin, Hostikka, and Vaari [18]
CONDUCTIVITY of CHAR	W/m/K	0.2		Hietenamin, Hostikka, and Vaari [18]
NU_FUEL	kg/kg	0.71		Cone Calorimeter
NU_RESIDUE, RESIDUE=’CHAR’	kg/kg	0.22		Cone Calorimeter
EMISSIVITY for CHAR	-	default=0.9		default
NU_WATER	kg/kg	0.07		Measure with balance before and after conditioning in oven.
THICKNESS	m	1.20E-02		Calliper
REAC	-	Cone: H=10 C=6 O=5 SBI: C=3 H=8		Chemical formula of cellulose and propane from SFPE Handbook 2nd edition.
BACKING	-	Cone: ’INSULATED’ SBI: ’VOID’		-

Table 3. Material and surface parameters for INCA

Parameter	Unit	Value	Method
DENSITY	kg/m3	43.1	Calliper and balance
EMISSIVITY	-	0.9	Default
SPECIFIC_HEAT	kJ/kg/K	0.68	TPS
CONDUCTIVITY	W/m/K	0.150	TPS
THICKNESS	m	0.008	Calliper

Table 4. Material and surface parameters for Isoflax1

Parameter	Unit	Value	Method
HEAT_OF_COMBUSTION	kJ/kg	1.55E+04	Cone Calorimeter
DENSITY	kg/m3	24.3	Calliper and balance
A	1/s	1.70E+21	TGA.
E	kJ/kmol	2.44E+05	TGA.
HEAT_OF_REACTION	kJ/kg	3000	Parameter study in cone calorimeter model
SPECIFIC_HEAT	kJ/kg/K	2.03	TPS
CONDUCTIVITY	W/m/K	0.058	TPS
EMISSIVITY	-	0.9	Default
SOOT_YIELD	kg/kg	0.0083	Calculated from Cone Calorimeter
NU_FUEL	kg/kg	0.88	Cone Calorimeter
THICKNESS	m	0.035	Calliper
REAC	-	Cone: H=10 C=6 O=5 SBI: C=3 H=8	Chemical formula of cellulose and propane from SFPE Handbook 2nd edition.
BACKING	-	’INSULATED’	-

Table 5. Material and surface parameters for Isoflax2

Parameter	**Unit**	**Value**	**Method**
HEAT_OF_COMBUSTION	kJ/kg	1.55E+04	Cone Calorimeter
DENSITY	kg/m3	24.3	Calliper and balance
REFERENCE_TEMPERATURE	°C	220	TGA. Temp at 5% reduction in mass.
HEAT_OF_REACTION	kJ/kg	3000	Parameter study in cone calorimeter model
SPECIFIC_HEAT	kJ/kg/K	2.03	TPS
CONDUCTIVITY	W/m/K	0.058	TPS
EMISSIVITY	-	0.9	Default
SOOT_YIELD	kg/kg	0.0083	Calculated from Cone Calorimeter
NU_FUEL	kg/kg	0.88	Cone Calorimeter
THICKNESS	m	0.035	Calliper
REAC	-	Cone: H=10 C=6 O=5 SBI: C=3 H=8	Chemical formula of cellulose and propane from SFPE Handbook 2nd edition.
BACKING	-	'INSULATED'	-

6 Experiments

The work included several different types of experiments, both to provide the input parameters but also to verify the simulation results. Experiments conducted to provide input include the Thermo Gravimetric Analysis, TGA, the Transient Plane Source, TPS, and the cone calorimeter. The SBI test was used for validation of both the FDS and the Conetools simulations. The cone calorimeter results were also used for comparing FDS simulation results during a preliminary investigation of the pyrolysis model.

6.1 TGA

The Thermo Gravimetric Analyser, TGA, is used to measure weight changes in sample materials as a function of temperature or time under a controlled atmosphere. Samples can be heated over a programmed temperature range (30ºC-900ºC) and weight changes resulting from chemical reactions, decomposition, solvent and water evolution can be measured. The analyser can also be used to gather and analyse data at isothermal temperatures to measure weight loss or gain in sample materials. It is useful for characterizing polymers, organic or inorganic chemicals, metals or other common classes of materials. Sample weight can range from 1 mg to 150 mg.

The tests were conducted to determine the A and E value used in the pyrolysis model of FDS.

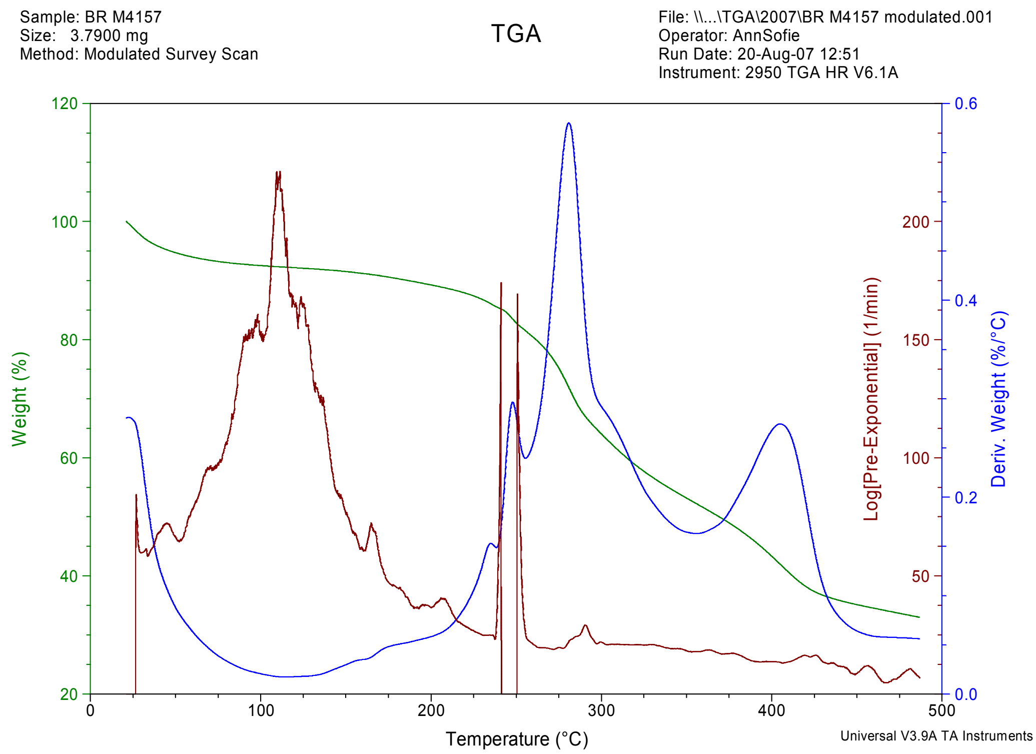

Figure 2. Example of TGA results for Isoflax at N_2 atmosphere and an average modulated heating rate of 2 ºC/min.

6.2 TPS

The Transient Plane Source, TPS, method[19] involves the use of a very thin double metal spiral shaped as a disk, 10 μm thick, sandwiched between two layers of Kapton (25 μm thickness), in close contact with the material to be investigated. The sample size can vary between 8 mm and 120 mm or larger. The double metal spiral serves both as the heat source and as a resistance thermometer. When making measurements in solid bodies, the spiral is clamped between two surfaces of the same material, as shown in the Figure 3.

Figure 3. TPS sensor is clamped between two samples of material. Note that the material in the photo is not part of this study but is only used to illustrate the method.

When current flows through the spiral, heat is developed which raises the temperature and thus the resistance of the spiral. The rate of this temperature rise depends on how quickly the heat developed in the spiral is conducted away through the surrounding material. Heating is continued for a constant period of time, with the voltage across the sensor registered. The change in voltage is proportional to the changes in the resistance of the sensor. The changes in resistance is in turn proportional to the transient temperature gradient developed on the surface of the sample and the electrical power applied to the sensor. With knowledge of the temperature gradient and the electrical heat applied, the thermal diffusivity, thermal conductivity and volumetric heat capacity can be calculated. The method is suitable for measuring thermal conductivities over the range of 0.005-500 W/mK and temperatures up to 700 ºC.

Determination of thermal conductivity of thin films, or textiles, can be carried out using a special technique consisting of two measurements. In the first measurement, the reference measurement, the TPS sensor is placed between two stainless steel blocks. In the second measurement, the sensor is placed between two specimens of textiles and this package is placed between the two stainless steel blocks. The thickness of the specimens and thermal properties of the sensor and the steel blocks determined during the first measurement are used as input data in the second measurement. The result obtain in the second measurements is the thermal conductivity of the specimen. The TPS sensor used in this technique has a diameter of 30.2 mm and a thickness of 46 μm.

The tests were conducted to determine the specific heat and thermal conductivity used in the FDS models and the results are presented in Table 6.

Table 6. TPS results

Material	Temperature (°C)	Specific Heat (kJ/kg/K)	Thermal Conductivity (W/m/K)
Particle Board	23.0	1.66	0.164
	74.5	2.07	0.186
	105.8	2.25	0.191
	148.9	2.74	0.184
Isoflax	20	2.03	0.058
Expanded INCA	20	0.68	0.154

6.3 Cone Calorimeter

In the Cone Calorimeter, ISO 5660-1[20], specimens of 0.1 m by 0.1 m are exposed to controlled levels of radiant heating. A horizontal specimen surface is heated up and an external spark ignitor ignites the pyrolysis gases from the specimen. The gases are collected by a hood and extracted by an exhaust fan for further analysis.

The heat release rate (HRR) is determined by measurements of the oxygen consumption derived from the oxygen concentration and the flow rate in the exhaust duct. The specimen is placed on a load cell during testing. A retainer frame covers the periphery of the specimen. The smoke production rate is measured with a laser system.

Results obtained from the cone calorimeter are related to time to ignition, energy released during combustion and smoke produced during combustion. The test apparatus is shown in Figure 4.

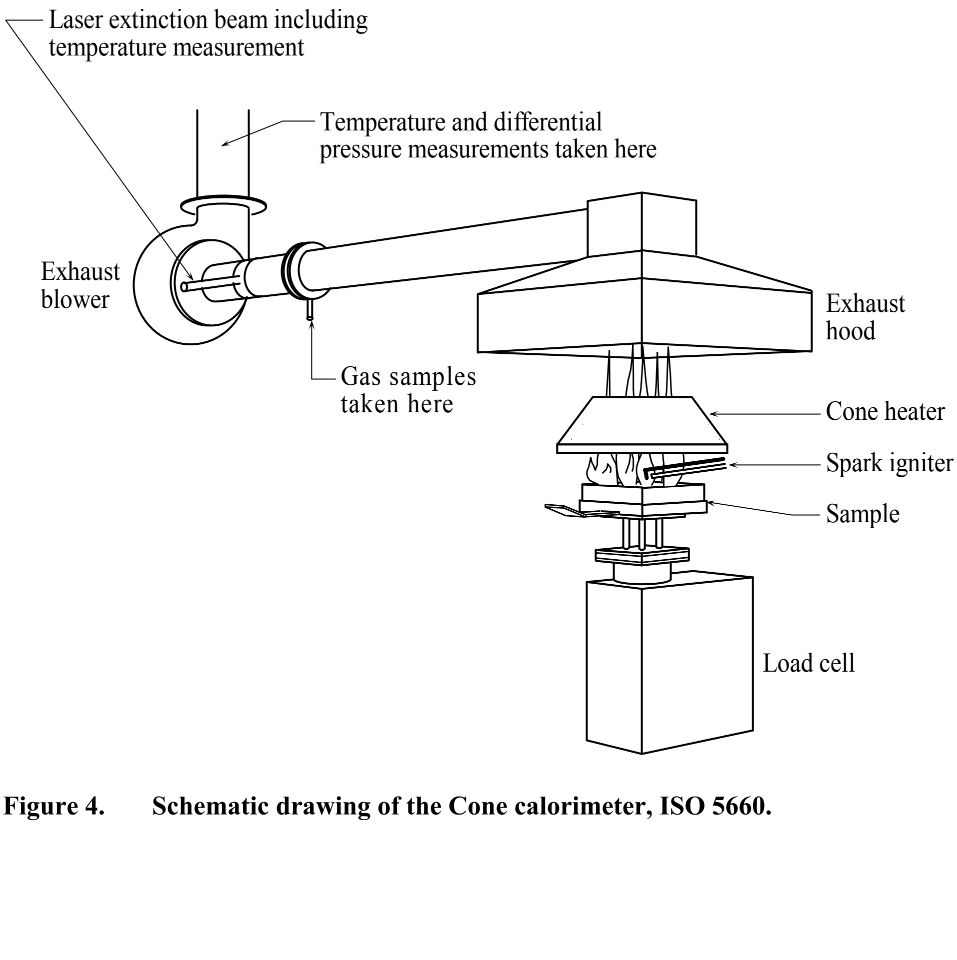

Figure 4. Schematic drawing of the Cone calorimeter, ISO 5660.

The tests were conducted to determine the heat of combustion, soot yield and the fraction remaining as residue, to be used in the FDS models. The heat release rate vs. time curve and time to ignition were used as input in Conetools. The heat release rate and mass loss over time were also used for comparison during the preliminary investigation of the FDS material model.

The results of the cone calorimeter tests for the various material are shown in Figure 5 to 8.

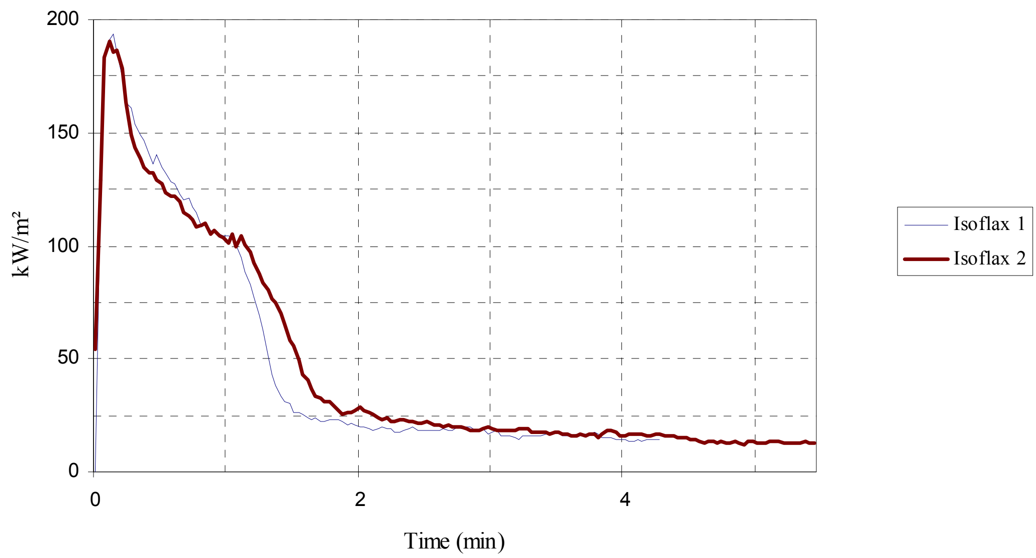

Figure 5. Cone calorimeter results at radiation level 50 kW/m^2 on Isoflax.

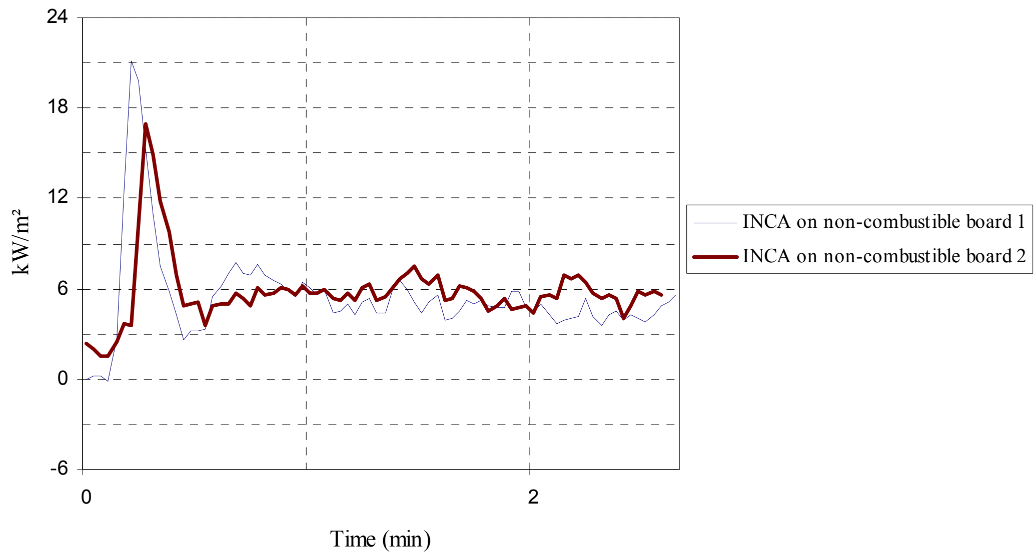

Figure 6. Cone calorimeter results from 2 tests at radiation level 50 kW/m^2 on INCA material glued on incombustible calcium silica board.

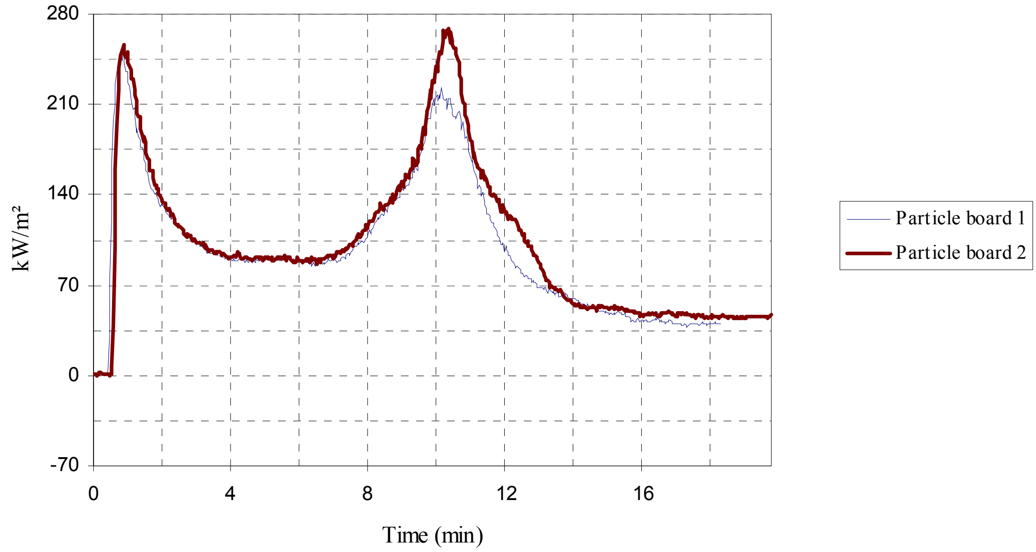

Figure 7. Cone calorimeter results from 2 tests at radiation level 50 kW/m² on PB.

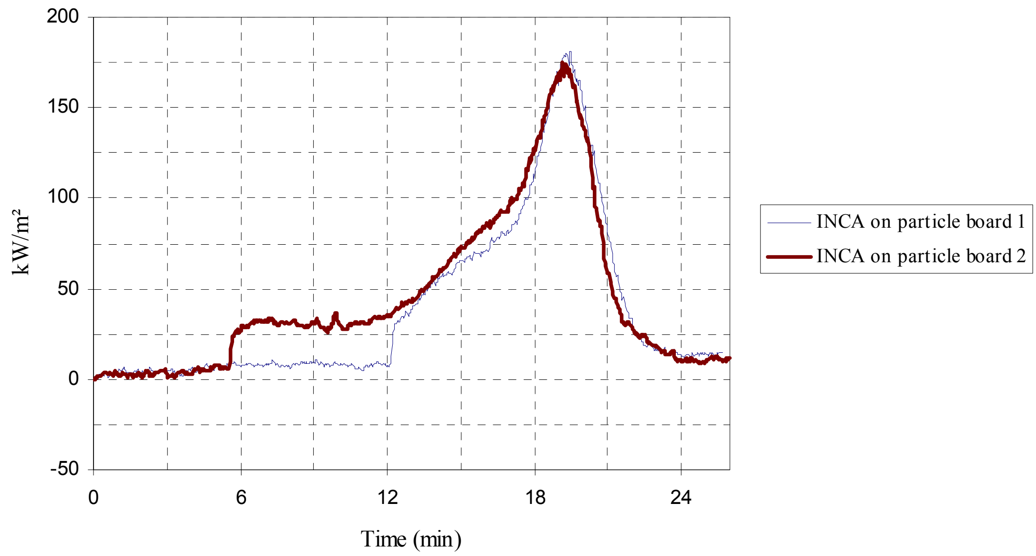

Figure 8. Cone calorimeter results from 2 tests at radiation level 50 kW/m² on INCA material glued on PB.

6.4 SBI

EN 13823, SBI[21], evaluates the potential contribution of a product to the development of a fire, under a fire scenario simulating a single burning item in a room corner near to the product. The SBI is the major test procedure for classification of linings in Europe and provides the basis for Euroclass classification.

The SBI is a so-called intermediate scale test. Two test samples, 0,5 m x 1,5 m and 1,0 m x 1,5 m are mounted in a corner configuration where they are exposed to a gas flame ignition source of 30 kW. Direct measurement of fire growth (Heat Release Rate, HRR) and light obscuring smoke (Smoke Production Rate, SPR) are principal results from a test. Other properties such as the occurrence of burning droplets/particles and maximum flame spread are observed. A schematic of the test apparatus is seen in Figure 9.

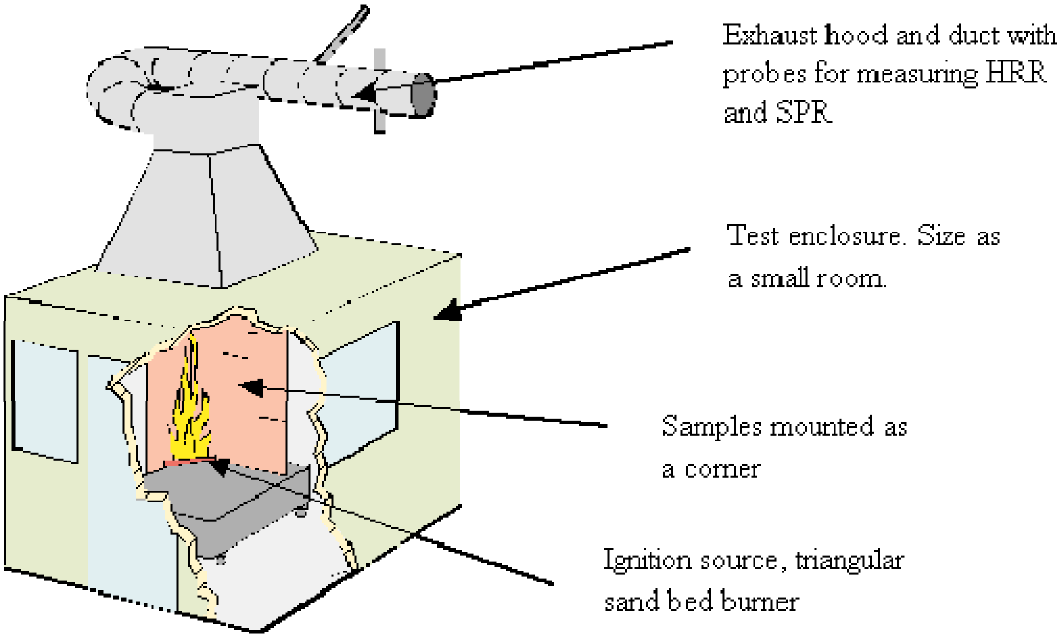

Figure 9. EN 13823, SBI, the Single Burning Item.

The THR_{600s}, total heat released during 600 seconds and the index FIGRA, FIre Growth RAte, is used to determine the Euroclass. The concept is to classify the product based on its tendency to support fire growth. Thus FIGRA is a measure of the largest growth rate of the fire during an SBI test as seen from the test start. FIGRA is calculated as the maximum value of the function (heat release rate)/(elapsed test time), units are W/s. A graphical presentation is shown in Figure 10.

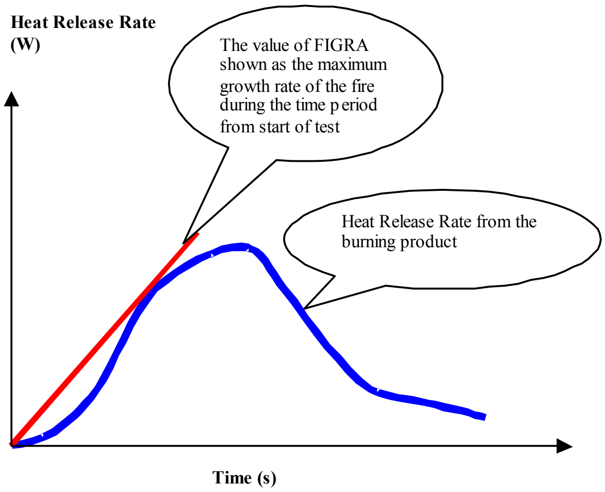

Figure 10. Graphical representation of the FIGRA index.

The results from the SBI tests obtained for INCA on particle board and Isoflax are listed in Table 7. The heat release vs. time curves are presented in Figure 11 and Figure 12.

Table 7. SBI test results.

Material	Test No	FIGRA (W/s)	THR_{600s} (MJ)	Preliminary SBI classification
INCA on particle board	1	53	7.1	A2/B
	2	53	6.9	A2/B
Isoflax	1	1544	4.7	E/F

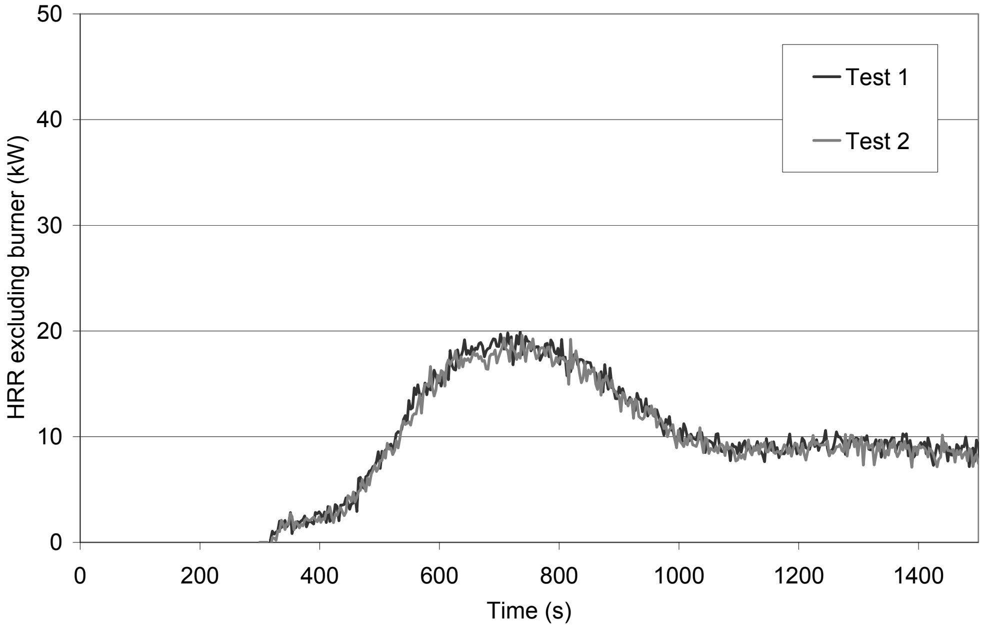

Figure 11. SBI results from 2 tests of INCA on particle board. The burner is ignited at 300 seconds.

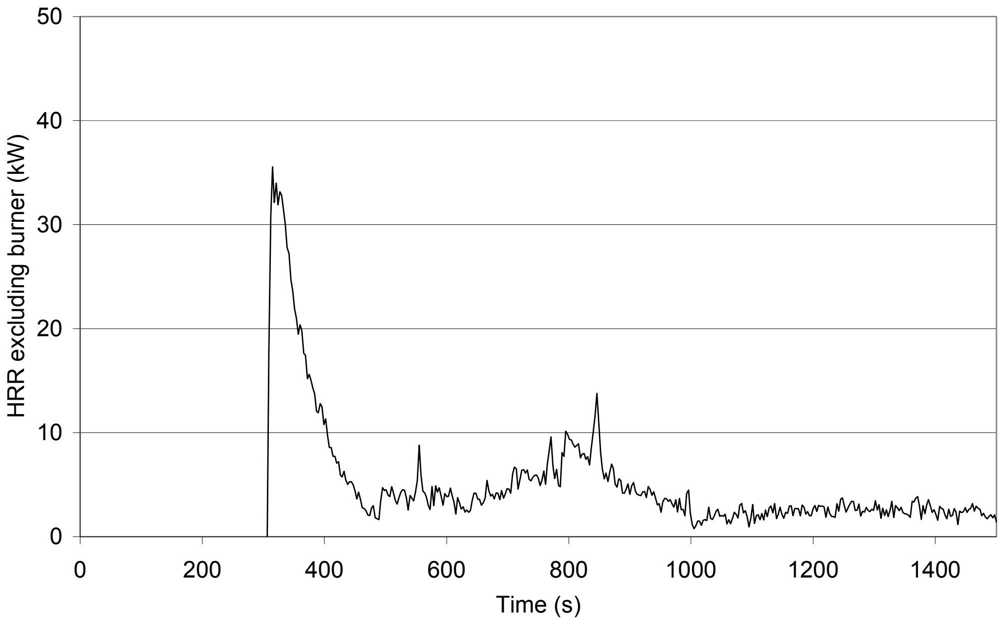

Figure 12. SBI results for Isoflax. The burner is ignited at 300 seconds.

7 Conetools simulations

The option in Conetools to predict SBI test results was used. Conetools uses cone calorimeter results as input and since duplicate cone calorimeter tests were run two simulations of each material were conducted.

7.1 Results

Two simulations of each material were conducted based on the different cone calorimeter tests. The simulation runs are presented in Table 8.

Table 8. List of Conetools simulations

Material	Run ID	Cone Calorimeter run	Time to ignition (s)
INCA on particle board	Conetools 1	INCA on particle board 1	731
INCA on particle board	Conetools 2	INCA on particle board 2	337
Isoflax	Conetools 1	Isoflax 1	1
Isoflax	Conetools 2	Isoflax 2	1

The simulation results are compared to the test results in Figure 13 to Figure 14 and in Table 9. Ignition of the burner occurred at 300 seconds into the test. The Conetools simulation results ends at 900 seconds, since data used as classification criteria is based on the heat release curve for the time period 300 to 900 seconds.

As is depicted in Figure 13 to Figure 14 the predicted heat release rates differ significantly from the test results. For the product INCA on particle board the increase in heat release rate are much lower for the simulation compared to the test. For the Isoflax the increase is approximately right but the peak reaches up to a higher level in the simulation. However, the results are accurate enough to give a correct fire rating for wall linings as is seen in Table 9. The differences are further discussed in section 9.

Since the time to ignition has proven to be a crucial parameter[9] a sensitivity analysis was conducted and the results of this sensitivity analysis are presented in Table 10.

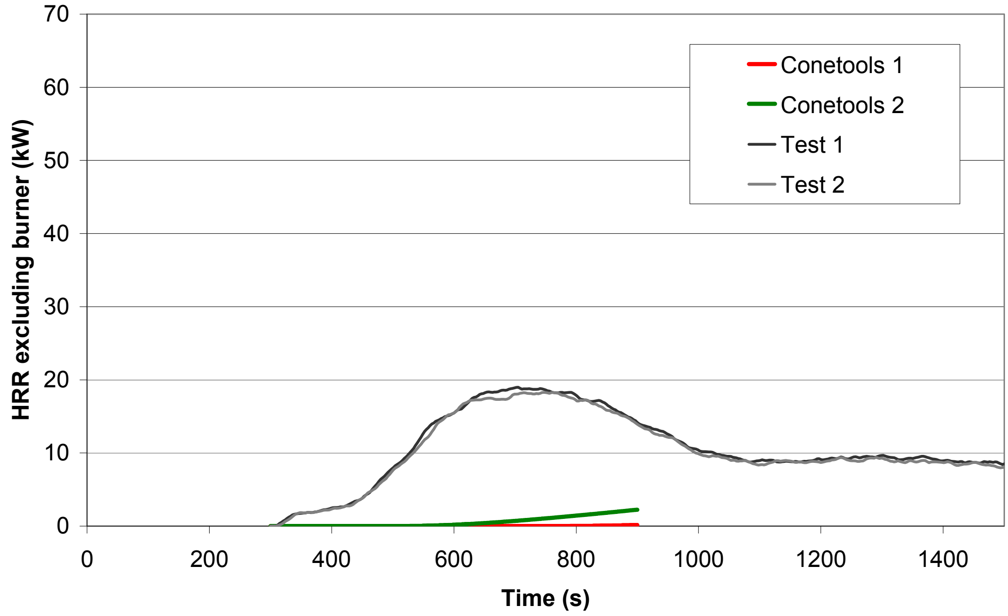

Figure 13. HRR results for INCA glued on particle board, Conetools results compared to SBI test, excluding HRR from the burner.

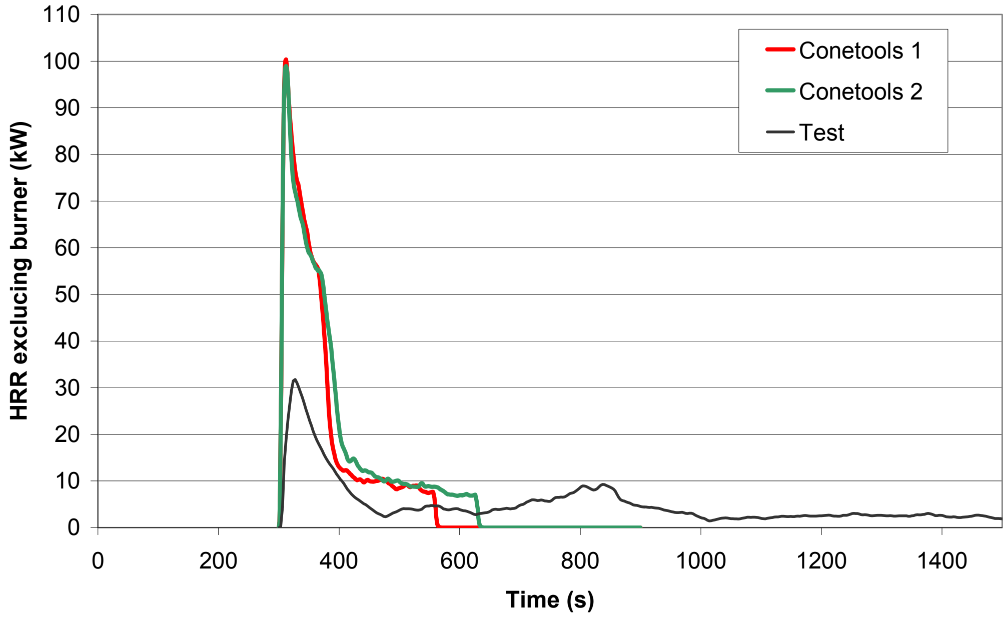

Figure 14. HRR results for Isoflax, Conetools results compared to SBI test, excluding HRR from the burner.

Table 9. Conetools results compared to SBI test results.

Material	Test/Simulation tool	FIGRA (W/s)	THR_{600s} (MJ)	Preliminary SBI classification
INCA on particle board	SBI Test 1	53	7.1	A2/B
	SBI Test 2	53	6.9	A2/B
	Conetools 1	0	0.006	A2/B
	Conetools 2	0	0.34	A2/B
Isoflax	SBI Test	1544	4.7	E/F
	Conetools 1	11170	7.0	E/F
	Conetools 2	11240	8.1	E/F

Table 10. Sensitivity analysis of the input parameter time to ignition.

Conetools run ID	**Time to ignition (s)**	**FIGRA (W/s)**	**THR_{600s} (MJ)**	**Preliminary SBI classification**
INCA on particle board - Conetools 1	731	0	0.0	A2/B
	+10%	0	0.0	A2/B
	-10%	0	0.0	A2/B
INCA on particle board - Conetools 2	337	0	0.3	A2/B
	+10%	0	0.3	A2/B
	-10%	0	0.4	A2/B
Isoflax - Conetools 1	1	11170	7.0	E/F
	+10%	9286	7.0	E/F
	-10%	10435	7.0	E/F
Isoflax - Conetools 2	1	11240	8.1	E/F
	+10%	9193	8.0	E/F
	-10%	10486	8.1	E/F

8 FDS simulations

A relatively simple model of the cone calorimeter was developed to investigate the FDS material parameters. These material parameters were then used in a model of a fire test in a larger scale, the SBI test. In the cone calorimeter model the entire surface of the material is exposed to an evenly distributed radiation, while in the SBI test the material will be ignited by the heat from a burner and the flame spread over the sample surface observed.

8.1 Radiated Surface Model (Cone calorimeter)

The radiated surface model consists of a 100 x 100 mm^2 sample surface which is exposed to radiation. The shape of the radiation cone in the calorimeter is not included in the model, instead the radiation is generated by a hot ceiling. The temperature of the ceiling was adjusted to get the prescribed radiation level on the sample surface. The model was used to check that the specified material parameters resulted in a realistic pyrolysis and to find a suitable value for the parameter HEAT_OF_REACTION.

The grid cell size was 25 x 25 x 25 mm^3. The one-dimensional grid for heat transfer through the surface was, for most materials, kept at the default of 10 nodes distributed over the surface thickness. The exception is the model of particle board for which 31 nodes were used. A low number of nodes produces an unstable HRR as is seen in the sensitivity analysis in Appendix A, Figure 36.

The heat release rate and mass loss rate was compared to the results from the cone calorimeter tests.

In contrast to the method described in the FDS Users Manual section 8.7, this model also includes combustion in the gas phase. The flames result in an increase of the radiative heat flux to the surface. This is also likely to happen in the real cone calorimeter tests[22], but the level of increase due to the flames in the model is not validated.

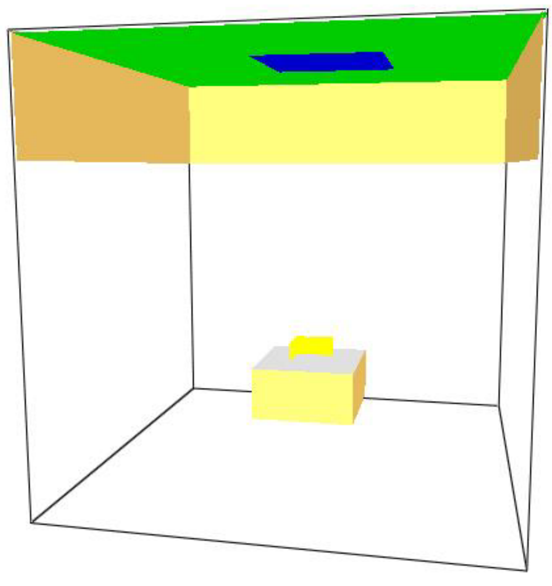

Figure 15. Radiated surface (cone calorimeter) model. The green surface is the hot ceiling and the blue area is an exhaust vent.

8.2 SBI Model

The FDS model of the SBI test was originally a model of the entire SBI room, see Figure 16. The geometry is according to the real test with two exceptions: the hood has a rectangular instead of a pyramidal shape and the diagonal side of the burner is jagged as the burner consists of several rectangles. The simulation domain was reduced to save computational time but still large enough to ensure the distance from the flames to the outer boundary was at least the diameter of the flame in this study. The height of the domain was selected to ensure all combustion in the gas phase was captured.

The model shown in Figure 17 was used when calculating the majority of the results. The grid cell size was 25 mm for the volume incorporating the panels and the burner, and 50 mm for the volume above. An alternative selection of domain boundaries and grid divisions were used during a grid size sensitivity study, see Appendix A, Figure 31.

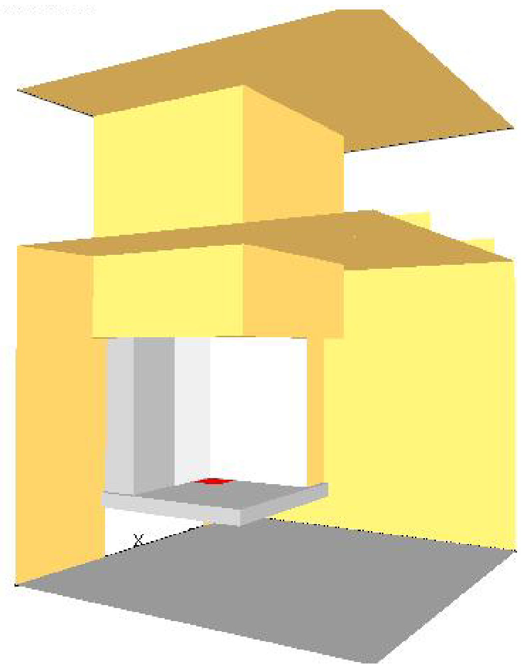

Figure 16. FDS model of the SBI test room. Two walls are removed in the picture for visualisation purposes.

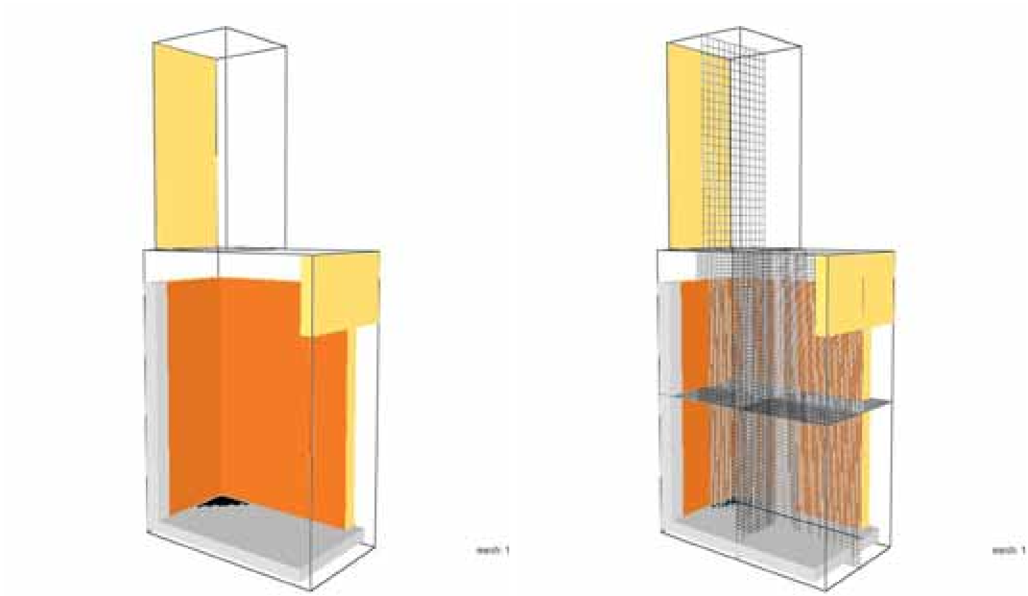

Figure 17. Simulation domain used in the study, without and with visualization of the grid.

Fundamental for modelling flame spread in FDS is the heat flux absorbed by the surface. The heat flux to the panels in the model was compared to measurements conducted in a round-robin study conducted within EGOLF of several SBI test equipments in Europe[23]. The panels used in the round-robin were 11 mm non-combustible calcium silica boards, the heat flux was measured in three locations. The locations are shown in Figure 18 and specified in Table 11.

To compare the radiation in the FDS SBI model with the round-robin tests the thermal properties of non-combustible calcium silicate boards were applied to the panels in the model. The heat flux as it would had been recorded by a heat flux meter, HFM, with the surface temperature of 20 °C were saved as output. Both test results and model results are average values for the time period of 240 to 300 seconds after ignition of the burner. An image of the heat flux distribution is presented in Figure 19 and the results of the comparison is presented in Table 11. The correlation between simulation and test is good for HFM1, where the difference is less than 5%. For HFM2 and HFM3 the difference is larger, but acceptable considering the value is averaged over the cell surface of 25 x 25 mm^2 and the high gradient in reduced heat flux moving along the panel surface in the direction out from the corner.

The heat release rate generated by the burner in the model is ensured to be 30 kW. All parameters related to radiation, except the radiative fraction, are kept at their default values. The radiative fraction was set to a value valid for propane found in literature[24].

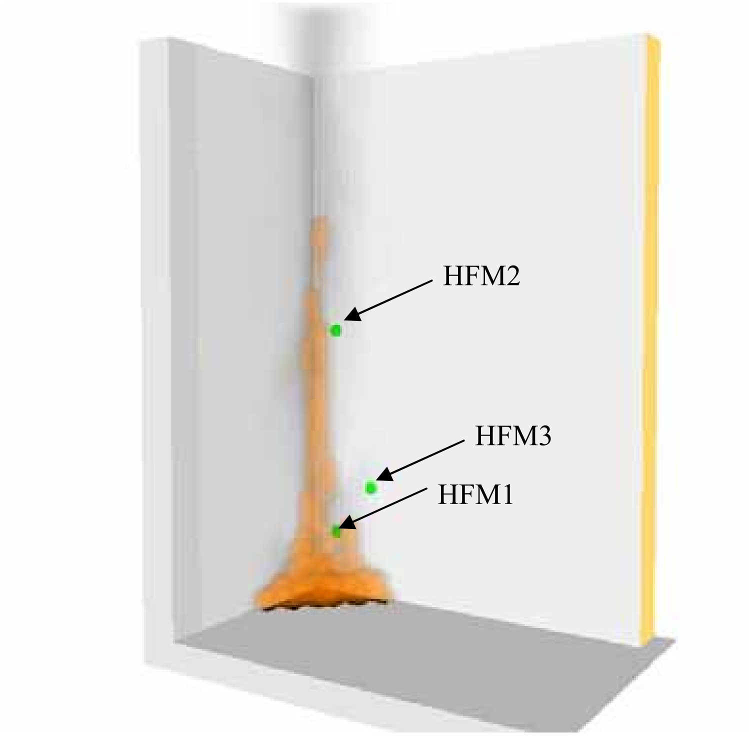

Figure 18. SBI model with burner flame.

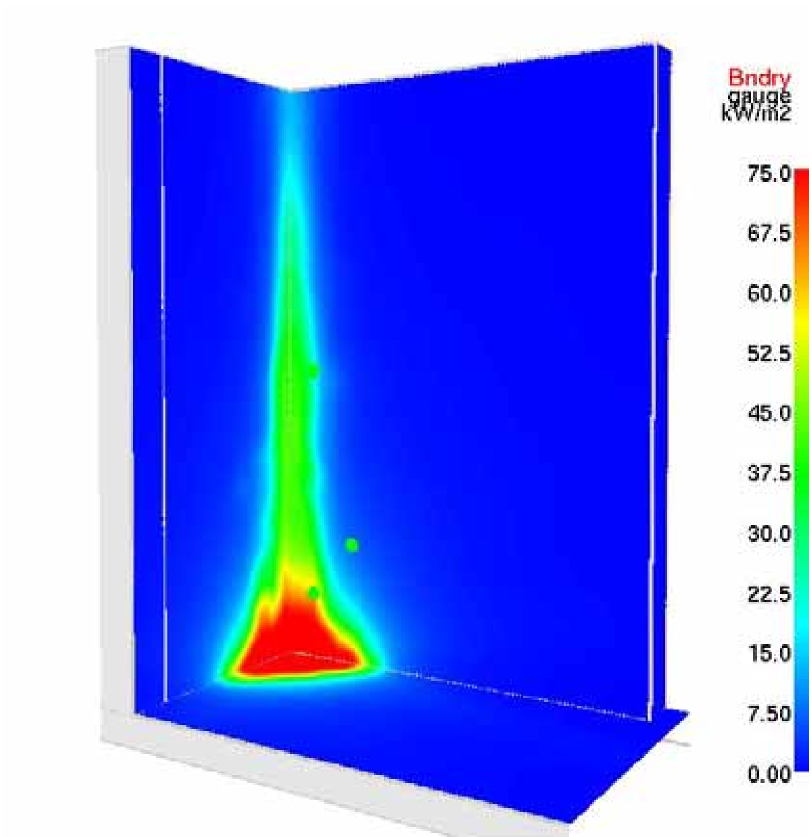

Figure 19. Heat flux levels on the panels as it would be recorded by a heat flux meter.

Table 11. Radiation on panels in FDS compared to real tests.

	HFM1	HFM2	HFM3
Horizontal distance from inner corner (m)	0.08	0.08	0.20
Vertical distance from upper edge of burner (m)	0.16	0.75	0.30
FDS model (kW/m^2)	52.33	13.45*	8.31
Measured in round-robin tests (kW/m^2)	54.81 $\pm$ 4.17	20.95 $\pm$ 2.94	13.79 $\pm$ 2.74

* HFM2 is located close to the edge of a grid cell. For the adjacent grid cell the radiation is 24.26 kW/m^2

8.3 Results

Each material model was used in the simulations of the cone calorimeter and the SBI. The simulations are listed in Table 12. The results of each of the simulations are discussed below and a summary of the SBI simulation results as well as the test results are presented in Table 13. In the following graphs of the SBI results the time point for start of test is adjusted to the one used in the SBI, i.e. the burner is ignited at 300 seconds into the test.

Several simulations were conducted to study the dependency of the grid cell size and sensitivity of several material parameters. The results are presented in Appendix A.

Table 12. List of FDS simulations

Material	**Cone/SBI**
Particle board	Cone 50 kW/m^2
INCA on particle board	Cone 50 kW/m^2
INCA on particle board	SBI
Isoflax1	Cone 50 kW/m^2
Isoflax1	Cone 35 kW/m^2
Isoflax1	SBI
Isoflax2	Cone 50 kW/m^2
Isoflax2	Cone 35 kW/m^2
Isoflax2	SBI

8.3.1 Particle board and INCA attached to particle board

The intumescing material INCA mounted on a particle board was tested both in the cone calorimeter and the SBI. The particle board with no surface covering was tested in the cone calorimeter. The three tests were simulated with FDS.

The HRR curve of the particle board in the cone calorimeter shows the typical shape of a charring material, see Figure 20. With production of char included in the FDS model the results follow the test results reasonably well.

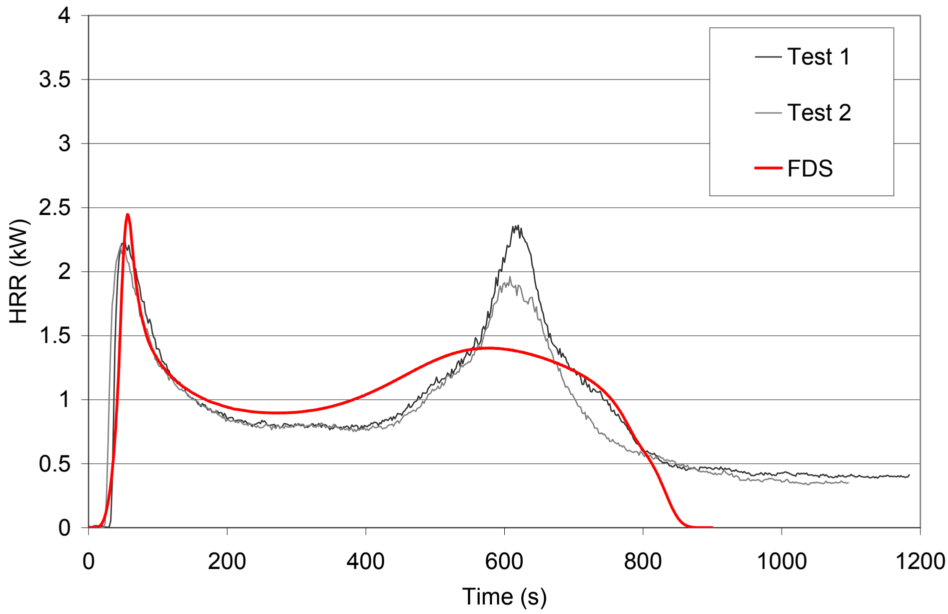

Figure 20. HRR of PB at radiation level 50 kW/m2, FDS model compared to cone calorimeter results.

When INCA is mounted on the particle board, the cone calorimeter results according to Figure 21 are obtained. When adding a top layer of expanded INCA to the FDS model the ignition is delayed and the peak heat release is reduced to about the same extent as in the test.

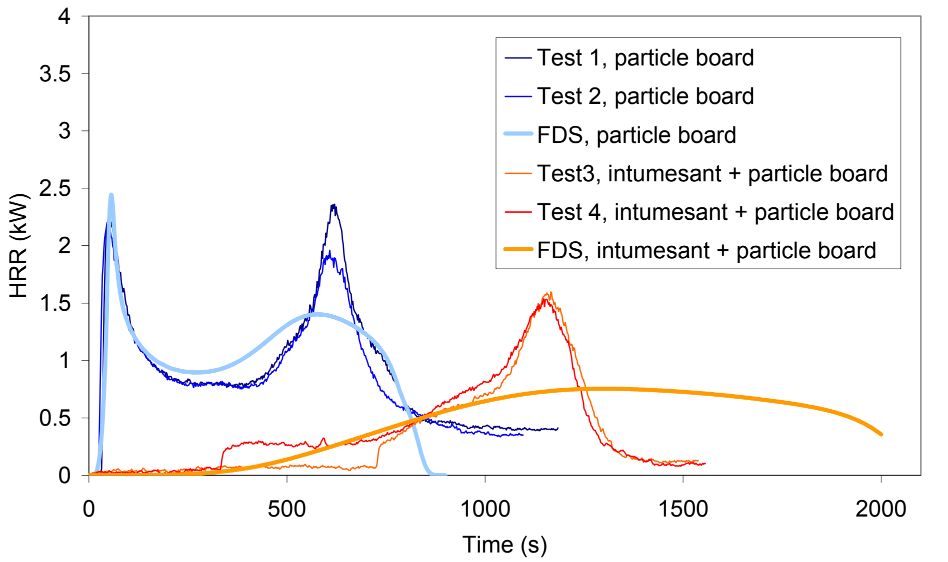

Figure 21. HRR of PB and PB+INCA at radiation level 50 kW/m2, FDS model compared to cone calorimeter results.

In both the SBI test and the model the particle board did ignite but the material involved were limited to approximately the area behind the flame of the burner and up to the top in the very inner corner. The limited flame spread is shown in Figure 23 where a photo from after the test is compared to the flame at the end of the simulation. The dark area in the photo is the expanded INCA, not material contributing to the fire. In the test, a small area of the particle board in the very low inner corner were consumed to its full thickness. In the model this total consumption of fuel in that area is not seen. This is also evident in the comparison of the HRR curves, see Figure 22. The results show the same discrepancy between simulation and test as was seen for Conetools. The difference is further discussed in section 9.

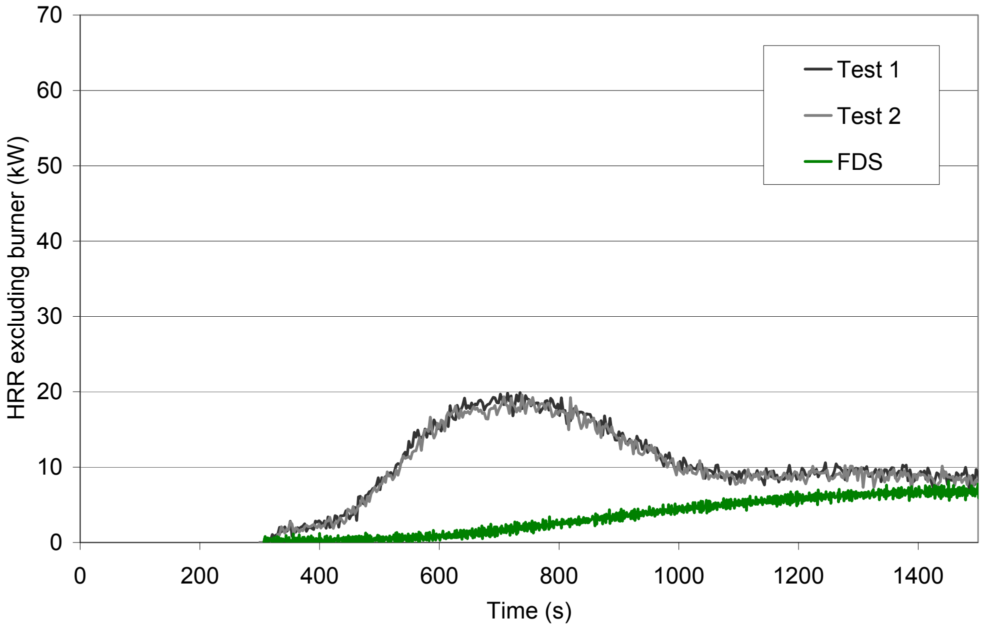

Figure 22. HRR of INCA on particle board, FDS model compared to SBI test results, excluding HRR from burner.

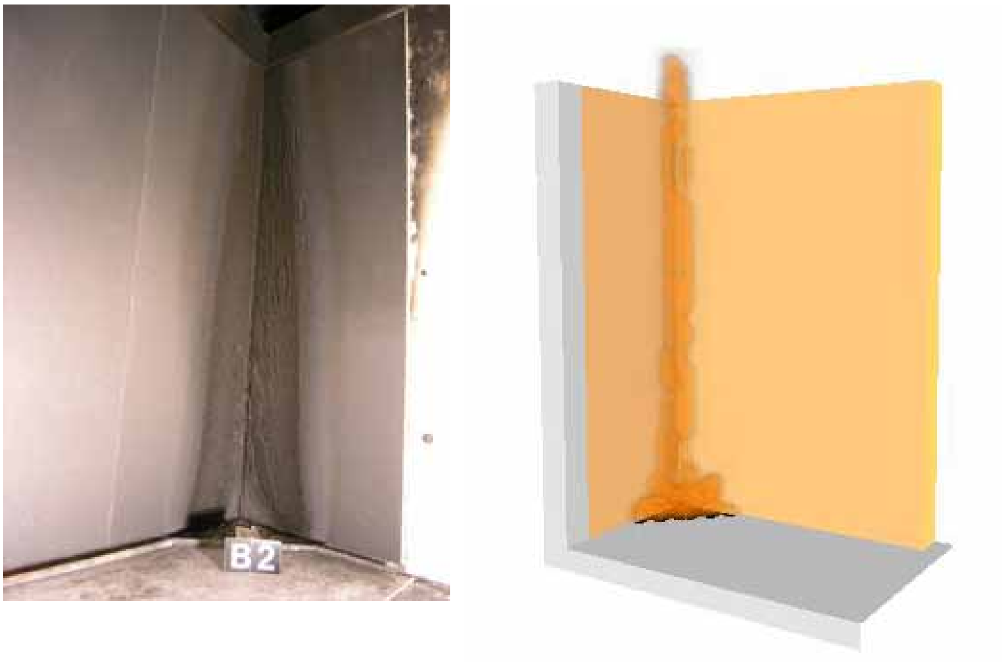

Figure 23. Area of the panels involved in the fire, flames in FDS model compared to photo after the test. The dark area in the left photo is the expanded INCA material at the end of the test. The geometry of model is reversed compare to the test set-up.

8.3.2 Isoflax

The insulating material Isoflax was tested in the cone calorimeter at two different heat flux levels and in the SBI. The test were simulated using FDS for the two material models Isoflax1 and Isoflax2.

The descending HRR curve of the cone calorimeter tests, see Figure 24 and Figure 25, indicates a charring material, but could also be the result of the surface of the sample gradually moving towards the back of the specimen holder as the material is consumed. As the surface descends, the heat flux received by the surface will decrease due to shielding by the sides of the sample holder and the longer distance to the radiator. The effect was assumed to be caused by the latter reason, thus the Isoflax was not modelled as a charring material. The mass loss for Isoflax2 is compared to the cone calorimeter results in Figure 26 and Figure 27.

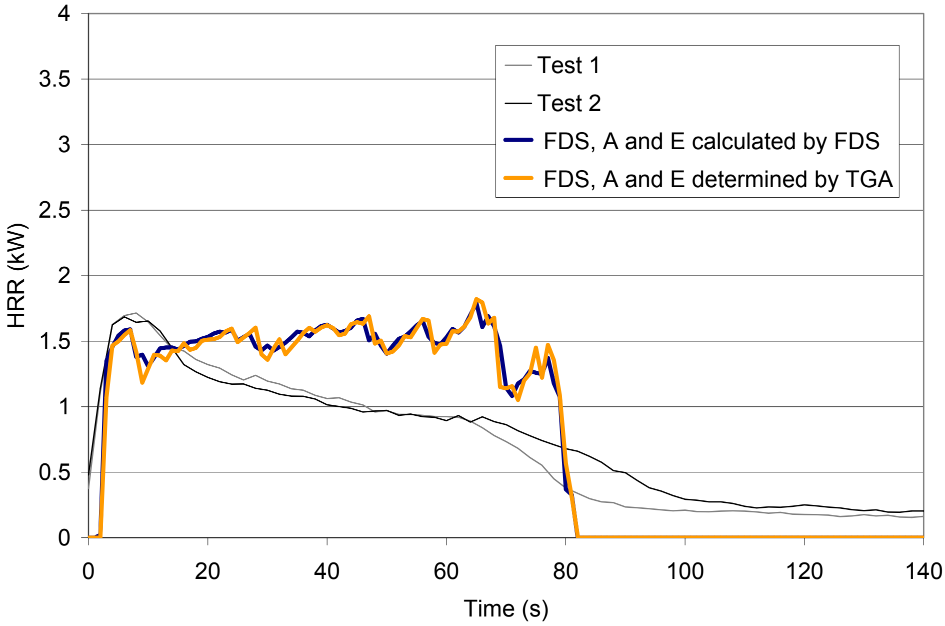

Figure 24. HRR of Isoflax1 and Isoflax2 at radiation level 50 kW/m2, FDS model compared to cone calorimeter results.

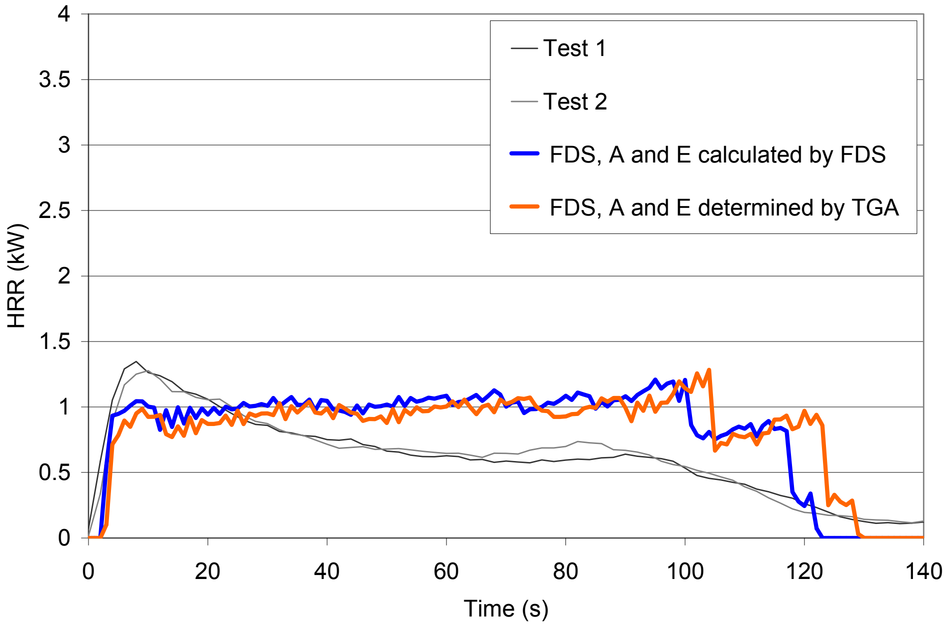

Figure 25. HRR of Isoflax1 and Isoflax2 at radiation level 35 kW/m2, FDS model compared to cone calorimeter results.

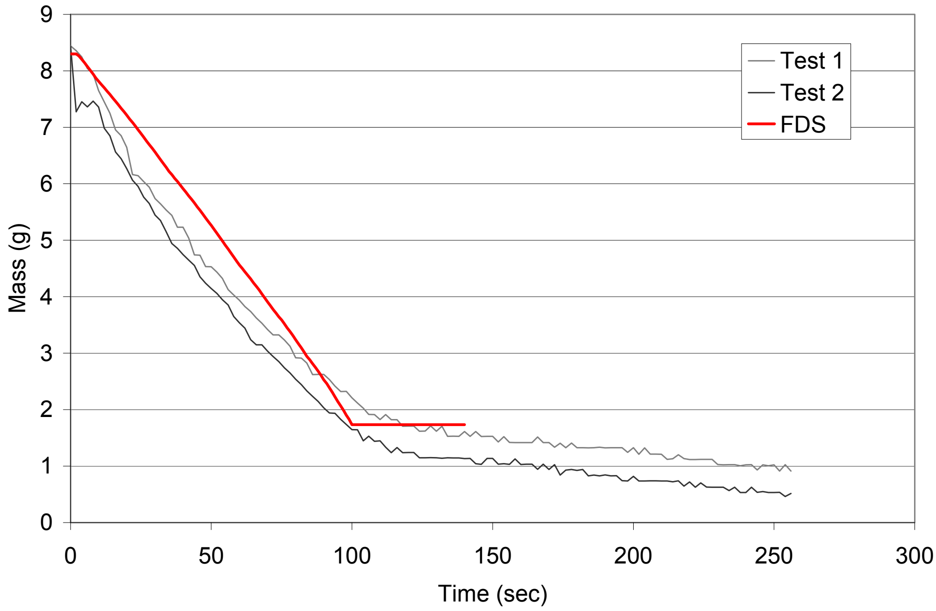

Figure 26. Mass loss of Isoflax2 at radiation level 35 kW/m2, FDS model compared to cone calorimeter results.

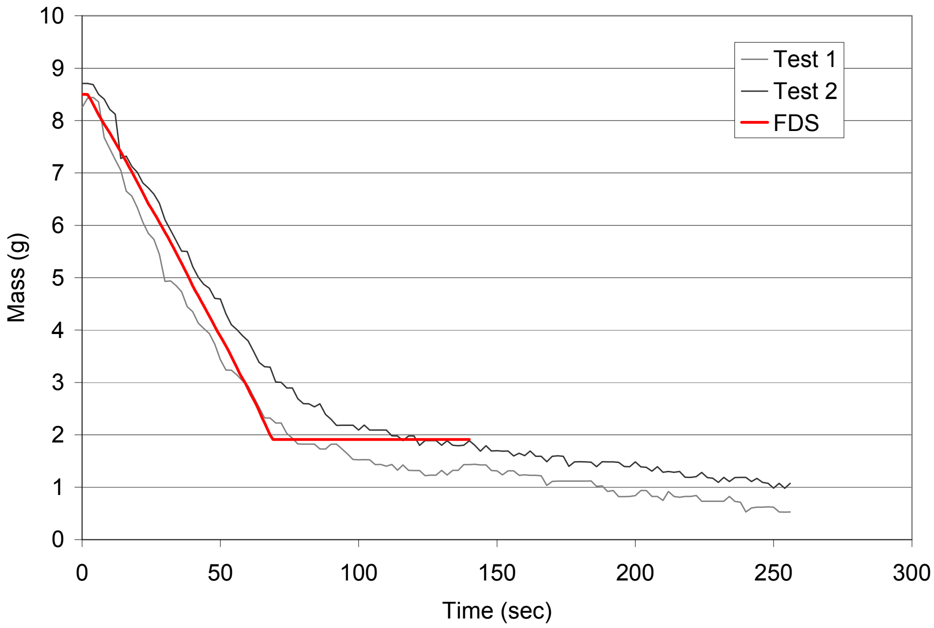

Figure 27. Mass loss of Isoflax2 at radiation level 50 kW/m2, FDS model compared to cone calorimeter results.

In the SBI test a rapid vertical flame spread to the top of the specimens occurred. The same rapid flame spread takes place in the FDS models as well, but the peak HRR is higher, as is depicted in Figure 29. In the test, a slow lateral spread of small flames and smouldering continues after the first HRR peak, resulting in a second lower peak at around 800 s, which is not seen in the FDS results. In the test, approximately a width corresponding to half the width of the short panel was consumed to its entire depth on both panels. A slightly smaller area was consumed in both models Isoflax1 and Isoflax2. The area of material totally consumed for Isoflax2 is shown in Figure 28 compared to a photo taken after the test.

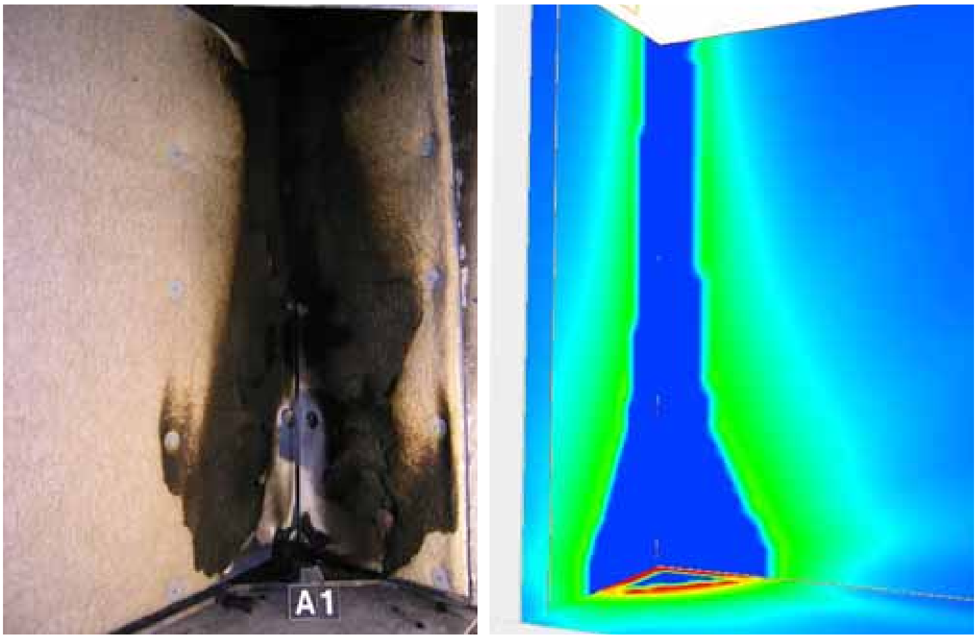

Figure 28. **Area of consumed material, FDS model Isoflax2 compared to photo after the test. Aproximately 80% of the black area in the photo is material consumed to its entire depth. The dark blue area in the FDS image is consumed material. The geometry of the model is reversed compare to the test set-up.**

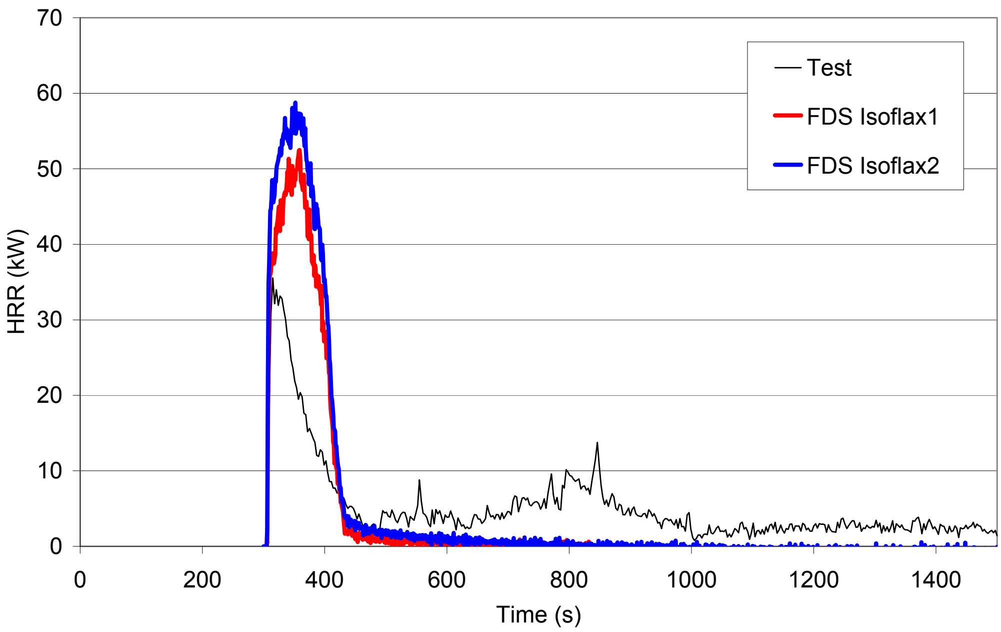

Figure 29. **HRR of Isoflax2, FDS model compared to SBI results, excluding HRR from burner.**

Table 13. FDS simulation results compared to SBI test results.

Material	Test/Simulation tool	FIGRA (W/s)	THR_{600s} (MJ)	Preliminary SBI classification
INCA on particle board	SBI Test 1	53	7.1	A2/B
	SBI Test 2	53	6.9	A2/B
	FDS	7	0.74	A2/B
Isoflax	SBI Test	1544	4.7	E/F
	FDS Isoflax1	1925	4.6	E/F
	FDS Isoflax2	2592	5.6	E/F

9 Discussion

This project has been focused on textiles, but the methodology to model and develop material parameters is relevant for other types of material as well.

For the FDS SBI model, the results depend on what was determined to be an acceptable material model based on the preliminary validation in the cone calorimeter model. For example, a choice of a lower HEAT_OF_REACTION parameter for the Isoflax would have resulted in a better correlation in the SBI results but the choice was made not to "fit" the results in this way. The maximum peak in the very beginning of the HRR curve in the cone experiment for Isoflax was not considered as being most representative for the burning rate over a longer period of time (see Figure 24 and Figure 25). Furthermore, as the later, lower part of the curve may be caused by the material receding from the surface of the sample holder, a correlation for the HRR level around 10 s for the flux level 50 kW/m^2 and around 30 s for flux level 35 kW/m^2 was considered most relevant.

The heat release curve predicted by Conetools differs significantly from the test results for both materials. This is expected in cases where the empirically obtained parameters used in Conetools are not suitable for predicting larger scale performacen of this product. However, since this difference is seen also in the FDS model where the pyrolysis depends on the heat feed back to the surface and in which the area involved in the fire coincide well with the test results this is hardly the reason. Instead, one explanation for the different results could be boundary effects. The front of the particle boards are covered by the INCA material while the two edges that meet and overlap in the corner of the test setup are not. These edges could contribute to the result although they are not directly exposed to the radiation from the fire. Supporting this theory is the observation of the large consumption of material on the very edge in the corner. In the cone calorimeter tests the edges are shielded by the frame of the sample holder.

Another effect that could contribute to the difference between the test and the two simulation models could be the permeability of the material. The difference in HRR between the cone calorimeter model and the test for the INCA material on particle board may be caused by the porous structure of the material which allowed the radiative heat to penetrate deeper into the material. Furthermore, this effect could be accentuated in a larger scale fire test where the material is expanding under different conditions, i.e. more freely without any sample holder and under varying heat flux which may result in a different structure in the material. An FDS material parameter introduced in version 5 called ABSORBTION_COEFFICIENT could be used to explore this further.

It may have been possible to achieve a better agreement between the FDS models and the cone calorimeter and SBI tests if the Isoflax had been modelled as a charring material producing an insulating layer. However, the residue from this lightweight insulation material had a texture which was very different from that of e.g. char from wood. It was very fragile and impossible to move, which made it impossible to conduct TPS measurements to determine the thermal properties of this material.

For Isoflax, the FDS parameter BACKING did not have any significant influence on the results, as is shown in Appendix A, Figure 33. However, this was a thick highly insulating material. For a thinner and more conducting material the parameter would be expected to have a greater influence. When modelling other scenarios and materials, this parameter must be chosen with care. If the sample material backs up to a board of another material and the conduction of heat to the backing material is considered important, one option is to include the backing material as an extra layer in a multi-layer surface model.

In general, the multi-layer surface model of FDS has the potential to be useful when modelling textile products which often consists of several layers of different materials.

The dependency of flame spread in FDS on the grid cell size is large, as is shown in Appendix A, Figure 32. No trend could be observed from the results for the three grid cell sizes studied in the SBI model. The sensitivity of the FDS results to the grid size is in fact currently a matter of great interest for FDS users as can be observed at the FDS discussion forum (http://groups.google.com/group/fds-smv) and is a limitation of the model. Unfortunately it has not been possible to explore this further within this study.

In summary, both numerical simulation methods described in this report base material input parameters on the cone calorimeter tests. In the case of Conetools this is achieved by using the heat release curve directly as input, while in the case of FDS the heat release curve was used in the preliminary validation of the material parameters. The poor agreement with test results for both Conetools and FDS when modelling the larger scale SBI test shows that for some materials it is difficult to fully predict their fire behaviour in a large or intermediate scale test based on a small scale test.

10 Conclusions

Two different approaches for modelling flame spread were used in this study i.e. the semi-empirical area-based code, Conetools, and the CFD-code, FDS. Two textile products with significantly different compositions and applications, representing material for which fire test results indicate a classification on either end of the rating scale for wall material according to EN 13501, were selected for the study.

Two FDS-models were developed for the simulations. The first FDS model was a relatively simple model of the small scale cone calorimeter test (ISO 5660) which served the purpose of a first preliminary validation of the pyrolysis of the material model. In the second FDS model, a model of the intermediate scale SBI test method (EN 13823), the fire scenario was expanded to simulate flame spread over a surface. The work included determining the necessary material properties. In Conetools, the option to predict an SBI test was used.

The results of the two simulation methods were compared to real SBI tests. Both models gave a relatively large disagreement in the heat release rate for these complex products. However, the results from both codes were accurate enough to give a correct fire rating for wall linings according to EN13501.

Conetools was originally developed for plastic and wood based wall products, textile is a new area for which the model may need adjustments. This study shows that the results may look inaccurate when studying the HRR curves but that the predicted Euroclass rating was correct.

The FDS model was able to predict the results better than Conetools. In addition, FDS has the advantage of being applicable to other fire scenarios. The latest version of FDS incorporates features, such as the ability to model a multi-layered material, which is useful when modelling textile products.

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Sensitivity analysis

The parameters for which sensitivity studies were conducted are presented in Table 14.

Table 14. Sensitivity analysis

Parameter	Values	Model	Material
Grid size	12, 25 and 50 mm	Cone	Isoflax2
Grid size	25, 37.5 and 50 mm	SBI	Isoflax2
BACKING	VOID, INSULATED	SBI	Isoflax2
HEAT_OF_REACTION	2700, 3000 and 3300 kJ/kg	Cone	Isoflax2
REFERENCE_TEMPERATURE	171, 220, 269 °C	Cone	Isoflax2
Number of nodes in 1D surface model	10,11,18 and 31	Cone	PB

Grid cell size

In Table 15 the grid cell size d is compared to the characteristic fire diameter D* calculated by the following expression[1]:

$$D^* \approx \left(\frac{\dot{Q}}{1100} \right)^{2/5}$$

Where $\dot{Q}$ is the characteristic heat release rate.

Table 15. Gridcell sizes relative characteristic fire diameter

Model	Q (kW)	D* (m)	d (m)	D*/d
Cone	2	0.080	0.0125	6
	2	0.080	0.0250	3
	2	0.080	0.0500	2
SBI	30	0.237	0.0250	9
	30	0.237	0.0500	5
	30	0.237	0.0375	6

In the SBI model used for studying grid dependency the grid size was constant over the whole simulation domain as shown in Figure 31. The original model was divided in two meshes of which the upper was courser to reduce simulation time as shown in Figure 17. The distance between the burner and the wall panels is one grid cell wide resulting in different distances of 25, 37.5 and 50 mm. In the actual test the distance was 25 mm.

[1] J. Hietaniemi, S. Hostikka, J. Vaari, FDS simulation of fire spread – comparison of model results with experimental data, 2004.

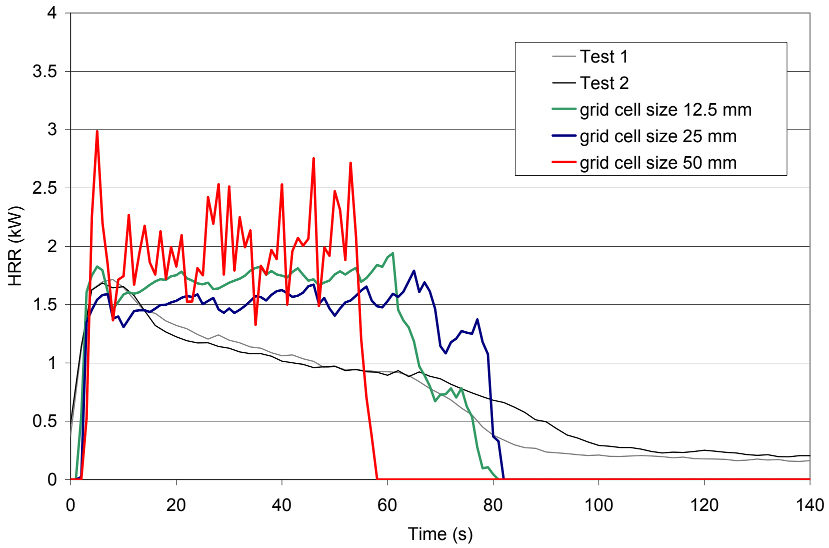

Figure 30. Sensitivity analysis of grid cell size in cone model for Isoflax2 at 50 kW/m2

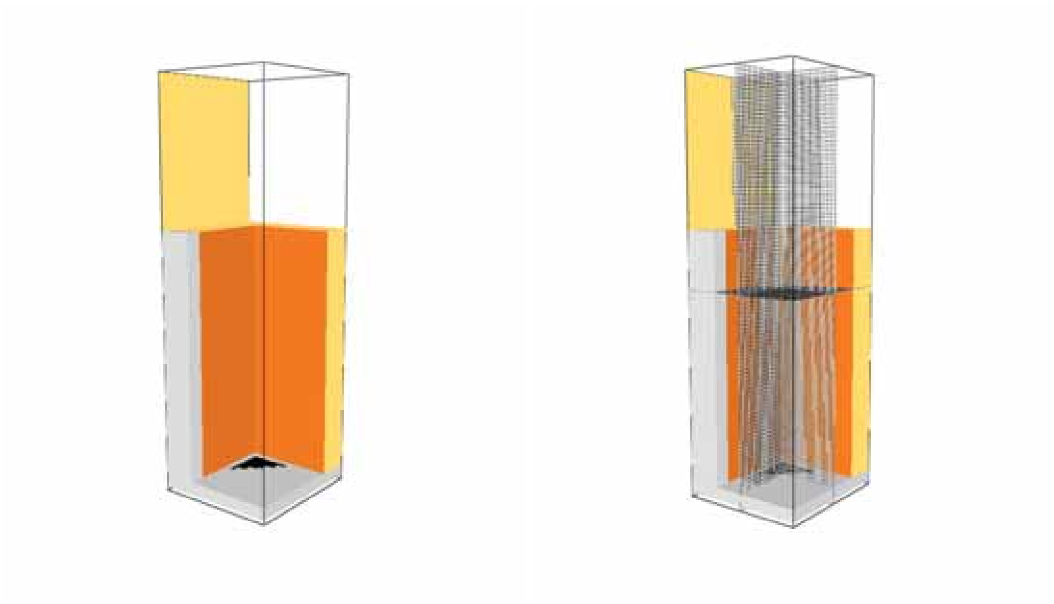

Figure 31. Alternative model used during grid sensitivity study. Image to the left shows the simulation domain, image to the right visualizes the grid cells in four planes.

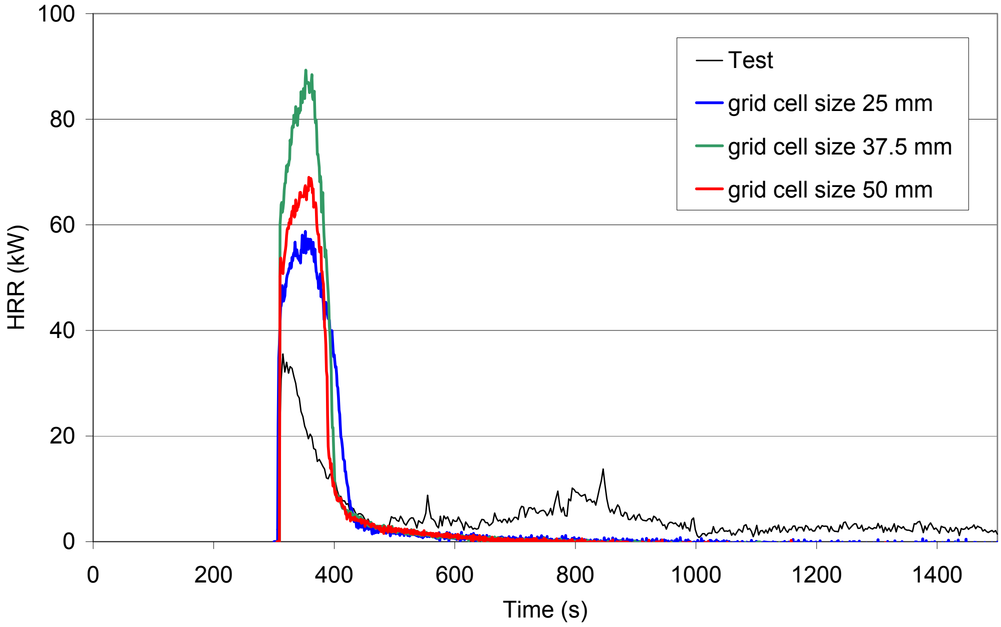

Figure 32. Sensitivity analysis of grid cell size in SBI model for Isoflax2. The distance between burner and wall panel is one grid cell wide, i.e. the distance differs between the different simulations.

The simulations proved to be grid dependent as seen in Figure 30 and Figure 32. The grid dependency of FDS is further discussed at the FDS discussion forum and is outside the scope of theis project. Currently it seems that the optimum grid size is about 20 cm for the material parameters used for Isoflax.

Other material and surface parameters

The different results received when specifying void or insulated back side of the surface is presented in Figure 33. The results are very similar for Isoflax, which is a thick highly insulated material.

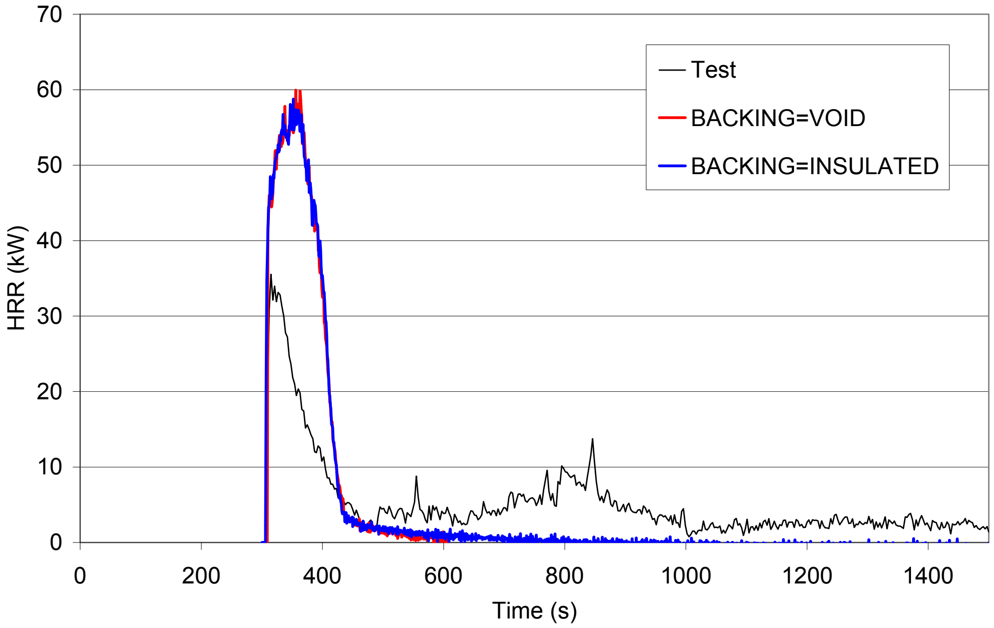

Figure 33. Sensitivity analysis of the parameter BACKING in SBI model for Isoflax2

The sensitivity for the parameter HEAT_OF_REACTION and REFERENCE_TEMPERATURE for Isoflax in the Cone Calorimeter model is shown in Figure 34 to Figure 35. A 10% variation of both parameters results in a significant change in the results as expected.

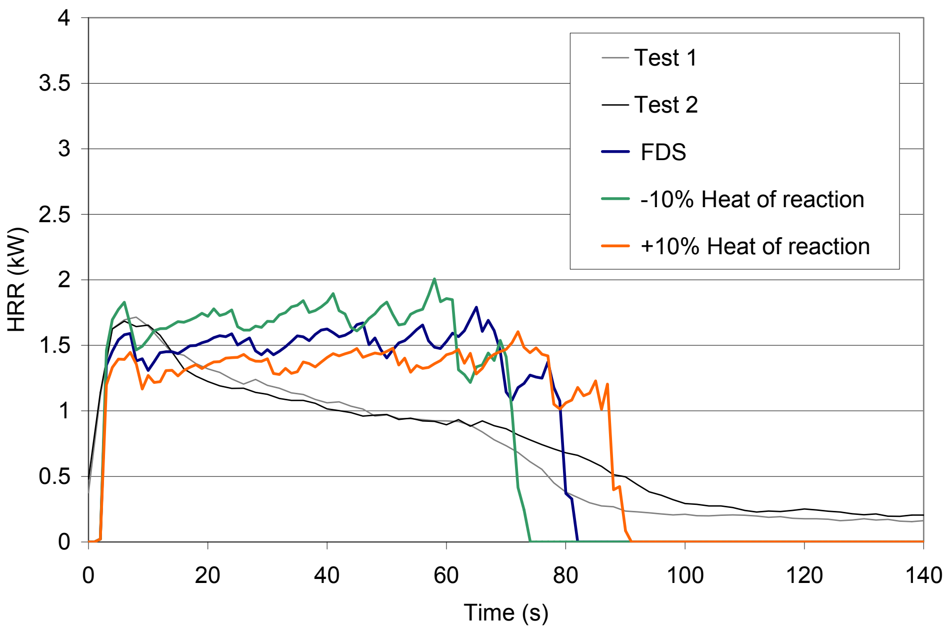

Figure 34. Sensitivity analysis of the parameter HEAT_OF_REACTION in Cone model for Isoflax2 at 50 kW/m2

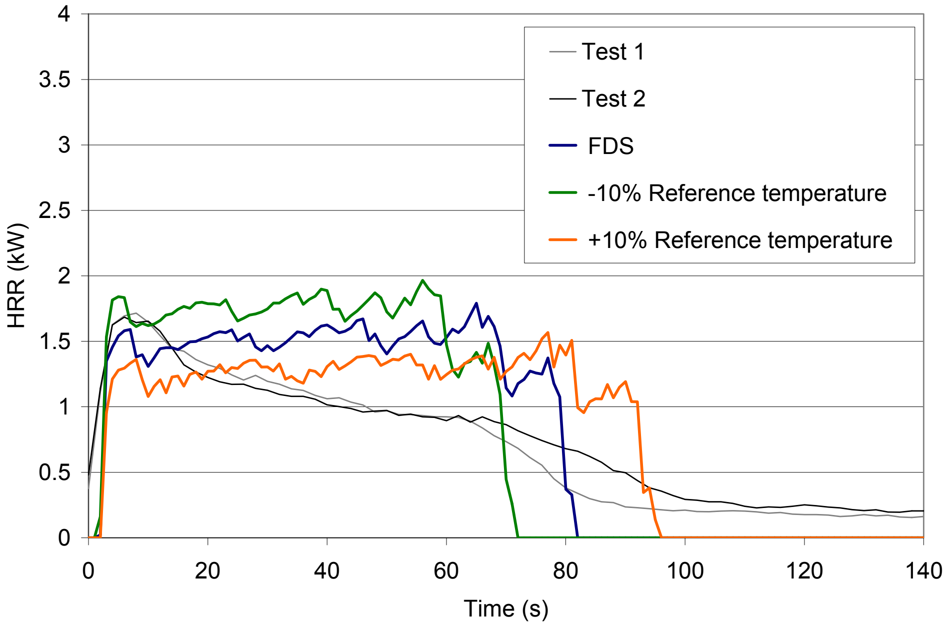

Figure 35. Sensitivity analysis of the parameter REFERENCE_TEMPERATURE in cone model for Isoflax2 at 50 kW/m^2. The variation is calculated in °C.

As seen in Figure 36 a low number of nodes shows a fluctuating HRR curve and the result is improved as the number of nodes is increased for particle board. No such fluctuations were observed for the other materials. With the default settings FDS uses 10 nodes for these material thicknesses.

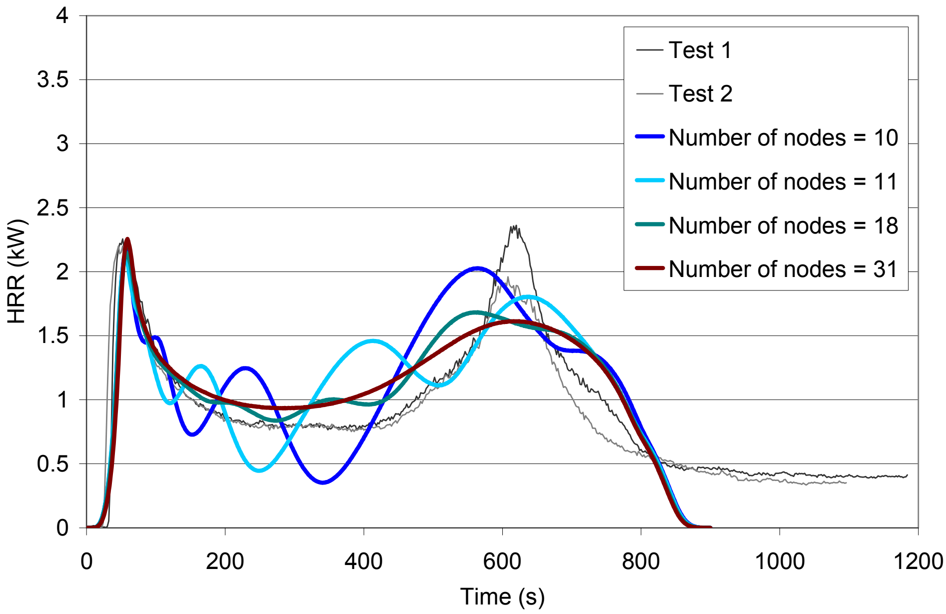

Figure 36. Sensitivity of number of nodes in 1-D surface model of the particle board in the cone calorimeter, distributed over the thickness of 12 mm.

FDS Material Properties for INCA-XO 300 on particle board (FDS version 5.0)

```
&REAC ID='CELLULOSE'
    H=10
    C=6
    O=5
    SOOT_YIELD=0.0053 /
------------------------------------------------------------------------------
&MATL ID                  = 'PB'
    N_REACTIONS           = 1
    NU_FUEL               = 1
    HEAT_OF_COMBUSTION    = 1.33E+04
    HEAT_OF_REACTION      = 500
    A                     = 2.38E+06
    E                     = 1.05E+05
    CONDUCTIVITY_RAMP     = 'KS'
    SPECIFIC_HEAT_RAMP    = 'CP'
    DENSITY               = 640.
    NU_FUEL               = 0.71
    NU_RESIDUE            = 0.22
    NU_WATER              = 0.07
    RESIDUE               = 'CHAR' /

&RAMP ID = 'CP', T = 20,   F =      1.66 /
&RAMP ID = 'CP', T = 75,   F =      2.07 /
&RAMP ID = 'CP', T = 105,  F =      2.25 /
&RAMP ID = 'CP', T = 149,  F =  2.74 /
&RAMP ID = 'CP', T = 500,  F =  2.74 /

&RAMP ID = 'KS',  T = 20,  F =      0.164 /
&RAMP ID = 'KS',  T = 75,  F =      0.186 /
&RAMP ID = 'KS',  T = 105, F =      0.191 /
&RAMP ID = 'KS',  T = 149, F =      0.184 /
&RAMP ID = 'KS',  T = 500, F =      0.184 /

&MATL ID                  = 'CHAR'
    CONDUCTIVITY          = 0.20
    SPECIFIC_HEAT         = 2.5
    DENSITY               = 129. /

&MATL ID                  = 'INCA4'
    CONDUCTIVITY          = 0.15
    SPECIFIC_HEAT         = 0.68
    DENSITY               = 43.1 /

&SURF ID                  = 'SAMPLE'
    MATL_ID               = 'INCA4', 'PB'
    CELL_SIZE_FACTOR      = 0.5
    COLOR                 = 'MELON'
    THICKNESS             = 0.008, 0.012
    BACKING               = 'INSULATED' / or 'VOID'/
```

FDS Material Properties for Isoflax (FDS version 5.0)

```
&REAC ID='CELLULOSE'
    H=10
    C=6
    O=5
    SOOT_YIELD=0.0083 /
-----------------------------------------------------------------------------
&MATL ID                             = 'ISOFLAX2'
    N_REACTIONS                      = 1
    NU_FUEL                          = 1
    HEAT_OF_COMBUSTION               = 1.55E+04
    HEAT_OF_REACTION                 = 3000
    REFERENCE_TEMPERATURE            = 220
    CONDUCTIVITY                     = 0.058
    SPECIFIC_HEAT                    = 2.03
    DENSITY                          = 24.3
    NU_FUEL                          = 0.88

&SURF ID                             = 'SAMPLE'
    MATL_ID                          = 'ISOFLAX2'
    COLOR                            = 'CHOCOLATE'
    THICKNESS                        = 0.035
    BACKING                          = 'INSULATED' /
--------------------------------------------------------------------------------
&MATL ID              = 'ISOFLAX1'
    N_REACTIONS         = 1
    NU_FUEL             = 1
    HEAT_OF_COMBUSTION    = 1.55E+04
    HEAT_OF_REACTION      = 2400
    A                   = 1.70E+21
    E                   = 2.44E+05
    CONDUCTIVITY          = 0.058
    SPECIFIC_HEAT         = 2.03
    DENSITY             = 24.3
    NU_FUEL             = 0.88

&SURF ID              = 'SAMPLE'
    MATL_ID             = 'ISOFLAX1'
    COLOR             = 'CHOCOLATE'
    THICKNESS           = 0.035
    BACKING             = 'INSULATED' /
```

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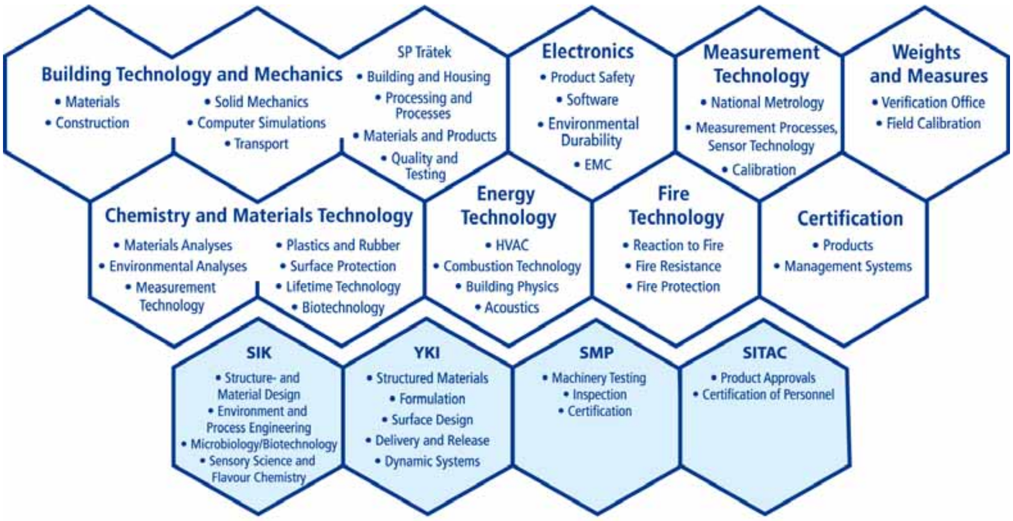

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