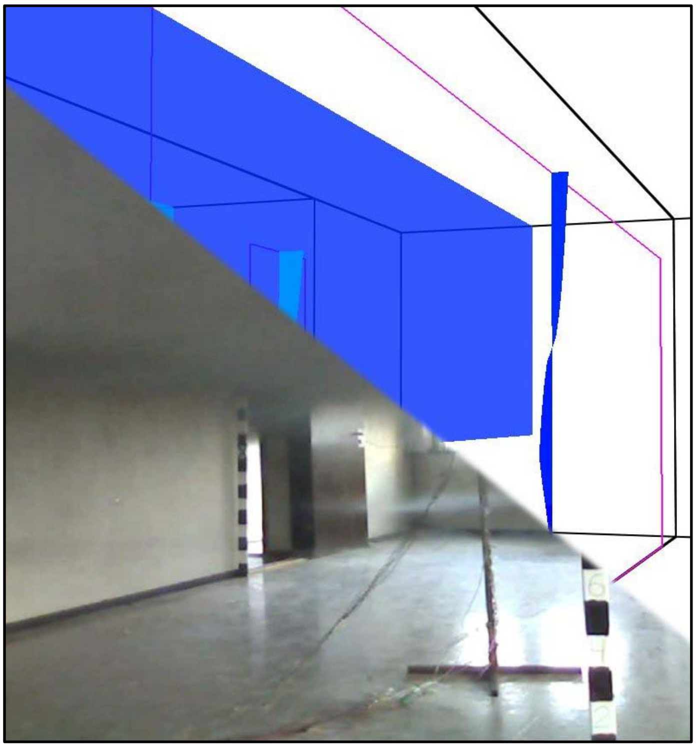
HØGSKOLEN STORD/HAUGESUND

The use of simulation in fire investigation



Bacheloroppgave utført ved

Høgskolen Stord/Haugesund – Studie for ingeniørfag

Sikkerhet, Brannteknikk

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PREFACE

When we were considering a possible area of research for our bachelor degree, we wanted to find a combination of practical and theoretical work. The possibilities of fire modelling came to our attention during the 5th semester, and we wanted to explore this further. When the teaching staff made us aware the insurance company If forsikringer were searching for a group to do further studies in simulation we were happy to accept.

We would like to thank the following for their aid in our work:
-Bjarne Hustedt (HSH) for being our internal supervisor, guiding us and pushing us to do better.
-Reidar Skrunes (If) for being our external supervisor and supplying us with a very interesting subject and moral support.
-Alf Reidar Nilsen (HSH) for aiding us in finding a thesis-project, introducing us to Reidar Skrunes and being our internal supervisor during the early stages.
-All the people at ResQ for letting us do a full-scale test on their old classroom building, and especially Arjen Kraaijeveld (HSH) and Svein Arne Aksland (ResQ) for coordinating and arranging the practical matters.
-Frode Dahle and Espen Hviding (both HSH-students) setting up all the measuring equipment, providing us with the results and being a great team to work with.
-Our significant others for putting up with us while we were busy writing our bachelor thesis.

I had come to an entirely erroneous conclusion which shows, my dear Watson, how dangerous it always is to reason from insufficient data

-Sir Arthur Conan Doyle
"Adventures of the Speckled Band"

ABSTRACT

Data from a full-scale test of temperature and smoke spread, in a realistic multi-room setting, was used to verify simulations done in the computer programs CFAST and FDS. A closely corresponding HRR-curve was used in the programs.

It was found that data from the top 0,5m of the full-scale test could be compared with reasonable accuracy to both simulation models. This would make simulations, used in fire investigation, more easily comparable to real life cases as the highest temperatures in each room could be compared to a probable fire cause. The simulations were found to provide satisfying results in CFAST, as an alternative to FDS.

With CFAST it was also found that close to a fire, in a geometrically complicated room, a more detailed model would be better suited. Outside the initial room the critical factor would be to cut down on the sections to as few as possible.

A sensitivity analysis was performed with both programs for the quality of the work, and as example for future usage.

A cone calorimeter test was performed on the ceiling, due to uncertainties about its possible contribution to the total fire load.

Differences and similarities between the simulations and the full-scale test, as well as critical factors for success are discussed.

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LIST OF NOMENCLATURE

Cell – The smallest part of an FDS-simulation volume. One cell computes one temperature and mass- and heat flow.

CFAST - Consolidated Model of Fire and Smoke Transport (short: CFAST) is a two-zone model developed and maintained by National Institute of Standards and Technology (short: NIST) of Gaithersburg, MD, USA.

CFD – Computational Fluid Dynamics or Computational Fire Dynamics, used interchangeably as the principles are the same.

Cone calorimeter – A mechanical instrument that records HRR and ignition point of materials by using a fixed radiative heat source, while measuring mass loss and oxygen-level in the smoke produced. Small pieces of the materials are used, approximately 10x10cm.

DNS - Direct Numerical Simulation, a simulation method that provide very detailed results. Used on supercomputers and not realistically usable due to consume of time and computer power.

FDS - Fire Dynamics Simulator (short: FDS) is a field model using the Navier-Stokes equations. It is especially developed for low-speed (normal) fires with smoke and heat transportation. It is developed and maintained by National Institute of Standards and Technology (short: NIST) of Gaithersburg, MD, USA.

Full-scale calorimeter – A test done in a specialized lab, with items or full furnished rooms that is completely on fire. This can measure mass loss, but usually relies on measuring HRR by identifying smoke content.

Grid – See “Mesh”.

HRR – Heat Release Rate ($\dot{Q}$): the amount of kW released. Often used as “HRR-curve”, where a kW output is measured over time.

LES – Large Eddy Simulation uses the Smagorinsky approach, to cut off small turbulent flows, so only the larger ones are computed using partial differential equations.

m – meter (distance)

Mesh – FDS requires defined areas to calculate turbulences and other output data inside. These are defined as “mesh” or “grid”, in the input file. The mesh is consisting of a number of cells, which all have the same dimensions, based on a division of the x, y and z-axis. Several meshes can be placed together, for computation on a parallel basis.

NIST - National Institute of Standards and Technology (short: NIST) of Gaithersburg, MD, USA. Founded in 1901, it is a non-regulatory federal agency within the U.S. Department of Commerce. They fund research on several topics including the fire sciences and have developed CFAST and NIST. See also: www.nist.gov .

RANS - Reynolds-averaged Navier–Stokes equations (short: RANS) is a method of computing time-averaged turbulent flows.

s = second (time)

VTT - Technical Research Centre of Finland. Largest of its kind in Northern Europe, and closely resembling the US NIST. Founded in 1942, it is under the domain of the Ministry of Employment and the Economy. See also http://www.vtt.fi .

1. INTRODUCTION

1.1. INTENT AND PURPOSE

The intent of the project is to further evaluate the possible use of simulation for investigative purposes, especially the two zone models. Other important factors are how to efficiently choose points of comparison and what is essential for a successful simulation. An additional purpose is to provide a research foundation for further study and a basis of knowledge for investigative work using computer simulation.

There are many software solutions available for fire simulation and separately there are many well documented theories in fire dynamics. Unfortunately for forensic personnel in insurance companies and public departments (police, fire department), the simulation models have not been verified extensively on a larger scale spanning several rooms. There are also questions about variables that need to be worked out, what kind of models are worth using to attain viable results and what information that is needed. Our goal is to provide a basis of comparative study of CFAST (a two-zone model) with FDS (a large eddy computational fluid dynamics simulator) against a full-scale test of a fire with smoke spread. These two were chosen for relative ease of use, visualization options and the principle of open software and availability without a high cost. With more research and validation studies it might reduce the need for full-scale tests and smaller scale tests. This will hopefully decrease costs and achieve early results without the need of large testing-facilities equipped with proper ventilation, personnel and fire-safety precautions.

Possible future use of computer simulations could be more extensive forensic evaluation of fire scenarios. Examples of this could be: verify or refute possible scenarios, Evaluation whether fire protection measurements was fulfilled and description of fire development.

1.2. PREVIOUS WORK

There are well-documented studies about computer models and the first set of rooms in a fire, notably for this work is the article by P. C. R. Collier on comparative studies between fire in a residential building and CFAST (Collier, 1996). Full-scale experiments have been done on t^2-fires with focus on smoke propagation (Matsuyama, Mizuno, & Wakamasu, 2001), and burning wood cribs in very large rooms (Cadorin, 2004). Work has been done on fire investigation, such as simulation after a school fire (Chitty & Foster, 2001) and after the Gothenburg dance hall fire (Yan & Holmstedt, 2001). The latter is noteworthy due to the beams in the roof of the dance hall, closely similar to the ones in the classroom and the start room of the full-scale test. One of the early applications of simulations in fire investigation was the Kings Cross incident (Cox, Chitty, & Kumar, 1989) where fluid dynamics principles were used (CFD-models would be the term used in present time), in addition to full scale tests, to confirm eye-witness reports of fire behaviour.

1.3. STATEMENT OF PROBLEM

How can fire simulations with two-zone models aid the investigations of a fire?

Complementary questions:

- What have been done before?
- What kind of input data is required in a simulation, which can be gathered by investigators after a fire? Are there any assumptions that have to be done?
- How will simplification, with respect to models used and grade of details in the model, affect the output data?

1.4. OUTLINE ASSUMPTIONS

The following is assumed: The full-scale test with a realistic multi-room setting will be successful and flashover will take place. Frode Dahle and Espen Hviding (Hviding & Dahle, 2009), fellow students in charge of the instrumentation of the full-scale test, will provide the needed results from full-scale tests to compare with simulations.

FIGURE 1: THE EASY CHAIR THAT WAS USED AS INITIAL FIRE IN THE FULL SCALE TEST.

1.5. METHOD

In this project there will be used literature studies, computer simulations and one full-scale test in addition to hand calculations. The main focus will be on the use of computer models, especially the two-zone model, and what makes them provide usable output data.

LITERATURE STUDIES

To obtain information about earlier work, previous relevant bachelor projects at HSH have been looked at. Search in the library, databases and the internet have been conducted.

INITIAL SIMULATIONS

The first simulations were run to see an estimate of what might happen during the full-scale tests and highlight areas of interest so they could be measured quantitatively. This was provided as a basis for the group in charge of the instrumentation, to optimize placement of equipment throughout the building.

THE FIRE AND SIMULATIONS

The basis for the simulations was a comparison with a full-scale test, which was provided by Espen Hviding and Frode Dahle (Hviding & Dahle, 2009). Many simulations were required to see the differences resulting from changing parameters, including fire load and room detail in the simulations. The inclusion or omission of the beam structure or dividing up the rooms was one of the details looked at in CFAST. By doing a lot of this work ahead of the fire (v.1.x-3.x in CFAST and number 1-9 in FDS) a closer understanding of working with a lack of information was achieved. As a forensic tool it would be used after the fire, but then in many cases without exact knowledge of the details. The full scale fire

The fire was observed in order to gain important points of interest.

2. DESCRIPTION OF MODELS USED

The study mainly used two different kinds of programs to simulate the development of the fire: the two-zone model and the computational fluid dynamics model (CFD), also known as the field model. The two programs differ in some ways. While the two-zone model is relatively simple in its structure, the CFD models are complex and require a lot of time-consuming data-processing. The differences, similarities and limitations of the program types, and specific programs used will be described in this chapter.

2.1. GENERAL DESCRIPTION OF MODELS USED

CFAST (a two-zone model) and FDS (a computational fluid dynamics model, CFD) was used for the simulations. Both types of programs require a great deal of knowledge from the user, with respect to understanding fire dynamics and fluid dynamics. In addition CFD-models may require extended knowledge of the program structure. The main differences, and the cause of the higher demands from CFD, are the equations solved during the calculations. In addition to the energy and the mass equations that two-zone models solve, CFD models also solve momentum equations. This means the CFD models provide the possibility to calculate velocities and observe the direction of small particles such as smoke and water droplets.

The specific programs used are developed mainly by the same organization, National Institute of Standards and Technology (NIST) in cooperation with VTT Technical Research Centre of Finland.

2.2. THE TWO-ZONE MODEL

The two-zone model is based on the assumption that a room-fire will create a hot and radiating smoke layer in the upper part of the room. Near the floor, in the lower layer, the temperature and the smoke concentration will be greatly reduced or even consist of fresh air.

This kind of model only calculates one average temperature in each zone, resulting in indifferent temperature output regardless of the observed part of the room. An aberrant example of this could be a large room with an intense fire in one corner. The output temperature will be an average of the entire room, resulting in a low temperature reported in the smoke layer.

This kind of model is not suitable in mainly two situations:

- **When the temperature and radiation in a room reach flashover.** This is because all the objects in the room burn, and create turbulence and thermal radiation in all directions. This causes the two-zone model to break up and replaces it with a one-zone model. Some of the programs available on the market can deal with these conditions to some extent.
- **When the smoke gets cooled-down or by any reason gets mixed with the fresh air.** For example due to active ventilation or when the smoke has travelled a long way (long hallways and/or high shafts). In either case the two-zone model is destroyed since there no longer is a distinct separation between the hot and the cold layer.

2.2.1. CFAST

CFAST represented the two-zone models in the study. The benefits of this program are:

- It is free of charge.
- It is well documented.
- It is updated regularly.
- It is compatible with the visualization tool Smokeview.

The user interface is easy to understand and use. The drawbacks on the other hand, are that it's only usable in the Windows operating system, and that the simple user interface can lead the user to believe that the program presents very accurate data. This can encourage a less critical analysis of the results. It is still important to properly evaluate the output data.

The way combustion is taking place in the model is of great importance. In the two-zone model CFAST, the actual settings cannot burn. Instead so called design fires have to be placed in the model. These can be pre-defined empirical test results from real objects, such as sofas, walls or wardrobes and also user-defined HRR-curves. This way to approach combustion could be much easier for the operator, since data from objects can be chosen directly in the program, or be entered manually. It has to be considered that fire spread, material properties and complex structures will intervene in real life. This also points out the need for a critical analysis of the output data.

For our simulations the two-zone model CFAST v. 6.0.10.61027 by NIST has been used. It recently was updated to 6.1.1.48, but the changes in the new version do not affect the curve in the fire growth phase. The graphical visualization program used was Smokeview v.5.3.10 from NIST.

2.3. The Computational Fluid Dynamics model (CFD)

The computational fluid dynamics (CFD) models, also known as a field models, presume a gas will behave similar to a fluid. By using this approach, the Navier-Stokes equations can be applied, and trough considerable data-processing a near-reality simulation can be achieved. This is often done by integrating the equations by each finite cell defined by the mesh. Then each of the cells interacts with the cells next to it in every step of the processing time.

Regardless of what specific program is being used, the procedure approximately follows these steps:

1. During pre-processing the boundaries, the size of the cells (the mesh), the geometry, the material properties, chemical reactions and similar factors are defined. Also, the output data and special conditions are specified before the actual simulation.
2. The simulation is performed.
3. A post-processor is used for visualization and interpretation of the data.

This kind of model is not suitable in mainly two situations:

- **When the temperature and radiation in an area close to the fire reach flashover.** This is because the immediate surroundings of the fire are affected by complex thermal driven flows and radiation.
- **When the capacities of the computers used are low, or the time at hand is short.** This is because of the big amount of calculations that have to be done in the volume, at every step of time during the simulation.

The CFD models are divided into subgroups depending on how the present model is dealing with the turbulent flows inside the volume. Two common ways, where the model is slightly simplified, are the large eddy simulations (LES) and the Reynolds-averaged Navier-Stokes equations (RANS) formulation. In addition there are a few other methods, of which the direct numerical simulation (DNS) is worth mentioning. This method solves all turbulent flows within the model, and provides a very detailed simulation, but requires unrealistic super computer performance.

2.3.1. Fire Dynamics Simulator (FDS)

To represent the CFD models the Fire Dynamics Simulator (FDS) program has been chosen. FDS has the same benefits as CFAST:

- It is free of charge.
- It is well documented.
- It is updated regularly.
- It is compatible with the visualization tool Smokeview

Even though the program is developed by the same organization as CFAST, the user interface is completely different, and a great deal more complicated. The pre-processing is made in a text-based environment, which requires extensive knowledge of the program. On the other hand the complex settings will in some circumstances lead to a more critical view of the output data. The program can be run on other operating systems including Mac and Linux. Several graphical user interfaces, built to be more user friendly, are available at a cost.

FDS is a fluid dynamics based model with modifications made to better suit thermal driven flow and combustion. To maintain a balance between the quality of the simulations, and the time to perform the calculations, the large eddy simulation technique is used to filtrate away all the minor turbulences and thermal flows. This means only the greater flows with the main part of the turbulent energy is calculated between the cells. The turbulences that do not exceed the cell size are treated by means of the Smagorinsky approach.

Since FDS has been adapted to above mentioned abilities it also have rendered it more unsuitable for calculations of rapidly growing fire, such as deflagrations or detonations. Only slow-progressing flow, such as natural convection from fires can be applied. (McGrattan, 2007)

The one of the basic input criteria of FDS is the size of the grid which separates the entire calculation volume into smaller cells (the mesh). The number and the size of these cells determine the calculation time and the quality of the simulation. All heat transfer, gas flow, radiation and momentum calculations are performed within and trough interaction between these cells.

FDS provides a number of possibilities for modelling fire development and behaviour. One method is the fire spread model, where properties of materials are defined and then ignited in some way. Unfortunately FDS is not suitable for modelling by solid material properties alone, as discussed by David Sheppard[1]. These material properties introduce possible errors to the process as they can be hard to come by and from different sources with varying assumptions. The use of this function must by this account just be used for testing purposes, and used with caution.

Another approach would be to use a flammable fluid or gas when appropriate, as reactions of hydro-carbon chains are simple to calculate by the program and provide a more accurate result than a solid material. A HRR-curve from a calorimeter test is the current preferred and most accurate approach. This is replicable in FDS by either

[1] David Sheppard, of the US Bureau of Alcohol, Tobacco, Firearms and Explosives, on the FDS-SMV mailing list, March 31th of 2009.

the SURF HRRPUA or the RAMP_Q-function. FDS is more appropriate to these sorts of reactions, and will produce more accurate results if this method is chosen (McGrattan, 2007).

Another option is to use the same method as in CFAST, and define a design fire scenario by using data from earlier tests or calculations.

Both the fire spread model and the design fire model has been used in the test, and for our simulations the 5.3.0 Parallel version (SVN Revision No: 3193) of FDS has been used.

3. ASSUMPTIONS AND IMPORTANT INPUT

The full-scale test was set up to resemble a real fire case. This chapter gives an overview of the room configuration, the objects in the rooms, specific circumstances and important events as well as possible sources of error during the full-scale test.

3.1. THE ROOMS AND FLOOR PLAN

The building, where the test was conducted, used to serve as classrooms and offices at ResQ AS (ResQ), and was put together out of 18 construction huts.

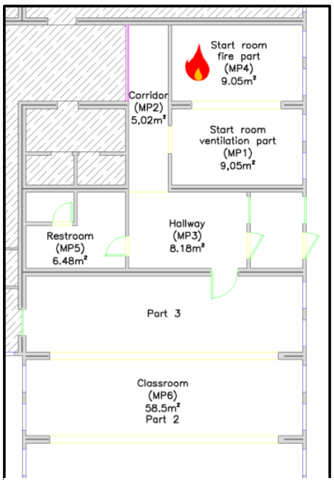

FIGURE 2: OVERVIEW OF THE ROOM CONFIGURATION IN THE FULL-SCALE TESTS. A MORE DETAILD PLAN CAN BE FOUND IN APPENDIX V.

- The start room is divided into two parts by a beam and extensions from the walls. The upper part, as seen in Figure 2, is called the fire part while the lower part is called the ventilation part.
- The corridor outside the start room is directly connected to the hallway, but is treated individually due to usage of programs. The corridor is a blind hallway.
- The hallway is located just inside the entrance, and is openly connected to the corridor.
- The restroom is, like the corridor, a blind hallway. The difference is the smaller opening between the volumes, to the restroom.
- The classroom is located most far away from the fire, and can be considered as a large room. The area is divided by three beams and extensions from the wall, like the one in the start room. The tree parts are named part 1-3, starting with the lower part, as can be seen in Figure 2.

The plan (Figure 2 or APPENDIX V) shows the building, and the parts where the test where performed. Originally the plans were obtained from the owner (ResQ), but due to changes of usage and rebuilding, the plans needed to be revised. The actual distances were then determined with a laser-measurements device. The revised plans are the basis of the geometrical data for all simulations.

Since the building was assembled out of construction huts, there were beams in the ceiling where the openings between the segments were cut out. In Figure 3 the one that divided the start room can be seen. These beams were presumed to have great importance for the building-up of the smoke layer, since the smoke had a possibility to accumulate behind them and radiate back to the surroundings.

FIGURE 3: ONE OF THE BEAMS IN THE CEILING, THIS ONE IN THE START ROOM. THE EXTENSION BELOW THE CEILING IS 40 CM.

3.2. LIVE TEST DATA

Data from the live test was collected and post-processed by Hviding and Dahle in their bachelor thesis focusing on how to do the burn and test phase to achieve the best results possible (Hviding & Dahle, 2009). More info on the detailed inventory can also be found included within their work.

When comparing data from full-scale tests to simulations, the average of the upper smoke layer is usually evaluated. This requires the smoke layer height to be known for every time interval. For investigative purposes this poses a problem, since the data is far from that detailed. The investigators rely on estimates of temperatures in the room, other forensic evidence of fire development, as well as witness observations, to theorize a possible scenario. Since the smoke layer temperature is highest at the upmost part, a two-zone model that could be shown to correspond would be a great value as an investigative resource. This would also be lot faster than using FDS.

3.3. MATERIALS AND FOCUS

This bachelor thesis will concentrate on the specific item the fire initiates from. Even though the room had more furniture and inventory than the chair the fire originated from, it was early decided to focus on the initial fire. The reason of this is because the initial fire is assumed to create a flash over by itself. After the flash over the other individual objects are irrelevant and only the total amount of fire load is interesting for a fuel-controlled fire. For a ventilation-controlled fire the area of the ventilation openings and the mixture of fresh air are essential.

For studies of post-flashover state some specific models have been developed (Yau, Graham, & Francis, 2001), but this will not be covered here.

3.4. INVENTORY IN THE START ROOM

In order to make the setting as realistic as possible, the start room was furnished with several pieces of furniture and objects natural to the setting. In Figure 4 Indexed positions can be seen, which are explained in Table 1 below.

The fire started and was concentrated around the positions 1-4, which lead to a higher degree of charring in that area.

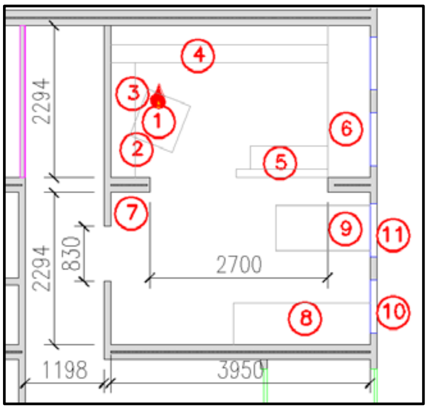

FIGURE 4: THE START ROOM, WITH INDEX NUMBERS TO INDICATE IMPORTANT OBJEKTS. THESE NUMBERS ARE EXPLAINED IN TABLE 1.

No.	Object	Involved in fire?	Comment
1	Easy-chair	Yes, completely	Initial fire
2	Rolled up mattress	Yes, completely	Early ignition and smoke production. Located above the chair. Falls to the floor after 155 seconds.
3	Shelf with books	Yes	Early ignition. Located above the chair.
4	Desk and locker	Yes	A small oven, some food, paper and video cassettes are placed on the desk. Most doors on the locker are closed. One is open and contain books
5	Book case and room divider	Yes, partly	Book case contains some porcelain and plastic objects
6	Desk	Yes, partly	Occupied by a microwave oven and some plastic cups
7	Paper bin	Yes, partly	Filled with pizza cartons and cotton fabric.
8	2-seat sofa	No	Plastic surface not affected.
9	Table with TV & coffee machine	No	Plastic details on TV and coffee machine partly melted.
10	Window with hole	Yes	Inner glass, out of two, completely destroyed.
11	Window opened by firemen	Yes	Inner glass, out of two, completely destroyed.

TABLE 1: THE INDEX NUMBERS IN FIGURE 4 EXPLAINED.

3.5. EVENTS DURING THE REALISTIC FULL-SCALE TEST

TIMELINE OF THE FULL SCALE TEST

Some of the major events are shown in Figure 5 below. These events marked are included in the events-simulation, except for the fire extinguishing.

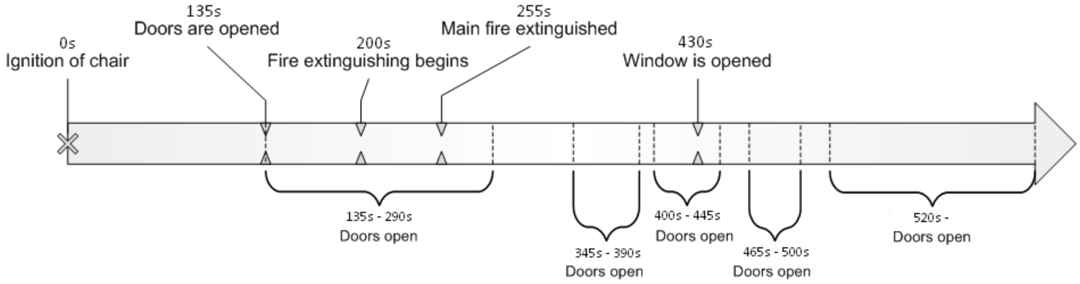

FIGURE 5: THE TIMENLINE OF THE FULL SCALE TEST. IMPORTANT EVENTS ARE SHOWN.

IGNITION

In the design-fire that were used (Särdqvist, 1993), it is not mentioned how the fire is started. In the live test the chair was however ignited by a rolled-up newspaper to assure ignition. That meant the ignition of the actual chair was delayed. By analyzing videos it is estimated that the delay from igniting the newspaper until the chair was on fire was approximately 65 seconds.

VENTILATION

In the full-scale test the fire was ventilated through the door and was able to reach fresh air from the large volume in the classroom. This oxygen supply was however limited. The opening in the window provided a second source of oxygen, but was strictly limited by the area of the hole. Altogether it can be assumed that there was an insufficient amount of oxygen available.

At 135s the entrance door is opened by the firemen and air is let in, and smoke is let out. This means an increased ventilation and availability of oxygen. At 430s the firemen opens a window to ventilate the smoke. This event, however, is occurring in the post-flashover phase and after fire-fighting measures was initiated. At that point the model and the measurements are affected by a large amount of external disturbances, such as applied water and changed ventilation.

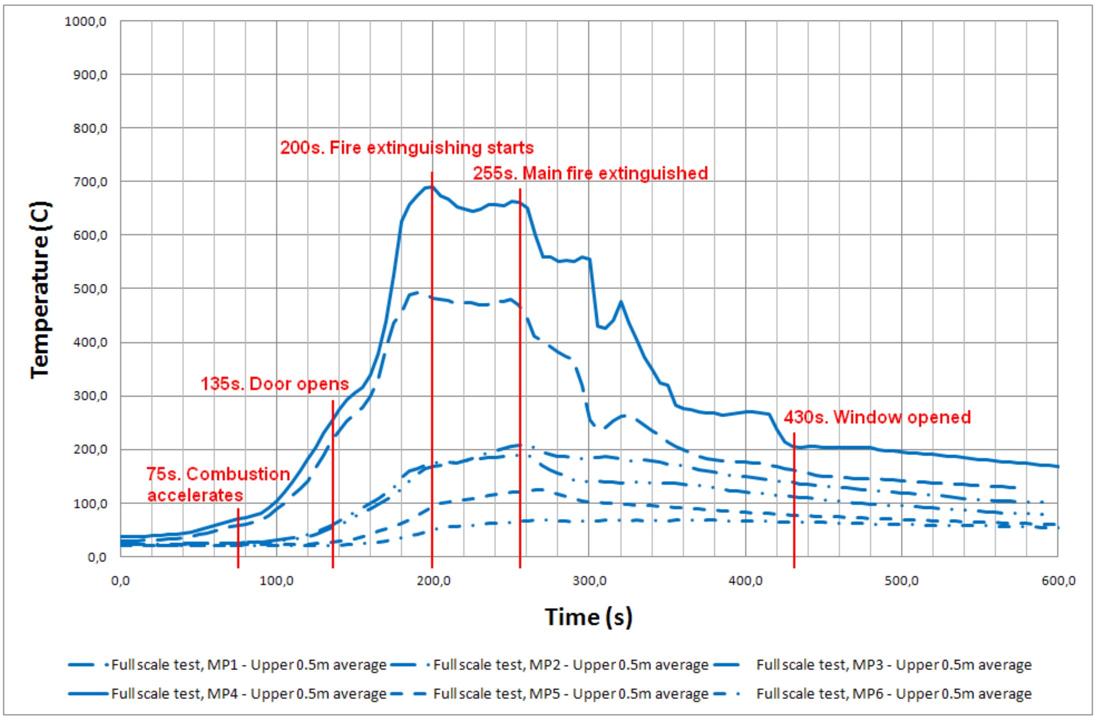

FIGURE 6: THE DATA FROM THE FULL-SCALE TEST, WITH THE MOST IMPORTANT EVENTS INCLUDED.

FIRE SPREAD

As a result of the realistic setup, there was an increased combustion due to fire spread. The main part of the extra energy most likely originates from the mattress, and the shelf, above the chair (object 2 and 3 in Figure 4).

A cone calorimeter test where performed on the ceiling, since it was assumed the plastic lined particle board would produce extra smoke and ignite at an early stage. This was however not the case. The cone calorimeter test showed low smoke production and long ignition time at the different radiation levels that were used in the test. (APPENDIX IV) This leads to the conclusion that the ceiling and walls did not contribute at a large rate at the initial stages of the fire.

THE APPLICATION OF WATER

At approximately 255s from the ignition, the firemen applied water as a part of their internal attack. The applying of water stops the combustion and fire spread, as well as is cools down the hot smoke. When observing the development of the fire this is a very critical event, and thus the data from the live test after that point is combined with uncertainties.

3.6. SOURCES OF ERROR

Several possible sources of error can affect the simulations and the quality of the output data. It is however assumed that the data that was received from the instrumentation group (Hviding & Dahle, 2009) is correct, due to thermocouples have a high level of accuracy. Below follows an extract of a few possible sources of errors.

- The thermocouples can be affected by radiation from the flames and the smoke layer above, which may be misinterpreted by the log, as a higher surrounding temperature than the actual gas temperature. This problem does however not affect our comparisons, since only the three uppermost thermocouples are used, and they are placed inside the smoke layer.
- There can be an inadequate number of thermocouples, and the positioning of these can be wrong, in order to achieve the best possible information.
- The thermocouples have some degree of transient temperature measurements, since it takes a few seconds for the values to stabilize. This is however compensated for in both of the programs by creating mean values over a fixed amount of time steps in the simulations.
- The HRR-curve of the initial fire that is used in the simulations may contain some uncertainties. For example, the ignition contains uncertainties, and external factors could have interfered during the test.

4. SIMULATIONS

Simulations of the full-scale test were performed both before and after the actual test. This chapter focus on the progress of the simulation modelling and changes of the item and room properties in the model. The main characteristics of the simulations will be listed. It is also described how the sensitivity analyses were performed.

4.1. GENERAL PROGRESS OF WORK

In order to assist the positioning of sensors in the live test, several simulations were performed before the live test. The objective was to estimate the temperature development, smoke production, smoke spread and the height of the smoke layer.

The FDS simulations proved at an early stage to be very complex, and clearly not suitable for work within close time limits. This lead to an approach of the problems where the CFAST simulations where used to make quick simulations and adjustments. When a conclusion was reached, or important changes were made, FDS was only used to visualize and verify the results. Less time spent on complicated programming of FDS meant more effective work with variable parameters. This proved to be a very effective way to work, but still the CFD modelling required a great deal of time. Also, there was some discussion whether a sofa, madras or an easy chair was to be the initial fire. This meant the scenario changed several times with new simulations as a result.

4.2. SIMULATION ERRORS

Except our case-specific types mentioned in "3.6 Sources of error" there are several general possible sources of error that can occur on-scene and during processing of collected information.

- There are many possible ways for human errors to intervene in the process. A few examples are :
  - Measurements of the room dimensions.
  - Measurements of the area of ventilation openings.
  - Writing data into CFAST graphic user interface or the FDS text file.
- Wrong assumptions can easily be made:
  - Especially the initial fire, of which few remains can be assumed. It is mainly the material and its properties that are in focus, since they have to be inserted into the programs direct or through a HRR-curve.
  - Obtaining a suitable HRR-curve can prove to be difficult, since few databases of HRR-curves exist, and an exact copy of the item in question can be hard to find.
- Sheer lack of knowledge, of fire dynamics and the programs in use, provides risk for faulty usage of the programs and misinterpretation of the output data.

4.3. GLASS BREAKAGE

There was some doubt whether the windows in the start room would shatter or not during the test. However, it was deemed that the windows would probably not break during the first test since the glass was insulated (double glass), and available literature suggests about 3-5 minutes lifetime for such windows (Cuzzillo & Pagini, 1998). Instead different settings where simulated with one of the windows completely open, partly smashed or totally closed, and the setting with a partly smashed window was finally chosen with respect to the set-up and sufficient ventilation.

4.4. OVERVIEW OF SIMULATIONS - CFAST

4.4.1. INITIAL SIMULATIONS - CFAST

The initial computer modelling was done to figure out where it was best to place the burning object. CFAST was used for running several models, as it is quick and provides data within minutes. Several models were done based on the measurements and AutoCAD drawings.

The first simulations (series 0 through 2) were done with a sofa from the CFAST fire item menu, as the original intent was to use a sofa in the full-scale test. At this point it was not essential to have exact values as the HRR level was around average and the simulations was more to see a general build up than empirical results.

Before doing the full-scale test it was decided to use a chair instead, a large upholstered armchair. A similar specimen was found in the works of Stefan Särdqvist (Särdqvist, 1993), and easy chair Y5.3/10 was chosen. This peaks at 2,1MW HRR after 200s, and is closely similar to the chair found in CFAST. This was used in the simulations v3.x, before the full-scale tests, and proved to be accurate enough to be used in evaluation.

CFAST version	Initial fire	Initial fire position	Detail level	Important factors
v0	Couch	Start room, fire part	Low	No air ventilation
v1	"	"	"	Air ventilation through 80x100cm window in start room
v2	"	"	Detailed	"
v3.2	Chair	"	"	Air ventilation through 23x39cm window in start room
v3.9	"	"	Low detail	Air ventilation through 80x100cm window in start room
v3.10	"	"	Mixed model	"
v4.1	"	"	Detailed	Air ventilation through 22x22cm window in start room
v4.2	"	"	Low detail	"
v4.4	"	"	Mixed model	"
v6.0	Couch	"	Detailed	"
v6.0b	"	"	"	Air ventilation through 22x22cm window in start room Open entrance door 80x200 cm in hallway
v6.1	Fast t^2-fire	"	"	Air ventilation through 22x22cm window in start room
v6.2	Medium t^2-fire	"	"	"
v6.3	Medium/fast t^2-fire	"	"	"

TABLE 2: OVERVIEW OF THE MAIN CHARACTERISTICS OF THE SIMULATIONS PERFORMED AND MENTIONED IN CFAST. A TOTAL AMOUNT OF 29 DIFFERENT MODELS WERE MADE IN CFAST, SPANNING OVER 7 VERSIONS.

Series 0 – Low detail model

The first series of simulations were done in low detail. The rooms were of the same length as in real life, but the beams were omitted as a contributing factor. The first low detail estimates were also with all doors and windows closed and no air supply. This indicated high temperatures, but perhaps not so high as would be expected. The hand calculations indicate that a HRR of 1,4MW (APPENDIX III) would be in the boundary area between the criteria of flash over and the fire extinguish itself.

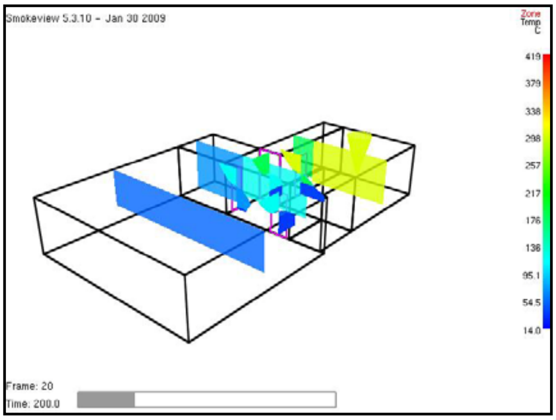

FIGURE 7: SERIES 0 – LOW DETAIL, NO BEAMS

Series 1-2 – Inlet of air and more detailed models

With series 1 inlet air was incorporated through a fully open window in the ventilation part of the fire room, simulating a window left open or broken into. Series 2 was a study of a more detailed simulation where the dividing beams were creating obstacles for smoke and thereby transport of temperature. Different locations for the sofa and the four possible window openings were examined. To exaggerate the fire the most, it was decided to locate it in the innermost part of the fire room where the beams would contain the smoke for a while, leaving it to grow intense while accessing fresh air from the door and window openings.

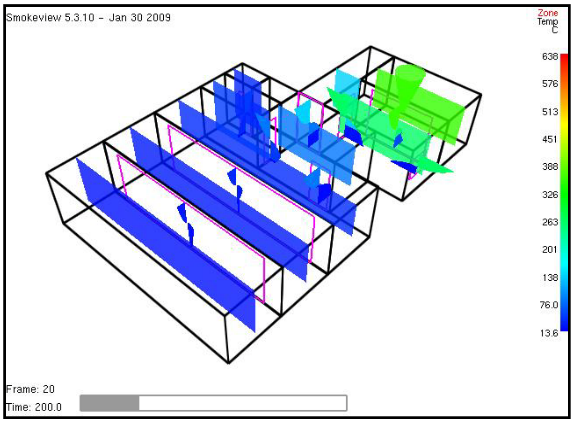

FIGURE 8: SERIES 2 – V2.1 HIGH DETAIL

SERIES 3 – CHANGING THE FIRE ITEM

Series 3 were the last simulations run before running the full-scale tests. During series 0-2 there had been continuous communication with Hviding and Dahle, who were in charge of the measurement. The points of measurements (MP1-6) were placed based on mutual agreement on areas of interest. This meant one in each of the fire room parts divided by the roof beam, one in the corridor outside, one in the hallway, one in the restroom and the last one in the classroom (Figure 9).

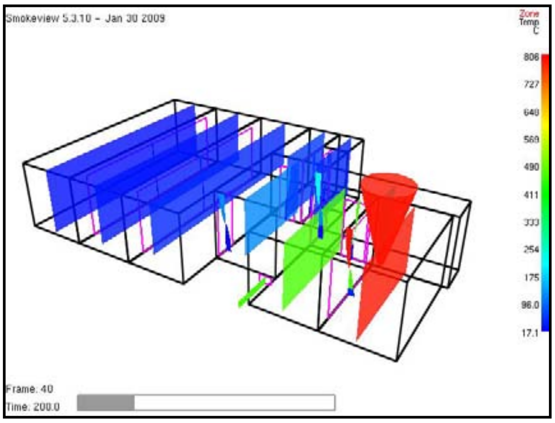

FIGURE 9: SERIES 3 – V3.2 WITH CHAIR

An easy chair (an armchair with upholstering) was thought to provide a more realistic scenario in the burn-part of the fire room, thus the series 3 were simulated with the Y5.3/10 Easy Chair (Särdqvist, 1993) instead of a sofa. There was some discussion on the window opening size, whether it would be entirely open, semi-open or partly shattered. Series 3 composed of 11 different simulations (v3.1-3.10b) with different configurations. Version 3.2 would turn out to be the closest to the real-life scenario with a small opening in the window. Version 3.9 (low detail) was also chosen in order to compare a very low detail model with the right geometry and a close matching HRR to the test results and the more accurate models (series 4) done after the full-scale tests.

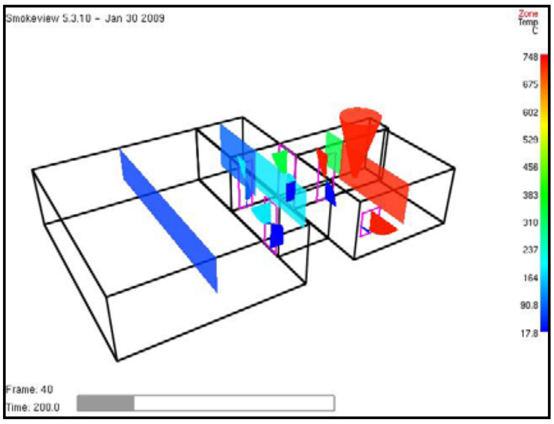

FIGURE 10: SERIES 3 – V3.9 LOW DETAIL WITH CHAIR

4.4.2. Final simulations - CFAST

Series 4 – After the fire

The main difference between series 4 and 3 is that in series 4 the area of the window opening was measured and taken into consideration. A square of 0,22m*0,22m was used as an approach to the full-scale test (APPENDIX II). Version 4.1 was with high detail similar to v3.2, and v4.2 was a low detail model similar to v3.9.

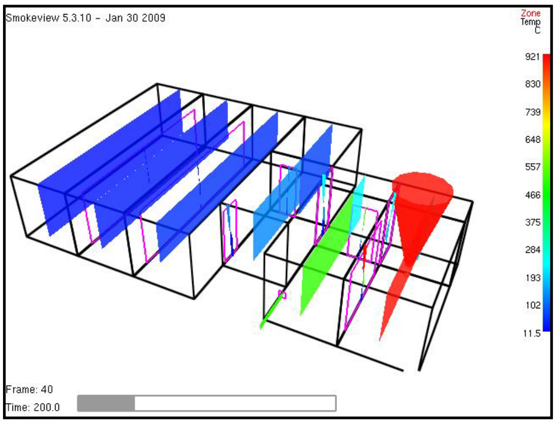

FIGURE 11: SERIES 4 – V4.1 HIGH DETAIL WITH CHAIR.

About the simulations chosen in CFAST

For evaluation and verification purposes it is relevant to observe the difference between a low detail simulation and a high detailed simulation. It is important to highlight factors that contribute to differing results in simulations done before and after a fire.

	Low detail simulation (v4.2 and v3.9)	**High detail simulation (v4.1 and v3.2)**
Pros	+Easier to model and adjust	+Accounts for smoke-build up and other possible phenomena's due to building design
Cons	-Doesn't account for building details that might be essential -Danger of over-simplification of model	-Modelling requires more work -What detail level is sufficient? -Room dividers has to be done with "holes" (horizontal air-vents), and this can lead to increasing error.

Another factor that is interesting to consider is the simulations before and after the fire (series 3 versus series 4). The simulations done before the fire can to some extent be compared to the problem of arriving at a scene after a fire (unless it is completely burned down). The general floor plans are known, but the exact way it will burn/has burned is still unknown. As it is, the version 4 is a more exact simulation in measurements of start fire location and window ventilation, but same HRR-curve as in series 3 as it was quite similar in curve-shape.

DATA POINTS AND AVERAGES IN COMPARATIVE STUDY TO CFAST

Some thought was given to how to properly compare the values of the upper smoke layer from CFAST to the full-scale test. CFAST only gives two temperature values per room, upper and lower layer. The full-scale test had 15 thermocouples ranging from 0.15m below the ceiling down to 0.25m above the floor. The two-zone model assumes a distinctive boundary between the two layers, something that is clearly visible on the videos obtained from the full-scale test, and yet the graphs from the live test shows that the temperature in the smoke is uniformly distributed and continues in the same fashion in the lower non-smoke layer.

There is also little in the user manual and technical reference of CFAST on how to measure a room effectually and correctly to obtain viable comparable results.

These observations lead to theories that some simplifications could be done. Achieving an average of the smoke layer temperatures as correct as possible is invariably connected to having detailed observations of the smoke layer height. Evaluating and adjusting the temperature averages with this in mind can actually be more work-intense in post-processing than observing the temperatures alone. The measuring points in the two parts of the fire room (MP1 and MP4) were placed close to the middle, without close proximity to cooling extremities such as door openings, walls and windows. An average of the top part (for example 0,5m) of the smoke layer would be easier to constantly evaluate and would be the part of the layer most interesting in sprinkler-activation, heat-dissipation to the ceiling and a very good pinpoint to whether or not the smoke layer meets the criteria's of a flashover as stated by researchers such as Drysdale (Drysdale, 1999).

In relevance to fire investigation, the average of the top part would also be easier comparable to a fire scene as signs of approximate temperatures often can be found. Examples might be certain melting temperatures and burn patterns, which experienced fire investigators are skilled at locating and identifying, as discussed in books on the matter, for example "Principles of fire investigation" (Cooke & Ide, 1985).

4.5. OVERVIEW OF SIMULATIONS - FDS

4.5.1. INITIAL SIMULATIONS - FDS

As previously discussed, the FDS simulations where used only when a theory was reached or important changes were made. This led to some extent of discontinuity in the chain of simulations, but the major modifications are listed below. Simulation number 1-9 is made before the actual full-scale test, which means not all data and input were available. Simulation 10-16 is the base for the sensitivity analysis, and simulation 17 and 18 is made for comparative studies.

The most important change of the scenario is the replacement of the fire spread scenario with the design fire scenario, which was done from simulation 10 and forward.

No.	Mesh size		Comments
	Combustion part	Smoke spread part	
1	10x10x10	-	Sofa in ventilation part next to window. Fire spread scenario.
2	10x10x10	-	Sofa in fire part in corner, windows break at 300C. Fire spread scenario.
3	10x10x10	20x20x20	Sofa in ventilation part below window, windows break at 300C. Fire spread scenario.
4	10x10x10	20x20x20	Sofa in fire part in corner, one window breaks at 300C. Fire spread scenario.
5	10x10x10	-	**Chair in fire part, final poss.** One window breaks at 300C. Fire spread scenario.
6	10x10x10	20x20x20	Chair in fire part, final poss. windows break at 300C. Fire spread scenario.
7	10x10x10	-	Chair in fire part, final poss. **One window smashed. Sensors placed**. Fire spread scenario.
8	U: 10x10x10 L: 20x20x20	40x40x40	Chair in fire part, final poss. One window smashed. Sensors placed. Fire spread scenario.
9	20x20x20	40x40x40	**Burner in final poss**. Window smashed. Sensors placed.
10	40x40x40 cm	40x40x40 cm	Sensitivity analysis. Design fire scenario.
11	20x20x20 cm	40x40x40 cm	Sensitivity analysis. Design fire scenario.
12	20x20x20 cm	20x20x20 cm	Sensitivity analysis. Design fire scenario.
13	10x10x10 cm	20x20x20 cm	Sensitivity analysis. Design fire scenario.
14	10x10x10 cm	10x10x10 cm	Sensitivity analysis. Design fire scenario. Chosen for evaluation
15	5x5x5 cm	10x10x10 cm	Sensitivity analysis. Design fire scenario.
16	5x5x5 cm	5x5x5 cm	Sensitivity analysis. Design fire scenario.
17	10x10x10 cm	10x10x10 cm	Simulation with events. Mesh extended 1 meter from entrance. Design fire scenario.
18	10x10x10 cm	10x10x10 cm	Comparative simulation with fire spread scenario.

TABLE 3: OVERVIEW OF MESH SIZES AND D*/DX RATIO IN MOST OF THE SIMULATIONS PERFORMED.

BEFORE THE LIVE TEST

THE INITIAL FIRE

Initially a sofa was placed in a position marked 1 in Figure 11. This position proved at an early stage to be unfavourable, due to the fact that the accumulation of smoke was delayed, because of ventilation through the open window and the open door. At this stage the effect of the burner placed on the sofa, was 100kW through the entire simulation. The temperature, which at a flashover can be assumed to be at least 600C˚, hardly reached beyond 200C˚, and this highlighted the need of adjustment. At this point the initial fire (the sofa) was of the kind that is described at page 168 in the FDS user manual (McGrattan, 2008) and consist mostly of Polyurethane (PU). Some adjustments were made to the ignition temperature. This approach proved to be clearly unsuitable at a later point. In Figure 12 a comparison between the fire-spread model and the design fire model, with the same mesh settings can be seen. This is to highlight the differences between the methods.

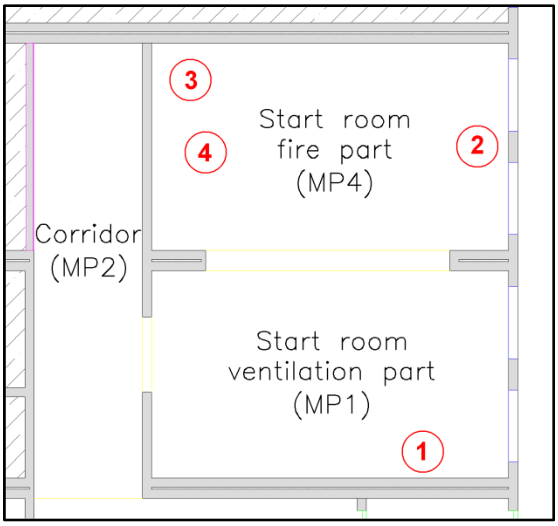

FIGURE 12: OVERWIEV OF THE START ROOM WITH POSITIONS FOR THE INITIAL FIRE MARKED OUT.

To achieve a smoke layer that radiated back at a higher degree, the same sofa was placed as shown as on Figure 11, location 2, and later at location 3. This meant that the smoke had a chance to accumulate, since the room is divided with a beam. These positions lead to higher temperatures, and showed signs of a flashover. The size of the sofa was adjusted to dimensions similar to a chair, which resulted in a more rapidly growing fire. After further evaluation, consisting of whether the initial fire should be placed close to the windows or not, the constellation on Figure 11 on position 4, was chosen with guidance from CFAST studies and with FDS verification. The criteria's was whether the glass was going to break and how well the smoke layer did build up.

VENTILATION OPENINGS

Initially the area and the amount of ventilation openings were not set. The discussion about whether the window glass would break or not lead to, with guidance from previous work on the subject (Cuzzillo & Pagini, 1998), that the windows were set to open at an ambient temperature of 300˚C in the FDS simulation. Depending on the location of the burning object, this causes the glass to break after approximately 1-3 minutes, in one or several of the windows in the simulations. After further discussion this event was removed and the ventilation area was set to only consist of the smashed window with an area of 0,049 m^2 as measured in the full scale test, through the entire simulation. (APPENDIX II)

AFTER THE FULL-SCALE TEST

As a result of visual observation and data to use as a point of reference, the fire spread scenario was replaced with a design fire scenario, since the fire spread scenario proved to be unsuitable and provided faulty output data (see Figure 12). This approach is also supported by the technical reference of FDS (McGrattan, 2007). The final code was established and used to perform a sensitivity analysis (APPENDIX I). Two simulations where performed after the sensitivity analysis:

- One simulation with incorporated events such as when the firemen opened doors, windows, and applied water on the fire.
- One simulation with the original modified sofa, which replaces the design fire scenario with a fire-spread scenario.

Table 4 shows an overview of the simulations performed after the sensitivity analysis which were studied, compared and evaluated.

No.	Mesh size		D^*/dx Ratio	Scenario	Comment
	Combustion part	Smoke spread part			
17	10x10x10 cm	10x10x10 cm	12,9	Design fire	Events included. Some changes in mesh.
18	10x10x10 cm	10x10x10 cm	12,9	Fire spread	Comparative fire spread simulation.

TABLE 4: OVERVIEW OF THE FINAL FDS SIMULATIONS PERFORMED AFTER THE SENSITIVITY ANALYSIS. THE D^*/dx RATIO ONLY IS BASED ON THE MESH IN THE COMBUSTION PART.

In Figure 12 a comparison between the live tests, the fire spread model and the design fire model (with and without events), with the same mesh settings can be seen. Simulation 14 and 17 shows small differences and thus events are unnecessary.

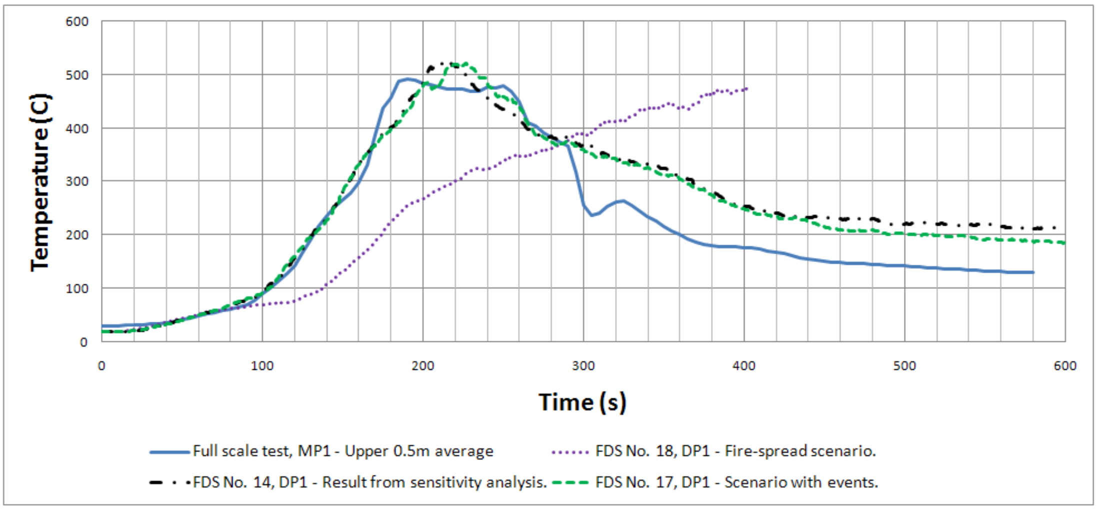

FIGURE 13: COMPARISON BETWEEN THE LIVE TESTS, THE FIRE SPREAD MODEL AND THE DESIGN FIRE MODEL (WITH AND WITHOUT EVENTS), IN THE START ROOM – VENTILATION PART.

4.6. SENSITIVITY ANALYSIS

4.6.1. SENSITIVITY ANALYSIS – CFAST

In CFAST there is only one way to make a connection through a wall, and that's called a "ventilation opening". This is used both for doorways, windows, and for any other openings. In the detailed simulations (v3.2 and v4.1) it was attempted to compensate for the beams by separating the start room and classroom. This created a separate ventilation opening with the dimensions of the opening under the beams, effectively making more room for smoke build-up and heat storage in each section of the room. As discussed in chapter 2, CFAST does not calculate as detailed as FDS. Generally speaking, for every new section beyond the one closest to the fire, the results got a little more uncertain. Two rough simulations (v3.9 and v4.2) were done to emphasize this, not correcting for any beams, with the start room and classroom as just one room each, and cutting down on several ventilation openings.

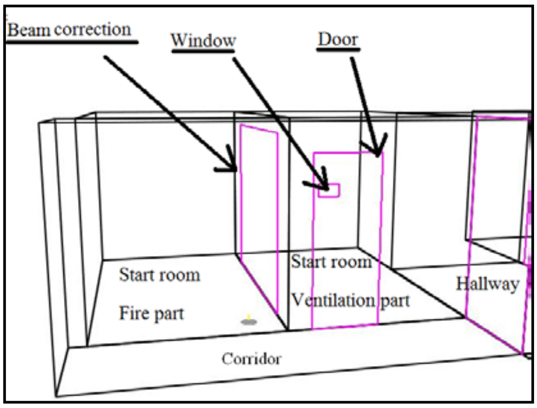

FIGURE 14: EXPLANATION AND VIZUALISATION OF "VENTILATION OPENINGS"

Two mixed simulations (v3.10 and v4.4) were made with the start room divided in two and the classroom preserved as one room without beams. The theory behind was that the fire part and ventilation part of the start room would be different due to the beam and the proximity to the fire. But to the contrary, the classroom would have a great deal of entrainment with the smoke, low temperatures and the beams would not make any difference. If the mixed simulations fit, it would give further support to the theory of "the fewer rooms, the better".

CFAST sensitivity analysis – Start room

All six simulations were done with a HRR-curve of the chair peaking at 200s.

A similar approach as a FDS sensitivity analysis (as shown in chapter 4.3.2) was attempted with CFAST. This was done comparing only four points of interest in each simulation, 50s, 100s, 150s and 200s.

The graph shows that v3.9 (700°C at 200s) and v4.1 (900°C at 200s) had the most extreme temperatures of the simulations, while v3.2, v3.10, v4.2 and v4.4 peaked at roughly the same temperature (800°C at 200s). Out of these, v4.2 and v4.4 were best suited to compare to the full-scale test.

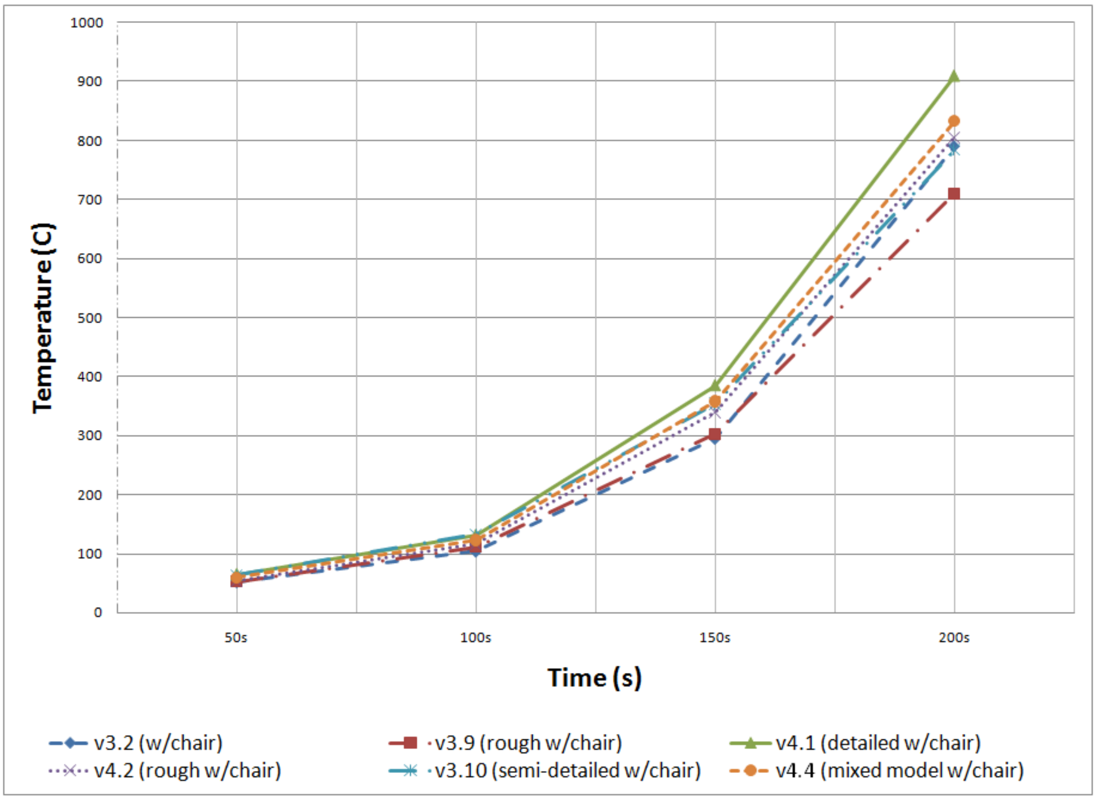

FIGURE 15: SENSITIVITY ANALYSIS MADE IN CFAST OF THE START ROOM.

CFAST SENSITIVITY ANALYSIS – CLASSROOM

The same application as above was done to data from the classroom. Points of interest were 50s, 100s, 150s and 200s. In the detailed versions (v3.2 and v4.1) data from the middle section (part 2) was used.

The graph shows that the low detail simulations, v3.9 and v4.2, resulted in the highest temperatures (60°C at 200s). The high detail simulations, v3.2 and v4.1, resulted in the lowest temperatures (35°C at 200s). The mixed models (v3.10 and v4.4) ended up with medium to high temperatures (45-50°C at 200s).

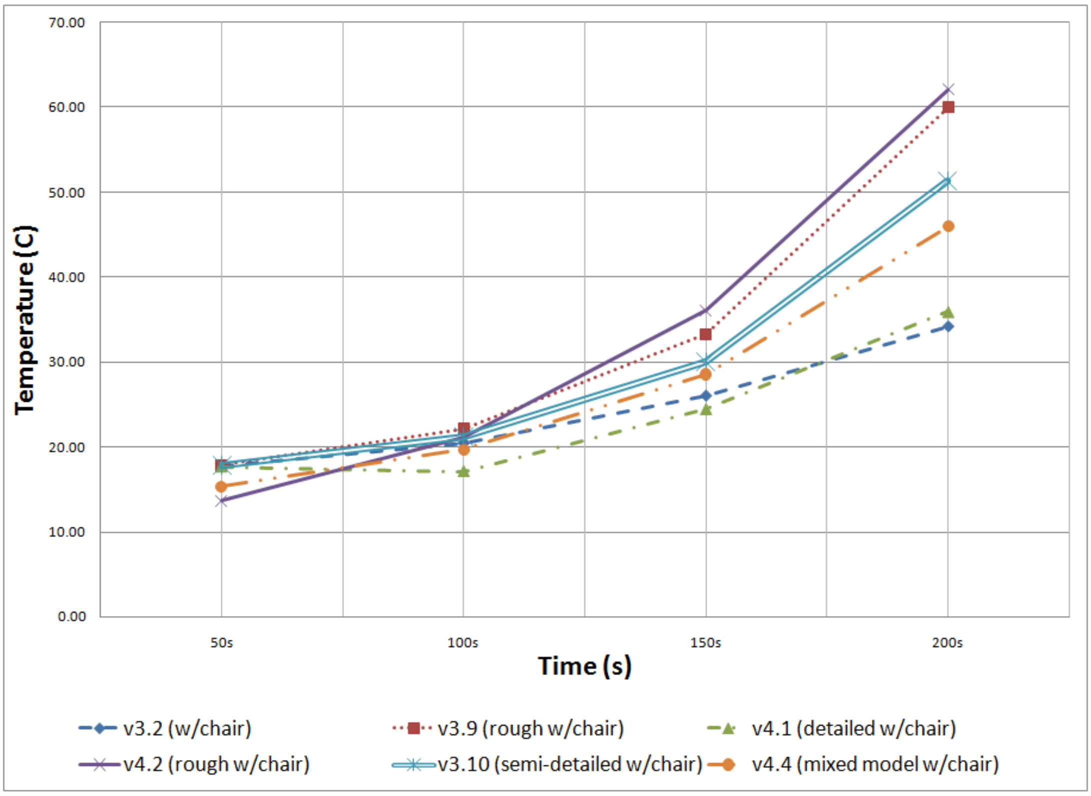

FIGURE 16: SENSITIVITY ANALYSIS MADE IN CFAST OF THE CLASSROOM.

4.6.2. Sensitivity analysis - FDS

The output temperatures vary strongly depending on the size of the mesh, and therefore a sensitivity analysis was performed, with a design fire scenario (events included such as opening of doors and windows). In order to perform the sensitivity analysis, seven simulations where performed with different mesh size. Table 6 gives an overview of the mesh size and the D^*/dx ratio for every given simulation. The D^*/dx ratio is suggested to be between 4 and 16 to achieve good simulation results, where *dx* is the length of one side of a cell in the mesh, and is *D** calculated by the equation (6.1):

$$D^* = 0.1 \times \left(\frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g}} \right)^{2/5}$$. (McGrattan, 2008)

No.	Mesh size Combustion part	Smoke spread part	Name	D^*/dx ratio	Simulation runtime
10	40x40x40 cm	40x40x40 cm	40_40	3,225	Approx. 10 minutes
11	20x20x20 cm	40x40x40 cm	20_40	6,45	Approx. 45min.
12	20x20x20 cm	20x20x20 cm	20_20	6,45	Approx. 2h.
13	10x10x10 cm	20x20x20 cm	10_20	12,9	Approx. 14.5h.
14	10x10x10 cm	10x10x10 cm	10_10	12,9	Approx. 24.5h.
15	5x5x5 cm	10x10x10 cm	5_10	25,8	Approx. 130h.
16	5x5x5 cm	5x5x5 cm	5_5	25,8	Approx. 360h. (runtime 196h for 358s)

TABLE 5: OVERVIEW OF MESH SIZES AND D*/DX RATIO IN THE SENSITIVITY ANALYSIS. OBSERVE THAT THE D^*/dx RATIO ONLY IS BASED ON THE MESH IN THE COMBUSTION PART (MESH 1: FIRE AND VENTILATION PART OF THE START ROOM, CORRIDOR, AND EXTENT FROM WINDOW)

An observation area was chosen in the hallway, since it is located in the second mesh, and therefore is affected by the properties of both the first mesh and the second. It also covers the entire height and no extra turbulence is present.

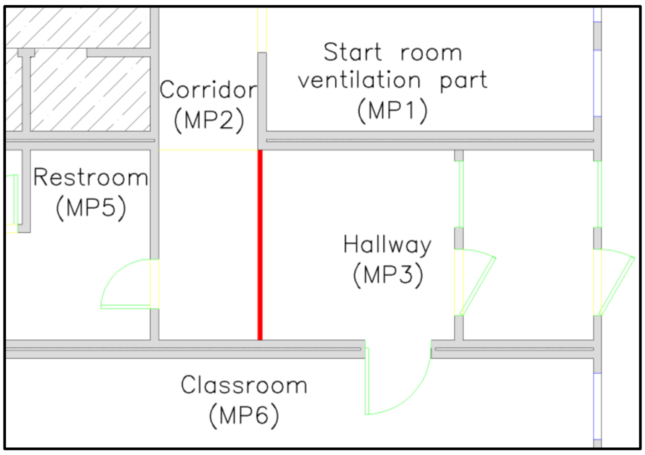

FIGURE 17: OVERVIEW OF THE ROOM CONFIGURATION. THE SLICE WHERE VELOCITIES WERE TAKEN TO THE SENSITIVITY ANALYSIS IS MARKED WITH RED.

Limitations in computer power meant the 5_5 simulation (number 16) was only run until 300s, but the data received is correct and used in the sensitivity analysis.

Some of the simulations have very large cells in the mesh (up to 0,4m sided-cubes). The sensors which reflects the positioning of the thermocouples, in the simulations, have a mutual distance of 0,15 m. This means some of the temperature measurements were done within the same cell, and therefore provide faulty output data. To compensate for this, slice-data was used instead of the data points, in the sensitivity analysis.

The temperature measurements in FDS are based on calculations of energy balances, while the velocity measurements are based on equations of motion. This means entirely different basis for output data is to be expected. The velocity data output was chosen as primary sensitivity analysis data.

To compensate for the momentary measurements that FDS provide, an average value from the output data was created over a defined span of time (a mean value of 8 time steps which corresponds to approximately 5,9s). This method is also suitable since there is some degree of transient temperature measurements from thermocouples.

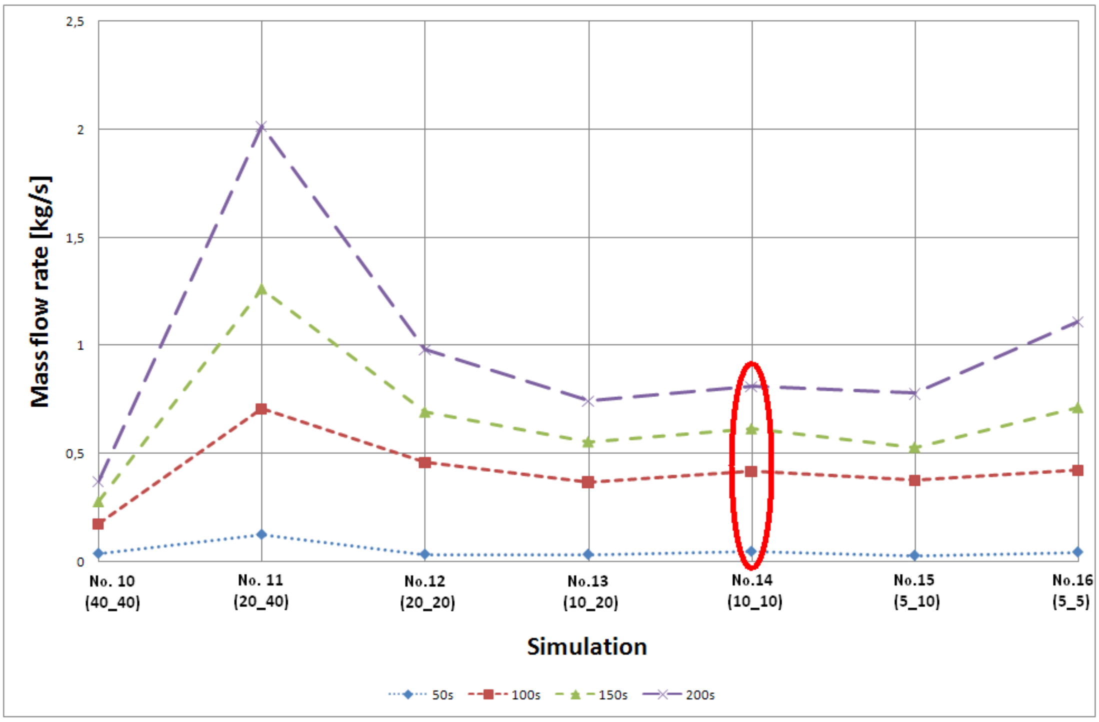

FIGURE 18: RESULTS FROM THE SENSITIVITY ANALYSIS PERFORMED IN FDS, BASED ON THE MASS FLOW RATE. THE 10_10 SIMULATION (NUMBER 14: MESH 1 = 10X10X10, MESH 2 = 10X10X10) SEEMS TO GIVE ACCEPTABLE RESULTS.

The mass flow rate, which was used as basis for the mass flow rate sensitivity analysis, was calculated as follows:

$$\dot{m} = \rho \cdot A \cdot v \quad \left[{}^{kg}/_{s}\right]$$

The density is found through:

$$\rho = \frac{353}{T+273,15} \quad \left[{}^{kg}/_{m^3}\right]$$ (Karlsson & Quintiere, 2000), eq. (5.9)

The mass flow rate in the positive direction (upper layer) were then summed up and plotted. Altogether four mass flow measurements were done for every simulation, which resulted in a total amount of 24 plotted data points.

Simulations number 10 and 11 show big differences in Figure 17. This is expected since the whole idea with the sensitivity analysis is to find the grade of details where the output data have stabilized towards an acceptable interval.

The simulation 5_5 (number 16) with very fine mesh shows an interesting effect. The values increase at the end, the more detailed the simulation is, and can be a source of error. With that in mind the recommendation from the user manual concerning the D^*/dx ratio ($4 < D^*/dx < 16$ is recommended) can be adjusted to be in the interval 10-15. This is a general guideline, and is applicable in other simulations than just this one.

Simulations 13 and 14 (10_20 and 10_10) have the same mesh properties in the combustion part of the model. They also show similar values. Number 14 is chosen for further evaluation since the distance between the data points will be larger than the cell size, and to avoid information loss in the mesh border area.

When looking at the temperature sensitivity analysis in Figure 18, it is difficult to make any conclusions since most of the graphs are very similar to each other. The more detailed simulations (15 and 16) show almost identical temperatures to number 14. It is then concluded that the 10_10 simulation (number 14) provides acceptable data.

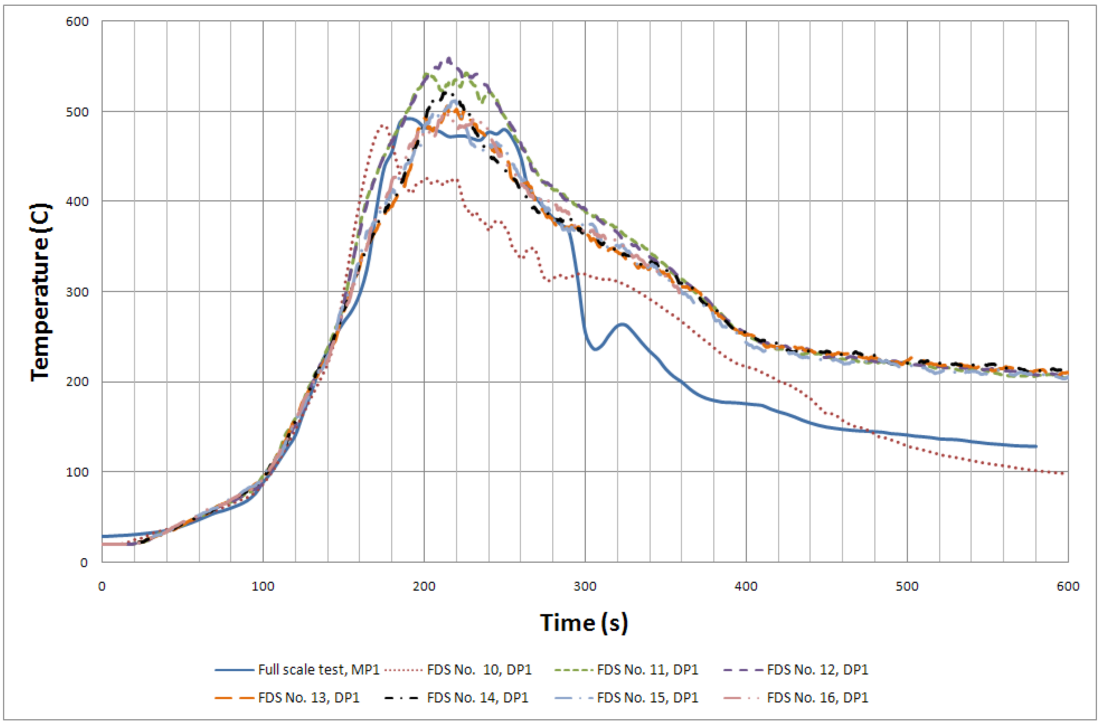

FIGURE 19: SENSITIVITY ANALYSIS BASED ON TEMPERATURE MEASUREMENTS FROM DATA POINTS IN FDS. MOST DATA SHOWS LITTLE VARIATION AND IS DIFFICULT TO ANALYZE.

4.7. SUMMARY OF SIMULATIONS

Several simulations were performed in CFAST and FDS before and after the full-scale test. CFAST simulations were used for examining problems and possible scenarios, and FDS where used to verify these. After the full-scale test new data and information became available, and was incorporated in the models. In CFAST the difference between high- and low-detail settings was investigated, and the effect of the choice further away than the first couple of rooms. The position and the type of the initial fire were also looked into. In FDS the mesh-properties and the combustion model was investigated and compared with CFAST. A sensitivity analysis was made with both of the programs. In CFAST this consisted of looking at the details of the model, while in FDS the size of the cells in the mesh was in focus. Finally a scenario was chosen in both of the programs that were to be compared to the data from the full-scale test, and discussed.

5. COMPARISON WITH FULL-SCALE TEST

From the simulations and the sensitivity analyses in chapter 4, CFAST simulation v4.4 and FDS simulation 10_10 (number 14) was chosen for further evaluation. In this chapter, a comparison of these will be done to the full-scale test, and additional simulations will be described. The purpose is to highlight the effect of over-simplification and an erroneous type and positioning of the initial fire.

5.1. GENERAL OBSERVATIONS

When comparing the model with reality, FDS shows that the ventilation in the simulation is much more effective than the live test. Through the smashed window in the simulation, a fire plume is extending horizontally where in the real test there only was smoke belching out slowly. With CFAST no such observations have been done.

FIGURE 20: PICTURE FROM THE FULL-SCALE TEST WHERE THE ACTUAL VENTILATION THROUGH THE WINDOW CAN BE OBSERVED.

Since there was a limited or insufficient amount of oxygen available, based on smoke thickness and available amount of plastic materials, it is assumed that this lead to decreased temperature growth. From videos it can be estimated that this process takes off at roughly 75s from the ignition of the chair. These assumptions correspond well with the decrease in temperature growth in the live test, which can be observed between 140 and 155 seconds in both parts of the start room (See Figure 24).

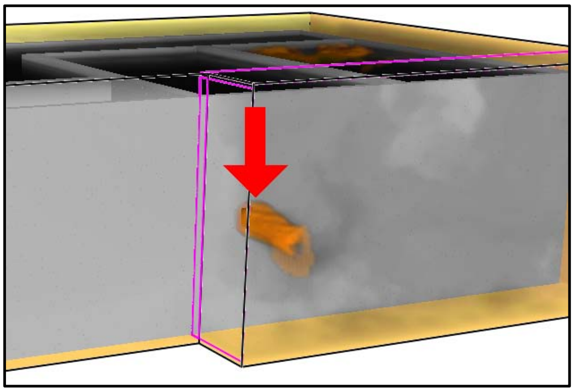

FIGURE 21: IMAGE FROM SIMULATION NUMBER 14 IN FDS. A FLAME EXTENDS HORIZONTALLY FROM THE VENTILATION OPENING THAT CORRESPONDS TO THE SMASHED WINDOW.

5.2. FULL-SCALE TEST TEMPERATURE EVALUATION

A theory was proposed to use the maximum temperatures in the smoke layer, instead of the upper layer average (chapter 3.2). Sprinkler activation and smoke/heat-detectors only use the upmost temperatures. At what level would the upmost temperatures be valid with comparisons to simulations?

The temperatures in the full-scale test were measured with thermocouples at 15cm intervals from the ceiling and down. It was estimated that the area each point would cover would represent a little bit beneath and above, as it measures fixed values. The top thermocouple could then be argued to represent the top 20cm, which would be a large span for just one data point. The next thermocouples would represent 15cm each, continuing down. It was agreed that at least two would have to be evaluated, up to a maximum of four. The upper layer would then measure 65cm.

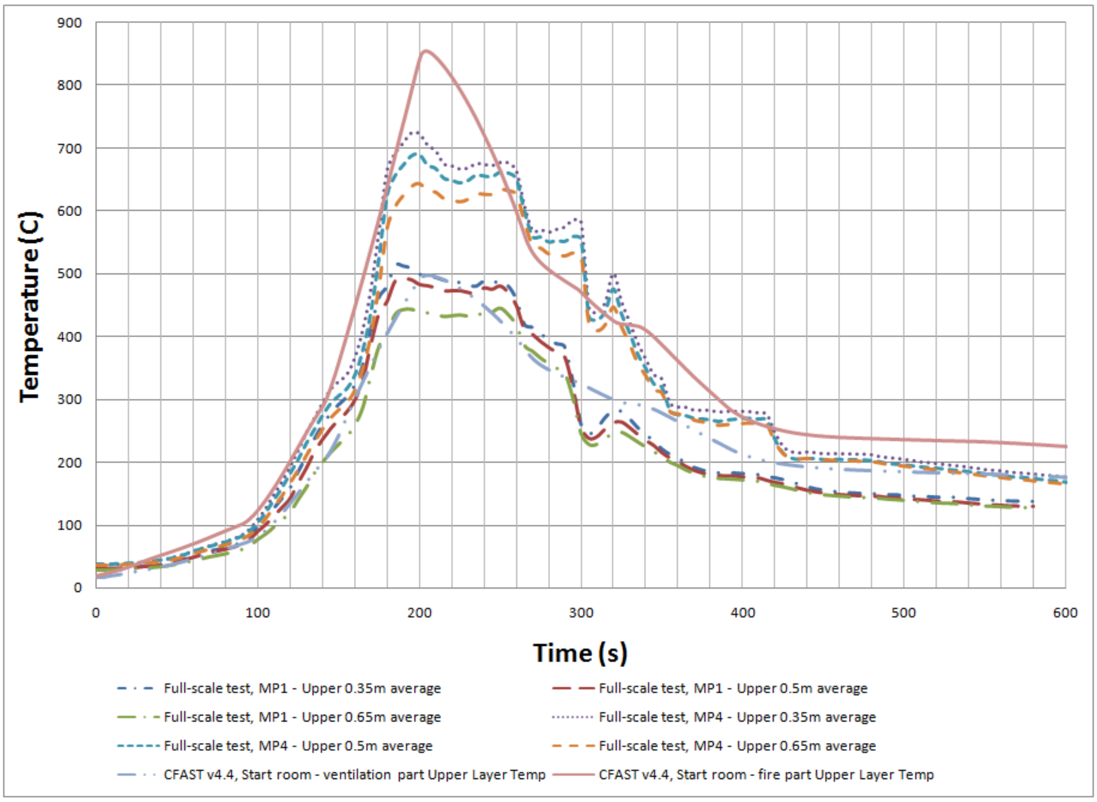

FIGURE 22: COMPARISON OF UPPER TEMPERATURE AVERAGES IN THE START ROOM – FIRE PART AND VENTILATION PART.

As seen on the figure above the theory seems to be plausible in the start room. The upper three thermocouples were chosen to use further on. With three points of data the results would still be high/extreme, while still providing an acceptable average of the top 0,5m (20cm + 15cm +15cm).

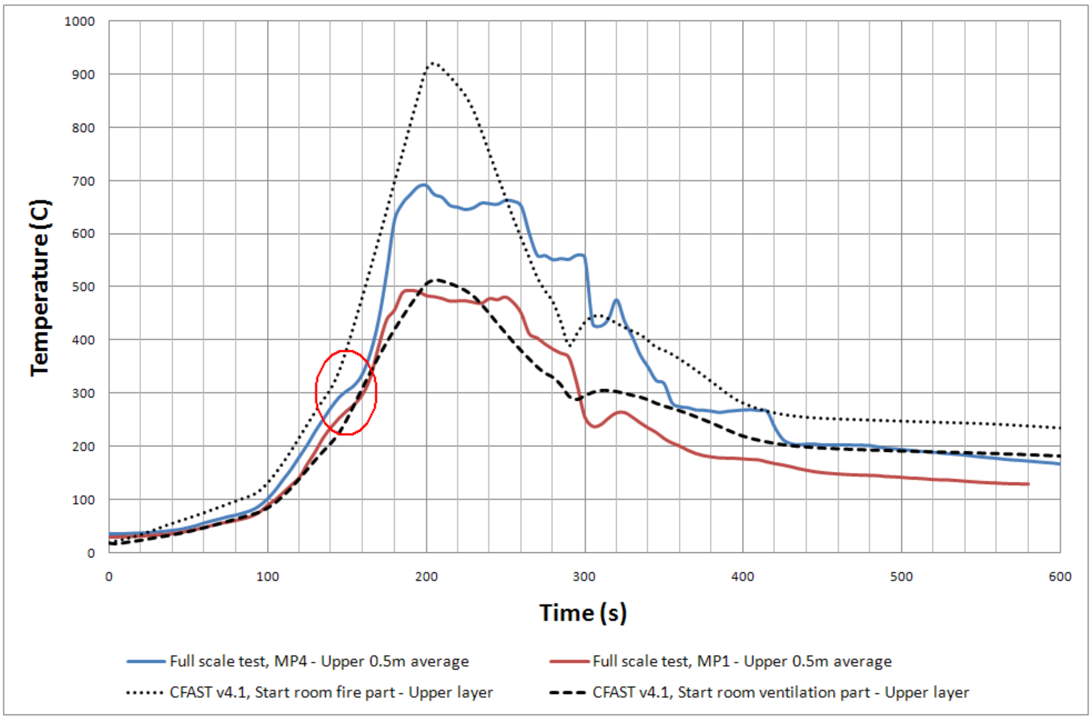

FIGURE 23: COMPARISON BETWEEN THE FULL-SCALE TEST AND CFAST SIMULATION. THE RED CIRCLE INDICATES THE PLACE IN THE FIRE DEVELOPMENT WHERE THE FIRE MOST LIKLEY BECOME VENTILATION CONTROLLED.

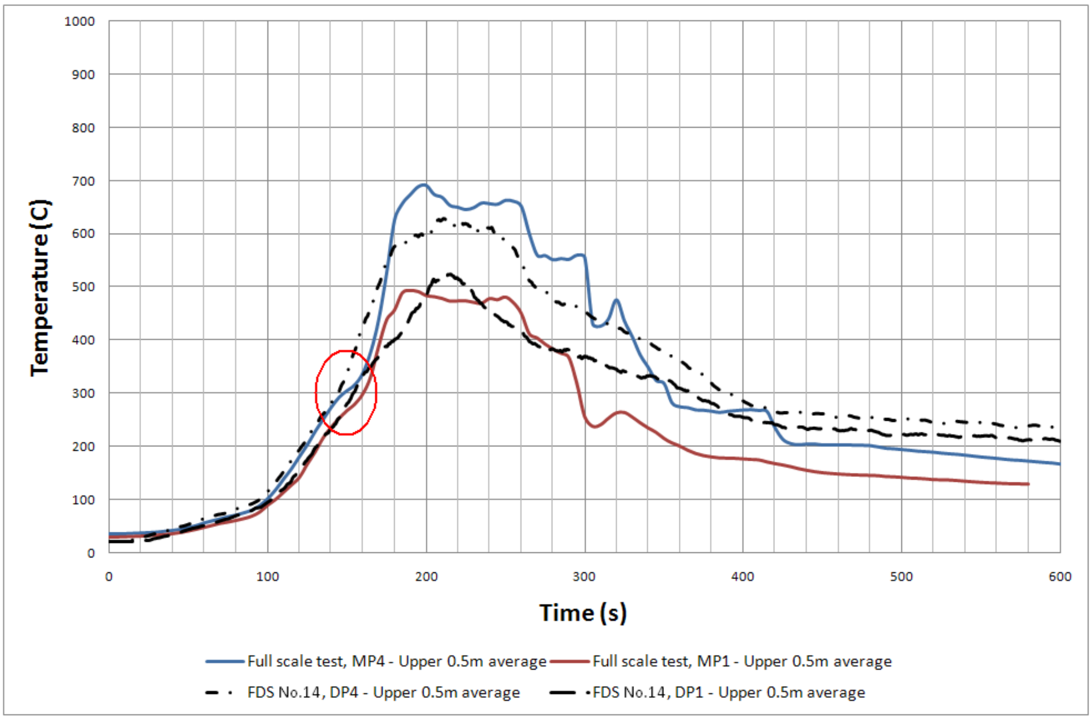

FIGURE 24: COMPARISON BETWEEN THE FULL-SCALE TEST AND FDS SIMULATION. THE RED CIRCLE INDICATES THE PLACE IN THE FIRE DEVELOPMENT WHERE THE FIRE MOST LIKLEY BECOME VENTILATION CONTROLLED.

The most likely cause of the rapidly increased smoke production, and the assumed ventilation controlled fire, is the mattress witch burns and falls to the ground. The point of separation (Figure 24) between the real data graph and the data graph from the FDS simulations corresponds well with the increased combustion of the mattress. In the CFAST simulations (Figure 23) it is more difficult to observe this event.

After the point where it can be assumed that the fire becomes ventilation controlled, the temperature growth suddenly rises in the start room, and becomes higher than the temperature in the simulations (170-180s). One theory on this effect is that increased ventilation from the entrance, which is opened by the firemen, is providing the fire with more available oxygen, and increases the rate of combustion.

About two minutes (totally 155s) after the firemen enters the building they apply water to the burning objects in the room. This results in the extinguishing of the fire. As mentioned before this is a very critical event, and thus the data from the live test and the simulations is to some extent difficult to compare after that point, depending on which part of the building is being observed.

START ROOM – FIRE PART

The CFAST and the FDS simulations follow the test data closely until the fire seems to become ventilation controlled, as can be seen below, in Figure 25. The two simulation methods then continue closely parallel for about 150s. Then the FDS simulation show signs of being limited by available oxygen or having run out of combustible materials. The CFAST simulation continues upwards and peaks at about 920C° at 205 seconds, which is a known issue (Jones, Peacock, Forney, & Reneke, 2005). In this specific case the FDS simulation seems so handle the turbulence better than CFAST, but it is not possible to make any general conclusions since only one test was performed. A ±25% margin of error was added to the CFAST simulation data. This was to illustrate the fact that CFAST in several experiments and comparisons with real fires have been found to have a 10-25% margin of error, as described in the technical reference (Jones, Peacock, Forney, & Reneke, 2005). According to the same source CFAST is known for producing too high values, and predominantly lower values than the full-scale data should be an indicator that the simulation is probably not accurate.

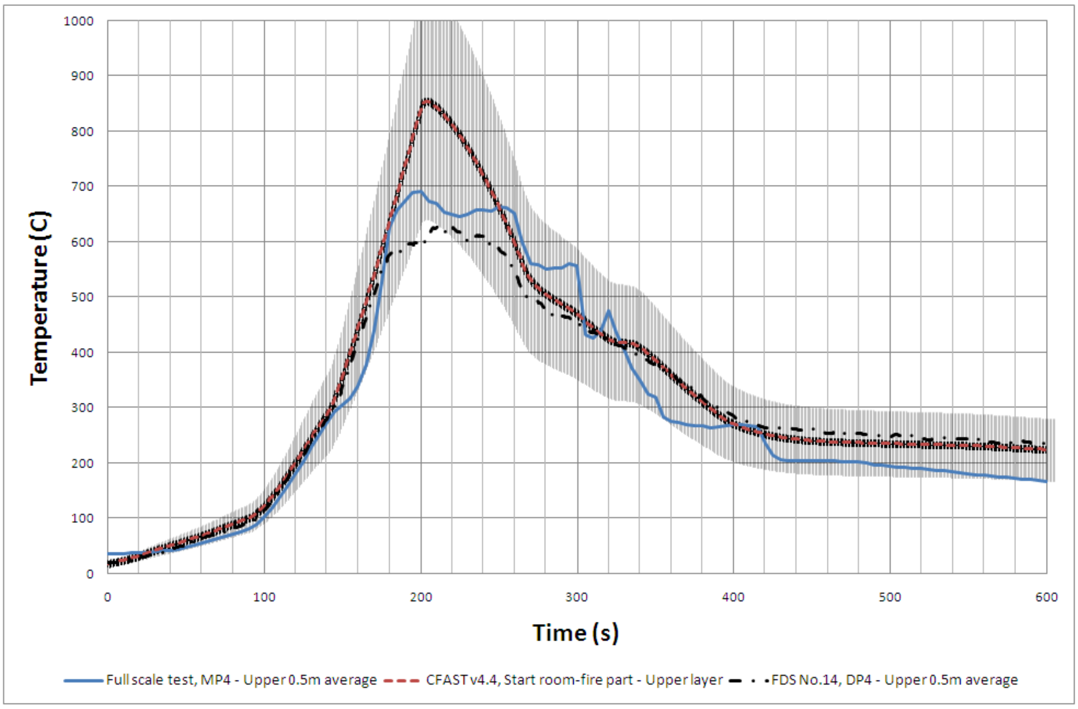

FIGURE 25: COMPARISON BETWEEN FULL-SCALE TEST DATA, CFAST DATA AND FDS DATA, IN THE FIRE PART IN THE START ROOM. THE LINES THAT EXTENDS VERTICALLY FROM THE CFAST GRAPH (RED, INTERMITTENT LINE) REPRESENTS THE 25% MARGIN OF ERROR. THE DATA FROM THESE SIMULATIONS ARE SOMEWHAT UNCERTAIN SINCE THE MODELS ARE NOT ADAPTED TO OPERATE CLOSE TO A LARGE FIRE DUE TO TURBULENCE.

START ROOM – VENTILATION PART

The same trend as in Figure 25 can be seen in Figure 26 below, but the maximum temperature of both simulations are much closer to the real values than in the first room (fire part). This may not be just a coincidence, since the current room is divided from the first with a beam, and thus create a form of second room. As earlier mentioned it is described in the user manual of both programs, that the model could be unsuitable in the immediate surroundings of the fire.

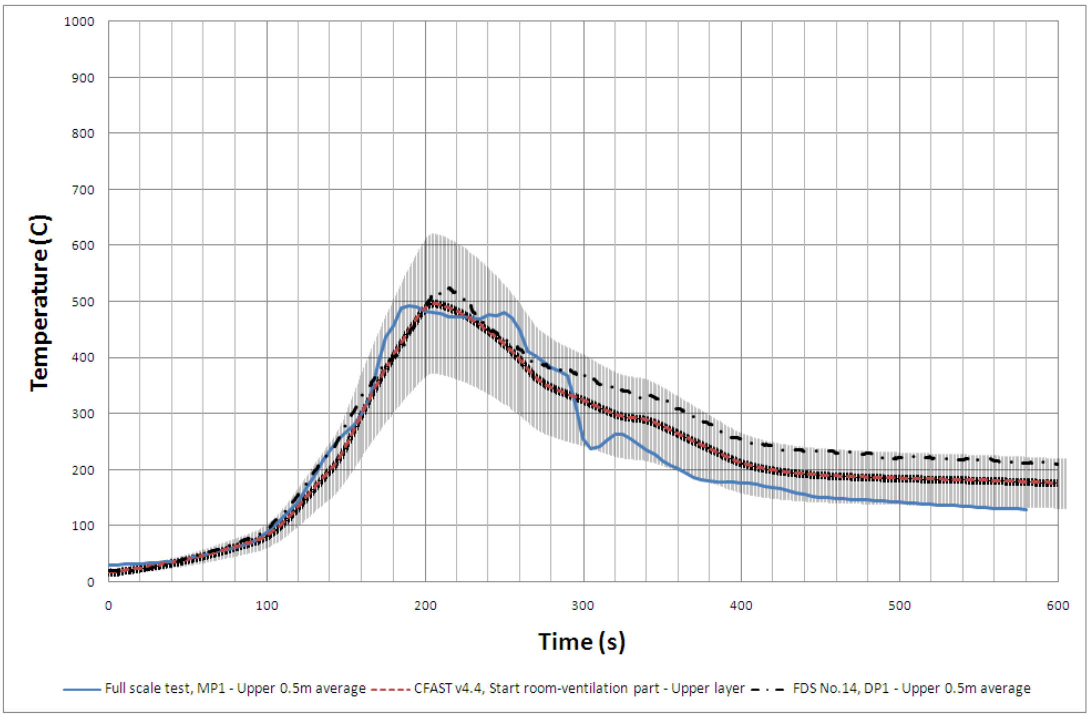

FIGURE 26: COMPARISON BETWEEN FULL-SCALE TEST DATA, CFAST DATA AND FDS DATA, IN THE VENTILATION PART IN THE START ROOM. THE LINES THAT EXTENDS VERTICALLY FROM THE CFAST GRAPH (RED, INTERMITTENT LINE) REPRESENTS THE 25% MARGIN OF ERROR.

CORRIDOR

In the corridor, outside the start room, the temperature is substantially lower and both the simulations differ from the full-scale test data. However, the two simulations give almost identical output, until a certain point where the rate of the temperature growth decreases. This is in the time between 170 and 240s where the building is largely affected by internal and external disturbance. First the ventilation controlled fire, then the ventilation and finally the applied water.

The reason of this difference in temperature could be because of how the programs handle the boundary layer where a flow of gas meets an area of static gas. In this case the blind hallway where the thermocouples were placed could have created such an area of immobile gas, and the models calculate more exchange of gas than in reality. It is somewhat surprising that FDS was not able to tackle this problem, but this could be just a coincidence.

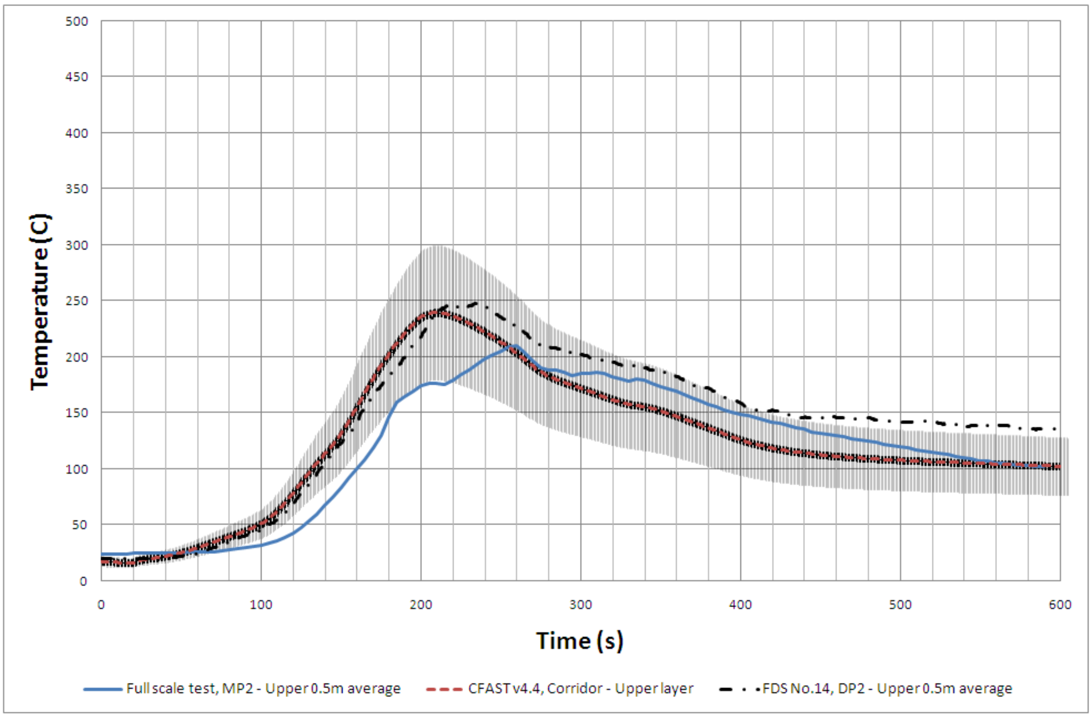

FIGURE 27: COMPARISON BETWEEN FULL-SCALE TEST DATA, CFAST DATA AND FDS DATA, IN THE CORRIDOR OUTSIDE THE START ROOM. THE LINES THAT EXTENDS VERTICALLY FROM THE CFAST GRAPH (RED, INTERMITTENT LINE) REPRESENTS THE 25% MARGIN OF ERROR. **NB!** THE Y-SCALE (TEMPERATURE) IS ½ OF THE ONES IN FIGURE 25 AND FIGURE 26.

HALLWAY

In the same way as in the corridor (Figure 27) the simulations in the hallway corresponds well to each other, then at a certain point they separate. This occurs approximately when internal and external factors are starting to intervene, just as in the corridor. The measuring points (FDS, CFAST) and the data points in this position are directly affected by the ventilation, since they are placed where the air from the classroom door is passing on its way to the start room, and where hot smoke/gas from the start room is ventilated to the classroom.

The temperatures differ from the accepted 25% during the first 160s. It should be noted that this is before the temperature reaches 100˚C. At 140s the temperature is just above 50˚C and the limit of error is around ±12,5˚C. From an investigation point of view the question could be raised whether this small difference in temperature would be noticed at all. That is also a point to be stated for the next couple of rooms where the temperatures are significantly lower than the room of the origin of the fire.

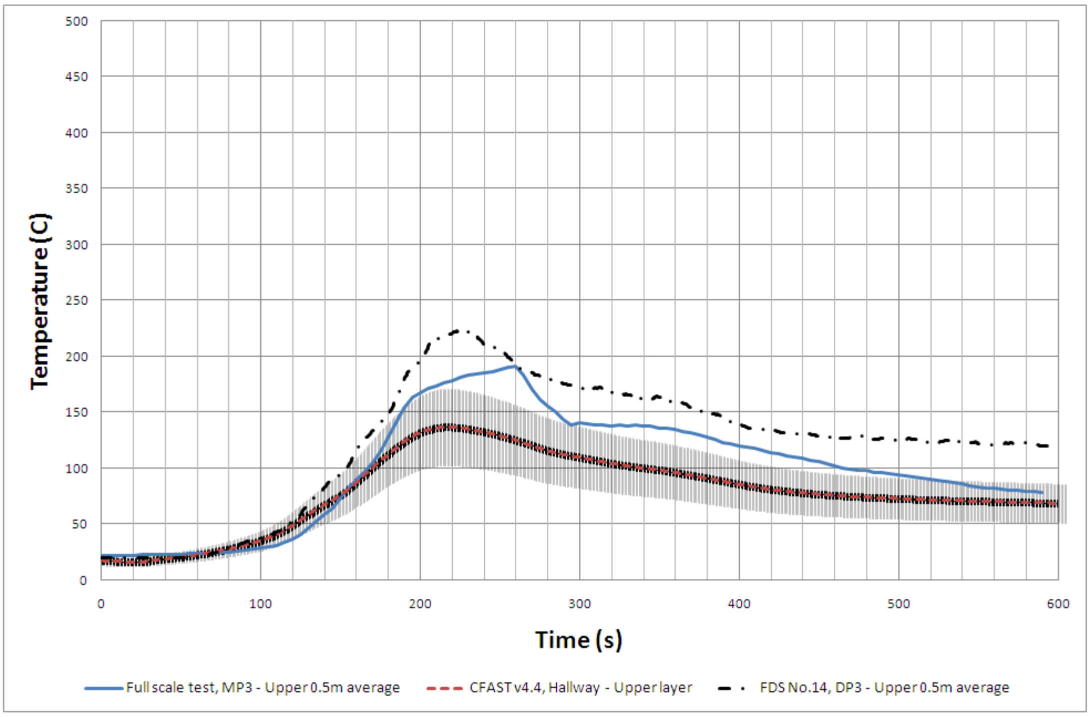

FIGURE 28: COMPARISON BETWEEN FULL-SCALE TEST DATA, CFAST DATA AND FDS DATA, IN THE HALLWAY. THE LINES THAT EXTENDS VERTICALLY FROM THE CFAST GRAPH (RED, INTERMITTENT LINE) REPRESENTS THE 25% MARGIN OF ERROR. **NB!** THE Y-SCALE (TEMPERATURE) IS ½ OF THE ONES IN FIGURE 25 AND FIGURE 26.

RESTROOM

The restroom is situated in a blind hallway, and would because of that show similar effects as the corridor. The ventilation of the area is, however, in this case limited by the doorway the smoke have to pass trough. As earlier discussed, concerning the corridor, the simulations may provide better ventilation than the full-scale test. This seems to be the case concerning the FDS simulation in this area, with guidance from the higher temperatures. CFAST is however not behaving as expected, which would be providing the same results as FDS, and a possible reason of this can be how much the CFAST model is affected by the area of the ventilation opening. To further investigate this, additional tests should be made without any external interference, such as fire fighting and changes of ventilation.

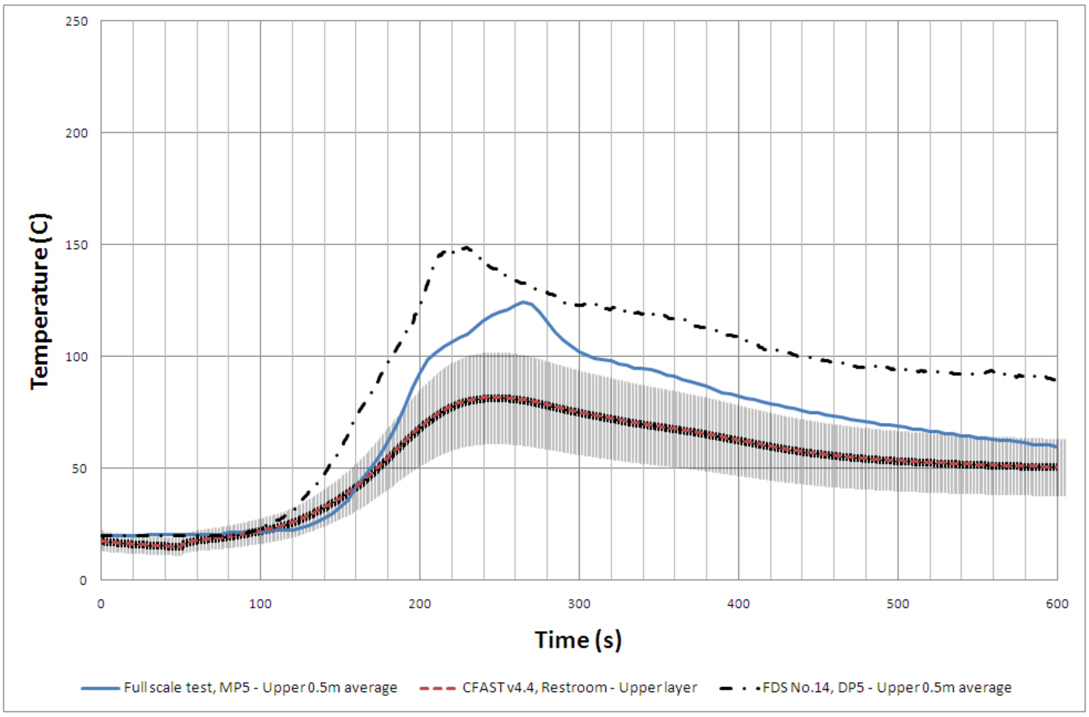

FIGURE 29: COMPARISON BETWEEN FULL-SCALE TEST DATA, CFAST DATA AND FDS DATA, IN THE RESTROOM. THE LINES THAT EXTENDS VERTICALLY FROM THE CFAST GRAPH (RED, INTERMITTENT LINE) REPRESENTS THE 25% MARGIN OF ERROR. **NB!** THE Y-SCALE (TEMPERATURE) IS ¼ OF THE ONES IN FIGURE 25 AND FIGURE 26.

CLASSROOM

The classroom is located the furthest away from the fire, and is interesting since very little research on two-zone models have been performed, with smoke and temperature spread on long distances in focus. Figure 30 shows that the temperature of the CFAST simulation is essentially lower than both the FDS simulation and the full-scale test data when the time passes 200s. However, this is around the time where external disturbances start to intervene, and until that moment the data corresponds well. Since the temperature is low (less than 100C˚) it is difficult to say something in particular about the possible variation. To investigate this further it is required to increase the time of undisturbed combustion, and possibly also to increase the amount of combustible materials, to create higher temperatures.

For the CFAST simulation the same section where the thermocouples were placed in has been chosen, which is the one in the middle (classroom part 2).

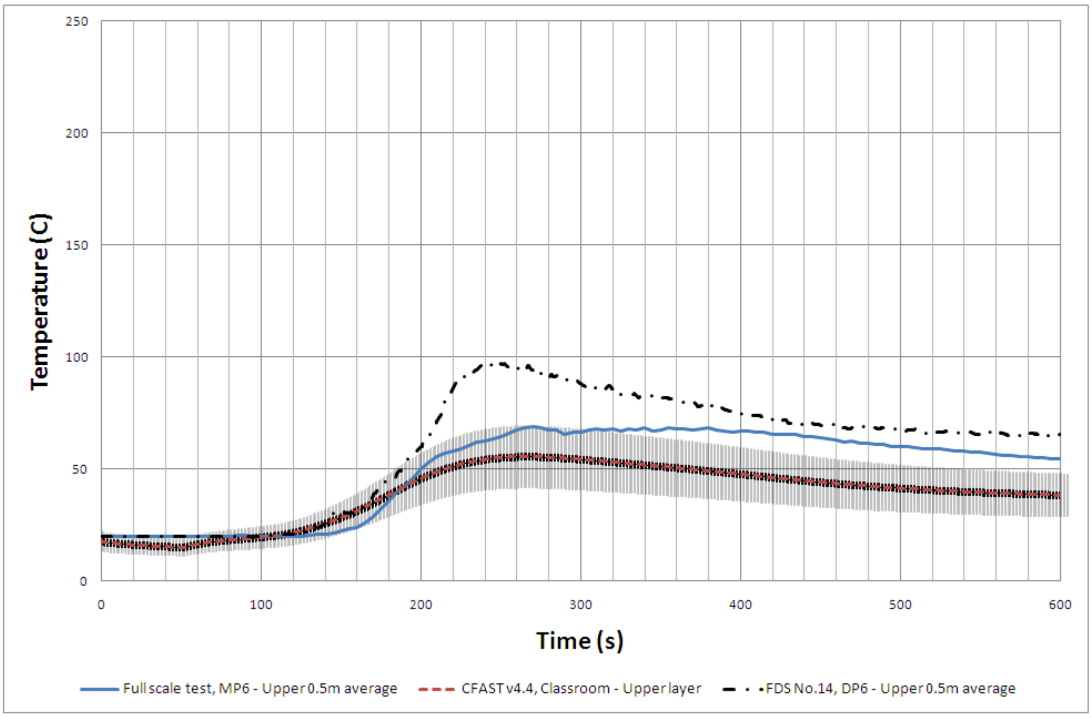

FIGURE 30: COMPARISON BETWEEN FULL-SCALE TEST DATA, CFAST DATA AND FDS DATA, IN THE CLASSROOM. THE LINES THAT EXTENDS VERTICALLY FROM THE CFAST GRAPH (RED, INTERMITTENT LINE) REPRESENTS THE 25% MARGIN OF ERROR. **NB!** THE Y-SCALE (TEMPERATURE) IS ¼ OF THE ONES IN FIGURE 25 AND FIGURE 26.

Smoke layer height in the Classroom

One of the visible effects after the fire is the smoke residue on the walls. Figure 31 shows an example of this in the classroom, and from the photo it can be estimated that the smoke layer reached down to approximately one meter from the floor. When looking at Figure 32 it can be seen that the measurements only reaches to about 200s, but during that time span it corresponds quite well with the simulation data. This kind of information can be useful in the verification of the simulations, since it provides additional input to temperature approximations and is possible to observe afterwards.

FIGURE 31: PICTURE TAKEN FROM CLASSROOM PART 3, VIEWING THE WALL SEPARATING IT AND THE HALLWAY. SMOKE-STAINS ARE CLEARLY VISIBLE DOWN TO APPROXIMATELY 1METER.

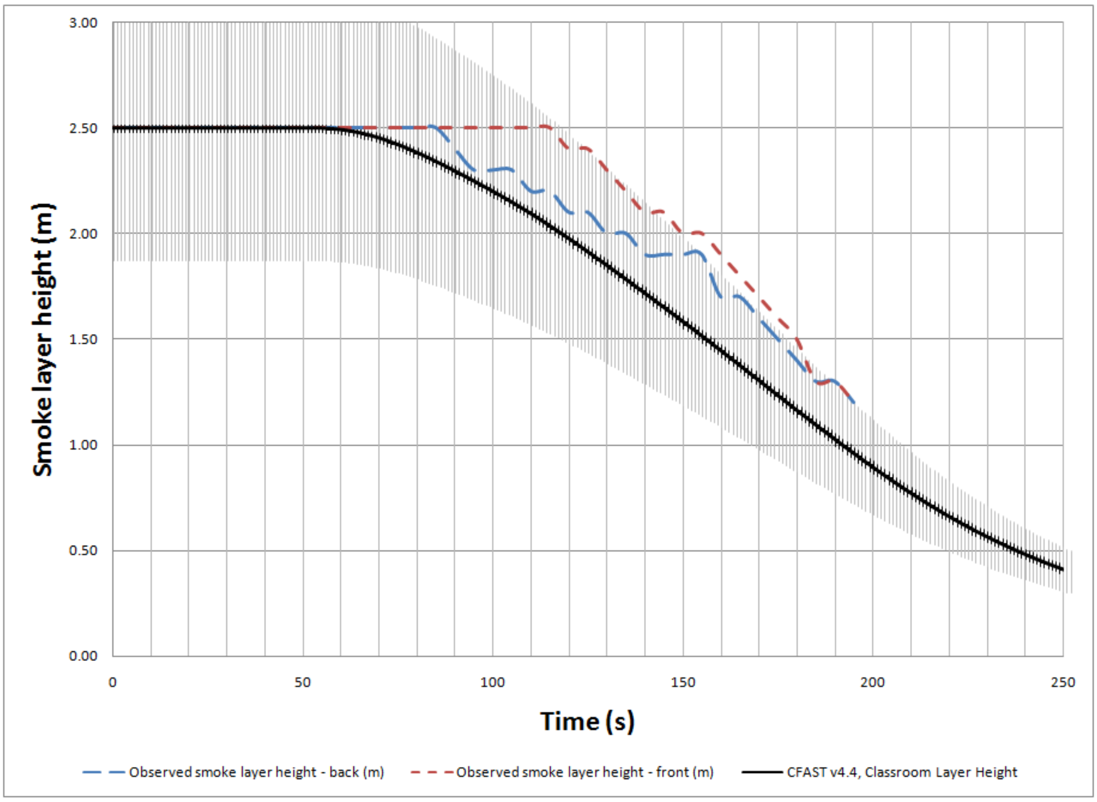

FIGURE 32: CFAST V4.4 SIMULATION COMPARISON WITH OBSERVED DATA OF THE SMOKE LAYER HEIGHT. “BACK” IS OBSERVED AT THE DOOR (FIGURE 31) AND “FRONT” NEXT TO MP6 IN CLASSROOM PART 2.

5.3. ADDITIONAL SIMULATIONS

Additional simulations (CFAST v6.x) were run with intentionally wrong fuel load (HRR-curve) and ventilation openings. This type of work could be of great value in an investigation of a fire, to add support or disprove a proposed scenario. Additional interesting simulations could be the same fuel load in other rooms, comparing smoke layer height and temperature. These simulations were mainly done in CFAST (v.6.1.1.54) as it takes a lot less time than running full FDS simulations.

An attempt to find a corresponding t^2-fire was also done. Standard curves have been described after studies of fires, and described with the equation in "Enclosure Fire Dynamics" (Karlsson & Quintiere, 2000):

"$\dot{Q} = \alpha \cdot t^2$, where α is a growth factor (often given in kilowatts per second squared $\left(kW/s^2\right)$) and t is the time from established ignition, in seconds."

CFAST has a built-in function to use t^2-fires. These are based on values identical to the NFPA 204M, as cited in Enclosure Fire Dynamics (Karlsson & Quintiere, 2000):

Growth Rate	α (kW/s^2)	Time (s) to reach 1055kW
ultra fast	0,19	75
fast	0,047	150
medium	0.012	300
slow	0.003	600

TABLE 6: t^2-FIRE VALUES TAKEN FROM NFPA 204M

In addition to using these factors to build a growth-curve, it is possible to set a peak HRR-value. In these 2000kW was used as peak value to resemble the v3.x and v4.x CFAST simulations. CFAST automatically limits the HRR in a steady phase. The value is set at 300s but is possible to change manually. Then a decay phase is entered, and a value of 300s is set but is possible to change manually.

Finding a t^2-fire (slow, medium, fast, ultra-fast or combinations) that corresponds well with the fire growth and peak could help in identifying what the initial fire object was. The evaluation of what might have burned with the corresponding produced temperature curve will still have to be done by a person skilled in fire science.

Sofa comparison – Ventilation Controlled

The sofa from CFAST item menu was used. According the HRR-curve, it should peak at 3MW after 400s. But in this case the fire does not peak after 400s, but around 240s, at a much lower temperature than could be expected. This indicates a lack of oxygen and a ventilation controlled fire. That would generate large amounts of smoke. A situation like that might cause large quantities of hot, combustible gasses to spread to the rest of the building, possibly flaming up and burning the oxygen in rooms they enters.

As mentioned in the technical reference (Jones, Peacock, Forney, & Reneke, 2005) CFAST is usually in the upper 10-25% of the limits of error, although a limit of error is usually set to ±25%. This scenario, being consistently very low, and in some places close to -50%, is not very likely.

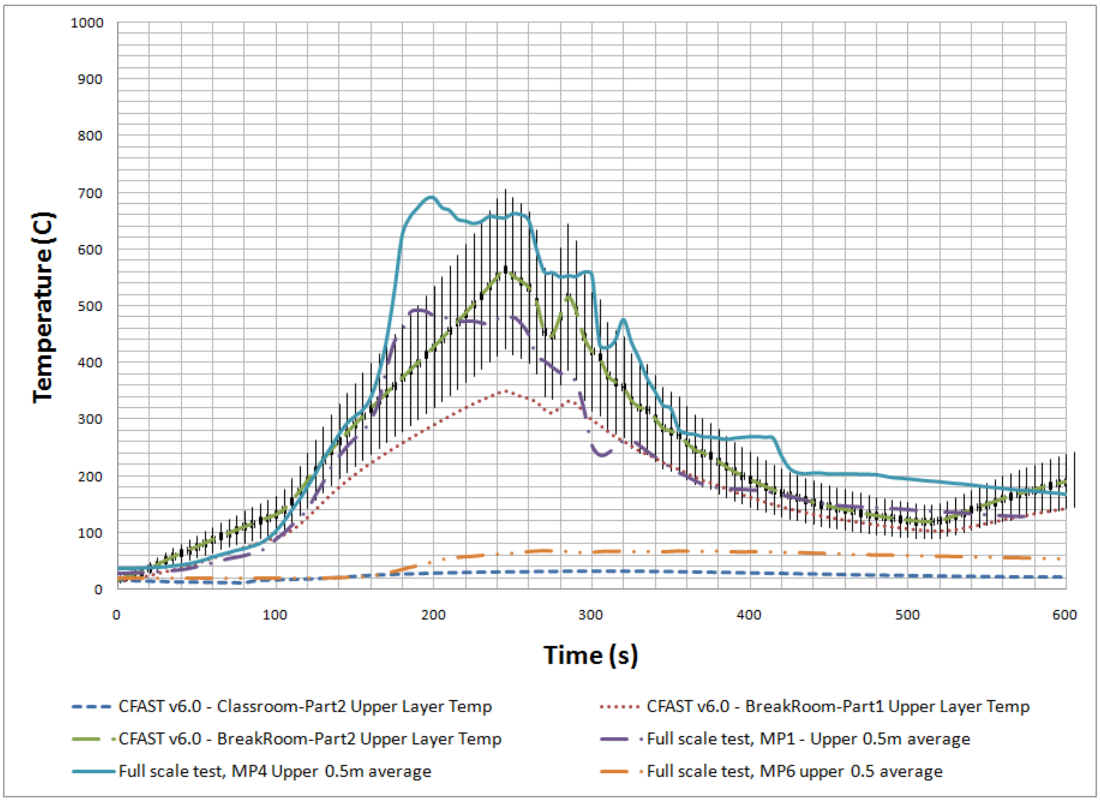

FIGURE 33: SIMULATION WITH A SOFA FROM THE CFAST ITEM MENU AS THE INITIAL FIRE. THE TEMPERATURE CURVES SHOWS THE START ROOM (FIRE PART AND VANTILATION PART) AND THE CLASSROOM.

SOFA COMPARISON – FUEL CONTROLLED

In this case the entry doors were fully open during the entire length of the simulation. The HRR rise is still too slow, but here it goes on to peak at 400s and well beyond 1000°C. The rise is too slow and the temperatures to high. This scenario is not very likely.

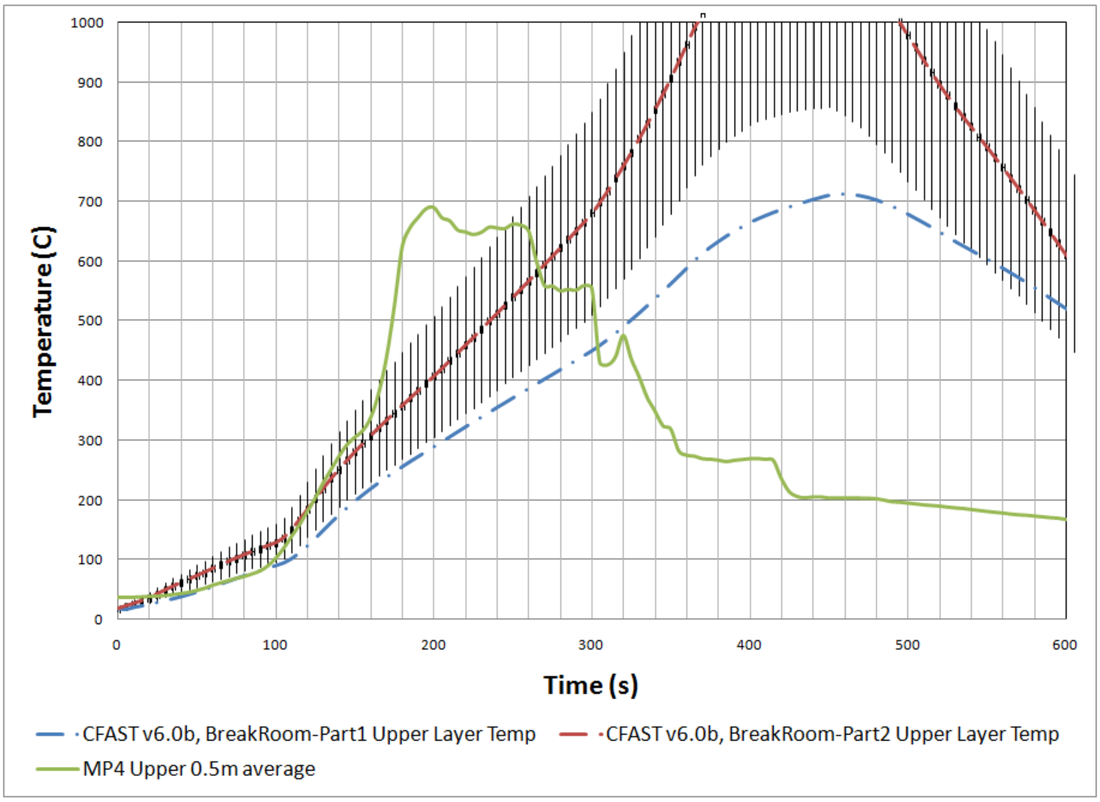

FIGURE 34: SIMULATION WITH A SOFA FROM THE CFAST ITEM MENU AS THE INITIAL FIRE. THE TEMPERATURE CURVES SHOWS THE START ROOM (FIRE PART AND VANTILATION PART). THE FIRE IS PROBABLY NOT VENTILATION CONTROLLED.

FAST t^2ALPHA-FIRE

A fast t^2 fire is generally defined by reaching 1055kW in 150s, according to NFPA standards as cited in table 3.5 in "Enclosure Fire Dynamics" (Karlsson & Quintiere, 2000). In this case the HRR has been increased using CFAST's built in t^2-function to retain as a correct growth phase as possible while developing to a 2MW fire, just like the chair, as can be viewed in chapter 4.5: comparison with full scale test.

Some furniture of easily flammable materials could be placed in the fast-category, attributing to catastrophic fires with loss of life as described by Nicolas Faith (Faith, 1999).

This scenario is very similar in time and temperature to peak, but has a much more linear and fast growth than what actually happened. The temperatures differ 200°C, from 100-180s.

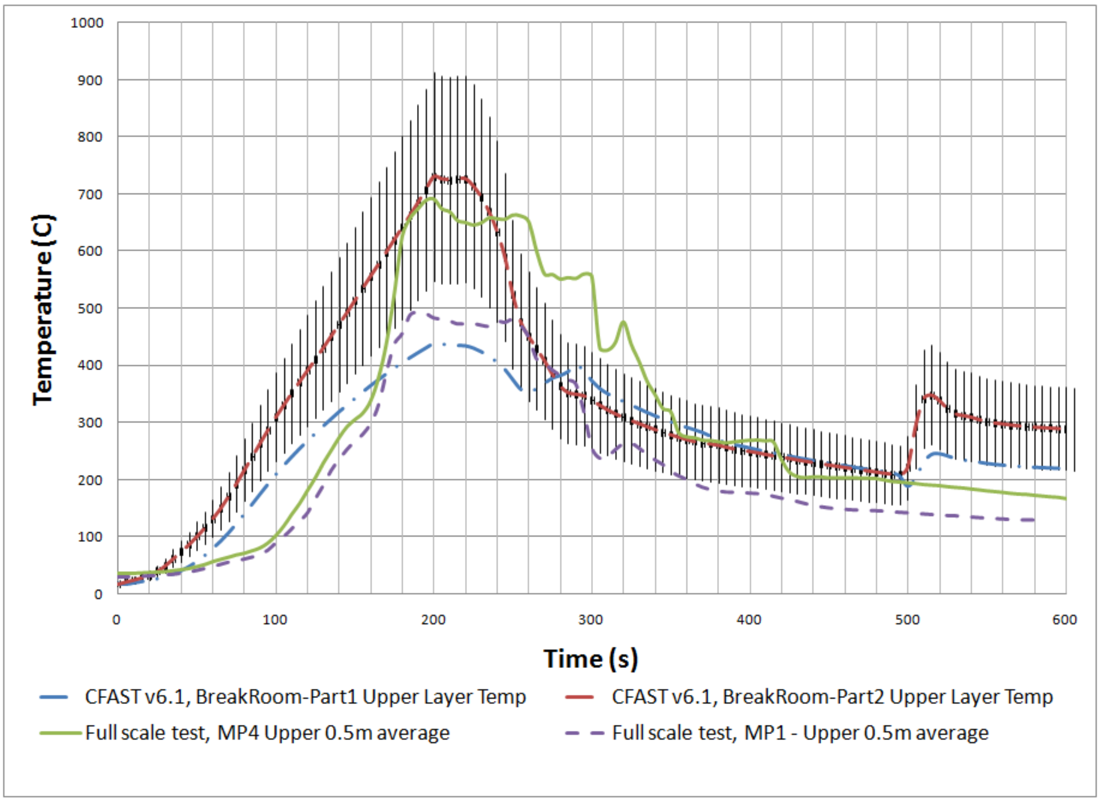

FIGURE 35: SIMULATION WITH A FAST t^2-FIRE FROM THE CFAST ITEM MENU AS THE INITIAL FIRE. THE TEMPERATURE CURVES SHOWS THE START ROOM (FIRE PART AND VANTILATION PART).

MEDIUM t^2ALPHA-FIRE

A medium t^2 fire is generally considered a fire that grows to 1055kW in 300s. It is often used as a standard fire for lower density objects like furniture with non-synthetic fibres. Arguments have been made that in modern fires, a fast t^2 –fire is more suitable, due to increasing use of synthetic materials. (Icove & DeHaan, 2004), (Karlsson & Quintiere, 2000).

In this case the HRR has been increased using CFAST's built in t^2-function to retain as a correct growth phase as possible while growing up to a 2MW fire, just like the chair in this example. Although the growth phase seems to coincide very well the first 120s, the medium t^2 fire is clearly growing too slowly. This scenario is not very likely.

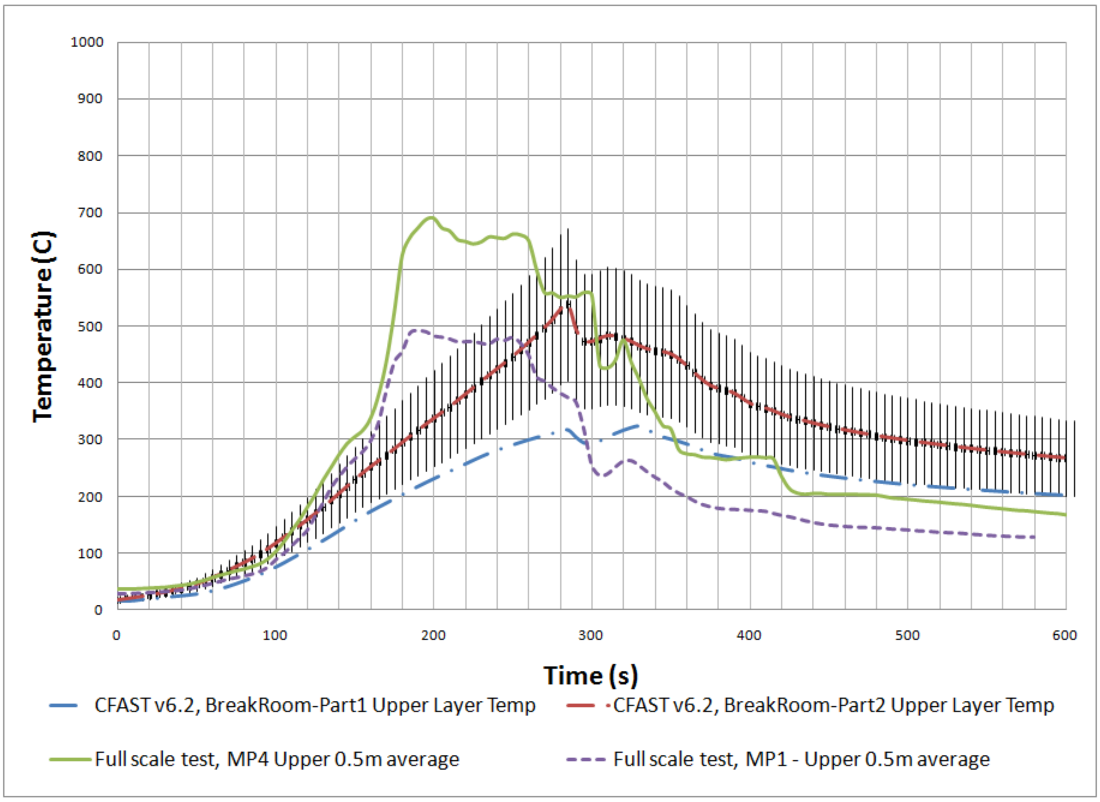

FIGURE 36: SIMULATION WITH A MEDIUM t^2-FIRE FROM THE CFAST ITEM MENU AS THE INITIAL FIRE. THE TEMPERATURE CURVES SHOWS THE START ROOM (FIRE PART AND VANTILATION PART).

MEDIUM/FAST t^2ALPHA -FIRE

An approximation between a medium t^2 -fire and a fast t^2 –fire was made, by adding half the difference in growth time. This resulted in a fire that would increase to 1055kW within 225s. The approximation of the fire is still not consistently within the limit of error (±25%) but this must be seen as the best approximation of the fast and the medium t^2 fires. This only emphasizes the fact that it is a theoretical fire. In lack of concrete test-results it might be a good choice, but data from a full-scale item burning would produce more precise results.

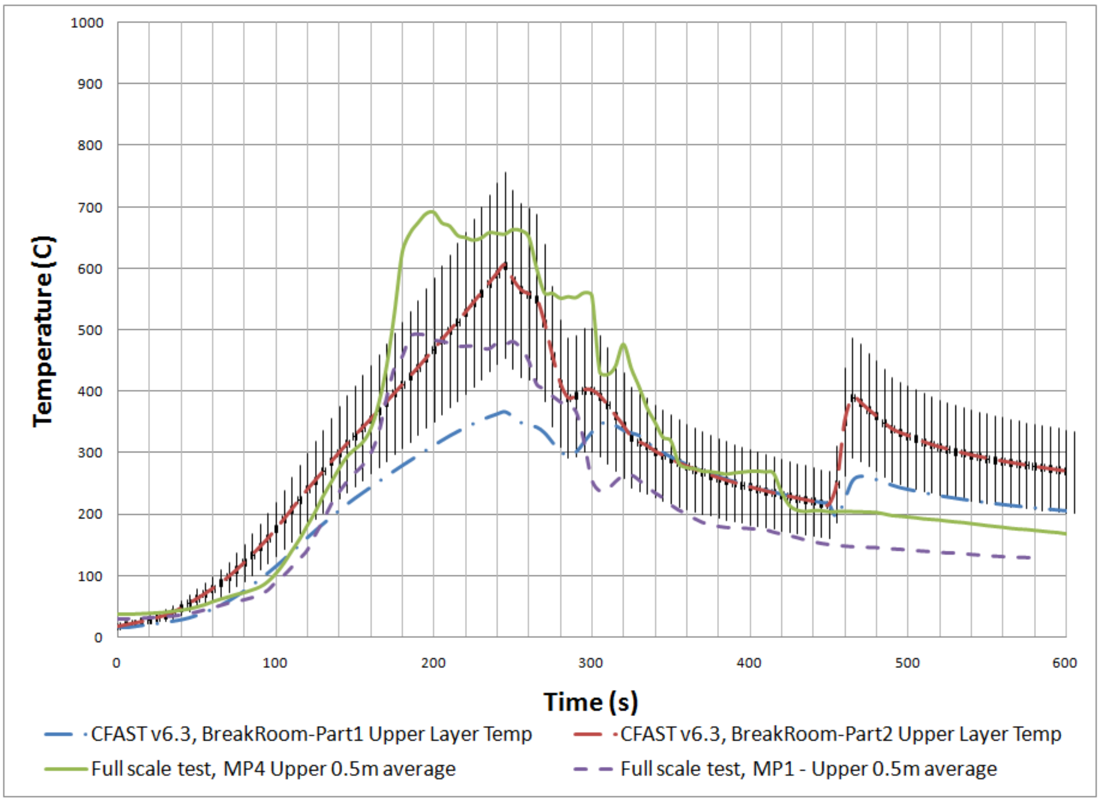

FIGURE 37: SIMULATION WITH A MEDIUM/FAST t^2-FIRE FROM THE CFAST ITEM MENU AS THE INITIAL FIRE. THE TEMPERATURE CURVES SHOWS THE START ROOM (FIRE PART AND VANTILATION PART).

6. Discussion

Two-zone models versus Field models

While field models like FDS have been extensively used in larger areas, like the Kings Cross fire (Cox, Chitty, & Kumar, 1989), the Gothenburg disco fire (Yan & Holmstedt, 2001) and the World Trade Centre investigation (Rehm, et al., 2002), two-zone models are not extensively verified beyond room two. CFAST and FDS are both originally intended as an aid in examining potential smoke and fire development when designing buildings. In this work, FDS was used in addition to data from the full-scale fire to validate results from the CFAST simulations.

The use of simulation in Fire Investigation

The goal was to compare a less time-consuming model than FDS using CFAST with a multi-room setting, especially aimed at simulations used in investigation after fires. This required listing of critical simulation inputs, including geometry of the model, to properly simulate a real fire scenario. It is worth mentioning that FDS provided somewhat more accurate data, but required considerable more computational time.

Results that support a theory such as “the fire started in the inner part of the start room” cannot empirically prove that it happened. It can however aid investigations in adding documentation of plausible fire scenarios and smoke spread in collaboration with findings on-site, witness observation and traditional investigation. An important part would also be the use of models, using differing HRR-curves of burning items, and varying the point of origin to refute or at least prove these scenarios less likely. This to emphasize what could not have happened due to the model showing results and temperature levels not found on site.

In this bachelor thesis several models and scenarios are discussed. Low detail models in CFAST have shown to produce acceptable output data in volumes beyond the first room, even with a low detail estimate of a complicated start room. The models show that even though the mix of smoke and air *beyond* the start room is correct, the values from the low detail model cannot be used as a comparison *inside* the start room. This is valid even when the rooms beyond can be classified as complicated as the classroom with two sets of beams, separating it into three parts. The full-scale test showed that dissipation of the smoke with the cooler air causes the upper layer to act uniformly in the classroom, and not be affected by the beams. The possible use of a rough model would be to get a quicker evaluation of smoke spread and temperatures outside the room of origin, as it will be faster and easier to put together.

The detailed models are necessary for viewing smoke temperature in a geometrically complicated start room. The beam separating the start room in this case is enough to classify it as complicated. As discussed above, the detailed model cannot be used with a complicated geometry outside the start room. The use of the detailed model alone would be to evaluate the start room and possibly rooms close by, without complicated geometry.

An alternative was found to be the "mixed model"-method. In these simulations the high detailed configuration of the start room was preserved, while the low detailed configuration is used beyond that, whether the real building has complicated geometry or not. This provided more accurate results in all rooms and sections.

SENSITIVITY ANALYSIS

To achieve best possible accuracy, sensitivity analyses were performed on both FDS and CFAST simulations. This is done to evaluate the models and the detail level in comparison to each other. Many of the models and versions looked promising, but by performing sensitivity analysis it is possible to choose a suitable version.

EXTERNAL INFLUENCES

The ceiling in the start room was inspected before the fire, and there was some uncertainty of whether the material could add to the fire-load in the room. A cone calorimeter test was performed (APPENDIX IV) and due to the results the ceiling was excluded from the total fire load in the room. There was charring on the back of the books in the shelf above the chair, a mattress located above the chair had burned, and in some of the shelves the plastic coating melted off and had started charring. More detailed simulations could have been run to account for all possible sources. To achieve this, a full-scale calorimeter test would have had to be performed with similar settings. As this is not a realistic option in many investigations, focus was maintained on the initial fire.

INFORMATION POSSIBLE TO OBTAIN FROM A FIRE

One of the questions considered was how to compare the results from a realistic scenario to the models. The usual way of comparing results from simulations are by the upper and lower smoke-layer temperature averages. This would be impractical in an investigation after a fire, since the fire department are not prone to take notes of the smoke layer height and temperature, but rather focuses on putting out the fire. Even with detailed results from the full-scale test there was the question of how to get results out of the comparison that could be useful for investigative purposes. It was theorized that if the simulation results could be compared to the upper layer of smoke residue and charring in a fire affected building, it could be very useful. Fire investigators are able to see signs of temperature by smoke residue, burn-patterns, charring, discoloration, melting and deformation of materials (Cooke & Ide, 1985). For verification purposes the measured temperatures were used as a basis instead of getting temperatures estimated by investigators. Further studies can be made in the area of comparing findings and simulations.

The t^2-fires

t^2-fires are a simplification of the growth phase of a fire.

The temperature results from an estimated fire load of a medium-fast fire in the simulations bore a close resemblance to the early growth phase of the full-scale burn, while a fast-fire peaked at the same time.

Simulation versus full-scale data analysis

The graphs have shown that with both CFAST and FDS simulations the temperature and direction of the fire are similar to the values measured in real life. There were minimal differences in the CFAST simulation results done before and after the fire, except for the more exact ventilation openings attained after. FDS-simulations were, not surprisingly, very close to CFAST when using the same RAMP-function as the two-zone model was based on.

In fire engineering there are many factors that can interfere, such as varying material compositions, placement, ventilation and sheer air pressure can greatly affect a scenario. +/-25% is therefore an acknowledged margin of error for CFAST as described in the technical reference (Jones, Peacock, Forney, & Reneke, 2005)

6.1. Important factors for success

Initial fire

By observing the HHR of different kind of sofas, chairs and similar objects in available literature, it is obvious that the properties can vary a great deal between different products. In our example an easy chair was chosen, and according to Stefan Särdqvist (Särdqvist, 1993) these can produce a HRR peak between 200 kW and 2000 kW. HRR-curves are, as discussed in chapter 5.3, in many cases the most suitable way to define a fire development in fire simulations.

The positioning of the initial fire in the room is also of great importance, and will provide output data that differs from the fire if placed wrong.

Geometry and room configuration

It was uncertain how the change of ventilation openings would affect the output data of these simulations. An FDS-simulation was run with the opening of doors and windows included. This showed minimal differences in temperature from the original simulation.

Level of user knowledge required

Finally the user has to be familiar with the computer simulation programs in question, and have a basic level of knowledge in fire dynamics. Both of the programs discussed in this work have limitations, as mentioned in chapter 2, that the user has to be aware of. For example the two zone model is unsuitable when modelling very large volumes, and neither of the program types in this work is suitable very close to the fire. If the programs are used in an inappropriate way, several sources of error could occur, and jeopardize the value of possible evidence from the results. To assure the correct use and quality of the simulations, a sensitivity analysis has to be done. Examples of this can be seen in chapter 4.6.

A summary of the important factors for success:

Information required about the initial fire

Type of information	Information needed
Kind and model of object	HRR-curve [kW]
Placing in the room	xyz-coordinates and size [m]
Surface properties	for estimation of ignition and fire spread, and to choose a HRR-curve
Source of ignition	for estimation of time from ignition, to established and accelerating fire.
Item soot yield	for estimation of smoke production properties

Information required about the surroundings

Type of information	Information needed
Geometric measurements	xyz-measurements of all rooms [m]
Estimation of temperatures	temperatures [°C], the position [m] and exposure duration of temperatures [s]
Estimation of smoke layer height	height and position [m]
Ventilation openings (doors, windows)	xyz-coordinates and size $[m]$, $[m^2]$
Surrounding objects	could they have interfered at an early stage?

Information required about external disturbance

Type of information	Information needed
Changed in ventilation	doors/windows opened/closed?
Fire fighting efforts	objects moved? water applied?

INFORMATION REQUIRED ABOUT THE PROGRAM

Type of information	Information needed
Strength and weakness of the programs	problems with certain geometric conditions? Suitable/unsuitable scenarios? Time-consuming?
Possible sources of error	general knowledge of the program
Sensitivity analysis	general knowledge of the program

7. CONCLUSION

A large number of simulations have been done in both CFAST and FDS. The geometry in FDS is correct at a detailed level, while detailed CFAST models are less correct beyond the start room. It seems to be due to lack of compensation for entrainment in low temperature smoke, and is easily corrected by using a less detailed model beyond the start room.

Our findings from the use of CFAST, extending several rooms, point to results from the simulation up to 50°C less in the rooms not involved in the start fire. With the lower temperatures these rooms display, this can mean a difference of 50%, which is beyond CFAST's documented level of error. Previous work spanning several rooms (Collier, 1996) does however support the findings that CFAST under-estimates temperatures at this level in volumes beyond the start room. Based on previous work and the results presented here a two-zone model could be used as an aid in fire investigation instead of FDS or other more advanced models.

Important observations found when using CFAST to evaluate a fire:

-Real temperature estimations 0.5m below the ceiling can be considered representative
-CFAST over-estimates peak temperatures in the start room
-CFAST under-estimates temperatures up to 50°C in rooms beyond start room not involved in the fire
-Obtaining correct HRR-data is crucial
-The detail in geometry should be kept as close to the real setting as possible in the start room
-The detail in geometry should be kept at a minimum beyond the start room

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9. LIST OF APPENDIXES

APPENDIX I : The generic input-file for the FDS sensitivity analysis simulation. The 10x10x10 mesh is active.

APPENDIX II: Window and ventilation calculations

APPENDIX III: Air mass-flow calculations

APPENDIX IV: Cone calorie meter test of the ceiling

APPENDIX V: Plan over the test site

APPENDIX I. THE GENERIC INPUT-FILE FOR THE FDS SENSITIVITY ANALYSIS SIMULATION. THE 10X10X10 MESH IS ACTIVE.

```
generic input file for sensitivity analysis
M1=10x10x10cm
M3=10x10x10cm

&HEAD CHID='genericHRR'/
&TIME T_END=600.00/

5_5 MESH
MESH ID='MESH1', IJK=128,104,56, XB=0.00,6.4,0.0,5.2,-0.05,2.75/ combustion part
MESH ID='MESH3',  IJK=176,200,56,  XB=-3.2,5.6,-10,0.0,-0.05,2.75/ smoke spread part
5_10 MESH
MESH ID='MESH1', IJK=128,104,56, XB=0.00,6.4,0.0,5.2,-0.05,2.75/ combustion part
MESH ID='MESH3',  IJK=88,100,28,  XB=-3.2,5.6,-10,0.0,-0.05,2.75/ smoke spread part
10_10 MESH
&MESH ID='MESH1', IJK=64,52,28, XB=0.00,6.4,0.0,5.2,-0.05,2.75/ combustion part
&MESH ID='MESH3',  IJK=88,100,28,  XB=-3.2,5.6,-10,0.0,-0.05,2.75/ smoke spread part
10_20 MESH
MESH ID='MESH1', IJK=64,52,28, XB=0.00,6.4,0.0,5.2,-0.05,2.75/ combustion part
MESH ID='MESH3',  IJK=44,50,14,  XB=-3.2,5.6,-10,0.0,-0.05,2.75/ smoke spread part
20_20 MESH
MESH ID='MESH1', IJK=32,26,14, XB=0.00,6.4,0.0,5.2,-0.05,2.75/ combustion part
MESH ID='MESH3',  IJK=44,50,14,  XB=-3.2,5.6,-10,0.0,-0.05,2.75/ smoke spread part
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MESH ID='MESH1', IJK=32,26,14, XB=0.00,6.4,0.0,5.2,-0.05,2.75/ combustion part
MESH ID='MESH3',  IJK=22,25,7,  XB=-3.2,5.6,-10,0.0,-0.05,2.75/ smoke spread part
40_40 MESH
MESH ID='MESH1', IJK=16,13,7, XB=0.00,6.4,0.0,5.2,-0.05,2.75/ combustion part
MESH ID='MESH3',  IJK=22,25,7,  XB=-3.2,5.6,-10,0.0,-0.05,2.75/ smoke spread part

VENT
&VENT SURF_ID='OPEN', XB=6.44,6.44,0.0200,5.02,0.00,2.71 / mesh 1 Xmax
&VENT SURF_ID='OPEN', XB=5.44,6.45,0.00,5.02,2.75,2.75/ mesh 1 Ymax
&VENT SURF_ID='OPEN', XB=5.44,6.45,0.00,0.00,0.00,2.71/ mesh 1 Ymin

BURNER
&VENT SURF_ID='EASYCHAIR', XB=1.5,2.34,3.5,4.34,0.81,0.81/ easy chair burner
&OBST XB=1.5,2.34,3.5,4.34,0.00,0.81/ burner foundation

&SURF ID='EASYCHAIR',
      COLOR='RASPBERRY',
      HRRPUA=2975,
      RAMP_Q='EASYCHAIR_RAMP_Q',
      PART_ID='smoke'/
&RAMP ID='EASYCHAIR_RAMP_Q', T=0, F=0/
&RAMP ID='EASYCHAIR_RAMP_Q', T=90, F=0.0431/
&RAMP ID='EASYCHAIR_RAMP_Q', T=140, F=0.2155/
&RAMP ID='EASYCHAIR_RAMP_Q', T=200, F=1/
&RAMP ID='EASYCHAIR_RAMP_Q', T=265, F=0.2845/
&RAMP ID='EASYCHAIR_RAMP_Q', T=390, F=0.0690/
&RAMP ID='EASYCHAIR_RAMP_Q', T=540, F=0.0690/
&RAMP ID='EASYCHAIR_RAMP_Q', T=940, F=0.0431/
&RAMP ID='EASYCHAIR_RAMP_Q', T=1940, F=0/

&PART ID='smoke',
      MASSLESS=.TRUE.,
      COLOR='BLACK',
      SAMPLING_FACTOR=1/

walls
mtrlprop.
&SURF ID='tra',
      BURN_AWAY=.TRUE.,
      MATL_ID(1,1)='YELLOW PINE',
      MATL_MASS_FRACTION(1,1)=1.00,
      THICKNESS(1)=0.0200/
&MATL ID='YELLOW PINE',
      SPECIFIC_HEAT=2.85,
      CONDUCTIVITY=0.1400,
      DENSITY=640.00/

object
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&OBST XB=0.00,5.44,0.00,5.02,-0.01,0.00, SURF_ID='tra'/ golv

&OBST XB=0.00,5.44,0.00,5.02,2.50,2.55, COLOR='INVISIBLE', SURF_ID='tra'/ combustion part roof
```

```
&OBST XB=-3.08,5.44,-10.05,0.00,2.50,2.55, COLOR='INVISIBLE', SURF_ID='tra'/ smoke spread part
roof

&OBST XB=-3.08, 5.44 , -10.05, -9.96, 0.00, 2.50, COLOR='GRAY 60', SURF_ID='tra'/ wall
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&OBST XB=-3.00, 5.35 , -7.67 , -7.44, 0.00, 2.50, COLOR='GRAY 60', SURF_ID='tra'/ wall
&OBST XB=-3.00, 5.35 , -5.15 , -4.92, 0.00, 2.50, COLOR='GRAY 60', SURF_ID='tra'/ wall
&OBST XB=-3.00, 5.35 , -2.63 , -2.40, 0.00, 2.50, COLOR='GRAY 60', SURF_ID='tra'/ wall
&OBST XB=-1.55, -1.45, -1.11 , -0.11, 0.00, 2.50, COLOR='GRAY 60', SURF_ID='tra'/ wall
&OBST XB=-3.08, 0.0  , -0.11 , -0.03, 0.00, 2.50, COLOR='GRAY 60', SURF_ID='tra'/ wall
&OBST XB=-3.01, -1.55, -1.11 , -1.01, 0.00, 2.50, COLOR='GRAY 60', SURF_ID='tra'/ wall
&OBST XB=-3.08, -3.00, -9.96 , -0.11, 0.00, 2.50, COLOR='GRAY 60', SURF_ID='tra'/ wall
&OBST XB=0.00 , 5.35 , 4.93  , 5.02 , 0.00, 2.50, COLOR='GRAY 60', SURF_ID='tra'/ wall
&OBST XB=1.30 , 1.40 , -0.11 , 4.93 , 0.00, 2.50, COLOR='GRAY 60', SURF_ID='tra'/ wall
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&OBST XB=1.40 , 5.35 , -0.11 , 0.12 , 0.00, 2.50, COLOR='GRAY 60', SURF_ID='tra'/ wall
&OBST XB=1.40 , 5.35 , 2.41  , 2.63 , 0.00, 2.50, COLOR='GRAY 60', SURF_ID='tra'/ wall
&OBST XB=-0.00, 0.10 , -2.40 , 4.93 , 0.00, 2.50, COLOR='GRAY 60', SURF_ID='tra'/ wall

openings
windows
&HOLE XB=5.35, 5.44, 0.54 , 0.76 , 1.10, 1.32,/  smashed window

doors
&HOLE XB=1.28 , 1.40 , 1.07 , 1.90 , 0.00, 2.10/ door
&HOLE XB=-2.23, -1.60, -1.11, -0.91, 0.00, 2.10/ door
&HOLE XB=-0.10, 0.10 , -2.03, -1.40, 0.00, 2.10/ door
&HOLE XB=2.58 , 3.42 , -2.64, -2.38, 0.00, 2.10/ door

portals
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&HOLE XB=-2.27, 4.62 , -5.15, -4.80, 0.00, 2.10/ portal
&HOLE XB=-2.27, 4.62 , -7.67, -7.38, 0.00, 2.10/ portal

output sensors
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corridor DP2
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hallway DP3
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```

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start room, fire part    DP4
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restroom DP5
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classroom DP6
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&DEVC ID='DP614', QUANTITY='TEMPERATURE', XYZ=0.50,-5.35,2.20/ classroom
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SLICES
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&SLCF QUANTITY='TEMPERATURE', PBY=3.50/
&SLCF QUANTITY='W-VELOCITY', PBY=3.50/
&SLCF QUANTITY='W-VELOCITY', PBX=0.60/
&SLCF QUANTITY='TEMPERATURE', PBX=3.00/
&SLCF QUANTITY='V-VELOCITY', PBX=3.00/
&SLCF QUANTITY='TEMPERATURE', PBX=1.30/
&SLCF QUANTITY='U-VELOCITY', PBX=1.30/
&SLCF QUANTITY='V-VELOCITY', PBX=1.30/
&SLCF QUANTITY='TEMPERATURE', PBX=0.60/
&SLCF QUANTITY='U-VELOCITY', PBY=1.50/
&SLCF QUANTITY='U-VELOCITY', PBY=3.50/
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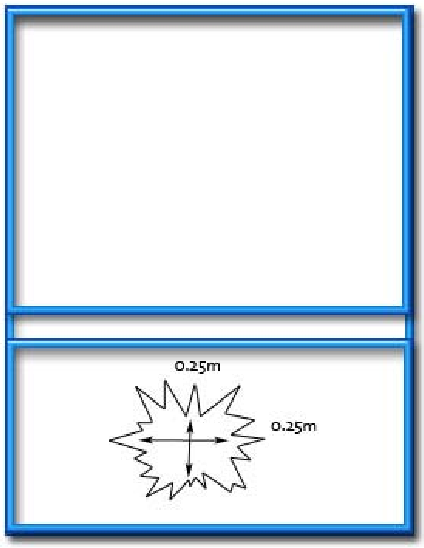
&SLCF QUANTITY='V-VELOCITY', PBY=1.50/
&SLCF QUANTITY='V-VELOCITY', PBY=3.50/
&SLCF QUANTITY='V-VELOCITY', PBX=0.60/
&SLCF QUANTITY='W-VELOCITY', PBY=1.50/

&TAIL /
```

APPENDIX II. WINDOW AND VENTILATION CALCULATIONS

The measurements on-site were found to be similar to a circle and 0.25m in diameter. Adjusting that to CFAST parameters included making it square instead of circular. The area was found to be:

$$A = \frac{D^2 \cdot \pi}{4} = \frac{0,25m^2 \cdot \pi}{4} = 0.049m^2$$



Window-illustration

The broken glass is assumed to interfere with the airflow. An adjustment from "assuming circle shape" to "assuming square shape" with the same area is therefore not assumed to greatly cripple the model. The measurements would then be:

$$S = \sqrt{A} = \sqrt{0,049m^2} = 0,2215m$$

The hole was in the middle of the lower part of the window, as illustrated.

Actual broken window

APPENDIX III. AIR MASS-FLOW CALCULATIONS

The fully developed fire is either fuel controlled (adequately ventilated) or ventilation controlled (not enough air in). This means that with a ventilation controlled fire we can estimate the mass flow of air consumed and the maximum possible fire in a room.

$$\dot{m}_{air} = 0,5 \cdot A_0 H^{1/2} \left[kg/s \right]$$ (10.16, Drysdale, 1999)

$\dot{m}_{air}$ is the mass loss rate of air. This can be put into another equation to determine the maximum Heat Release Rate and compared to the criteria for flashover.

$$\Delta H_{C,air} = 3\left[kJ/g(air) \right]$$ (Table 1.13: (Drysdale, 1999))

$$\dot{Q}_C = \dot{m}_{air} \cdot \Delta H_{C,air} \left[kW \right]$$ (1.27, Drysdale, 1999)

$$\dot{Q}_{FO} = 600 \cdot A_0 H^{1/2} \left[kW \right]$$ (9.9, Drysdale, 1999)

$$\dot{Q}_{FO} = 600\left(h_k A_T A_0 H^{1/2} \right)\left[kW \right]$$ (9.22, (Drysdale, 1999) and 6.20, (Karlsson & Quintiere, 2000))

h_k is the coefficient for Convective Heat Transfer. It's measured in $\left[W/m^2 K \right]$. It's an estimate of free or forced convection in air and differs with geometry, material surfaces and the properties of the fluid. In relation to Fire Dynamics the fluid in question is air with free convection. The values differ between 5-25 $\left[W/m^2 K \right]$ and a number in between has been chosen, 23 $\left[W/m^2 K \right]$ or 0,023 $\left[kW/m^2 K \right]$. 18 $\left[W/m^2 K \right]$ is also commonly used in fire engineering.

H is the height of the openings. In this case there is both the door and the window. It's based on squares, and the hole in the window is approximate round, 25cm diameter.

$$A = \pi \cdot r^2 = \frac{\pi \cdot D^2}{4} = \frac{\pi \cdot 0,25^2}{4} = 0,0491 m^2$$

This area can then be approximated to a square with equal sides, as an approximate for use with simulations and height in calculations.

$$H_{WINDOW}[m] = \sqrt{A[m^2]} = \sqrt{0,0491} = 0,2215\,m$$

A_O is known as "Area of ventilation opening" and measured in m^2. This is typically windows and doors. This is also known as A_W in "An introduction to Fire Dynamics" (Drysdale, 1999), but the abbrevation from Enclosure Fire Dynamics (Karlsson & Quintiere, 2000) will be used here.

$$A_0 = 0,0491(window)[m^2] + 1,68(door)[m^2] \approx 1,7\,m^2$$

A_T is the walls and floor of the area, excluding the openings (A_O) and also measured in m^2

$$\begin{aligned} A_T &= 3,95 \cdot 4,588(ceiling)[m^2] + 2 \cdot 3,95 \cdot 2,5(wall)[m^2] \\ &\quad + 2 \cdot 4,588 \cdot 2,5(wall)[m^2] - 0,0491(window)[m^2] - 1,68(door)[m^2] \\ &= 59,1\,m^2 \end{aligned}$$

We can then calculate the mass lossrate

$$\begin{aligned} \dot{m}_{air} &= 0,5 \cdot A_O H^{1/2} \\ &= 0,5 \cdot \left(0,0491 \cdot \sqrt{0,2215} + 1,68 \cdot \sqrt{2,1}\right) \\ &= 0,5 \cdot (0,023 + 2,435) \\ &= 1,229\,[kg/s] = 1229\,[g/s] \end{aligned}$$

And from that the maximum heat loss rate

$$\begin{aligned} \dot{Q}_C &= \dot{m}_{air} \cdot \Delta H_{C,air}\,[kW] \\ &= 1079[g/s] \cdot 3[kJ/g(air)] = 3,69[MW] \end{aligned}$$

The simple equation of required Heat release rate required to cause flashover:

$$
\begin{aligned}
\dot{Q}_{FO} &= 600 \cdot A_0 H^{1/2} \left[kW\right] \\
&= 600 \cdot \left(0,0491 \cdot \sqrt{0,2215} + 1,68 \cdot \sqrt{2,1}\right) \\
&= 600 \cdot 2,458 = 1,47 \left[MW\right]
\end{aligned}
$$

The more complicated equation of required Heat release rate required to cause flashover using a h_k value of 0,023 (not unusual in fire calculations):

$$
\begin{aligned}
\dot{Q}_{FO} &= 610 \left(h_k A_T A_O H^{1/2}\right)^{1/2} \left[kW\right] \\
&= 610 \sqrt{0,023 \left[W/m^2 K\right] \cdot 59,1 \left[m^2\right] \cdot 1,7 \left[m^2\right] \cdot \left(\sqrt{2,1 \left[m\right]} + \sqrt{0,2215 \left[m\right]}\right)} \\
&= 610 \cdot \sqrt{4,436} = 1,28\, MW
\end{aligned}
$$

With an estimated h_k of 0,018 (Davies, 2004) (citation: s 12)

$$
\begin{aligned}
\dot{Q}_{FO} &= 610 \left(h_k A_T A_O H^{1/2}\right)^{1/2} \left[kW\right] \\
&= 610 \sqrt{0,018 \left[W/m^2 K\right] \cdot 59,1 \left[m^2\right] \cdot 1,7 \left[m^2\right] \cdot \left(\sqrt{2,1 \left[m\right]} + \sqrt{0,2215 \left[m\right]}\right)} \\
&= 610 \cdot \sqrt{3,472} = 1,14 \left[MW\right]
\end{aligned}
$$

The chosen heat release rate graph of a padded chair exceeds 2MW after 200s and it is assumed that the room will go into a flash over given time.

APPENDIX IV. CONE CALORIE METER TEST OF THE CEILING FROM THE FULL-SCALE TEST

First test (pages 1-5)

Radiation =15kW

Second test (pages 1-5)

Radiation =20kW

Cone Calorimeter Test Report

Laboratory name	Lab 3
Conecalorimeter	
Operator	morten
Filename	C:\CC5\DATA\09030002.CSV
Sample description	test 1 resq tak
Material name/ID	

Specimen information

E	13.1 MJ/kg	Specimen number		Conditioned?	Yes
Thickness	11 mm	Nominal duct flow rate	24 l/s	Temperature	No°C
Initial mass	79.9 g	Edge frame used?	Yes	RH	N/A%
Surface area	100 cm²	Grid used?	No		
Heat flux	15 kW/m²	Manufacturer			
Separation	25 mm	Sponsor			
Orientation	Horizontal				

Test

Standard used	ISO 5660-1
Date of test	18/03/2009
Time of test	11:01
Date of report	05/05/2009

Pre-test conditions

Ambient temperature	N/A
Ambient pressure	N/A
Relative humidity	N/A

Test times

Time to ignition	299 s
Time to flameout	1170 s
End of test criterion	ISO 5660-1:2002
End of test time (for calculations)	1160 s

Apparatus specifications

C-factor	0.04252
Duct diameter	0.114 m
O2 delay time	18 s
CO2 delay time	11 s
CO delay time	12 s
OD corr. factor	1.0336

Initial conditions

Baseline oxygen	20.948%
Baseline carbon dioxide	0.0080%
Mass at sustained flaming	74.7 g

Heat Release Results

THR (0-300)	0.66 MJ/m²
THR (0-600)	25.77 MJ/m²
THR (0-1200)	-
Fuel load	7.35 MJ/kg

Test results (between 299 and 1160 s)

Total heat release	58.7 MJ/m²
Total oxygen consumed	35.7 g
Mass lost	54.9 g
Average specific MLR	7.26 g/(s·m²)
Total smoke release	170.0 m²/m²
Total smoke production	1.7 m²
MAHRE	51.6 kW/m²

	Mean	Peak	at time (s)
Heat release rate (kW/m²)	67.96	149.41	325
Effective heat of comb. (MJ/kg)	10.71	32.09	1055
Mass loss rate (g/s)	0.063	0.199	780
Specific extinction area (m²/kg)	27.39	179.59	340
Carbon monoxide yield (kg/kg)	0.0127	0.3765	1145
Carbon dioxide yield (kg/kg)	1.35	3.92	1055

Test averages

from ignition to ignition plus...	1 min	2 min	3 min	4 min	5 min	6 min	0 s - 299 s	299 s - 1160 s
Heat release rate (kW/m²)	139.17	126.67	110.57	95.83	83.72	75.43	0.12	67.96
Effective heat of comb. (MJ/kg)	10.52	10.44	10.32	10.12	9.93	9.81	0.07	10.71
Mass loss rate (g/s)	0.132	0.121	0.107	0.095	0.084	0.077	0.018	0.063
Specific extinction area (m²/kg)	133.78	102.41	78.21	66.32	59.99	54.70	716.37	27.39
Carbon monoxide yield (kg/kg)	0.0088	0.0060	0.0046	0.0049	0.0067	0.0087	0.0098	0.0127
Carbon dioxide yield (kg/kg)	1.14	1.23	1.26	1.26	1.24	1.23	0.35	1.35

Smoke results

Total smoke release: non-flaming phase (0 s - 299 s)	373.4 m²/m²
Total smoke release: flaming phase (299 s - 1160 s)	170.0 m²/m²
Total smoke release: whole test (0 s - 1160 s)	543.4 m²/m²

Soot results

Soot mass collected	N/A g
Soot mass ratio	1:No
Total soot mass flow	0.00 g
Average soot yield	0.00 kg/kg

The test results relate to the behaviour of the test specimens of a product under the particular conditions of the test; they are not intended to be the sole criterion for assessing the potential fire hazard of the product in use.

Cone Calorimeter Test Report

Laboratory name	Lab 3
Conecalorimeter	
Operator	morten
Filename	C:\CC5\DATA\09030002.CSV
Sample description	test 1 resq tak
Material name/ID	

Additional specimen preparation information

Pre-test comments

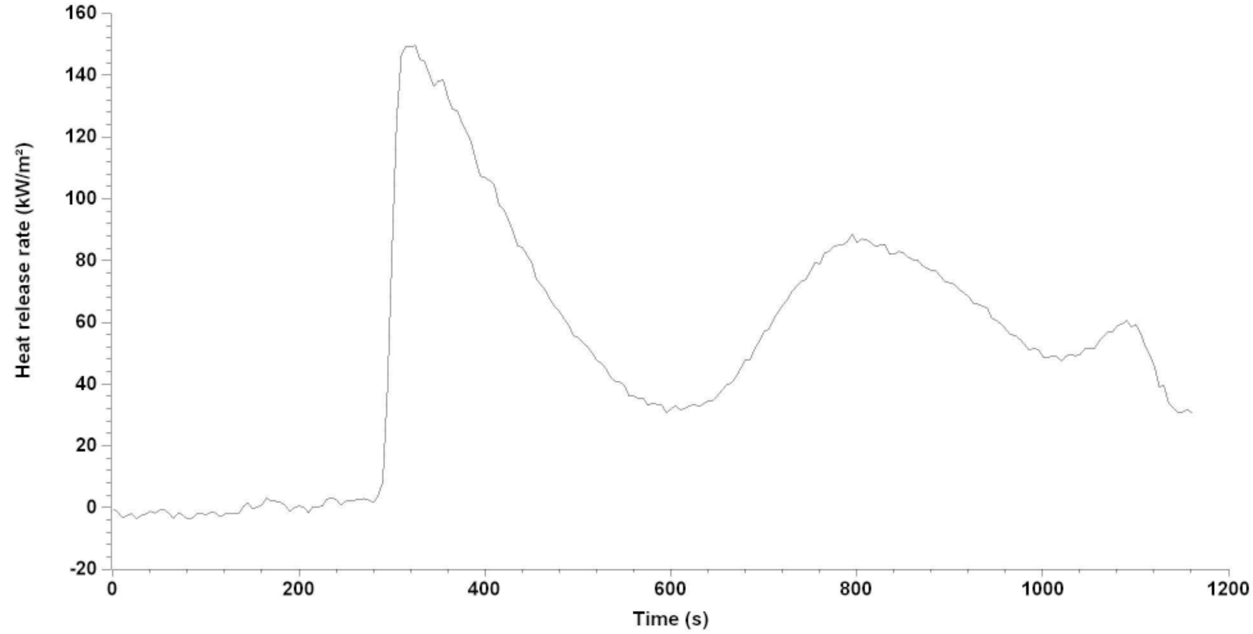
After-test comments

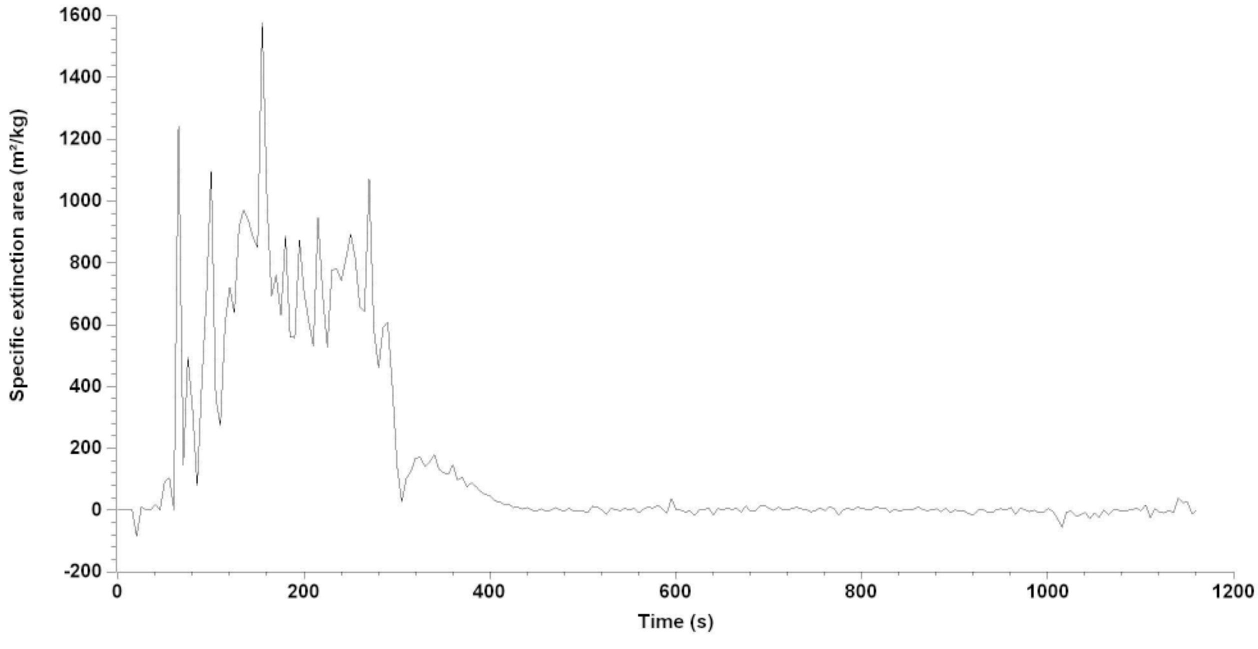
Recorded events

Time (s)	Event
53	bobler
90	røyk
293	flamme blaff

Cone Calorimeter Test Report

Laboratory name	Lab 3
Conecalorimeter	
Operator	morten
Filename	C:\CC5\DATA\09030002.CSV
Sample description	test 1 resq tak
Material name/ID	





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Conecalorimeter	
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Filename	C:\CC5\DATA\09030002.CSV
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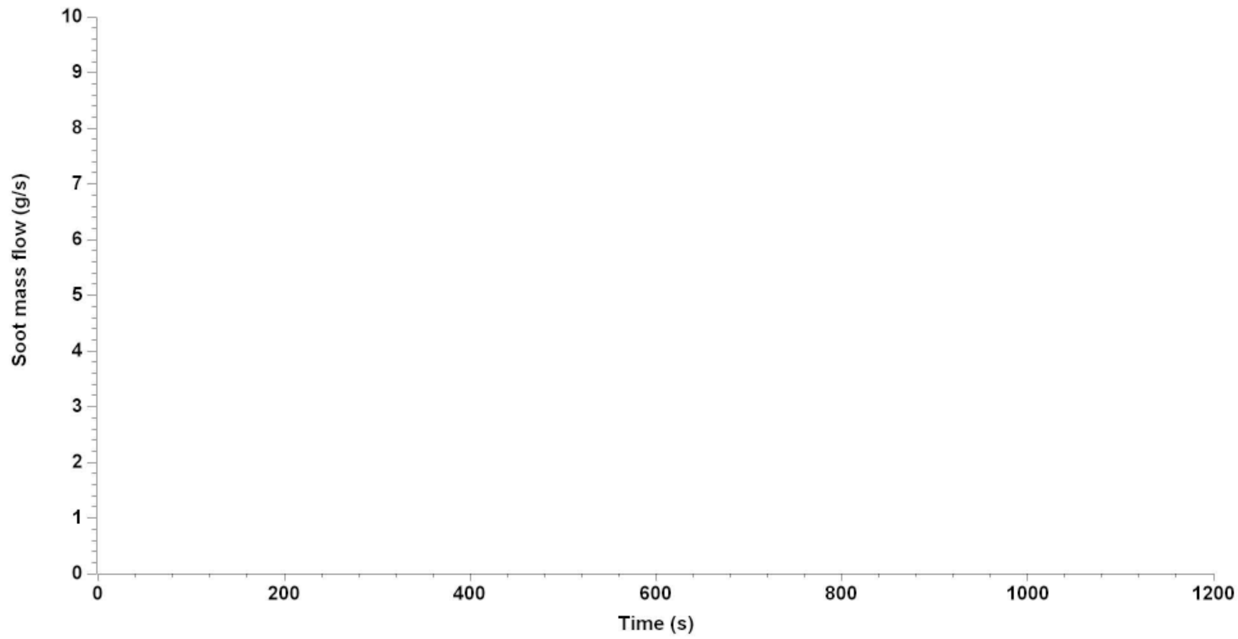

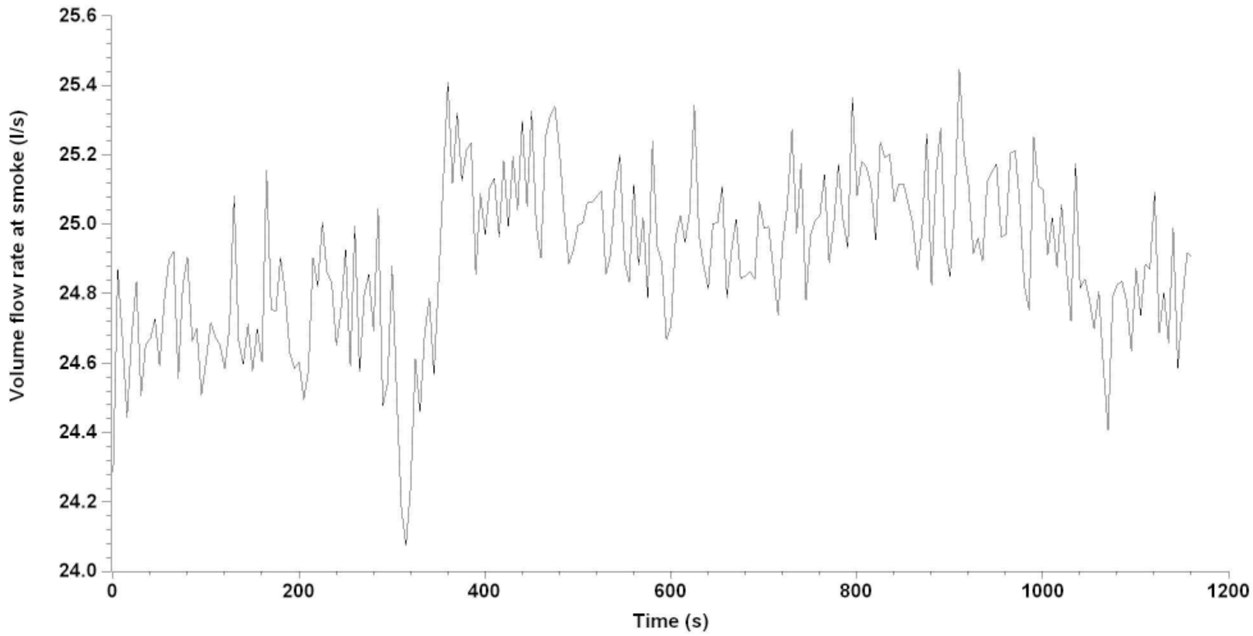

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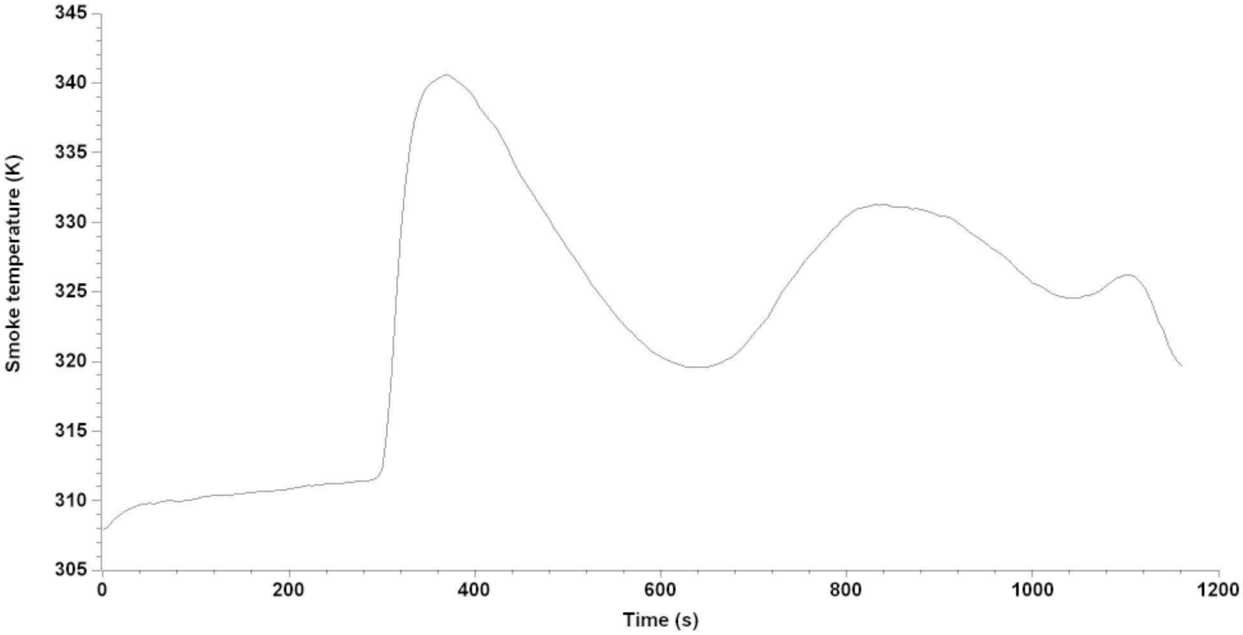

Cone Calorimeter Test Report

Laboratory name	Lab 3
Conecalorimeter	
Operator	morten
Filename	C:\CC5\DATA\09030003.CSV
Sample description	test 2 resq tak
Material name/ID	

Specimen information

E	13.1 MJ/kg	Specimen number		Conditioned?	Yes
Thickness	11 mm	Nominal duct flow rate	24 l/s	Temperature	No°C
Initial mass	82 g	Edge frame used?	Yes	RH	N/A%
Surface area	100 cm²	Grid used?	No		
Heat flux	20 kW/m²	Manufacturer			
Separation	25 mm	Sponsor			
Orientation	Horizontal				

Test

Standard used	ISO 5660-1
Date of test	18/03/2009
Time of test	11:35
Date of report	05/05/2009

Pre-test conditions

Ambient temperature	N/A
Ambient pressure	N/A
Relative humidity	N/A

Test times

Time to ignition	114 s
Time to flameout	923 s
End of test criterion	ISO 5660-1:2002
End of test time (for calculations)	920 s

Apparatus specifications

C-factor	0.04252
Duct diameter	0.114 m
O2 delay time	18 s
CO2 delay time	11 s
CO delay time	12 s
OD corr. factor	1.0336

Initial conditions

Baseline oxygen	20.944%
Baseline carbon dioxide	0.0137%
Mass at sustained flaming	81.4 g

Heat Release Results

THR (0-300)	62.89 MJ/m²
THR (0-600)	82.95 MJ/m²
THR (0-1200)	-
Fuel load	13.08 MJ/kg

Test results (between 114 and 920 s)

Total heat release	107.2 MJ/m²
Total oxygen consumed	70.9 g
Mass lost	59.8 g
Average specific MLR	7.91 g/(s·m²)
Total smoke release	178.0 m²/m²
Total smoke production	1.8 m²
MAHRE	242.2 kW/m²

	Mean	Peak	at time (s)
Heat release rate (kW/m²)	132.93	5599.50	230
Effective heat of comb. (MJ/kg)	17.83	66.95	205
Mass loss rate (g/s)	0.075	0.308	300
Specific extinction area (m²/kg)	24.60	789.62	130
Carbon monoxide yield (kg/kg)	0.0065	0.1216	895
Carbon dioxide yield (kg/kg)	1.40	20.68	390

Test averages

from ignition to ignition plus...	1 min	2 min	3 min	4 min	5 min	6 min	0 s - 114 s	114 s - 920 s
Heat release rate (kW/m²)	136.85	469.81	344.06	276.41	233.46	203.65	1.89	132.93
Effective heat of comb. (MJ/kg)	10.57	37.28	30.03	26.29	24.13	22.59	3.64	17.83
Mass loss rate (g/s)	0.129	0.126	0.114	0.105	0.096	0.090	0.001	0.075
Specific extinction area (m²/kg)	128.70	102.35	79.08	63.94	54.11	47.37	1748.90	24.60
Carbon monoxide yield (kg/kg)	0.0098	0.0069	0.0053	0.0043	0.0043	0.0047	0.0173	0.0065
Carbon dioxide yield (kg/kg)	1.11	1.23	1.26	1.26	1.27	1.27	1.33	1.40

Smoke results

Total smoke release: non-flaming phase (0 s - 114 s)	100.4 m²/m²
Total smoke release: flaming phase (114 s - 920 s)	178.0 m²/m²
Total smoke release: whole test (0 s - 920 s)	278.4 m²/m²

Soot results

Soot mass collected	N/A g
Soot mass ratio	1:No
Total soot mass flow	0.00 g
Average soot yield	0.00 kg/kg

The test results relate to the behaviour of the test specimens of a product under the particular conditions of the test; they are not intended to be the sole criterion for assessing the potential fire hazard of the product in use.

Cone Calorimeter Test Report

Laboratory name	Lab 3
Conecalorimeter	
Operator	morten
Filename	C:\CC5\DATA\09030003.CSV
Sample description	test 2 resq tak
Material name/ID	

Additional specimen preparation information

Pre-test comments

After-test comments rare meldinger på HRR-kurvan

Recorded events

Time (s)	Event
29	bobbler
54	flash

Cone Calorimeter Test Report

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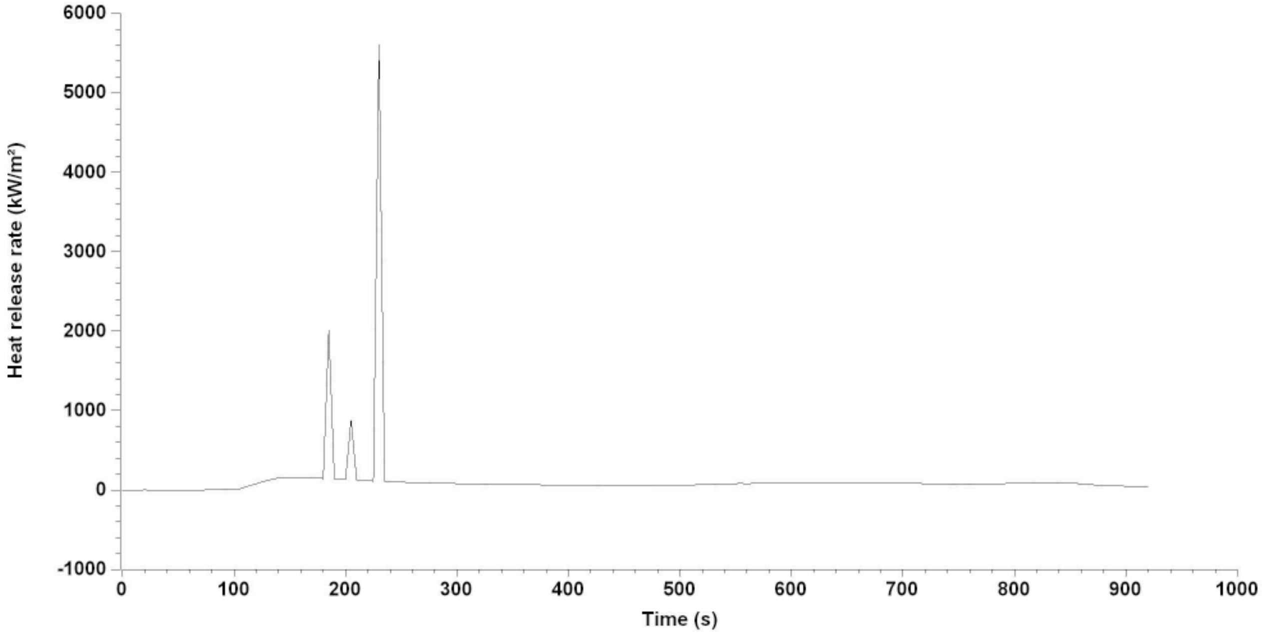

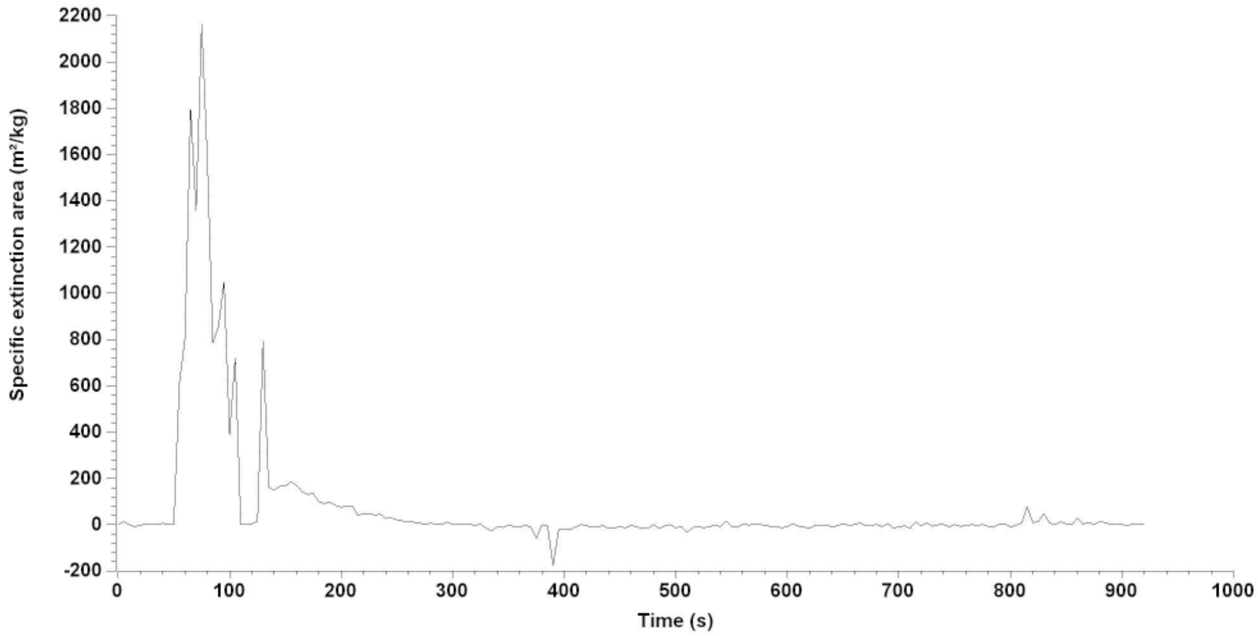

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 Conecalorimeter
Operator morten
Filename C:\CC5\DATA\09030003.CSV
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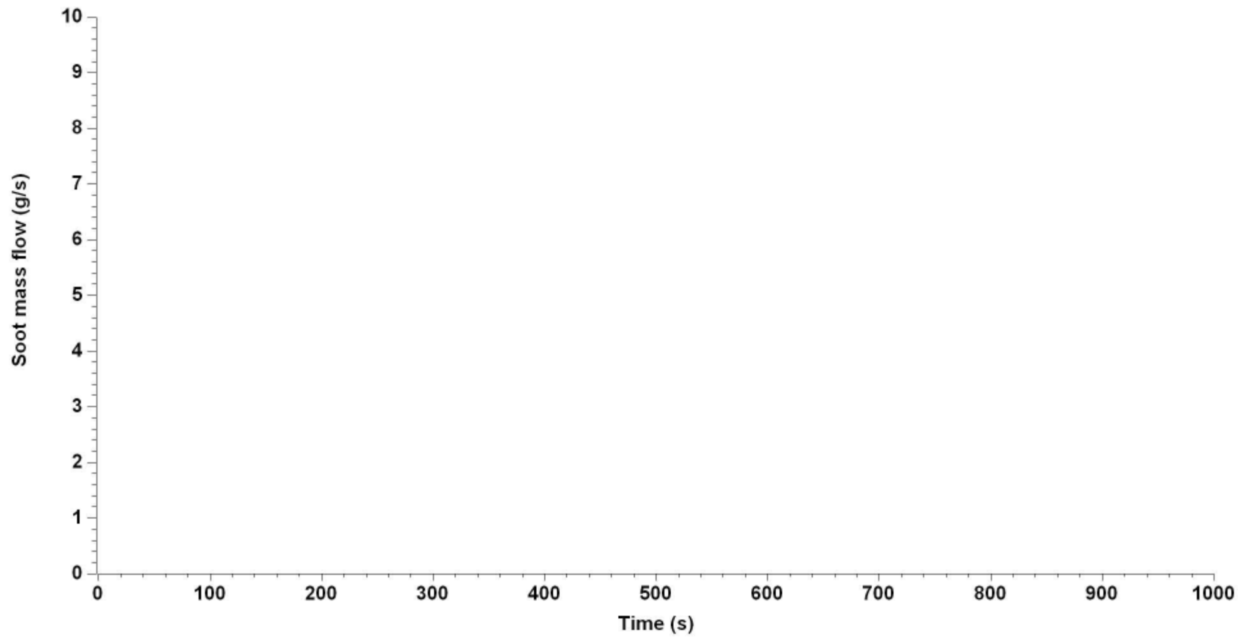

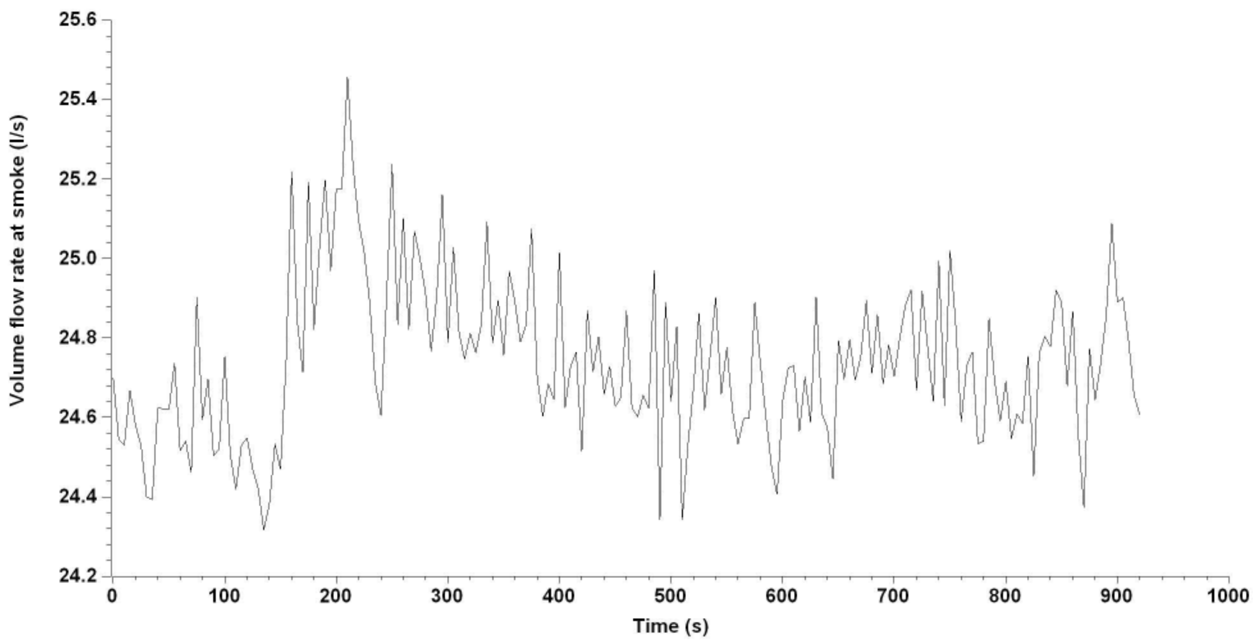

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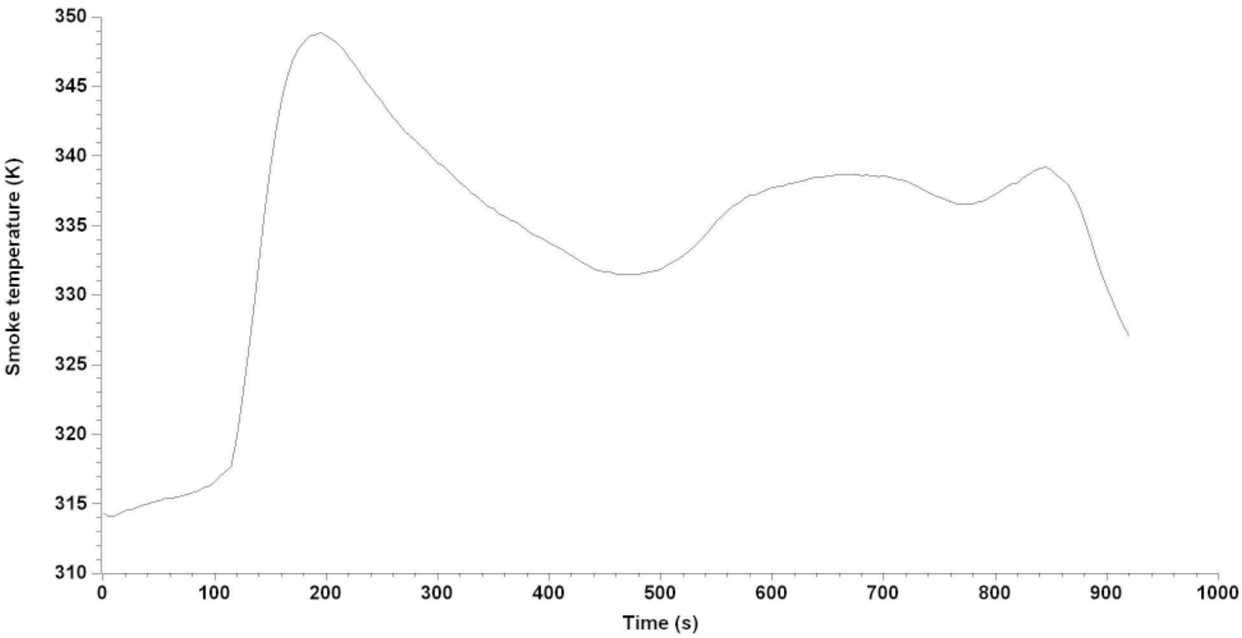
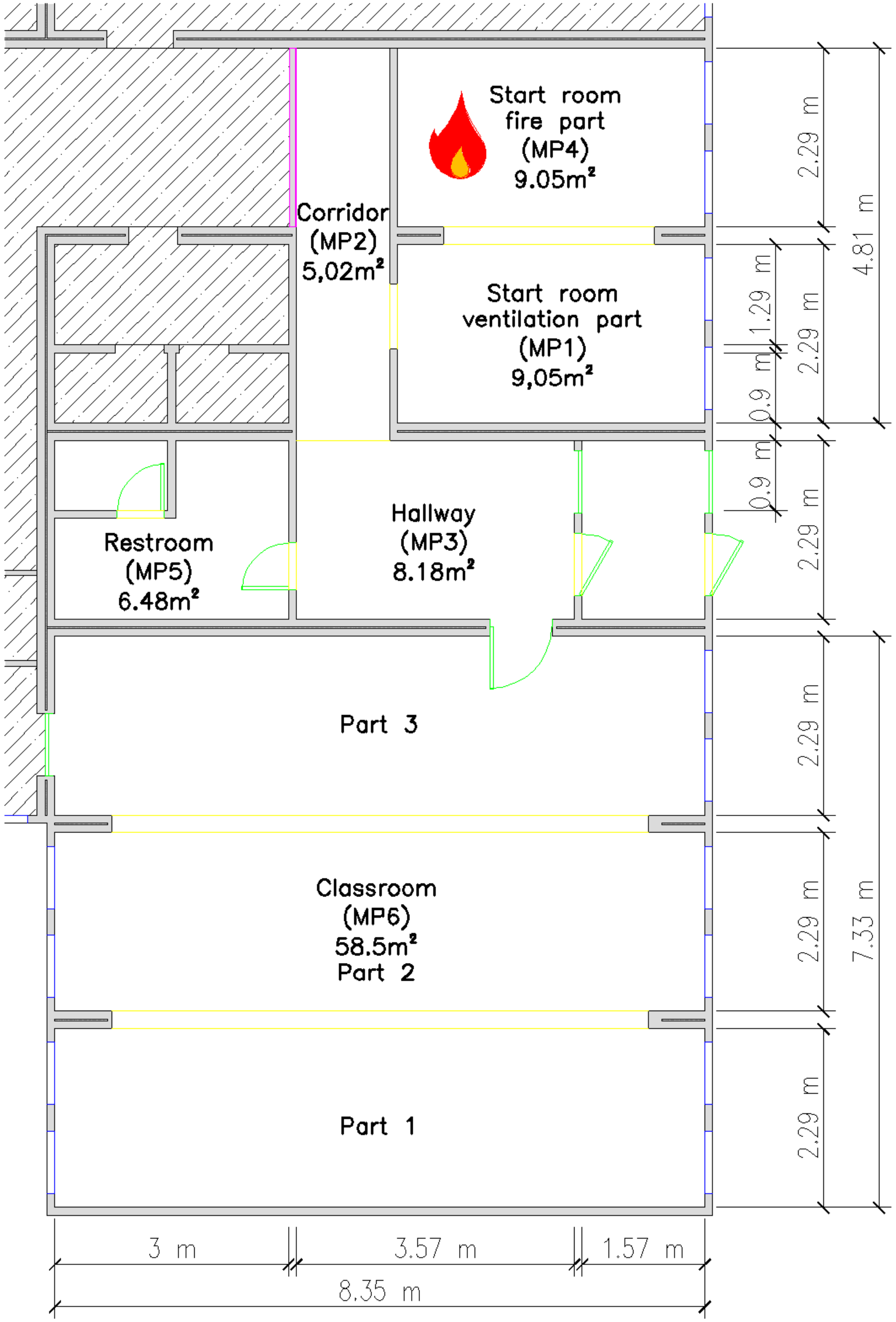
Material name/ID	




Start room
fire part
(MP4)
9.05m²
Corridor
(MP2)
5,02m²
Start room
ventilation part
(MP1)
9,05m²
Restroom
(MP5)
6.48m²
Hallway
(MP3)
8.18m²
Part 3
Classroom
(MP6)
58.5m²
Part 2
Part 1
2.29 m
4.81 m
1.29 m
0.9 m
7.33 m
3 m
3.57 m
1.57 m
8.35 m