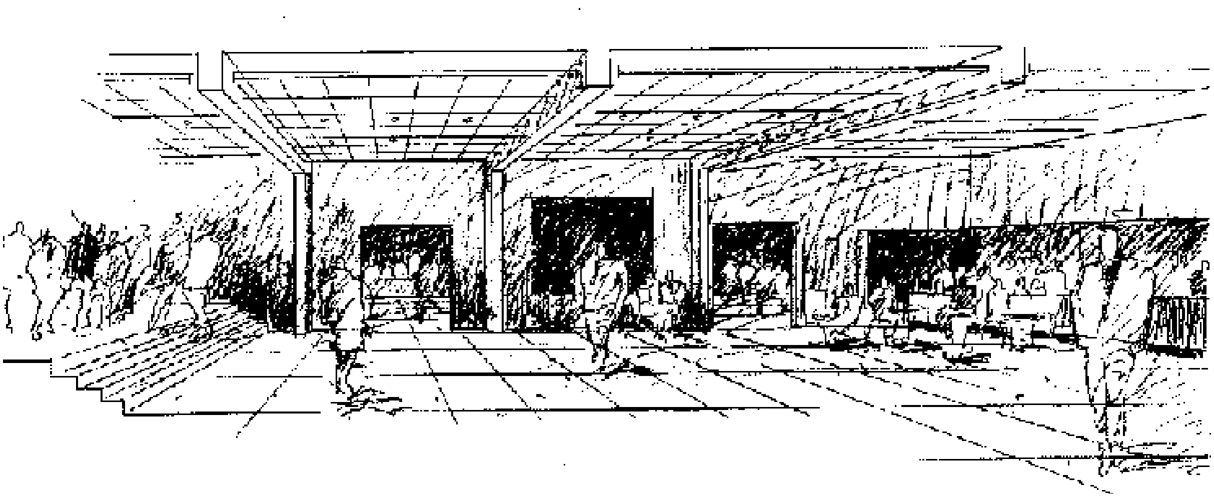
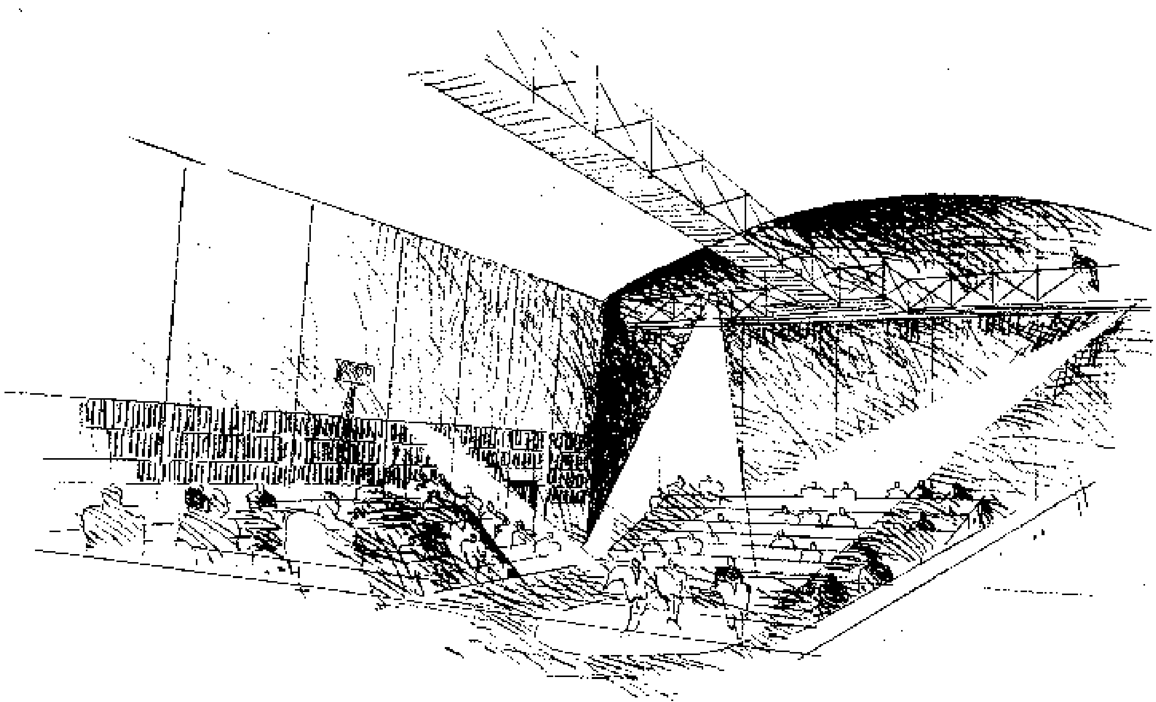
Fire safety evaluation of
Amager Bio





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S y n o p s i s

On basis of the theme "Fire Safety Evaluation an analysis of "Amager Bio" was carried out in order to evaluate the present fire safety level. "Amager Bio" is an old cinema which is rebuild into an place for cultural events and is located on the Danish Island Amager. "Amager Bio" is provided with mechanical smoke ventilation to compensate for one-sided location of the escape routes (80% in one direction).

The fire safety level was evaluated by comparing the time to which the condition inside the building becomes critical to human safety (critical time) to the time it will take to evacuate the building (evacuation time).

The critical time was determined by setting up probable fire scenarios and by investigating the consequences of them. Of the analysed fire scenarios it was determined that a fire on the stage will give critical condition fastest (approximately after 4 minutes).

Evacuation times were determined by setting up evacuation scenarios where the fires' locations were taken into account. "Amager Bio" was evaluated for seated as well as for standing visitors.

The fire safety analysis leads to a non-satisfactory fire safety level concerning human safety with the present fire precautions.

Improvements are suggested in order to obtain a satisfactory fire safety level concerning human safety. If no improvements are done the number of visitors shall be reduced.

The mechanical ventilation is not sufficient enough to avoid critical smoke filling at larger fire loads. This leads to insufficient time for evacuating.

ranking, Fire Safety Engine-ering.

Preface

This report is done as a part of the course “Fire Safety Evaluation” in the period from January 13th 1997 to May 5th 1997 at the School of Fire Safety Engineering, Institute of Technology, Lund University, Sweden.

This report is divided into two:

- Main report.
- Appendices.

⊇ Text marked as shown is where the reader should pay special attention.

In the report the figures, the tables, the equations and the pictures are numbered with two numbers, where the first indicates the number of the Chapter and the second is the figure’s number in the Chapter. Ex. “Figure 2.1” indicates that this is figure 1 in Chapter 2.

During the report the references are made by using the Harvard Method as follows [….] and in Chapter 13 “References” the used literature are listed in alphabetic order.

All the variables which are used in this report will be defined when they are introduced. In Chapter 14 “Nomenclature” the variables used in this report are listed.

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- The staff at “Amager Bio”, Denmark.

Lund 5th of May 1997

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Appendices (not included in the www-version)

1. Introduction

Peoples knowledge about fires are generally very poor. They may have knowledge of how a fire starts, but they do not know how it develops, how it spreads and how much smoke and toxic gasses a fire can produce. [DSMS, Chapter 1]

People know that engineers traditionally take care of the structural designing and they might therefore feel safe when visiting a building. Furthermore, people often have the opinion that "*it doesn't happen to me*, *it happens for the neighbours*".

Earlier a fire safety evaluation contained an investigation of whether the escape routes, their length, their width, the elaboration of the escape routes and the size of the exits were in accordance with the known regulation. Since the buildings have become more and more complex further knowledge about the fire development and how people react and behave during an evacuation situation is necessary.

This project contains a fire safety analysis of the object "Amager Bio" and is carried out in accordance to the Danish building regulations (prescribed regulations) and the Swedish building regulations (performance based regulations). In general this report deals with personal safety inside the building, where the traditional fire safety deals with the structural safety during a fire. It is beyond the scope of this project to investigate the structural behaviour performance during a fire in detail.

The object "Amager Bio" can be categorised as an assembly-hall and therefore some general information about assembly-halls in a fire safety point of view will be given.

1.1 Assembly-halls

Assembly-halls can be used for several activities such as theatre, stand-up comedy, discotheques etc. It is common that:

- Many people are visiting the facility.
- The persons have no or little knowledge about the building (escape routes).
- There may be insufficient lightning inside the building.
- There might be a high noise level inside the building.
- Some people can be under influence of alcohol.

The mentioned sentences above describe very well what could be expected for the object "Amager Bio" (the object is described in detail in Chapter 2 "Description of the object").

Many people visiting "Amager Bio" may result in that there could be areas with a high density of people and together with lack of knowledge about the building this could create some difficulties during an evacuation. Often people will evacuate through the exit of which they entered the building and therefore create bottlenecks. Bottlenecks will slow down the evacuation procedure, because people do not move fast in a crowd.

The evacuation could be made difficult in case of insufficient lightning. Orientating problems inside the building may arise due to this. It might be difficult to alert people if the noise level is high or if the people are under influence of alcohol. Therefore it is of importance that the building is designed correct in a fire safety view point so the people will not be trapped inside the building if a fire breaks out.

An example of peoples lack of knowledge about fires is the fire at “Stadshotellet” in Borås on the 10th of June 1978. When the fire was detected there were ca. 170 persons inside the building. The fire started in a wastebasket under a roulette table. After the fire was detected the attempt to extinguish the fire failed. The security tried to evacuate the building, but the visitors were not eager for evacuating. [B&R78]

Earlier the same month a smoke bomb was tossed in an assembly hall in Borås. The visitors thought that this time it also was a smoke bomb and therefore moved slowly toward the cloakroom to get their coats. Some visitors took time to finished up their drinks before the moved toward the cloakroom. A window was opened to ventilate out the smoke which gave a fast fire development and a fast smoke filling. The fast smoke filling resulted in panic among the guests. [B&R78]

It was not until 5 minutes after the fire was detected an alarm was given to the fire brigade. When the fire brigade arrived at the location 120 persons have managed to escape unaided. The firemen, equipped with smoke helmets, had a good knowledge of the building and they were able to rescue 30 persons. 20 persons were trapped inside the building and they were later found dead. [B&R78]

1.2 Fire safety level

In order to obtain a satisfactory safety level of a building it shall be demonstrated that people inside the building do have time enough to get out before the conditions inside the building becomes life-threatening. In other words the time used to evacuate the building shall be minor to the time when conditions within the building becomes critical. A measure on this safety level is called the fire safety level i.e. the safety for the people that visit the object. This leads to the following relationship:

$$t_{evacuation} < t_{critical} \tag{1.1}$$

where

$t_{evacuation}$ is the time it takes to evacuate the building [s].
$t_{critical}$ is the time to which the conditions inside the building becomes critical to humans [s].

The fire safety level concerning human safety is determined as the fraction between the critical time and the evacuation time. The fire safety level is determined in Chapter 11 “Fire safety level”. Further in Chapter 11 “Fire safety level” an overall evaluation of the building’s safety level using another method, which takes into account the building’s facilities, is applied.

To obtain the fire safety level of “Amager Bio” the following investigations are to be done:

- Building analysis.
- Fire scenario analysis.
- Evacuation analysis.

1.3 Building analysis

By building analysis it is meant an overall evaluation of the building regarding fire. The evaluation contains an investigation of the building to see if it fulfils the regulative. This evaluation will be done in accordance with prescribed building regulations (Danish building regulations) and in accordance with performance based building regulations (Swedish building regulations). The analysis is done in Chapter 3 “Legal authorities”.

1.4 Fire scenario analysis

An analysis of possible fire scenarios is necessary in order to get information about the consequences in case of an outbreak of fire within the building.

One of the methods to obtain the consequences of an outbreak of fire within the building is to analyse the temperatures and the smoke layer heights developments. The temperatures and the smoke layer height can lead to a time where the conditions inside the building becomes critical. Before the calculation some criteria for critical conditions are to be listed. The analysis is done in Chapter 4 “Fire scenarios” and Chapter 5 “Fire scenario analysis”.

Another method to obtain the consequences of an outbreak of fire within the building is to analyse the smoke production and hereby the changes in visibility within the building during a fire. This analysis is made in Chapter 6 “Smoke analysis”.

The fire scenario analysis and the smoke analysis can lead to a time, where the conditions inside the building becomes critical to humans and this time is called the critical time. The critical time is determined in Chapter 7 “Critical time” and is to be compared to the evacuation time in accordance with the relationship in equation (1.1).

1.5 Evacuation analysis

An analysis of the evacuations of “Amager Bio” is done to investigate if the people that are inside the building will be able to get out before the conditions are critical. The evacuation analysis is done with the computer software “*Simulex*”. This analysis is carried out in Chapter 9 “Evacuation of “Amager Bio””. (“*Simulex*” is described in Appendix G “Computer Software”).

The result of the above mentioned analysis is a time to which all people inside the building have reached the exits. The walking time leads to an evacuation time and this time is determined in Chapter 10 “Evacuation time”.

1.6 Improvements

In Chapter 12 “Improvements” different changes are listed. The changes could/would lead to a better safety level of the object “Amager Bio”. The listed improvements is discussed and briefly they are analysed from an economic point a view.

2. Description of the object

This Chapter contains an introduction to the object called “Amager Bio” and it is divided into three parts:

- The story behind “Amager Bio”.
- Description of “Amager Bio”.
- Present fire precautions.

2.1 The story behind “Amager Bio”

Back in 1939 inspired by the functionalism and Bauhaus the architects Wittmark and Hvalsøe constructed - for that time - a very superb building in reinforced concrete. The address was Amagerbrogade 123 and the building was “Amager Bio”. “Amager Bio” contained one big hall with the possibility to play theatre on a big permanent stage in front of the white screen.

In 1941 “Amager Bio” opened and it was immediately taken into use by the “Dansk Skolescene”. From the beginning “Amager Bio” was more than just an ordinary cinema. It also housed meetings and performances were set up on the big stage.

Throughout the seventies the local citizens started to fade in their interest for the old cinema. It became rare that the shows were sold out. The cinema was therefore rebuilded into a two hall cinema and the stage was removed. The cinema survived until 1986 where “Amager Bio” was sold to “Dansk Supermarked”, a big supermarket organisation. “Dansk Supermarked” planned to convert “Amager Bio” into a discount supermarket called “Netto”. The community and the local promoters protested. “Sundby lokalnævn” (Sundby neighbourhood council) requested that “Dansk Supermarked” would give “Amager Bio” to the local citizens. After prolonged negotiations the town council stated that “Amager Bio” only should and could be used for cultural activities.

In 1988 “Dansk Supermarked” and the town council finally agreed upon the future of “Amager Bio”. The final negotiation resulted in an agreement where the municipality could hire “Amager Bio” for 20 years for the total rent of one DKr. Meanwhile “Dansk Supermarked” was given a vacant building site just beside “Amager Bio”. A new “Netto” was build and it was ready to open a few months later.

In 1989 the Chief Burgomaster for the municipality of Copenhagen officially turned over “Amager Bio” to the “Sundby lokalnævn”. “Amager Bio” needed restoration and alteration but it was used anyway to different activities, ex. concerts, cafés and theatres.

During 1990 the “Amager Bio’s Kulturråd” (The cultural board of “Amager Bio”) was founded. The main purpose of this board was to support the establishment and the start of cultural activities in “Amager Bio”.

In 1991 “Amager Bio” was closed down by the Fire Department after a minor fire. The cultural board was though allowed to continue with a minor café-arrangements until “Amager Bio” was cleaned up and turned into a construction site.

In 1992 the town council promised 10 millions DKr to rebuilding and furnishing of “Amager Bio”. But there should go many years before these plans were carried out. The cultural board came up with several ideas, but all of them was rejected by the council and therefore “Amager Bio” was a kind of a ghost house for many years.

Finally in 1996 something happened. The assignment was handed over to “KUC” and in company with “De Samarbejdende Arkitekter” the “Amager Bio” will now appear as described in the following.

2.2 Description of “Amager Bio”

“Amager Bio” is located on the Danish island called Amager which lies on the south east of the Danish capital Copenhagen, see Figure 2.1.

Figure 2.1: The location of Amager in relation to Denmark.

For a more detailed description of the location of Denmark and Amager please refer to a different map over Denmark or special literature.

The present use of “Amager Bio” is for cultural events (opera, theatre, concert, discotheque etc.). Next the following will be described:

- Location of the “Amager Bio”.
- Geometry of “Amager Bio”.
- The present use of “Amager Bio”.
- The present fire precautions.

2.2.1 Location of "Amager Bio"

The location of the "Amager Bio" is showed in Figure 2.2.

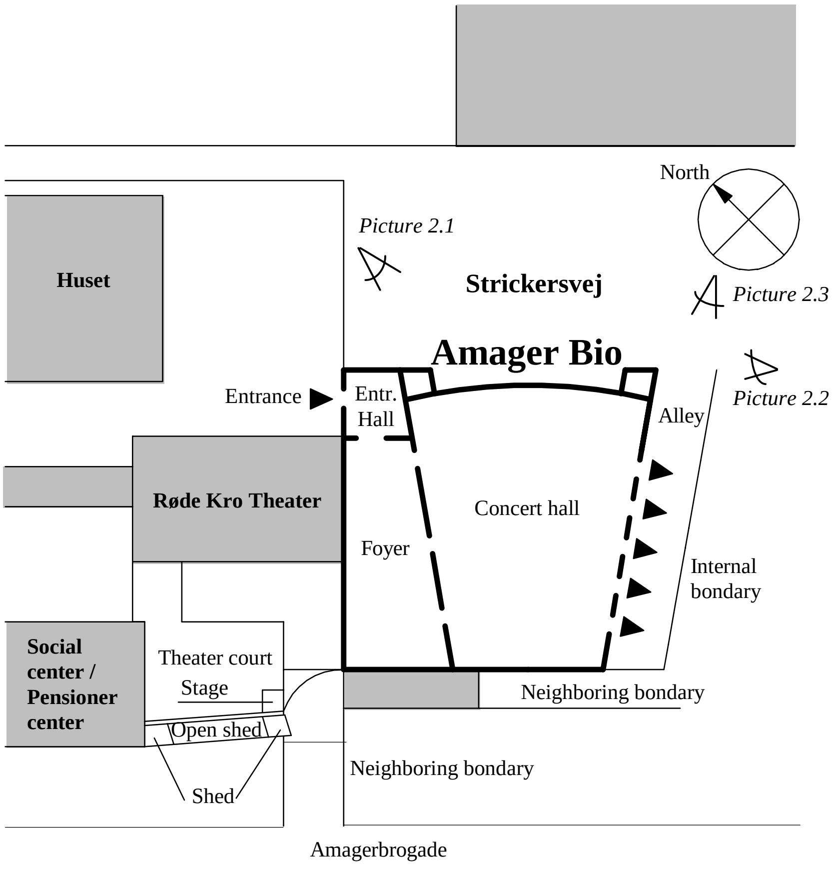


Figure 2.2: The location of "Amager Bio".

A picture of "Amager Bio" seen from the North is showed in Picture 2.1.

Picture 2.1: "Amager Bio" seen from the North.

“Amager Bio” seen from the East is showed in Picture 2.2.

Picture 2.2: "Amager Bio" seen from the East.

Another picture, see Picture 2.3, shows “Amager Bio” when looking down the alley.

Picture 2.3: "Amager Bio" when looking down the alley.

2.2.2 The geometry of “Amager Bio”

In Figure 2.3 a perspective view of “Amager Bio” is shown.

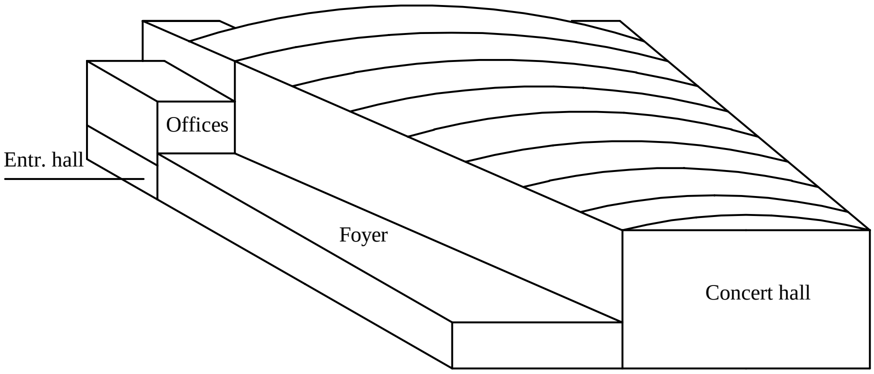


Figure 2.3: A perspective view of "Amager Bio".

The ground plan of “Amager Bio” is shown in Figure 2.4.

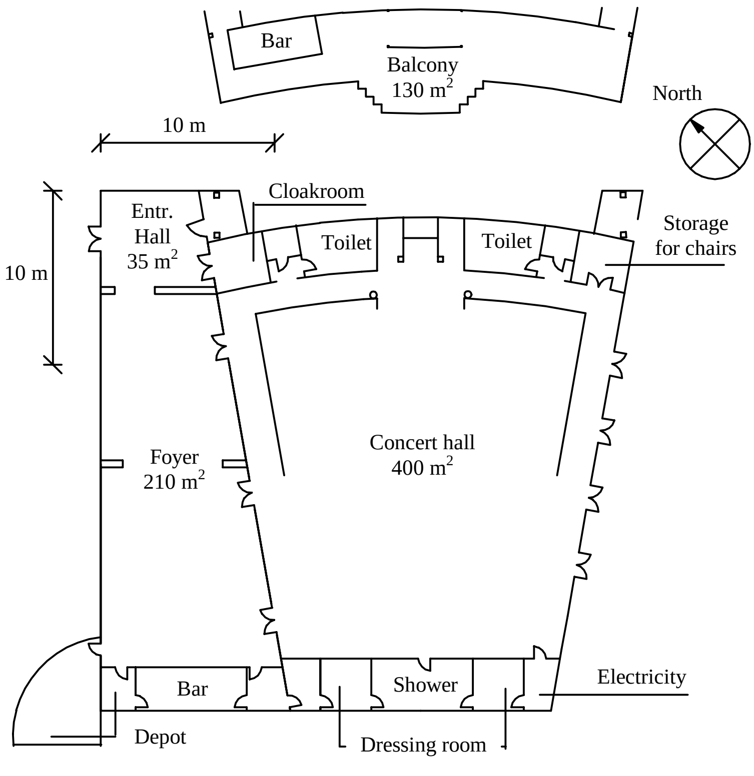


Figure 2.4: Ground plan of "Amager Bio".

In Figure 2.4 is shown the balcony and the balcony is located above the section with the toilets. The balcony is open so that people can see from the balcony in the concert hall, see Picture 2.4 and Picture 2.6. Between the balcony and the concert hall are two open stairs down to a landing platform and one open stair from the landing platform to the concert hall. Further more there are two staircases from the balcony, one from the balcony to the entrance and one from the balcony which leads to the open.

Picture 2.4: The balcony seen from the concert hall.

There is also a basement under "Amager Bio". This basement is not under the entire building, but it is only located under the section with toilets, see Figure 2.5.

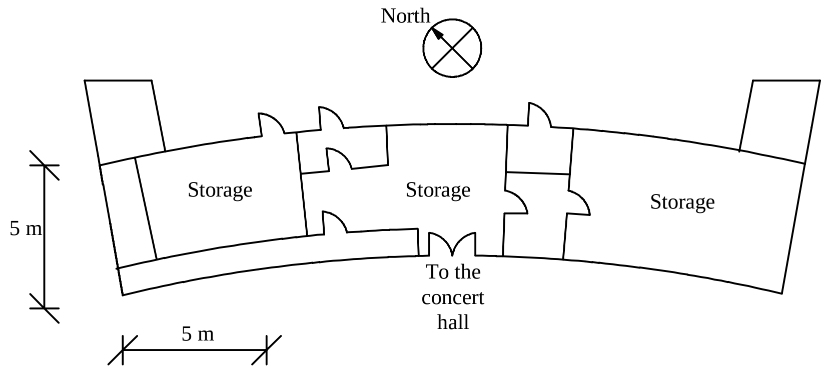


Figure 2.5: The geometry of the basement.

In Figure 2.6 is shown a sectional view of the building.

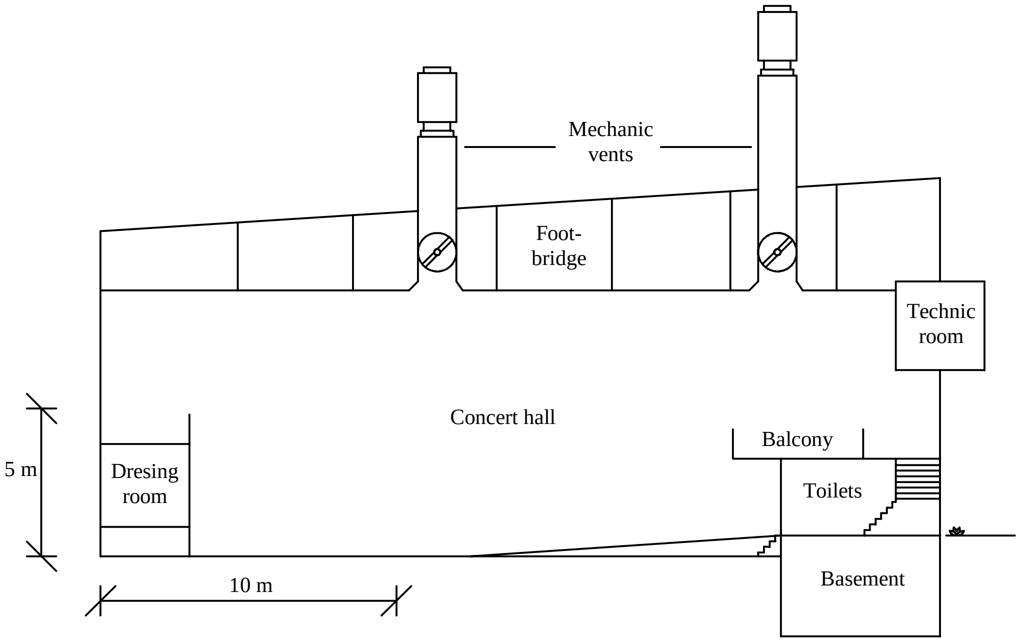


Figure 2.6: Sectional view of "Amager Bio".

From Figure 2.6 it is seen that there are a difference in level between the toilet section and the concert hall.

In Table 2.1 the floor space, heights and volumes of some rooms is listed.

Room	Floor space [m^2]	Room height [m]	Volume [m^3]
Entrance hall	app. 35	app. 2	app. 70
Foyer	app. 210	app. 3	app. 630
Concert hall	app. 400	app. 9	app. 3600
Toilet	app. 110	app. 3	app. 330
Balcony	app. 130	app. 5,5	app. 715
Basement	app. 110	app. 3	app. 330

Table 2.1: Floor space, heights and volumes of different rooms.

2.2.3 The present use of “Amager Bio”

“Amager Bio” is used for several activities like:

- Concert.
- Discotheque.
- Theatre.
- Stand-up comedy.

The above mentioned activities result in different fire scenarios and different number of people (the expected number of people is listed in Table 2.2. These events will be described when describing the fire scenarios and the evacuation scenarios, see Chapter 5 “Fire scenario analysis” and Chapter 9 “Evacuation of “Amager Bio””.

Activity	Expected number of people
Concert	1000
Discotheque	1000
Theatre	300
Stand-up comedy	300

Table 2.2: Expected number of people at different activities.

As seen in Table 2.2 there are no information of the expected number of people in the offices section, which lies upon the entrance hall (see Figure 2.3). The technic room as well as the offices are not evaluated further in this project.

2.3 Present fire precautions

In the following the present fire precautions in “Amager Bio” is described.

2.3.1 Detection of fire

9 ion-detector has been placed in the concert hall, see Appendix A. The detectors are connected to the alert system and the smoke ventilation.

2.3.2 Smoke ventilation

There are no natural smoke ventilation in “Amager Bio”. Instead “Amager Bio” is provided with mechanical ventilation that is activated by the detectors. There are two outlets from the concert hall that each has a separate ventilator with the capacity of 20000 m^3/h i.e. 5.5 m^3/s. By activation the ventilators start simultaneously. No emergency measures have been arranged in case of electrical failure. Instead the ventilators are connected with fire proof electrical cables to separate circuit. For location of the mechanical smoke ventilation, please see Figure 2.6. In order to compensate for the outflow of smoke inlets for ambient air have been installed under the toilet section, see Picture 2.5.

Picture 2.5: Location of air inlets (marked by the circle).

2.3.3 Alerting

An internal fire detection system with a delayed taped alert message has been installed and is activated by the smoke detectors. This system has no connection to the fire brigade. The alert signal is given by a tape recorder which is placed in the technic room together with its amplifier. Loudspeakers are placed in the concert hall and the foyer.

As further arrangement a small loudspeaker will be placed by the sound mixer in order to make the operator aware of the alert so he or she can turn of the ordinary sound system.

2.3.4 Fire fighting

Water-filled fire hoses are placed in accordance to the Danish legislation. This means that from an arbitrary location inside “Amager Bio” there must be no more than 25 metres to the nearest fire hose. One is placed in the foyer, another in the room beside the bar and the third by the landing platform between the concert hall and the balcony.

2.3.5 Further precautions

Emergency and panic lighting installed. There is an box for alert instructions. The staff have been instructed in case of an evacuation.

3. Legal authorities

In order to be able to plan a certain building and get the final building license it is necessary to have knowledge of the different laws, instructions, regulations etc. and knowledge of who the administrative authorities are.

In this fire safety evaluation two type of building regulations will be discussed. "Amager Bio" is located in Denmark and therefore the planning of the rebuilding is provided by the Danish law. The Danish building regulations are so-called pre-scribed regulations. This means that the solutions these regulations provides mostly rely on "rule of thumb" and old experiences. Opposite the pre-scribed building regulations are the performance based building regulations which are based on scientific solutions. The performance based building regulations are not used in Denmark but are under development. In Sweden the performance based regulations have been used since 1994.

⊇ "Amager Bio" will be evaluated after the Danish prescribed (BR95) and the Swedish performance based (BBR94) regulations. This gives us the opportunity to compare the prescribed and performance based regulations for this type of building.

3.1 The Danish building regulations

As mentioned above the BR95 (read: the Danish building regulations) is so-called prescribed regulations. When planning a building in Denmark you must fulfil the Building Act (DK: Byggeloven) and the Fire Act (DK: Beredskabsloven). To help the consulting engineers and architects the different authorities have made different regulations to provide legal solutions.

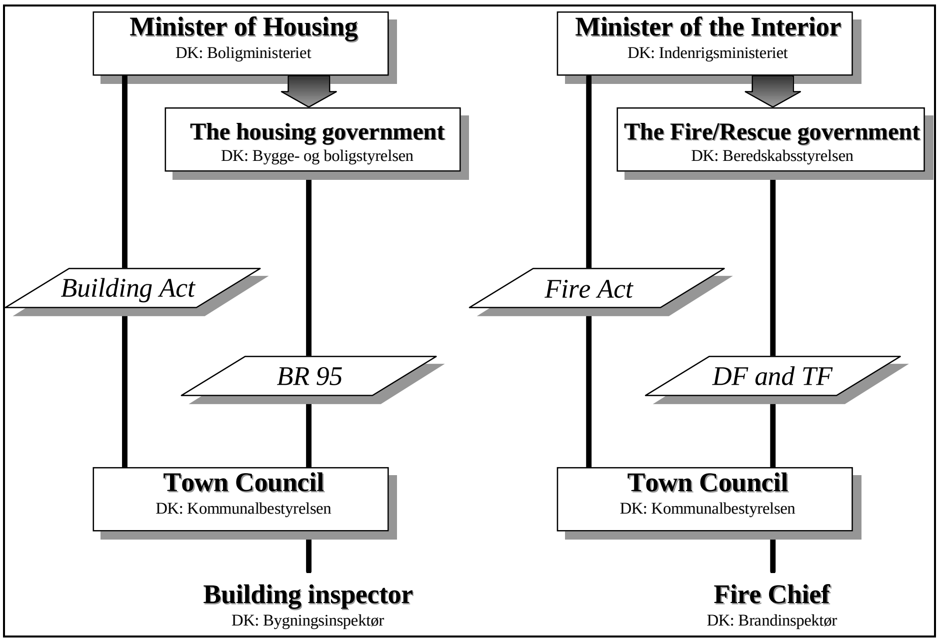


Figure 3.1: The structure of the Danish building respectively fire legislation.

- BR95: The Danish building regulations (DK: Bygningsreglementet 95).
- DF: Regulations for operation (DK: Driftmæssige foreskrifter.
- TF: Technical regulations: (DK: Tekniske foreskrifter).

- *BR 6.1 part 1*
  "Buildings shall be carried out in such a way that the building reaches a satisfactory safe level regarding fire and fire spread between buildings on or to nearby sites. There shall be secure opportunities for partly rescuing people and partly fire fighting".

In such way begins the Chapter concerning fire in the Danish building regulation. This is according to Danish law fulfilled if the BR95 is followed.

To fulfil the Danish law with respect to fire "Amager Bio" shall fulfil the following sections in BR95:

6.1	Over all.
6.2	Fire technical terms.
6.3	Distances.
6.4	Fire walls and fire section walls.
6.5	Escape routes.
6.6	Rescue.
6.7	Constructions.
6.11	Assembly halls.

In the following only the relevant parts of the BR95's chapter 6 are included.

	BR95	"Amager Bio"
6.1	***OVER ALL***	
6.1 part 1	*Buildings shall be carried out in such a way that the building reaches a satisfactory safe level regarding fire and fire spread between buildings on or to nearby sites. There shall be secure opportunities for partly rescuing people and partly fire fighting.*	This is fulfilled if the sections 6.1, 6.2, 6.3, 6.4, 6.5, 6.6, 6.7 and 6.11 are followed.
6.1 part 2	*Building that can be compared with respect to amount of people, sizes of fire compartments and fire sections, fire loads, exits, possibilities of fire fighting etc. to these building types that are described in section 6.8 - 6. 18 can be carried out after these regulations. Other building types can be build after those fire technical demands from the town council.*	"Amager Bio" can be compared to an assembly hall as described in section 6.11.
6.2	***Fire Technical Terms***	
6.2.1	***Fire compartments and fire sections***	
6.2.1 part 1	*A fire compartment is one or multiple rooms that are separated from other rooms or building with at least BD-60. A fire compartment is only allowed to cover 2 floors.*	An over all definition of fire compartments *BD-60* = flammable, but will prevent fire spread for at least 60 minutes.
6.2.1 part 2	*A fire section is one or multiple fire compartments that separate from nearby fire sections or buildings with at least BS - 60.*	An over all definition of fire sections. *BS-60* = not-flammable and will prevent fire spread for at least 60 minutes.
6.2.5	***Emergency light and panic lights***	
6.2.5 part 1	*Emergency lights shall be carried out as illuminated signs over or nearby escape exits. These signs shall be complemented with illuminated signs so any one from an arbitrary place in the escape route can see a sign leading to an exit.*	OK Signs have been placed so it is possible see signs leading to an exit.

6.2.5 part 2	*Panic lights shall illuminate the floor area with at least 1 lux in escape routes and on escape routes areas out the building.*	OK. Panic lights placed in the ceiling. We assume that they will illuminate the floor area as required.
6.3	***Distances***	
6.3 part 1	*Buildings that are build nearer that 2,5 m to neighbour boundary or centres of roads or paths shall be build with a fire wall against neighbour boundary, roads or paths.*	OK "Amager Bio" fulfils 6.3 part 1. Have fire wall towards nearby buildings.
6.4	***Fire walls and fire sections walls***	
6.4 part 1	*A fire wall shall be constructed as at least BS-120 and keep its stability no matter what side is influenced by fire.*	Definition.
6.4 part 2	*A fire section wall shall constructed as at least BS-60 and keep its stability no matter what side is influenced by fire.*	Definition.
6.5	***Escape routes***	
6.5.1	***Escape routes - over all***	
6.5.1 part 1	*Escape routes shall be constructed as passages and stairs in such a way that they provide safe possibility for the persons to access safe location outside the building.*	Definition.
6.5.2	***Escape routes***	
6.5.2 part 3	*A fire compartment designed for more than 50 persons shall have 2 independent escape routes with access to safe location outside the building. The exits shall be placed in opposite directions. The distance from an arbitrary place with in the fire compartment to nearest exit must not exceed 25 m. The exit doors from the fire compartment, escape routes and doors in escape routes shall have a total width of at least 10 mm for each person using this fire compartment.*	N.B The concert hall, foyer and the entry is an independent fire compartment. It can be discussed whether this fire compartment fulfils the requirement of two independent escape routes. The escape is very one sided i.e. main through out the exits in the concert hall. The exit door in the entry can only provide escape for 180 persons according to BR 6.5.2 part 3. This means that only 180 persons can be located more than 25 m away from the exits towards the alley. This is practically not possible. Therefore one may say that "Amager Bio" does not fulfil BR95 6.5.2 part 3.
6.5.4	***Stairs, staircases and lift shafts***	
6.5.4 part 1	*Stairs used as escape route shall be placed in staircase - except for exterior stair in 2-storey buildings. The staircase shall have directly access to a safe location outside the building. The staircase shall be carried out as a independent fire section.*	N.B. Escape route from the balcony is through staircases. One of them leads directly to the outside. The other leads to the entrée i.e. not directly to the outside. One may say that coming from the staircase into the entrée there will be no misunderstanding to what way the further escape shall go. Therefore one can interpret 6.5.4 so escape from the staircase through the entrée to the outside as a directly access to a safe location outside the building.
6.5.4 part 2	*Stairs used as escape route shall be carried out as at least BS-30. In a 2-storey building the stairs can be constructed in class B material.*	OK "Amager Bio" is a 2-storey building. The stairs are made of flammable materials (at least class B).
6.5.5	***Doors in escape routes***	
6.5.5 part 1	*Doors in escape route shall open in escape direction and easily open in escape direction without key or special tools.*	OK All doors open in the primary escape routes direction without use of key or special tools.

6.5.5 part 3	*Doors in escape route from halls designed for more than 150 persons shall each have a passing width of 1 m.*	OK "Amager Bio" is designed for more than 150 persons. All doors in escape route for more than 150 persons are at least 1,8 m wide.
6.6	***Rescue***	
6.6.2	***Areas for rescue and fire fighting***	
6.6.2 part 1	*It shall be possible to carry equipment for fire fighting to any door with access to terrain. There shall be a consolidated carriage road no more than 40 m. from doors with access to terrain.*	OK Fire trucks are able to drive all the way up to "Amager Bio".
6.7	***Constructions***	
6.7.1	***Over all***	
6.7.1 part 1	*Constructions shall be built together in such a way that the final construction with respect to fire is the standard as required for each construction.*	Definition.
6.7.2	***Constructions***	
6.7.2 part 1	*The load-bearing constructions in a building with only 1 storey shall be carried out as at least BD-30 in building with a floor area no more than 600 m^2.With a floor area higher than 600 m^2 the load-bearing construction shall be carried out as BD-60.*	OK "Amager Bio" have a floor area higher than 600 m^2 but the load-bearing construction are carried out as concrete construction (BS). We may assume that they will keep their stability and load-capacity for at least 60 min.
6.7.2 part 3	*In 1-storey buildings with basement the horizontal division and the bearing of the horizontal division shall be carried out as at least BS-60.*	OK The basement and the concert hall are separated by a concrete floor. The door between the basement and the concert hall is a *BS-60* door.
6.7.4	***Surfaces***	
6.7.4 part 1	*Outside walls in 1-storey buildings shall be carried out with outside surface as at least class 2 surface*	OK
6.7.4 part 4	*Interior surfaces on walls and ceilings shall be carried out as at least class 1 surface.*	OK
6.11	*Assembly halls*	
6.11.1	***Fire compartments and fire sections***	
6.11.1 part 1	*An assembly hall shall be carried out as an independent fire compartments and shall be separated from other room with at least BD-30-M door.*	"Amager Bio" are divided in to a major fire compartment (the foyer, entrée and the concert hall) and some other minor fire compartments. An approximate measure on the total width of the doors in escape routes is 11000 mm which gives a maximum person capacity of 1100 people in the concert hall. The fire compartments is separated from other rooms by BD-30-M doors.

6.11.1 part 2	*A section of assembly halls shall be carried out as an independent fire section of which the floor area must not exceed 1000 m^2 in multiple storey buildings and 2000 m^2 in 1-storey buildings. If one assembly hall in a 1-storey building are more than 2000 m^2 it shall be carried out as a independent fire section. This fire section can be carried out without sprinklers (any see 6.11.1 part 3).*	OK "Amager Bio" (concert hall, foyer, entree, dressing rooms etc.) is separated from the basement and the offices as a fire section.
6.11.1 part 3	*For assembly halls which primary use is exhibition or other events that can provide a enlargement of the fire load the town council can demand extra arrangement to reach that safety level as described in 6.1 part 1.*	N.B. The town council has required an investigation of the smoke ventilation.
6.11.1 part 4	*Surfaces on walls and ceilings in the assembly hall can be carried out as class 2 in 1-storey building if the floor area in the assembly hall is no more than 100 m^2.*	OK
6.11.1 part 5	*The flooring in assembly halls shall be qualificated with respect to fire. Class G flooring.*	OK In concert hall: wooden floor directly on concrete. In foyer vinyl-floor directly on concrete.
6.11.2	***Escape routes***	
6.11.2 part 1	*The way to the exits in assembly halls shall be a clear passage with a minimum width at 1,3 m, still at least 10 mm for each person expected to use the passage to get to the exit.*	O.K at least 1,8 m.
6.11.2 part 2	*The number of persons in assembly halls shall be calculated as 2 person per m^2 floor area. In assembly halls with non variable seats and in other assembly halls that are only used according to the seat accommodation approved by the Fire Chief one can calculated with this number of persons.*	N.B. "Amager Bio" has no fixed settings and shall be designed to the total amount of approx. 1000 persons.
6.11.2 part 3	*All exit doors from assembly halls shall be carried out as doors in an escape route.*	OK All doors opens in the direction of the escape route.
6.11.3	***Installations***	
6.11.3 part 1	*In a assembly hall designed for more than 150 persons and in escape routes designed for more than 150 persons shall have installed emergency lights and panic lighting.*	OK
6.11.3 part 2	*In a assembly hall without side lights and with larger floor area than 200 m2 the town council can demand fire ventilation.*	N.B. Town council have demanded mechanical smoke ventilation. The mechanical smoke ventilation will be evaluated in this report.
6.11.3 part 3	*A assembly hall designed for more than 150 persons and a escape route designed for more than 150 persons shall have installed water-filled fire hoses.*	OK Location of the water-filled fire hoses is shown in Appendix A.

3.2 The Swedish building regulations

The Swedish codes are as mentioned earlier performance based. It though is important to emphasise that performance based engineering and performance based codes are far from being identical. In performance-based fire safety engineering the engineer translates the maximum acceptable loss objective set by the authorities into engineering terms and develops design alternatives based on these and in performance-based codes the loss objectives are set by the codes defining fire safety goals and performance objectives.

The Swedish building regulations are BBR 94 (in Swedish: Boverkets Byggregler) which must be fulfilled along with the Building Act PBL (in Swedish: Plan och Bygglagen) in order to fulfil the criteria for a planned building. The relations of the Swedish building and fire legislation are shown in Figure 1.2.

Chapter 5 in BBR 94, ”Safety in case of fire” is subdivided into following sections:

5.1 General.
5.2 Fire resistance classes and other conditions.
5.3 Escape in event of fire.
5.4 Protection against the outbreak of fire.
5.5 Protections against the spread of fire inside a fire compartment.
5.6 Protection against the spread of fire and fire gases between fire compartments.
5.7 Protection against the spread of fire between buildings.
5.8 Load bearing capacity.
5.9 Fire fighting facilities.

Further Chapter 10 in BBR94, ”Resistance in case of fire” should be consulted in fire design.

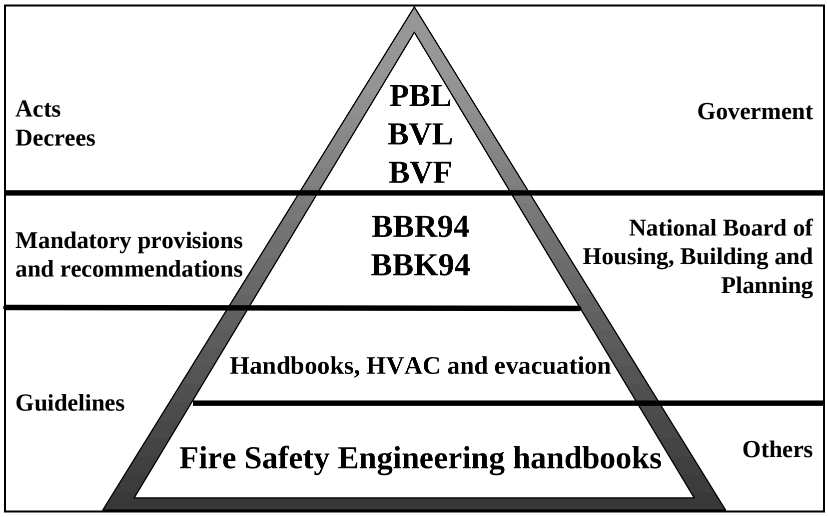


Figure 3.2: Swedish Building regulations.

The Swedish Building regulations is displayed in Figure 3.2 where:

- PBL Planning and Building act.
- BVL Act on Technical Requirements for Construction Works etc.
- BVF Decree on Technical Requirements for Construction Works etc.
- BBR94 Building regulations.
- BKR94 Construction Design Regulations.

	BBR94	“Amager Bio”
5:1	**General**	
	Can action by the rescue service be expected within the normal attendance time?	The fire brigade of Copenhagen judges the attendance time as 5 minutes to ”Amager Bio”
5:11	***Alternative design*** *Fire protection may be designed in a way different from that specified in this section if it is shown by a special investigation that the total fire protection of the building will not be inferior to that which would be obtained if all the requirements specified in the section had been complied with.*	”Amager Bio” is provided with mechanical smoke ventilation system. For a detailed description and analysis see Chapter 5 “Fire Scenario analysis” and Chapter 6 ”Smoke analysis”.
5:12	***Documentation*** *Fire protection documentation shall be drawn up. This shall set out the conditions on which fire protection is to be based and the design of the fire protection.*	As ”Amager Bio” is on a Danish ground it is not necessary according to BR 95 to draw up documentation and it has therefore not been done.
5:13	***Design by calculation*** *If design of fire protection is based on calculation, calculations shall be based on a carefully selected design fire and shall be performed in accordance with a model, which gives a satisfactory description of the problem at hand. The calculation model selected shall be stated. (BFS 1995:17)*	With the same reasons as stated in the comments for BBR94 5:12 no calculations have been done.
5:14	***Control of design for escape*** *In buildings where there is a risk of injury to persons, design for escape by calculation may be used only if the correctness of the calculation can be demonstrated by design control.*	This is done in Chapter 5 ”Fire scenario analysis”, Chapter 6 ”Smoke analysis, and Chapter 9 ”Evacuation of “Amager Bio””.
5:2	**Fire resistance classes and other conditions**	
5:21	***Buildings*** *A building shall be constructed to Class Br1, Br2 or Br3. Classifications shall take account of factors, which affect the possibility of escape and the risk for injury to persons in the event that the building collapses. The possibility of escape shall be assessed in view of the height and volume of the building and the activity which shall be carried on in the building at the same time and the likelihood that these persons can reach safety on their own. A building where a fire entails a high risk of injury to persons shall be constructed to Class Br1. In such buildings the most stringent requirements are imposed by on e.g.*	”Amager Bio” is a two-story building but has a few technical rooms on the third floor not directly connected to the rest of the building. It has an assembly hall on the first floor with a balcony within the assembly on the second floor, see Figure 2.6 and Picture 2.4. This does not make it an assembly hall on the second floor but it complicates the evacuation as the lowest acceptable level of critical smoke height for the whole assembly hall increases. The light conditions may also be insufficient in a theatre or a discotheque. On the balcony, which is 130 m^2, up to 200 people can be placed and according to recommendations, the building shall be classed in a class higher than the original class if the building is larger than 200m^2 and the internal balcony is larger than

finishes and load bearing and separating structures. A building where a fire may entail a moderate risk of injury to persons shall be constructed to Class Br2. Other buildings may be constructed to Class Br3.

50m^2[BVL].

In light of the facts above it is reasonable to class ”Amager Bio” as a *Br1* building.

5:22 ***Elements of structure, materials, claddings and surface finishes.***
Depending on their function, elements of structure are assigned in this status to the following classes:

- *R (load bearing capacity).*
- *E (integrity).*
- *I (insulation).*

The building has not been assigned to these classes but to classes in accordance with Danish rules, these being different from Swedish rules.

5:23 **Other general conditions**

5:232 ***Fire compartment***
The structures enclosing the fire compartment may comprise elements of structure with a lower fire resistance than that corresponding to the prescribed time if spread of fire in conjunction with these elements can be prevented by e.g. the action of the rescue service.

See detailed analysis in BBR94 5:6.

5:233 ***Escape route***
An escape route shall be an exit directly to a street or similar or an exit to a terrace, courtyard etc. from which a street or a similar space can be reached easily. An escape route may also be a space in a building which leads from a fire compartment to such an exit.

See detailed analysis in BBR94 5:3.

5:241 ***Places of assembly***
The term places of assembly refers to any premises of group of premises in a fire compartment in which a large number of persons who do not have full knowledge of the premises may be present.

”Amager Bio” does fulfil the criteria to be called a place of assembly.

5:3 **Escape in the event of fire**

5:31 ***General***
Buildings shall be designed so that satisfactory escape can be effected in the event of fire. Special attention shall be paid to the risk that persons may me injured by the fall of elements of structure or due to falls and congestion. and to the risk that persons may be trapped in recesses or dead ends.

The escape from ”Amager Bio” does not fulfil the BBR 94 escape regulations, se Chapter 9 “Evacuation of “Amager Bio””. The risk for a fall of elements of structure should be considered as minimum.

5:311 ***Access to escape routes***
Dwellings or premises other than those refers to in the subsection 5:313 where persons are present other than occasionally shall be provided with not less than two mutually independent escape routes. If the dwelling or premises have more than one story, at least one escape route shall be provided on each story.

The main escape route from the big assembly hall is through four exits out to an alley separated from the street by a fence. These are theoretically four different escape routes which is sufficient for the assembly hall but it is though recommended that the escape routes are wider spread around the concert hall [BS].

Escape from an assembly hall through another fire compartment is not allowed but in reality people will move through the foyer in the case of fire [Håkan Frantzich].

The rooms at the back of the stages are classed in the same fire compartment as the assembly hall.

The internal balcony has as two external escape routes in form of two stairways.

The foyer has only one escape route, which should not accepted. In practice the escape will be trough the assembly hall if for example a fire breaks out in the cloakroom [Håkan Frantzich].

The rooms on the third floor have as escape routes the two stairs were the external balcony serves as a way to escape route.

5.312 ***Windows as escape route***
In dwellings -but not alternative forms of dwelling -, offices and comparable spaces in a building, one of the escape routes may consist of a window provided that escape can take place safely. In assessing the situations, consideration shall be given to whether or not the equipment of the rescue service can be used for escape.

One of the two exits from the two offices on the second floor, over the foyer, will have to be through a window. This can be accepted as it leads to a place where the fire brigade will be able to come to rescue. The minimal width should be 0.5 m, the height 0.6 m and the sum of width and height at least 1.5 m [BS]. Only few persons are supposed to be present at each time in the offices.

5:313 ***Only one escape route***
A stairway, Tr1, may be the only escape route from dwellings, … offices and comparable premises in a building irrespective of the number of storeys. The stairway may not be in communication with the basement.

Not relevant.

5:33 Travel distance

5:331 ***Travel distance to an escape route***
The travel distance inside a fire compartment to the nearest escape stairway leading into the street or similar space shall not be so great that the compartment cannot be evacuated before critical conditions arise.

See Chapter 9 “Evacuation of "Amager Bio”".

5:332 ***Travel distance along an escape route***
Along an escape route, the travel distance to the nearest stairway leading to another storey, or to an exit leading into the street or similar space, shall not be so great that escape cannot take place rapidly.

See Chapter 9 “Evacuation of “Amager Bio””.

5:34 Access

5:341 ***The dimensions of escape routes***
Escape routes shall be designed to be so spacious and to permit such ease of movement that they are capable of serving the number of persons for which they are intended.

Although the stairs are narrow for the escape from the third floor they are judged as sufficient for the persons who may be expected to be present at each time.

5:342 ***Doors in escape route***
Doors to or in an escape route shall normally open outwards in the direction of escape and shall be easy to identify as exits. Inward opening doors may be used only if they are intended for:

- *a small number of persons, e.g. the doors of dwellings or guest rooms in hotels,*

The doors leading in and out of the stairways are on the other hand to narrow (80 cm) and the width should be increased to at least 90 cm. The doors leading to the outside are of sufficient width (1.8 m) and so are the doors between the assembly hall and the foyer.

All the doors leading directly to the outside does open

- *a moderate number of persons who may be expected to have a good knowledge of the premises, e.g. the doors of class rooms in schools, or*
- *small premises.*

Other types of doors such as revolving or sliding doors are permitted if they provide the same degree of safety for escape as outward opening side hung door.

in the primary escape direction.

5:35 **Equipment**

5:351 ***Guidance sign***

Guidance signs for escape shall be provided if the persons considered may be expected not to have good knowledge of the premises, such as hotels, institutional buildings (apart from nursery schools and similar) and places of assembly. The same requirement shall apply to premises in which it is difficult to find one's way about or into which daylight does not penetrate. Guidance signs shall be provided in such numbers and shall be positioned in such a way that escape is not impeded by difficulty in finding one's way in the building. Signs shall be an illuminated or luminous green panel with a prominent white symbol.

The guidance signs have to placed as shown in Appendix A "Drawings". This placement is accordance to [BBR94] and Swedish Standard [SS 3611 (1)] or in accordance with the general recommendations of the Swedish Board of Occupational Safety and Health (AFS 1994:47).

Generally can be said that placements of guidance were well in order with respect to [BBR 94] as the Danish regulation [BR 95] are similar to the Swedish one.

5:352 ***Emergency lighting***

Emergency lighting shall permit escape in a safe and effective manner even in the event of power failure. Emergency lightning shall be provided in the escape routes in buildings containing hotels, institutional premises or places of assembly.

The emergency lighting shall perform its function in every escape route which has not been blocked by fire. In the event of power failure the emergency lighting shall provide the intended illumination for not less than 60 minutes.

Emergency lightning is installed.

5:354 Alarm systems

5:354 1 ***Automatic fire alarm***

In buildings or art of buildings where early detection of fire is a requirement, an automatic fire alarm shall be installed. Where this is possible, detection shall be by means of smoke detectors. the system shall transmit a signal to a staffed position when persons are present in the building.

Smoke detectors are present but not connected to the fire brigade.

5:354 2 ***Escape alarm***

In buildings or part of buildings where an escape alarm or loudspeaker installation intended for escape announcements is required, it shall be possible for the affected persons to be reached by information regarding the appropriate action to be taken for escape. In the event of power failure the function of the installation shall be maintained for not less than 60 minutes.

Assembly halls should be provided with escape alarms "Amager Bio" is provided with escape alarm (spoken signal).

5:36 Design conditions

5:361 ***Critical conditions in the event of escape.*** *Design with respect to the safety of escape, the conditions in the building shall not become such that the limiting values for critical conditions are exceeded during the time needed for escape.*

The total safety level is described in Chapter 11 “Fire safety level”.

5.37 Special conditions

5:371
1 ***Places of assembly*** *Escape routes from places of assembly shall be designed for the number of persons who are permitted to be present in the premises. Escape from places of assembly shall not take place through other places of assembly. As a general recommendation, places of assembly should have not less than three escape routes if they are intended for more than 600 persons, and not less than four if they are intended for more than 1000 persons.*

See BBR 94 5:311 and 5:361.

5:371
1 ***Escape alarm*** *Places of assembly shall be provided with an escape alarm, which is activated automatically or from a staffed position when a fire is indicated.*

Escape alarm in the concert hall and the foyer

5:5 ***Protection against fire spread within a fire compartment***

5:51 **Requirements regarding materials, surface finishes and claddings**

5:511 ***General*** *Materials in elements of structure, fittings and fixtures shall have such properties or form part of the element of structure in such a way that in the event of fire they do not give rise to ignition or rapid flame spread of fire, nor do they rapidly evolve large quantities of heat or fire gases.*

According to Danish material classification the interior on walls and ceilings should be Class 1 and floors Class 2. This is fulfilled in ”Amager Bio”.
See BR 95 6.7.4 and 6.11.1 part 3.

5:512 ***Surface finishes and claddings in escape routes.*** *Surface finishes and claddings in escape routes shall be of material which provide negligible contribution to the spread of fire. In buildings of class Br1 the floor covering in escape routes shall be constructed of a material with a moderate propensity to spread and evolve fire gases.*

See BR 95 6.7.4 and 6.11.1.

5:6 Protection against the spread of fire and fire gases between fire compartments

5:61 ***Division into fire compartments***

Buildings shall be divided into fire compartments separated by elements of structure which impede the spread of fire and fire gases. Each fire compartment shall comprise a room - or associated groups of rooms - in which the activity has no immediate connection with other activities in the building. Each fire compartment shall be separated from other spaces in the building by elements of structure (including service penetrations, necessary supports, connections and similar) constructed to not less than the fire resistance class commensuated with the requirements in section 5:6-5:8.

The ”Amager Bio” should be divided into fire compartments. These are as follows:

- The entrance hall, the foyer and the big assembly hall have to be formed as one fire compartment.
- The two narrow stairs at the back of the balcony must be formed as separate fire compartments as the bind together the basement, ground floor second floor and the separated third floor.
- The compartments on the third floor are one fire compartment and so is the basement.

Figures showing the fire compartments are shown in Appendix A.

5:62 ***The fire resistance class of elements of structure separating fire compartments.***

The elements of structure separating the compartments shall be imperforate to the penetration of flames and gases, and shall have such thermal insulation that the temperature on the side not affected by fire does not give rise to the risk of fire spread. The element of structure shall be constructed in such a way that is maintains its separating function for the period of time specified in the requirements concerning the fire resistance of the structure, set out in Subsection 5:621 (design by classification), with fire action in accordance with Swedish Standard SIS 02 48 20 (2) or in accordance with a design based on a model of a natural fire sequence.

As stated above ”Amager Bio” is a *Br1* building with a fire load more than 200 MJ but less than 400 MJ and therefore it will have to have separation of Class EI 120.

There is only 60 minutes separation between the fire compartments, which is according to BR 95 and that of course applies also to doors.

5:621
4 ***Doors, shutters and access panels***

Doors, shutters and access panels in elements of structure separating compartments shall normally be constructed to the same fire resistance class as that which applies to the element of structure in question.

For buildings in Class Br1, doors and similar between routes and dwellings or offices, schools, hotels, residents' store rooms and comparable fire compartments may be constructed to not less than Class EI 30.

Due to the fact that people will escape in less than 10 minutes and due placement of escape routs should be necessary that the doors, shutters and exit panels can be constructed in class EI 60.

See also Chapter 9 ”Evacuation of Amager Bio”

5:63 ***External walls and windows***

Facade cladding shall not in the event of fire evolve heat and smoke to such an extent that escape and fire fighting are impeded or in such a way that there is a serious risk of injury to persons in its vicinity.

”Amager Bio” has cement claddings on the outside and shall not increase the flame spread.

5:7	Protection against the spread of fire between buildings	
5:72	***Design depending on the distance between buildings*** *Buildings erected nearer than 4.0 m from the boundary of neighbouring building plot shall be designed so that the risk of the spread of fire to buildings on the neighbouring plot is nevertheless not less than 8.0 m.*	As ”Amager Bio” contains very few windows the danger of fire spread to neighbouring buildings is minimum.
5:74	***Fire walls*** *A fire wall shall limit a fire without the action of the rescue service. The wall shall have such a stability and load bearing capacity that it is possible for buildings on either side to collapse without an appreciable reduction in the properties of the fire wall.* *The fire wall shall withstand the mechanical stresses which are likely to occur in the event of fire and be designed so that it can be easily located by the rescue service.* *Elements of structure or services placed on or adjacent to a fire wall shall have such facilities for movement that deformations caused by a fire do not jeopardise the function of the wall. Junctions with other elements of structure shall be designed so that there is no adverse effect on the function on the fire wall.*	”Amager Bio” is separated from another building by a wall as seen in Figure 1.3. Fire resistance class for fire walls are REI M120 for a fire load of ≤400 MJ. This is fulfilled for ”Amager Bio” The wall is judged to be able to withstand mechanical stresses and be able to remain it’s function in the case of fire.
5:8	**Load bearing capacity in the event of fire**	
5:81	***General*** *Load bearing structures shall be designed and sized so that in the event of fire there is adequate structural safety with respect to material failure and instability in the form of local, overall and lateral buckling and similar.*	Load bearing structures are made of concrete. The temperature from the design fire is far from being sufficiently high to jeopardise the structural capacity in the case of fire.
5:9	**Fire fighting facilities**	
5:93	***Equipment for manual fire fighting*** *In buildings with large differences in level, in larger buildings and in buildings where a fire is likely to spread rapidly, assume very high intensity or entail a serious risk of injury to persons, permanent equipment which facilitated fire fighting shall be provided.*	Water filled fire hoses are present. Individual distance no larger 50 m. No portable fire extinguishers.
5:94	***Access for the rescue service*** *If the street network of similar does not afford access for the vehicles of the rescue service for evacuation and fire fighting, a special carriageway (rescue road) shall be provided. This shall be signposted and provided with hardstandings which have sufficient space for the intended vehicles.*	Copenhagen fire brigade has equipment to deal with buildings like ”Amager Bio” and ”Amager Kulturpunkt” and a neighbourhood like the one that surrounds it.

4. Fire Scenarios

In 1995 in Denmark the total amount of fires to which the fire brigades responded was 19.543 costing 95 lives. The fires where the direct damage was over 1.000.000 DKr each mounts up in 332 fires resulting in 1.069.800.000 DKr paid out by the fire insurance companies. Each these fires was carefully investigated to find the probable cause of fire [BV96]. In Table 4.1 the causes are listed to give an idea to where a fire in “Amager Bio” likely would start. Approximately 15% of all these fires, costing more that 1.000.000 DKr each, are believed to have been started deliberately. 35% are caused by incautiousness. Technical failure gives the same percentage. We believe that causes like smoking, incautious with fire and other kinds of incautiousness leading to fire are likely for “Amager Bio” besides technical failures. Also probable outbreak of arson fires will be given.

Established or presumed cause of fire	Number of fires in 1995
Unknown/not cleared up	50
Arson / vandalism	50
Children playing with fire	2
Fireworks	4
Spontaneous ignition	21
Chimney fire	11
Work on roofing felt	2
Welding	16
Smoking	11
Incautious with fire	22
Other kinds of incautiousness leading to fire	25
Incautiousness	114
Short circuit or other electrical failure	69
Superheating and friction heat	29
Other technical failure	16
Technical failures	114
Lightning	4
Other weather conditions	0
Weather	4
All fires	332

Table 4.1: Probable causes of fire. [BV96].

The fire loads in “Amager Bio” are accumulated on different locations. The largest fire loads are present on the stage, in the cloakroom, in the dressing rooms and in the storage for chairs. In the following different outbreaks of fires will be discussed and it will be described how the fires spread. We have chosen to list some fire scenarios that we believe will cause life threatening situations for persons inside “Amager Bio”. Hereby we have deselected minor fire scenarios such as fire in a waste basket etc. This has been done, based on the sensitivity analysis of Hazard I showing that minor fire scenarios will not generate enough heat to build a two-zone-model. For further discussion please refer to Chapter 5 “Fire scenario analysis”.

Probable fire scenarios that will generate enough heat and smoke to cause a potential danger for persons inside “Amager Bio”:

- Fire on stage.
- Fire under seat when having a show.
- Fire in the electrical installations.
- Fire in the cloakroom.
- Fire in the dressing room.
- Fire in the storage for chairs.

4.1 Fire on the stage

It is Saturday night. The concert hall is filled with people anxious to see tonight's show. The light subdues and the act starts. It is a very interesting act. Suddenly smoke is coming up from underneath the stage. The playgoers thinks that this is a nice detail, but the smoke continues getting more dense and after a short while flames are visible on and under the stage. A short circuit in some electrical installation incautious placed under the stage has ignited some papers. It is very difficult to put out the fire due its location under the stage. The fire spreads to the stage where it ignites a sofa and from here it spreads to the set pieces. Now the fire has grown to such a size that it is impossible for the fire guard to put out the fire and it accelerates.

Picture 4.1: The stage with set pieces.

4.1.1 Rate of heat release

In order to be able to described how the fire develops we have picked certain items that will ignite during the ongoing fire. We assume that the fire starts at time equals zero seconds ($t = 0$) by igniting the sofa. At this time the playgoers become aware of the danger and starts the evacuation, please refer to Chapter 8 "Evacuation". We assume that the fire spreads to the set pieces at $t = 60$. The rate of heat release for a sofa has been determined by experiments. The rate of heat release for the set piece has been calculated from assumptions and knowledge on the rate of combustion and data on wood material. Please refer to Appendix B "Fire scenarios" for calculations leading to the following rate of heat release for fire on the stage.

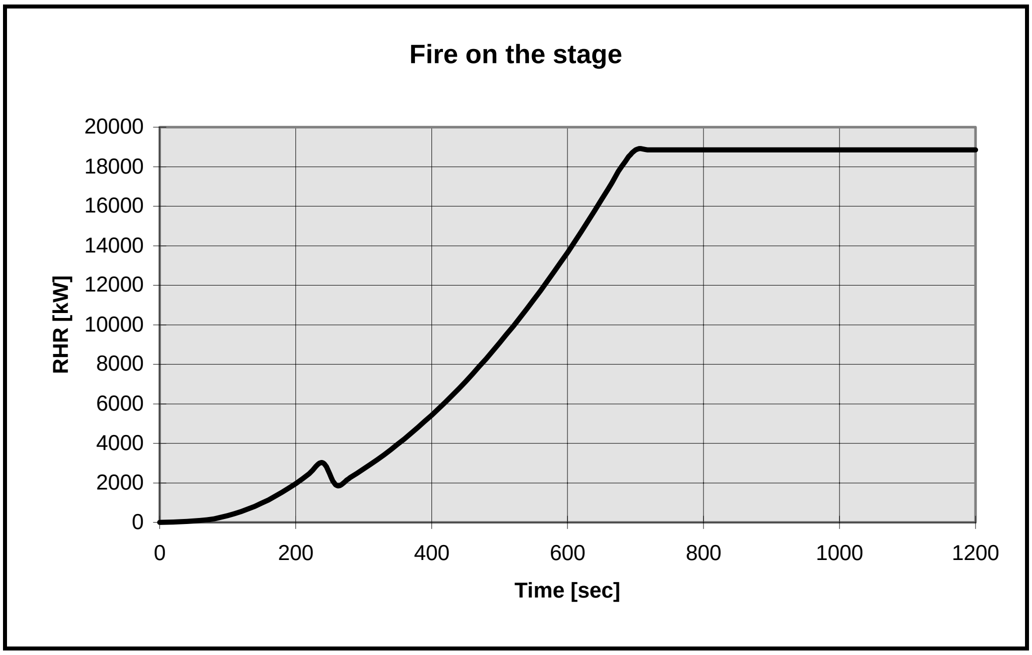


Figure 4.1: RHR for fire on the stage.

4.2 Fire under the seats when having a show

Under the seat terrace it is possible to store different kind of equipment. When visiting “Amager Bio” we saw several cardboard boxes stored under the seat terrace, please see Picture 4.2. These boxes can be ignited by accidentally dropped cigarette or a short circuit in some electrical installations. First there will be smouldering and after a while the boxes will ignite giving a fast fire spread to nearby boxes. The fast fire spread is caused by the plastics inside the boxes. It is possible for the flames to rise up between the seats.

Picture 4.2: Boxes under seat terrace.

We believe the fire first will be discovered when dense smoke or flames are coming up between the seats. This can perhaps cause a panic situation, which will be described in Chapter 8 “Evacuation”. When the boxes starts smouldering the playgoers will be able to smell the smoke but it can be very difficult to locate the ongoing fire. Another matter could be that the playgoers do no pay any attention to this smell because it could be a part of the show or something else.

4.2.1 Rate of heat release

At t = 0 the fire will burn with visible flames and we will for this moment ignore the smouldering phase. The smouldering phase can produce considerable amount of “cold” smoke, please refer to Chapter 6 “Smoke analysis”. By judgement we assume that each of the boxes are having approximately the same rate of heat release as a sack filled with rubbish giving a peak heat release on 150 kW for each box [Initial, Y3.4/23]. We assume the fire starts in one box and spread further to 3 boxes after 60 seconds. These 3 boxes reaches the peak of 450 kW at t = 120 giving a fire spread to further 6 boxes. These 6 boxes ignites 12 boxes at t = 150. Here after we have a decay phase.

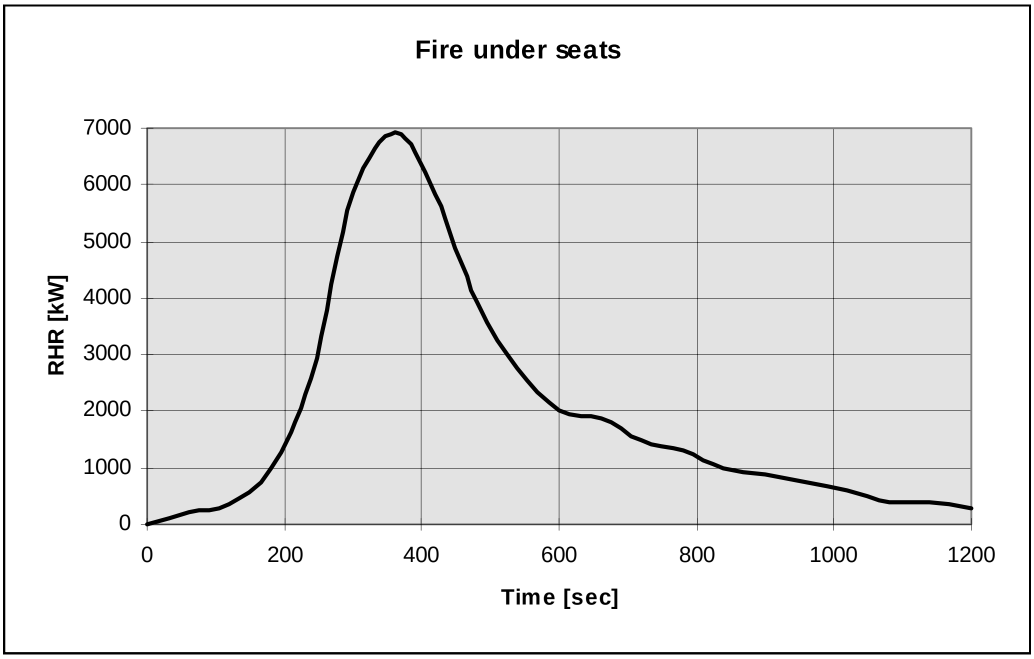
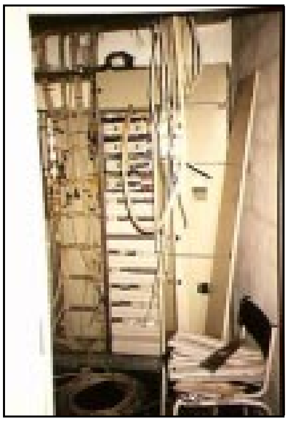


Figure 4.2: RHR for fire under the seats.

4.3 Fire in electrical installations

A special room for electrical installations are located beside the dressings rooms (see Figure 2.4). The probability for outbreak of fire in this room is present according to Table 4.1. A fire in the electrical installations will produce lots of dense smoke that will result in difficult escape for persons inside the “Amager Bio”. The doors to this room will probably be closed. But if further electrical connections are needed in the concert hall some may open door and maintain it open in order to draw cables from this room to the concert hall. Picture 4.3 shows the room during the rebuilding phase and is therefore not representative for the present conditions in this room. At our inspection at “Amager Bio” the door between this room and the concert hall was maintained open. So the assumed scenario is possible.



Picture 4.3: Electrical installations.

When a fire breaks out in this room it can be very difficult to discover due to the room’s location. The room is located in the far corner just beside the stage, please see Figure 2.4. The door between this room and the concert hall is elevated about 1,2 metres leaving the top of the door in a height of 3,2 metres. When the lights in the concert hall is subdued it can be very difficult to see the smoke coming out of the door. We believe that the fire be discovered when flames are out the opening. At this point a flashover in the room has occurred producing a tremendous amount of smoke spreading into the concert hall.

4.3.1 Rate of heat release

The room is very small but with 2 doors. Therefore a flashover is probable to occur. The fire will be guided by the rate of heat release for cables [Initial, J4/10] and the peak of the heat release will be determined by the ventilation areas. By ventilation areas are meant whether the doors are opened or not. For calculations of peak heat release please refer to Appendix B “Fire scenarios”.

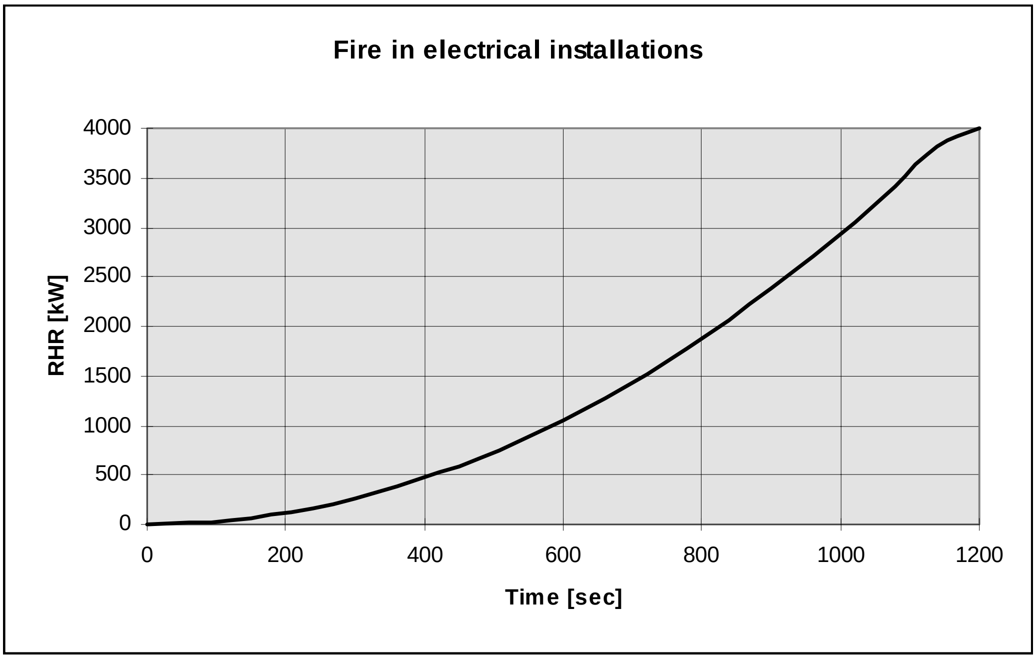


Figure 4.3: RHR for fire in the electrical installations.

4.4 Fire in the cloakroom

The cloak room is equipped with doors that automatically closes when a fire is detected by one of the 2 smoke detectors placed at the ceiling on each side of the door. The doors are maintained opened by electromagnetic devices. It is a known fact that after a while these electromagnetic devices will turn in to a permanent magnetic device that will not release in case of fire detection. Arrangements at “Amager Bio” will lead to many people inside the concert hall leaving many jackets in the cloakroom. An arson fire in this room can have fatal consequences if the doors would not closed due to the above mentioned phenomenon.

Picture 4.4: Cloakroom seen from the foyer.

The cloakroom will then have a tremendous fire loads compared to the size of the room. This will probable lead to flashover. On the other hand a fire in room can easily be extinguished. But if the unfortunate conditions are that the employee in the cloakroom panics and the fire are allowed to develop spreading smoke into the foyer. The fire will result in all the people escaping throughout the exits against the alley.

4.4.1 Rate of heat release

We assume that there will be 500 jacket in the cloakroom when the fire begin in the wastebasket or ignited by an arsonist. We also assume that all the jacket are made of polyester. The rate of heat release can be determined for polyester and the peak of heat release are dependent of the inflow of air. Please refer to Appendix B “Fire scenarios” for calculations leading to the following rate of heat release for fire in the cloakroom.

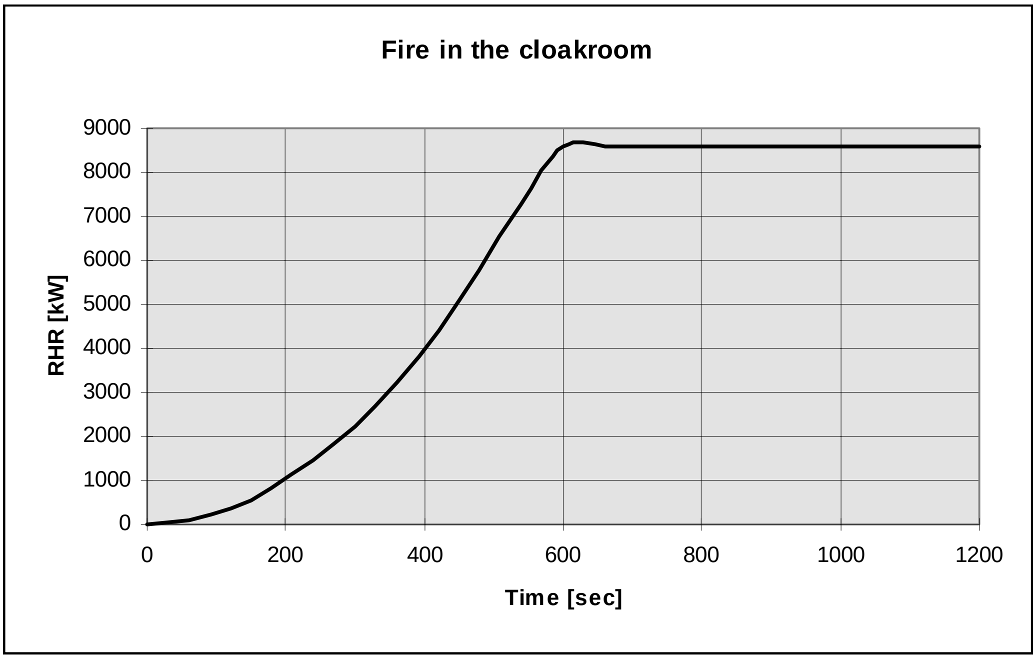
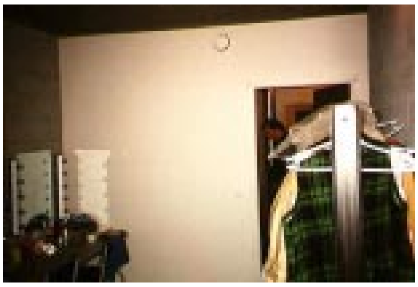


Figure 4.4: RHR for fire in the cloakroom.

4.5 Fire in the dressing room



Picture 4.5: The dressing room.

The dressing room for the actors are also a potential location for outbreak of fire. An ashtray emptied in a wastebasket can ignite the contents of the wastebasket. The fire can spread to the clothes hanging on the hanger. Many other items in the room will catch fire and suddenly we may have a flashover. This is again dependent on whether the fire can get oxygen enough or not. In other words whether the door is closed or open.

4.5.1 Rate of heat release

Almost the same fire scenario as in the cloakroom. The number of jackets/clothes are not the same. The dressing room is also a small compartment. Therefore the flashover will again give us the upper limit for the peak heat release.

Figure 4.5: RHR for fire in the dressing room.

4.6 Fire in the storage for chairs

Picture 4.6: Stacked chairs placed under the stairs - not in the storage for chairs.

"Amager Bio" can be used for concerts as well as for theatres. At concerts all the chairs used for theatre will be stored in a separate room. A room like this could be a possible target for an arsonist. The door between this room an the concert hall is equipped with a door spring. Therefore it shall be a sum of unlucky circumstances before a fire in this room will be a direct treat to the people inside "Amager Bio". Please observe that Picture 4.6 do not represent the room for storage of chairs but only shows stacked chairs. First we shall have a outbreak of the fire. The cause of fire can be different thing ex. arsonist, technical failures etc. Next the door could be open to get a major development in the fire. There are no windows or other openings beside the door that can contribute with oxygen to the fire.

4.6.1 Rate of heat release

It can be very difficult to estimate the fire development but we assume that the fire development follows an αt^2 - fire growth where the fire growth equal a medium fire development.

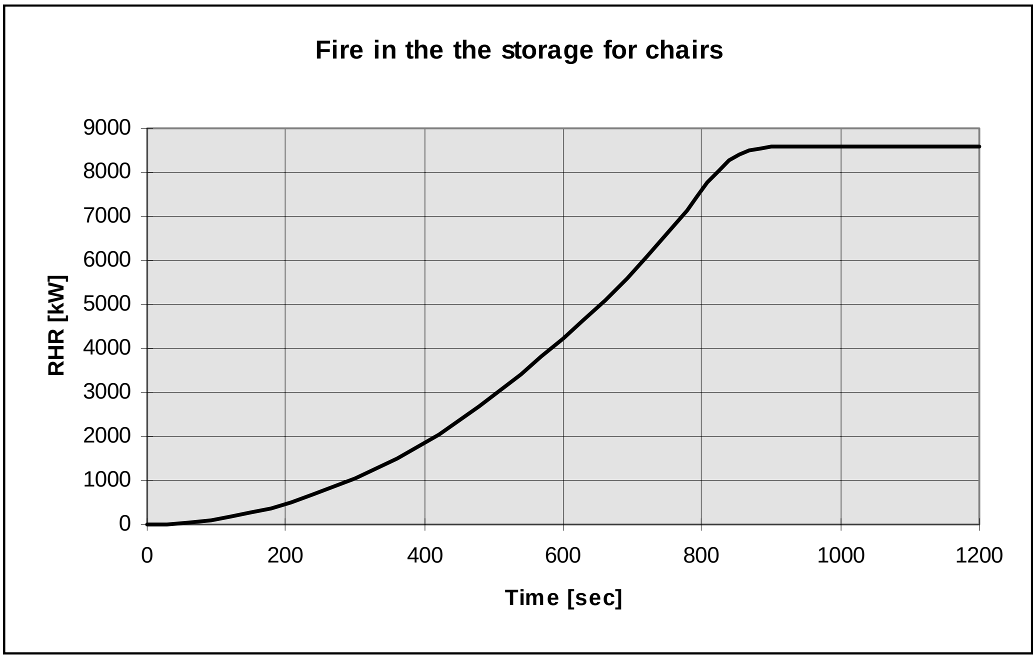


Figure 4.6: RHR for fire in the storage for chairs.

5. Fire scenario analysis

A most important parameter in the fire safety evaluation is the critical time. Critical time we define as the time from the fire outbreak to the time where conditions in the building becomes life-threatening due to the fire development. In order to determine whether the conditions are life-threatening or not we will define some criteria for life-threatening conditions. These criteria are not necessary directly life-threatening but can result in danger to health. Why do we want to determine a critical time? We have to estimate the time to which the evacuation shall be completed in order to secure human lives!

We will in the following use the terminology “upper layer” and “lower layer”. If we divide the fire compartment into two halves, the smoke filled part is called the upper layer and the non-smoke filled part is called lower layer, please see Figure 5.1. This is of course a qualified truth because it is not possible to state a clear boundary between smoke filled and non-smoke filled layer. Instead we have a diluted area dividing the upper and the lower layer.

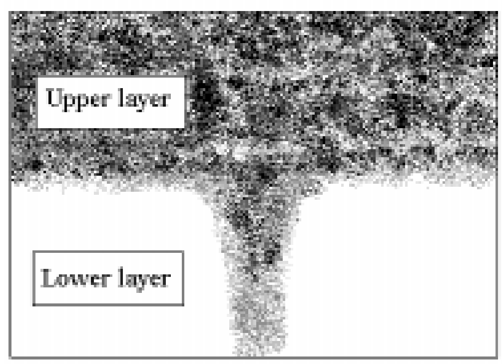


Figure 5.1: Definition of the upper and the lower layer.

We have chosen to define the following criteria in order determine whether we have critical conditions or not.

- The mean temperature in the upper layer > 500°C.
- The mean temperature in the lower layer > 80°C.
- The height of the lower layer < 2,5 m.
- The visibility inside the building < 10 m.
- The radiation at the floor > 1 kW/m^2.

As the fire develops the temperature in the upper layer increases. If the mean temperature in the upper layer exceed 500°C there is an impending danger of flash over. The radiation from the upper layer will spontaneously ignite any flammable objects in the fire compartment. Different criteria have been set for the flash over. Other means that flash over occur when the temperature is above 450°C or when the radiation to the floor is 20 kW/m^2. The fire can also heat up the lower layer. A temperature greater than 80°C can result in a hard evacuation of the people inside the building. The hot gasses can be hampering to lungs and eyes and can in worst case cause lung oedema. People shall be able to orientate throughout the evacuation. Therefore they shall not be disturbed by the smoke layer. This is the reason why a limit for the height of the lower layer shall be set. The height is calculated to 2,5 m (see Appendix B). In real life it is as mentioned above not possible to define a sharp separation between the upper layer and the lower layer. There will be diluted smoke in the lower layer as well. Therefore a criterion could be that the diluted smoke in the lower layer must not worsen the evacuation. This is assumed fulfilled if the visibility in the height of 2 m. is no less than 10 m matching 1 obscure. For further reading about visibility analysis please read Chapter 6 “Smoke analysis”. The last criterion we have stated as a critical condition is the radiation at the floor. If this value exceeds 1 kW/m^2 it will worsen the evacuation [BS, page 79]. This criterion is of course exceed if flash over occurs.

Through different kind of analysis the aim is to estimate the critical time. The critical time is calculated on the basis of the probable fire scenarios listed in Chapter 4 “Fire scenarios”. All the listed criteria will be examined in this chapter except the criterion about visibility which will be examined in Chapter 6 “Smoke analysis”.

Here under are listed the different steps in the examination in order to estimate the critical time:

- The rise of plume.
- Flame heights.
- Modelling of “Amager Bio”.
- Sensitivity analysis of the models.
- Sensitivity analysis of the selected model.
- Simulation of the different fire scenarios in Hazard.

The following analysis is takes its origin in the so-called two-zone model. Briefly the two-zone model is based on an equilibrium of mass and energy plus the equation of continuity used on the upper and lower layers. For further reading about the two-zone model, please refer to Appendix H.

In order to determine whether the two-zone model can be used or not it is necessary to estimate the rise of the plume. The buoyancy and hereby the effect of the fire shall be large enough to lift the smoke to the ceiling. If the flame heights are at such a size that the flame will reach the ceiling the two-zone modelling can not be used in the fire compartment. In order to simulate the fire scenarios in “Amager Bio” one must set up a model of “Amager Bio” for use in Hazard. Hazard is a fire scenario simulation software based upon two-zone-modelling and is described in details in Appendix H. We have set up 3 different kinds of models to simulate the fire scenarios. A sensitivity analysis of the models will give us a model for further use and a sensitivity of this model will estimate the suitability of this model. Finally the different fire scenarios will be simulated in order to estimate the critical time.

5.1 The rise of the plume

When the plume rises from the fire it will retrain air that will cool down the plume. If the difference between the mean temperature in the plume and the ambient temperature is less than approximately 30°C the buoyancy force is not sufficient enough to lift the plume. In order to estimate a upper and a lower layer the difference in temperature must be at least 30-40°C [SEM]. Else the smoke will loose its buoyancy force and therefore mix with ambient air. Hereby one will have a diluted smoke in the building and no clear line between upper and lower layer. This means no two-zone modelling. If this happens the analysis should be carried out as in Chapter 6 “Smoke analysis”.

The rise of the plume is calculated for different rate of heat releases and can be used in general to see the height of the plume. For calculations and assumptions please read Appendix C “Fire scenario analysis”.

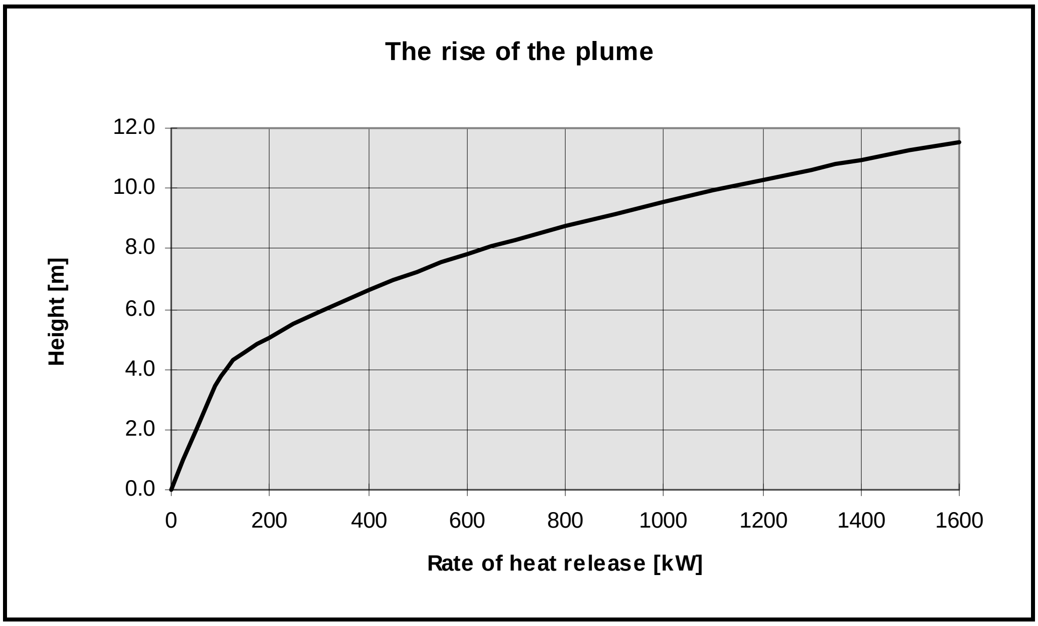


Figure 5.2: Rise of the plume as a function of the rate of heat release.

It can be observed in Figure 5.2 that the plume will reach the ceiling in the concert hall when the rate of heat release exceeds 900 kW. Until the rate of heat release reaches 900 kW the two-zone modelling can not be used. For example a waste basket which have the rate of heat release at approx. 100 kW will not develop enough heat to make the plume rise to the ceiling in the concert hall. Instead the smoke from the fire in the waste basket will mix with the ambient air and by time get well-stirred. Calculations on well-stirred mixtures are described in Chapter 6.

5.2 Flame heights

Another limitation to the use of two-zone modelling is the flame heights. If the flame heights reaches the ceiling the two-zone modelling or Hazard can not be used for the room where the fire breaks out. The reason is that the flames will heat up the gasses nearby an therefore give a worse case than the two-zone modelling can show. It is therefore interesting to observe the flame heights as functions of the heat release from and the diameter of the fire. The calculations are accounted in Appendix C "Fire scenario analysis". The fire scenario where it can be interesting to observe the flame height is at the fire on the stage. The stage is elevated approximately 1 m above floor level and set pieces are elevated approximately 3 m above floor level. When having a fire on the stage the flames shall be no higher than 6 m. When modelling the fire scenario on the stage it is important to compare the rate of heat release and the flame heights. As seen in Figure 5.3 the mean flame height varies with the *RHR* and the area of the burning surface. Take a *RHR* = 15000 kW and a burning area = 20 m^2 the mean flame height is calculated to 6 m. Therefore the burning area shall be larger than 25 m^2 if the flames not shall reach the ceiling. Using 650 kW/m^2 as a guide for the rate of heat release for each square meter burning set piece [Ondrus, Chapter 6] one can calculate that approx. 30 m2 will be burning when having the max. RHR for the fire on the stage (please refer to Appendix C "Fire scenario analysis").

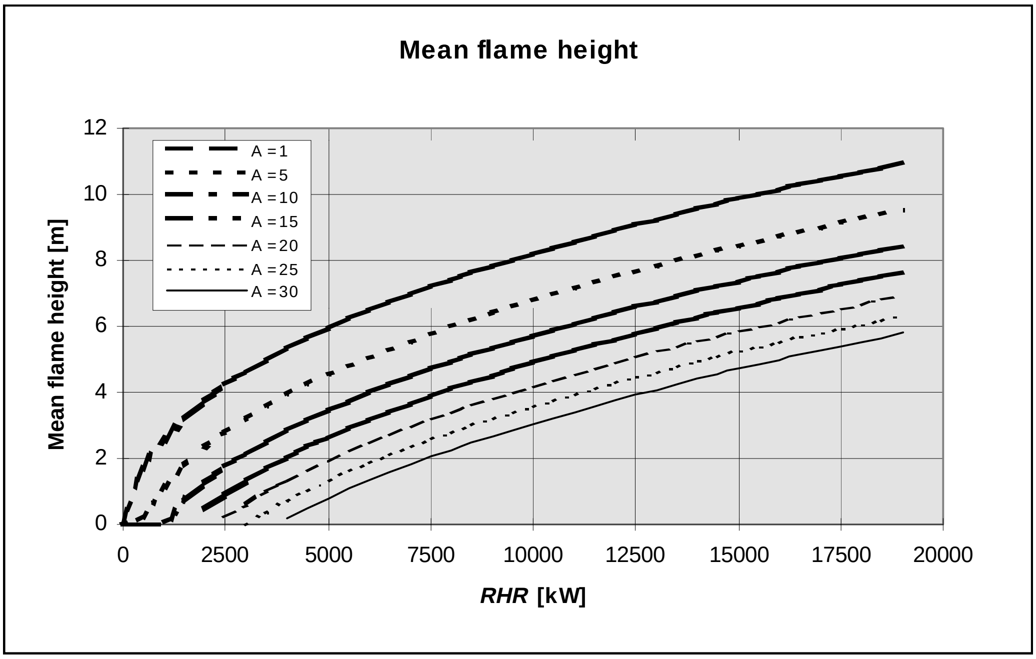


Figure 5.3: Mean flame height as a function of the RHR and the burning area.

5.3 Models for use in Hazard

Hazard is one of many tools one can use in estimating the critical time. One has to set up a model for use in Hazard. For description of Hazard please read Appendix H. Hazard can operate with 15 different rooms each connected trough ventilation area such as doors, ceiling vents etc. Each room shall have the shape of a box. Therefore it is not possible to set up an exact model of "Amager Bio". Instead one may try to approximate the building with box-like shapes as shown in Figure 5.5 - Figure 5.7. When setting up a model it is of great importance that the boxes' volumes are in accordance with the real building's volume.

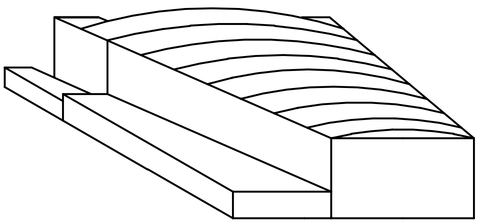


Figure 5.4: Perspective drawing of "Amager Bio".

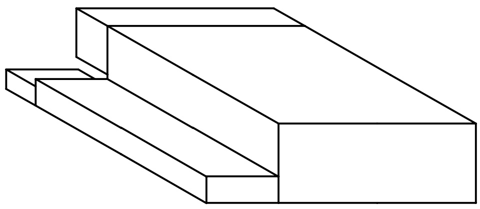


Figure 5.5: Hazard model 1 (HM1).

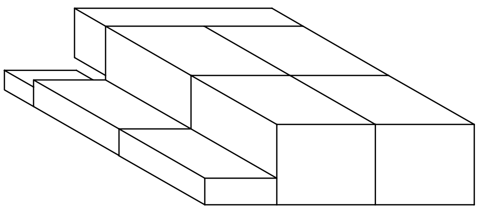


Figure 5.6: Hazard model 2 (HM2).

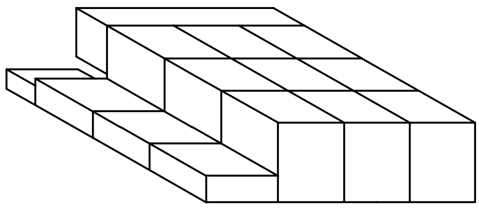


Figure 5.7: Hazard model 3 (HM3).

As observed different kinds of divisions of the "Amager Bio" model can be set up. The Hazard model 1 is the most simple model and Hazard model 3 is the most complicated. Other kinds of models can be set up but these three different kinds of models are the ones we have chosen to use. In order to determine which model is the most suitable regarding accuracy, time-consuming and computer-capacity one may carry out a sensitivity analysis.

5.4 Sensitivity analysis

In order to determine which model will provide us with the best results during the simulations of the different fire scenarios in “Amager Bio” one should carry out a sensitivity analysis. By comparing the difference in the results from the same fire scenario simulated in all three models it is possible to pick out the model for further use in this fire safety evaluation.

The fire scenario chosen to carry out this sensitivity analysis is a fictive fire in the concert hall as shown in Figure 5.8.

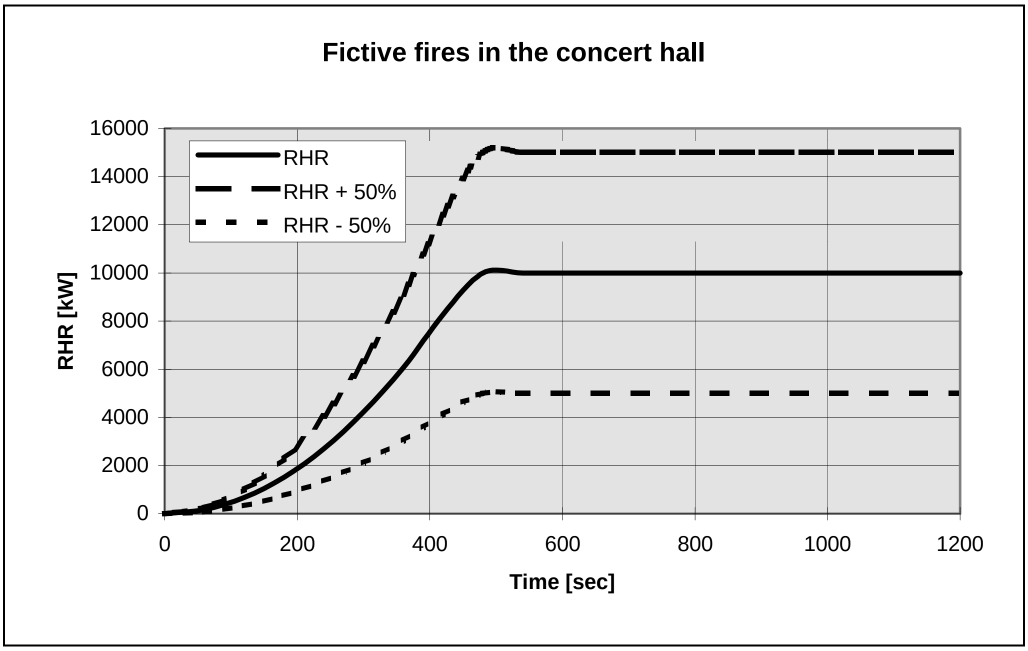


Figure 5.8: Fictive fires in the concert hall.

In order to see how different fires effect the models one may increase and decrease the *RHR*. We have chosen to increase and decrease the *RHR* with +50% respectively -50%. By doing this we will have fire scenarios in the size of the probable fire scenarios in “Amager Bio” and hereby get an idea how the models will respond to these fire scenarios. All simulations appear in Appendix H “Hazard simulations”.

In the following the three models will be named HM1 (Hazard model 1), HM2 (Hazard model 2) and HM3 (Hazard model 3).

5.4.1 Sensitivity analysis of the different models

In this sensitivity analysis we will only compare the effect of making the model more complex i.e. the effect of dividing the building into several boxes as seen in Figure 5.5 - Figure 5.7. In HM1 the building has been divided into 4 different boxes, in HM2 into 7 different boxes and finally in HM3 into 14 different boxes. We will compare the smoke-filling and temperature development in each model.

The sensitivity analysis was carried out on all three models. In order to determine which model shall be used for the fire scenario analysis one may compare the results from all of the simulations. In the following we will present the most important results from this sensitivity analysis. One shall be aware of the limitations in using computer-software to simulate fire development and smoke spread. If a complex model i.e. a model with many boxes is chosen then there will be a risk of bad harmony in modelling rooms far away from the origin of the fire. Opposite if a simple model i.e. a model with few boxes is chosen there will be a risk of slow smoke-filling and too high temperatures, which can result in unreal simulation. Using Hazard for simulation one shall be aware of when dividing the boxes with balks the software calculates with line-plumes as shown in Figure 5.9. This will result in a dilution of the smoke which again will result in lower temperatures and faster smoke-filling. There are many things to take into consideration before selecting the model for further use in the analysis.

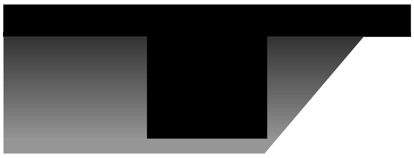


Figure 5.9: Fundamental illustration of a line plume at a balk.

Figure 5.10 shows the comparison of the temperatures in the concert hall i.e. the temperatures in the box where the fire breaks out. As observed the temperatures do not vary much no matter which model is chosen.. If we instead observe the temperature development in the foyer one may see, as expected that the HM1 provides the highest temperatures and HM3 provides the lowest temperatures. For mapping of the temperature development in the foyer, please see Appendix C "Fire scenario analysis".

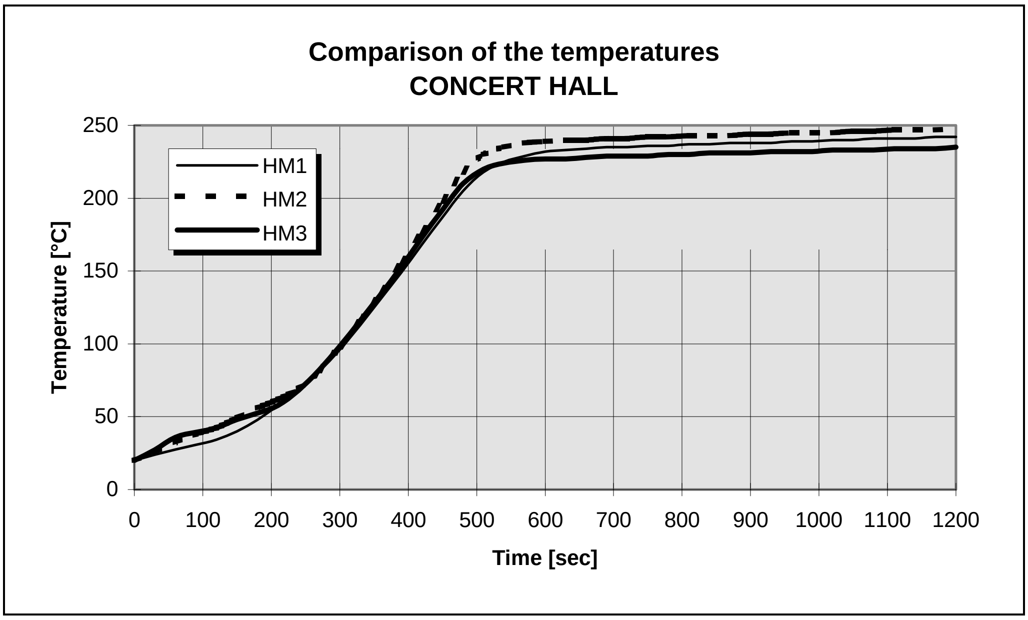


Figure 5.10: Comparison of the temperatures in the concert hall.

The comparison of the temperatures in different room can not provide us with a selection of model. Instead we will compare the smoke layer heights in different boxes. Again one may compare the smoke layer height in the box where the fire starts, please see Figure 5.11. As predicted the smoke-filling happens faster in HM3 than in HM1. It is very difficult to say which model provides us with the best results.

If one compare the smoke layer height in the foyer one may see that the use of HM1 gives us a slower smoke-filling than using HM2 or HM3. For comparison of the smoke layer height in the foyer, please see Appendix C "Fire scenario analysis". The results from HM1 have a minor deviation from the results of HM2 and HM3. Therefore we choose to deselect HM1 leaving HM2 and HM3.

The sensitivity analysis of the different models shows no outstanding deviations between the different models so no matter what model was selected it would provide us with results that could be use to the determination of critical time. The model we choose to use to determine the critical time is HM2. The results from the sensitivity analysis show that HM2's result lies in between the results from HM1 respectively HM3 and will therefore provide us with "mean" results.

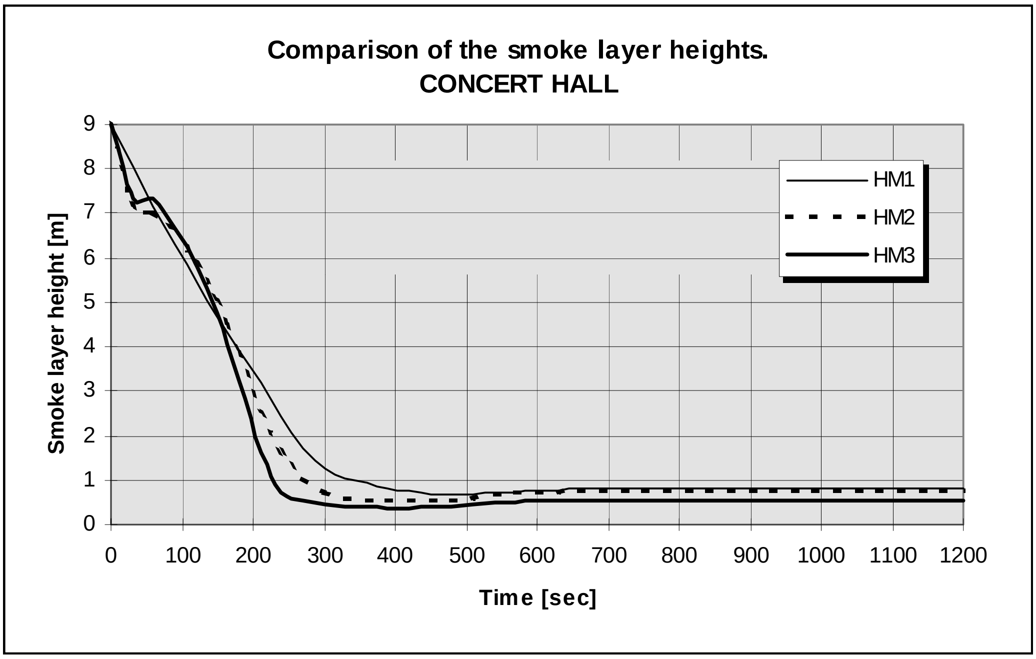


Figure 5.11 : Comparison of the smoke layer heights in the concert hall.

5.4.2 Sensitivity analysis of Hazard model 2

After selecting HM2 as the model to use for determination of the critical time one may continue the sensitivity analysis by comparing how the temperatures and smoke layer heights varies with the in-flow area. First we will compare the effect of changing the size of the fire i.e. the effect of RHR (T1), RHR+50% (T2) and RHR-50% (T3). Only two comparisons will be present here in the main report, see Figure 5.12 and Figure 5.13 The remaining comparisons are mapped in Appendix C "Fire scenario analysis".

First a comparison of how the temperature and smoke layer heights changes with change in RHR, see Figure 5.12. As observed in Figure 5.12 Hazard responds to the increase (T2) and decrease (T3) of RHR by varying the mean temperature in the upper layer approximately ± 80°C. The percentage in rise of temperatures (T2) is not the same as the percentage of decrease (T3). This being due to the increase loss of heat through the construction when having increased temperatures. The smoke layer heights do not vary much with the different tests. This model responds very well on increase and decrease of RHR and the smoke layer heights are almost constant i.e. they do not have the same percentage in increase and decrease as the temperatures do. What can be questioned is the density of the smoke. When the temperatures in the upper layer are high the assumption of two-zones will be in accordance with reality. Opposite we believe when having too low temperatures in the upper layer the smoke will mix with the lower layer resulting in a approximated well-stirred mixture. Analysing Figure 5.12 one will observe that the mean temperatures are approximately 50 - 75 °C when having critical smoke layer heights. The question is if there is enough buoyancy in the smoke to build an upper and a lower layer? This is of course an estimation and therefore one shall not rely 100% on such simulations. The fire scenario analysis shall in such cases be complemented with other kinds of calculation such as visibility-analysis and calculations by hand.

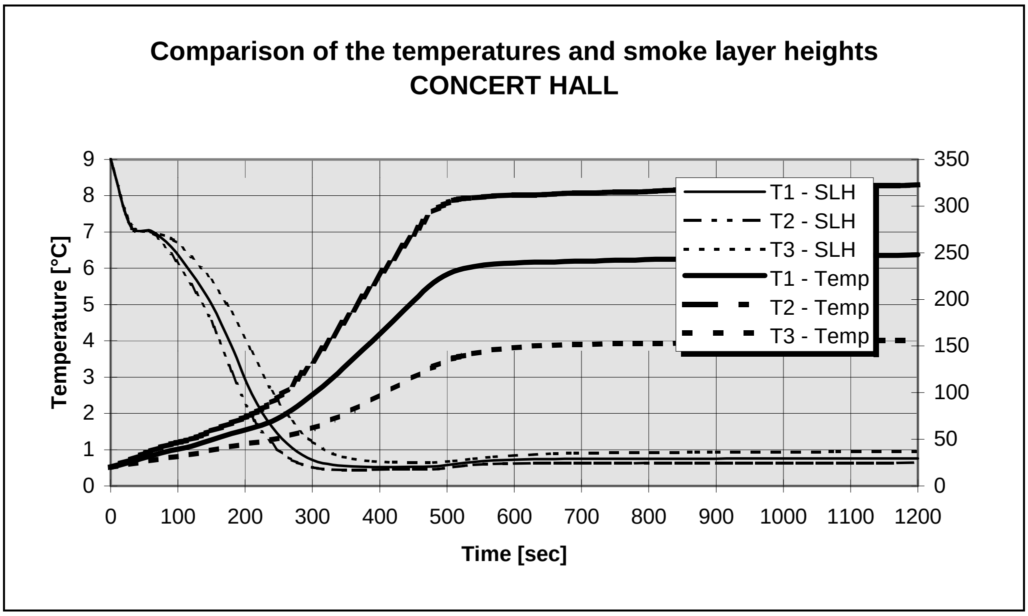


Figure 5.12:Comparison of the temperatures (Temp) and the smoke layer heights (SLH) in Box 7. (T1 = RHR, T2 = RHR+50%, T3 = RHR-50%).

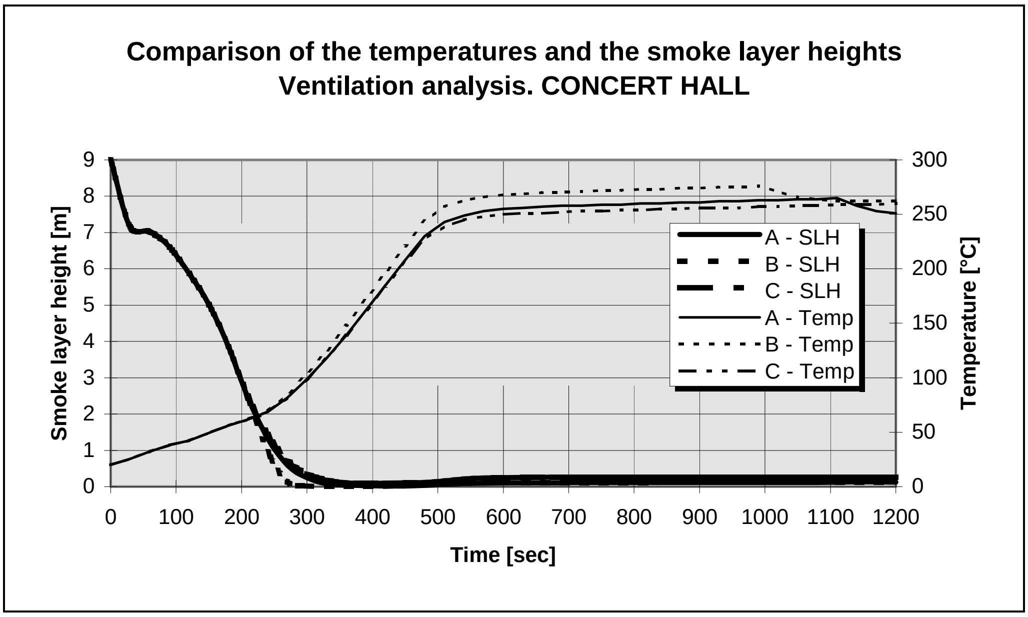


Figure 5.13: Comparison of the temperatures and smoke layer heights in Box 7 (Concert hall). Fictive fire in the concert hall. (A = all doors open, B = all doors to the outside and the foyer closed, C = three doors to the alley closed).

The next comparison is the effect of the in-flow areas. One may be interested in how the areas of the in-flow and hereby the access to oxygen will influence the temperatures and smoke layer heights, see Figure 5.13. We have chosen to carry out three different kinds of simulations. First where all doors in the building was opened (A). Second where the doors to the foyer and the outside was closed. Hereby we could see the effect of having the fire in the concert hall and no in-flow at all (B). Finally the only in-flow areas was two doors to the outside. The door in the entry and one door in the concert hall. Hereby we could observe an effect in between totally opened and totally closed. As seen in Figure 5.13 the inflow areas have practically no effect on the fire development. After approximately 1000 seconds the temperatures in (B) and (C) have a tendency of decrease due to lack of oxygen. But this happens in the final stage of the simulation and have no effect no the determination of critical time. Therefore one may conclude that the simulations can be carried out without any attention to the in-flow areas (exit doors).

The results of these sensitivity analysis are that Hazard model 2 has been chosen since there was no worth mentioned difference between the three different models (HM1, HM2, HM3) and HM2 “gave results in between”. The further sensitivity analysis of HM2 showed good response to increase and decrease in rate of heat release plus no influence of changing the areas of inflow. Therefore HM2 and hereby Hazard will be used as one of the calculations to determine the critical time.

5.5 Fire in “Amager Bio”

All the fire scenarios described in Chapter 4 “Fire scenarios” has been simulated in Hazard using HM2. The results from each simulation appear in Appendix H “Hazard simulations”.

In Chapter 4 we have made the assumption that in some fire scenarios the maximum rate of heat release would be guided by the inflow during flash over. Therefore we should check up on if flash over actually occurs and hereby make certain that the assumption is OK. In all the fire scenarios where flash over will guide the maximum RHR flash over actually occurs resulting in that the assumption is all right.

One may determine a design fire leading to a critical time. The design fire is the fire that first will lead to critical conditions. Therefore a comparison of the different simulations are to be done. The people are concentrated in the foyer and the concert hall and the balcony. Therefore the comparison will be carried out in these rooms. Taking there three rooms the only condition leading to critical conditions is the smoke layer height and therefore the comparison will be done on smoke layer heights.

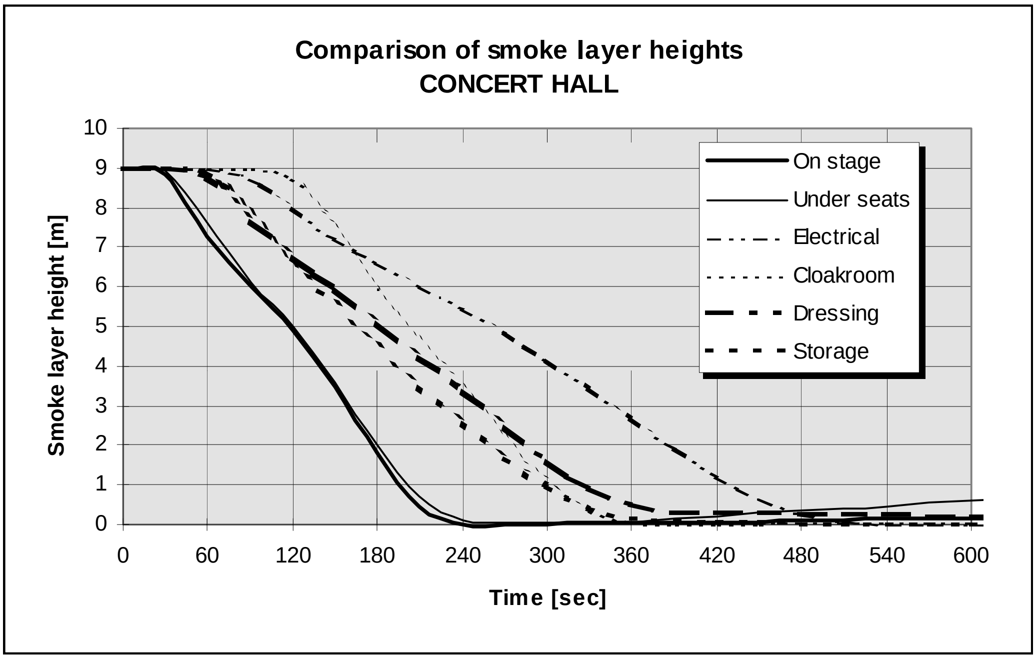


Figure 5.14: Comparison of the smoke layer heights in the concert hall.

In the concert hall it is the fire on the stage that will lead to critical conditions after approximately 170 seconds, see Figure 5.14.

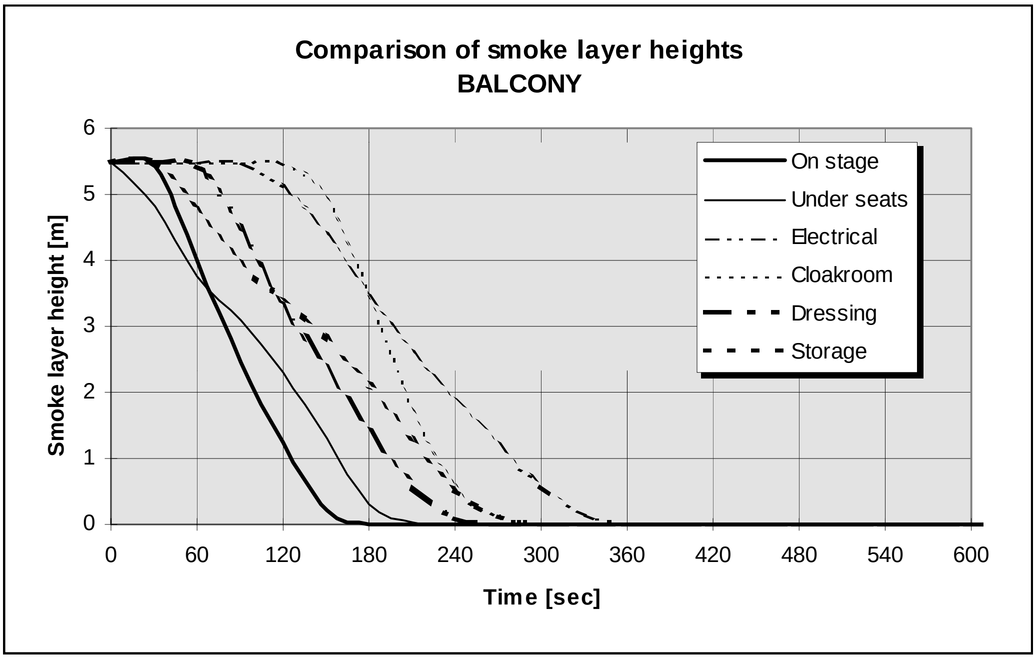


Figure 5.15: Comparison of the smoke layer height on the balcony.

We will have critical conditions on the balcony after approximately 100 seconds when having a fire on the stage, see Figure 5.15.

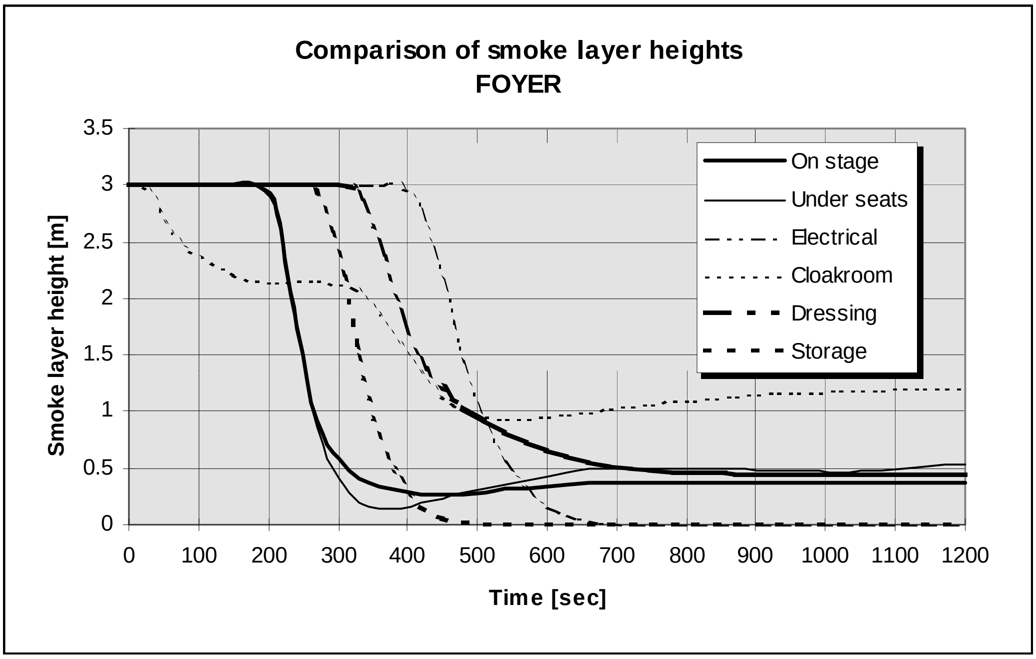


Figure 5.16:Comparison of the smoke layer heights in the foyer.

Critical conditions will be reached in the foyer after approximately 240 seconds, please see Figure 5.16.

5.5.1 The design fire determined by Hazard

The design fire in "Amager Bio" will be the fire on the stage in accordance to the Hazard simulations. The fire on the stage will in all simulations lead to critical conditions in shortest time. One shall be aware of that the design fire has been selected without paying attention to the mechanical ventilation and that the fire on the stage may not be the design fire in other method for determination of critical time. One may assume that the mechanical ventilation will decrease the critical time, Please refer to Chapter 7 "Critical time".

5.5.2 Critical time determined by Hazard (No ventilation)

Critical times have been determined for the different fires. In Table 5.1 the critical times for every fire scenario are listed for use in the comparison with the evacuation time. One should that the absolute critical time and compare this with the absolute slowest evacuation time. The reason why one may list all the critical times is that the fires' location can block certain exit and therefore have a worsen effect on the evacuation time. A comparison of critical times determined by different methods has been made in Chapter 7 "Critical time".

Please notice that the critical times in Table 5.1 have been calculated without any smoke ventilation.

Location of fire	Critical time		
	Concert hall [sec]	Balcony [sec]	Foyer [sec]
Fire on the stage	170	90	230
Fire under the seats	170	130	230
Fire in electrical installations	380	240	460
Fire in the cloakroom	270	210	230
Fire in the dressing room	270	160	380
Fire in the storage for chairs	260	180	300

Table 5.1: Critical times determined by Hazard simulations.

5.6 Smoke management in large spaces

The Hazard simulations shall not be used without any kind of scruples. The concert hall has a very large volume compared with the sizes of the fires. As observed in earlier figures of Hazard simulations the smoke-filling is almost total before the temperatures are at such a size that one definitely calculate the concert hall as a two-zone. In order to complement and verify the results from Hazard one may carry out a calculation by hand. We have chosen to use an equation based on experimental data in large spaces with the ratio of the cross-section area to the square of the height of the large space (A/H^2) $\in$ [0.9;14] [DSMS, 10.4.12]. This is fulfilled for the concert hall. For the calculations and the equations, please refer to Appendix C "Fire scenario analysis". The equation is based on unobstructed plume flow, which we can assume occurring since the fires are located away from any walls.

The calculations are done for the fire on the stage and for the fire under the seats since these fires are the only ones occurring directly inside the concert hall. We may assume that the plume flow from fire under the seats is unobstructed i.e. no spread under the seat terrace.

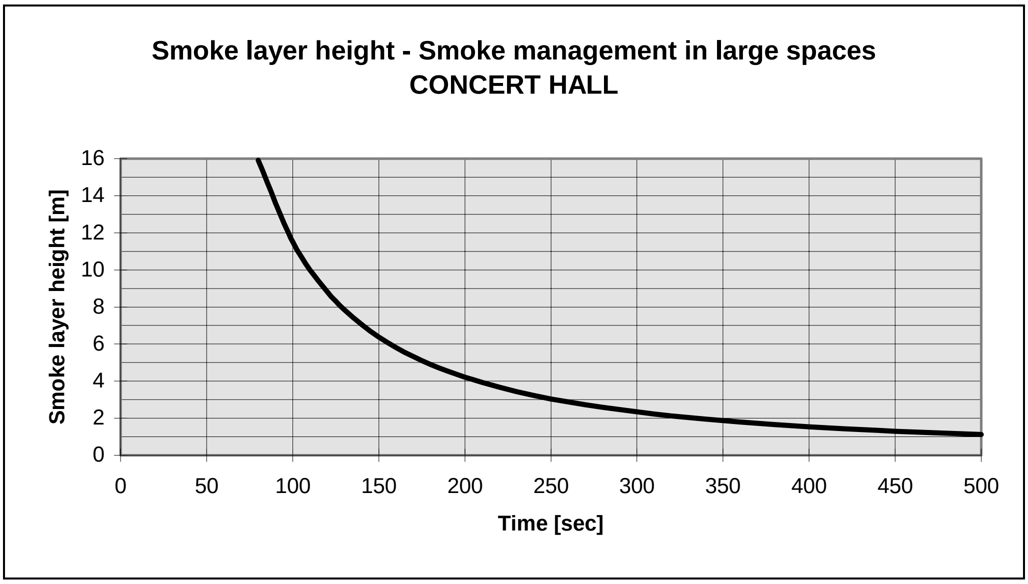


Figure 5.17: Fire on the stage. Smoke layer height calculated on experimental data.

As seen in Figure 5.17 the smoke layer height is located above the ceiling until approximately 120 seconds. This shall be interpreted to mean that a uniform smoke layer over the entire cross section area of the concert hall has not yet been formed [DSMS, 10.4.1.1]. After 275 seconds. critical conditions occur. The smoke layer height has been calculated without taking the mechanical ventilation into account. For the effect of the mechanical ventilation, please read Chapter 7 “Smoke ventilation”.

Figure 5.18 shows the smoke layer height when having a fire under the seats. Here a uniform smoke layer is formed after approx. 130 seconds. Critical conditions occur after approx. 325 seconds.

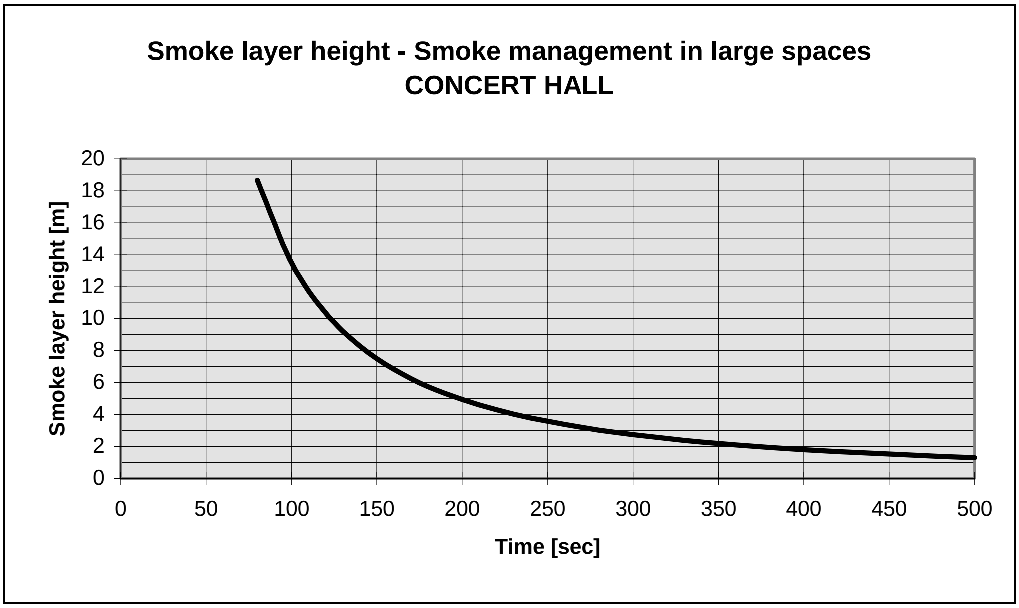


Figure 5.18: Fire under the seats. Smoke layer height calculated on experimental data

5.6.1 Critical condition by the use of equation based on experiments

The critical conditions, see Table 5.2, is calculated by use of the equation described in Appendix C "Fire scenario analysis". One shall be aware of that these critical conditions are calculated without the mechanical ventilation taken into consideration. The influence of mechanical ventilation is calculated in Chapter 7 "Smoke ventilation".

Location of the fire	Time to uniform smoke layer [sec]	Critical time [sec]
Fire on the stage	120	275
Fire under the seats	130	325

Table 5.2: Critical conditions by the use of equation based on experiments.

The critical time determined by the equation we observe the almost the same shape on graph but the critical time is approx. 100 seconds larger than the critical time determine by Hazard without mechanical ventilation (see Table 5.1). The reason can be that Hazard calculates a twozone from the beginning while the equation "waits" for a uniform smoke layer to be build. Hereby the critical time will be move in positive direction.

5.7 Smoke ventilation

In order to determine the effect of the present mechanical smoke ventilation one may carry out calculations showing its influence on the critical time. The effect of the mechanical ventilation will be calculated in three different ways:

- By the use of Hazard.
- By the use of CCFM.
- By the use of the Tanaka - Yamana equations.

For the above standing methods the smoke ventilation's effect will be calculated on basis of the temperature and smoke layer height development. For the influence of the ventilation on the visibility, please refer to Chapter 6 "Smoke analysis".

Hazard has in Chapter 5 "Fire scenario analysis" been used for calculating the critical time without paying any attention to the mechanical smoke ventilation. Therefore it would be natural to continue with Hazard when calculating the influence of the mechanical smoke ventilation on the critical time. Our experience with the use of Hazard to calculations involving mechanical ventilation is limited. To test the sufficiency of Hazard to this type of calculation one may compare the results from Hazard to the results from the other methods. The results from Hazard will be compared to results from CCFM-vent, obscure calculations and results from Tanaka-Yamana.

The prior calculations of the critical time was without taking the smoke ventilation into consideration. In the following the effect of the smoke ventilation on the critical time will be discussed.

5.7.1 The present smoke ventilation

The mechanical smoke ventilation is to be considered as a substitute to natural smoke ventilation (buoyancy). "Amager Bio" is as described in Chapter 2 an old building rebuilded into a concert hall etc. The character of the building is the special concrete ceiling which would be a shame to partly destroy in order to install natural smoke ventilation. Therefore the fire department i.e. the town council demanded mechanical smoke ventilation instead. There are placed two outlets in the ceiling of the concert hall, please refer to Chapter 2 "Description of the object". The total capacity of these ventilators is approximately 40000 m^3/h i.e. 11.1 m^3/s. The mechanical smoke ventilation is activated by smoke detectors.

5.7.2 Smoke ventilation by use of Hazard

As mentioned above spoken from experience the results when using Hazard to calculate the effect of the smoke ventilation can not be used without any scruples. The results from Hazard shall be complemented with other methods of calculation. It is assumed that the smoke ventilation and the fire starts simultaneously. This is of course not correct due to the activation time of the smoke detectors and will therefore result in a solution on the non-safe side.

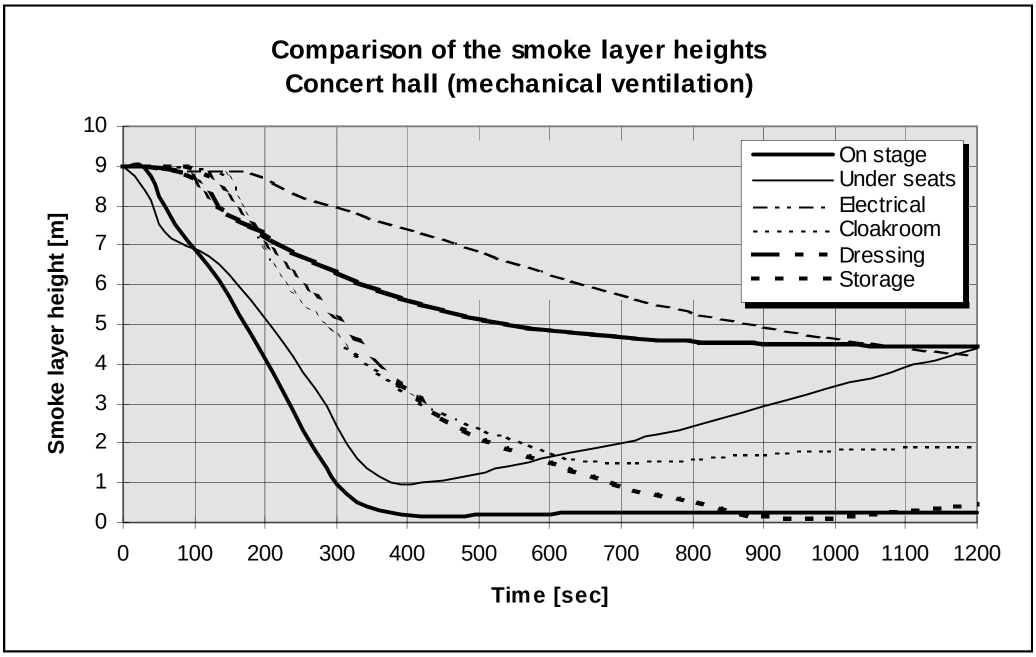


Figure 5.19: Comparison of the smoke layer heights in the concert hall. Mechanical smoke ventilation activated. Results mapped for the different fire scenarios.

The effect of the mechanical ventilation has been calculated for each fire scenario and is mapped in Figure 5.19, Figure 5.20 and Figure 5.21. Please observe when critical conditions i.e. smoke layer height < 2.5 m are occurring.

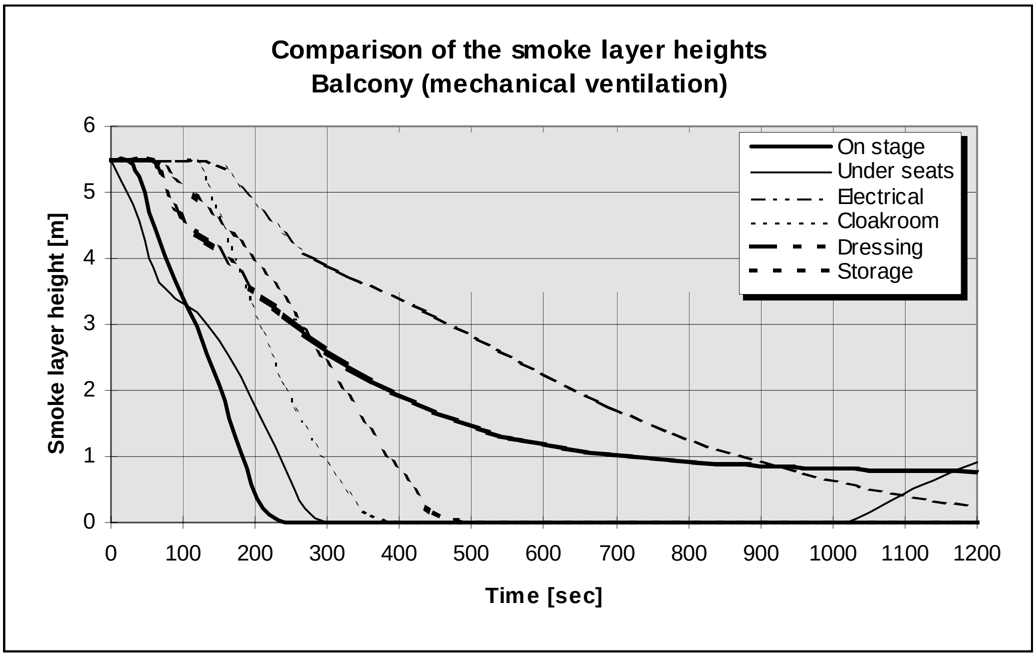


Figure 5.20: Comparison of the smoke layer heights on the balcony. Mechanical smoke ventilation activated. Results mapped for the different fire scenarios.

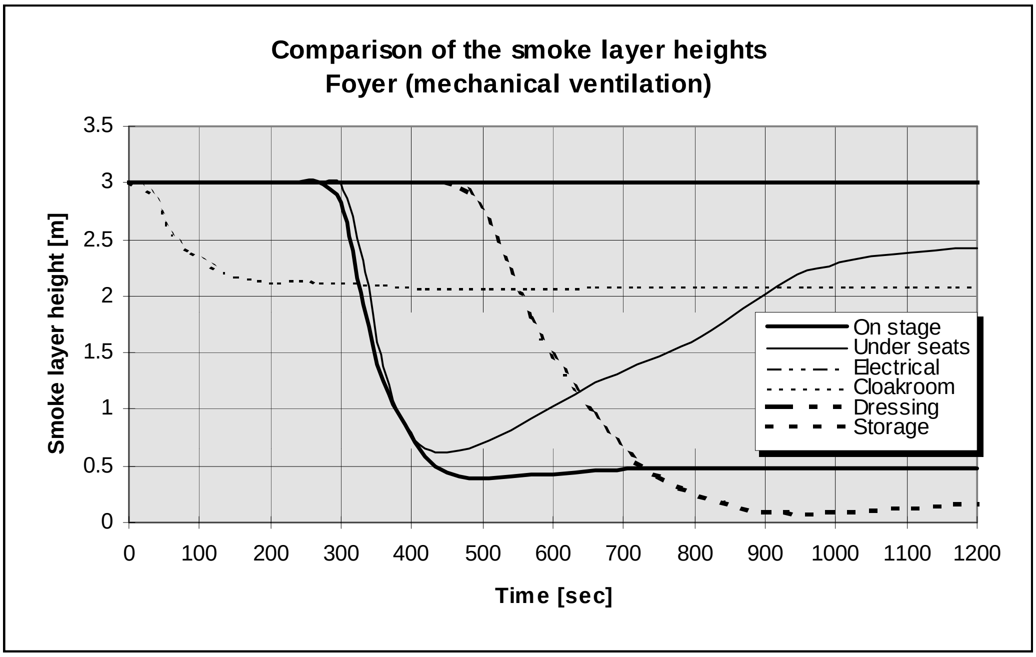


Figure 5.21: Comparison of the smoke layer heights in the foyer. Mechanical smoke ventilation activated. Results mapped for the different fire scenarios.

As observed the fire scenario that causes most problems regarding the smoke layer height is the fire on the stage. Therefore we will analyse this scenario further in order to determine whether the smoke ventilation is sufficient or not. First one may map the smoke layer height with and without ventilation in order to see the direct effect of the smoke ventilation, please see Figure 5.22.

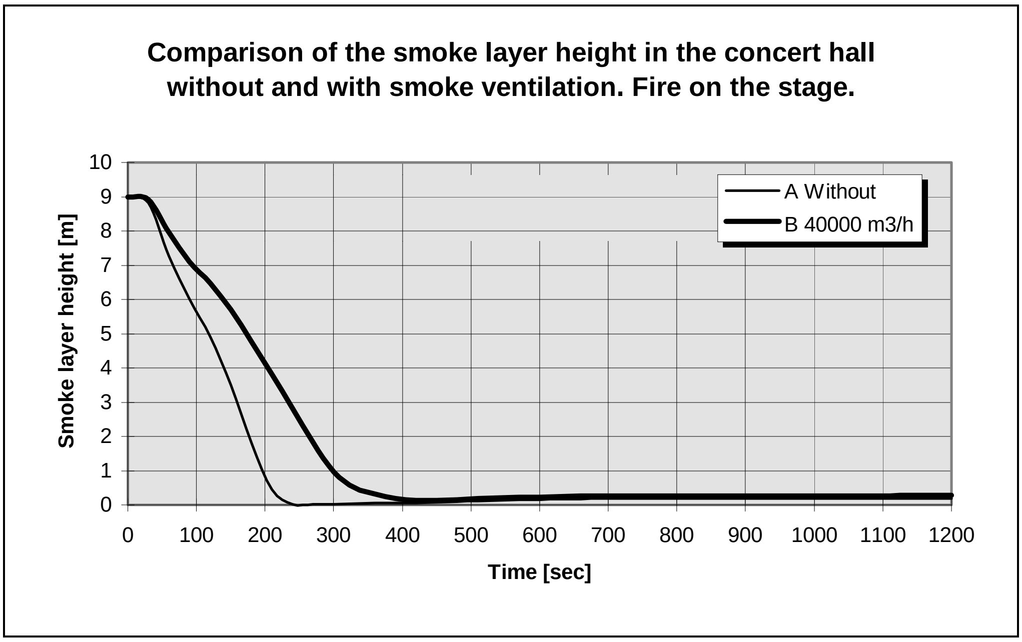


Figure 5.22: Comparison of the smoke layer heights in the concert hall. (A = no smoke ventilation and B = the present smoke ventilation 11.1 m^3/s).

By observing the development in smoke layer height the critical conditions will be reached after approximately 170 seconds if no smoke ventilation is activated. If the mechanical smoke ventilation is activated the critical time will occur after approximately 250 seconds. This means that activation of the mechanical smoke ventilation will result in a delay of the critical time on approximately 80 seconds. If one instead would be interested in the outflow required if critical time is not to be reached one may compare different outflows from the mechanical ventilation. In Figure 5.23 the effect of the outflows from mechanical ventilation is mapped. The outflows varies from 20000 m^3/h to 200000 m^3/h. If the smoke ventilation shall balance the smoke layer in a height of approx. 2 m the capacity of the mechanical ventilation is calculated to 200000 m^3/h or 55.5 m^3/s.

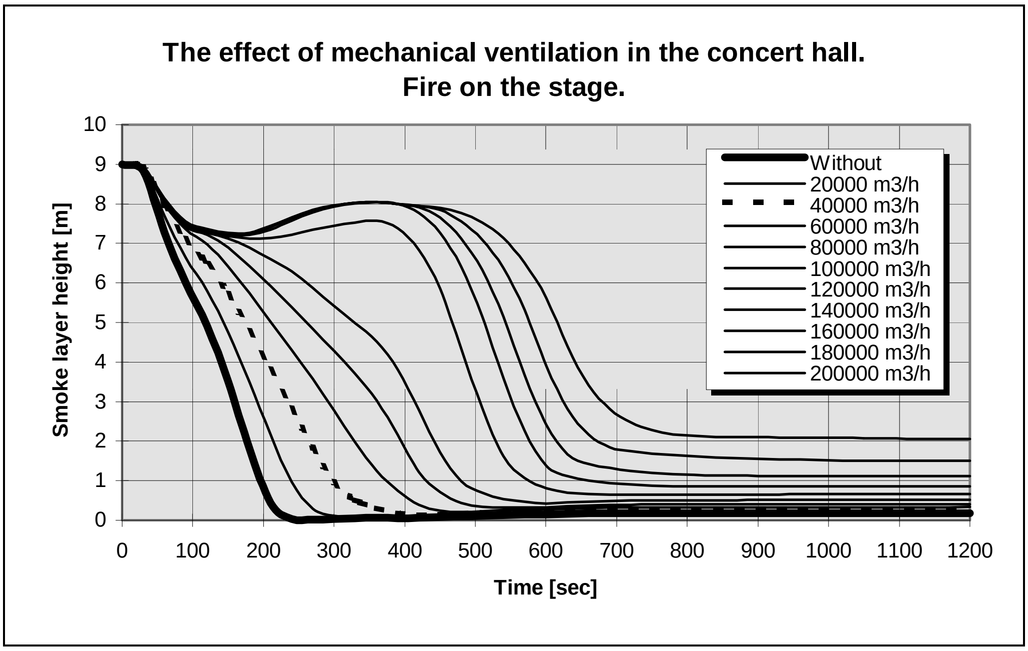


Figure 5.23: The effect of different mechanical ventilation flows in the concert hall. Fire on the stage.

In order to secure non-critical conditions at all time the capacity of the mechanical smoke ventilation must be larger than 200000 m^3/h. One may say that 200000 m^3/h is unrealistic (we agree) and that the fire will not produce 200000 m^3 smoke per hour. Our calculations shows that in the first phase of the fire the production of smoke will be approximately 400000 m^3/h and will be approximately be 70000 m^3/h when the smoke layer height is about 3 m. The smoke production will vary with the smoke layer height due to entrained air. When the smoke production is above the smoke ventilation's capacity a smoke layer will be build.

If one instead wants to replace the mechanical smoke ventilation with natural smoke ventilation i.e. ventilation due to buoyancy, one can map the effect of different areas of natural smoke ventilation. The smoke ventilation has been placed on the wall against the alley near the ceiling i.e. horizontal ventilation areas.

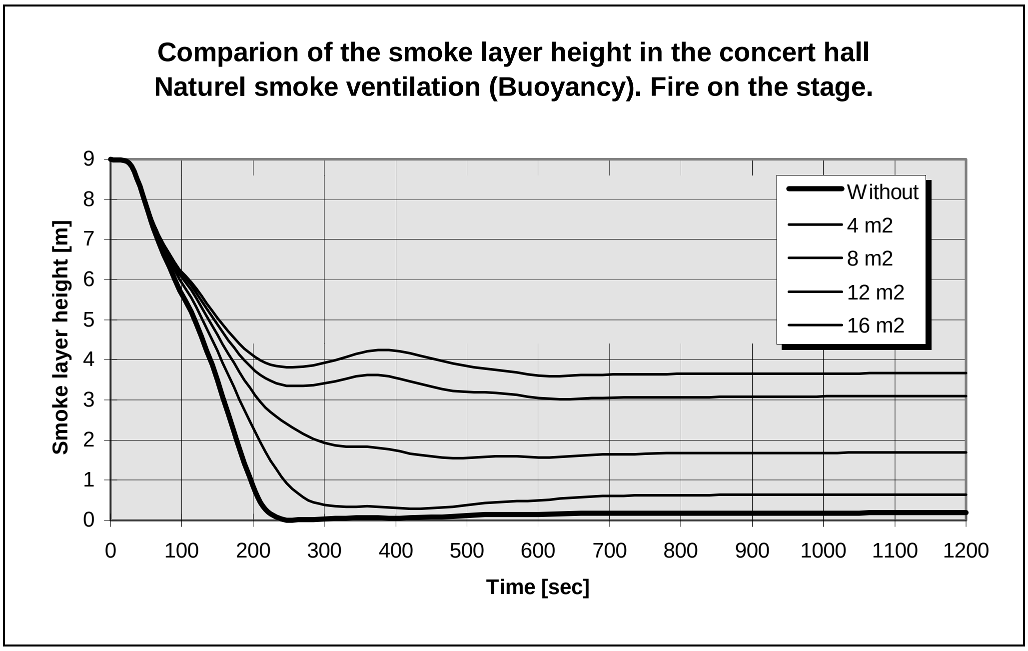


Figure 5.24:The effect of natural ventilation in the concert hall. Fire on the stage.

As seen in Figure 5.24 a ventilation area of 12 m^2 will balance the smoke layer in a height of 3 metres i.e. above the critical condition on 2.5 m.

The conclusion must be that even a minor natural ventilation area will be more efficient than mechanical smoke ventilation. I Denmark normally a 5% natural smoke ventilation is demanded which will be more than sufficient in our case. This can be stated on only one condition that the fire is of such a size that the smoke will rise to the ceiling i.e. have enough buoyancy force. At minor fires i.e. fires where the smoke will not reach the ceiling the mechanical ventilation will be preferable. The wind’s influence on the natural ventilation has not been examined. Dependent on the wind’s direction there will be a positive or negative pressure on the ventilation area resulting in either a decreased or an increased effect of the natural smoke ventilation.

5.7.3 Critical time determined by Hazard (mechanical ventilation)

The present mechanical smoke ventilation provides another critical time than the one determined without smoke ventilation. The critical time under influence of mechanical smoke ventilation is given in Figure 5.19, Figure 5.20, Figure 5.21 and collected in Table 5.1.

Location of the fire	Critical time		
	Concert hall [sec]	Balcony [sec]	Foyer [sec]
Fire on the stage	250	150	330
Fire under the seats	300	190	350
Fire in electrical installations	not occurring	650	not occurring
Fire in the cloakroom	490	250	200
Fire in the dressing room	not- occurring	390	not - occurring
Fire in the storage for chairs	460	330	560

Table 5.1: Critical time with mechanical ventilation determined by Hazard simulations.

5.7.4 Smoke ventilation by use of CCFM

The fire scenario "fire on the stage" has been analyses with CCFM.VENTS in order to gain more information about the influence of the mechanical ventilation. The smoke layer height when having a fire on the stage will be investigated. CCFM.VENTS is described in Appendix G "Computer software".

Usually the mechanical ventilation's pump curve should be taken into consideration. In our case the ducts are very short and directly connected to the outside. Therefore a resistance before and after the ventilator can be neglected i.e. constant flow can be assumed. The ventilators have as mentioned before a total outflow of 40000 m^3/h.

The model consists of only one room which is the concert hall. It is though of great importance that the total volume and the heights of both the concert hall and the balcony are used for this model as the volume and the heights influences on the temperatures and the smoke layer heights. A sensitivity analysis has been carried out and is fully described in Appendix E "Smoke ventilation". The sensitivity analysis shows that the inflow areas under the toilet section is sufficient enough to avoid such a pressure build-up inside the concert hall. This means that there will be no problems in opening the exit doors when the ventilation has started.

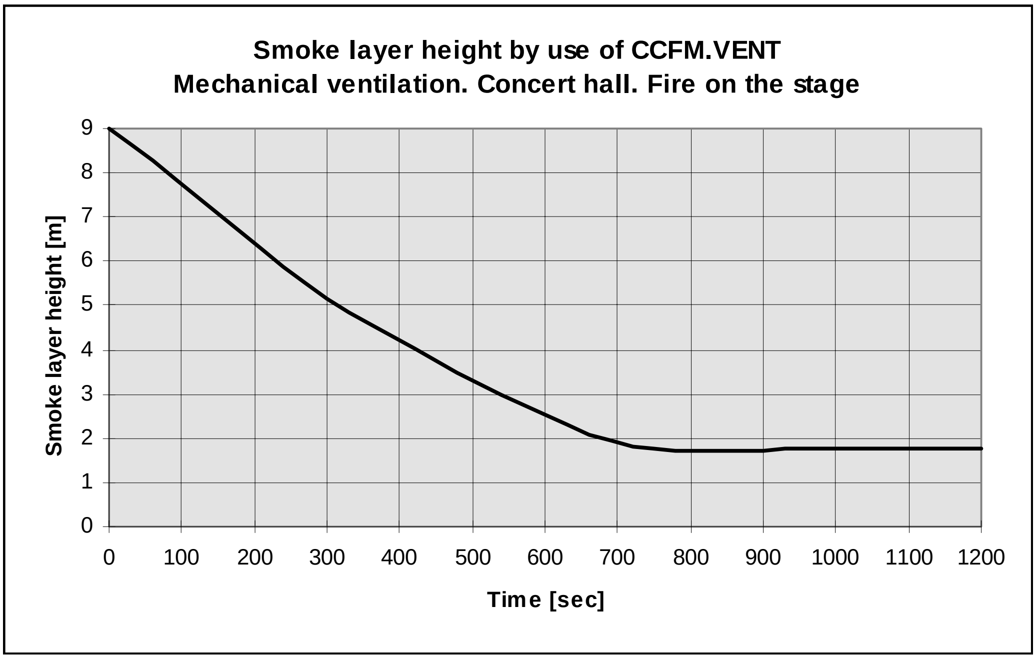


Figure 5.25: The smoke layer height determined by CCFM.VENT. Fire on the stage with mechanical ventilation of 40000 m^3/h. Concert hall.

In order to determined whether there are homogeneity between the CCFM.VENT model and the Hazard model the results from the two models are mapped in the figure. One shall pay attention to the following: the CCFM.VENT model only contains one room for modelling the concert hall. The Hazard model uses four rooms for simulating the concert hall. As mentioned in Chapter 5.3 "Models used for Hazard" a Hazard model (HM1) was made with only one room to simulate the concert hall. This model was meanwhile deselected in the sensitivity analysis but in order to see how Hazard will calculate this model it is also mapped in Figure 5.26.

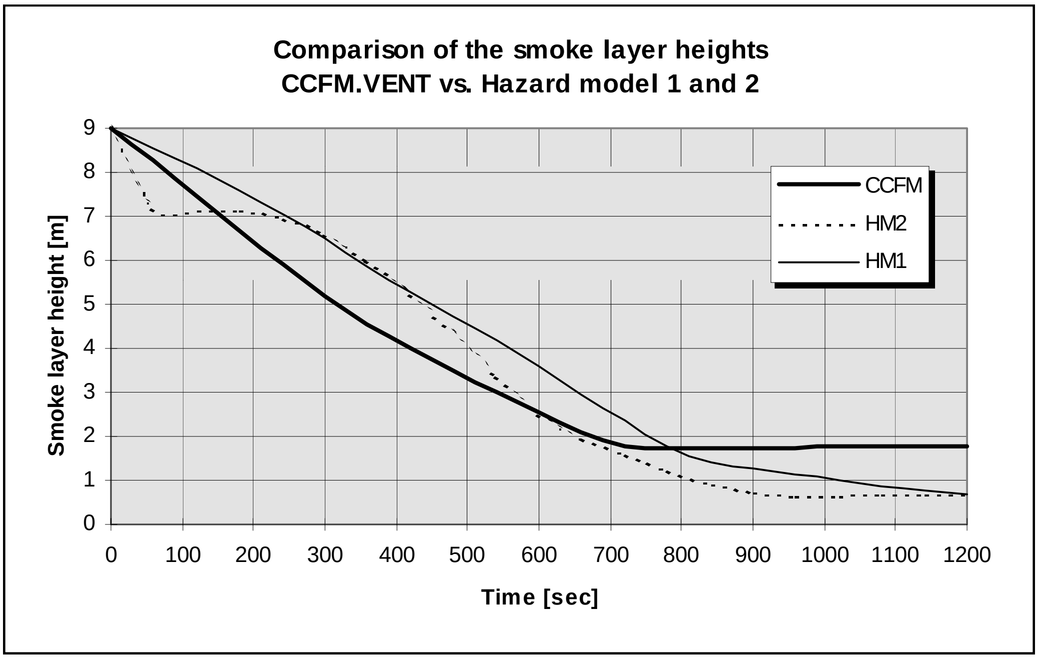


Figure 5.26: Comparison of the smoke layer heights in the concert hall with mechanical ventilation for the fire scenario "Fire on the stage" by usage of different models: CCFM.VENT, Hazard model 1 and Hazard model 2.

As observed in Figure 5.26 the curves for the CCFM and Hazard model 1 (HM1) are almost similar in shape. Both CCFM and HM1 models the concert hall as one room but the plume models used in the software is different. Therefore the shapes are similar but not identical. The curve from the Hazard model 2 varies from the two others due to increase entrainment of air and due to the concert hall is modelled as four rooms. There is a good harmony between the different models and therefore our conclusion is that Hazard gives usable results.

5.7.5 Smoke layer height determined by use of Tanaka - Yamana

The Tanaka - Yamana method is based upon analytically theories for simplified smoke control problems. The method uses conservation of the mass and energy for the upper layer. This leads to a smoke layer height where an equilibrium between the plume flow and the ventilation flow exits. The method is only valid for steady state fires. Therefore the peak heat release rate has been used in the calculations. For the iteration procedure, please refer to Appendix E "Smoke ventilation".

By iterating it is found that the smoke layer height becomes approximately 2,9 m for the fire scenario "fire on stage" with ventilation of 40000 m^3/h. It should be noted here that a critical time cannot be obtained because the Tanaka-Yamana equations calculates the height at which an equilibrium is maintained. This means that after the smoke filling procedure and after some smoke has been ventilated out by the mechanical ventilation the smoke free zone is approximately 2,9 m high. The method does not take into account whether the smoke layer at some time has been reached critical conditions.

The Tanaka - Yamana method can not be used to determine the critical time but it can be used to investigate whether the smoke layer is balanced under or over the critical height. At which time the balance occur can not be estimated.

6. Smoke analysis

In the last chapter the critical time was determined of basis of the temperatures and the smoke layer heights. A two-zone model was stated. In case the temperatures are not enough to build an upper layer a state of mixture between the smoke and the ambient air can occur. Therefore the critical time in this chapter is calculated on basis of the visibility.

Humans are very sensitive to exposure during a fire that is the radiation from the fire and from the smoke, heat generated by the fire and the toxic gasses produced by the combustion. As mentioned earlier one of the greatest threats to humans during a fire is the combination of light obscuration and toxicity of smoke. Over 50 % of all fatalities can be attributed to the inhalation of smoke and toxic gasses produced during a fire [NFPA96, table 1].

Almost every fire produces smoke and the production of smoke is very important for the safety of the people which are trapped inside a building during a fire. The smoke can be so dense that the persons cannot orientate or the smoke can contain toxic gasses such as carbon monoxide, carbon dioxide, hydrogen chloride, etc.

In this report only the light obscuration by the smoke (visibility) is investigated. The influence of toxic gasses is not investigated further due the complexity in a combustion process. The theory behind determining the visibility is described in Appendix D “Smoke analysis”.

Smoke is produced when a combustion of a fuel is incomplete. In a complete combustion the fuel will be converted into stable gaseous products. A complete combustion is seldom achieved in a real fire. Therefore it is necessary to determine the amount of smoke produced from a combustion of the fuel.

The production of smoke particles can be evaluated from the smoke potential of a fuel. In this analysis it is assumed that the smoke is well-stirred inside the compartment, i.e. the smoke and the ambient air inside the compartment is well-stirred.

6.1 Visibility

Visibility is defined as the distance which a person can see. By reducing the visibility it can delay the time for the persons to escape and therefore cause them to be exposed to toxic gasses for an unacceptably long period of time.

During a fire the visibility should be at least 10 m - i.e. a person should be able to see at least 10 m through the smoke, see Figure 6.1. If the visibility is less than 10 m the people inside the building could become disorientated and therefore the evacuation could be difficult or perhaps impossible. [FSJ79]

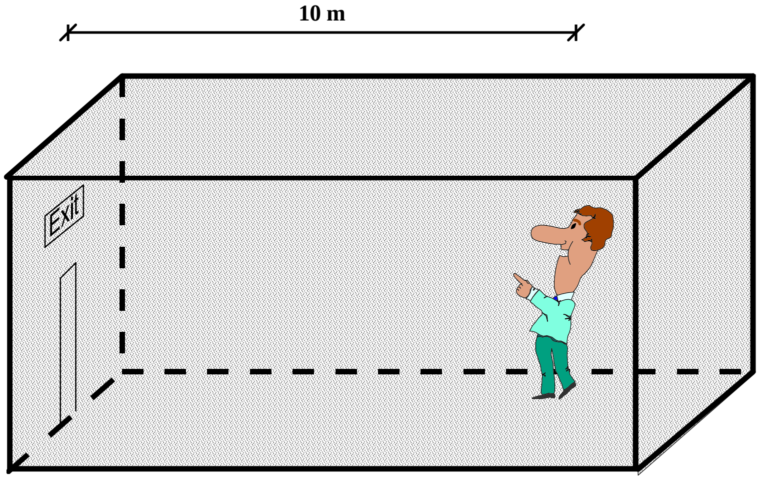


Figure 6.1: Illustration of visibility inside a compartment filled with smoke.

The visibility correlates with the smoke potential and therefore the smoke potential is described next.

6.2 Smoke potential

The smoke potential is a measure of how much smoke a fuel will develop during a combustion. In Appendix D "Smoke analysis" the smoke potential of different fuels are listed. A light damping of 1 dB/m is the same as the visibility of 10 m, which means that a person can see 10 m in a compartment. The light damping of 1 dB/m is also the same as 1 ob. In Appendix D "Smoke analysis" the correlation between the smoke potential and the visibility is shown and it will be reproduced here for completeness [FD, equation 11.3]:

$$D_o = \frac{D}{L} \cdot \frac{V}{W_l} \tag{6.1}$$

where

D is the optical density [dB].
D_0 is the smoke potential [(dB/m)·m^3/g] or [ob·m^3/g].
L is the path length of the optical beam (length between light source and photocell) [m].
V is the volume of the test chamber [m^3].
W_l is the mass of material volatilized during the test [g].

From this correlation the total mass of material volatilized can be calculated if the optical density and the smoke potential are known. Rewriting equation (6.1) and using the correlation between the energy release rate and the mass loss rate the following relation is developed (see Appendix D "Smoke analysis"):

$$\frac{D}{L} = \frac{\alpha \cdot D_0}{3 \cdot \chi \cdot \Delta H_c \cdot V} \cdot t^3 \tag{6.2}$$

where

$\frac{D}{L}$ is the optical density per meter [dB/m] or [ob].
α is the growth rate [kJ/s^3] or [kW/s^2].
χ is the combustion efficiency.
ΔH_c is the heat of combustion [kJ/g].
t is the time [s].

The variables which should be used in equation (6.2) are listed in Table 6.1 for the fire scenarios described in Chapter 5 “Fire scenario analysis”.

Fire scenario	α [kJ/s^3]	D_0 [ob·m^3/g]	χ	ΔH_c [kJ/g]	Volume [m^3]
Fire on stage	0,04327	2,08	0,7	28,00	4195
Fire under seats	0,05355	1,22	0,7	29,58	4195
Fire in electrical installations	0,00278	1,52	0,7	43,28	4195
Fire in cloakroom	0,02389	1,78	0,7	29,58	700
Fire in the dressing room	0,02268	1,78	0,7	29,58	4195
Fire in the storage for chairs	0,01062	1,22	0,7	43,31	4195

Table 6.1: Variables for equation (6.2).

The critical time is determined when the visibility is reduced to 10 m, which means that the optical density per meter is 1 obscure, i.e. *D/L* equals one in equation (6.2) and the times are listed in Table 6.3. In appendix D “Smoke analysis” the correlation between optical density per meter and time are illustrated in Figure D.2 to Figure D.7. In Figure 6.2 the optical density per meter as a function of time for all the fire scenarios is shown.

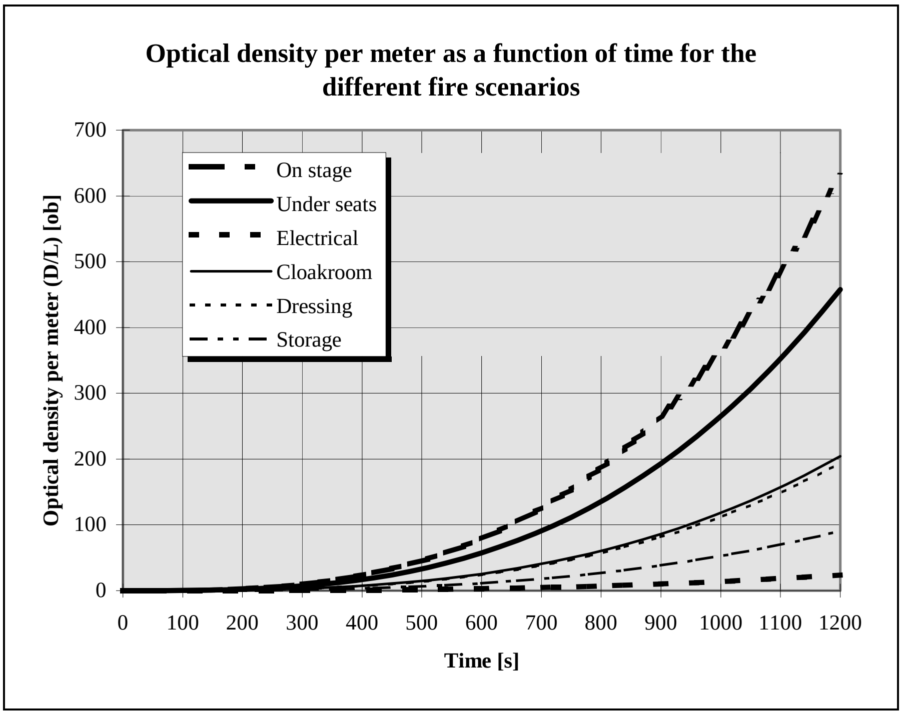


Figure 6.2: The optical density per meter as a function of time for all the fire scenarios.

6.3 Toxicity

An incomplete combustion can besides carbon dioxide and water also produce carbon monoxide, hydrogen chloride, hydrogen cyanide and nitrogen dioxide etc.

It is most common that carbon monoxide is produced in an incomplete combustion. Carbon monoxide creates a stronger binding to the Haemoglobin in the blood than for example oxygen does. This means that if a person breathe carbon monoxide the person wouldn’t get enough oxygen. In Table 6.2 the effects of breathing carbon monoxide. [SFPE, Chapter 2.8]

Vol% carbon monoxide	Effect
0,01	No effect after several hours
0,06	perceptible effect after one hour
0,10	Unpleasant after one hour
0,15	Dangerous after one hour
0,40	Lethal after one hour
1,00	Lethal after 1 minute

Table 6.2: Toxic effects for different concentrations of carbon monoxide. [SFPE, Appendix 2-8]

A natural fire is a complex combustion process, where it is difficult to predict the actual products from the combustion. This leads to that by determining the toxicity of a real fire is done with a great uncertainty and therefore the toxicity analysis will not be used as a method for calculating critical time.

6.4 Critical time by visibility analysis (no ventilation)

One of the criteria for critical conditions (critical time) was defined as the time to which the visibility inside the compartment is 10 m. In Appendix D "smoke analysis" the critical time is calculated for the different fire scenarios which are possible in "Amager Bio" (see Chapter 5 "Fire scenario analysis") and the result of these calculations are listed in Table 6.3.

Fire scenario	Critical time [s]	Critical time [min]	Comments
Fire on stage	140	2,3	Volume of concert hall and balcony
Fire under seats	159	2,7	Volume of concert hall and balcony
Fire in electrical installations	449	7,5	Volume of concert hall and balcony
Fire in cloakroom	101	1,7	Volume of entrance hall and foyer
Fire in the dressing room	186	3,1	Volume of concert hall and balcony
Fire in the storage for chairs	309	5,2	Volume of concert hall and balcony

Table 6.3: Critical time for different fire scenarios determined by a visibility analysis without any ventilation.

From Table 6.3 it is seen that it is the fire scenario "Fire on stage" which gives the largest decrement in visibility. It is the fire scenario that fastest reaches the limit on visibility on 10 m, i.e. the critical time is 140 seconds or roughly 2,3 minutes. No smoke ventilation activated.

6.5 Influence of the ventilation on the visibility

The visibility correlates as mentioned earlier with the optical density per meter. Therefore it is investigated how the optical density changes with ventilation. An analogy to gas concentration in a compartment can be done and therefore the concentration of gas in a vented compartment is investigated.

6.5.1 Concentration

As described in Appendix E "Smoke ventilation" the change in gas concentration expressed in terms of the produced gas inside the compartment and the air inflow as a function of time. In the analysis it is assumed that the gas in the compartment is ideal and well-stirred.

The capacity of the mechanical ventilation which "Amager Bio" is 40000 m^3/h and therefore the variation in concentration as a function of time for the ventilation rate is evaluated and the results are presented in Figure 6.3.

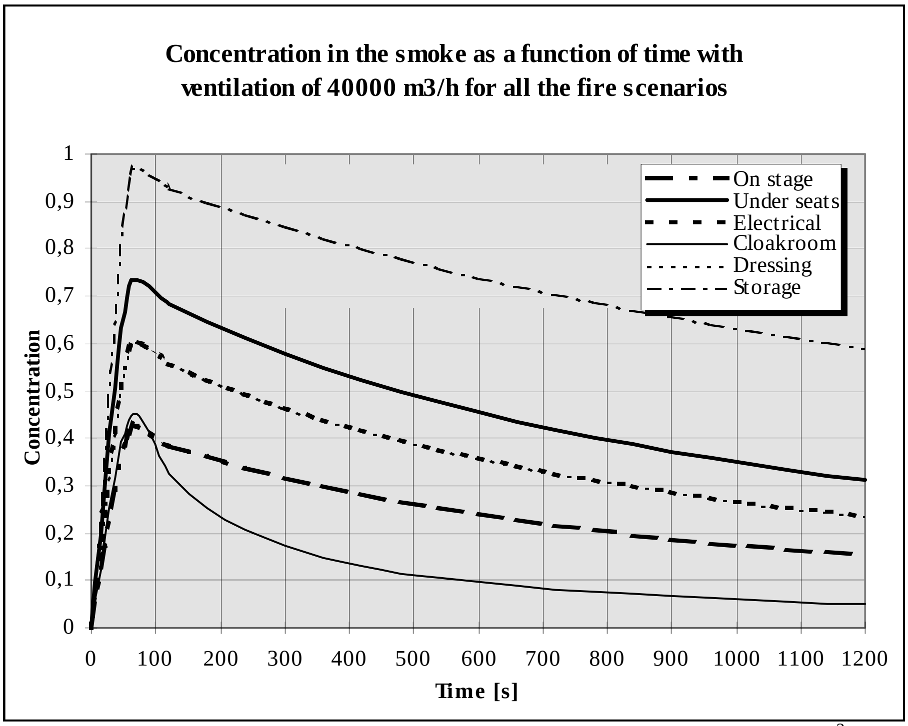


Figure 6.3: Concentration as a function of time with ventilation of 40000 m^3/h for all the fire scenarios.

6.5.2 Optical density per meter

The change in gas concentration is rewritten to describe the change in the optical density as a function of optical density produced by a fire, the air inflow and the time (see Appendix E "Smoke ventilation").

As for the change in concentration it is investigated how the optical density per meter varies as a function of time with ventilation of 40000 m^3/h (the capacity of the mechanical ventilation in "Amager Bio") is shown in Figure 6.4.

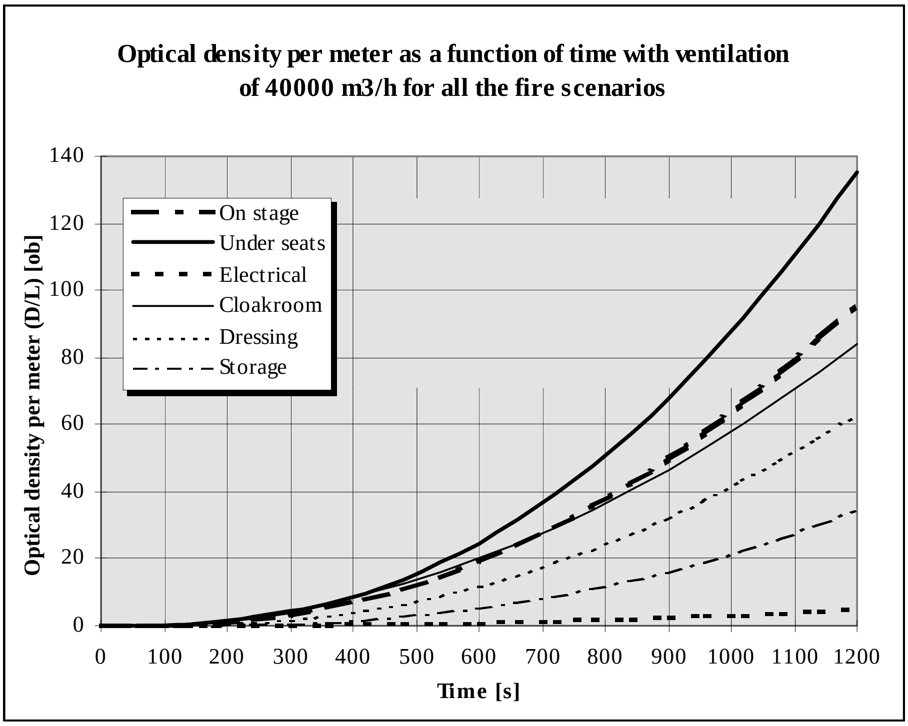


Figure 6.4: Optical density per meter as a function of time with ventilation of 40000 m^3/h for all the fire scenarios.

6.5.3 Visibility

As mentioned earlier the optical density per meter correlates with the visibility and the visibility inside "Amager Bio" with ventilation of 40000 m^3/h is shown in Figure 6.5.

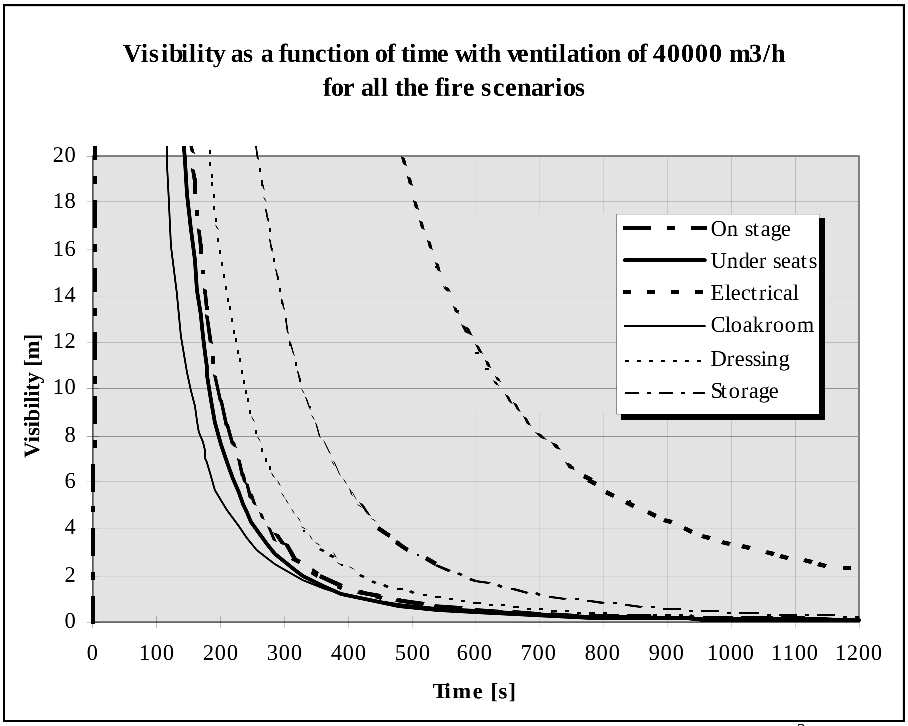


Figure 6.5: The visibility as a function of time with ventilation of 40000 m^3/m for all the fire scenarios.

The critical times determined by visibility analysis are listed in Table 6.4 for each fire scenario.

Location of the fire	Critical time	
	Concert hall and Balcony [sec]	Foyer [sec]
Fire on the stage	200	-
Fire under the seats	183	-
Fire in electrical installations	640	-
Fire in the cloakroom	-	152
Fire in the dressing room	327	-
Fire in the storage for chairs	240	-

Table 6.4: Critical times determined by visibility analysis with mechanical smoke ventilation (40000 m^3/h).

The visibility analysis is only suitable in those scenarios where a two zone model can not be used due to lack of buoyancy in the rise plume.

7. Critical times

In the following Chapter 5 “Fire scenario analysis” and Chapter 6 “Smoke analysis” will be summarised.

In Chapter 4 “Fire scenarios” different scenarios was described. We found six fire scenarios that would be possible in “Amager Bio”. More probable fire scenarios can of course be stated but we believe that these six fire scenarios describe well the consequences of a fire in “Amager Bio”. Therefore different evacuation scenarios occur. No attention to the probability of outbreak of fire was paid. Small fires that will not cause serious fire spread is neglected such as a fire in a wastebasket in the concert hall. The volumes and the heights of the rooms in “Amager Bio” are of great importance when analysing the consequences of a fire. The fire shall be of such a size that it will become a treat to persons inside “Amager Bio”.

The chosen fire scenarios are:

- Fire on the stage.
- Fire under the seats.
- Fire in the electrical installations.
- Fire in the cloakroom.
- Fire in the dressing room.
- Fire in the storage for chairs.

By analysing the consequences of the listed fire scenarios it is possible to determine the critical times for each fire scenario i.e. the time to which each fire scenario causes critical conditions in the “Amager Bio”.

7.1 Criteria for critical time

- The mean temperature in the upper layer > 500°C.
- The mean temperature in the lower layer > 80°C.
- The height of the lower layer < 2,5 m.
- The radiation at the floor > 1 kW/m^2.
- The visibility inside the building < 10 m.

7.2 Critical time determined by Hazard

One way to determine the critical time is to observe the development in temperature and smoke layer height. In order to observe the development the fire must be of such a size that a two-zone can be assumed. Hazard has been used to calculate the temperatures and the smoke layer heights. The results from Hazard have be verified through other method and good harmony appear.

The critical times determined by Hazard (mechanical ventilation taken into account) are listed in Table 7.1.

Location of the fire	Critical time		
	Concert hall [sec]	Balcony [sec]	Foyer [sec]
Fire on the stage	250	150	330
Fire under the seats	300	190	350
Fire in electrical installations	not occurring	650	not occurring
Fire in the cloakroom	490	250	200
Fire in the dressing room	not- occurring	390	not - occurring
Fire in the storage for chairs	460	330	560

Table 7.1: Critical time determined by Hazard with mechanical ventilation.

7.3 Critical time determined by visibility analysis

Another way to obtain the critical times is by calculating the visibility within the "Amager Bio". Here we may assume that the smoke is well-stirred i.e. a homogeneous mixture of air and products from the combustion in the total volume. Only the visibility has been investigated. A investigation concerning the toxicity could be carried out but due to no exact knowledge of the different components in the product from the combustion the accuracy at which the critical time could be determined is unknown. Therefore the investigation concerning toxicity was not carried out and only the visibility has been taken into consideration.

When the fire does not have enough buoyancy the smoke will stop its upwards flow and instead mix with the ambient air. This effect can be intensified by the mechanical ventilation when turn on probably will create turbulence in the concert hall. Whether the mechanical smoke ventilation will create turbulence or not can be investigated by carrying out an experiment with "cold smoke". This experiment is planned to be carried out during the summer of 1997.

The validity can be question in some of the fire scenarios. This can be done in the fire scenarios where the fire is of such size that a two-zone model can be assumed. In room located far from the origin of fire the well-stirred assumption can be applied if the temperature difference in the smoke layer in minor to 30°C.

Location of the fire	Critical time	
	Concert hall and balcony [sec]	Foyer [sec]
Fire on the stage	200	-
Fire under the seats	183	-
Fire in electrical installations	640	-
Fire in the cloakroom	-	152
Fire in the dressing room	327	-
Fire in the storage for chairs	240	-

Table 7.2: Critical times determined by visibility analysis with mechanical ventilation.

7.4 Critical times for “Amager Bio”

It can be difficult to determined the exact critical times for “Amager Bio”. First of all Hazard starts the smoke filling from the ceiling and downwards instantaneously when the fire breaks out. Hazard does not take into account that the fire shall have a certain size before the smoke rises to the ceiling. In reality the smoke will partly mix will the ambient air until the mean smoke temperature is higher than 40-60°C. Until this happens a mixed situation will occur. In how a big part of the rooms volume is diluted is very difficult to predict. Therefore we assume that total mixing (well-stirred) within the volume.

With the above standing borne in mind it is likely that the fires with high rate of heat release create the needed temperature differences for two-zone modelling i.e. the critical time can be approximated by Hazard. Smaller fires will instead have a tendency of mixing with the ambient air i.e. critical time can be approximated by the visibility analysis.

In order to determine the critical times for “Amager Bio” we have used the critical times for the different fire scenarios so that the critical time for the fires resulting in high temperatures are approximated by the times determined by Hazard clockwise the fires creating low temperatures are approximated by the visibility analysis.

Carrying out the experiment with “cold smoke” the mechanical ventilation’s influence on the flow patterns within “Amager Bio” could be determined. The results from the experiment could verify whether our assumptions is applicable or not.

Location of the fire	**Critical time**			**Comments**
	Concert hall [sec]	**Balcony [sec]**	**Foyer [sec]**	**Critical time determined by**
Fire on the stage	250	150	330	Hazard
Fire under the seats	300	190	350	Hazard
Fire in electrical installations	640	640	-	Visibility
Fire in the cloakroom	490	250	200	Hazard
Fire in the dressing room	327	327	-	Visibility
Fire in the storage for chairs	460	330	560	Hazard

Table 7.3:Critical times for “Amager Bio” with mechanical ventilation.

The critical times listed in Table 7.3 are to be compared to the evacuation times which are determined in Chapter 10 “Evacuation times”. Comparison of the critical times and the evacuation times leads to a fire safety level as described in Chapter 11 “Fire Safety level”.

8. Evacuation

The evacuation times are to be determined in the following chapters and finally to be compared to the critical times in order to fulfil equation (1.1). First some general information about evacuation and human behaviour will be given.

The safety for the people visiting a location is important. From an evacuation point of view this means that an evacuation should be able to be carried out without any danger to life or health. Unfortunately an evacuation doesn't always follow this theory. An example on this is an evacuation of “Slagthuset” in Malmö.

“Slagthuset” in Malmö is probably, from a fire safety viewpoint, one of the safest places in Sweden. The fire loads are small and an evacuation plan is developed. In this plan the people that work in “Slagthuset” have to help people to evacuate. One night somebody threw a military smoke bomb in the discotheque just after a go-go girl has finish her performance. First the people thought that it was a part of the show and took no notice of the threat. [B&R97]

The bartender alerted the disc jockey, who turned of the music and told the people to begin evacuating. The personal helped during the evacuation, but soon some visitors discovered that it was not a real fire. Therefore many people wouldn't leave without finishing their drinks. After finishing the drinks they walked towards the cloakroom in order to get their clothes. This lead to a line up just out side the cloakroom, which is located far from the dance floor. Fortunately nobody was serious injured this night, but it could have been a major disaster if a real fire had broken out instead. [B&R97].

In the rest of this Chapter the evacuation procedure and the influencing factors will be described.

8.1 Evacuation procedure

By evacuation is meant the procedure where people is rescued to a safe level - either on their own or by the help of others. When evacuation routes are designed it is necessary to know that other factors than the length of the escape route and the width of the doors can be of importance. It might seem easy to get people to begin an evacuation, but there are many psychological and physical factors which can delay the start of this event. In order to use an engineering approach the evacuation time is divided into three main times [BS, Chapter 9]:

- “Time to alert” (Alert time).
- “Time for the person to react and make a decision” (Reaction time).
- “Time for the person to reach a safe level” (Walking time).

“Time to alert” is defined as the time from the beginning of the fire or threat to the time when an alert is given. By “time for the person to react and make a decision” is meant the time from an alert is given to the time when the person becomes aware of the threat and begins evacuating. The “time for the person to reach a safe level” covers the time that the person needs to come from his or hers present location to the nearest safe level. [BS, Chapter 9]

8.2 Factors which influence on evacuation

Though it might seem easy to evacuate people from a building it can be difficult, because there are many factors that can influence on the evacuation procedure. These factors can be divided into three main categories [BS, Chapter 9]:

- “Human factors”.
- “Building factors”.
- “Fire factors”.

“Human factors” are of physical and psychological kind. Factors that describes the geometry of the building are of importance during an evacuation. Finally there is the development of the fire and the toxicity of the products produced by the fire. The different factors is listed in Table 8.1.

Factors which depend on		
Human factors	**Building factors**	**Fire factors**
Age	Orientation	Production of smoke
Sex	Escape route signs	Production of heat
Physical (need help of others)	Lighting conditions	Production of toxic gasses
Social relations, leaders	Number of escape routes	
Alcohol / medicine	Location of escape routes	
Grade of disorientation	Design of escape routes	
Influence of smoke	Distance to escape routes	
Personnel (safety organisation)	Sprinkler systems	
Fire department	Automatic fire alarm	
	Alert system	
	Safety organisation	

Table 8.1: Different factors which influence on the evacuation. [BS, Figure 9.1]

8.2.1 Human factors

People are a product of the inheritance and environment. This is what creates the personality of each human being and this is why all humans generally are very different. The personality is developed during the life time of the person.

The person’s behaviour in a fire situation and the time to react and make a decision varies with age as well as the person’s sex i.e. a young boy does not move or react in the same way as an elderly woman. Another factor which influence on the person’s behaviour is whether the person is capable to evacuate without help from others or if the person needs help of others to get to a safe level.

A person’s social relations influences on the way the person will react in a situation which is not normal to the person. A person will also react different when he or she have been drinking alcohol. Medical products can have the same effect.

If the person feels disorientated he or she might panic and unable to reach a safe level. A factor that can increase the grade of disorientation is smoke produced in a fire. The smoke can also influence on the human respiration. If the fuel of the fire doesn’t completely react to carbon dioxide and water and instead produces other products as carbon monoxide. It should be noticed that carbon monoxide creates a stronger binding to the bloods Haemoglobin than oxygen and carbon monoxide and can therefore be fatal to the person.

The staff that work in a building is of importance in an evacuation situation, because they can help others to escape if they have been trained for an evacuation situation. During an evacuation the fire brigade can rescue people from the building.

The mentioned factors is what makes an evacuation complex and this complexity and different actions that can occur during an evacuation is schematic illustrated in Figure 8.1.

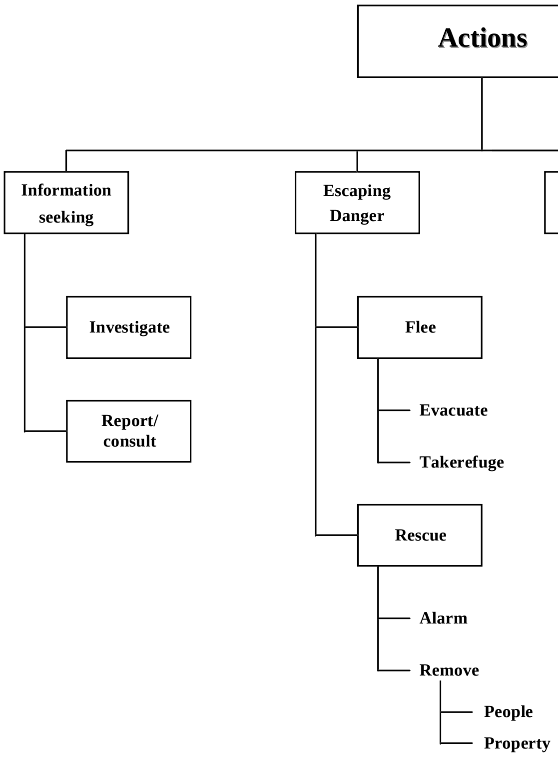


Figure 8.1: Types of actions during an evacuation. [SFPE, Figure 3-14.7]

Humans need time to make decisions and Figure 8.1 illustrates very well the different decisions the person have to take before acting.

8.2.2 Building Factors

Evacuation from a building can be difficult if the person can not orientate inside the building, because of the building's geometry is very complex. Evacuation will depend on the number of escape routes in the building and whether or not there are enough escape route signs and if they are placed on the right places. The lighting condition inside the building can make the evacuation easier or more difficult. The location of the escape routes in the building influence on the evacuation as well as the design of the escape routes. Here is meant that it is not enough to have many escape routes if they are located so that the people will have a long distance to reach them or the escape routes are not designed for the number of people that will use this way for during an evacuation or the escape routes are through storage rooms or other places where people not usually come.

Installation of a sprinkler system can help to control the development of the fire and perhaps prevent the fire from spreading to other locations, but it can also bring down the smoke and make evacuation impossible. An automatic fire alarm can in an early stage make people aware of the present threat if the building also have a system that will alert the people. In this situation a safety organisation can help to alert people and help them getting to a safe level.

8.2.3 Fire factors

Evacuation of people from a building also depends on the production of smoke, heat and toxic gasses from a fire. The smoke will decrease the visibility inside the building. A fire that produces a dense smoke will increase the grade of disorientation for the people that are inside the building. Heat production from the fire also influence on the persons behaviour, because a person exposed to high temperatures cannot move fast. The production of toxic gasses will influence on the maximal time that the persons have to reach a safe level.

8.3 Evacuation time

The evacuation, t_{evac}, time can be expressed as [BS, equation 9.2]:

$$t_{evac} = t_{alert} + t_{reac} + t_{walk} \tag{8.1}$$

where

- t_{alert} is the time from the start of the fire to when an alert is given [s].
- t_{reac} is the time from an alert is given to the time when person makes a decision to act [s].
- t_{walk} is the time from when the decision is taken to the time when the person is located on a safe level [s].

Critical time (t_{cr}) is defined as the time at which the evacuation will be impossible and the critical time for “Amager Bio” was determined in Chapter 8 “Critical time”. From equation (1.1) in Chapter 1 “Introduction” we get that the following relation must be fulfilled (reproduced her for completeness):

$$t_{evac} < t_{cr} \tag{8.2}$$

Determination of the critical time is done in the fire scenario analysis, see Chapter 5 “Fire scenario analysis” and an analysis of the smoke was made in Chapter 6 “Smoke analysis”. In order to investigate whether or not the above equation or criteria is fulfilled it is necessary to determine the evacuation time. The evacuation time is calculated in Chapter 10 “Evacuation of “Amager Bio””.

8.3.1 Alert time, reaction time and time to make a decision

The time it will take to alert people with different types of alert devices, the time for the person to react to the alert given and the time it will take for the person to make a decision are listed in Table 8.2.

Type	**Fire detector**		**Reaction time and time to make a decision**			
	No [min]	**Yes** [min]	**No** [min]	**Alert bell** [min]	**Taped message** [min]	**Personal message** [min]
Supermarket	3,0	1,5	5,0	3,0	2,0	2,0
Restaurant	2,5	1,5	3,0	2,5	2,0	2,0
Discotheque	5,0	2,0	5,0	4,0	3,0	3,0
Theatre	-	-	5,0	4,0	2,0	2,0
Cinema	5,0	-	5,0	4,0	2,0	2,0
Rest home	-	2,0	3,0	2,0	2,0	1,0
Hotel	-	2,0	4,0	4,0	3,0	3,0

Table 8.2: Time to alert people, time for people to react and time to make a decision (“-“ indicates that no value is presented in the literature. [BS, table 9.2]

The experimental times in Table 8.2 indicates how the time to alert people and the time to react and make a decision varies with the alert device. It is seen that by choosing a taped message instead of an alert bell the time to alert people and for the people to react and make a decision will be reduced by up to 50%.

Other alert times and reaction times can be defined dependent on used source. The alert time and the reaction time from [NKB], without fire detector, is listed in Table 8.3.

Type	Alert time [min]	Reaction time [min]
A (ex. Residence)	5	1
B (ex. Hotel, nursing home)	10	2
C (ex. Store, assembly hall)	2	2
D (ex. School, office)	5	2

Table 8.3: Alert time and reaction time for different building categories without fire detector. [NKB, Chapter 8.1.2]

A schematic illustration of the decision process and during a fire is shown in Figure 8.2.

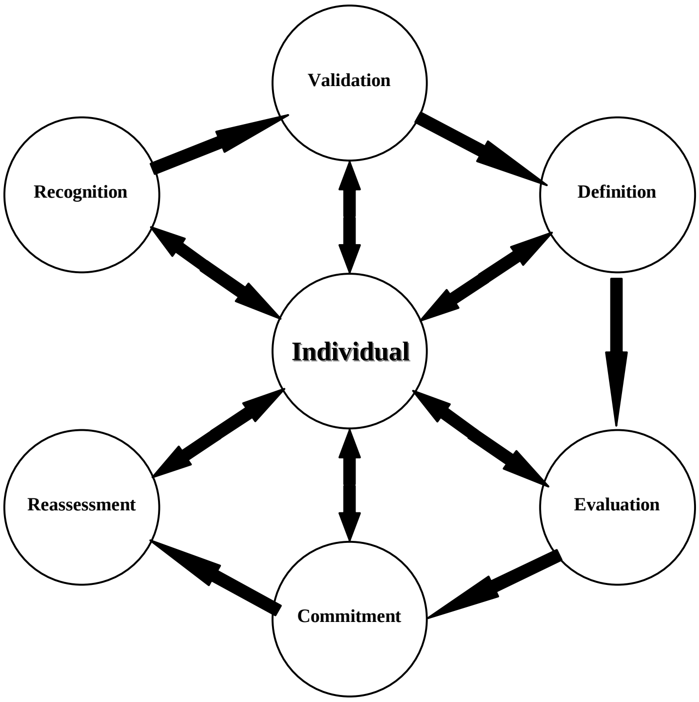


Figure 8.2: The decision process of the individual during a fire. [SFPE, Figure 3-12.1]

Figure 8.2 illustrates that the individual first has to recognise the threat and then investigated if the threat is valid. By definition it is meant that the individual attempts to relation the information to a known phenomena. After the information is related to a known phenomena the individual evaluate the information and respond to the threat. After responding to the threat the individual initiate the behavioural responses that were formulated in the evaluation process. The last stage (reassessment) is where the individual becomes stressed and act without thinking of the consequence of the action.

All the factors that influence on the evacuation should be borne in mind when reading the Chapter concerning evacuation of “Amager Bio”.

9. Evacuation of “Amager Bio”

As mentioned earlier in this report an analysis of evacuation scenarios of “Amager Bio” is done. The analysis will be carried out by the use of two different methods:

- Simulation by “Simulex”.
- Calculation by hand using NKB regulations.

Only the walking time will be calculated by “*Simulex*” while the walking time determined by the use NKB is based on door capacity. In order to obtain the evacuation time the walking time shall be combined with the alert and reaction times defined in the previous Chapter.

Two evacuation scenarios are investigated for “Amager Bio”. The two evacuation scenarios are for two different activities and they are categorised as:

- Theatre.
- Discotheque.

These two scenarios are chosen, because of partly the complexity partly the number of people. At theatre there will be seats etc. that will make the interior complex. Discotheque will have the largest number of people. Each of the two evacuation scenarios mentioned above can further be divided into six different simulations, where the fire’s location are taken into account, i.e.:

- All doors available (*model 1*).
- Backdoors on the balcony are not in use (*model 2*).
- Backdoors on the balcony are not in use and the doors to the foyer are closed (*model 3*).
- Backdoors on the balcony are not in use and the doors to the alley are closed (*model 4*).
- Backdoors on the balcony are not in use and the doors near the stage are not in use (*model 5*).
- The stairs between the balcony and the concert hall are not in use (*model 6*).

When all doors are available (*model 1*) could describe a fire that is not large enough to block any of the escape routes or the exits. The second scenario (*model 2*) describes when the people do not use the back-doors on the balcony, i.e. they escape through the concert hall. This scenarios is most likely to happen because people will not escape through a way which they do not know where escape route will lead to. *Model 3* describes when a fire breaks out in the foyer and blocks the doors between the foyer and the concert hall.

In scenario four (*model 4*) it is investigated that a fire will block the doors from the concert hall to the alley or the alley is blocked. A fire behind the stage or a fire on the stage might block the doors near the stage and this is investigated in scenario five (*model 5*) where the doors near the stage are closed. Finally *model 6* should simulate a fire near the toilet section that will block the stairs from the balcony to the concert hall.

Further the above mentioned evacuation scenarios are divided into two different scenarios:

- People walk to the nearest exit.
- 60% escapes through the entrance.

Normally it is assumed that the people will walk to the nearest exit in case of an evacuation. Experiences show meanwhile that people often will try to evacuate throughout the door they have entered the building (this way is familiar). In order to evaluate the last mentioned scenario we have assumed that 60% of the visitors will use the entrance door as their escape exit. This is though only done, when it is possible, i.e. 60% of the people cannot escape through the entrance if the doors between the foyer and the concert hall are assumed blocked. (When the simulation is named ex. "*Teat-1*" it means that the people walk towards the nearest exit and ex. "*Teat-11*" it means that 60% walks towards the entrance).

9.1 Evacuation from theatre by the use of *Simulex*

By "evacuation from theatre" it is meant activities in "Amager Bio" where the visitors are seated. This could be theatre, stand-up comedy, opera or some concerts.

The model for all simulations of evacuation from theatre is shown in Figure 9.1.

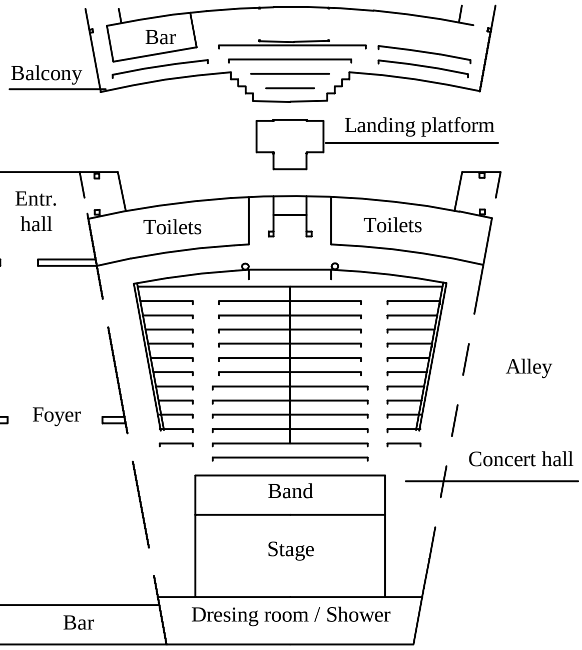


Figure 9.1: Model for evacuation from theatre.

There will be variation in this model for the mentioned scenarios. These variations are shown in Appendix F "Evacuation of "Amager Bio"". In Table 9.1 are listed the different simulations which will be simulated in "*Simulex*".

File	**Type**	**Number of people**		**Comments**
		Hall	**Balcony**	
Teat-1	Theatre	300	75	All doors available
Teat-11	Theatre	300	75	All doors available
Teat-2	Theatre	300	75	Backdoors on balcony not in use, doors to foyer not in use
Teat-22	Theatre	300	75	Backdoors on balcony not in use, doors to foyer not in use
Teat-3	Theatre	300	75	Backdoors on balcony not in use, doors to alley not in use
Teat-4	Theatre	300	75	Backdoors on balcony not in use, doors to alley not in use
Teat-5	Theatre	300	75	Backdoors on balcony not in use, doors near stage not in use
Teat-55	Theatre	300	75	Backdoors on balcony not in use, doors near stage not in use
Teat-6	Theatre	300	75	Stairs between balcony and concert hall not in use
Teat-66	Theatre	300	75	Stairs between balcony and concert hall not in use

Table 9.1:The different simulation of evacuation from theatre.

In Figure 9.2 the result of simulation *Teat-4* (the same as *model 4*), which is the scenario with the longest walking time, is illustrated with time as the horizontal axis and total number of people reached the exits as the vertical axis. The other simulations mentioned in Table 9.1 is placed in Appendix F “Evacuation of “Amager Bio””.

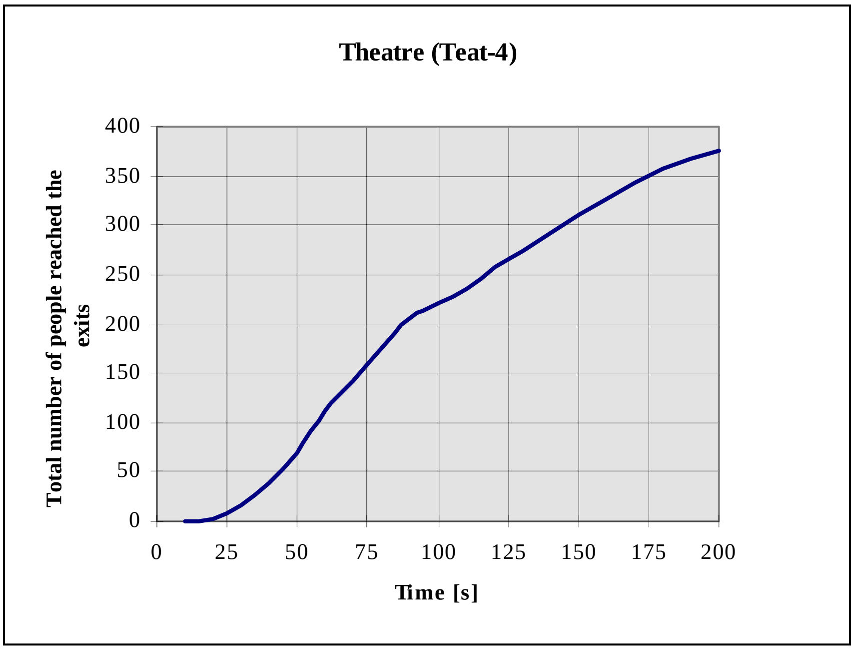


Figure 9.2: Results of scenario with longest walking time when simulating evacuating from theatre (Teat-4). Doors to alley closed.

From Figure 9.2 it is seen that it will take approximately 200 seconds or roughly 3,3 minutes for all the people to come from their present location to the nearest exit. Note that this time is only the walking time. Therefore in order to get the evacuation time the alert time and the reaction time should be added. This is done in Chapter 10 “Evacuation time”.

9.2 Evacuation from discotheque by use of *Simulex*

By “evacuation from discotheque” it is meant activities in “Amager Bio” where the visitor’s are standing. The events could be discotheque and concerts.

“Amager Bio” is designed for approximately 1000 visitors. Inspections on discotheques often show that more visitors are present than allowed. To obtain a satisfactory safety level even with overcrowding we have simulated the “Amager Bio” with the total amount of 1500 visitors present at discos or similar arrangements.

The model used for simulating evacuation is seen in Figure 9.3.

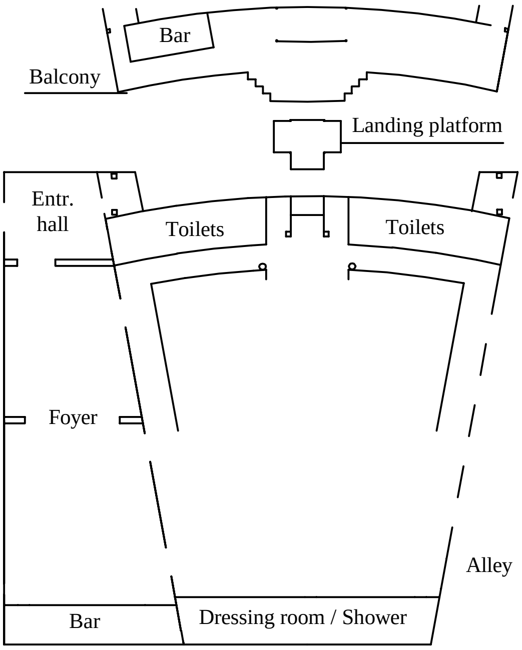


Figure 9.3: Model for evacuation from discotheque.

There will be variation in this model for the mentioned scenarios. These variations are shown in Appendix F "Evacuation of "Amager Bio"". In Table 9.2 are listed the different simulations which are simulated in "*Simulex*".

File	Type	Number of people: Hall	Number of people: Balcony	Number of people: Foyer	Comments
Disc-1	Disco	1100	200	200	All doors available
Disc-11	Disco	1100	200	200	All doors available
Disc-2	Disco	1100	200	200	Backdoors on balcony not in use, doors to foyer not in use
Disc-22	Disco	1100	200	200	Backdoors on balcony not in use, doors to foyer not in use
Disc-3	Disco	1100	200	200	Backdoors on balcony not in use, doors to alley not in use
Disc-4	Disco	1100	200	200	Backdoors on balcony not in use, doors to alley not in use
Disc-5	Disco	1100	200	200	Backdoors on balcony not in use, doors near stage not in use
Disc-55	Disco	1100	200	200	Backdoors on balcony not in use, doors near stage not in use
Disc-6	Disco	1100	200	200	Stairs between balcony and concert hall not in use
Disc-66	Disco	1100	200	200	Stairs between balcony and concert hall not in use

Table 9.2: The different simulation of evacuation from Discotheque.

After simulating the two first simulation listed in Table 9.2 we observed that there was a tendency of crowding at the doors i.e. the doors' capacity will control the evacuation. Therefore we have chosen to calculate the walking time at discotheque by the use of NKB.

9.3 Evacuation by use of NKB

The regulation NKB can also be used to predict the evacuation time for different evacuation scenarios. The regulation builds on the person capacity through a door as a function of the door width. This means that the theory don't take into account that people have a distance before reaching the door.

The theory is described in Appendix F "Evacuation for "Amager Bio"". As it is seen in this Appendix the walking time is determined by the total number of people divided by the product of a factor which describes the capacity of a given door as persons that can pass through the door per unit time and unit width multiplied by the width of the door. This calculation procedure gives an idea of what the evacuation time will be.

9.3.1 Evacuation from Theatre by use of NKB

In Appendix F "evacuation of "Amager Bio"" the theory for determining the walking time by use of NKB regulations are shown. The walking time are determined for the evacuation scenarios listed in Table 9.1 and for *Teat-4* (scenario with longest walking time) the walking time is 208 seconds or roughly 3,5 minutes. To this time should be added the alert time and the reaction time and this is done in Chapter 10 "Evacuation time".

9.3.2 Evacuation from discotheque by use of NKB

In Appendix F "evacuation of "Amager Bio"" the theory for determining the walking time by use of NKB regulations are shown. The walking time are determined for the evacuation scenarios listed in Table 9.1 and for *Disc-4* (scenario with longest walking time) the walking time is 833 seconds or roughly 13,9 minutes. To this time should be added the alert time and the reaction time and this is done in Chapter 10 "Evacuation time".

10. Evacuation times

By using equation (8.2) and Table 8.2 the evacuation time can be calculated for the two evacuation scenarios. Two different method have been used in order to determine the evacuation times

- Simulation by use of "*Simulex*".
- Calculation by use of NKB.

"Amager Bio" is provided with fire detectors and alert system with taped message. The alert time and the time for reaction and decision can be set according to Chapter 8 "Evacuation".

The evacuation times have been calculated on the assumption that when calculating the theatre-scenarios the numbers of people inside of "Amager Bio" equals 375 persons, while the discotheque scenario equals 1500 persons. This is an over estimation of number of the persons but gives a kind of safety margin.

10.1 Evacuation times determined by "*Simulex*"

The different evacuation scenarios evaluated by "*Simulex*" are listed in Table 10.1.

Type	Fire detector	Walking time [min]	Alert device	Alert time [min]	Rea/Dec time [min]	Evacuation time [min]
Teat-1	Yes	2,5	Tape	2,0*	2,0	6,5*
Teat-11	Yes	2,8	tape	2,0*	2,0	6,8*
Teat-2	Yes	2,7	Tape	2,0*	2,0	6,7*
Teat-22	Yes	2,8	Tape	2,0*	2,0	6,8*
Teat-3	Yes	2,7	Tape	2,0*	2,0	6,7*
Teat-4	Yes	3,3	Tape	2,0*	2,0	7,3*
Teat-5	Yes	2,7	Tape	2,0*	2,0	6,7*
Teat-55	Yes	2,8	Tape	2,0*	2,0	6,8*
Teat-6	Yes	2,3	Tape	2,0*	2,0	6,3*
Teat-66	Yes	2,5	Tape	2,0*	2,0	6,5*
Disc-1	Yes	3,7	Tape	2,0	2,0	7,7
Disc-11	Yes	-	Tape	2,0	2,0	-
Disc-2	Yes	-	Tape	2,0	2,0	-
Disc-22	Yes	-	Tape	2,0	2,0	-
Disc-3	Yes	-	Tape	2,0	2,0	-
Disc-4	Yes	-	Tape	2,0	2,0	-
Disc-5	Yes	-	Tape	2,0	2,0	-
Disc-55	Yes	-	Tape	2,0	2,0	-
Disc-6	Yes	-	Tape	2,0	2,0	-
Disc-66	Yes	-	Tape	2,0	2,0	-

Table 10.1: Evacuation times determined by use of Simulex. (Times marked by "" indicates that no value were available in the literature and the times are assumed the same as for discotheque).*

"*Simulex*" has not been used to calculated the walking times from the discotheque. Instead we have use the NKB's method due to crowding at the doors.

For the other analysed scenarios please see Appendix F “Evacuation of “Amager Bio””, where all the evacuation times are listed.

10.2 Evacuation times determined by NKB

The different evacuation scenarios evaluated by NKB are listed in Table 10.2.

Type	Fire detector	Walking time [min]	Alert device	Alert time [min]	Rea/Dec time [min]	Evacuation time [min]
Teat-1	No*	0,7	Tape	2,0*	2,0	4,7*
Teat-11	No*	2,1	tape	2,0*	2,0	6,1*
Teat-2	No*	0,7	Tape	2,0*	2,0	4,7*
Teat-22	No*	2,1	Tape	2,0*	2,0	6,1*
Teat-3	No*	0,9	Tape	2,0*	2,0	2,9*
Teat-4	No*	3,5	Tape	2,0*	2,0	7,5*
Teat-5	No*	1,7	Tape	2,0*	2,0	5,7’
Teat-55	No*	2,1	Tape	2,0*	2,0	6,1*
Teat-6	No*	0,7	Tape	2,0*	2,0	4,7*
Teat-66	No*	2,1	Tape	2,0*	2,0	6,1*
Disc-1	No*	2,8	Tape	2,0	2,0	6,8
Disc-11	No*	8,3	Tape	2,0	2,0	12,3
Disc-2	No*	2,8	Tape	2,0	2,0	6,8
Disc-22	No*	8,3	Tape	2,0	2,0	12,3
Disc-3	No*	3,5	Tape	2,0	2,0	7,5
Disc-4	No*	13,9	Tape	2,0	2,0	17,9
Disc-5	No*	7,0	Tape	2,0	2,0	11,0
Disc-55	No*	8,3	Tape	2,0	2,0	12,3
Disc-6	No*	2,8	Tape	2,0	2,0	6,8
Disc-66	No*	8,3	Tape	2,0	2,0	12,3

Table 10.2: Evacuation times determined by use of NKB.

The calculations from the use of NKB are not suitable for evacuation the theatre because the simulations by “Simulex” showed that the distance to the exit and the complexity of the interior was of great importance to the walking time. This means that NKB can not be used when it only takes the doors’ capacity into account.

10.3 Evacuation times for “Amager Bio”

The walking times determined by “*Simulex*” will be used because “*Simulex*” takes the walking distance into account. The NKB can only be used if the doors’ width will be the limitation of the evacuation i.e. situations or scenarios where queues by the doors will occur. Two “Simulex” simulations have been carried out at the discotheque scenario. The simulations shows that queues are occurring by the doors and therefore we have chosen to determine the walking time when have many people inside the building by the use of NKB. Simulations at theatre shows that it is the seats placement and the walking distance that will determine the walking time.

The evacuation times used for determining the Fire Safety Level for theatres will be the ones calculated by “*Simulex*” and the evacuation times used for determining the Fire Safety Level for discotheques will be the ones calculated by use of NKB. The term “theatre” covers arrangements where people are seated, while the term “discotheque” covers arrangements with large number of standing audiences.

Type	Fire detector	Walking time [min]	Alert device	Alert time [min]	Rea/Dec time [min]	Evacuation time [min]
Teat-1	Yes	2,5	Tape	2,0*	2,0	6,5*
Teat-11	Yes	2,8	tape	2,0*	2,0	6,8*
Teat-2	Yes	2,7	Tape	2,0*	2,0	6,7*
Teat-22	Yes	2,8	Tape	2,0*	2,0	6,8*
Teat-3	Yes	2,7	Tape	2,0*	2,0	6,7*
Teat-4	Yes	3,3	Tape	2,0*	2,0	7,3*
Teat-5	Yes	2,7	Tape	2,0*	2,0	6,7*
Teat-55	Yes	2,8	Tape	2,0*	2,0	6,8*
Teat-6	Yes	2,3	Tape	2,0*	2,0	6,3*
Teat-66	Yes	2,5	Tape	2,0*	2,0	6,5*
Disc-1	Yes	2,8	Tape	2,0	2,0	6,8
Disc-11	Yes	8,3	Tape	2,0	2,0	12,3
Disc-2	Yes	2,8	Tape	2,0	2,0	6,8
Disc-22	Yes	8,3	Tape	2,0	2,0	12,3
Disc-3	Yes	3,5	Tape	2,0	2,0	7,5
Disc-4	Yes	13,9	Tape	2,0	2,0	17,9
Disc-5	Yes	7,0	Tape	2,0	2,0	11,0
Disc-55	Yes	8,3	Tape	2,0	2,0	12,3
Disc-6	Yes	2,8	Tape	2,0	2,0	6,8
Disc-66	Yes	8,3	Tape	2,0	2,0	12,3

Table 10.3:Evacuation times for “Amager Bio” (Times marked by “” indicates that no value were available in the literature and the times are assumed the same as for discotheque).*

⊇ The evacuation times listed in this Chapter shall be compared to the critical times which were determined in Chapter 7 “Critical times”. This comparison is done to investigated if there is time enough for the people visiting “Amager Bio” to evacuate before the conditions inside the building becomes critical to humans. In order for people to have enough time to evacuate equation (1.1) should be fulfilled, i.e. the evacuation time could be less than the critical time. This comparison leads to determining the fire safety level of the building and it is don in the Chapter 11 “Fire safety level”.

11. Fire Safety Level

The most important part in the fire safety evaluation is to determine whether “Amager Bio” and its interior provides a satisfactory safety level in order to secure the life and health of the people visiting “Amager Bio” if a fire breaks out. The fire safety level shall be respected and can be used to evaluate the effect of different fire protective solutions.

Two different kinds of Fire Safety Levels will be determined in this Chapter:

- Fire Safety Level concerning human safety.
- Fire Safety Level concerning overall safety.

The Fire Safety Level concerning human safety deals with whether the persons inside the building are able to evacuate or not before conditions inside the building becomes life-threatening due to fire. The Fire Safety Level concerning overall safety deals with an overall evaluation of the building in order to evaluate the frequency of fires, treats to life, financial risk and the total loss that can be caused by fire.

The Fire Safety Level concerning human safety and the fire safety level concerning overall safety are not directly comparable but in the following we will try to enlighten the reader on the methods and their differences.

11.1 Fire Safety Level concerning human safety

In the following the critical times determined in chapter 7 “Critical times” will be compared to the evacuation times determined in Chapter 10 “Evacuation times” in order to observe whether the evacuation time is minor to the critical time in order to fulfil the criterion that will determine the human safety :

$$t_{evacuation} < t_{critical} \tag{11.1}$$

where
$t_{evacuation}$ is the time it takes to evacuate the building [s].
$t_{critical}$ is the time to which conditions inside the building becomes critical to humans [s].

We determine the Fire Safety Level concerning human safety (FSL_{Human}) by rewriting equation (11.1) into:

$$FSL_{Human} = \frac{t_{critical}}{t_{evacuation}} > 1 \tag{11.2}$$

The Fire Safety Level concerning human safety (FSL_{Human}) shall exceed unity if a satisfactory safety level is to be achieved.

Each fire scenario provides different evacuation scenario due to the fire’s location and influence on the exits. Therefore we will take each fire scenario and compare its critical time to the evacuation times from the suitable evacuation scenarios.

11.1.1 Comparison of fire scenarios and evacuation scenarios

The fire scenarios are to be compared to the evacuation scenarios in order to determine the influence from the fires’ locations on the evacuation. This leads to probable evacuation situations for each fire scenario.

Evacuation scenario	Fire scenario					
Theatre	**On stage**	**Seats**	**Electrical**	**Cloakroom**	**Dressing**	**Storage**
All doors available	●	●	●	-	●	-
Doors to foyer blocked	-	-	-	●	-	-
Doors to alley blocked	●	●	●	-	●	-
Doors near stage blocked	●	-	●	-	●	-
Stair from balcony to concert hall blocked	-	●	-	-	-	-

Table 11.1: Probable combinations of evacuation and fire scenarios when having seated audiences. "●" indicates the probably combinations of fire scenarios and evacuation scenarios determined by engineering judgement.

Evacuation scenario	Fire scenario					
Discotheque (concert)	**On stage**	**Seats**	**Electrical**	**Cloakroom**	**Dressing**	**Storage**
All doors available	●	-	●	-	●	●
Doors to foyer blocked	-	-	-	●	-	-
Doors to alley blocked	●	-	●	-	●	●
Doors near stage blocked	●	-	●	-	●	-
Stair from balcony to concert hall blocked	-	-	-	-	-	●

Table 11.2: Probable combinations of evacuation and fire scenarios when having standing audiences. "●" indicates the probably combinations of fire scenarios and evacuation scenarios determined by engineering judgement.

The above mentioned evacuation scenarios have been divided into two different scenarios:

- People walk to the nearest exit.
- 60% escapes through the entrance.

Normally it is assumed that the people will walk towards the nearest exit in case of an evacuation. Experiences show meanwhile that people often will try to evacuate throughout the door they have entered the building (this way is familiar to them). In order to evaluate the last mentioned scenario we have assumed that 60% of the visitors will use the entrance door as their escape exit. The evacuation scenarios where people walk to the nearest exit will in the following be referred to as "Nearest" and when 60% walks towards the entrance is referred to as "60-40".

11.1.2 Modification of alert time and reaction/decision time

Normally the values concerning alerting and reaction/decision times can be applied the walking time by using the values listed in Table 8.2. Meanwhile conditions caused by fire can modify the time to which people become aware of the treat and start acting. We assume that people will be aware of the treat and starts acting either if the thickness of the smoke layer exceeds 3-4 metres or at the times listed in Table 8.2. Hereby we assume that the smoke layer is visible to the people and the smoke detectors are activated.

By using engineering judgement based on the above the following alert times and reaction/decision times can be listed for each fire scenario, see Table 11.3. The modified alert times and reaction/decision times will be used in order to determine the Fire Safety Level concerning human safety.

Fire scenarios	Alert, reaction and decision time [min]		
	Table 8.2	Change	Modified
Fire on the stage	4	-2	2
Fire under the seats	4	-2	2
Fire in electrical installations	4	none	4
Fire in the cloakroom	4	none	4
Fire in the dressing room	4	none	4
Fire in the storage for chairs	4	-1	3

Table 11.3: Modified alert times and reaction/decision times.

11.1.3 Fire on the stage

The fire safety levels concerning human safety FSL_{Human} for the fire scenario “Fire on the stage” are listed in Table 11.4 and Table 11.5.

Fire on the stage	Critical time [min]	Evacuation time [min]		FSL_{Human}	
Evacuation scenario for theatre.		**Nearest**	**60-40**	**Nearest**	**60-40**
All doors available	4,2	4,5	4,8	0,9	0,6
Doors to foyer blocked.	-	-	-	-	-
Doors to alley blocked.	4,2	5,3	-	0,6	-
Doors near stage blocked.	4,2	4,3	4,8	0,6	0,6
Stairs from balcony to concert hall blocked	-	-	-	-	-

Table 11.4: Fire Safety Level concerning human safety during theatre when having a fire on the stage.

Fire on the stage	Critical time [min]	Evacuation time [min]		FSL_{Human}	
Evacuation scenario for discotheque.		**Nearest**	**60-40**	**Nearest**	**60-40**
All doors available	4,2	4,8	10,3	0,9	0,4
Doors to foyer blocked.	-	-	-	-	-
Doors to alley blocked.	4,2	15,9	-	0,3	-
Doors near stage blocked.	4,2	9,0	10,3	0,5	0,4
Stairs from balcony to concert hall blocked	-	-	-	-	-

Table 11.5: Fire Safety Level concerning human safety during discotheque when having a fire on the stage.

For fire on the stage the FSL_{Human} have not reached a satisfactory level for either the theatre or the discotheque scenarios.

11.1.4 Fire under the seats

The fire safety levels concerning human safety FSL_{Human} for the fire scenario “Fire under the seats” are listed in Table 11.6.

Fire under the seats	**Critical time [min]**	**Evacuation time [min]**		***FSL_{Human}***	
Evacuation scenario for theatre.		**Nearest**	**60-40**	**Nearest**	**60-40**
All doors available	5	4,5	4,8	1,1	1,0
Doors to foyer blocked.	-	-	-	-	-
Doors to alley blocked.	5	5,3	-	0,9	-
Doors near stage blocked.	-	-	-	-	-
Stairs from balcony to concert hall blocked	5	4,3	4,5	1,2	1,1

Table 11.6: Fire Safety Level concerning human safety during theatre when having a fire under the seats.

⊇ The FSL_{Human} have reached a satisfactory level for fire under the seats if the doors towards the alley can be used as an escape route..

11.1.5 Fire in electrical installations

The fire safety levels concerning human safety FSL_{Human} for the fire scenario “Fire in the electrical installations” are listed in Table 11.7 and Table 11.8.

Fire in electrical installations	**Critical time [min]**	**Evacuation time [min]**		***FSL_{Human}***	
Evacuation scenario for theatre.		**Nearest**	**60-40**	**Nearest**	**60-40**
All doors available	10,7	6,5	6,8	1,6	1,6
Doors to foyer blocked.	-	-	-	-	-
Doors to alley blocked.	10,7	7,3	-	1,5	-
Doors near stage blocked.	10,7	6,7	6,8	1,6	1,6
Stairs from balcony to concert hall blocked	-	-	-	-	-

Table 11.7: Fire Safety Level concerning human safety during theatre when having a fire in the electrical installations.

Fire in electrical installations	**Critical time [min]**	**Evacuation time [min]**		***FSL_{Human}***	
Evacuation scenario for discotheque.		**Nearest**	**60-40**	**Nearest**	**60-40**
All doors available	10,7	6,8	12,3	1,6	0,9
Doors to foyer blocked.	-	-	-	-	-
Doors to alley blocked.	10,7	17,9	-	0,6	-
Doors near stage blocked.	10,7	11,0	12,3	1,0	0,9
Stairs from balcony to concert hall blocked	-	-	-	-	-

Table 11.8: Fire Safety Level concerning human safety during discotheque when having a fire in the electrical installations.

⊇ A satisfactory FSL_{Human} have been reached during theatre for the fire scenario “Fire in electrical installations”. When having discotheque the FSL_{Human} will not reach a satisfactory level if 60% evacuates through the entrance or if the escape route through the alley is blocked.

11.1.6 Fire in the cloakroom

The fire safety levels concerning human safety FSL_{Human} for the fire scenario “Fire in the cloakroom” are listed in Table 11.9 and .Table 11.10.

Fire in the cloak room	**Critical time [min]**	**Evacuation time [min]**		FSL_{Human}	
Evacuation scenario for theatre.		**Nearest**	**60-40**	**Nearest**	**60-40**
All doors available	-	-	-	-	-
Doors to foyer blocked.	8,2	6,7	-	1,2	-
Doors to alley blocked.	-	-	-	-	-
Doors near stage blocked.	-	-	-	-	-
Stairs from balcony to concert hall blocked	-	-	-	-	-

Table 11.9: Fire Safety Level concerning human safety during theatre when having a fire in the cloak-room.

Fire in the cloak room	**Critical time [min]**	**Evacuation time [min]**		FSL_{Human}	
Evacuation scenario for discotheque.		**Nearest**	**60-40**	**Nearest**	**60-40**
All doors available	-	-	-	-	-
Doors to foyer blocked.	8,2	7,5	-	1,1	-
Doors to alley blocked.	-	-	-	-	-
Doors near stage blocked.	-	-	-	-	-
Stairs from balcony to concert hall blocked	-	-	-	-	-

Table 11.10: Fire Safety Level concerning human safety during discotheque when having a fire in the cloakroom.

⊇ For the fire scenario “Fire in the cloakroom” a satisfactory FSL_{Human} is reached.

11.1.7 Fire in the dressing room

The fire safety levels concerning human safety FSL_{Human} for the fire scenario “Fire in the dressing room” are listed in Table 11.11 and Table 11.12.

Fire in the dressing room	**Critical time [min]**	**Evacuation time [min]**		FSL_{Human}	
Evacuation scenario for theatre.		**Nearest**	**60-40**	**Nearest**	**60-40**
All doors available	5,5	6,5	6,8	0,8	0,8
Doors to foyer blocked.	-	-	-	-	-
Doors to alley blocked.	5,5	7,3	-	0,8	-
Doors near stage blocked.	5,5	6,7	6,8	0,8	0,8
Stairs from balcony to concert hall blocked	-	-	-	-	-

Table 11.11:Fire Safety level concerning human safety during theatre when having a fire in the dressing room.

Fire in the dressing room	Critical time [min]	Evacuation time [min]		FSL_{Human}	
Evacuation scenario for discotheque.		**Nearest**	**60-40**	**Nearest**	**60-40**
All doors available	5,5	6,8	12,3	0,8	0,4
Doors to foyer blocked.	-	-	-	-	-
Doors to alley blocked.	5,5	17,9	-	0,3	-
Doors near stage blocked.	5,5	11,0	12,3	0,5	0,4
Stairs from balcony to concert hall blocked	-	-	-	-	-

Table 11.12: Fire Safety Level concerning human safety during discotheque when having a fire in the dressing room.

⊇ Satisfactory Fire Safety level can not be obtained in any case when having a fire in the dressing room. The critical time is based on visibility analysis which is an analysis on the safe side. The buoyancy in the smoke has not been taken into account. The calculations uses a well-stirred volume which can occur when the mechanical ventilation starts. An analysis of the effect of the mechanical ventilation on the flow patterns inside the concert hall can tell if the assumptions are correct.

11.1.8 Fire in the storage for chairs

The fire safety levels concerning human safety FSL_{Human} for the fire scenario "Fire in the storage for chairs" are listed in Table 11.13.

Fire in the storage for chairs	Critical time [min]	Evacuation time [min]		FSL_{Human}	
Evacuation scenario for discotheque.		**Nearest**	**60-40**	**Nearest**	**60-40**
All doors available	7,7	5,8	11,3	1,3	0,7
Doors to foyer blocked.	-	-	-	-	-
Doors to alley blocked.	7,7	16,9	-	0,5	-
Doors near stage blocked.	-	-	-	-	-
Stairs from balcony to concert hall blocked	7,7	5,8	11,3	1,3	0,7

Table 11.13: Fire Safety Level concerning human safety during discotheque when having a fire in the storage for chairs.

⊇ Under the assumption that people will go to the nearest exit the FSL_{Human} have a satisfactory level for fire in the storage for chairs. If 60% try to walk through the entrance then "Amager Bio" does not obtain a satisfactory FSL_{Human}

11.1.9 Human safety in "Amager Bio"

In the previous sections the human safety have been evaluated for each fire scenario separately and in this section the over all human safety will be evaluated.

We believe that the evaluated fire scenarios very well represent the probable consequences of fires in "Amager Bio". The fire scenarios develops in such a way that the number of people inside the building is too high if they should be able to evacuate before reaching critical conditions. These investigations point in the directions that the mechanical ventilation is not sufficient enough for ventilating out the smoke if a fire load equal or larger than "Fire on the stage" exists. A satisfactory FSL_{Human} can not be reached when having a fire in the dressing room. The reader shall be aware of the calculation method which is based on visibility and the assumption for the method.

Due to the one-sided escape routes within the concert hall i.e. 80% of the exits leads towards the alley, these doors or the alley may never be blocked when having arrangements in "Amager Bio". Our investigation shows that almost every fire scenarios provide conditions that will lead to non-satisfactory FSL_{Human} if the doors towards the alley or the alley itself are blocked

During the evacuation analysis a higher density of people were deliberately used in order to take panic situations and overcrowding into account. Inspections on discotheques or similar arrangement often show a tendency to letting in more people than allowed. To analyse the consequences of overcrowding we have calculated with a 50% increase in the present allowance of person density when having discotheque or similar. This shall not be understood as an expectancy of the overcrowding but as an safety margin on the FSL_{Human}. Our investigations show that in order to obtain a satisfactory FSL_{Human} with the present fire precautions. When having a discotheque or similar, where a stage (equal or larger fire load) is present, the total number of people inside “Amager Bio” should be decreased to 750 persons. At theatres or similar arrangements the total number of persons must not exceed 300 persons in order to obtain a satisfactory FSL_{Human}.

This Fire Safety Evaluation concludes that the present fire safety level concerning human safety is not satisfactorily, but a satisfactory Fire Safety Level concerning human safety can be obtain with the present fire precautions if:

- The number of people when having standing audiences (discotheque) is decreased to 750.
- The number of people when having seated audiences (theatre) will not exceed 300.

11.2 Risk assessment

Fire safety has often a major impact on the function and design of a building, but is often a subject to scepticism and considered as a cost-increasing factor heaving no obvious benefits. It is must therefore be one of the goals for fire protection engineer to influence on other parts in the design process and try to harmonise the fire safety design with the building design.

11.2.1 Fire Risk Ranking - The Gretner Method

Risk ranking assigns values based on judgement and past experience to produce a rapid and simple estimate of relative fire risk. It is an aggregation of entities into a single index that is assumed to represent the building and making it possible to comprehensively compare different buildings and even different parts in a building.

It is important to realise that in this aggregation there are factors which usually are not accounted for in usual risk assessment and the risk evaluation e.g. the influence of fire extinguishers. The minimum requirements should though be stated in respective country’s fire safety regulation (se Chapter 3, ”Legal authorities”).

The risk ranking method to be used in this analysis is called the Gretner method, developed by M. Gretner at Switzerland Fire Prevention Service. The Gretner method is a quantitative risk assessment system which evaluates the frequency of a the fire, life and financial risks and the total loss that can be caused [Pettersson,1991].

The method is to compare the building risk status R_o to the one that can be accepted R_{accept} and the criteria for a ”safe” building can be stated as:

$$R_0 \leq R_{accept} \tag{11.3}$$

Into the building risk status are taken factors like the probability for the fire to start, how the building contributes to possible ignition and spread of fire and the passive fire protection as well as detection and extinguishing possibilities. These factors are then compared with the acceptable risk level which can be dependent on the number of people within a fire compartment and their capabilities of being rescued but it can also be calculated based on possible financial loss. (For detailed description of the method please refer to Appendix I “Fire safety level”).

For ”Amager Bio”, the building risk status (R_o) was calculated as 0.88 which is lower than the acceptable risk level (R_{accept}), which is equal to 1.05. In other words: The building possess low risks according to this method.

It is interesting to notice that the personal risk is the design factor for the acceptable risk level. This risk factor is only based upon the number of people and this is of course far to simple to be able to give reasonable estimation of the acceptable personal risk in the building. This is also partly because of uncertainties in estimating the total financial loss for the building.

The primary focus in the Gretner method is on the risk for financial losses and as a matter of fact it might be able to give a reasonable estimation of that risk. The factors governing the ”safety” of the building itself are not as complicated as the one’s for personal safety and can be described in a more satisfying way with a method like this. Factors leading to lower risk status are ex. that the structure is made of concrete and the relatively low fire load in a rather large hall will not give temperatures high enough for structural collapse.

Even though this method tries to take into account both personal safety and financial safety, the far more complicated personal safety comes secondary. Evacuation, for example, is not handled at all. It is important to point out that this method was originally constructed in the early sixties and has not been updated for today’s understanding of personal safety.

The conclusion is that the risk ranking method discussed above might give a hint of the building’s financial risk level. More cases would have to be analysed in order to be able to put forward some general conclusions for that matter. Personal safety must to be analysed by other methods. In our case the personal safety is analysed in the previous Chapters.

It is important that a simple method like this one is not followed blindly but combined with fire engineering judgement to account for uncertainties. For example it is worth a thought what may happen if a fire breaks out in “Amager Bio” while no activities and no one present. Please remember that the detection system is not connected to the fire brigade. As there are no windows in the assembly hall a fire would probably be detected by an a passer-by when the smoke is coming out through the mechanical smoke ventilation. During the night, it can be difficult to observe the black smoke and the odour of flames coming out of the mechanical smoke ventilation openings might become the observation factor for the fire. Although the mechanical smoke ventilation system would probably respond quickly its efficiency is not enough to ventilate out the hot smoke and a flashover might be a reality.

11.3 Conclusion

This Fire Safety Evaluation concludes that the present fire safety level concerning human safety is not satisfactorily, but a satisfactory Fire Safety Level concerning human safety can be obtain with the present fire precautions if:

- The number of people when having standing audiences (discotheque) is decreased to 750.
- The number of people when having seated audiences (theatre) will not exceed 300.

The fire loss costs will be limited mostly to the interior while the load - bearing structure will take little or no damage.

In order to reach a satisfactory safety level concerning human safety some improvements have to be done if the present activities with the number of persons which is allowed today should continue. Our suggested improvements are motivated in Chapter 12 “Improvements”.

12. Improvements

As described in the previous chapter a satisfactory Fire Safety Level concerning human safety (FSL_{Human}) is not reached. In order to increase the present Fire Safety Level to a satisfactory Fire Safety Level concerning human safety some improvements are to be done.

- Improve smoke ventilation capacity, or
- Decrease the number of people visiting “Amager Bio”
- Further improvements.

12.1 Improvement of smoke ventilation

By improving the smoke ventilation capacity the critical time can be increased leading to higher Fire Safety Level concerning human safety (FSL_{Human}.). In order to obtain a satisfactory FSL_{Human} in all scenarios by improving the mechanical ventilation the capacity shall be increased to at least 160000 m^3/h i.e.44,4 m^3/s. This has been obtained by calculating the critical time that corresponds to the evacuation scenario where 60% of the people use the entrance door as an exit in case of a fire on the stage (please see Figure 5.25). Mechanical ventilation of such capacity can be a problem to provide. Therefore other solutions may be more realistic and suitable.

Natural smoke ventilation can be a solution. Our investigation shows that a natural smoke ventilation area of 12 m^2 is sufficient enough to secure a satisfactory safety level concerning human safety. The natural ventilation can not be implemented in the ceiling due to the very special load-bearing structure. Instead we will suggest that the natural ventilation areas should be located on the walls in the concert hall. The ventilation areas shall be well-spread horizontally near the ceiling. The natural smoke ventilation will of course only be effective when having a fire which produces enough hot gasses to rise the plume to the ceiling.

If the fire does not produce enough hot gasses to rise the plume to the ceiling the mechanical ventilation will be preferable. The mechanical smoke ventilation can be used to ventilate out the smoke from smaller fires while the natural ventilation can ventilate out the smoke from larger fires. We suggest that the mechanical smoke ventilation is maintained but complemented by natural smoke ventilation. A further investigation of the interaction between mechanical and natural smoke ventilation shall uncover how carry out and control such a system.

12.2 Decreasing the number of people

If the time to which critical conditions occur can not increase the evacuation time must decrease in order to obtain a satisfactory FSL_{Human}. The evacuation time can be decrease either by decrease the alert and reaction/decision time or by reducing walking time. The walking time can be reduced by reducing the number of people visiting “Amager Bio” or by implementation of extra exits doors.

The alert time can be reduced by changing the alert system so the detectors can activate an immediately alert signal. Today the alert signal has a delay so the staff have the possibility to investigate whether a fire is under progress or not. The delay time is not at this moment known to the authors of this report and therefore a judgement of the reduction in evacuation time can not be given.

The reaction/decision time can be reduced by training the staff in evacuation procedures. The evacuation procedure should among other things contain:

- Making people aware of the treat.
- Instruction of the evacuees to go to the nearest exit.
- Opening of the exit doors.
- Guide the evacuees out of the alley.

It is difficult to estimate the reduction in the evacuation time but the Fire Safety Level concerning human safety will for certain be increased.

The walking time be reduced by implementing extra exit doors. The best location for extra doors is the foyer. If one door identical to the other exit door is implemented in the wall against the “Røde Kro”’s theatre court the evacuation time can probably be reduced with 4 minutes at discotheques and 1½ minutes at theatre. This requires a further evacuation analysis.

If no improvements are done the number of people visiting “Amager Bio” should be reduced in order to secure a satisfactory Fire Safety Level concerning human safety. The density of the people shall be reduced to approximately 300 people i.e. a reduction of 75 people, when having theatre. At discotheques with a stage or equivalent fire loads the number shall be reduced to 750 persons.

12.3 Further improvements

Our investigation show that obstruction of the alley or the doors leading to the alley will be critical to Fire Safety Level concerning human safety. To avoid any obstructions of the escape exits from the concert hall to the alley the staff must secure before letting people in to “Amager Bio” that the alley is not obstructed by any objects. Extra lights should be installed in the alley and they should be sufficient enough to light the whole alley.

Whether a sprinkler system is an improvement or not should be investigated further.

The doors between the basement and the concert hall must be held closed under each arrangement. It should be controlled before letting in people.

The self closing device on the doors to the cloakroom must be tested regularly.

All doors equipped with door springs must never be obstructed in open position.

Fire guard at arrangement with large person density.

Detectors connected to the fire brigade. This will not improve the Fire Safety Level concerning human safety compared critical time. If the detectors are connected to the fire brigade they shall be investigated further in order to avoid any false alarm calls of the fire brigade.

Education of the staff in simple fire fighting in order to rise the staff’s knowledge of fires.

12.4 Conclusion

We recommend that each the above standing improvement are further analysed in order to obtain a solution that can increase the Fire Safety Level concerning human safety.

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14. Nomenclature

In this Chapter a list of all the symbols used in the report are listed. The list is divided into three; fire scenarios, smoke analysis, evacuation scenarios and risk assessment.

14.1 Fire scenarios

A is the area [m^2].
A_b is the burning area [m^2].
A_T is the total surface area [m^2].
C_m is the constant proposed by Zukoski.
c_p is the heat capacity of gas [kJ/(kg·K)].
C_p is the specific heat of gas [kJ/(kg·K)].
D is the diameter [m].
F_{O2} is the weight fraction of O_2 in air.
h is the heat transfer coefficient [$kW/m^2 \cdot K$].
H is the height of the ventilation opening [m].
H_{air} is the net heat of complete combustion of oxygen [MJ/kg].
L is the mean flame height [m].
$\dot{m}$ is the rate of mass loss [kg/s].
$\dot{m}_{air}$ is the air inflow [kg/s].
m_e is the rate of smoke venting [kg/s].
q_{acc} is a fuel load [kJ].
q_{remain} is the remaining fuel load [kJ].
q_{total} is the total fuel load [kJ].
Q_{max} is the peak heat release rate [kW].
Q_{peak} is the peak heat release [kW].
$\dot{Q}$ is the energy release rate [kW].
RHR is the rate of heat release [kW].
t is the time [s].
T_a is the ambient temperature [K].
T_s is the smoke layer temperature [K].
V is the volume of the chamber [m^3].
V_e is the rate of smoke venting [m^3/s].
W is the width [m].
z is the height [m].
α is the growth factor [kW/s^2].
χ is the combustion efficiency.
ΔH_c is the heat of combustion [kJ/g].
ΔT is the temperature difference in the plume [°C] or [K].
ρ_a is the density of air [kg/m^3].
ρ_s is the smoke layer density [kg/m^3].

14.2 Smoke analysis

C is the concentration of gas.
D is the optical density [dB (decibel)].
D_0 is the smoke potential [(dB/m)·(m^3/g)] or [ob·m^3/g].
I is the intensity of light falling on the photocell in the presence of smoke.
I_0 is the intensity of light falling on the photocell in the absence of smoke.
L is the distance between the light source and the photocell [m].
m is the total mass loss [kg].
$\dot{m}$ is the rate of mass loss [kg/s].
Q_a is the air inflow [kg/s].
Q_g is the air inflow [kg/s].
$\dot{Q}$ is the energy release rate [kW].
t is the time [s].
V is the volume of the chamber [m^3].
W_l is the mass of material volatilized during the fire [g].
α is the growth factor [kW/s^2].
χ is the combustion efficiency.
ΔH_c is the heat of combustion [kJ/g].

14.3 Evacuation scenarios

B is the capacity of the door [s^{-1}·m^{-1+}].
F is the walking time [s].
P is the number of people inside the building.
t_{cr} is the critical time [s].
t_{evac} is the evacuation time [s].
t_{alert} is the alert time [s].
t_{walk} is the walking time [s].
t_{reac} is the reaction time [s].
W is the effective door width [m].

14.4 Risk Assessment

A is the activity factor.
c is the level of combustion.
e is the number of floors.
f is the smoke formation.
F is the fier resistance of the building.
g is the largest fire compartment area [m^2].
i is the fire load additions from the building.
M is the protective measures.
N is the standard fire safety measures.
P is the potential hazard.
q is the fire load.
R_{accept} is the accepted risk level.
R_{normal} is the normal risk level.
R_p is the personal risk level.
R_v is the financial risk level.
R_0 is the building risk status.
S is the special fire safety measures.