2003-01-07

Building Performance Evaluation: An Organization for Documentation

Johannes AlmÃ¥s
Worcester Polytechnic Institute

Repository Citation
AlmÃ¥s, Johannes, "*Building Performance Evaluation: An Organization for Documentation*" (2003). *Masters Theses (All Theses, All Years)*. 954.
https://digitalcommons.wpi.edu/etd-theses/954

Master's Thesis

BUILDING PERFORMANCE EVALUATION: AN ORGANIZATION FOR DOCUMENTATION

by

Johannes Almås

A Thesis

Submitted to the Faculty

of the

WORCESTER POLYTECHNIC INSTITUTE

in partial fulfillment of the requirements for the

Degree of Master of Science

in Fire Protection Engineering

by

____

August 2002

APPROVED:

____

Professor Robert Fitzgerald, Major Advisor

____

Professor Jonathan Barnett, Reader

____

Professor David A. Lucht, Head of Department

ABSTRACT

An organization of a variety of useful references and tools for evaluating typical situations that have to be addressed in a performance based fire safety design are structured in this project. The chapters in this paper are arranged the same way as the situations may appear in fire scenarios. Each chapter discusses relevant issues for regulatory required sub evaluations in fire safety engineering. In this paper the sub evaluations are named; Fire spread within the origin, Barriers and fire spread beyond the origin, Fire detection and initial action, Automatic sprinkler systems, Smoke movement, control and toxicity, Structural frame, Fire brigade intervention and Life safety. The paper addresses standards and publications to evaluate fire safety in buildings. The tools and references presented are an assortment from a variety of methods and correlations that have been developed through the years in order to achieve knowledge of the dynamics of the fire and how to control its severity. The topics for the sub evaluations are codes and standards, design fire development, fire protection efficiencies in fires, reliability issues, building and construction characteristics, occupant characteristics, evaluation tools and evaluation software.

ACKNOWLEDGEMENT

Thanks to Professor Fitzgerald for his involvement in my work. During his lecture in 1999, he was the first to introduce me to a new concept of building performance in case of fires. His classes challenged me to extend my knowledge of fire dynamics and I started searching after methods and tools to better understand the dynamics of fires.

Thanks to Norconsult AS for partly funding the education.

Thanks to my wife, Marianne, who patiently waited for me during my residence in USA, and for her support and help to complete the education.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1 INTRODUCTION

Building fires and human behavior in fire scenarios are complicated and difficult to predict. However, prediction of fire performance and risk characteristics is necessary when performance based codes are used to design fire safety in buildings. The traditional methods to design fire safety are described by the prescriptive codes. These codes have continuously evolved from older codes where the methods described have provided satisfied firesafety. When buildings are to be designed according to a performance based code, focus must be re-directed from the prescriptive methods to building performance in fires. In performance based design the focus is on the building's potential for fire development and smoke spread, the performance of fire detection systems and suppression systems, performance of structural frames, building performance for fire brigade intervention, and human actions. These factors either influence on time available for egress or time necessary for egress.

An enormous amount of deterministic information on fire defenses and behavior is available. Tests have been performed on building materials to address their properties in fires and tabulated data can be found, tests have been performed on animals to derive toxic thresholds, and surveys and interviews have been performed to understand human behavior in building fires. The development in computer programs have supplied the fire protection engineers with better tools to achieve more credible information about fire scenarios.

Prescriptive codes are applied to a building, the firesafety level may be overrated or in some cases insufficient. Building designs shall at least have a minimum level of firesafety, which can be developed from the understanding of building performance and occupant behavior in fires. A minimum or sufficient level of fire safety may be a vague way of expressing safety. Here, the prescriptive codes can be useful for comparision.

A continuous development in fire protection engineering is in progress. The perspective has been moved from detailed regulations and approval to private engineering firms with liability at law. The qualifications in fire protection consultancy are increasing, and fire protection engineers need interdisciplinary qualifications in building projects generally, and qualifications in fire protection design specifically. The consultants are required to use suitable and applied method of analysis and calculation to give satisfaction documentation of the fire safety design.

The Norwegian performance based code (TEK) [1] is discussed throughout this paper. The fire protection section of the code starts with the statement that compliance to fire safety requirements as specified in TEK shall be documented either by executing the construction works in conformity with pre-accepted design criteria and solutions, or by analyses and/or calculations which proves a satisfactory safety against fire. This paper addresses the issue of documenting fire safety by analysis and calculation, with references to appropriate documents.

The requirements in TEK [1] and the pre-accepted methods to satisfy the requirements written in REN [2] are discussed in order to organize their means of fire protection. So that the traditional means of fire protection can better be understood and evaluated comparative to an alternate fire protection design. The analysis and/or calculation in the evaluations shall simulate the fire development and present the necessary margins of safety for the most unfavorable conditions which may occur in the use of the construction works. The essential and difficult part of a fire safety evaluation is to establish an appropriate design fire. Information to develop a design fire for each particular sub evaluation can be deduced in standards and publications. When the design fire has been established a general understanding of the specific factors affecting constructions, systems and humans in fires needs to be documented. The construction and systems efficiency and reliability in resisting, suppressing and controlling, the fire can be evaluated qualitatively. As the technology in fire protection develops better quantitative measures can also be performed. Today, tests to measure flame spread on surfaces are conducted at national building and fire laboratories in industrial countries, and they conduct tests to measure structural and barrier resistance to fire. Numerical methods to evaluate construction behavior in fires have been standardized.

Smoke production and movement can be evaluated with simple tools and complex field models. The model's accuracy depends more on the design fire characteristics than the model itself. Numerical methods to evaluate smoke detectors and sprinkler activations are based on physical phenomena in nature, and good predictive methods are available. Better technology to predict sprinkler suppression will probably be available in a few years, but rough predictions can be performed with the tools available. Research has also led to better understanding of human behavior in fires, so that the results of numerical simulation of egress can be adjusted.

A performance based design appears to rely on three sources of information; objectives; a design guide and reference material. The objective may be written in a performance-based code, a design guide may be NS3901 that describes the methodology for a performance based design, and, the reference material may be one or more publication that addresses a specific aspect of fire safety. The goal of this paper is to identify some of the references that can be used to characterize building performance and human behavior in fires, but also a general description of the code objectives and design methodology is presented.

Publications and literature are usually based on experience, test, interviews, statistics or others methods to achieve knowledge about reality. This information may be based on reality so that it can be used to understand the performance of buildings, systems and humans in fires. The goal of this document is to identify a format that enables references for performance evaluations to be retrieved efficiently. The references are listed systematically so that the reader can more easily find appropriate information for evaluation. The listed references are discussed or referred to in the text section. Some references are listed under several sections because they include information about several aspects of the evaluation.

1.1 REFERENCES

1. National Office of Building Technology and Administration (Norway): TEK-97, Regulations concerning requirements for construction works and products for construction works, 22 January 1997 No. 33 Technical Regulations under the Planning and Building Act 1997.
2. National Office of Building Technology and Administration (Norway): REN, Guidance to Regulations concerning requirements for construction works and products for construction works, 2nd edition, April 1997.

2 FIRE SPREAD WITHIN THE ROOM OF ORIGIN

Fires usually start with an ignition initiated by an arc, hot plate, cigarette ember or by an intentional act. From a tiny ignition source, the fire may be able to grow continuously to full room involvement (FRI). The availability of nearby kindling fuels combined with items of sufficient fire load are necessary factors to make the fire grow. Fire can spread from item to item by radiation from flames or by radiation from the developing hot smoke layer. The identification of fuel arrangements, fuel surfaces and the room geometry can make a fire protection engineer (FPE) able to evaluate the likelihood of fire growth and FRI.

This chapter will introduce methods, and selected references, the fuels and their arrangement, room container, and ventilation affect fire behavior. Different configurations pose different potential hazard conditions and times to FRI. Fire dynamic fundamentals are the basis by which room classifications may be determined. Strategies to perform a performance evaluation of fire spread within the room of origin can be established. It is important to note that in evaluating fire growth potential it is assumed that no automatic or manual suppression of any type operates.

2.1 OBJECTIVES

The objective of an evaluation is to be able to classify room contents as to the relative hazard and time to FRI. In order to do this evaluation it will first be necessary to gather information about the room geometry, ventilation conditions and heat isolation, then the room content, fuel arrangements, fuel loads, surfaces and ignition properties should be identified. With this information a room fire hazard classification can be done. Normally, this is a simple judgment between a large room fire scenario and a small room fire scenario. Thereafter, software or hand calculation tools together with knowledge of the fuel surfaces can be used to evaluate the likelihood of fire spread from established burning, to the enclosure point, ceiling point and finally FRI.

2.2 APPLICATION OF CODES AND STANDARDS

The Norwegian performance based code [35] emphasis that "*materials and surfaces that do not contribute to unacceptable development of fire shall be used*". This means that unacceptable development of fire shall be seen in relation to evacuation and Fire Department manual suppression efforts. Further on "*consideration should be given to time to flashover, heat release, smoke production and development of toxic gases*". In order to predict the fire characteristic the surface materials should be classified according to national or international fire tests or at least compared to similar classified products.

Nationally pre accepted solutions (REN) [36] to the codes have been developed through decades. That is, the pre accepted solutions were the codes just a few years ago. Experience from fires has taught the governments what kind of surfaces shall be used in the egress paths, in nursing homes, hospitals, offices, homes etc. So far, it is more common to classify materials as incombustible, difficult to ignite and weakly heat producing (In1/Ut1), normal ignition and normal heat producing (In2/Ut2), and no requirements. Based on the risk for humans and properties, the human characteristics and building characteristic the governments recommends tall buildings to be built with exterior incombustible surfaces and nursing homes and hospitals should have incombustible interior surfaces. The recommendations are simply based on the fire department's reduced ability to extinguish or control fires in tall buildings, and that older and sick people need more time to evacuate a building.

These requirements for internal and external surfaces given in REN are just a small part of the total concept for fire safety in a prescriptive designed building. Usually the requirements will lead to a good fire safety concept. In other cases, the requirements cannot stand alone, but are used together with other fire protection systems, building layout, geometry and room contents. This evaluation is only for the potential of fire growth - unrestricted by other automatic systems.

When not using the requirements in the REN, the fire safety shall be documented and proven by analysis. The Norwegian Standardization Counsil (NSF) has developed the standard (NS3901) [37] which describes how an analysis shall be performed. The standard distinguishes among three methods to evaluate fire safety in buildings: against probabilistic, deterministic and comparative -acceptance criteria [38]. A probabilistic acceptance criterion might be described as the probability of more than two rooms are involved in a fire or more than five people are killed. A deterministic criterion might say no one shall be lost during evacuation (because the concentration of toxic gases is below the accepted criteria). A comparative criterion is a measurement against the prescriptive codes.

A probabilistic evaluation is perhaps the most uncertain analysis, because events are based on randomness and, therefore are difficult to measure. In fire protection, evaluation tools to evaluate the probability of the number of people killed in a future fire are difficult or almost impossible. On the other hand, statistical probabilities of fire spread through doors, cracks and openings should be relatively easy to achieve. Historical data can be used as a basis to evaluate fire loads, and the knowledge about future furnishings can be used to evaluate the likelihood of fire spread. Although the future arrangements of fuels and their characteristics are seldom known in detail, the room content classification must be generally described. Words like widely scattering, dens, 10 or 100 kg pr fuel package, easy ignitability, difficult to ignite can be used together with quantitatively data as less than a foot, several meters, ignites at less than 20 kW/m^2 etc.

A deterministic analysis is more similar to "will happen" or "will not happen". This analysis must presuppose that a standard fire development can occur and that there are enough fuel and air to drive the fire to FRI. Time to FRI or HRR at FRI are deterministic evaluations. Information needed to do a time to FRI evaluation includes the combustion and fire spread properties of both fixtures and fittings. For most buildings a standard fire development can be mathematically described with a time dependent exponential function for heat release rates (HRR). Only a simple constant needs to be identified.

A comparative analysis should not be used to evaluate fire spread within the room of origin alone, but a comparison can be performed after other sub evaluations have been performed. For example, if sprinklers or smoke ventilation are options for fire safety, the time to FRI or probability of FRI may be better when designing to a performance based code then the prescriptive code.

NS3901 [37] allows the analysis to be either qualitative or quantitative, or a combination. The most important consideration is that the FPE is satisfied with his judgment. An experienced engineer may be able to describe the results without doing correlation or software simulations. Others need to do simulations or tests to gain information about quantities in fire dynamics.

2.3 IDENTIFICATION OF ROOM FIRE LOADS

The room size has a significant influence on fire behavior. Fires in small rooms can develop to FRI in a short period of time. Larger rooms need more energy to be heated up to that point. Mainly, there are two different types of room fire scenarios:

- A small room fire scenario shall be identified by the likelihood of a large energy source relatively to the room. Relative to the fire, the room can be characterized as small because one fire source may be sufficient to generate a hot smoke layer and drive the fire to FRI. Fires in small rooms tend to develop similar to a predictable curve. When FRI occurs, the rate of heat release increases dramatically because the other room surfaces ignite almost simultaneously. The fire will then stabilize due to the availability of air.
- A large room fire scenario shall be identified by the likelihood of a small energy source relatively to the room. In a large room, one fire is rarely sufficient to cause FRI. However, if other fuel items are close enough, the fire will tend to spread from item to item.

The classification of rooms in fire protection evaluation is dependent on the arrangements of fuels, estimated fire sizes and amount of energy in the fuel packages. By doing this analysis, it could be found that a warehouse of 1000 m^2 and 10 meters in height shall be considered and analyzed as a "small room", because the warehouse contains large amounts of combustibles. Another geometrical small room could be analyzed as a "large room" fire scenario because it only will contain small and few combustible items (e.g. corridors or staircases).

Identification of HRR at flashover may be evaluated with hand calculation tools or with software. The hand calculation tools can give important first order information [21,22]. If better approximations are needed the zone model CFAST, may be used [1]. The state of the art software simulation technique is the computer fluid dynamic (CFD) models. Fire Dynamic Simulator [2] may be used to find necessary HRR to cause FRI. The latter evaluation will be time consuming and normally not necessary to distinguish between "small" or "large room" fire scenarios.

The evaluated HRR needed to cause FRI shall be measured against the maximum HRR for typical room furniture and fixtures. Measured HRR for common materials may be found in books and papers [9,10,14]. HRR from fire in wall linings may be calculated. The HHR per unit surface area can be known by estimating flame emissivity and irradiation, heat of gasification and heat of combustion [33].

A listing of furniture and fixtures with information of weight, heat of combustion and fuel load should be made. The summarized fire load can be compared to statistical data for fire loads [7,8].

2.4 IDENTIFICATION OF FUEL SURFACES

After the room is classified as "small" or "large", the next step is to evaluate the fuel surfaces and their fire properties. After a judgment of the likelihood of FRI has been made, the time relationships are then determined. In order to evaluate time to enclosure point, ceiling point and FRI, more detailed information about the fuel surfaces is needed. First hand information like conductivity (k), density (ρ), specific heat (c_p) and ignition temperatures can be found in tables [34]. Materials with low values of $k\rho c_p$ and low ignition temperature may cause a fire to spread faster.

Several test methods for evaluation material properties have been developed. The European Committee for Standardization has recently approved five new test methods for classification of material in the classes A to F. Where A has the best fire performance and F has no requirements.

Table 2-1. Standard test methods

Test	*Description*
EN ISO 1182	The specimen is placed furnace with constant temperature (750°C). Time duration of flames and mass loss is recorded. The test is used to classify incombustibility, and the method is a foundation for classification in classes in Euroclasses A1, A2, $A1_{fl}$, and $A2_{fl}$.
EN ISO 1716	A specific amount of test material is burned in a cylindrical volume (the bomb). The material is ignited and burns in an oxygen rich atmosphere and a pressure of 3.0-3.5 MPa. The bomb is placed in surrounding water. The increase in the surrounding water temperature is measured and consumed energy is calculated. The test is used as a foundation for classification in classes in Euroclasses A1, A2, $A1_{fl}$, and $A2_{fl}$.
EN 13823	The specimen is configured as a corner with sides 0.5 and 1.0 and height 1.5 meters, and exposed by flame radiation from a 30 kW propane burner. The test is placed within a room of 3.0 x 3.0 meters. A ventilation hood such the combustion products and measure several parameters during the test period of 20 minutes. The test reports containes among others the Fire Growth Rate Index (FIGRA) and Smoke Growth Rate Index (SMOGRA), Lateral Flame Spread (LFS) and Total Heat Release (THR). The test is used as a foundation for classification in Euroclasses A2, B, C and D.
EN ISO 11925-2	The test specimen is placed vertically above a tilted propane burner. The flames is in contact with the specimen for 15 or 30 seconds. During the test flame spread (Fs) is measured and ignition of filter-paper by burning droplets is observed. The test is used as a foundation for classification in Euroclasses B, C, D, E, B_{fl}, C_{fl}, D_{fl} and E_{fl}.

ISO 9705, The Room Corner test was the developed before the five methods for classification in Euroclasses. The room corner test is still not used for classification purposes, but as a reference for the development of EN 13823.

Measurements from the oxygen consumption calorimeter can be used to predict time to flashover in the room corner test. Time to ignition and total heat release in the bench scale test together with surface material density is measured. Measured or calculated time to flashover can be used in building fire performance evaluation. Methods for doing calculation are described in [21].

Table 2-2. Classification of building products

Products	*Time to flashover ISO 9705*	*Norwegian classification*	*Euroclass*
Stone, concrete	> 20 min	In1	A1
Gypsum board	> 20 min	In1	A2
Fireproof wood	> 20 min	In1	B
Wallpaper on gypsum board	> 10 min	In2	C
Wood	> 2 min	In2	D
Light weighted fibre board	> 2 min	-	E
Some plastics	> 2 min	-	F

(Source: BEnytt nr. 3 / November 1998)

The cone calorimeter was invented by NIST in 1982 [42]. Since then, methods to predict full scale HRR from bench scale test have been developed. This can be done by measuring average HRR during 180 seconds after ignition with 35 kW/m^2 exposure [21,40]. With this method, the HRR at full scale testing can be predicted.

The LIFT apparatus was developed by to predict flamespread, and methods to evaluate the results are developed by Quintiere and Harkleroad [11]. The test specimen is placed vertically and exposed by a tilted flame panel. Time to ignition and lateral flame spread is recorded. The test results can be used to calculate fire spread rate by hand calculation method [12,16] or software simulations with Fire dynamic simulator [2].

A large database containing test data from numerous different materials have been established at NIST [32]. The database contains ignition data and HRR data, as well as mass loss rate, CO, CO_2, soot and smoke extinction. These tests are performed both as full scale and bench scale.

2.5 ESTIMATION FIRE GROWTH

Evaluation of the likelihood of fire spread is difficult and includes much uncertainty because the fundamental input for the evaluation is crucial. A good description of room content, surfaces, flamespread properties and fuel load in relation to the room geometry could end up in a clarifying conclusion.

In "large room" fire scenarios the likelihood of flame spread by ignition of other fuel items can be evaluated by hand correlation. The maximum fire size can be found [9,10,14] and then emissivity, configuration factor and irradiation from the flames to another object can be found [31]. The probability estimate could be based on maximum distance for ignition compared to expected distances between the items [41]. Software programs such as CFAST and FPETOOL do also provide simple tools for evaluating safe separation distance from a prescribed fire size [1,4].

FDS Version 2 can also be used to evaluate the likelihood of flame spread [2]. The program routines for calculating irradiance will normally lead to an over prediction. And, the program is not fully able to simulate melting and charring. Although, the program can use all the other parameters it is not fully able to predict reality.

2.6 REALMS OF FIRE GROWTH

The realms of fire growth can be divided into four stages. The main reason is that the fire makes different threats to humans and property during its development from established burning to FRI. Each of the realms has characteristic properties.

The initiation of a fire can start with a small ignition source. Before the fire has established, it needs an incubation period. This period can take just a few seconds or several minutes, or in some cases, several hours. The incubation period is an uncertainty factor which can be neglected by assuming that the fire starts with established burning (EB). This also makes the analysis more conservative. The fire at this stage is still small and a practicable fire size for occupant manual suppression effort.

When the fire has grown to about 300-400 kW it will produce significant amounts of hot toxic smoke. For small rooms the upper layer will start to heat and the fire can spread to other items by radiation heat transfer. The next stage is when the fire reaches the ceiling. The flame will now spread horizontally and causing radiate heat transfer to increase. In small room fire scenarios, the ceiling point is only a short duration before FRI.

At FRI, the fire may become under ventilated and produce huge amounts of toxic carbon monoxide. The fire compartment temperature can reach temperatures at about 1000°C. The fire can now spread to rooms beyond the origin if the constructions surrounding the fire allow it to do so.

Table 2-1. Fire growth phases

ID	*Fire stage and typical fire sizes*	*Description*
EB	Established Burning, 40 kW	A fire has occurred and the likelihood of continued fire spread depends on the combustibility of the material.
E	Enclosure point, 300-400 kW	The fire produces significant amounts of energy and ignition of the second item depends on distances and fuel distribution in the room of origin. The fire would also produce significant amounts of smoke and could become a significant threat to humans in the room of origin.
C	Ceiling point, 800-1000 kW	The fire may be close to trigger FRI, flames can mushroom across the ceiling.
FRI	Flashover + 1500 kW	The fire can damage building construction elements and spread to other rooms if barriers are weak. Fire gases can spread rapidly to rooms beyond the origin and cause danger to humans.

2.7 FIRE GROWTH RATE

A standard t^2-fire growth can be chosen in most cases. The t^2-fire is valid during the room growth period of the fire if the fire spreads above a horizontal surface. In cases where fire spreads upward (e.g. in stacks or on walls), the fire may be a t^3-fire in the early stages because of the three dimensional situation.

For a t^2-fire, some comparative values can be found in the appendices in NFPA 72 [6]. But in each scenario, the engineer must decide whether the fire grows slow, medium, fast or ultra fast. Geometry and wind must also be included. These factors can have a significant influence on the rate of fire growth [8].

The primary importance of the appropriate selection of the design fire's growth is in obtaining a realistic prediction of detector and sprinkler activation, time to start of evacuation, and time to initial exposure of occupants. Thus, this is important to an egress analysis, which makes up the majority of alternative design analyses. In addition, since the effectiveness of fire brigade intervention is dependent on the fire size at initial water application, the t^2-fire classification enables a fire to be estimated more rationally.

$$Q = \alpha t^2.$$

where,

Q is the Heat Release Rate

α is the fire growth coefficient in kW/s^2

t is time in seconds

These specific sets of fire growth curves have been incorporated into several design methods such as for the design of fire detection systems in NFPA 72, National Fire Alarm Code. They are also referenced as appropriate design fires for performing alternative design analyses in Australia and Japan, and in product fire risk analysis methods published in USA [15]. In the Australian methodology, the selection of growth curve is related only to the fuel load (mass of combustible material per unit floor area). This may not be the only approach since growth rate is also related to the form, arrangement, and type of material and not simply its quantity. Consider 10 kg of wood, arranged in a solid cube, sticks arranged in a crib, and as a layer of sawdust. These three arrangements would have significantly different growth rates while representing identical fuel loads.

Time dependency on fire growth is a function of fuel surfaces, fuel arrangements and fuel geometries. Fire spread on vertical and horizontal surfaces can be evaluated with the results from LIFT measurements [11,12]. The calculation procedures are rather complex and almost dedicated to computer models. The fire Dynamic Simulator version 2 [2] includes a numerical solution to the flame-spread model presented by Gamal et. al [16]. Other flame-spread models are described in [12,17,18,19,20].

Usually, the fire growth is described as a t-squared standard fire. This is a simplification that makes fires reasonably easy to predict. By selecting an appropriate value for the fire growth rate constant a quick first order approximation about time to flashover can be predicted. Information to obtain the fire growth coefficient α, can be found in [5,6]. Correlations for minimum HRR for flashover [9,11,12] can be evaluated against the t-squared fire in order to predict likelihood of flashover.

Table 2-1. Bukowski recommendations for fire intensity coefficient [5]:

Fire curve	*Characteristics of fuels*	*Fire intensity coefficient* a, ($Q=at^2$).
Slow	Fires involving thick solid objects (solid wood table, bedroom dresser or cabinet)	0,00293 kW/s^2
Medium	Fuels of lower densities (upholstered furniture and mattresses)	0,01172 kW/s^2
Fast	Fires involving thin, combustible items (paper, card boxes, draperies)	0,0469 kW/s^2
Ultra fast	Some flammable liquids and some older types of upholstered furniture and mattresses or other highly volatile fuels	0,1876 kW/s^2

2.8 SUMMARY

The probability of an established fire to grow to flashover depends on the availability of fuels in the fire room. The codes have requirements for surface materials, but no requirements for other fuels stored in a compartment. The evaluation of fire spread within the room of origin is an evaluation of fire sizes relatively to the room size or initial fire relatively to distances to other fuel items. The fuels can be characterized with their ignitability and heat load, measured in standard tests for surface material fire rating. Prescribed fires can be used in computer models to evaluate the probability of flashover or evaluate minimum safe separation distance.

A room fire can be divided into realms, where each realm has specific consequences for the environment and occupants. The fire growth rate is usually described as a t-square fire, and the growth rate are evaluated from the characteristics of the surface materials predicted to be used in the specific type of occupancy.

2.9 REFERENCES

2.9.1 Computer programs that may be used to make calculations or get information that relates to room fire development.

1 Jones and Forney. “A Programmer's Reference Manual for CFAST, the Unified Model of Fire Growth and Smoke Transport,” Natl. Inst. Stand. Technol. 1990, Tech. Note 1283, 104 p.

2 McGrattan, Baum, Rehm, Hamins, Forney, Floyd, Hostikka: Fire Dynamics Simulator (Version 2) – Technical Reference Guide. NISTIR 6783. National Institute of Standards and Technology. November 2001

3 Spearpoint, Mowrer and McGrattan; Simulation of a Compartment Flashover Fire Using Hand Calculations, Zone Models and a Fire Model.

4 Deal; Technical Reference guide for FPETOOL version 3.2. NIST, NISTIR 5486, 1994:123pp.

2.9.2 Fire growth rate and fire loads

5 Bukowski; Predicting the fire performance of buildings: Establishing appropriate calculation methods for regulatory applications.

6 National Fire Protection Association; NFPA 72, National fire alarm code, 1996 edition.

7 Fire Safety Jounal vol 10, no 2, pp 101-118, (1986)

8 Norges Byggforsknings Institutt; NBI.520.333, Brannbelastning i bygninger - Beregninger og statistiske verdier.

2.9.3 Fire sizes

9 National Fire Protection Association; NFPA 204M, Smoke and heat venting, 1991 edition.

10 National Office of Building Technology and Administration (Norway); Notification HO-3/2000, Røykventilasjon, December 2000.

14 Babrauskas; Will the second item ignite, Fire Safety Journal, 4 (1981/81) 281-292.

32 National Institute of Fire and Technology; FASTdata, NIST Standard Reference Database Number 75, January 1999 Release.

2.9.4 Flame spread on surfaces.

11 Quintiere and Harkleroad; New Concepts for measuring flame spread properties, Fire Safety Science and Engineering.

12 Quintiere; Surface Flame Spread, Society of Fire Protection Engineers, The SFPE Handbook, 2nd edition, chapter 2-14.

13 Babrauskas; Fire performance of upholstered furniture and mattresses. NFPA Handbook

chapter 4-17.

14 Babrauskas; Will the second item ignite, Fire Safety Journal, 4 (1981/81) 281-292.

15 Bukowski, R.W., A Review of International Fire Risk Prediction Methods, Interflam’93. Fire Safety. 6th International Fire Conference March 30-April 1, 1993, Oxford England, Interscience Communications, Ltd., London, England, C.A. Franks, editor, 437-466 pp., 1993.

16 Gamal, Ahmed, Mark, Dietenberg, Walter, Jones; Calculating flame spread on vertically and horizontal surfaces, NIST April 1994.

17 Cleary, Quintiere; A framework for utilizing fire property tests, Fire Safety Science–Proc 3rd Int Symp, New York, NY: Elsevier, 1991:647–56.

18 Mitler; Predicting the spread rates of fires on vertical surfaces, 23rd Symp (Int) on Combustion, Pittsburgh, PA: Combustion Institute, 1990:1715–21.

19 Brehob; Upward flame spread on vertical walls with external radiation. Ph.D. Thesis, Penn State Univ., Mechanical Eng’g Dept., 1994.

20 Kulkarni A, Kim C, Kuo C. Turbulent upward flame spread for burning vertical walls made of finite thickness. Nat’l Inst. Stds. Technol. NIST-GCR-91-597, May, 1991.

2.9.5 Room flashover correlation.

21 National Fire Protection Association; NFPA 555, Evaluating potential for room flashover, 1996 edition.

22 Society of Fire Protection Engineers; The SFPE Handbook, 2nd edition, chapter 3-6.

23 Peacock, RD, Breese JN, Computer fire modeling for the prediction of flashover. National Bureau of Standards (US), NBSIR, 1984.

24 Babrauskas V, Full-scale burning behavior of upholstered chairs. National Bureau of Standards (US), TN 1103, 1979

25 Thomas PH. Testing products and materials for their contribution to flashover in rooms. Fire

Master 1981;5'103-111

26 Babrauskas V. Estimating room flashover potential. Fire Technology 1980;16(2):94-103.

27 Hägglund B. Estimating flashover potential in residential rooms (FOA Rapport C 2--369-A3)

28 Deal and Beyler; Correlating preflashover room fire temperatures. Journal of Fire Protection Engineer 1990, Vol 2 no 2 pp 33-48.

29 Foote, Pagni and Alvares; Temperature correlations for forced-ventilation compartment fires. Proceedings of 1st International Symposium Association for Fire Safety Science.

30 Peacock, Reneke, Bukowski, Babrauskas: Defining flashover for fire hazard calculations. Fire Safety Journal 32 (1999) 331-345.

2.9.6 Heat transfer

31 Tien, Lee, Stetton; Radiation Heat Transfer, Society of Fire Protection Engineers, The SFPE Handbook, 2nd edition, chapter 1-4

2.9.7 Material properties needed for calculations.

32 National Institute of Fire and Technology; FASTdata, NIST Standard Reference Database Number 75, January 1999 Release.

33 Drysdale; An introduction to fire dynamics, John Wiley and sons, January 1992. Chapter 5-2.

34 Society of Fire Protection Engineers; The SFPE Handbook, 2nd edition, Table B-7.

2.9.8 General useful information that doesn't fit easily into the above categories.

35 National Office of Building Technology and Administration (Norway): TEK-97, Regulations concerning requirements for construction works and products for construction works, 22 January 1997 No. 33 Technical Regulations under the Planning and Building Act 1997.

36 National Office of Building Technology and Administration (Norway): REN, Guidance to Regulations concerning requirements for construction works and products for construction works, 2nd edition, April 1997.

37 National Building Standardization Council (Norway): NS3901, Risk analysis of fire in buildings and civil engineering works, May 1998

38 National Building Standardization Council: Guidance to NS3901, Guidance to risk analysis of fire in buildings, October

39 National Building Standardization Council: Guidance to NS3901, Guidance to risk analysis of fire in road tunnels, May 1998.

40 American Society for Testing and Materials; ASTM E Standard test method for determining the heat release rate of upholstered furniture and mattresses using a bench scale oxygen consumption calorimeter.

41 Ramachandran; Stochastic Models of Fire Growth, Society of Fire Protection Engineers, The SFPE Handbook, 2nd edition, chapter 3-15.

42 Babrauskas; Ten Years of Heat Release Research With the Cone Calorimeter, National Institute of Fire and Technolgy, Gaithersburg, 1993.

3 BARRIERS AND FIRE SPREAD BEYOND THE ORIGIN

Historically, barriers have been the major fire spread limitation method used. Building officials in large cities required construction works to be separated by firewalls in order to save surrounding buildings. During the last century, the use of barriers in fire limitation has been more comprehensive. Barriers are now used to limit the fire within the building and to protect the egress paths.

Barrier effectiveness and reliability can be estimated by evaluating the heat application rate onto the barrier relatively to the barrier resistance and the influence of the holes we use in the barriers. Doors, ducts and other technical installations are necessary to make the building useable, but these installations may also be the cause of barrier failure if the door are left open or the penetrations are left unstopped.

3.1 OBJECTIVES

The effectiveness of barriers influences fire spread, property protection, life safety and successful fire fighting intervention operation. Effective barriers have an important role in the safety of non-sprinklered buildings.

As mentioned above, fire rated barriers are the traditional mean of fire protection, and still the codes have requirements that address the aspect of barrier performance.

Barrier evaluation is an integrated part of fire performance analysis. The type of barrier failure has an important influence on the speed and certainty of fire propagation in the adjacent room. For example a hot spot failure will cause a small ignition and relatively normal fire growth in the adjacent room. On the other hand, a large opening, such as a collapse or open door, will allow a massive inflow of fire gases into the next room. This will result in a rapid, relatively certain full room involvement (FRI).

The purpose of evaluating barriers is to estimate time and energy necessary for a small barrier failure and ignition on the unexposed side of the construction. And further on, the estimation of time to a large breakdown of the barrier so that a large volume of fire gases can pass through the barrier. These two situations are named a T-bar-failure (a small hot spot) and a D-bar-failure (a large breakdown of the barrier).

There are three main aspects in barrier evaluation:

- The barriers capability to absorb heat and still be able to prevent too much heat from penetrating the wall.
- The barriers capability to absorb heat and still be able to maintain its integrity.
- The heat energy and time of application against the barrier

Sprinkler and fire brigade intervention are not included in the barrier analysis.

3.2 APPLICATION OF CODES AND STANDARDS

The building code (TEK) requires that [40] *Construction works shall be divided into fire sections and fire compartments, in order to reduce or prevent spread of fire and smoke inside, unless such spread is prevented by other means.* This means that barriers are an option to prevent fire spread. Other systems like automatic sprinklers could be used to obtain the same safety level.

Fire sections and fire compartments are two different types of barriers and should, therefore, be evaluated differently. Firewalls and sections shall work together with fire-fighting efforts and make a highly reliable barrier throughout the fire endurance. Establishment of fire partitions shall divide the building so that *different threats to life and health to persons and different probabilities of fire to develop* shall be separated. Fire compartment shall also be of *such lay out and interior design that escape and fire fighting may be* *accomplished in a rapid and efficient way*.

The prescriptive code recommend [41] to use fire partition with classification EI-30 or EI-60 and firewalls classified as REIM-90, REIM-120 or REIM-240. Fire partitions are basically meant to be a mean of egress. The fire partitions are designed to prevent too much heat from penetrating the construction (denoted as I for isolation), and to maintain its integrity (denoted E). Firewalls are designed to withstand complete fire endurance and are denoted by REIM. The R means frame temperature resistance and M means frame mechanical resistance. With the R and M classifications the frame shall be able to withstand a standard fire endurance test.

The three different types of acceptance criteria mentioned in NS3901 [42,43] are evaluated differently. A comparative analysis should not be evaluated only from this barrier analysis, but from the final safety level from both barrier and fire protection systems with regard to egress and fire department manual suppression. A probabilistic analysis is an evaluation of the probability of barrier failure during the time necessary to evacuate the building. And the deterministic analysis concerns about the consequences of failure. For example, evaluation of the concentration of toxic gases in the egress path.

The easiest and perhaps the best acceptance criteria is a measurement against the prescriptive code. This is a comparative acceptance criterion. A comparative evaluation of barriers cannot be done from only this sub-analysis, because the comparative measurement factor is safe egress and efficient fire fighting. The barrier analysis is then a sub-analysis that have to be used together with analyzes of fire detection, sprinkler suppression, fire department suppression and egress. The comparative analysis is therefore only presented in the chapters describing the evaluation of fire department suppression and egress.

The prescriptive code only requires fire partitions as a mean of safe egress and fire department manual suppression. The area of one fire partition can therefore be large. In fire performance evaluation, the overall layout of the building and its barriers, fire classified or not, can be evaluated.

3.3 DESIGN FIRE

There are two types of fires to be considered in a design fire evaluation for barrier performance. The first design fire is the standard ISO fire. During the standard fire endurance the temperature rise is programmed and may not be relevant to a natural, post-flashover fire.

Barrier performance depends upon the construction, the heat application rate and the fire duration. A design fire for barrier resistant evaluation is mainly based on the temperature course in natural fires. The room fire temperature after flashover depends both on the fuel characteristics and the buildings characteristics. The building or fire compartment are usually characterized with size and geometry of the compartment, vent areas and compartment insulation. The fire is usually characterized with a growing or constant fire in kilowatts or the compartment fuel load. Fuel loads can be found in Fire Safety Journal [31] or NBI-papers [32].

In 1928 Ingeberg [1] conducted a series of tests to measure the severity of compartment fires. He developed curves that show the relations between ventilation openings and fuel load.

The intensity and duration of fire in buildings can vary widely, and several studies have been carried out to investigate the determining factors. It is possible to estimate the temperature course of fire in enclosures under various conditions, provided that the values of the parameters are known. Several of these parameters, however, such as the amount of combustible materials, are unpredictable as they may change with time and often vary from compartment to compartment in a building. It is possible, however, to indicate for any enclosure a time temperature curve that, with reasonable likelihood, will not be exceeded during the lifetime of the building. These curves are useful as a basis for design of fire partitions and firewalls.

3.3.1 Hand calculation methods

Quantitative methods to evaluate the hazard of compartment fires can be found in the Mowrer reference [2], Walton & Thomas reference [3] and Lie [9]. The method developed by Law [3] does only take into account the compartment geometry, characterized by its surface area and ventilation openings. In this correlation the fire size is implicit described by the ventilation openings. The method of Babrauskas [4,5] estimates the upper layer temperature based on several factors accounting for different physical phenomena, and the Swedish method [6] is based on the conventional mass and energy balance equations.

A more complex hand calculations method have been derived by Kawagoe & Sekine [7] This correlation for room fire temperature is based on test with wood fires. And, perhaps the state of the art correlation for fire-room temperature is described in the Eurocodes. This method is valid for fire compartments up to 100 m^2 of floor area, without any openings in the roof and for maximum compartment height of 4 meter [8]. This correlation is more conservative than the Kawagoe and Sekine method

3.3.2 Zone models

The input to the zone models are mainly the building or room geometry and the heat release rates, continuously growing fires or steady state. CFAST [11], HARVARD 6 code [12] and CCFM [13] can be programmed with vent openings and surronding surfaces properties. These factors makes the fire size limited due to the availability of air, and the heat loss due to mass flowing out of the compartment and heat transferred to the boundaries are estimated automatically. Simpler programs like ASET [14] cannot calculated heat loss and a user defined constant fraction of the heat generated are lost to the boundaries.

The useful output for barrier performance evaluation is the upper layer temperature

3.3.3 Field models

Field models are complex to program because of the requirements of detailed information about the fire source, boundary conditions, building geometry and ambient conditions. Most field models include an algorithm to calculate heat transfer into surrounding surfaces. The model Fire Dynamic Simulator [15] uses the program Smokeview [15] to view boundary conditions. Some useful output can be surface temperature or radiant heat transfer to the surfaces.

3.4 BARRIER PROPERTIES

The material of the barrier is of great importance for fire resistance. Barriers made of non fire classified materials can maintain its integrity for a longer period of time, or it can break down after only a relatively modest temperature rise. Fitzgerald [22] describes the material properties in fires comprehensively.

3.4.1 Concrete

In a fire lasting for 1 to 2 hr, concrete will be generally only moderately damaged. In long lasting fires, such as those, which may occur in large warehouses and department stores, severe damage to concrete may occur.

The significant difference between conventional reinforced concrete and prestressed concrete in fires is the performance of the high-tensile-steel wire or rods used for pre- or post stressing. Under fire conditions, the stressed steel units are liable to rapid loss of strength at temperatures in excess of 400°C.

3.4.2 Brick

During production, clay bricks are exposed to temperatures in excess of 1100°C, hence their strength is retained in actual fires. Reinforcing steel embedded in the center of a clay brick wall would normally be protected by a minimum of 75 to 100 mm of brick and not be affected.

3.4.3 Wood

Wood is the oldest and most widely used building material. Its behavior in fire conditions varies considerably, depending upon the species of wood and the design configuration, i.e. solid sawn lumber, glue laminates, plywood, wood chipboard etc. The effect of fire on glue laminates may be considered approximately the same as that on solid sawn lumber. Generally, phenol-resorcinol and melanin are used as adhesives in glued laminate.

3.4.4 Gypsum

Gypsum products, such as plaster and plaster boards, are excellent fire protection material. The gypsum has high proportion of chemically combined water. Evaporation of this water requires large amounts of energy. This makes gypsum a cost effective, excellent, fire resistant building material and therefore very common in commercial buildings.

3.4.5 Glass

Glass is utilized in three common ways in building construction. The most obvious is glazing for windows and doors. In this capacity the glass has little resistance to fire. It quickly cracks due to temperature differences between the surfaces. Double-glazing does not provide much improvement. Wire-reinforced glass is an improvement, as it provides somewhat greater integrity if it is properly installed.

Tempered glass may resist elevated temperature at a longer period, but neither is this glazing recommended for fire protection. Tempered glass is common in atria to protect against elevated upper layer temperature. Temperature limits for glasses are [23]:

Single glass	40°C temperature difference between the surfaces.
Double glazing	80-100°C temperature difference between the surfaces.

Tempered glass	200°C temperature difference between the surfaces.

3.4.6 *Barrier combined with sprinklers*

Water film's ability to protect exterior glazing has been tested with satisfaction results. The tests indicated that tempered or heat-strengthened glass protected by a dedicated automatic sprinkler system would remain intact for more than one hour [45]. NFPA 80A [46] also describes different methods to combined exterior sprinklers with glazing in firewalls.

3.5 FIRE TESTING VS. REAL FIRES

Fire approved barriers have to be tested according to national or international standards. The Norwegian standard is NS-ISO 834 (US standard is ASTM E-119). This standard describes a logarithmic time - temperature curve in which the test assemblies are to be tested against. The temperature within the furnace is regulated with temperature sensors and shall therefore not be compared to real compartment fire temperatures. On the other hand, test procedures can be used to gain insight into how much energy a barrier can absorb. The time classifications shall therefore be recalculated to accumulated applied energy and compared to the energy consumption rate in a real fire. By doing these correlations it can be possible to estimate time to failure, which later on can be a useful number in the safe egress evaluation.

These correlations can simply be performed in an Excel spreadsheet with numerical solutions of standard heat transfer equations (convective heat transfer and radiation). For more information see [16,17,18,19]. Estimates of applied energy during fire testing are referred in table 3-1.

Table 3-1. Calculated applied energy onto test assembly during the ISO-834 fire test

Fire rating	*30 min*	*60 min*	*90 min*	*120 min*
Applied energy according to ISO 834	120 MJ/m^2	330 MJ/m^2	610 MJ/m^2	930 MJ/m^2

3.6 BARRIER RELIABILITY STATISTICS

The reliabilities of barriers are important issues in both comparative and probabilistic analysis. Masonry constructions are historically more reliable than gypsum constructions, and doors with closers are more reliable than doors without. Historical data shall not be used to judge the reliability of separating constructions, because the future may not be comparable to history. This may be due to mechanical systems, materials and human behavior that may change over time. Nevertheless, statistical data can be used to calibrate and compare. The data in tables 3-2 to 3-4 are collected from [33,34].

Table 3-1. Published Estimates for passive protection systems operational reliability

	Warrington Delphi UK (Delphi group)	*Fire Eng. Guidelines Australia (Expert Survey)*	*Japanese Studies (Incident data)*	
Protection System			Tokyo FD	Watamabe
Masonry construction	81% 29% probability an opening will be fixed	95% if no opening 90 if opening with auto closer	NA	NA
Gypsum partitions	69% 29% probability of opening will be fixed	95% if no opening 90 if opening with auto closer	NA	NA

(Probability of success (%)) (NA = Not Addressed)

Fire doors will not necessarily close properly when a fusible link or detector is actuated. Their propensity to hang up has been determined through an extensive series of automatic closure tests conducted annually or semiannually by the Factory Mutual Engineering Association (FMEA) [33]. They estimated the probabilities of failure and causes of failure. These tests were conducted in 1984 to 1988 and improvements of door hangers have been done since then.

Table 3-2. Fire door closure data (FMEA Surveys 1984 - 1988)

Type of door	*# Failures*	*# Tests*	*% Failure*
Rolling steel	1177	5587	21.1%
Horizontal sliding	377	2463	15.3%
Vertical sliding	17	156	10.9%
Swinging	166	1183	14.0%

Table 3-3. Causes of fire door closure (from FMEA survey)

Cause of failure	*Rolling steel*	*Horizontal sliding*	*Vertical sliding*	*Swinging*	*Overall*
Spring tension	33%	5%	0	0	23%
Snagged chain	23%	37%	0	3%	23%
Opening blocked	10%	6%	25%	3%	9%
Damaged tracks	9%	17%	0	0	9%
Damaged closer	16%	3%	50%	38%	16%
Hood/curtain	5%	0	0	0	3%
Damaged binder	0	8%	0	21%	4%
Other	3%	24%	25%	35%	11%
Sum	99%	100%	100%	100%	98%

3.7 BARRIER RESISTANCE EVALUATION TOOLS

The Nordic Wood project “Fire Safe Wooden Buildings” [27] presents design solutions for timber frame structures based on the "adding up method". This is a method for calculating fire resistance for separation structures and load-bearing structures. This method estimates the fire resistance grading that a similar structure would have in a fire test. These results may be recalculated to fire resistance in a real fire scenario.

The basic principal for the addition method is the relation between the layers base value and theirs position relative to the fire strain. The following parameters must be determined:

- Wallboard thickness, density and type.
- Isolation thickness, density and type.
- Material combination; influence of isolation, air gaps and material location in the wall.

Although, the Nordic Wood project only include wood and gypsum, The NFPA handbook [22] describes several other constructions that can be compared to classified constructions. Also the Eurocodes includes calculation methods to do estimate of fire test performance for different structures [25,26].

3.8 LARGE AND SMALL BARRIER FAILURES

During a fully developed fire, barriers will burn if they are combustible, incombustible barriers will deteriorate due to the heat applied to the construction. Over time, the fire will be able to make a tiny hole or a complete breakdown. Both can happen, but failure due to large amounts of energy application is usually not the cause of fire spread. Fires can spread through small openings, created when the electrician installed the computer cable network or when the plumber installed the HVAC system. Due to these small openings, the fire can penetrate into other rooms, by small flames igniting nearby fuels or by heat conducted by the air canal. These installations are required to be properly secured against fire spread where the walls are meant to assure safe egress or to separate different fire risks (fire partitions). In other walls these weaknesses should be expected to exist. Small barrier failures can ignite fuels in the room beyond and initiate a fire development similar to the one in the room of origin.

The other common barrier failure is that the door is open, or that the door is made of simple glass. A door open will cause massive flow of energy flowing into other rooms. The amount energy flowing into other rooms can cause a second flashover even though the second room is clean for combustibles. The HRR penetrating into the room beyond calculated. This situation can be similar to a window plume [44].

When the type of barrier failure is stipulated fire growth in the room beyond can be evaluated with greater confidence. Knowledge of the fire in the room of origin (chapter 2) provides a basis for estimating the behavior when the room becomes a subsequent room for fire propagation.

3.9 SUMMARY

Fire rated interior barriers are one of the traditional methods to design safe egress paths, and exterior barriers have been used for centuries to prevent fire spread in some cities. The code acceptance criteria for barriers are denoted by E, I, R and M, meaning integrity, insulation, thermal resistance and mechanical resistance respectively. Barrier performance depends upon the construction, the heat application rate and the fire duration. Evaluation of temperatures in natural building fires is the main characterization of the design fire. There are several methods available, both as hand calculation and computer program.

Different barrier materials behave different in fires. Their fire endurance rating may be transferable to natural fires by estimation of accumulated heat application. On the other hand, natural fires may develop substantially higher temperatures than a standard fire test furnace. Elevated temperatures can cause the barrier material to behave different and causing failure in a shorter period of time than predicted. Knowledge of the barrier material is important in this evaluation.

Based on statistics, the probability of unstopped penetrations or other fixed openings tends to be higher in gypsum barriers than in masonry barriers. The size of the opening, made by the fire or fixed before the fire event, influence on the fire development in the next room.

3.10 REFERENCES

3.10.1 Hand calculation method for post-flashover temperatures estimation

1 Ingeberg; Tests of the severity of building fires. NFPA Quaterly, Vol 22 No 1, pp 43-61 (1928)

2 Mowrer; Methods of quantitative fire hazard analysis, EPI TR-100443, Electric Power Research Institute (1992)

3 Walton & Thomas; Estimating temperatures in fires, The SFPE handbook chapter 3-6

4 Babrauskas & Williamson; Post flashover compartment fires - Basis of a theoretical model. Fire and Materials Vol 2, no 2 pp 39-53 (1978)

5 Babrauskas & Williamson; Post flashover compartment fires - Application of a theoretical model. Fire and Materials Vol 3, no 1 pp 1-7 (1979).]

6 Magnusson & Thelandersson; Temperature-time curves of complete process of fire development - Theoretical study of wood fuel fires in enclosed spaces. Acta Polytechnica Scandinavia, Civil engineering and building construction series no 65, Stockholm (1970)

7 Kawagoe & Sekine; Estimation of fire temperature-time curve in rooms. Tokyo: Building Research Institute (1963).].

8 European Committee for Standardization, Eurocode 1-2.2, Basis of design and actions on structures, Action on structures exposed to fire.

9 Lie: Fire Temperature time relations, SFPE Handbook 1-3.

10 Harmathy; A new look at compartment fires, Part I. Fire technology vol 8, no3, pp 196-217 (1972).

3.10.2 Computer programs for post-flashover temperature estimation

11 Jones and Forney; “A Programmer's Reference Manual for CFAST, the Unified Model of Fire Growth and Smoke Transport,” *Natl. Inst. Stand. Technol.* 1990, *Tech. Note 1283*, 104 p.

12 Gahm, J. B., "Computer Fire Code VI, Volume I," *Nat. Bur. Stand. (U.S.)* 1983, *NBS GCR 83-451*, 116 p.

13 Forney and Cooper; The Consolidated Compartment Fire Model (CCFM) Computer Application CCFM.VENTS - Part II: Software Reference Guide, Nat. Inst. Stand. Technol., NISTIR 90-4343 (1990).

14 Cooper; "A Mathematical Model for Estimating Available Safe Egress Time in Fires," *Fire and Materials.* 1982, *6(4)*, 135-144.

15 McGrattan, Baum, Rehm, Hamins, Forney, Floyd, Hostikka: Fire Dynamics Simulator (Version 2) – Technical Reference Guide. NISTIR 6783. National Institute of Standards and Technology. November 2001

3.10.3 Fire endurance testing vs. real time endurance evaluation

16 Drysdale; An introduction to fire dynamics, John Wiley and sons, January 1992. Chapter 2.

17 Tien, Lee, Stretton, Radiation heat transfer, SFPE handbook 1-4.

18 Atreya, Convective heat transfer, SFPE handbook 1-3.

19 Rocket, Milke, Conduction of heat in solids, SFPE handbook 1-2.

3.10.4 Fire endurance calculation

20 Lie: Fire Temperature time relations, SFPE Handbook 1-3.

21 European Committee for Standardization, Eurocode 1-2.2, Basis of design and actions on structures, Action on structures exposed to fire.

22 Fitzgerald: Structural Integrity during fire, NFPA Handbook 7-8.

23 National Office of Building Technology and Administration (Norway); Notification HO-3/2000, Røykventilasjon, December 2000.

24 Fire Safe Wooden Buildings, Nordic Wood, Trätek (Sweedish)

25 Eurocode 5-2.1 Design of timber structures, Structural fire design.

26 Eurocode 2-2.1 Design of concrete structures, Structural fire design.

3.10.5 Barrier properties and design of structures

27 Fire Safe Wooden Buildings, Nordic Wood, Trätek (Sweedish)

28 Eurocode 5-2.1 Design of timber structures, Structural fire design.

29 Eurocode 2-2.1 Design of concrete structures, Structural fire design.

30 Gyproc Håndbok del A

3.10.6 Fire load evaluation

31 Fire Safety Journal vol 10, no 2, pp 101 - 118 (1986).

32 Norwegian Building Research Institute; Brannbelastning i bygninger Beregninger og statiske verdier, Byggdetaljer 520.333, (1999).

3.10.7 Probability evaluation information

33 Bukowski, Budnick and Schemel; Estimates of the Operational Reliability of Fire Protection Systems.

34 Factory Mutual Training Resource senter: Fire Doors, Closing the safety gap, 1986 and 1988.

3.10.8 Sensitivity and vulnerability

35 NFPA 69, Explosion prevention systems.

36 Eurocode 1-2.7, Basis of design and actions on structures, Accidental actions.

37 Zalosh, Explosion Protection, SFPE handbook 3-16

38 Stevenson, Evaluating Structural damage, NFPA handbook 7-11.

39 National Fire Protection Association; NFPA 80, Fire Doors and Fire Windows, 1996 edition.

3.10.9 Other information that doesn't fit into the categories above

40 National Office of Building Technology and Administration (Norway): TEK-97, Regulations concerning requirements for construction works and products for construction works, 22 January 1997 No. 33 Technical Regulations under the Planning and Building Act 1997.

41 National Office of Building Technology and Administration (Norway): REN, Guidance to Regulations concerning requirements for construction works and products for construction works, 2nd edition, April 1997.

42 National Building Standardization Council (Norway): NS3901, Risk analysis of fire in buildings and civil engineering works, May 1998

43 National Building Standardization Council: Guidance to NS3901, Guidance to risk analysis of fire in buildings, October

44 National Fire Protection Association; NFPA 92B, Smoke management in malls, atria and large areas, 1995 edition.

3.10.10 Barrier performance in combination with sprinklers

45 Kim, Taber, Laughed; Sprinkler Protection of Exterior Glazing, National Research Council, Canada, Fire Technology Vol 34, No 2, 1998.

46 National Fire Protection Association; NFPA 80A, Protection of Buildings from Exterior Fire Exposures, 1996 edition.

4 FIRE DETECTION AND INITIAL ACTION

In our modern society, fire protection is generally associated with detection and fire alarm systems. If a fire detection system were installed in the building, most people would say that the building is fire proofed. One of the reasons may be that a fire detection system is both visible and audible, and it encourages the occupants to take action. But also, the smoke detector is well known as a fire protection system because it gives early warnings of a fire.

Early detection and alerting can help the occupants take action and evacuate the building before critical fire situations occur. Fire and smoke detection systems is therefore a vital part of the fire safety concepts for many buildings. Generally, smoke detection systems are required in buildings that may be occupied by many people, sick people or sleeping people. On addition, early warning enables fire brigades (FB) to be notified earlier, thus encountering a smaller fire upon arrival.

4.1 OBJECTIVES

Detector reliability depends on several factors relating to the fire, the building geometry and the systems within the building. The objectives of a detection and initial action evaluation are to identify and evaluate the parameters concerning detection reliability and detector actuation time. First of all, the design fire characteristics for human or instrument detection, should be analyzed. The variety of different detectors are large, and different manufacturers produce different automatic functions to increase reliability, decrease the number of false alarms and decrease detection times. The most important factor is the likelihood that smoke will actually reach the detector, or that the detector (human or instrument) can sense the fire.

Detection is the first event, before a series of other actions can occur. The principal actions can be the notification of the FB and the alerting of building occupants. Before leaving this topic, an evaluation is made of time delays between detection and notification of the FB and time delays between detection and occupant alerting.

In most fires the FB is notified manually. Someone must make the call. The last objective is then to identify a minimum and maximum notification time relative to the FB intervention.

4.2 APPLICATION OF CODES AND STANDARDS

The National Technical Regulations (TEK) [35] requires that smoke detectors shall be installed in homes and smoke detection systems to be installed in hospitals, hotels and assembly areas. The general requirement for all buildings is that available egress time shall be longer than necessary egress time including a safety factor, and installed automatic detection systems may be a factor to obtain safe egress. REN [36] recommends fire detection systems also be installed in kindergartens and schools. Building owners must install partial smoke detection systems with automatic FB notification if their building base area is between 1200 and 1800 m^2. This recommendation is based on the decrease in anticipated loss because of early and reliable notification of the FD.

In order to do a performance-based evaluation of building fire safety, the evaluation of detection, occupant alert and FB notification is not enough. Detection and occupant alert is only the first, but very important factor of a safe egress evaluation and fire department manual suppression. The acceptance criteria for fire safety cannot be completely evaluated from only this sub-analysis.

A statistical evaluation of fire detection would measure the reliability of fire detection systems based on historical data or tests performed by the manufacturer. The weakness with historical data is that they may not reflect the actual building or system characteristics being evaluated. For example; how the building HVAC system or barriers between the fire and detector would influence on the likelihood of the occurrence of fire detection. A comprehensive evaluation of probabilities is difficult, and a good portion of engineering skills and insight into technical systems and human minds is necessary to obtain reliable estimates.

The deterministic analysis is an evaluation of the fire size and characteristics necessary for detection. Initially, the reliability is not of interest. The analysis is more like; detection will occur if …. Or will not occur if … Of course, the probabilistic and deterministic evaluation may be combined. The fire safety evaluation can be a comparative analysis against the pre-accepted fire design methods. The management of the acceptance criteria for safe egress and fire department manual suppression is more extensively discussed in respective chapters.

Specific information about the design of smoke detection systems can be found in national and international literature [8,9,10].

4.3 DESIGN FIRE FOR DETECTION EVALUATION

The design fire can be characterized by fire and smoke and fire properties and fire growth rate relative to the room geometry and ambient conditions. The first part of the evaluation of the design fire is to describe the properties of the fire and its products of combustion.

As soon as a fire starts it produces a variety of combustion products. The fire develops a signature that is special for different types of fires. The idea of detection is to recognize this signature. Table 4-1 describes some of the signatures from fires.

Table 4-1. Detectable fire signatures

Fire properties	*Signature*
Flame	Electromagnetic radiation, ultraviolet, visible, infrared
Heat	Elevated temperatures of air atmosphere above fire
Smoke	Particles suspended in air atmosphere (liquid and solid particles generated by incomplete combustion)
Fire gases	Gaseous combustion product CO, CO2, possibly HCl
Other	e.g. hot embers, water vapor, (per NFPA 72) ionized molecules

The first row in table 4-1 is a description of the visible flames. A flaming fire produces radiation. For many combustibles, the irradiative portion of combustion is about 30%. In order to detect flames the detector must be able to “see” the fire. Location of detector and distance between fire and detector would influence on detection times. The size of the fire viewed by a flame detector is proportional to the square of the distance.

The term heat is produced by a flaming fire and depends on the convective fraction of total HRR [1].

Gases and smoke are produced in all fires. The material composition of the burning fuel tells much about how the smoke would appear. Materials containing halogens (e.g. cables) could produce chloride gas and hydrochloric acid. Well-ventilated fires would produce large amounts of carbon dioxide, and as the fire grows and becomes under-ventilated, the percentage of carbon dioxide will increase substantially.

Smoke is defined as the smoke aerosol or condensed phase component of the products of combustion (POC) [2]. The American Society for Testing and Materials also includes the evolved gases as well. Smoke aerosols vary widely in appearance and structure, from light colored smoldering combustion to black soot from carbonaceous flaming combustion. The average size of the smoke particle and specific optical density are factors that influence the time to detector actuation [2].

Fire growth may be the most important factor for time to detection. For residential occupancies and fuel surfaces with approximately 2 dimensional geometry, the fire growth rate can be expressed with a t-square fire, and described as an ultra fast, fast, medium or slow growth rate. It should also be noted that t-squared curves represent fire growth starting with a reasonably large, flaming ignition source. With small sources there is an incubation period before established flaming, which can influence the response of smoke detectors and result in an underestimate of time to detection. This can be simulated by adding a slow, linear growth period until the rate of heat release reaches 25 kW. For more information about heat release rates in the early period, see chapter 2.

Time to smoke detection depends on design fire characteristics such as rate of fire growth rate, convective fraction of HRR, particle sizes, plume buoyancy, ceiling jet velocity and temperature, ventilation conditions and room geometry. The room geometry and ventilation conditions are important in order to predict that POC's actually reach the detector. Barriers that could obstruct the smoke from reaching the detector could be beams, doors, sloped ceilings etc. Ventilation could also prevent smoke from reaching the detector. Ventilation conditions that cause smoke to move faster at the detector location would also be an important factor for choosing adequate detector type. Ionization detectors tend to be more sensitive to high velocities and small particles, while photo electric detectors tends to be more sensitive to lower velocities and larger smoke particles. Particle size is also a function of velocity because the rate of smoke particle coagulation varies with the velocity.

4.4 HUMAN DETECTION AND NOTIFICATION

Human detection is simply a function of human presence and the ability to smell, watch or feel the products of combustion (POC). Humans can sense smoke earlier than an instrumental detector if the detecting human is present in the vicinity of the fire. The reliability of human detection can be evaluated by a characterization of the occupancy. A fire in a train or in an underground station would probably be detected by humans in the vicinity of the fire, and as the fire grows more humans would be aware of the danger. A fire in a warehouse or in an educational institute would probably not be detected at night. Generally, humans cannot detect fires in technical rooms or other rooms that are not designed for occupancy.

The weakness of human detection is alerting. Relatives or other humans that have been connected and developed human bonds or human acquaintance would probably try to alert each other in a case of fire. Humans living in urban block apartments may not know their neighbors, and therefore it may not be a natural act to alert them.

However, personal notification in residential occupancies is the most frequently reported means of initial perception of fire [32]. Only 7% were aware of the fire due to fire alarm, all the others became aware due to flames, smoke or noise. A research of the fire incident in the south tower of World Trade Center in 1993 documented that the personnel were primarily alerted due to either single or a combination of several cues, like explosion, loss or flickering of lights or telephones, smoke or dust, sirens and alarms, information from others, and people movement. A study involving college students reported that the presence of other people inhibited the individuals from taking action [32,33]. When one student was alone in the room the presence of artificial smoke were reported by 75% of the students within 6 minutes. When two passive non-committal persons joined the student only 10% reported the smoke. When the experimental groups were of three naive students, one person in 38% of the groups reported smoke.

Human fire department notification could also be evaluated by judgmental estimates. The judgments could be based on human a characterization or evaluation of the safety organization, if it exists. Clues could be age, sex, number of affected humans, and their attitude to safety, safety instruction and safety training. A U.S. study found that notifying the fire department was the third out of twenty-nine most frequent actions after precipitation of a fire. The most frequent was notifying others [32].

Table 4-1. Summary of first second and third actions of the occupants [32]

Actions	*1st action (percent)*	*2nd action (percent)*	*3rd action (persent)*
Notified others	15.0	9.6	5.8
Searched for fire	10.1	2.4	0.8
Called fire department	9.0	14.6	12.7
Got dressed	8.1	1.8	0.3
Left building	7.6	20.9	35.9
Got family	4.6	5.7	11.5
23 other actions	45.6	45	33

Human notifications have a major dependence on building location, occupancy and incident time of day. Occupants may choose to extinguish the fire, they can be stressed or they have to evacuate first. Nevertheless, mobile phones are common and it can be expected that someone choose to notify the fire department only minutes after they have detected the fire, if they choose to do it at all.

4.4.1 Notification systems

Time dependent probability of notification must be evaluated specific for each particular situation. Fitzgerald [40] described the advantages and disadvantages of these systems. It is only the auxiliary fire alarm system, central station and remote station that have a high reliability and rapid notification.

A proprietary supervising station is located within the building. When the fire-alarm has actuated, an attendant must choose whether to notify the fire department immediately or investigate the detected area.

A central station is normally remote from the protected building and is operated by a person or a company whose business is to furnish a variety of services related to fire protection systems.

A remote station is almost the same as a central station, but the remote station is not required to be approved by the local AHJ. Both systems have a set of procedures, and they will take immediate action and retransmit a fire alarm signal to the fire department. Some of the disadvantages are that the attendance may want to contact the building owner before re-transmitting the signal or the attendance may be poor trained.

In hospitals and nursing homes, the code officials usually require an auxiliary fire alarm system to be installed. This system enables a fire alarm actuation to be directly transmitted to the local fire department center. This system is the fastest and most reliable types of fire brigade notification.

4.5 INSTRUMENT DETECTION - HAND CALCULATION

In rooms with normal ceiling height and no special conditions that could prevent the smoke from reaching the detector, the time to detection can be set to an expected time, such as 30 seconds. Or, the fire is detected at a fire size of 20 kW. In most situations a simple judgment should be sufficient. In other situations, e.g. high ceilings height or special fire scenarios like combustible liquids, a more comprehensive evaluation may be needed. Fire size at detection is the more functional evaluation for buildings.

Time to detection for a smoke detector depends on geometry; smoke properties, detector and HRR. For large rooms and small fires the initial transport delay would increase detection times substantially. Before conventional smoke detectors actuate the smoke must penetrate into the detector chamber. A length, L, characterizes this time. The difference in concentration inside and outside the detector is given with the equation.

$$C_i = C_0 (1 - e^{-vt/L})$$

C_0 is the smoke concentration outside a spot detector.

C_i is the smoke concentration inside the detection chamber.

v s the plume velocity at the spot.

t is time to actuation

L is the characteristic length.

L = 5.3 +- 2,7 for photoelectric detectors and .

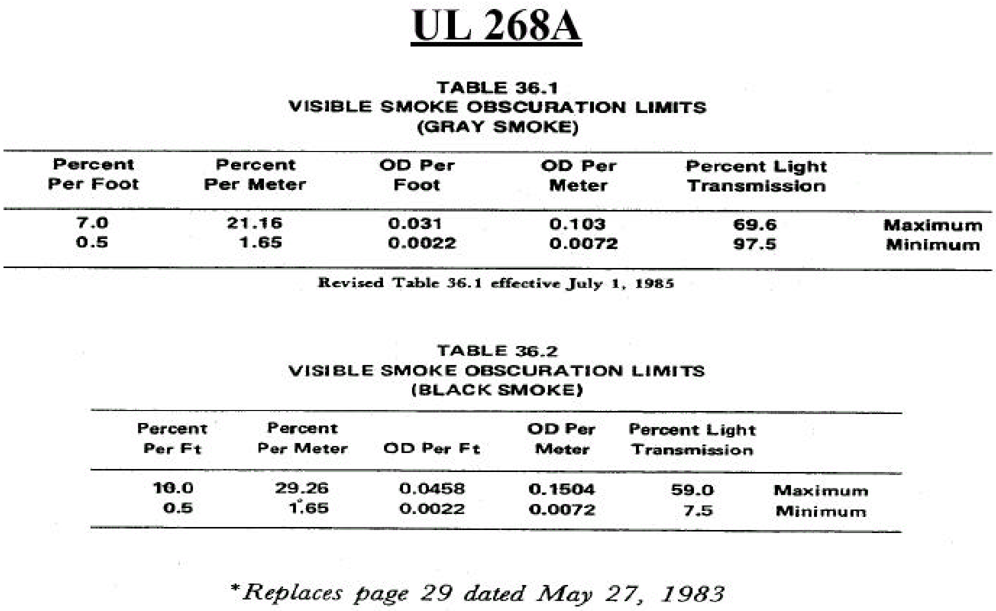
L = 3.2 for ionization detectors.

Time to detection can be derived from the equation above.

$$t = \left(\frac{-L}{v}\right)\ln\left(1 - \frac{C_i}{C_0}\right)$$

Minimum and maximum smoke concentration for detector actuation (Underwriters Laboratory) is presented in table 4-3.

Table 4-1. Smoke obscuration limits for listed detectors (UL).



UL 268A

TABLE 36.1
VISIBLE SMOKE OBSCURATION LIMITS
(GRAY SMOKE)

Percent Per Foot	Percent Per Meter	OD Per Foot	OD Per Meter	Percent Light Transmission	
7.0	21.16	0.031	0.103	69.6	Maximum
0.5	1.65	0.0022	0.0072	97.5	Minimum

Revised Table 36.1 effective July 1, 1985

TABLE 36.2
VISIBLE SMOKE OBSCURATION LIMITS
(BLACK SMOKE)

Percent Per Ft	Percent Per Meter	OD Per Ft	OD Per Meter	Percent Light Transmission	
10.0	29.26	0.0458	0.1504	59.0	Maximum
0.5	1.65	0.0022	0.0072	7.5	Minimum

**Replaces page 29 dated May 27, 1983*

The easiest way to calculate detection time is to use simple correlations for ceiling jet temperature. There are several correlations that can be used. The Alpert correlation is described in the SFPE handbook [3]. By assuming that the detector would actuate at a temperature rise of 5-10°C for smoke detectors, a very rough estimate for detection time can be performed.

It is possible to estimate time to detection within the room of origin by using the properties of smoke and non-dimensionalizing the variables. The non-dimensional variables have been defined by Heskestad and Delichatsios and are described in [3]. To incorporate the properties of smoke a new formula must be derived and solved by using the 4th order Runge-Kutta method to solve the differential equation.

$$\frac{d\overline{C}_{in}}{dt^*} = \tilde{a}_1 (t_2^* - t_f^*)^2 - \tilde{a}_2 (t_2^* - t_f^*)^{2/3} \overline{C}_{in}$$

Where;

$$g_1 = \left(b_1 / b_2^{3/2}\right)\left(t_{ch} U_{ch} / L\right)\left(r_\infty C_p \mathrm{Y}_s \,\text{ÄT}_{ch} / (C_{act} \Delta H_{chem}\, c_{conv} (1 - c_{ceil}))\right)$$

$$g_2 = \left(b_1 / b_2^{1/2}\right)\left(t_{ch} U_{ch} / L\right)$$

and

$$b_1 = 0.68(r/H)^{-0,63}, \qquad b_2 = 0.126 + 0.210(r/H)^{4/3} \qquad [27]$$

where, r is the horizontal distance between the fire source and the detector and H is the ceiling height. The equations for t_{ch}, U_{ch} and ΔT_{ch} can be found in the SFPE handbook [3].

This method solved with Runge-Kutta accounts for several important parameters that is not included in other detector actuation models. This method solves the concentration of smoke inside the detector chamber. Parameters like smoke yield and detector sensitivity is important input to the calculation. By solving the equations in an Excel spreadsheet the user can evaluate smoke transport time, temperature, ceiling jet velocity and heat release rate at the time the smoke concentration inside the detector chamber is sufficient to cause actuation.

4.6 INSTRUMENT DETECTION - SOFTWARE PROGRAM

Several simple software programs can model time to detection. The advantage of these programs is that they can give good indications on detector activation time. They do not include all the properties of the smoke, only the temperature of the ceiling jet is included. But, considering the uncertainty factors about the design fire, these fast and relatively reliable methods are normally good enough. These programs can be downloaded from the websites of National Institute of Standards and Technology [15].

It is important to understand the physics of the computer models and the assumptions built into each code. FPETOOL, written by Nelson [16,17] and DETACT-QS, written by Evans and Stroup [18,19], are each based on experimental correlations developed by Alpert for steady-state fires [14]. These correlations give the maximum temperature and maximum velocity as a function of the heat release rate of the fire, the radial distance to the fire, and the height of the ceiling above the fire. These correlations assume a smooth, unconfined ceiling. They also assume that steady state correlation can be applied to a growing fire over small time intervals. In both programs, the transport time of the smoke and hot gases from the fire to the thermal detector is neglected. Also in both programs the detector is subjected to the maximum temperature and velocity of the ceiling jet. FPETOOL accounts for the impact of the hot gases entrained into the ceiling jet on the temperature and velocity of the jet as it passes through the hot smoke layer; DETACT-QS des not.

LAVENT, written by Davis and Cooper [20], is similar to FPETOOL and DETACT-QS in that it assumes steady state correlations can be applied to a growing fire over small time intervals; and it also neglects the transport time of the smoke and hot gases from fire to thermal detector. LAVENT does account for the impact of the hot upper layer on the ceiling jet. LAVENT also accounts for position of thermal detector below the ceiling in the ceiling jet.

The zone model JET [21,22] evolved from the zone model LAVENT and therefore contains many of the features found in LAVENT. The major differences between JET and LAVENT include the ceiling jet temperature and velocity algoritms, the thermal activation algorithm, and the use of variable radiative fraction as a function of fire size and type.

CFAST [23] is also a member of a class of models referred to as zone or finite element models. The major difference in CFAST relative to other zone models is that it can simulate multiple fires and multiple rooms. Like the other models, each room is divided into two volumes (zones), in which the temperature and smoke and gas concentrations are *assumed* to be exactly the same at every point. CFAST can simulate smoke spread through openings so that estimates of detectors located in a corridor can be obtained even though the design fire is in another room.

Computerized Fluid Dynamics models (CFD), also named Field models solves the Navier-Stokes equations for energy and mass conservation. The program decides the room(s) into thousands of small numerical grids. CFD models can be used to evaluate smoke detector actuations, and may be the preferred tool for detector evaluation in buildings with complex geometry or complex ventilation conditions. Fire Dynamic Simulator [24] includes subroutines for smoke concentration. FDS can create gas species that closely resembles air in its molecular weight. By creating this species and giving it an appropriate yield, the model can accurately track spread and concentration of this “smoke” throughout the domain. For more information see the D'Souza et. al. reference

[40]. FDS can also be used to evaluate smoke detection times with heat detectors. A heat detector can simulate a smoke detector by using a low actuation temperature and a low RTI value. By using thermal detectors, FDS can be programmed to trigger special events like removal of blocks (i.e. windows) or opening of vents (i.e. smoke and heat ventilation) when detectors actuates.

4.7 SMOKE DETECTOR MODELING

The following sub-chapters are based on the paper Fire Detection Modeling – The Research-Application Gap [23].

4.7.1 Light obscuration smoke detectors

For projected beam type detectors, fire or smoke models that calculate the optical density per unit length, D_u, in a space or the total optical density in the path of the detector, optical density, D, may be used to determine when the detector would respond. Manufacturer specifications will typically indicate at what levels of total obscuration or total optical density the detectors respond. Projected beam smoke detectors generally have adjustable response thresholds. Reference for properties of smoke [2]

4.7.2 Light scattering (photoelectric) smoke detectors

Information about smoke properties related to light scattering is presently limited to a few types of fuels and is not readily available to practicing fire protection engineers. In addition, the data may not be in a useable format. For instance, the data must match the wavelength of the light source used in the detector being modeled. Scattering data at other wavelengths introduces errors and uncertainties.

A scattering type detector will respond at different optical densities for different types of smoke. For example, a scattering type smoke detector that responds at an optical density of .029 m-1 (2.0%/ft obscuration) to smoke produced by a smoldering gray cotton lamp wick may not respond until an optical density of 0.15 m^{-1} is reached for smoke from a kerosene fire.

4.7.3 Ionization smoke detectors

The signal produced by the chamber of an ionization detector has been shown to be proportional to the product of the number of particles and their diameter. Given the quantity and size distribution of smoke particles and the chamber constant (from the manufacturer), it is possible to model the ionization smoke detector. Unfortunately, there are no fire models that provide the required detector model input. In addition, manufacturer specifications do not presently include chamber constants.

4.8 DETECTOR RELIABILITY

The reliability of detection and depends on numerous of components that have to function in order to succeed. The fire alarm systems have to be designed according to the fire scenarios, it must be tested and maintained, and quality of the systems tends to vary with the occupancies it is meant to protect. The NFPA Handbook includes several chapters on the topics of fire alarm systems [12].

4.8.1 Statistics

Detector reliability can be defined in several ways. The most useful definition of detector reliability is the probability that the detector will actuate when the fire signature reaches its sensing chamber. This can be statistically based from a sample of detectors at the time of manufactures. However, the fire protection literature commonly defines reliability that a detector will operate as expected. This definition combines both the inherent detector operation (operational reliability) with the design expectations (performance reliability). One must be careful to understand the basis for reliability estimates when applying them to buildings.

Fire alarm performance is defined as the ability of the system to accomplish the task for which it was designed and installed. The operational reliability of a system depend on the reliability of individual components and their failure rates, the interdependencies of the individual components that compose the system, and the maintenance and testing of components and system once installed to verify operability. All of these factors are of concern in estimating operational reliability [18]. The reliability presented in table 4-4 is operational reliability. The reliability estimates in table 4-3 includes both performance and operational reliability, but the usefulness of these estimates may be limited because possibility of inaccurate methods used to derive the estimates.

Table 4-3. Published estimates for fire reliability of smoke detection systems [26]
(Probability of success (%)) (NA = Not Addressed)

Protection System	*Warrington Delphi UK (Delphi group)*		*Fire Eng. Guidelines Australia (Expert Survey)*		*Japanese Studies (Incident data)*	
	Smold-ering	*Flaming*	*Smold-ering*	*Flaming/ Flash over*	*Tokyo FD*	*Watamabe*
Heat detector	0	89	0	90/95	94	89
Home smoke detector	76	79	65	75/74	NA	NA
System smoke detector	86	90	70	80/85	94	89
Beam smoke detector	86	88	70	80/85	94	89
Aspirated smoke detector	86	NA	90	95/95	NA	NA

A summary of operational reliability estimates for selected occupancy groups were calculated and are shown in the next table. The estimates, including the mean reliability and 95% confidence limits [26].

Table 4-1. Operational reliability estimate for smoke detectors [26]

Occupancy	*Property use*	*Mean Reliability (%) n=10*	*95% upper Confidence interval*	*95% Lower Confidence interval*
Residential	Apartments	69.3	69.9	68.7
	Hotels/Motels	77.8	79.3	76.4
	Dormitories	86.3	88.4	84.3
Commercial	Public assembly	67.9	69.8	65.9
	Stores & offices	71.7	73.5	69.9
	Storage	68.2	70.0	66.3
	Industry & Manufacturing	80.2	81.3	79.1
Institutional	Care of aged	84.9	86.6	83.3
	Care of young	84.0	86.3	81.6
	Educational	76.9	79.6	74.1
	Hospitals & Clinics	83.3	85.4	81.2
	Prisons & Jails	84.2	85.9	82.5
	Care of Mentally Handicapped	87.5	90.3	84.8

4.8.2 Judgmental evaluations

Smoke detection and alarm system can be evaluated based on knowledge about the fire detection system, the fire and the building geometry. Generally, the probability of fire detection can be evaluated by analyzing whether enough products of combustion will reach the detector to cause actuation for the most sensitive setting for this type of detector, and will the detector actuate with the amount of products of combustion that is expected for the specified fire size. The first factor is an evaluation of the design fire and smoke transport to the detector, and the second is an evaluation of the detector sensitivity and the components reliability. This evaluation can be divided into steps or processes that functionally occurs. The major parts that would be evaluated include the following [30]:

1. Collect the information that seems appropriate for the performance evaluation. Sketch layouts where appropriate.
2. Develop a strategy for evaluation.
3. Describe the design fire and the time relationship for products of combustion release that is associated with the component performance. The definition of the design fire is one of the most important parts of performance evaluation.
4. Identify the functional and operational behavior of the component being evaluated as well as the relationship of the component to the design fire characteristics.
5. Estimate the component performance.

4.8.3 Residential Smoke Detector

Hall noted the following information in the September/October 1994 NFPA Journal [27].

Twenty percent of U.S. residences have non-operational smoke detectors such that there is no automatic detection capability at all in the residence. Eleven percent have no batteries in the detectors. Another five percent have dead batteries, and the batteries were disconnected in another three percent of the residences. Thus 95% of the non-operational detector households are caused by neglect or deliberate removal /disconnection of batteries. AC (hard-wired) powered detectors are much less likely to experience power supply problems.

The inherent greater reliability of hard-wired detectors simulated the current NFPA 101 Life Safety Code requirement for hard-wired detectors in new residential construction. Most of battery problems result from deliberate deactivation due to frustration with false alarms. Design changes that could reduce the frequency of false alarms and thereby reduce the occurrence of deliberate battery deactivation could be:

- Use of photoelectric light scattering detectors because there are less sensitive to the smaller particles associated with cooking smoke and with condensed moisture.

- Uses of aerodynamically designed entrances to the sensing chamber such that smaller particles would flow around the chamber while larger particles would flow directly into the chamber.
- Using a higher strength (larger ion generation rate) source that is less prone disruption, i.e. activation, by small particles. One drawback of the higher strength (alpha particle) source is the higher radiation level in the vicinity of the detector. Another approach would be to use a higher electrode bias voltage to reduce disruption/activation by smaller particles. These effects, which are described in NBS Technical Note 973, may in some cases also decrease overall sensitivity, which is not the most desirable way to reduce false alarm.
- Incorporating silencers that shut off the alarm either while pressing a button or for a short period following button contact closure, such that there would be less need to remove/deactivate batteries upon false alarm.

4.9 RESPONSE TIME

A mathematical method to evaluate response time does not exist. The evaluations have to be based on experience and knowledge about humans. The literature presents response times from 1-2 minutes to over 10 minutes. The building layout, the arrangement and marking of egress paths, and the human characterization are important factors. Important human characterization factors are; number of humans, what they do, familiarity in the building, awake or asleep, health etc.

In buildings occupied by a modest number of humans, were the egress paths are short and well arranged, and the fire is notified by audible alarm bells, the response time is generally the largest time delay. Researchers on this topic have concluded that the response time depends on the systems that make the alert. The response times is found to be shortest when humans can see or smell the fire or notified by others, the second best clue is a direct message over a loudspeaker system, the third is a pre-programmed message and the fourth is the ordinary alarm bell.

A Canadian study about fire risk in offices and residential buildings resulted in a method to evaluate the risk for personal injuries, FiRECAM. A sub model in FiRECAM [34] is to evaluate the decision and response time.

Table 4-1. Decision and response time for FiRECAM

Information method	*Decision and response time (seconds)*
Heat, smoke or flames	50
Warned by the arrival of FD	50
Warned by other persons	100
Warned by oral message over loudspeakers	100
Warned by a central alarm system	250
Warned by a local smoke alarm/detector	250

The British standard DD 240, BSI (1997) for response time is also referred in the guidance to Norwegian standard, NS 3901 [3]. This standard distinguishes between different alarm systems, and in addition four different occupant categories make a matrix that can be a good base for further evaluation.

Table 4-2. Estimated time to recognize and understand the alarm signal

Occupancy	Time to recognize and understand		
	Warning system		
	Oral message	Pre-programmed message	Siren or alarm bell
Offices, industry and schools	< 1	3	> 4
Stores, exhibition locals, museums and assembly areas	< 2	3	> 6
Hotels	< 2	4	> 6
Hospitals and Health care facilities	< 3	5	> 8

4.10 SUMMARY

The design fire for detector actuation is the fire size and fire growth potential, the products of combustion relatively to the building geometry. In buildings fires can be detected by instruments or by humans. Human detection depends on the fact that someone has to be there to smell or see the fire. Instrument detection time can be estimated with hand calculation tools or computer programs. The reliability of actuation is a matter of the fire characterization, smoke transport between the fire and detector, and the detector component characterization relative to the fire characterization. The methods used to alert the occupants influence on response times.

4.11 REFERENCES

4.11.1 Design fire information

1 Archibald Tewarson; Generation of heat and compounds in fires, The SFPE handbook of fire protection engineering, chapter 3-4.

2 Mulholland; Smoke production and properties, The SFPE handbook of fire protection engineering, chapter 2-15.

3 Evans; Ceiling jet flows, The SFPE handbook of fire protection engineering, chapter 2-4

4 Selection and specification of the ‘Design fire’ for performance based Fire Protection Design, Proceedings SFPE Engineering Seminar Nov. 15, 1993

5 Delichatsios; Air Entrainment Into Boyant Jet Flames and Pool Fires, The SFPE handbook of fire protection engineering, chapter 2-3.

6 Babrauskas; Burning Rates, The SFPE handbook of fire protection engineering, chapter 3-1.

7 Cooper; Compartment Fire-generated Environment and Smoke filling, The SFPE handbook of fire protection engineering, chapter 3-10.

4.11.2 Smoke detection systems and design

8 National Office of Building Technology and Administration (Norway): Brannalarm - Temaveiledning, Melding HO-2/98.

9 Norwegian Insurance Association, FG; Regler for automatisk brannalarm (1986).

10 National Fire Protection Association; NFPA 72, National fire alarm code, 1996 edition.

11 National Fire Protection Association; NFPA 101, Life Safety Code.

12 Several editors; Detection and alarm, The NFPA handbook, section 5.

13 Schifililit, Meacham and Custer; Design of Detection Systems, The SFPE handbook of fire protection engineering, chapter 4-1.

4.11.3 Smoke detection actuation times - hand calculation and theory

2 Mulholland; Smoke production and properties, The SFPE handbook of fire protection engineering, chapter 2-15.

3 Evans; Ceiling jet flows, The SFPE handbook of fire protection engineering, chapter 2-4

14 Alpert; Calculation of Response time of ceiling mounted fire detectors, Fire Technology, Volume 8 no 3 (1972).

27 Hall, NFPA Journal, September/October 1994

4.11.4 Computer programs for smoke detection evaluation

15 National Institute of Standards and Technology, Building and Fire Research Laboratory, http://www.bfrl.nist.gov/

16 Nelson; FPETOOL: Fire protection engineering tools for hazard estimation, NISTIR 43870, National Institute of Standards and Technology, Gaithersburg, MD (1990).

17 Nelson; FPETOOL Users guide, NISTIR 4439, National Institute of Standards and Technology,

Gaithersburg, MD (1990).

18 Evans & Stroup; Methods to calculate the response time of heat and smoke detectors installed below large unobstructed ceilings, NBSIR 85-3167, National Institute of Standards and Technology, Gaithersburg, MD (1985).

19 Stroup, Evans and Martin; Evaluating Thermal Fire Detection Systems, NBS SP 712, National Institute of Standards and Technology, Gaithersburg, MD (1986).

14 Alpert; Calculation of Response time of ceiling mounted fire detectors, Fire Technology, Volume 8 no 3 (1972).

20 Davis and Cooper; User Guide for the computer code Lavent, NISTIR 89-4122, National Institute of Standards and Technology, Gaithersburg, MD (1989).

21 Davis, Notarianni and Tapper*;* An Algorithm for Calculating the Plume Centerline Temperature and Ceiling Jet Temperature in the Presence of a Hot Upper Layer, NISTIR 6178, National Institute of Standards and Technology, Gaithersburg, MD.

22 Davis; Zone Fire Model JET: A Model for the Prediction of Detector Activation and Gas Temperature in the Presence of a Smoke Layer. (3390 K) NISTIR 6324; 55 p., National Institute of Standards and Technology, Gaithersburg, MD (1999).

23 Jones and Forney; “A Programmer's Reference Manual for CFAST, the Unified Model of Fire Growth and Smoke Transport,” *Natl. Inst. Stand. Technol.* 1990, *Tech. Note 1283*, 104 p.

24 McGrattan, Baum, Rehm, Hamins, Forney, Floyd, Hostikka: Fire Dynamics Simulator (Version 2) – Technical Reference Guide. NISTIR 6783. National Institute of Standards and Technology. November 2001

40 D'Souza, Sutula, Olenick, Zhang and Roby; Use of the Fire Dynamics Simulator to Predict Smoke Detector Activation, Proceedings of the Technical Meeting of the Eastern States Section of the Combustion Institute, December 2001.

4.11.5 Detector reliability

25 Schifiliti; Fire Detection Modeling – The Research-Application Gap, National Institute of Standards and Technology (2001)

26 Bukowski, Budnick and Schemel; Estimates of the Operational Reliability of Fire Protection Systems.

28 The Directorate for Fire and Electrical Safety (DBE): http://www.dbe.no/Internett.asp

29 Hall, Fire Safety Journal, 15 (1989) 471-475

30 Fitzgerald; The anatomy of building firesafety - Volume 1 - A way of thinking, or a macro view of building performance evaluation, Draft 5, Worcester Polytechnic Institute (2001)

4.11.6 Human behavior

31 Wood; The behavior of peoples in fires, Fire Research Station, England (1972).

32 Bryan; Human Behavior and Fire, NFPA handbook chapter 8-1.

33 Latane and Darley; Group Inhibition of Bystander Intervention in Emergency, Journal of Personality and Social Psycology, Vol 10, No 3, 1968, pp 215-221.

34 Proulx and Hadjisophocleous; Modeling Occupant Response and Evacuation in Apartment and Office Buildings. Proc. 2nd Pasific Rim SFPE Conf. Maui (1998).

4.11.7 Other information that doesn’t fit into the categories above

35 National Office of Building Technology and Administration (Norway): TEK-97, Regulations concerning requirements for construction works and products for construction works, 22 January 1997 No. 33 Technical Regulations under the Planning and Building Act 1997.

36 National Office of Building Technology and Administration (Norway): REN, Guidance to Regulations concerning requirements for construction works and products for construction works, 2nd edition, April 1997.

37 National Building Standardization Council (Norway): NS3901, Risk analysis of fire in buildings and civil

engineering works, May 1998

38 National Building Standardization Council: Guidance to NS3901, Guidance to risk analysis of fire in buildings, October

39 National Building Standardization Council: Guidance to NS3901, Guidance to risk analysis of fire in road tunnels, May 1998.

40 Fitzgerald; The anatomy of building firesafety - Volume 2 - The Framework, Draft 4, Worcester Polytechnic Institute (1999)

5 AUTOMATIC SPRINKLER SYSTEMS

An automatic sprinkler system is a unique active fire protection system for developing performance based fire protection designs. A properly designed sprinkler system improves life safety and property protection to a magnitude far better than similar buildings without sprinkler systems. In fire protection engineering only two types of buildings exist: Sprinklered and non-sprinklered. By using the knowledge of sprinklers reliability and effectiveness, the design of building layouts, egress paths, structural frames, fire partitions, arrangement for fire brigade intervention may be performed differently than in buildings without sprinkler installed.

This chapter introduces methods and references that may be used to evaluate the reliability and effectiveness of automatic sprinkler systems. Also methods to evaluate fire size at sprinkler actuation and the relations between fire size and water application are presented. A few software programs are discussed, and a discussion of how a reliable sprinkler system could affect the fire environment in buildings.

5.1 OBJECTIVES

The objectives of automatic sprinkler suppression evaluations are to estimate the system reliability, its effectiveness in fire suppression or fire control. These factors influence the fire environment and its influence on building performance. Figure 5-1 indicates the parts of a sprinkler system evaluation. Based on [1].

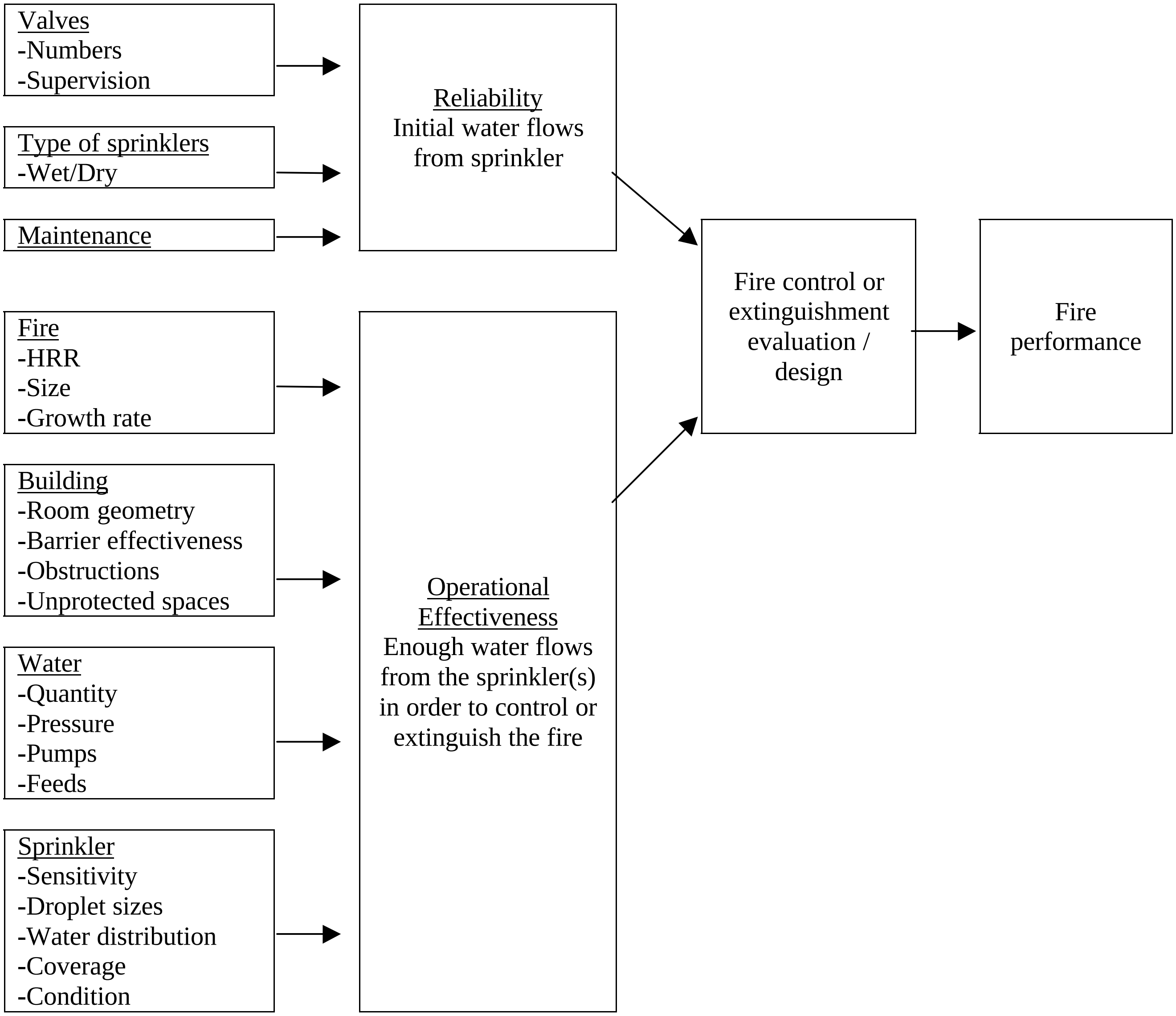


Figure 5-1. Objectives of sprinkler evaluation

Figure 5-1 shows that there are two main aspects of a fire sprinkler evaluation, operational reliability issues and operational effectiveness. Reliability is related to the fact that water actually flows through the valves, piping and sprinklers when the sprinkler link is heated to sufficient temperature. Operational effectiveness to suppress or control a fire depends among others, on the fire size at actuation, the building geometry, water quantities and sprinkler sensitivity and discharge characteristics.

5.2 APPLICATION OF CODES AND STANDARDS

The Technical Regulation (TEK) [52] includes several statements about sprinkler systems with barely mentioning the word sprinklers. The main reason is that there are also other fire protection systems that can be used. This code allows sprinklers to compensate for fire partitions if it is possible to document sufficient reliability and effectiveness of the sprinkler system: *The division shall be such that areas of different threats to the life and health of persons and/or different possibilities of fire to develop, are separated into different fire compartments, unless same level of safety are obtained by other means*. The code does not directly allow sprinklers to compensate for building frame with weaker fire resistance. The code requires that: *In calculations of stability and load-bearing capacity the total (accidental) load to be expected in the construction works shall be considered*. The Eurocodes [57] recommended the total accidental load to be reduced by a factor of 0.6 when a sprinkler system is installed according to the national standard. But this factor was not included in the revised Norwegian load standard. A more useful statement in the code is: *Where such measures are not sufficient* (automatic fire and smoke detection), *the available time for escape shall be increased by means of active measures, such as automatic fire-fighting installations, smoke control systems etc*. Meaning that, for example, an automatic sprinkler suppression system, alone or together with other systems, in some situations can compensate for an unusual layout of egress paths.

The guidelines to the Technical Regulation (REN) [53] recommend automatic sprinkler system to be installed when the area of the fire section exceeds 1200 m^2. In buildings with an automatic fire alarm system installed, this area increases to 1800 m^2. The recommendation is based only on property protection and the society's acceptance to property loss in fires. REN also follows up the statements in TEK by saying that sprinkler systems may be necessary in some buildings.

The deterministic acceptance criteria in NS3901 [54] can be relatively easy to document when sprinkler systems are installed. Quantitative numbers of the concentrations of carbon monoxide, oxygen, upper layer temperature and radiation can be calculated or found in reference material. The view length may be more difficult to estimate, but a good approximation can be made if one can be satisfied with the evaluation of sprinkler effectiveness and reliability.

The deterministic evaluation of the sprinkler system may be compared with a deterministic evaluation of fire doors and fire partitions in order to make a judgment of safe egress. Such a comparative analysis may be presented in an event tree [58], a decision tree [56] or as a curve [1]. NS 3901 states that risk analysis can be done by probabilistic-, deterministic- or comparative analysis. The comparisons can use appropriate information for any of these sources.

There are several standards that give guidelines on how to design a sprinkler system sufficient to control fires in different fire hazards. So far the sprinkler systems have generally been designed to control a fire with standard sprinkler sprays [15,16,17]. During the last decade new sprinkler technology has been developed, but only one sprinkler type is a complete fire suppression sprinkler. This is the Early Suppression Fast Response (ESFR) [16,17] sprinkler head, which is designed to suppress high challenge fires in warehouses. An intermediate system is the residential sprinkler. These sprinklers have the fast response technology and they have been tested for fire suppression. The residential sprinklers may be good fire suppression systems, but the standards for designing residential sprinklers [18,19] does not require sufficient water application rate and duration to ensure fire suppression. On the other hand, one of standard's requirements for residential sprinklers is to delay flashover to over 10 minutes. Today, manufacturers do not know about water distribution pattern and water drop size distribution that appears below the sprinkler link. These factors are necessary to predict sprinkler suppression.

Because of the scarcity of this knowledge, sprinkler systems are usually designed to control fires. When designing a sprinkler control system, the technology of sprinkler suppression system must not be mixed in. Sprinkler control is designed to control fires by preventing fire spread beyond a design area.

5.3 DESIGN FIRE FOR SPRINKLER EVALUATION

Sprinkler design standards relate potential fires with occupancy classifications. These classifications [15,16] are described Light Hazard; Ordinary Hazard; Extra Hazard and Special Hazards. In essence, these classifications are associated with water delivery and its supply. One might view these classifications as "design fires". However, they are not design fires from an evaluation or performance viewpoint.

A design fire for a sprinkler system involves three concepts [1]:

1. A relationship between the time of fire growth and the rate of heat release rate
2. A relationship between heat release rate and floor area of fire involvement
3. A relationship between the fire plume momentum and the floor area of fire involvement

When one wants to evaluate the fire size at the time of first sprinkler actuation, the fire growth rate provides a basis for the estimate. As one considers the speed of fire spread and the ability of the sprinklers to control or extinguish the design fire, the heat release rates and floor areas becomes important in making the estimations for water distribution and quantity.

The design fire is the same whether one evaluates the system for fire control or fire extinguishment. The rules for early suppression fast response (ESFR) are different from those for traditional fire control. In addition, water mist is sometimes considered a suppression system. While the design fire remains a single description that considers the type of fire growth expected for the room configuration, the sprinkler performance is dependent upon the sprinkler design, the water density, distribution, and continuity, and the presence of obstructions.

5.4 SPRINKLER ACTUATION

In the suppression mode the actuation time and convective heat release rates at actuation are another important factors to achieve suppression. Sprinkler actuation can be predicted numerically by using formulas for ceiling jet velocities and temperatures and a heat balance equation for the sprinkler link [3,30] (the radiation part of the equation can be excluded).

Sprinkler link temperature:

$$\frac{dT_L}{dt} = \frac{\sqrt{U}(\Delta T_g - \Delta T_L)}{RTI} + \frac{Q_r}{mc_L} - \frac{C_{cond}}{RTI}\Delta T_L$$

where,

m = sprinkler link mass (kg)

c_L *= sprinkler link specific heat (kJ/kg.K)*

DT_L *= Change in link temperature (K or C)*

DT_g *= Change in gas temperature at the link (K or C)*

Qr = Radiation (kW/m^2*)*

RTI = Response Time Index ($m^{½}s^{½}$*)*

The values for link mass, conduction parameters, specific heat capacity etc. of fast response links are not always know. For convenience some useful link data are presented in table 5-1.

Table 5-1. Typical sprinkler head data

Sprinkler link details	*Fast response sprinkler*	*"Slow" response conventional sprinkler*	*Fast response sprinkler*	*Conventional sprinkler*
Link type	Solder	Solder	Bulb	Bulb
Link mass, kg	0.00094	0.009	0.0006	0.002
Link actuation temperature, °C	74	139°C	74	70
RTI, $(\text{m.sec})^{0.5}$	29.8	302	24.6	342
Heat capacity of link, kJ/kg°C	0.385	0,385	3.3	3.3
Link area, m^2	0.000384	0.0094	0.0001	0.00024
Conduction parameter C	0.5	1.52	0.5	1.0

Time dependent velocities and temperature in the ceiling jet must be calculated to estimate actuation time. Several correlations are listed in the reference section.

5.5 SPRINKLER CONTROL MODE

In this evaluation, occupancy and commodity classifications are the most important factors. If the fire hazard is underestimated the fire can overpower the water application rate. According to the standards [6-8] it is presupposed that the fire will be controlled within the required design area with the required water application rate. The standards give guidelines onto how different occupancies can be classified into fire hazards.

The design fire for sprinkler control is primarily occupancy classification. But also ceiling height and sprinkler configuration must be considered according to the standards.

5.6 SPRINKLER SUPPRESSION THEORY

The standard that describe sprinkler suppression with ESFR is NFPA 13 [15], NFPA 231C [17] and the CEA standard [16]. The ESFR sprinklers have a special design; they can deliver large quantities of water at high pressure, with high water density and force, directly below the sprinkler head.

In 1984, Factory Mutual Research Corporation (FMRC) initiated the ESFR research program. A significant development that resulted from the ESFR program was the establishment of a systematic approach to sprinkler performance evaluations using relationships between quantifiable sprinkler discharge characteristics and the fire challenge. This approach compares the amount of water required for fire suppression with the amount of water actually delivered to the burning surface. These terms are called the Required Delivered Density (RDD) and Actual Delivered Density (ADD). For a given heat release rate early suppression can be predicted if ADD is higher than RDD.

RDD is measured with a horizontal and circular array of collectors on top of the fuel array. RDD is the water densities found to be necessary to suppress the fire. ADD is measured after the droplets have fallen through a heptane fire plume. ADD is therefore dependent on the sprinkler head’s ability to penetrate the fire plume at the fire size being evaluated.

The sprinkler suppression mode must be designed with the criteria: The sprinkler link must fuse early and quickly suppress the fire and prevent actuation of more than those sprinkler links that the system is designed to operate within.

A rough prediction of sprinkler suppression rate can be predicted if the fuel characteristic is known. Yu, Lee and Kung at FMRC [25] have correlated the fire response of delivered water density in rack-storage. They found that the fire intensity after water application could be expressed as:

$$\dot{Q}_a = \dot{Q}_{a0}\, e^{-k(t-t_0)}$$

where k is a measured constant dependent on the water application density per unit exposed surface area (water that has penetrated the buoyant plume, ADD), and Q_{a0} is the HRR at water application

Critical water application rates for different fuels can be found in the SFPE handbook [26]. When fuels burn in normal air and no external heat flux occur, the critical water application rate is low. When the fuel is exposed to its own flames or other external heat flux, the critical water application rate increases. These values includes that no puddle at the surface occurs, and, they can be compared with an evaluated ADD.

Table 5-1. Critical water fluxes for flame extinction

Fuel	*Critical water application rate without external radiation g/m^2.s*	*External radiation kW/m^2*	*Critical water application rate without external radiation g/m^2.s (mm/min)*
Polypropylene	3.0	67	29 (1.7)
Polyethylene	3.8	61	27 (1,6)
Polyethylene foams	3.5-4.1		
Polystyrene	5.1	75	34 (2.0)

Measurements of required water delivery to suppress a light hazard scenario (vinyl covered upholstered chair with padding made of 30% polyurethane foam and 63% shredded PU and 7% cotton) indicated that RDD of 5 mm/min could be used to suppress a fire in light hazard occupancies [23,24].

5.6.1 Sprinkler design for suppression

The most common sprinkler head is the standard spray sprinkler, with an activation temperature of 68-74 °C a 6 mm in diameter bulb (if a fusible link is not used). These sprinklers have a normal Response Time Index (RTI) and a water density distribution that are not appropriate for early suppression, but they are appropriate for a sprinkler control design. A standard sprinkler with a smaller activation bulb (3 mm) or fusible link and a RTI below 50 $(ms)^{½}$ is called a fast response sprinkler. The water distribution pattern is similar to the standard spray. Even though these sprinklers activate early they are normally not designed to deliver proper amount of water for suppression directly below the sprinkler head. The distribution pattern is not uniform. A standard response sprinkler link is appropriate for sprinkler control, but a fast response sprinkler in a sprinkler control mode can cause further sprinklers to open than assumed in the sprinkler design area, causing the water application rate per sprinkler to drop. Fast response must therefore be selected with care.

Residential sprinklers also have low RTI values and are designed to enhance the probability of suppression/control with smaller water densities in order to make the system achievable for housekeepers. But, on the other hand, residential sprinklers are designed to control or extinguish a fire within the periphery of on sprinkler head. The water distribution pattern is more uniform. The water demand delivered from residential sprinkler systems is less than usually required for commercial sprinkler suppression. The requirement, according to NFPA 13R and –D, is to delay flashover in 10 minutes. With higher water densities than required, residential sprinklers may be the most efficient suppression sprinklers in light and ordinary hazards [27].

Besides the sprinkler spray distribution and water flow, the next important factor is water droplet size. Larger drops have larger momentum and more efficient in penetrating the fire plume. The droplet size is an inverse function of water pressure and a proportional function to sprinkler orifice (the K-factor) [30].

The last and decisive factor is the fire vs. sprinkler configuration. Fires between four sprinklers would be exposed to higher water flux and the water would penetrate into the plume with an angular attack. The ADD will decrease, as the fire becomes vertically closer to the sprinkler link. The figure 5-2 shows the test results from a residential sprinkler with the minimum of required water delivery rates [23].

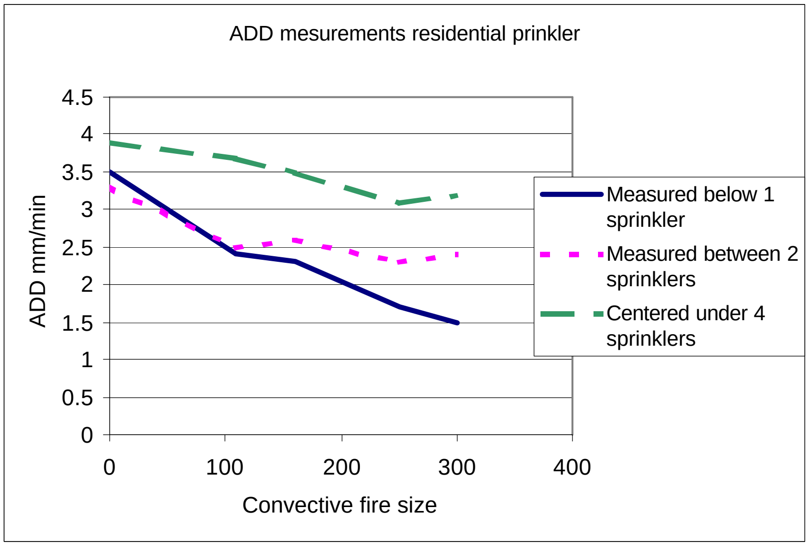


Figure 5-1. Measured ADD for a specific residential sprinkler

Table 5-1. Corresponding water delivery rates to figure 5-2

Number of sprinklers	*Water deliver rate*
1 sprinkler actuates (ignition under one)	68 L/min
2 sprinkler actuates (ignition between two)	49 L/min pr sprinkler head
4 sprinkler actuates (ignition between four)	49 L/min pr sprinkler head

5.6.2 Water droplet size distribution

The water droplet size distribution and water density distribution from a sprinkler head is a crucial factor for predicting sprinkler performance. Especially, the size and density of water reaching the area directly below the sprinkler head is important in sprinkler suppression mode. The distribution varies between sprinkler designs. An example of water distribution is given in figure 5-3 and 5-4. These figures are derived from measurements of water flows and droplet sizes from a standard sprinkler link [25]. Note that the water distribution and droplet sizes at about 1-2 m^2 directly below this sprinkler head is more appropriate for control than for suppression.

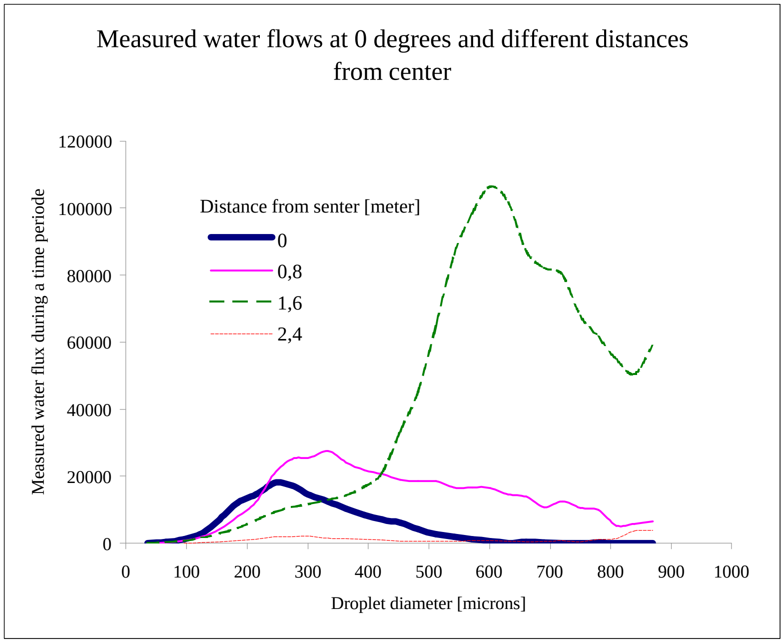


Figure 5-1. Measured droplet size and water flow at different distances from center under a standard pendent sprinkler head.

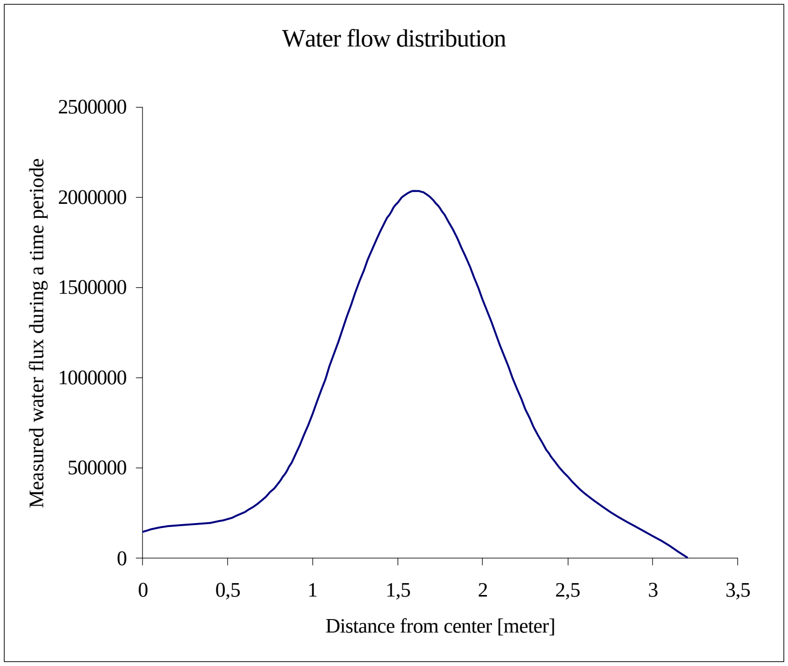


Figure 5-2. Measured water flow distribution from a standard pendent sprinkler head.

5.7 AUTOMATIC SPRINKLER RELIABILITY

5.7.1 Statistics

Statistics may be used to describe certain data of a sprinkler system. However, statistics alone shouldn't be used for an evaluation of a protection system.

Reliability is normally defined as an estimate of the probability that a system or component will function as designed over a designated time period. As mentioned in chapter 4, there are two components to overall reliability. Operational reliability is a measure of the probability that a system or component will operate as intended when called upon. It is directly affected by the types and frequency of testing and maintenance performed on the system. Performance reliability (i.e., capability) is a measure of the adequacy of the system, once it has operated, to successfully perform its intended function. For a sprinkler system, operational reliability accounts for the “readiness” of the system to apply water under a fire scenario, while performance reliability addresses the “capability” of the sprinkler to perform satisfactorily under specific fire exposures. The operational reliability of a sprinkler component system can be high. Based on different statistical sources the reliability of sprinklers varied from 86% to 99% [39].

Table 5-4 [39] provides a summary of the reliability estimates provided in four studies. Significant differences exist in the individual reliability estimates depending on the parameters used to develop these estimates. Depending on the required accuracy in predicting future operational performance of fire protection systems, dependence on the range of estimates from these studies could significantly alter the results. In addition, the uncertainty associated with a single estimate of reliability or the existence of potentially important biases in the methods used to derive these estimates may limit their direct usefulness in addressing either operational or performance reliability [39].

Table 5-1. Published Estimates for operational reliability of sprinkler systems [39]

Protection System	*Warrington Delphi UK (Delphi group)*	*Fire Eng. Guidelines Australia (Expert Survey)*	*Japanese Studies (Incident data)*	
	Flaming	*Flaming/ Flash over*	*Tokyo FD*	*Watamabe*
Sprinkler operate	95	95/99	97	NA
Sprinkler control but did not extinguish	64	NA	NA	NA
Sprinkler extinguish	48	NA	96	NA

(Probability of success (%)) (NA = Not Addressed)

The estimates presented in table 5-5 generally indicate relatively high operational reliability for sprinkler systems. While some of the data sources included fire control or extinguishment as part of the reliability assessment, the reported data were not consistent. Therefore, operational reliability in table 5-5 was assumed to be limited to sprinkler operation.

Table 5-2. Reported Automatic Sprinkler Reliability Data (percent) [39]

Occupancy	*References*	*Reliability values*
Commercial	Milne [1959]	96.6/97.6/89.2
	Automatic sprinkler [1970]	90.8-98.2
	Miller [1974]	86
	DOE [1982]	98.9
	Maybee [1988]	99.5
	Kook [1990]	87.6
	Taylor [1990]	81.3
	Sprinkler focus [1993]	98.4-95.8
	Linder [1993]	96
General	Building research Est. [1973]	92.1
	Miller [1974]	95.8
	Miller [1974]	94.8
	Powers [1974]	96.2
	Richardson [1985]	96
	Finuance et. Al. [1987]	96.9-97.9
	Marryat [1988]	99.5
Residential	Milne [1959]	96.6
Institutional	Milne[1959]	96.6

5.7.2 Water supply failure

The available water supply is sometimes insufficient to control fires. This problem is often present in areas with ground water or where local ponds are used as sprinkler water supplies. Seasonal variations in rainfall and the occasional drought affect the "height" of the underground water level and causing low level in water tanks. Reference: Wilcox [41].

After treatment water is distributed into a system of pipes made of cast or ductile iron. These pipes tend to corrode with time and lose their capacity to withstand the combination of surface loads and pressures due to soil, frost heave and water. Newer pipes are often made of PVC and the problem is reduced significantly. Schultz [42].

Walski and Pellicia [40] performed a study of water main breakages and provided a compilation of the frequencies, f_{bl}, of water main breaks in various municipalities. The corresponding water main probability of outage is given by:

$$p = f_{bl} \times L \times t_f$$

where:

p is the probability of water main being unavailable

f_{bl} is the frequency of main breaks and leaks per mile-yr or pr km-yr.

L is the length (mile or km) of main from water source to plant connection

t_r is the average time to repair break/leak (yr)

The repair times are given by the formula:

$$t_r = 6.5 \times (D)^{0.285}\ hr$$
$$t_r = 7.4 \times 10^{-4} \times (D)^{0.285}\ yr$$

where:

D is the water main diameter in inches

In some areas, earthquakes, floods and forest fires can occur. Floods can affect the water supply system and destroy pumps. Ice formations can make pipes freeze, put pumps and storage tanks out of service etc. Forest fires can involve and destroy water storage tanks, pumping stations, and water treatment facilities thereby cutting of the water supply.

5.7.3 Reliability of pumps, valves, pipes and operation of sprinkler heads

Automatic sprinklers are thermo sensitive devices, designed to react at predetermined temperatures by automatically releasing a stream of water: The water is feed to the sprinkler through a system of piping, valves and sometimes pumps. The pipes are connected to the ceiling with special hangers, and the sprinkler heads are placed relative to the ceiling and beams. The reliability of the sprinkler system depends on each component functionality, installation and maintenance [20,21].

Although sprinkler systems historically are very reliable, there are some malfunction modes that should be considered. A way to prevent system malfunction is to install redundant systems [39].

Table 5-1. Failure modes for sprinkler system components

System component	Failure modes	Redundancy / failure prevention efforts
Pumps	Loss of power supply	Additional power supply
	Motor malfunction	Two pumps
Valves	Valves are closed	Automatic valve supervising, periodically supervising
Pipes	Pipes are corroded	Acid-proof piping, water circulation system, inhibitor.
Sprinkler heads	Sprinkler head becomes clogged at actuation.	Circulation system with filters (requires a loop system), prevent loose parts like o-rings

5.7.4 Obstructions

Obstructions can reduce or remove parts of the sprinkler spray. Sprinkler heads located close to ducts or ceiling beams/girders can obstruct a portion of the spray and cause the fire to grow uninterrupted. Ideally, obstructions in the ceiling should be located in the center between the sprinkler links.

5.8 COMPUTER PROGRAMS FOR AUTOMATIC SPRINKLER MODELING

In the suppression mode the time to actuation is a critical factor and this part of the evaluation is essential. There are many ways to predict actuation times; some of them are listed in the reference section [43-54]. Other software like CFAST and FastLite can also be used to predict sprinkler actuation times [50].

The CFD code Fire Dynamic Simulator [51] calculates both actuation and suppression. FDS can be programmed to include median droplet size, water flux and water distribution pattern. This program is exceptional if sufficient information about sprinkler links water spray distribution pattern is available.

Sprinkler actuation is modeled similar to heat detectors. More information about the computer tools for modeling heat detection is presented in chapter 4.

5.9 SUMMARY

Sprinkler system installation may be a useful to document sufficient fire safety with regard to several aspects of building firesafety. The code require a sprinkler system to be installed according to the standards [] occupancy classification. A sprinkler performance evaluations starts with an evaluation of a design fire, and then evaluation of operational reliability and operational effectiveness. Evaluations of a sprinkler control systems and sprinkler suppression systems shall be distinguished. Computer programs can be used to evaluate sprinkler actuation, and some field models can be used to simulate sprinkler suppression.

5.10 REFERENCES

5.10.1 General design fire information

1 Fitzgerald; The anatomy of building firesafety - Volume 1 - A way of thinking, or a macro view of building performance evaluation, Draft 5, Worcester Polytechnic Institute (2001)

2 Selection and specification of the ‘Design fire’ for performance based Fire Protection Design, Proceedings SFPE Engineering Seminar Nov. 15, 1993

5.10.2 Sprinkler related fire dynamics and sprinkler actuation

3 Heskestad and Bill; Quantification of Thermal Responsiveness of Automatic Sprinklers Including Conduction Effects, Fire Safety Journal 14:113-125, 1988.

4 Alpert; Turbulent Ceiling-Jet Induced by Large Scale Fires, Comb. Sci. Tech., 11 (1975) 197-213.

5 Heskestad and Delichatsios; NBS-GCR-77-86 and NBS-CGR-77-95, National Bureau of Standards, 1977.

6 Motevalli and Marks; Characterizing the Unconfined Ceiling Jet under Steady State Conditions: A Reassessment, in Fire Safety Science -- Proceedings of the 3rd International Symposium, Elsevier Applied Science, London, UK (1991) 301-312.

7 Kung, Spaulding, You; Response of Sprinkler Links to Rack Storage Fires, Factory Mutual Research Corporation, 1986.

8 Evans; Ceiling Jet Flows, The SFPE Handbook 2nd edition chapter 2-4.

9 Davis, Notarianni and Tapper; An Algorithm for Calculating the Plume Centerline Temperature and Ceiling Jet Temperature in the Presence of a Hot Upper Layer, NISTIR 6178, National Institute of Standards and Technology, Gaithersburg, MD.

10 Archibald Tewarson; Generation of heat and compounds in fires, The SFPE handbook of fire protection engineering, chapter 3-4.

11 Evans; Ceiling jet flows, The SFPE handbook of fire protection engineering, chapter 2-4

12 Delichatsios; Air Entrainment Into Boyant Jet Flames and Pool Fires, The SFPE handbook of fire protection engineering, chapter 2-3.

13 Babrauskas; Burning Rates, The SFPE handbook of fire protection engineering, chapter 3-1.

14 Cooper; Compartment Fire-generated Environment and Smoke filling, The SFPE handbook of fire protection engineering, chapter 3-10.

5.10.3 Sprinkler system and sprinkler design

15 National Fire Protection Association; NFPA 13, Installation of Sprinkler Systems, 1996 edition.

16 The European Insurance Company (CEA); Sprinkler System, CEA 4001:2001-04, Planning and Installation.

17 National Fire Protection Association; NFPA 231C, Rack Storage of Materials, 1995 edition.

18 National Fire Protection Association; NFPA 13D, Sprinkler Systems in one- and two Family Dwellings and Manufactured Homes, 1996 edition.

19 National Fire Protection Association; NFPA 13R, Sprinkler Systems in Residential Occuoancies up to and Including Four Stories in Height, 1996 edition.

20 Puchovsky; Automatic Sprinkler Systems - Handbook, National Fire Protection Association, 1996.

21 Solomon; Automatic Sprinkler Systems, NFPA Handbook 18th edition.

5.10.4 Sprinkler performance and sprinkler efficiency

22 Bill, Kung, Vincent, Brown and Spaulding; Predicting The Suppression Capability of Quick Response Sprinklers in a Light Hazard Scenario Part 1: Fire Growth and Required Delivered Density (RDD)

Measurements, FMRC, Journal of Fire Protection Engineering 3(3), 1991 pp 81-93.

23 Bill, Kung, Brown and Spaulding; Predicting The Suppression Capability of Quick Response Sprinklers in a Light Hazard Scenario Part 2: Fire Actual Delivered Density (ADD) Measurements and Full-scale Fire Tests, FMRC, Journal of Fire Protection Engineering 3(3), 1991 pp 81-93.

24 Putori, Belsinger and Twilley; Determination of Water Spray Drop Size and Speed from a Standard Orifice, Pendent Spray Sprinkler, National Institute of Standards and Technology, September 21, 1995 (revised May 27, 1999).

25 Yu, Lee, Kung; Parametric Study With a Computational Model Simulating Interaction Between Fire Plume and Sprinkler Spray «Suppression of Rack Storage Fires by Water», Factory Mutual Research Corporation, Fire Safety Science, Fourth International Symposium 1994, pp901-912.

26 Tewarson; Generation of Heat and Compounds in Fires, Table 3-4.27 and 3-4.28

27 Cote and Fleming; Fast Response Sprinkler Technology, NFPA Handbook 6-13 18th edition.

28 Vincent, Stavrianidis and Kung; Use of Quick Response Sprinklers for Industrial Fire Protection Applications; FMRC, J. of Fire Protection Engineering 2(4), 1990 pp 99-110.

29 Chan; Measurements of Water Density and Drop Size Distribution of Selected ESFR Sprinklers, , FMRC, J. of Fire Protection Engineering 6(2), 1994 pp 79-87.

30 Grattan and Forney; Numerical Simulation of Sprinkler Performance, National Institute of Standards and Technology, 1999.

5.10.5 Sprinkler reliability

31 Modarres; Reliability and risk analysis, University of Maryland, Marcel Dekker Inc. New York (1993)

32 Hughes Associates, Inc. “Pilot Study: Automatic Sprinkler System Reliability Analysis,” Hughes Associates, Inc., Baltimore, MD, September 30, 1998.

33 Miller, M.J. “Reliability of Fire Protection Systems,” *Loss Prevention ACEP Technical Manual*, 8, 1974.

34 Linder, K.W. “Field Probability of Fire Detection Systems,” Balanced Design Concepts Workshop,

NISTIR 5264, R.W. Bukowski (Ed.), Building and Fire Research Laboratory, National Institute of Standards and Technology, September 1993

35 Marryat, H.W. *Fire: A Century of Automatic Sprinkler Protection in Australia and New Zealand 1886-1986*, Australian Fire Protection Association, Melbourne, Australia, 1988.

36 Powers, R.W. “Sprinkler Experience in High-Rise Buildings (1969-1979),” *SFPE Technology Report 79-1*, Society of Fire Protection Engineers, Boston, MA, 1979.

37 Richardson, J.K. “The Reliability of Automatic Sprinkler Systems,” *Canadian Building Digest*, Vol. 238, July 1985.

38 Finucane, M, and Pickney, D. “Reliability of Fire Protection and Detection Systems,” United Kingdom Atomic Energy Authority, University of Edinburgh, Scotland.

39 Bukowski, Budnick and Schemel; Estimates of the Operational Reliability of Fire Protection Systems.

40 Walski and Pellicia; Economic Analysis of Water Main Breaks, Journal of American Water Works Association, 1982.

41 Wilcox; Water Storage Facility and Suction Supplies, The NFPA Handbook 18th edition chapter 6-2.

42 Schultz; Water Distribution Systems, The NFPA Handbook 18th edition chapter 6-3.

5.10.6 Computer programs for sprinkler evaluation

43 National Institute of Standards and Technology, Building and Fire Research Laboratory, http://www.bfrl.nist.gov/

44 Nelson; FPETOOL: Fire protection engineering tools for hazard estimation, NISTIR 43870, National Institute of Standards and Technology, Gaithersburg, MD (1990).

45 Nelson; FPETOOL Users guide, NISTIR 4439, National Institute of Standards and Technology, Gaithersburg, MD (1990).

46 Stroup, Evans and Martin; Evaluating Thermal Fire Detection Systems, NBS SP 712, National Institute of Standards and Technology, Gaithersburg, MD (1986).

47 Alpert; Calculation of Response time of ceiling mounted fire detectors, Fire Technology, Volume 8 no 3 (1972).

48 Davis and Cooper; User Guide for the computer code Lavent, NISTIR 89-4122, National Institute of Standards and Technology, Gaithersburg, MD (1989).

49 Davis; Zone Fire Model JET: A Model for the Prediction of Detector Activation and Gas Temperature in the Presence of a Smoke Layer. (3390 K) NISTIR 6324; 55 p., National Institute of Standards and Technology, Gaithersburg, MD (1999).

50 Jones and Forney; "A Programmer's Reference Manual for CFAST, the Unified Model of Fire Growth and Smoke Transport," *Natl. Inst. Stand. Technol.* 1990, *Tech. Note 1283*, 104 p.

51 McGrattan, Baum, Rehm, Hamins, Forney, Floyd, Hostikka: Fire Dynamics Simulator (Version 2) – Technical Reference Guide. NISTIR 6783. National Institute of Standards and Technology. November 2001

5.10.7 g. References that don't fit into the above categories

52 National Office of Building Technology and Administration (Norway): TEK-97, Regulations concerning requirements for construction works and products for construction works, 22 January 1997 No. 33 Technical Regulations under the Planning and Building Act 1997.

53 National Office of Building Technology and Administration (Norway): REN, Guidance to Regulations concerning requirements for construction works and products for construction works, 2nd edition, April 1997.

54 National Building Standardization Council (Norway): NS3901, Risk analysis of fire in buildings and civil engineering works, May 1998

55 National Building Standardization Council: Guidance to NS3901, Guidance to risk analysis of fire in buildings, October

56 Clemen; Making Hard Decisions - An Introduction to Decision Analysis,

57 Eurocode 1 - Basis of design and actions on structures - Part 2-2: Actions on Structures Exposed to Fire

58 39. Aven; På litelighets og Risikoanalyse, Universitetsforlaget, 1991.

6 SMOKE MOVEMENT, CONTROL AND TOXICITY

Smoke and fire gases, are air borne products of combustion (POC). The amount and spread of POC's have critical influence on life safety and fire brigade intervention. The POC's contains toxic gases, particles, water and air. Both, toxicity and visibility increases with fire size, and, in some fires, the volume of smoke produced can fill the involved building. In large fires, an enormous smoke plume is generated.

This chapter identifies references for evaluating smoke movement in buildings, smoke control systems and toxicity aspects of smoke. Several computer programs for smoke movement and control are also identified.

6.1 OBJECTIVES

Evaluation of smoke production, movement and control are the main factors for the identification of tenable conditions for safe egress. Smoke evaluation involves a wide range of uncertainty because of the variety of different fuel properties and conditions that can affect smoke spread. Smoke control systems usually assume a two-zone smoke layer environment. Smoke can move through open doors, cracks or holes and penetrate into the egress paths, and causing untenable conditions. The reliability issues of doors are important to do a comparative analysis.

6.2 APPLICATION OF CODES AND STANDARDS

The Technical Regulation [56] does not include any requirement of smoke control systems. But, smoke control systems or other active fire protection systems shall be used where egress paths can't be designed with adequate physical and passive safety systems. Where fire compartments are not designed with such layout and interior design that escape and fire fighting can be accomplished in a rapid and efficient way.

Smoke control in atria is a common fire design used to compensate for a higher likelihood of fire and smoke spread. This is due to the atria's ability to collect heat and smoke and, without smoke control, causing rapid fire and smoke spread to several floors and fire partitions.

NFPA 92A [1], NFPA 92B [2], and NFPA 204M [3] and HO-3/2000 [4] cover smoke control systems in egress paths, atria, malls and large spaces. The standards include tools to classify fire hazards and smoke production, as well as methods to design smoke control systems. These standards are discussed in this chapter.

6.3 DESIGN FIRE FOR SMOKE MOVEMENT

6.3.1 Design fire for smoke movement, general aspects

As a fire burns, it [21]:

1. Generates heat.
2. Changes major portions of the burning material or fuel from its chemical composition to one or more complex compounds, such as carbon dioxide, carbon monoxide, water, and/or other compounds.
3. Often, due to less than 100% combustion efficiency, transports a portion of the fuel as soot or other material that may or may not have undergone a chemical change.

A major portion of the heat generated as fuel burns, remains in the mass of products liberated by the fire. This mass expands, is lighter than the surrounding air and rises as a plume. The rising plume is turbulent, and because of this entrains large quantities of air from the surrounding atmosphere into the rising gases. This entrainment:

- Increases the total mass and volume of the plume.
- Cools the plume by mixing the entrained air with the rising hot gases.
- Dilutes the concentration of fire products in the plume

For the purpose of describing smoke movement in buildings, the treatment of smoke movement is divided into two general areas; the hot smoke zone and the cold smoke zone. The hot smoke zone includes those areas in a building where the temperature of the smoke is high enough, so that the natural buoyancy of the body of smoke tends to lift the smoke towards the ceiling while clean, or at least less polluted, air is drawn in through the lower portion of the space. Normally, this condition exists in the room of origin. Depending upon the level of energy produced by the fire and the size of connecting openings, such as open doors, hot smoke zones can readily exist in adjacent rooms or corridors. The cold smoke zone includes those areas in a building where mixing and other forms of heat transfer have reduced the driving force of the fire to the point at which buoyant lift in the smoke body is a minor factor. In these areas, the movement of smoke is primarily controlled by other forces, such as wind and stack effects, ventilation, air conditioning, or other air movement systems. In these areas, the movement of smoke is essentially the same as the movement of any other pollutant.

The design fire for smoke production is related to a description of a time dependent fire growth. The smoke quantity is then related to this fire. The design fire for smoke properties and toxicity becomes more complex if measures for all toxic gases are included. But, according to NS3901 [58] measures of the most common gases like carbon monoxide, carbon dioxide and oxygen is sufficient in most buildings. A design fire characterized by fire size, ventilation conditions, ceiling height and room size, can be used to identify the smoke and gas production of a fire. By adding estimates of particle sizes from the burning fuels [20] it would also be possible to evaluate smoke visibility.

Since smoke production is dependent on both fire size and factors affecting air entrainment, the room geometry is important. The fire plume rises upwards with continuously increasing plume diameter. Ceiling height and the fire area at the bottom of the plume affects air entrainment and volume of smoke produced. Geometries where the hot fire gases can be transported horizontally beneath a ceiling before it rises into a larger space can be evaluated as a balcony spill plume. The volume of smoke entering the larger volume depends on balcony width, ceiling height above the balcony and the balcony height. In buildings where smoke can penetrate through a window or door opening before it enters the larger space, a window plume evaluation may be appropriate [2].

6.3.2 Design fire size

Fire sizes are usually described in kilowatts or fire area. Fire growth may be described as a t-square fire. The fire size is usually estimated from necessary egress time, fire department arrival, characterization of commodities or limited fire size due to partitions and/or sprinkler. Building design with a sprinkler control system can be designed with a smoke control system designed according to an expected sprinkler controlled fire size. The fire protection society in the UK has developed and accepted design fires for atrium vent areas based on statistics [7].

Table 6-1. Recommend fire areas designing atria smoke ventilation [7].

Occupancy / hazard	*Area*	*Deign fire*
Sprinklered retail premises	10 m^2	5 MW
Sprinklered offices	16 m^2	1 MW
Sprinklered offices	47 m^2	6 MW
Unsprinklered hotel rooms	Largest bedroom	1 MW

For either a continuously growing design fire or a limited design fire where the vent areas or the exhaust fans are not able to exhaust the smoke generated, the descending smoke layer must be compared to the time necessary to evacuate and rescue people inside the building.

6.4 SITUATIONS TO EVALUATE SMOKE MOVEMENT AND CONTROL

6.4.1 Smoke movement beyond the room of origin

Fire and smoke spread to rooms beyond the origin are important aspects in life safety evaluation. Smoke spread into corridors and staircases is usually prevented with passive barriers composed of walls and doors. Due to the temperature generated pressure difference smoke tend to penetrate through cracks or openings in the barriers. Winds can also contribute to smoke spread.

The governing factor for smoke spread is temperature generated pressure differences. A fully involved fire room can cause temperatures up to, and in some cases, beyond 1000°C. The room temperature depends on wall insulation, room size and vents. There are several correlations that can be used [8]. Air is sucked into the fire compartment below the neutral plane and smoke is exhausted above this plane. At the neutral plane, the pressure is the same as the ambient. The neutral plane in the fire compartment is relative to the ambient conditions and may not be relative to the neutral plane within the building. The building’s neutral plane may lie below or above the fire compartment. Where the neutral plane in the building is above the fire compartment, smoke can be assumed to penetrate through air gaps around doors and construction crack also near the floor. [2,5,9]

Air gaps between door leafs and frames varies. Old doors may have large gaps while new fire rated doors may have smaller gaps. Fire rated and tight doors can be almost 100% smoke tight. References for cracks in walls [13,15]. Reference for airgaps around doors [4].

Table 6-1. Typical leakage areas for walls and floors of commercial buildings [9]

Construction element	*Wall Tightness*	*Area Ratio A/A_{wall}*
Exterior building walls (includes construction cracks, cracks around windows and doors)	Tight	0.70×10^{-4}
	Average	0.21×10^{-3}
	Loose	0.42×10^{-3}
	Very Loose	0.13×10^{-2}
Stairwell walls (includes construction cracks but not cracks around windows or doors)	Tight	0.14×10^{-4}
	Average	0.11×10^{-3}
	Loose	0.35×10^{-3}
Elevator shaft walls (includes construction cracks but not cracks around windows or doors)	Tight	0.18×10^{-3}
	Average	0.84×10^{-3}
	Loose	0.18×10^{-2}
Floors (includes construction cracks around penetrations)	Average	$A/A_{Floor} = 0.52 \times 10^{-4}$

Ambient wind velocity and wind direction can also affect smoke movement. Wind generated pressure difference around the building can also cause pressure differences within the building through open windows and doors. Pressure differences due to elevation are important factors for shafts and staircases.

6.4.2 Smoke control in atria

In addition to the design fire characteristics mentioned in chapter 6.4.1, egress time and fire brigade arrival could be used to estimate smoke layer height and temperature during egress time and fire size at water application time.

6.4.3 Smoke control in road tunnels and subways

The materials which burn in tunnel and underground station fires come from the vehicles involved. They include elements of the vehicles such as seats, tires, plastic materials and the finishing, or even the body itself, the fuel from the vehicle tanks, which can amount to hundreds of liters for trucks as well as the cargo, principally for goods vehicles. The fuel load may vary from 3 GJ for a small private car and up to 1500 GJ for a petrol tanker.

The most common method of smoke control in tunnels is tunnel jet fans to establish a one way smoke movement (longitudinal smoke control). There are also three other methods for mechanical ventilation: Fully transverse, semi transverse and partial transverse. All of these methods use ducts to exhaust and/or supply the tunnel with smoke/air. The design fire is the same for all methods and a proper choice of heat release rate, together with the cross section area, tunnel height, tunnel slope and external wind are required to design a sufficient ventilation system.

References for smoke control in tunnels can be found in PIARK [6], and the guidance to risk analysis of road tunnels [60].

6.5 SMOKE MOVEMENT EVALUATION TOOLS

Smoke movement is caused by pressure differences due to elevated temperatures, stack effects, and wind. All fires produce smoke, and the fire generates a hot smoke zone that can penetrate into other rooms or egress routes. The basic information about smoke movement dynamics can be found in the Drysdale, Klote/Nelson and Cooper references [21,22,23].

6.5.1 Smoke production in the room of origin

Smoke production within the room of origin is essential for evaluation of egress from or through a fire partition. Common situations may include egress from large assembly areas or egress through atria. Smoke production depends on the convective portion of heat release rate at the time being evaluated and the smoke transport length up to the ceiling. During transport, air is entrained and the amount of smoke increases. Common tools for this evaluation are presented in NFPA 92B [2].

6.5.2 Smoke spread through orifices/cracks/large openings

Barriers rated or not will, with varying effectiveness prevent smoke from moving from one room to another. This method is required for most buildings designed after prescriptive codes. The amount of smoke spread depends on room fire temperature, which can be estimated by hand calculation tools, the crack sizes and the normal planes in fire room and building. The amount of smoke penetrating the cracks can be calculated with the orifice equation [7].

$$V = CA\sqrt{\frac{2\Delta P}{\rho}}$$

Where,

V Volumetric flow rate through opening (m^3/s)

C Dimensionless flow coefficient (for cracks 0.6-0.7)

A Flow leakage area, m^2

ΔP Pressure difference across path

ρ Density gas in path

The effectiveness of barriers to prevent smoke spread depends on the sizes of the holes and cracks. An open door will cause enormous volumes of smoke penetrating into the corridor or into the staircase. It is therefore appropriate to evaluate smoke movement both with doors opened and with doors closed, and to compare the results with smoke movement in a sprinkler controlled fire.

6.5.3 External wind effects on smoke spread

Wind action is another feature in the movement of smoke. Tall and short buildings behave somewhat differently in this regard. These pressures are caused by the movement of mass of air around and over the structure. The velocity of these movements is the primary cause of the pressures on the building.

The effect of wind pressures and suctions modifies the natural air movement within a building. For example, the negative pressure on the roof of a tall building can have an aspirating effect on a vertical shaft with openings at the roof level. Horizontal pressures and suctions cause natural planes in buildings to move. Positive wind pressure would tend to raise the natural plane, while negative pressure will lower it. The effects of wind are a function of shape and size of the building and of surrounding objects. The exterior pressures on a building due to wind are related to the wind velocity by the expression [7].

$$P_{wind} = \frac{1}{2} C \rho_0 \left(U_{w10}\right)^2$$

Where,

P_{wind}	Pressure in Pascal
U_{w10}	Wind velocity at 10 meter above ground level, m/s.
C	Wind pressure coefficient

The wind pressure coefficient, C, varies between -1 and 1, depending on the wind direction angle. At the most exposed point on the windward side CF can be as high as 1, but on average a value of 0.7 can be used. On the leeward side a value of -0.5 can be used. A flat roof has a typical value of -0.8 but can be as high as -2 [5,7,10].

Flow of gases from fire compartment to other parts of the building and to the opposite exterior wall or roof can be calculated by assuming open windows in addition to the leakage areas. The orifice equation can be used.

6.6 MECHANICAL AND NATURAL SMOKE CONTROL SYSTEMS

Smoke control systems are designed to exhaust smoke or prevent smoke infiltration. The overall principles are natural ventilation systems, mechanical exhaust systems and mechanical pressurization systems. These systems are commonly used to increase available safe egress time or to protect areas of refugees (AOF). General information about smoke control systems can be found in the SFPE Handbook and Fire Protection Handbook [9,15].

Smoke production rate depends on both the ceiling (atria roof) height and the fire size. The design fire could grow continuously or it could be limited by a suppression system or by insignificant availability of fuels. From an initial analysis viewpoint, smoke contamination is based on a fire that continues to burn. From this result, the effectiveness of smoke control measures can be recognized.

6.6.1 Ceiling vents

The mass flow through the openings in the roof would depend on the hot smoke layer temperature and depth. Necessary roof ventilation area is (NFPA 204M) [3]:

$$Av = 0.012\ Q^{3/5}\ (H-d)/d^{1/2}$$

where:

Av	Ventilation area in m^2
Q	Heat release rate in kW
H	Ceiling height in meter
d	Depth of smoke layer in meter

Ceiling vents are commonly used methods for smoke control in atria and malls. The system includes vents for air supply to the lower smoke free zone and veiling vents to exhaust the smoke and fire gases. Smoke control systems in atria are used to obtain safe egress through the atria and to prevent flashover. Atria can be design as a fire partition or not depending on the building size or whether the building is sprinklered or not [2,4,11].

6.6.2 Smoke ventilation shafts

Shafts can be used for smoke ventilation of rooms. The advantage of shafts is that pressure differences between the ceiling and smoke layer increases due to elevation, and the suction effect becomes larger than with ordinary ceiling vents. In addition, the amount of smoke production halts when smoke rises through the shaft. The disadvantages are that the suction effect can plug a hole in the smoke layer and cause fresh air to be sucked up into the shaft. Also long narrow shafts can resist the smoke flow [4].

6.6.3 Mechanical exhaust systems

Mechanical extractors are generally used where adverse pressure due to wind could seriously reduce the efficiency of a natural convection venting system. The extractors can keep the fire room almost clean for smoke or it can postpone smoke layer descending time and furthermore increase available evacuation/rescue time.

The volume of smoke exhausted should be equal to or larger than smoke generated by the design fire. Or, the capacity should be enough to increase available evacuation/rescue time according to egress evaluation. The main problem with exhaust systems is a phenomenon called “Plugholing”. Plugholing is caused by the velocity of the flow into a vent. The flow will cause a small reduction in pressure at the base of the layer of hot gases, and there is a critical rate of extract through a vent above which air from beneath the layer of hot gases is drawn into the vent. The onset of this phenomenon depends on a Freude number, Fc [7].

6.6.4 Pressurization systems

Systems using pressurization produced by mechanical fans are referred in NFPA 92A [1] and HO-3/2000 [4]. A pressure difference across a barrier can prevent smoke from penetrating through gaps around doors. The high-pressure side of the door can be either an area of refuge (AOR) or an egress route. The low-pressure side is exposed to smoke from a fire. Airflow through the gaps around the doors and through construction cracks prevents smoke infiltration to the high-pressure side.

6.6.5 HVAC systems for smoke ventilation (dilution)

Dilution can be used to maintain an acceptable smoke concentration in a compartment subject to smoke infiltration from an adjacent space. This can be effective if the rate of smoke leakage is small compared to either the total volume of the safeguarded space or the rate of purging air supplied to and removed from the space. Dilution can also be beneficial to the fire department for removing smoke after a fire has been extinguished.

The efficiency of smoke dilution should not be over-valued. There is no theoretical or experimental evidence that using a building’s heating, ventilation, and air conditioning system for smoke dilution will result in any significant improvement in tenable conditions within the fire space. Thus, smoke-purging systems intended to improve hazard conditions within a fire space or in spaces connected to room of origin by large openings shall not be used [7].

A simple analysis for smoke dilution after the fire is extinguished is presented. This correlation assumes a uniform distribution of smoke in the compartment [12,21].

$$a = \frac{1}{t}\ln\left(\frac{C_0}{C}\right)$$

$$t = \frac{1}{a}\ln\left(\frac{C_0}{C}\right)$$

where

C_0	Initial concentration of containment.
C	Concentration of containment at time t.
a	Dilution rate of air changes per minute.
t	Time after smoke stops entering space or time after smoke production has stopped.

6.6.6 Upstream smoke propagation

Systems to prevent upstream smoke propagation are longitudinal tunnel ventilation and pressurized staircases.

Buoyant gravity flow causes the leading edge of a hot smoke layer to propagate away from the fire source in a corridor. Thomas (1970) [16] performed wind tunnel tests to measure the critical air velocity required to prevent upstream smoke propagation. Thomas expression for critical air velocity is:

$$U_{critical} = \left(\frac{gQ}{r_0 C_P T_0 W}\right)^{1/3} = 0.303\left(\frac{Q}{W}\right)^{1/3}$$

where,

Q	Fire size in kW
W	Width of corridor

Other commonly used correlations which have been extracted from experimental results, are Hinkley (1970) [17], Heselden (1978) [18] and Danziger et.al. (1982) [19].

The above correlation concentrate on the environment close to the fire, not incorporating buoyancy forces, external wind and natural draft which occurs in tunnels. In general, to be able to control the direction of smoke gases from fire in a tunnel, the ventilation system shall be designed to overcome the pressure rise from the fire itself, buoyancy forces set up by the smoke gases, external wind and natural draft set up by temperature differences between inside and outside the tunnel. A set of simple correlations for calculating critical ventilation conditions for fires up to 20MW in inclined tunnels, has been developed by Opstad and Aune (1997) [13].

Tunnel ventilation is a complex system and must be designed with caution. Elevated temperatures decrease the gas density and the effect of the tunnel jet fans. Fans that are located to close to the fire can cause turbulence and initiate smoke to mix with the lower layer, or even blow air jet directly into the fire. The design and location of activated fans are important. PIARK [6] includes design methods and strategies for the design of tunnel ventilation systems.

Longitudinal ventilation can have a significant influence on fire growth and fire size. Carvel, Beard and Jowitt (2001) [14] did a Bayesian probabilistic approach and found that an expert panel underestimated the influence of air velocity onto fires.

6.6.7 Smoke control interaction with sprinkler spray

The use of heat and smoke vents in sprinklered buildings is a controversial subject. The interactive use of automatic sprinkler and fire vents has been debated for decades, but there are still no practical solutions or recommendations available. In order to improve the knowledge about the effects of combining these systems SP

Fire Technology performed numerous tests and a literature survey to place together test results and test critics during the latter decades [26]

Potential benefits of vents in sprinklered buildings are qualitatively the same as those in unsprinklered buildings; namely, they can delay loss of visibility and maintain a longer period with tenable conditions for evacuation and easier conditions for manual fire fighting. Potential drawbacks in sprinklered buildings are:

- Ventilation can increase the burning rate by providing unlimited supply of oxygen
- Sprinkler spray can cool of the hot layer and decrease its buoyancy
- Air movement can draw smoke into an egress segment in the path of the smoke exhaust

A fire test for industrial applications involving sprinklers and vents were conducted in Gent, Belgium (1990) [27]. The tests were conducted with steady state and growing hexane pool fires. The fire size at sprinkler actuation was as large as about 10 MW. The tests indicated that the vents caused a minor delay in sprinkler actuation but the vents caused a significant reduction in the numbers of sprinklers opened. The roof vents also allowed a clear area beneath the smoke layer, overcoming the tendency of the sprinkler spray to drive the smoke layer downward.

The hexane test indicated that the sprinkler spray couldn’t suppress the fire. The velocity and temperature of the upstream plume were high enough to overcome the water spray cooling. In a sprinkler suppression mode the smoke will tend to move downwards and cause smoke logging as the fire size decreases. That means that smoke logging occur when water application rate is large according to the fire size [28].

6.6.8 Smoke control systems in areas of refuge

One proposed solution for providing safety for persons with mobility limitations is the concept of area of refuge (AOR) where these people can "safely wait" until they can be assisted in leaving the building. This reference presents information about the design of smoke control systems to prevent smoke infiltration into an AOR. Pressure differences produced when windows break, both with and without wind, can be significant, and the design of a smoke control system for an AOR needs to address these pressure differences. The reference identifies the need for wind data specifically for the design of smoke control systems. The pressure fluctuations due to opening and closing building doors during fire situations can also be significant, and the design of a smoke control system for an AOR needs to address these fluctuations. An example of analysis incorporating the pressure effects of broken windows, wind, and open doors illustrates the feasibility of designing smoke control systems for areas of refuge [10]

6.6.9 Smoke control reliability

Smoke control reliability depends on the system that is used to obtain control. Passive barriers depend on the probability of cracks, gaps or open doors, and wind direction. Electrical powered systems depend on the power source and the reliability of electrical motors and other components that activates the system, and in addition the cooperating doors and barriers are important for successful smoke control. Exhaust vents can be activated by a signal from the fire alarm system or by fusible links. For all of them except those with fusible links, testing, maintenance and control are important to maintain reliability.

6.7 SMOKE TOXICITY AND VISIBILITY ASPECTS

According to NS 3901 [3] the deterministic acceptance criterions for smoke tenability in buildings are given in the standard's table 1. These tenability criterions are developed from several laboratory tests and sufficient for most fire hazards. In special cases, where the fuel includes chemicals or additives that develops other toxic gases, the effect of other toxic gases must also be evaluated [59].

Table 6-1. Deterministic acceptance criterion for smoke toxicity [59]

Radiant flux Exposure < 6 seconds Accumulated radiant heat flux	 10 kW/m^2 60 kJ/m^2 + the energy from 1 kW/m^2
Gass temperature	60 °C
Fraction of gases CO CO_2 O_2	 Max 2000 ppm Max 5% Min 15%
Visibility at 2 meters elevation In fire partition In egress path	 Min 3 meter Min 10 meter

6.7.1 Test methods for measuring smoke production and toxicity

There are essentially two ways in which toxic hazards in fire can be assessed [24]:

1. From large-scale fire tests that include the measurements of the concentration/time profiles of the major toxic gases, and existing knowledge of the toxic effects of these gases.
2. From battery or small-scale tests and mathematical models.

Of these, full-scale simulation and large-scale tests are most valuable because they enable the first two major parameters (fire growth and products yield) to be measured directly. For the third parameter (toxicity), an algorithm for calculating times to incapacitation and death for humans is presented in ISO 9122-5 [34].

Smoke production and toxicity in world scale tends to be costly and difficult. For regulatory hazard ranking, it is more common to use battery or small-scale methods. Small-scale methods suffer from the difficulty that they are several steps removed from a full-scale test. Typically the variable selected is the toxic potency denoted as LC_{50}, which is a measure of amount of the toxic products in a chamber that causes 50% probability of lethality. ISO 13344 [35] was the first normative international standard to address the issue of fire toxicity. This standard did not provide any information on suitable computation techniques for assessing the toxic fire hazards in real fire situations.

ISO 13344 introduced the Fractional Effective Dose (FED). FED is an arithmetic, linear equation where the toxic effects of various gases are assumed to be linear. The expression for the most common fire gases is:

$$FED = \frac{CO}{5000} + \frac{HCN}{150} + \frac{HCl}{3800} + \frac{HBr}{3000} + \frac{NO}{1000} + \frac{NO_2}{200}$$

Where the gas concentrations is denoted in ppm. Note that the value for CO in this equation is 5000 ppm, while the acceptance criterion is 2000 ppm. This is due to the higher concentration that is needed for the probability of 50% lethality. When FED is 1, the summarized toxicity is assumed to correspond to LC_{50}.

The fraction of lethal gases (LC_{50} and FED) in full scale fire hazards is difficult to measure in bench scale and comparison against full scale LC_{50} have indicated that the bench scale values were not sufficiently accurate [25].

Smoke specific optical density may also be measured in small scale tests using chambers [37,38] or Oxygen Consumption Calirometer [36].

Full scale tests are standardized in the ISO 9705 room. Full scale test fires behave more similar to building fires and the test results give better approximations. The ISO room is used to test wall coverings [39] and pipe insulation [40]. The gases can be measured and the test reports usually includes values of CO and CO_2 production vs. time. This information can be used to calculate the fraction of these toxic gases in the fire plume and smoke layer. Särdquist [41] has collected information to an extensive database with test results for building materials. This reference does also present conversion factors for smoke potential and specific extinction coefficient, as well as CO conversion. Some of the tests were performed in the ISO room, but also a free burning furniture calorimeter and a free burning industry calorimeter were used. A similar database can also be found at NIST (FASTdata) [30].

The EN 13823 [41] test procedure includes the SMOGRA index. This index is a measurement of smoke production for products excluding flooring exposed to a thermal attack by a single burning item. This test is developed in order to approve surface materials, and may be suitable to distinguish between different products and to give first hand information. SMOGRA is not suitable for numerical calculations of fire hazards.

6.7.2 Fire room conditions in sprinklered buildings

A sprinkler controlled fire or early-suppressed fire has a tremendous influence on the room fire condition. In non-sprinklered buildings the fire may drive to flashover and may become under-ventilated, causing huge amounts of carbon monoxide to be produced, dramatically increase of temperature and high radiation levels. With a proper and functional sprinkler system installed, these situations shall not appear.

During a large-scale test for toxicity in fires [31] they classified the toxicity into three categories.

Table 6-1. Fire toxicity dependence on fire development stage [31]

Fire	*Rate of growth*	*CO2/CO*	*Toxic hazard*	*Time to incapacitation*	*Escape time available*
1. Smoldering/non-flaming: victim on room of origin	Slow	~1	CO 0-1500 ppm low O2 15-21%, irritants smoke	Hours	Ample if alerted
2. Flaming: victim in room of origin	Rapid	1000 decreasing towards 50	CO 0-1%, CO_2 0-10%, O_2 10-21%, irritants, smoke heat	A few minutes	A few minutes
3. Fully developed: (Postflashover) victim remote	Rapid	< 10	CO 0-3%,. HCN 0-500ppm, irritants, smoke and possibly heat	< 1 min near fire	Escape may be impossible, or time very restricted. More time at remote locations

In sprinklered buildings, the fire should stop early in category 2 (Flaming). Resulting in a far more tenable environment for successful egress. Both American and Japanese tests with measurements of toxic gases in residences and hospitals protected with fast response or residential sprinklers have concluded that the environmental conditions may be relatively good [32,33].

6.7.3 Visibility estimates

According to NS 3901 [4] estimates of visibility can replace the gas toxicity assessments. Visibility in fire hazards can be estimated from HRR, specific smoke extinction and air entrainment into the fire plume. Mulholland [20] describes methods to evaluate smoke optical density and visibility. Correlation for air entrainment can be found in NFPA 92B [2].

6.8 SOFTWARE FOR MODELING SMOKE MOVEMENT AND SMOKE CONTROL

6.8.1 Zone models

The most common fire model, known as a zone model, generally uses two control volumes to describe a room, an upper layer and a lower layer. In the room with the fire, additional control volumes for the fire plume or the ceiling jet may be included to improve the accuracy of the prediction. Simple “room filling” models such as the Available Safe Egress Time (ASET) model [43] run quickly on almost any computer, and provide good estimates of a few parameters of interest for a fire in a single compartment. A special purpose model can provide a single function. For example, COMPF2 [44] calculates post-flashover room temperatures and LAVENT [45] includes the interaction of ceiling jets with fusible links in a room containing ceiling vents and draft curtains. Very detailed models like the HARVARD 5 code [46] or FIRST [47] predict the burning behavior of multiple items in a room, along with the time-dependent conditions therein.

In addition to the single-room models mentioned above, there are a smaller number of multi-room models which have been developed. These include the BRI transport model [48], the HARVARD 6 code [49], FAST [42,50,51], CCFM [52] and the CFAST model [53].

6.8.2 Multizone modeling (Network model

A Multizone model uses one element per room and is used to predict conditions in spaces far removed from the fire room, where temperatures are near ambient and layering does not occur. Multizone modeling refers to analysis techniques that use a simplified, zonal representation of a building to study building airflows, pressure differences, and contaminant transport. Each zone is assumed to have uniform temperature, pressure, and contaminant concentrations. Zones typically represent individual rooms but can be entire levels depending on the building layout and the goals of the modeling. Zones are connected through flow paths represented mathematically by pressure-flow relationships. This reference describes CONTAMW, a multizone modeling tool [54].

6.8.3 Field models (CFD)

The field model goes to the extreme, dividing the room into thousands or even hundreds of thousands of grid points. Such models can predict the variation in conditions within the layers, but typically require far longer run times than zone models. Thus, they are used when highly detailed calculations are essential. CFD models can simulate smoke penetration through openings; exhaust vents and extractors, and pressurization systems. The CFD model Fire Dynamic Simulator can also simulate sprinkler and smoke ventilation interaction [55].

6.9 SUMMARY

The design fire for smoke movement and smoke control evaluation is characterized with a time dependent fire size. The smoke quantity is related to the fire size. Smoke production within the room of origin and smoke movement beyond the origin are important life safety evaluations. Smoke control systems are commonly used in large spaces, atria, staircases and tunnels. The systems can be based on buoyancy forces and venting through ceiling vents or shafts. Mechanical systems can be used to exhaust smoke from the fire room or pressurize other rooms to prevent smoke spread. In sprinklered fire scenarios, the amount of smoke produced and the smoke toxicity is only a fraction of the amount and concentrations to be found in unsprinklered fire scenarios. Sprinkler spray and smoke ventilation may interact on each other in several ways. Sprinkler and smoke interaction and smoke movement can be simulated with field models. Smoke filling rate and smoke spread can be evaluated with zone models, and multizone models can be used to evaluate smoke conditions in spaces far beyond the fire source.

6.10 REFERENCES

6.10.1 Design fire information

1 NFPA 92A: Recommended Practice for Smoke-Control Systems, National Fire Protection Association (1996)

2 NFPA 92B: Guide for Smoke Management Systems in Malls, Atria and Large Spaces National Fire Protection Association (1995)

3 NFPA 204M: Guide for Smoke and Heat Venting, National Fire Protection Association (1991)

4 HO-3/2000: Røykventilasjon, National Office of Building Technology and Administration (Norway) (2000)

5 Meland, Skåret and Jensen, Røykkontroll - Personsikkerhet ved brann i bygninger, SINTEF.

6 PIARK Committee on Road Tunnels; Fire and Smoke Control in Road Tunnels (1999).

6.10.2 Smoke control system performance evaluation

1 NFPA 92A: Recommended Practice for Smoke-Control Systems, National Fire Protection Association (1996)

2 NFPA 92B: Guide for Smoke Management Systems in Malls, Atria and Large Spaces National Fire Protection Association (1995)

3 NFPA 204M: Guide for Smoke and Heat Venting, , National Fire Protection Association (1991)

4 HO-3/2000: Røykventilasjon, National Office of Building Technology and Administration (Norway) (2000)

5 Meland, Skåret and Jensen, Røykkontroll - Personsikkerhet ved brann i bygninger, SINTEF.

6 PIARK Committee on Road Tunnels; Fire and Smoke Control in Road Tunnels (1999).

7 Hinkley; Smoke and Heat Venting, The SFPE Handbook chapter 3-9.

8 Walton and Thomas; Estimating Temperatures in Compartment Fires, The SFPE Handbook chapter 3-6.

9 Klote; Smoke Control, The SFPE Handbook chapter 4-12.

10 Klote; Design of Smoke Control Systems for Areas of Refuge, National Institute of Standards and Technology (1993).

11 Milke; Smoke Management in Covered Malls and Atria, The SFPE Handbook chapter 4-13

12 Klote; Moving Systems and Fire Protection, National Institute of Standards and Technology (1993)

13 Opstad and Aune; Fire Emergency Ventilation Capacity for Road Tunnels with Considerable Slope, SINTEF Energy (1997).

14 28. Carvel, Beard and Jowitt; The Influence of Longitudinal Ventilation Systems on Fires in Tunnels (2001).

15 Heskestad; Venting Practices, NFPA Handbook chapter 7-7.

16 Thomas; Movement of Smoke in Horizontal Corridors Against an Air Flow, The Institute of Fire Engineers Quarterly, 45 (1970)

17 Hinkley; The Flow of Hot Gases Along an Enclosed Shopping Mall: A Tentative Theory, Fire Research

Note No 807, Fire Research Station.

18 Heselden; Studies of Fire and Smoke Behaviour Relevant to Tunnels, Building Research Establishment Current Paper CP66/78 (1978)

19 Danziger and Kennedy; Longitudinal Ventilation Analysis for the Glenwood Canyon Tunnels, 4th Symposium on the Aerodynamics and Ventilation of Vehicle Tunnels (1982)

6.10.3 General smoke movement and toxicity theory

15 Heskestad; Venting Practices, NFPA Handbook chapter 7-7.

16 Thomas; Movement of Smoke in Horizontal Corridors Against an Air Flow, The Institute of Fire Engineers Quarterly, 45 (1970)

17 Hinkley; The Flow of Hot Gases Along an Enclosed Shopping Mall: A Tentative Theory, Fire Research Note No 807, Fire Research Station.

18 Heselden; Studies of Fire and Smoke Behaviour Relevant to Tunnels, Building Research Establishment Current Paper CP66/78 (1978)

19 Danziger and Kennedy; Longitudinal Ventilation Analysis for the Glenwood Canyon Tunnels, 4th Symposium on the Aerodynamics and Ventilation of Vehicle Tunnels (1982)

20 Mulholland; Smoke Production and Properties, The SFPE Handbook chapter 2-15.

21 Klote and Nelson; Smoke Movement in Buildings, Fire Protection Handbook 18th edition, section 7, chapter 6

22 Drysdale; An Introduction to Fire Dynamics, chapter 11 The Production and Movement of Smoke

23 Cooper; Compartment Fire Generated Environment and Smoke Filling, The SFPE Handbook chapter 3-10

24 Purser; Toxicity Assessment of Combustion Products, The SFPE Handbook chapter 2-8

25 Babrauskas; Fire safety Improvements in the Combustion Toxicity Area: Is there a role for LC50 tests? pp 213-224 in Flame Retardants, Interscience Communications, London (1998)

26 Ingason and Arvidson; Samtidig Användning av Sprinkler och brandgassventilation, SP Sveriges Provnings och Forskningsinstitute (2001)

6.10.4 Tests, reports or databases concerning smoke movement or toxicity

26 Ingason and Arvidson; Samtidig Användning av Sprinkler och brandgassventilation, SP Sveriges Provnings och Forskningsinstitute (2001)

27 The Gent Fire Test, Colt Int. Ltd (1990).

28 Ingason; Samverkan mellan Sprinkler och Brandventilation, Sveriges Provnings- och Forskingsinstitut (2001).

29 Särdqvist; Initial Fires, Lund University, Sweden (1993)

30 National Institute of Fire and Technology; FASTdata, NIST Standard Reference Database Number 75, January 1999 Release

31 Purser; Toxicity Assessment of Combustion Products, The SFPE Handbook 2nd edition.

32 Notarianni; Measurements of Room Conditions and Response of Sprinklers and Smoke Detectors During A Simulated Two Bed Hospital Room Fire, National Institute of Standards and Technology, July 1993.

33 Sekizawa, Takemoto, Kozeki, Yanai, Suzuki; Experimental Study of Fire Hazard of Residential Fires before and After Sprinkler Activation, Fire Research Institute - Fire Defense Agency, Tokyo Japan 1997 (English translation by Beal, NIST).

6.10.5 Test methods for smoke toxicity

34 ISO 9122-5, Toxicity Testing of Fire Effluents, International Organization for Standardization, Geneva

35 ISO 13344: Determination of Lethal Toxic Potency of Fire Effluents, International Organization for Standardization, Geneva

36 ASTME 1354 - 9: Standard Test Methods for Heat and Visible Smoke Release Rates for Materials and

Products Using and Oxygen Consumption Calorimeter.

37 NT FIRE 012

38 ASTM E662, Standard Test Methods for Specific Optical Density of Smoke Generated by Solid Materials (1993)

39 ISO 9705:1993 (E) Fire tests – Full-scale room test for surface products, International Organization for Standardization, Geneva

40 Pipe Insulation: Fire Spread and Smoke production - Full Scale test NT FIRE 036 Nordtest, Espoo (1988)

41 EN 13823 (SBI):1999 E Reaction to fire tests for building products – Building products excluding floorings – exposed to thermal attack by a single burning item (SBI).

6.10.6 Computer programs

42 Jones, W. W. and Peacock, R. D., Refinement and Experimental Verification of a Model for Fire Growth and Smoke Transport, Proceedings of the 2nd International Symposium on Fire Safety Science, Tokyo (1989)

43 Cooper, L.Y., “A Mathematical Model for Estimating Available Safe Egress Time in Fires,” *Fire and Materials.* 1982, *6(4),* 135-144.

44 Babrauskas, V., “COMPF2-A Program for Calculating Post-Flashover Fire Temperatures,” *Natl.Bur. Stand. (U.S.)* 1979, *Tech. Note 991,* 76 p.

45 Davis, W. D. and Cooper, L. Y., “Computer Model for Estimating the Response of Sprinkler Links to Compartment Fires With Draft Curtains and Fusible Link-Actuated Ceiling Vents,” *Fire Technology* 1991, *27 (2)*, 113-127.

46 Mitler, H.E. and Emmons, H.W., “Documentation for CFCV, the Fifth Harvard Computer Fire Code,” *Nat. Bur. Stand. (U.S.)* 1981, *NBSGCR 81-344,* 187 p.

47 Mitler, H. E. and Rockett, J., “A User's Guide for FIRST, a Comprehensive Single Room Fire Model,” *Natl. Bur. Stand. (U. S.)* 1987, *NBSIR 87-3595*.

48 Tanaka, T., “A Model of Multiroom Fire Spread,” *Nat. Bur. Stand. (U.S.)* 1983, *NBSIR 83-2718*, 175 p

49 Gahm, J. B., “Computer Fire Code VI, Volume I,” *Nat. Bur. Stand. (U.S.)* 1983, *NBS GCR 83-451*, 116 p.

50 Jones, W. W., A Multicompartment Model for the Spread of Fire, Smoke and Toxic Gases, Fire Safety Journal *9*, 55 (1985)

51 Jones, W. W. and Peacock, R. D., “Technical Reference Guide for FAST Version 18” Natl. Inst. Stand. Techol. Tech. Note 1262 (1989).

52 Forney, G. P. and Cooper, L. Y., The Consolidated Compartment Fire Model (CCFM) Computer Application CCFM.VENTS - Part II: Software Reference Guide, Nat. Inst. Stand. Technol., NISTIR 90-4343 (1990).

53 Jones, W. W. and Forney, G. P. “A Programmer's Reference Manual for CFAST, the Unified Model of Fire Growth and Smoke Transport,” *Natl. Inst. Stand. Technol.* 1990, *Tech. Note 1283*, 104 p.

54 Dols; Tool for Modeling Airflow and Contaminant Transport,

55 McGrattan, Baum, Rehm, Hamins, Forney, Floyd, Hostikka: Fire Dynamics Simulator (Version 2) – Technical Reference Guide. NISTIR 6783. National Institute of Standards and Technology. November 2001

6.10.7 Other references that don't fit into the above categories

56 National Office of Building Technology and Administration (Norway): TEK-97, Regulations concerning requirements for construction works and products for construction works, 22 January 1997 No. 33 Technical Regulations under the Planning and Building Act 1997.

57 National Office of Building Technology and Administration (Norway): REN, Guidance to Regulations concerning requirements for construction works and products for construction works, 2nd edition, April 1997.

58 National Building Standardization Council (Norway): NS3901, Risk analysis of fire in buildings and civil

engineering works (1998).

59 National Building Standardization Council: Guidance to NS3901, Guidance to risk analysis of fire in buildings (1998).

60 National Building Standardization Council: Guidance to NS3901, Guidance to risk analysis of road tunnels.

7 STRUCTURAL FRAME

The framework is designed to bear its own weight, wind and snow loads, and live loads. In fire scenarios, the framework shall be designed to resist the environment caused by fire loads. This chapter introduces the design fire for structural analysis and references for evaluating the performance of structural frames made of wood, steel or concrete.

7.1 OBJECTIVES

The objectives of a structural frame evaluation are to predict the performance of the construction material during a fire scenario. Buildings always have a certain degree of fire resistance, even though the building constructions may never have been classified. Newer buildings designed in accordance with modern building codes are classified into fire classes and thereby the frames are designed with the code specified fire rating. Evaluation of building construction works involves an evaluation of a design fire, identification of the building construction properties in fire scenarios, and evaluation of construction resistance in a predicted fire scenario.

According to the code requirements [1], the goal of an evaluation can be three fold. The requirements depend on the fire classes and hazard classes. One of these requirements must be satisfied for every load bearing systems in a building:

1. Stability and load bearing for egress
2. Stability and load bearing for egress and rescue operations
3. Stability and load bearing through a complete fire development

Both egress and rescue operations are time dependent. Performance based code requirements does implicits require a translation of standard fire exposure into a fire scenario, and, where the structures are required to resist a complete fire scenario, the structural resistance can be evaluated from a design fire, often described using statistical fire load.

7.2 CODES, STANDARDS AND PUBLICATIONS FOR EVALUATING FIRE RESISTANCE

Code requirements (TEK) [1] for construction works depend on the fire class and the hazard classification the building has been placed into. Construction works in fire classes 1 and 2 shall maintain the stability and load-bearing capacity for at least the time required to escape and rescue persons being in and on the construction works. For construction works in fire class 1 intended for activity in hazard classes 1 and 2 (usually garage and office buildings) there is no requirement for stability and load-bearing capacity except for the provisions ensuring personal safety during the time of escape. For larger buildings, where the consequences of fires are serious or very serious, the bearing system shall be made so as to let the construction works maintain stability and load-bearing capacity through a complete fire development. But, load bearing systems for one story only (or the roof) shall maintain their stability and load-bearing capacity during the time necessary for escape and rescue of persons in and on the construction works [1].

A performance based evaluation according to NS 3901 [2] can be performed by using the design fire temperature development in Eurocode 1 [4]. This is an evaluation based on fire load and ventilation openings. The temperature course in this evaluation may be different from the time-temperature of a standard fire test, but it is possible to recalculate and compare the two different temperature courses, so that the amount of energy over time can be adjusted. Standard heat transfer equations can be used [5,6], but caution shall be taken to probable changes in material properties at elevated temperatures.

Fire loads shall be based on statistics. The loads can also be found in the Eurocode 1 standard or international publications [7] NBI- product sheet [8].

The fire rating of structures can be found in Norwegian standards[12,18] or the Eurocodes [9,10,11]. The reduced utility factor is due to the fact that design load is different in case of fire than in other situations. For example wind is excluded and snow has only a factor of 0.8 [NS 3478], and the live load has a safety factor of 1.0. Design criteria for fire ratings and methods to calculate fire ratings are presented in both Eurocodes and Norwegian standard. And in addition several international publications for analyzing the fire rating of structures are available. These references are presented in table 7-1.

The fire rating of reinforced concrete beams and girders is usually dependent on the web dimension and reinforcement covering. The tabular design criteria for achieving different fire ratings for concrete structures according to Eurocode 2 [9], presupposes a 70% degree of utility. Older structures may not be valid for the tabulated design criteria in these standards. In the case of older structures, the fire resistance may be evaluated with the Fleishmann reference [13].

The Eurocode 3 [10] reference includes methods for calculating fire resistance for unprotected and protected steel. The calculation methods are numerically based on standard fire temperature exposure. Milke [15] discusses several other methods for protection and mathematical methods for prediction of fire rating.

Wood loses fire resistance as the wood decomposes and chars. One part is the calculation charring velocity. The second part is the calculation of remaining required cross sectional area required to bear the structural- and live load. Methods for calculating load bearing capacity can be found in NS 3470 [18]. The load bearing capacity for vertical wood structures are dependent on the cross sectional area and length. For horizontal wood structures, the wood members strength is related to the cross sectional area times the height of the member. According to Eurocode 5 [11] a 60% degree of utility can be assumed.

Table 7-1. References for evaluating fire resistance of structures

Construction	*Eurocode*	*Norwegian standard*	*Publications and literature*
Reinforced concrete	9	12	13,14
Steel	10		14,15
Wood	11	18	14,16,17

7.3 DESIGN FIRE

In general, the design fire for structural frames are characterized by time and temperature. These factors are then dependent on several other factors such as room size, ventilation, fire load, and thermal properties of the bounding surfaces. The time requirement can be a matter of necessary time to egress described in chapter 9 or time for rescue operations evaluated in chapter 8. Or, the time may be a matter of the fire endurance described by the total heat load, combined with the ventilation openings.

Except for extremely large spaces or special constructions like indoor football halls and tunnels, the temperature course is usually characterized with a uniform temperature distribution after flashover. The factors for describing this temperature are ventilation openings, heat load, compartment geometry and wall insulation. The temperature course can be developed based on equations in Eurocode 1 [4].

In structures where the heat load is localized, the temperature is dependent on the fire size and the flame length relative to the construction geometry, ventilation and insulation. This design fire may be evaluated from the fire-spread evaluation (chapter 1).

7.4 CONSTRUCTION MATERIAL PROPERTIES

7.4.1 Concrete

Concrete is able to resist heavy loads when the load only causes compression of the member, but it has to be reinforced to resist tensile strength. Therefore, steel reinforcement is placed into the members and slabs to achieve sufficient strength. High performance concrete (HPC) can be produced for special purposes by adding special additives and water reducing mixtures. HPC can have a compressive strength over 100 MPa. According to NS 3473 concrete is classified by its compressive strength. Usually conventional concrete C35 (compressive cube strength of 35 MPa) is used in buildings and C45 where higher performance is required.

Concrete construction systems appear in different configurations depending on the desired performance. A standard office building may be designed with flat slabs supported on steel beams and columns. Large warehouses may need to be designed with a heavy live load on longer spans, and ribbed slabs may be preferred. Concrete systems may be pre fabricated, pre-stressed or poured in place. The slabs may be continuously or simply supported, one-way or two ways. Their properties in fire actions can vary substantially.

The mechanical properties of concrete in general are adversely affected by thermal exposure. The main failure mode is that heat diffuses into the concrete and causes a temperature rise of the reinforcement. When the steel temperature reaches temperature around 550-600°C it looses its tensile strength and causes failures. The exposures are largest for systems with the reinforcement located near the edges. Columns and ribbed slabs are therefore more vulnerable to fires than flat poured in place walls and decks.

Thermal expansion of concrete is similar to that of steel for temperatures up to about 540°C. Thermal expansion of a concrete floor slab heated form below can cause large thermal thrust forces to be exerted on surrounding structures and the lateral movement may cause structural collapse. If no expansion is allowed, the thermal trust force would be very high, which could cause compression failure of the concrete. The thermal expansion depends on the types of aggregate used in the concrete. Sanded expanded shale aggregate expands less than siliceous aggregate concrete. At 600°C the concrete may expand up to 1%. Most fire tests of floor slabs are conducted with the specimen mounted within a restraining frame, which restricts the thermal expansion. The amount of restraining force provide by the frame varies from laboratory to laboratory [19].

Concrete does also lose compressive strength due to elevated temperatures. Though, this is strongly dependent on the aggregate. Carbonated concrete maintains its strength almost unaffected up to 650°C, but siliceous aggregate concrete has lost about 50% of its strength at the same temperature [19].

Another failure mode is explosive spalling. Explosive spalling is basically due to the evaporated forces of water and thermal stresses within the material. A test conducted at NIST [20] proved that explosive spalling is primarily caused by internal pore pressure due to evaporated water. Thermal stresses might have a secondary role in this failure. The pore pressure is relative to the permeability within the concrete. The permeability is again a function of the cement to water ratio. This indicates that high performance concrete is more subjected to spalling than conventional concrete.

Eurocode 2 [9] gives instructions in a schematic way of how to estimate the risk of spalling based on the web dimension and the compression stress. This may be an oversimplification. In a research performed by Bengtsson [21], two simply supported concrete beams with haunched I-sections were evaluated when exposed to fire in full-scale furnace tests. That paper indicates that the factors that increase the risk of explosive spalling are:

- High moisture content in the concrete
- Compressive stress due to external load or pre-stressing
- Fast temperature rise
- Significant dissymmetric temperature distribution
- Cross sections with slim section parts

- High reinforcement densities
- Little permeability

7.4.2 Steel

Steel is the major constructional material in industrial buildings. It's strength, ductility, consistency and availability makes it unique for structural framework. However, it is significantly weakened at fire temperatures. Unprotected steel usually can only achieve a fire rating of 10-20 minutes, depending on the ratio of exposed surfaces relative to the steel volume to absorb the heat. Steel columns immersed in flames can fail after only a few minutes with intensive fire exposure.

The critical temperature of steel members depends on the degree of utility. The critical temperature can be found in tables [10], and it is usually around 550°C. At this temperature the steel has lost about 60% of its yield strength [15]. It is therefore necessary to protect the steel with insulation.

As with concrete members, thermal expansion of steel can also cause structural collapse due to trust forces onto surrounding structures. At 540°C steel expands about 0.8% [24]. A span over 30 meters can expand about 25 cm before it looses its strength.

Steel columns that are not provided with the desired level of fire protection, may, theoretically be protected with water spray. Water spray will develop a thin film surrounding the column/beam and prevent heat to conduct into the material [26]. The required water flux is:

$$m_W^{//} = \frac{q_c^{//} + q_r^{//}}{r_W (L_v + c_p (100 - T_0))}$$

Where,

m_w is the required water spray density per unit exposed steel surface area ($m^3/m^2.s$)

q_c is the convective heat flux to steel surface (kW/m^2)

q_r is the radiant heat flux to steel surface (kW/m^2)

Lv is the heat of vaporization of water (kJ/kg)

T_0 is the initial temperature of water prior to heating (°C)

This theory is based on the critical assumptions that the water spray can be applied in a manner that will allow it to absorb the entire heat flux at the surface. This is extremely difficult, if not impossible, because:

- Gas or wind velocities dues to the buoyancy of the fire may prevent the spray from reaching the surface.
- The water may rebound or drip of rather than cover the steel with a film.

7.4.3 Wood

When wood is exposed to high temperatures it decomposes and chars. The rate of decomposition depends on the chemical composition of natural polymers, density and moisture content. Inorganic impurities like salt will also have a significant influence on the burning behavior. As wood burns it develops a protective char layer that prevents heat flux from penetrating into the unburned solid. But, the decomposition rate will increase with higher exposures, which is the case in standard fire testing. In the standards the charring rate is assumed to be a constant depending only on the density of the timber. It ranges from 0.5 mm/min for solid or glued hardwood with a characteristic density above 450 kg/m^3 and 0.8 mm/min for wood with a characteristic density below 290 kg/m^3 [11,12].

Timber structures with insufficient density can be protected with gypsum, mineral insulation, asphalt boards, plywood or hardboard to achieve the required fire resistance rating [11,16,17].

7.5 COMPUTER MODELING OF STRUCTURAL FIRE RESISTANCE FOR CONCRETE MEMBERS

The most important problem with regards to the use of a theoretical approach is that it requires access to a good database on material properties under elevated temperatures. A knowledge of the thermal and mechanical properties as a function of temperature is critical to the accuracy of the calculation model.

Computer programs have been developed for the purpose of numerical simulation of temperature gradients in structural members. For example, FIRES-T3 and TASEF-2 are two computer programs for calculating heat transfer from fires to structures [22,23]. Both rely on the finite element technique, one in two dimensions (TASEF-2), the other in three dimensions (FIRES-T3). An even simpler model is HSLAB. This model uses numerical methods to analyze linear heat transfer into material with up to ten different layers [24]

Utilizing the information produced by the heat transmission analysis and that contained in available databases on material properties, a designer can assemble a picture of the strength and deformation characteristics of a structural member at any given stage of the heat exposure. The stress, stability and deformation analyses normally require, as a first step, the use of a finite element program to define the continuum in terms of smaller, interdependent elements (particularly if the geometry of the structural member is not symmetrical) and account for the non-uniform temperature distribution within the member. For each element, the incremental strain or deformation caused by the increase in temperature is calculated, and a new stress level is obtained with the help of the stress-strain relationship applicable for the temperature in question. Finally, the usual structural mechanics theory can be used to calculate the residual load, shear or moment capacity of the member and compare it with the anticipated applied load (shear forces or moments) to determine whether or not failure is imminent [*25*]

7.6 REFERENCES

7.6.1 General codes and standards references

1 National Office of Building Technology and Administration (Norway): TEK-97, Regulations concerning requirements for construction works and products for construction works, 22 January 1997 No. 33 Technical Regulations under the Planning and Building Act 1997.

2 National Office of Building Technology and Administration (Norway): REN, Guidance to Regulations concerning requirements for construction works and products for construction works, 2nd edition, April 1997.

3 National Building Standardization Council (Norway): NS3901, Risk analysis of fire in buildings and civil engineering works (1998).

7.6.2 Fire loads, fire development references and heat transfer - publications and standards

4 Eurocode 1 - Basis of design and actions on structures - Part 2-2: Actions on Structures Exposed to Fire

5 Atreya, Convective heat transfer, SFPE handbook 1-3.

6 Tien, Lee, Stetton; Radiation Heat Transfer, Society of Fire Protection Engineers, The SFPE Handbook, 2nd edition, chapter 1-4.

7 Fire Safety Journal vol 10 no 2. pp 101-118 (1986).

8 NBI.520.333 Brannbelastning i bygninger - beregninger og statiske verdier.

7.6.3 Methods to determine the fire resistance of building constructions

9 Eurocode 2: Design of Concrete Structures - Part 1-2: General rules - Structural fire design, European Committee for Standardization, Brussels.

10 Eurocode 3: Design of composite steel and concrete structures Structures - Part 1-2: General rules - Structural fire design, European Committee for Standardization, Brussels.

11 Eurocode 5: Design of Timber Structures - Part 1-2: General rules - Structural fire design, European Committee for Standardization, Brussels.

12 NS 3473: Prosjektering av betongkonstruksjoner - Beregnings og konstruksjonsregler, Norges Standardiseringsforbund (1998).

13 Fleishmann; Analytical Methods for Determining Fire Resistance of Concrete Members, SFPE Handbook chapter 4-10

14 NBI.520.323 [Brannmotstand for bjelker og søyler]

15 Milke; Analytical Methods for Determining Fire Resistance of Steel Members, SFPE Handbook chapter 4-9.

16 Brandsäkra trähus, Nordic Wood, Trätek.

17 White; Analytical Methods for Determining Fire Resistance of Wood Members, SFPE handbook chapter 4-11.

18 NS 3470: Prosjektering av trekonstruksjoner - Beregnings og konstruksjonsregler - Del 1: Almenne Regler.

7.6.4 Concrete properties in fires

19 Fleishmann; Analytical Methods for Determining Fire Resistance of Concrete Members, SFPE Handbook chapter 4-10

20 Phan, Lawson and Davis: Effects of elevated temperature exposure on heating characteristics, spalling, and residual properties of high performance concrete, National Institute of Standards and Technology, Gaithersburg, USA (2001).

2. Bengtsson; Brandpåverkade betongbalkar med slanka tvärsnitt, Sveriges Provnings- och Forskningsinstitutt, SP rapport 1997:35.

7.6.5 Computer programs for fire resistance modeling

22 Iding, R., B. Bresler and Z. Nizamuddin, 1977. *FIRES-T3 - A computer program for the fire response of structures - thermal*, University of California, Berkeley, Report No. UCB FRG 77-15.

23 Wickstrom, U., 1979. *TASEF-2, A computer program for temperature analysis of structures exposed to fire,* Lund Institute of Technology, Sweden, Report No. 79-2

24 Eker and Vlachos; HSLAB, Lund (1991)

25 *Gosselin;* Structural Fire Protection - Predictive Methods, National Research Council Canada (1987)

7.6.6 Steel protected by sprinklers

26 Lev and Strachan; A Study of Cooling Water Requirements for the Protection of Metal Surfaces Against Thermal Radiation, Fire Technology, pp 213 - 229, August 1989.

8 FIRE BRIGADE INTERVENTION

The roles of today's public fire department are at least twofold. The departments are divided into two major services; fire prevention and fire emergency action. The first category includes fire prevention education, existing building inspections, building plans review and technical assistance to the municipal building authorities. While this category is new and developing, the other category, fire emergency action, is old and traditional. However, new techniques for manual fire suppression are continuously developing, and fire fighter's knowledge about fire dynamics is increasing. Although, the traditional fire brigade is well established and acknowledged in most communities, their capabilities are usually over estimated. The probability of successful fire suppression depends much more on the building design and building accessibility than for example the travel time. This chapter points out the major factors that should be considered in evaluating fire brigade efforts at the fire site.

Detection and initial action is the first stage of this evaluation, and is referred to in chapter 5.

8.1 OBJECTIVES

Evaluation of fire brigade suppression can be divided into several steps from fire detection to suppression or controlled burn out, whenever the uncontrolled fire becomes controlled. Fire suppression depends on whether the on ground-operating commander decides to initiate an offensive or defensive tactic to respectively attack or control the fire. The commander's decision will depend on factors such as fire size, his crew, the equipment and the number of fire fighters to operate the equipments and the vehicles.

8.2 THE BUILDING CODE

The Norwegian code [1] includes a short paragraph about arrangements for fire brigade intervention. The code states that: "All construction works shall be so located and designed that personnel for fire rescue and extinction, with the appropriate equipment, have a feasible access to and inside the construction works for rescue and fire fighting operations". The prescriptive solution to the code requirements includes requirements for the access road, grounds designed for operating the ladder vehicle.

The other statement in the code is that: "Construction works shall be so arranged that a fire can easily be located and fought". This statement is followed up with REN's [2] requirements to availability to attics, shafts and cavities. And, implicit a requirement of functional fire partitions needed to limit the fire size.

8.3 FIRE SERVICES

Most fire and rescue activities are organized around a system of decentralized fire stations so that personnel and equipment can respond quickly and effectively to emergency incidents. This organization may be staffed by professional, part-time or volunteer personnel and may reflect a variety of characteristics derived from local traditions, needs and structure. The Paulsgrove [10] reference provides an overview of the elements involved in the organization, administration, management and operation of a fire department.

8.4 CRITICAL FIRE AND BUILDING CHARACTERISTICS FOR MANUAL SUPPRESSION

A fire can be measured in number of rooms involved, fire volume or heat release rate. A critical fire is a measurement of the severity of the fire that would cause the incident commander to choose a defensive tactic instead of an offensive tactic. This is an extremely important decision, because it is a choice that influence on life safety to the fire fighters. A deliberated portion of risk aversion in his judgment should be included. The evaluated critical fire should therefore be conservative. The fire can be characterized by:

- Fire size in mega watts
- Fire area
- Toxic products
- Explosions flashover, backdraft and smoke gas explosion
- Visibility
- Building characteristics

Fire size and fire area influence the amount of water application needed to extinguish the fire. Water demand rate for suppression with fire hoses can be compared to water application rate for sprinkler suppression. Särdqvist [3] made theoretical approaches for defendable fire sizes, relative to water application rate and droplet sizes, and made a series of test. Some of his results are referred in table 8-1.

Table 8-1. Heat absorption capacity for different nozzles

Equipment	*Water flow rate (kg/s)*	*Efficiency factor*	*Heat absorption capacity (MW)*
Standard nozzle (7 mm)	1,3	0,4	1,4
Standard nozzle (14 mm)	4.5	0,4	5,0
Standard nozzle (22 mm)	9,2	0,3	7,2
Large capacity nozzle	16,7	0,3	13
Monitoring nozzle	40	0,2	21

Fire sizes in megawatts or fire area are usually of major interest for outdoor fires or where fires can be suppressed without penetrating the building. But, usually a fast manual suppression effort will require a fast and efficient inside building fire attack. The likelihood of successful fire suppression depends on many factors. One of them is the temperature. Fires that have developed to flashover can cause extremely high temperature also in rooms beyond the room of origin. In some cases the fire fighters can use their hoses to cool down the surroundings as they are moving towards the fire origin. In larger spaces where a hot smoke layer have been created, the fire fighters may not be able to cool down the temperature before the fire is extinguished. Room fire temperature is referred in chapter 2 and a critical temperature for fire fighting can be evaluated against performance requirements for fire fighters clothing. According to NFPA 1971 [4] the clothes shall resist temperatures at 260°C for protective garment, textiles and hardware and a radiated heat of 10 kW/m^2 for helmets.

Heating can also cause other incidents in the fire room. Pressurized gas, combustible or not can explode due to increase in pressure. These incidents may be a significant problem where bottles are not stored properly in appropriate rooms and/or equipped with safety overpressure relief valves.

Explosions can also take place without pressurized gas. Underventilated fires can produce unburned gases, and over time the concentration of unburned gases accumulates in the room of origin or in other rooms. When the fire fighters open the door, fresh air will mix with the gases and a partly premixed combustion occurs. This phenomena is called backdraft [5].

In special situations it may be possible for the fire gases to mix well with air before the ignition takes place. This can happen in spaces not far from the fire compartment and consequently an enormous pressure may be built up if the gases are ignited [5].

Industrial buildings or warehouses may contain pesticides, flammable liquids, flammable gases, explosives, oxidizers, nuclear materials etc. The fire behavior in buildings containing such hazardous materials can cause enourmous problems for fire fighting efforts. Hazardous materials shall be classified and special response strategy, tactics and protective equipment shall be preplanned. Wright describes how to manage the response to hazardous material incidents [6].

Evaluation of building construction is discussed in chapter 7. Fire resistance and construction classification influence on the safety for fire fighters inside the building. Brannigan presents the highlights of the problems that building presents to suppression forces [7].

8.5 FIRE BRIGADE TIMELINE PREDICTION

One major goal of fire brigade suppression evaluation is to predict and construct a timeline. The first and often critical factor, is early detection. A fire that is not detected will not be notified to the fire department. Buildings without a fire alarm system will only occasionally be notified before the flames are visible from the outside. These fires are already fully developed within the fire origin and fire spread is more dependent on the barriers than the fire brigade.

A timeline can be a tabular description of time dependent events during the fire. The following subchapters include information and references to construct a fire brigade intervention timeline. The first part of the timeline is detection and fire brigade notification. This part is described in chapter 4. For more information about timeline construction, the reader is encouraged to read the Fitzgerald reference [8],

Time to fire brigade arrival may be important or it may not be important at all. Särdqvist [9] performed a study of fires in non-residential fires London in the period 1994-1997. Among several other conclusions he stated that:

- No support was obtained for the hypothesis that the time from ignition to when the fire brigade intervened is correlated with the fire area.
- At half of the fires, the final area of fire spread was equal to the area at discovery, and at three-quarters of the fires, the final area of fire was equal to the area when the fire brigade arrived.

8.5.1 Alarm processing time

The alarm processing time is the time between the receiving of the alarm and alerting the responding fire companies. This process will take only about 30 seconds to 1 minute, but it is important to consider the reliability of correct alarm receiving. The fire department must understand the correct address. Consideration shall be taken to the person who is notifying the fire department. He may be stressed or in other ways not able to notify the fire department properly.

8.5.2 Turn out time

Turnout time is usually short. In the analysis it should be distinguished between professional, call on duty, call on scene and volunteer FD, and night and day response [10].

Table 8-1. Rule of tumbs for prediction of turn out time [10]

On duty	*Call on duty*
2 min (required)	6 min (average)

8.5.3 Travel time

Travel time is easy to estimate. The estimate should be based on average speed and distance between the station and the site. Also, a few other parameters must be considered:

- Traffic
- Route access
- Nearest station is not available because of other fires
- Road characteristics (e.g. steep rise, curves, width, road surface)
- Weather

8.5.4 Fire ground operations

At every fire and rescue operation there must be an incident commander who commands the operation and decides what personnel and other resources to use during the operation. Fire ground operation is a management issue. The officer in command is responsible for all the operations taking place. He has to make rapid decisions and chose an appropriate strategy for controlling or fighting the fire. The commander may not be an educated fire protection engineer, but his decision can be based on years of experience and training. Before deciding the fire attack strategy he must achieve information about the building construction and plan layout, the fire characteristics, occupants, water supply and available resources for fire fighting. For more information about incident management, fire fighting tactics, commander responsibility and safety the reader may read specific parts of the Pulsgrove reference [10].

All fire departments shall include a safety program. In the U.S. this program are outlined in NFPA 1500 [11].

8.5.5 Set up time

The set up time is the time needed to park the engine, connect to the water supply and general preparation time for fire attack. The first two parameters depend on the site layout and distance to water supply. Urban fire brigades do not have to connect to water main before they attack the fire. The driver can do that while the firefighters penetrate the building. The main part of this analysis would be the evaluation of time to penetrate the building, localize the fire and time to water application.

A method to evaluate firefighter penetration time is developed by Callery [15]. This method does not just make use of geometric distances, but uses equivalent distances, based on the obstacles encountered. An example with raw distance data is shown below.

Table 8-1. Examples of geometric distances for fire-fighters

Situation	*Distance*
Front Door, locked, glass	1
Lobby	35
Corridor	130
Stairway Door, unlocked, metal	1
Stairway	48
Hose Use Begins	0
Corridor Door, locked, metal	1
SCBA Use Begins	1
Corridor	15
Suite Door, locked, glass	1
Hallway	30
Office door, open, wood	1

However, other data is added so that a proper equivalent time can be determined for the entire operation. For example, a locked corridor door may have an actual distance of 1 ft., but an equivalent distance of 200 feet, due to the time necessary to force the door open. When the 200 feet is divided out by the average distance that the firefighter moves and equivalent time is created.

8.6 RESCUE OPERATIONS

It is difficult to estimate precise information for evaluation of time to rescue people trapped in a building. Even though the code asks the right questions for designing construction works, the technology may not exist. Even though there is a lack of sufficient information, this part of the evaluation may be discussed with the fire department. It is possible to make a good qualitative description of the difficulties the rescue team may come up with during their rescue efforts. This judgment shall be based on the evaluated design fire and the building characteristics. Some useful factors may be building complexity, building fire hazard classification including the number of people that usually occupies the building, and their familiarity in the building, the fire hazard described with fire, smoke and heat development, and smoke and heat movement through open doors or barrier failures. With a good prediction of a fire scenario, the fire brigade suppression and rescue tactics, and an agreement with an experienced fire officer, this can provide a good evaluation of a rescue operation.

Sandberg and Sandberg measured the rescue time based on test in kindergarten buildings. They found that the total time needed to rescue three children was 30 minutes. On average four minutes was used to dress up one child, but with a little training the time was reduced to 40 seconds [12].

The time consuming factors in this rescue operation test were [12]:

1. Search and find trapped occupants. Usually the trapped occupants are children or elderly or other persons that may be disabled and not available to evacuate by them self.
2. Put breathing apparatus and protective clothing on the victim.
3. Movement to safe area.
4. Undress protective clothing.

Rescuing with the ladder vehicle as a secondary egress route in old buildings is an accepted mean of egress in Oslo [13] and other cities where the fire brigade has sufficient personnel and resources. Windows or balconies are accepted as a means of egress up to 12 meters above terrain.

For general information about rescue operations the reader is referred to the Naum reference [14].

8.7 SUMMARY

The building code have design requirements for buildings. The building shall be designed so that the fire brigade have a feasible access to and inside the building. Fire brigade efficiency can be weighted against the fire scenario in a building. The extinction capability of fire hoses can be evaluated against an evaluated fire size. A small fire can be suppressed with an offensive fire attach inside the building. In larger fire the incident commander may chose a passive strategy, and try to control the fire outside the building. A timeline for fire development can be evaluated against a timeline for fire brigade operations, such as arrival time, set up time and water application time.

8.8 REFERENCES

8.8.1 Codes and standards

1 National Office of Building Technology and Administration (Norway): TEK-97, Regulations concerning requirements for construction works and products for construction works, 22 January 1997 No. 33 Technical Regulations under the Planning and Building Act 1997.

2 National Office of Building Technology and Administration (Norway): REN, Guidance to Regulations concerning requirements for construction works and products for construction works, 2nd edition, April 1997.

4 NFPA 1971; Protective ensemble for structural fire fighting (1997).

11 NFPA 1500: Standard on Fire Department Occupational Safety and Health Program, National Fire Protection Association (1997).

13 Veiledning for tiltakshaver/søker - Innredning av Leiligheter på Loft og Kjeller i Murbygninger, Blankett 72-0566, Oslo Kommune (99).

8.8.2 Design fire information

3 Särdqvist; An Engineering Approach to Fire Fighting Techniques, Lund 1996.

5 Bengtsson; Flashover, Backdraft and Smoke Gas Explosion from a Fire Service Perspective, Lund Tekniska Høgskole, Lund 1999.

8 Fitzgerald: The Anatomy of Building Firesafety, Volume 2 Draft 4, Worchester Polytechnic Institute (1999).

8.8.3 Fire brigade operation

6 Wright; Managing the Response to Hazardous Material Incidence, NFPA Handbook chapter 10-9.

8 Fitzgerald: The Anatomy of Building Firesafety, Volume 2 Draft 4, Worchester Polytechnic Institute (1999).

10 Paulsgrove; Fire Department Administration and Operation, NFPA Handbook chapter 10-1.

12 Sandberg och Sandberg; Skydds Sökning och Evakuering, Statens Rädningsverk (1988).

14 Naum: Rescue Operations, NFPA Handbook Chapter 10-10

15 WPU thesis written by Callery

8.8.4 Fire brigade suppression capability

4 NFPA 1971; Protective ensemble for structural fire fighting (1997).

7 Brannigan: Building Construction Concerns of Fire Departments, NFPA Handbook chapter 10-11.

8 Fitzgerald: The Anatomy of Building Firesafety, Volume 2 Draft 4, Worchester Polytechnic Institute (1999).

9 Särdqvist; Real Fire Data - Fires in non-residential premises in London 1994-1997, Lunds Tekniska Högskola, Lunds Universitet, Lund 1998.

9 LIFE SAFETY

Life safety is a primary concern in fire protection. All building codes are primarily concerned about the safety for the occupants. The building frames, the linings, fire partitions, fire protection installations and the egress paths shall all be designed in a way that encourages safe egress

9.1 DOCUMENTATION OF THE CODE REQUIREMENTS FOR SAFE EGRESS

The general code requirement for safe egress is that "construction works shall be designed and executed for rapid and safe escape". And "the time available for escape shall exceed the time necessary for escape from the construction works. Allowance shall be made for a satisfactory safety margin". This requirement is further specified with tenability during time needed for egress.

The traditional method to provide safe egress is to use fire rated constructions to separate the fire hazards from the egress paths. In Norway, the separation constructions are rated for 30 or 60 minutes according to the standard fire test. Doors are usually rated for only 30 minutes. According to the Technical regulations (TEK) [1] fire protection systems like automatic fire alarm systems and guidance systems are only required in risk class 5 and 6 occupancies (assembly areas, hotels, hospitals). Sprinkler systems and smoke control systems are not required by the code, but in some cases recommended in the prescriptive code (REN) [2]. Sprinkler systems are, in special cases, required as a means of personal safety. For example, sprinklers in roofed areas in connections with atria and large spaces, or in buildings with openings over several floors and a total area exceeding 800 m^2. Automatic fire alarm systems with detectors in the corridors are recommended in educational buildings with two or more floors. The difference in detection with a detector in a corridor or a detector within the room of origin can be significant.

The code requires smoke detectors to be installed only in risk class 4 objects (residences). In complex blocs of flats, neighbors cannot expect to be alarmed due to the first smoke detector activation, causing the fire rated separation constructions to be extremely important to ensure safe egress because it can take a long time for all the occupants are alerted and aware of the threatening fire.

Smoke control systems are recommended in REN for buildings with more than 8 floors or risk class 4 objects with only one egress path. The intent of both sprinkler systems and smoke control systems is to increase available safe egress time. In buildings where sprinklers or smoke control systems are recommended, there may not be any regulatory requirements or recommendations for fire alarm systems.

Based on the risk class and number of floors, REN recommends pressurized stairs with locks (Tr3) or corridors (Tr2) between the fire partitions and staircases. For buildings with eight floors or less, REN recommends Tr2 stairs in occupancies with sufficient number of people and where egress time are expected to be significant (risk class 3, 5 and 6).

TEK requires that "fire compartments for a large number of persons shall have a sufficient number of exits, at least two, to the escape route". On the other hand, REN recommends two egress paths for all risk classes.

In a performance based evaluation, the fire safety value of fire protection installations can be measured against the level of safety achieved by designing after the prescriptive code. In every building with a touch of complexity there are usually several ways of achieving a sufficient level of fire safety.

The documentation of the fire safety level shall be performed and written according to NS 3901 [3]. The three different types of acceptance criterion are all useful for different fire protection designs. The former sections of this chapter should indicate that a comparative judgment is probably the easiest and most economic way to compose the required document. Combinations of the design of egress paths, number of egress routes, installation of fire protection systems and the evaluation of their influence on life safety, the likelihood of fire spread, barrier effectiveness and reliability in keeping tenable conditions in the egress routes, and fire department suppression and rescue operations can all be evaluated together and measured by an increase in safe egress time or decrease in necessary egress time relative to the prescriptive fire protection design.

9.2 AVAILABLE SAFE EGRESS TIME

Available safe egress time is a matter of fire spread and time to untenable conditions in the egress paths. The tenability criterion and deterministic measures are discussed in chapter 6, and the likelihood of fire and smoke spread through open doors or barrier failures are discussed in the barrier chapter. With this information available safe egress time can be evaluated.

The essential and major problem by evaluating safe egress time is the description of the design fire and the building geometry. The rate of fire growth influence on the time to generation of a hot smoke layer, temperatures and concentration of toxic gases. The building geometry influences on the volume that has to be filled with smoke and the openings between the rooms influence on smoke movement. Doors are never a 100% reliable obstruction. Therefore, it is necessary to evaluate the situation with doors open and doors closed. Available safe egress time based on deterministic evaluation of tenability can vary from 2 minutes to 30 minutes, depending on the doors. Deterministic acceptance criteria for evaluating tenability in egress paths are not available, but comparative judgments can be performed.

Evaluating available safe egress time in the room of origin is easier. The likelihood of doors open or not can be excluded. In this evaluation, only the design fire and room geometry is of interest. The fire growth rate can be evaluated from prediction of fire load characteristics. The smoke and heat-filling rate can be evaluated with equations programmed into a spreadsheet, or zone- or field models described in the smoke movement chapter.

9.3 REQUIRED EGRESS TIME

The time needed to evacuate can be divided into thee steps, detection, reaction, and, the time needed to move to a safe place. Detection and reaction was discussed on the Detection chapter. Movement is both an issue of human characterization and numerical calculation of movement velocity through corridors, doors, stairs and other bottlenecks. The human characterization is the essential factor; the movement part can be evaluated with simple computer programs or only simple calculations.

9.3.1 Human characterization factors for movement

The Pauls [4] reference in the SFPE handbook does a general summary of several references that covers this subject. The conclusions drawn about fire related human behavior is:

- Panic is very rare even in very serious fires.
- A central motivation and activity in fires is to seek information about the nature and seriousness of the situation.
- Evacuation and response to fire generally is often a social response.
- The movement of people observed in normal building use and in many simulated emergency evacuations is a good basis for predicting their movement in a fire emergency.

All of these factors are essential to evaluate human's motivation to evacuate in fires. The motivation to seek information can be compared the ease of achieving this information in a building with a specific layout and design. The social response issue may be present in an office building, and may not be present in a mall. And probably the most important factor in evaluating the egress time is that people tend to evacuate in the same route that they use every day. It may be unrealistic to assume an optimum distribution of people to all egress paths. The latter factor has been underlined by McClinton [5]. He called it "Movement towards the familiar". Another particular factor for movement is "Learned irrelevance". The significance of "Learned irrelevance" was measured by interviews in retail stores by Shields and Boyce [6]. They found that 86% failed to notice emergency exit signs anywhere in the store, and 75% could not indicate the location of any emergency exit signs even when prompted with a simple schematic of the store.

Handicapped people may have a variety of limitations that increase their risk in fires and make them unable to evacuate. Their problems may be deafness, blindness, or mobility that may entail the need for a vehicle chair. Intellectual problems such as mental retardation or dementedness, alone or in combination with other handicaps, can also hinder them from evacuating a building. Handicapped people may also have a concern about their personal risk, especially in high-rise buildings or in residences where rescue help is not continuously present. Horizontal evacuation to an area of refugee (AOR) can be appropriate for some buildings, and, according to REN, AOR is recommended for nursing homes and hospitals. The Levin and Nelson reference deals with the issue of disabled persons and fire safety [7].

Boyce, Shields and Silcock [19,20,21,22] have produced four papers that collectively provide a substantial body of knowledge of disabled people who frequent public-assembly buildings. This information can be used to derive working estimates of the prevalence and nature of disability among building populations when characterizing building occupancies.

9.3.2 Methods to evaluate the movement time

There are numerous methods to predict the movement time ranging from simple and fast calculations to complex geographical software. The easiest first hand estimate of movement time, assuming an optimum density through the doors, corridors and stairs, is to assume a flow rate of 1 person per second per meter egress path width [4]. An assembly area with 1000 persons evacuating through three doors with total 3-meter opening width will at an optimum take about 300 seconds (5 minutes). Time to move to a safe place must be added to this estimate. The speed can be assumed to be about 1 m/s, but the speed is reduced in stairs or corridors where the densities of persons are increased.

Movement equations programmed into a spreadsheet or preprogrammed software tools can perform a more credible prediction, but there is a danger of getting sidetracked by their apparent sophistication. The models and equations can take on a reality of their own and keep us from understanding the world as is it actually exists [4]. The models should therefore at least take into account the effect of flow times vs. effective width per person. Some models also assume that all people start evacuating at the same time and that they wait at every choke point. This may cause an unrealistic over prediction. Disabled persons can also block one of the egress paths for a period. Spreadsheet models and graphs that can be used to estimate movement times are presented in [8,9].

EXIT89 [10] is one model that uses mathematics to describe in detail the process of movement and waiting. This is an evacuation model designed to handle the evacuation of a large population of individuals from a high-rise building. It has the ability to track the location of individuals as they move through the building so that the output from this model can be used as input to a toxicity model that will accumulate occupant exposures to combustion products. Models like CFAST [11] and FPETool [12] do also include simple modeling tools for egress time.

Network models can usually import computer-aided graphics. These models are characterized by the description of structures as lists of nodes and arcs. Nodes can be sources of people, destinations for people, or places where people accumulate. Nodes are typically used to model rooms, hallways, stairways and exits. Nodes have capacities, and sometimes additional information, depending on the model. Arcs connect nodes. Arcs have flow-rates, and regulate the speed at which occupants may flow from one node in a structure to another. Network models are, EVACNET+ [13], Simulex [14], STEP [15], PedGo [16] and EXODUS [17].

A summary of different computer models for evaluating egress times can be found in the Watts reference [18].

9.4 SUMMARY

The traditional code required method to provide safe egress is to use fire rated constructions to separate fire loads from egress paths. Performance based codes allows other methods to be used as long as available safe egress time is longer than required egress time including a safety factor. Available safe egress time is usually a matter of fire development and smoke spread, and, required egress time is a matter of human behavior in fires and necessary time to move to a safe place. Movement time can be evaluated with computer programs.

9.5 REFERENCES

9.5.1 Building codes and standards

1. National Office of Building Technology and Administration (Norway): TEK-97, Regulations concerning requirements for construction works and products for construction works, 22 January 1997 No. 33 Technical Regulations under the Planning and Building Act 1997.
2. National Office of Building Technology and Administration (Norway): REN, Guidance to Regulations concerning requirements for construction works and products for construction works, 2nd edition, April 1997.
3. National Building Standardization Council (Norway): NS3901, Risk analysis of fire in buildings and civil engineering works (1998).

9.5.2 General egress

4. Pauls; Movement of People, The SFPE handbook chapter 3-13
5. McClintock; A Behavioural Solution to Increasing the Efficiacy of Emergency Exits, University of Ulster
6. Shields and Boyce; In Unannounced Evacuations of Retail Stores, University of Ulster (2000)
7. Levin and Nelson; Firesafety and Disabled Persons, Fire Journal, Vol 75, No 5 pp 35-40 (1981)

8. NBI.520.385: Beregning av Rømningstid, Norges Byggforsknings Institutt (1997)

9. Bryan; Human Behavior and Fire, NFPA Handbook chapter 8-1

19 Boyce, Shields, and Silcock; Toward the Characterization of Building Occupancies for Fire Safety Engineering: Prevalence, Type, and Mobility of Disabled People. Fire Technology Volume 35, no. 1 First Quarter 1999

20 Boyce, Shields, and Silcock; Toward the Characterization of Building Occupancies for Fire Safety Engineering: Capabilities of Disabled People Moving Horizontally and on an Incline. Fire Technology Volume 35, no. 1 First Quarter 1999

21 Boyce, Shields, and Silcock; Toward the Characterization of Building Occupancies for Fire Safety Engineering: Capability of Disabled People to Negotiate Doors. Fire Technology Volume 35, no. 1 First Quarter 1999

22 Boyce, Shields, and Silcock; Toward the Characterization of Building Occupancies for Fire Safety Engineering: Capability of People with Disabilities to Read and Locate Exit Signs. Fire Technology Volume 35, no. 1 First Quarter 1999

9.5.3 Computer models

10. Fahy; EXIT89: An Evacuation Model for High-Rise Buildings. Model Description and Example Applications, International Association for Fire Safety Science. Fire Safety Science. Proceedings. 4th International Symposium. July 13-17, 1994, Ottawa, Ontario, Canada, Intl. Assoc. for Fire Safety Science, Boston, MA, Kashiwagi, T., Editor, 657-668 pp, 1994

11. Jones and Forney. “A Programmer's Reference Manual for CFAST, the Unified Model of Fire Growth and Smoke Transport,” *Natl. Inst. Stand. Technol.* 1990, *Tech. Note 1283*, 104 p.

12. Deal; Technical reference Guide for FPETool ver. 3.2, National Institute of Standards and Technology (1995).

13. Kisko and Francis; *EVACNET+: A computer program to determine optimal building evacuation plans*,

Fire Safety Journal, Vol. 9, 1985, pp 211-220

14. Thompson and Marchant; A Computer Model for the Evacuation of Large Building Populations. Fire Safety Journal Vol. 24, No. 2 pp 131-148. 1995.

15. Mott MacDonald Inc, England.

16. König, Klüpfel, and Schreckenberg; A microscopic model for simulating mustering and evacuation processes onboard passenger ships, Institute of Ship Technology, Gerhard-Mercator-University,

17. Owen, Galea and Lawrence; Advanced Occupant Behavioural Features of the building-EXODUS Evacuation Model, University of Greenwich (1996).

18. Watts; *Computer Models for Evacuation Analysis*, Fire Safety Journal, 12(1987), pp. 237 -- 245

CONCLUSION

This document provides references in an organized sequence. This was done to make literature and publications more easily available to a fire protection engineer who evaluates fire safety in a performance based perspective. The extent of available literature is large, and much of it is easily available through the Internet. There is an increasing interest for the building and the fire protection systems performance in fire scenarios and lots of literature addresses this topic. However, each particular publication may only cover a limited area of the phenomena that may occur in a fire scenario. Even though the use of literature and international knowledge is used to understand the building and its occupants it can still be possible to make mistakes. A performance based design also require technical firesafety knowledge so that the relations between the different facts can be established, whereas the literature may describe facts for a specific frame of a fire scenario analysis. This can be compared with the skills necessary to pass a strenuous river by jumping from stone to stone. This requires courage, strategy, certainty and balance.

The accuracy in simulation methods and models varies. For example, sprinklers suppression efficiency is difficult to estimate because the sprinkler manufacturers don't have appropriate data to characterize the sprinkler spray. The speed of fire development in a room can be estimated with a relatively decent accuracy if the location of the fire source and the room's furniture and fixtures are known. Methods to estimate smoke production are good and available, but evaluation of smoke movement in a building is difficult and the simulation results are strongly dependent on the chosen assumptions. In general, the variety and dynamics in fire scenarios are extensive. Therefore, the characterization of the building, its occupants and design fires is probably the most difficult and the most important part of any firesafety evaluation.

Several countries have chosen a performance-based code for the future. And, there is an increasing interest for performance among the engineers. The profession can develop such that the fire protection engineers can evaluate any building design with sufficient accuracy, and recommend a firesafety design that gives sufficient level of firesafety without regard to how the building industry develop. Focus on performance instead of pre-accepted design may be the only way the fire protection profession can survive and still be an interesting part of any building engineering team. While the structural-, electrical- and the HVAC engineers, need to get updated in new products, the focus of the fire protection engineers aims at the development of new theories, models and tests in order to gain better knowledge to evaluate fire safety. An important competition advantage for fire protection engineers is sufficient knowledge of the literature and its application, application of models, and ability to communicate in such a way that the firesafety level is presented in an understandable perspective.