Demand for Extinguishing Media in Manual Fire Fighting

Särdqvist, Stefan

2000

Citation for published version (APA):
Särdqvist, S. (2000). *Demand for Extinguishing Media in Manual Fire Fighting*. [Doctoral Thesis (compilation), Division of Fire Safety Engineering]. Department of Fire Safety Engineering and Systems Safety, Lund University.

Total number of authors:
1

LUND UNIVERSITY

PO Box 117
221 00 Lund
+46 46-222 00 00

LUND UNIVERSITY · SWEDEN
INSTITUTE OF TECHNOLOGY
DEPARTMENT OF FIRE SAFETY ENGINEERING
REPORT LUTVDG/(TVBB-1021)

Demand for Extinguishing Media in Manual Fire Fighting

Stefan Särdqvist

Lund 2000

Demand for Extinguishing Media in Manual Fire Fighting

Stefan Särdqvist

Lund 2000

Akademisk avhandling

som för avläggande av teknologie doktorsexamen vid tekniska fakulteten vid Lunds universitet offentligen försvaras vid avdelningen för Brandteknik, John Ericssons väg 1, sal V:B, torsdagen den 28 september 2000, kl 10.15.

Demand for Extinguishing Media in Manual Fire Fighting

Stefan Särdqvist

Report 1021
ISSN: 1402-3504
ISRN: LUTVDG/TVBB--1021--SE

Number of pages: 158

Illustrations and photographs: Stefan Särdqvist. Cover illustration: Ingemar Wallgren, reprinted from *Handbrandsläckare 1986*, SBF Brandförsvarsföreningen, with permission.

Keywords: Fire brigade, fire fighting, fire suppression, extinction, extinguishing agents, water.

Sökord: Räddningstjänst, brandsläckning, släckmedel, vatten.

Abstract
Risk analysis and intervention planning are important in fire prevention and risk management strategies. This study has shown that it is possible to use fire safety engineering models to estimate the development of fires on a realistic scale, and the corresponding requirement for extinguishing media. Data from the London Fire Brigade (UK) were used to investigate a possible correlation between the area of the fire and the fire-fighting measures employed. This data, together with data from two old investigations, published in the literature, were used to evaluate existing models for the dimensioning of manual fire suppression using water. The demand for water was also investigated theoretically and experimentally. Theoretical investigations were carried out using data from small-scale tests found in the literature, and data from real fires in London (UK). Experimental studies were carried out employing large-scale suppression tests in order to evaluate the difference in efficiency between a low-pressure and a high-pressure nozzle. The heat stress on the fire fighters was also studied. Apart from water, gaseous extinguishing media were also investigated with regard to the effect of external heat radiation on the required medium concentration.

Brandteknik
Lunds tekniska högskola
Lunds universitet
Box 118
221 00 Lund

brand@brand.lth.se
http://www.brand.lth.se

Telefon: 046 - 222 73 60
Telefax: 046 - 222 46 12

Department of Fire Safety Engineering
Lund University
P.O. Box 118
SE-221 00 Lund
Sweden

brand@brand.lth.se
http://www.brand.lth.se/english

Telephone: +46 46 222 73 60
Fax: +46 46 222 46 12

A little fire is quickly trodden out;
Which, being suffered, rivers cannot quench.

W. Shakespeare

Contents

Introduction

The research presented in this thesis is part of the requirements for the degree of Doctor of Philosophy in Engineering (PhD Eng.) at the Department of Fire Safety Engineering at Lund University.

The following six papers, presented at international symposiums or submitted to peer-reviewed journals are included in the thesis:

I Särdqvist, Stefan; *An Engineering Approach to Fire Fighting Tactics*, Proceedings, The Second International Conference on Fire Research and Engineering, Society of Fire Protection Engineers, Bethesda, MD, USA, 1998, pp 351-361.

II Särdqvist, Stefan & Holmstedt, Göran; *Correlation Between Fire-fighting Operation and Fire Area: Analysis of Statistics*, Fire Technology, vol. 36, No. 2, 2000, in press.

III Särdqvist, Stefan; *Fire Brigade Use of Water*, Interflam '99, Proceedings of the Eighth International Conference, Vol. 1, Interscience Communications Ltd. 1999, pp 675-683.

IV Särdqvist, Stefan & Holmstedt, Göran; *Water for Manual Fire Suppression*, submitted to the Journal of Fire Protection Engineering, 2000.

V Särdqvist, Stefan & Svensson, Stefan; *Fire Tests in a Large Hall, Using Manually Applied High- and Low-pressure Water Sprays*, submitted to Fire Science and Technology, 2000.

VI Särdqvist, Stefan; Andersson, Magnus; Dagneryd, Anders; Skogetun, Pontus & Holmstedt, Göran; *Cup Burner Tests Under the Influence of External Heat Radiation on Normal and Large Scales*, submitted to Fire Technology, 2000.

Other related publications by the author, which are not included in this thesis:

- Särdqvist, S., *An Engineering Approach to Fire Fighting Tactics*, Dept. of Fire Safety Engineering, Lund University, Report 1014 (Licentiate Dissertation), 1996.
- Särdqvist, S., *Initial Fires. RHR, Smoke Production and CO Generation from Single Items and Room Fire Tests*, Dept. of Fire Safety Engineering, Lund University, Report 3070, 1993.

- *Övertrycksventilation. Förstudie över brandventilation med mobila fläktar*, Räddningsverket, rapport P21-092/94, 1994 (in Swedish).
- Andersson, B., Andersson, P., Holmstedt, G., Särdqvist, S., *Naturgas Säkerhetsnivå Riskanalys*, Dept. of Fire Safety Engineering, Lund University, Report 3073, 1994 (in Swedish).
- Bengtsson, L. G., Karlsson, B., Särdqvist, S., *Brandventilation i teori och praktik*, Räddningsverket, rapport R53-146/96, 1996 (in Swedish).
- Särdqvist, S., *Djupanalys av tre storbränder*, Dept. of Fire Safety Engineering, Lund University, Report 3096, 1998 (in Swedish).
- Särdqvist, S., *Real Fire Data, Fires in Non-residential Premises in London 1994-1997*, Dept. of Fire Safety Engineering, Lund University, Report 7003, 1998.
- Särdqvist, S., *Manuell brandsläckning med vatten*, Dept. of Fire Safety Engineering, Lund University, Report 3106, 1999 (in Swedish).
- Andersson, B., Babrauskas, V., Holmstedt, G., Särdqvist, S., Winter, G., *Simulated Fires in Substances of Pesticide Type*, Dept. of Fire Safety Engineering, Lund University, Report 3087, 1999.
- Lundström, S., Svensson, S., Särdqvist, S., *Släckförsök vid brand i stor lokal*, Räddningsverket, rapport P21-328/00, 2000 (in Swedish).

Reports from the Department of Fire Safety Engineering, Lund University, are available as PDF documents, free of charge, at http://www.brand.lth.se/.

Acknowledgements

The work presented in this thesis is based to a large extent on input from fire fighters and officers of the fire brigades of London (UK), Lund and Malmö (Sweden).

Professor Göran Holmstedt has supervised the work with enthusiasm and commitment. Berit Andersson and Sven-Ingvar Granemark have provided valuable support during the course of this research. These and other friends at the Department have helped me both with practical matters and with motivation when things didn't work out.

My wife Maria also deserves to be mentioned for her patient support.

Thanks to all of you!

The work behind this thesis has mainly been financed by Brandforsk, The Swedish Fire Research Board, which is gratefully acknowledged. The project is entitled *En modell för räddningstaktik* (A Model for Rescue Tactics), and has the project numbers 501-971, 503-981 and 508-991. A reference group has been connected to the project, consisting of the following members: Kaare Brandsjö (Fire and Rescue Consultant), Jonas Evbäck (Swedish Municipal Workers' Union), Göran Holmstedt (Lund University), Birger Lennmalm (Brand & Riskteknik AB), Mats Rosander (Helsingborg Fire Brigade), Tommy Magnusson (Vattenfall), Claes Nicklasson (The Swedish Rescue Services Agency), Stefan Svensson (The Swedish Rescue Services Agency) and Per Widlundh (Malmö Fire Brigade). Räddningsverket, the Swedish Rescue Services Agency, supported the experimental work, which is also acknowledged.

BRANDFORSK
Styrelsen för svensk brandforskning

RÄDDNINGS
VERKET

Brandforsk, the Swedish Fire Research Board, and Räddningsverket, the Swedish Rescue Services Agency, who financed this research.

Sammanfattning
(Executive summary in Swedish)

Då avhandlingen är skriven på engelska, följer här en svensk sammanfattning av innehållet i de sex uppsatser som avhandlingen lagts samman av. Tanken som genomsyrat arbetet är att det i förväg går att bedöma storleken på bränder och att det i förväg går att bedöma resursbehovet för att kunna hantera dem. För vissa släckmedel, till exempel mellanskum och lättskum finns redan praktiskt användbara metoder för dimensionering. För släckning med vatten är läget annorlunda. Därför ägnas största intresset just vatten, det släckmedel som används vid de allra flesta bränder.

Uppsats I

I den första uppsatsen konstateras att det är möjligt att i förväg bedöma hur stor en brand kommer att bli, genom att utnyttja de olika ingenjörsmodeller som finns tillgängliga. Med hjälp av ett händelseträd kan sedan olika brandförlopp analyseras. Det handlar om att först göra en bedömning av hur stor en brand i en given byggnad kan bli, exempelvis beroende på om brandsektioneringen fungerar eller inte. Efter detta kan en bedömning göras av resursbehovet för att släcka branden i de olika fallen. Detta resursbehov kan sedan ställas mot den mängd släckmedel och personal som finns tillgängliga på platsen och hos räddningstjänsten. Det går också att värdera vilken släckmetod som är lämpligast. Här tas hänsyn till skadeutfallet och eventuellt också till kostnaden för släckinsatsen. I många fall har en traditionell rökdykarinsats störst fördelar. I andra fall kan användning av ett pulveraggregat krävas för att nå tillräcklig effekt. I andra fall är lättskumsfyllning ett smidigare alternativ. Det går alltså att i förväg analysera vilka av alla metoder på räddningstjänstens palett som ger önskad släckeffekt. Det går också att bedöma vilken metod som ger minst skador på människa, egendom och miljö till minst insats beträffande personal, släckmedel och materiel. Vissa situationer kommer också att upptäckas där räddningstjänsten inte har tillräcklig släckkapacitet. Att dessa situationer identifieras i förväg innebär också att de kan hanteras på lämpligt sätt av exempelvis den berörda företagsledningen.

Uppsats II

Tyvärr finns det stora brister i att kunna bedöma släckeffekten vid släckinsatser med vatten. I den andra uppsatsen redovisas en statistisk undersökning av material insamlat av brandorsaksutredare vid London Fire

Brigade. Bränder i byggnader utom bostäder undersöktes och av den typen inträffade 307 mellan åren 1994 och 1997. En analys om förhållandet mellan brandens slutliga storlek och olika tidsintervall gjordes. Inget statistiskt säkerställt samband upptäcktes mellan vare sig tid till antändning, tid till upptäckt, tid till larm eller tid till släckinsatsen påbörjas och brandens slutliga storlek för gruppen av bränder som helhet. Det är alltså andra parametrar än räddningstjänstens insatstid som styr hur stora bränder blir, förmodligen bränslets mängd och fördelning. Hälften av bränderna blev inte större, än när de först upptäcktes och tre fjärdedelar blev aldrig större än när räddningstjänsten var på plats. För den mindre gruppen av bränder, en fjärdedel, som fortfarande spred sig när räddningstjänsten var på plats finns ett svagt samband mellan insatstid och brandyta. För gruppen av bränder som helhet konstaterades däremot ett samband mellan kontrolltid respektive släcktid och brandens slutliga storlek. Detta kan sammanfattas i att ju större branden är, desto längre tid tar den att släcka. Beträffande släckmedelsåtgången, konstaterades att både vattenflödet och kontrolltiden är proportionella mot roten ur brandytan. Den totala mängden vatten blir därmed direkt proportionell mot brandytan.

Uppsats III

Vid en hastig överblick tycks det som om räddningstjänstens dimensionering är mer baserad på traditioner och ekonomiska eller politiska överväganden än på bedömningar av vilka krav som bränderna faktiskt ställer. I den tredje uppsatsen redovisas en genomgång av vilka modeller för dimensionering av manuell brandsläckning med vatten som finns. Särskilt mycket arbete har inte gjort inom området. Undersökningar av faktiska släckinsatser tycks endast finnas tre stycken, utöver den ovan nämnda gjordes en i början av 70-talet och en i slutet av 50-talet. De tre undersökningarna, två med engelska data och en med amerikanska, ger ett i stort sett samstämmigt resultat. Intressant nog visar sig tillgängliga experimentella data passa in i samma mönster. Experiment kan alltså ge en rättvisande bild av verkliga släckinsatser, åtminstone i den storlek av bränder som experimenten representerar. Dock används mindre vatten vid experimenten än i verkligheten, förmodligen beroende på att räddningstjänsten har mindre möjlighet att välja strålrör efter brandens storlek, men också på att det krävs en mindre säkerhetsmarginal när brandens storlek är känd i förväg. Beträffande jämförelsen med tillgängliga modeller kan konstateras att ingen av dessa ger en bra återspegling av vattenåtgången vid verkliga bränder. Nästan alla modeller bygger på principen att det krävda vattenflödet är proportionellt mot brandens storlek. Det faktiska flödet som räddningstjänsten använder är snarare proportionellt mot roten ur brandytan, alltså proportionellt mot sidan på branden. De flesta modeller ger en rimlig uppskattning av vattenflödet i något storleksintervall, men ingen av dem ger rimliga vattenmängder för alla bränder från små till stora. Dessutom är det oklart vad modellerna bygger sina rekommendationer. Någon av dem är förmodligen baserad på samma brandkårsdata som här används för jämförelse. Värt att notera är också att här jämförs modeller med den vattenmängd som faktiskt används och inte den mängd som skulle behövas. För att kunna utveckla modellerna krävs att brandutredningarna utvecklas ytterligare till att omfatta även en beskrivning av branden (bränsletyp, mängd och placering) och släckinsatsen (vem gjorde vad, när, var och varför).

Uppsats IV

Den fjärde uppsatsen behandlar ytverkan vid brandsläckning. Genom att studera energibalansen vid bränsleytan, kan vattenbehovet för släckning uppskattas. Denna termiska släckteori brukar kallas *Fire Point Theory*, och validerades genom att jämföra teoretiskt beräknad lägsta vattenpåföring för släckning med det minsta flöde som uppmätts vid experiment i liten och medelstor skala. Detta flöde är ca 0.002 g/m²s, räknat per bränsleyta. Det minsta flödet för släckning är dock inte det som ger den minsta totala mängden vatten, och därmed det bästa resursutnyttjandet. Med hjälp av experiment kunde konstateras att det finns ett flöde som är högre än det minsta flödet för släckning som ger en minsta total volym vatten. Detta flöde ligger cirka tio gånger högre, 0.02 g/m²s. Om flödet ökas ytterligare, kommer totalmängden att börja stiga. Genom att använda statistiken från uppsats II kunde förhållandet mellan vattenmängd och vattenflöde studeras även för verkliga bränder. Det visade sig att förhållandet får samma principiella utseende. Det flöde som gav lägsta totalvolym är 0.2 g/m²s, det vill säga tio gånger högre. Skillnaden förklaras till åtminstone en faktor 2 av att flödet normerats mot golvytan snarare än bränsleytan. Räddningstjänstens optimala vattenflöde ligger alltså i storleksordningen 5 gånger högre än motsvarande flöden för experiment. Kontrolltiden vid experimenten, definierad som den tid vid vilken bränslets vikt börjar att öka, är kort vid den minsta totalvolymen, i storleksordningen 10 s. Vid de verkliga bränderna mättes släckningens varaktighet till 300 s vid den minsta totala vattenförbrukningen. De två olika tidsdefinitionerna orsakar åtminstone en faktor 5 av skillnaden. Dessutom hålls strålrören sällan öppna kontinuerligt vid de verkliga bränderna, vilket gör att den tid som verkligen använts för släckning i realiteten är en faktor 2-3 kortare än vid motsvarande experiment. Dessutom blir tiden kortare vid experiment där samma scenario upprepas, än vid verkliga bränder där varje scenario är unikt och okänt i förväg, vilket ger i storleksordningen en faktor 1.5 i skillnad. Under dessa förutsättningar förklaras hela skillnaden mellan experimenten och de verkliga bränderna. Vid det flöde som gav lägst totalvolym blev den totala mängden 0.2 l/m^2 vid experimenten och 60 l/m^2 vid de verkliga bränderna, en skillnad som förklaras av de tidigare beskrivna faktorerna. En annan, förmodligen viktig, faktor är att statistiken från de verkliga bränderna är bristfällig och bygger på subjektiva uppskattningar. Denna faktor kan förmodligen endast uppskattas om (några) brandbilar utrustas med vattenflödesmätare.

Uppsats V

Den näst sista uppsatsen redovisar en experimentell försöksserie i stor skala. Dels undersöktes behovet av släckvatten och dels studerades skillnaderna mellan släckning med lågtryckssystem och högtryckssystem. Dessutom studerades värmepåverkan på de rökdykare som genomförde släckinsatsen. Sex brandförsök genomfördes i en lokal som mäter $14.0 \cdot 7.7$ m^2. Branden utgjordes av sex staplar med lastpallar, 13 st i varje stapel. Bränslets vikt, temperaturen i rummet, tryck och strålning i rummet mättes. Två strålrör användes, med 7 bar respektive 25 bar i munstyckstryck samt 1.92, 3.83 och 4.75 l/s i flöde. Testen visade att möjligheten att nå det brinnande bränsleytorna är en avgörande faktor för hur väl släckinsatsen lyckas. Dessutom visade sig högtryckssystemet vara effektivare än lågtryckssystemet i det aktuella scenariot, med en vattenförbrukning som var ungefär två tredjedelar för samma släckeffekt. Puls och hudtemperatur samt viktförändring hos rökdykarna mättes också. Mentala faktorer och värmepåverkan visade sig ge en kraftig pulshöjning hos rökdykarna under försöken, trots att den fysiska arbetsintensiteten var låg.

Uppsats VI

Den sjätte och sista uppsatsen behandlar gasfasverkan vid brandsläckning. I uppsatsen konstateras att extern värmestrålning ökar den nödvändiga koncentrationen av släckmedel för att nå släckning. I uppsatsen beskrivs två försöksserier. Den första genomfördes i en cup burner monterad i en konkalorimeter. Gaserna Halon 1301, HFC-227ea, HFC blend A, CO_2 och N_2 användes för att släcka bränder i PMMA, heptan och metanol, med och utan extern värmestrålning. Den nödvändiga koncentrationen av släckmedel ökar kraftigt om den brinnande ytan utsätts för extern värmestrålning, vilket innebär att nuvarande principer för dimensionering av fasta släcksystem för rumsskydd kan ifrågasättas. Att utgå från inerteringsgränsen vid dimensionering ger alltså system med en bättre definierad prestanda än om dimensioneringen görs utifrån cup-burner-data med en säkerhetsmarginal. Dessutom blir dimensioneringen mindre beroende av vilken försöksutrustning som används. I en storskalig cup burner, 3.0 m i diameter och med en bränsleskål 0.150 m i diameter användes halon 1301, HFC-227ea och HFC blend A för att släcka bränder i heptan och metanol. När utrustningens skala ökades, ökade den nödvändiga koncentrationen av släckmedel för att nå släckning något.

Background

The scope of this thesis was to demonstrate the possibility of determining the demand for resources in advance for the manual suppression of room fires. This is important to facilitate the extinction of fires and the dimensioning of resources, i.e. to quantify the knowledge conveyed by Shakespeare [1]:

> "A little fire is quickly trodden out;
> Which, being suffered, rivers cannot quench."

At a SFPE workshop in February 2000 to develop a research agenda for the fire protection engineering profession, current knowledge in the subject was summarised. Regarding fire suppression, it was asserted that [2]:

> "In the area of fire suppression, there has been a fair amount of research into halon alternatives and water mist; however, a quantitative understanding of fire suppression is still lacking in most areas. The minimum water application rates for sprinkler systems, which are the most widely used suppression systems, to achieve fire suppression or control are unknown in all but a limited number of cases. Research is needed to better predict suppression system efficacy."

The above concerns primarily active fire suppression systems. A quantitative understanding of manual fire suppression is lacking to an even greater extent, although we have long had a qualitative understanding of how to suppress fires, as illustrated in Figure 1, first published in 1968 [3].

The work presented in this thesis concerns manual fire suppression of diffusion flames at normal gravity. The focus is on room fires, mainly in wood, but other fuels will be discussed briefly. Water is the primary extinguishing medium, but it is compared with other extinguishing media. Small-scale experiments are included, but the main effort has been devoted to fires of larger scale, i.e. the size of fires normally confronting fire brigades. I hope to bridge part of the gap between theory and small-scale testing on the one hand, and practice and large-scale tests on the other. The focus of the work is on the interaction between the extinguishing medium and the fire. This means that events taking place after the extinguishing agent leaves the nozzle of the fire-hose are considered. Events taking place before the medium leaves the nozzle, e.g. the problems of getting the nozzles to the right place at the right time, are matters of command, which is a management issue. This topic is indeed interesting, but beyond the scope of this thesis.

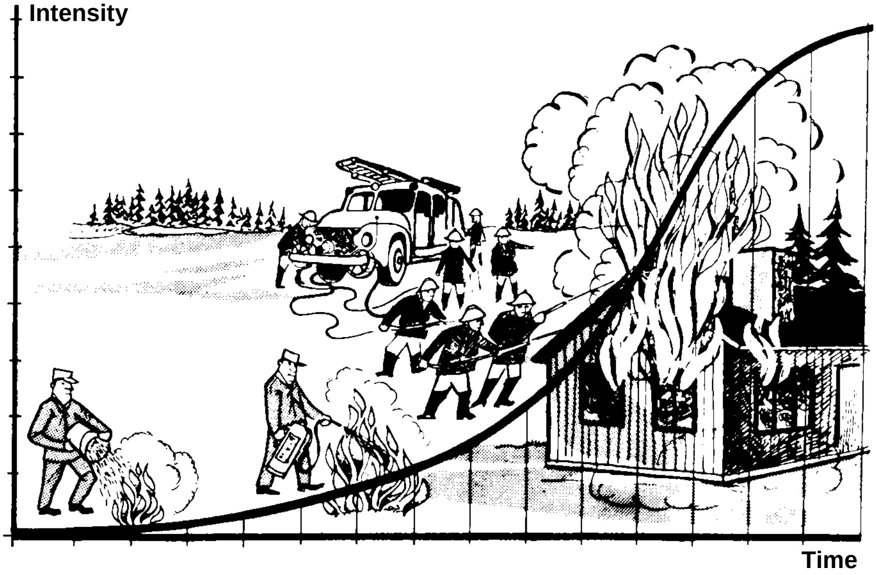

Figure 1. Qualitative knowledge regarding the relation between time and intensity of a fire and the corresponding fire-fighting operation. From [3], with permission.

Planning of fire-fighting operations
(Paper I)

At the end of the 19th century, when the first full-time fire brigades were founded in Sweden, they normally consisted of one shift. Firemen lived at the station and were on duty more or less day and night, all year around. At the end of the 20th century, with four shifts and regulated holidays, the time fire fighters are on duty has been reduced. The time available to keep up to date with all special hazards and new equipment has decreased over the years, due to larger response areas and shorter working hours.

Fire brigades rely on the use of water in fighting almost every fire. At the same time, water is a costly resource. In Sweden, the development during recent decades is toward smaller water mains [4]. The reason is that consumers are using less water, leading to smaller water flows in the mains. Smaller flows require smaller pipes, to maintain high water quality. Some fire brigades have solved this problem by using tank trucks to a greater extent. Thus, one cannot be sure of unlimited water supply and must plan for the best use of the extinguishing agent to obtain the highest extinction capacity.

There are two main elements in fire fighting strategy: *context* and *optimisation* [5]. The context includes knowledge of the situation and the possibility of the incident commander to gain an overview of the situation. Optimisation is concerned with the demand for resources made by the fire and the resources which can be provided by the fire brigade. Optimisation means aiming as high as the resources allow. Access to information on the object is perhaps one of the greatest problems when fighting fires. One study has shown that at major fires, the commanding officer did not know the extent of fire spread at critical points in time during the operation [6]. In some cases, the fire did spread, while in others the spread of the fire was halted due to compartmentalisation, but the interesting point is that the fire brigade was unaware of the degree of spread of the fire. One of the reasons why the fire brigade could not handle the fires studied appears to be difficulties in putting the fire into context, e.g. knowing the extent and spread of the fire in relation to the building layout, fire compartmentalisation and active systems.

One answer to the problem of keeping fire fighters updated with the right information about risk objects and problems involved in changes in resources is pre-fire planning based on risk analysis. The process of putting the fire into context is also facilitated by having a pre-fire plan.

This process of pre-fire planning is outlined in a licentiate dissertation [7] and condensed into Paper I, where it was shown to be possible to dimension resources for extinguishing fires in buildings. Using an event tree technique and fire safety engineering models, the size of fires at specific premises can be estimated and compared with the available fire brigade resources. The total damage caused by the fire and the methods that can be used to fight it can then be evaluated. (See figure 10 in Paper I.) The method is exemplified by an analysis of one large and one small chemical warehouse, located at different places, leading to the availability of different resources. It was shown to be possible to introduce risk management procedures and fire safety engineering models into fire fighting tactics.

The process of pre-fire planning consists of two parts. The first involves an estimation of the consequences of fire. The determination of the size of fire in terms of, for example, the rate of energy release or volume, is the foundation on which an evaluation of the damage can be based. The damage can be divided into injury to persons, and damage to property and the environment. An important aspect of this evaluation is to assess the development of fire, and the effects of active and passive fire protection systems. It is, for example, necessary to identify possible fire containment lines.

The second part is concerned with the evaluation of the capacity of the fire brigade, expressed in terms of extinction potential. If the fire-fighting operation is expressed in the same terms as the fire, the two may be compared. An extinction capacity greater than the demand made by the fire means that it is possible to launch an offensive operation. If, on the other hand, the demand made by the fire is greater than the extinction capacity, an offensive operation will not attain its aim, and a defensive approach is preferable, i.e. directing efforts towards containing the fire within its boundaries.

Whichever the choice of extinguishing agent, the method to analyse fire-fighting operations is similar regardless being used before the fire, in a pre-fire planning situation, during a fire to analyse the situation, or after a fire for evaluation purposes. Used for pre-fire planning, it is part of the risk management process. In this process, scenarios may be revealed in which intervention is insufficient to reduce the consequences below the accepted level. These cases should instead be managed by fire-prevention measures.

In making a risk analysis, plausible fire scenarios at different premises are identified. The outcome in terms of injury to people on and off site, and damage to property and the environment is evaluated. The resources available; i.e. the number of fire brigade units and the flow of water is known in advance of almost every case of fire. It is therefore possible to identify, by pre-fire planning, which fires can be extinguished with the resources available and which fires can not. This is, or at least ought to be, valuable information for the owner of the premises.

The first part of the process, evaluation of the development of the fire, is relatively straightforward. The field of engineering has grown in this area during recent decades and there are a number of textbooks dealing with this subject [8] [9]. Comprehensive handbooks are also available, for example [10].

Regarding the second part of the analysis, optimisation of the fire-fighting operation, the number of engineering models available is smaller. No handbooks are available and knowledge is more fragmented in research reports.

Dimensioning of manual fire fighting
(Papers I and V)

In the previously referred licentiate dissertation [7], an overview of methods of dimensioning, depending on the choice of extinguishing medium was presented. Note that dimensioning here refers primarily to the amount of extinguishing agent required. This, in turn, will give rise to a demand for resources in terms of equipment and personnel.

Low- and medium-expansion foam

The use of low- and medium-expansion foam is commonly associated with the extinction of fires in pools of flammable liquids. The dimensioning model is empirical, and is based on a two-dimensional approach. The surface area of the fire is estimated and multiplied by a flow rate obtained experimentally or from tables [11] [12]. The type of fuel affects the dimensioning, e.g. polar or non-polar. The type of foam concentrate, e.g. film forming or alcohol resistant, also has an effect on the dimensioning. The heat radiating from the fire breaks down the foam at a rate of about 0.01-0.03 m/min, depending on the type of foam and the radiation level [13]. There are recommendations for the required flow in l/m^2min considering the type of fuel, the type of foam concentrate and the foam number (the relation between expanded and non-expanded foam volume flow). If the desired flow rate per unit area is known, the total flow rate, i.e. the number of foam nozzles required can be calculated. With a given submerging time, increased with a sufficient safety margin in case of re-ignition, the total volume of water and foam concentrate can be estimated. In the case of large pool fires (above the order of 1000 m^2), the rate of foam spread over the fuel surface becomes important [14].

Medium-expansion foam is also used to fight fires in concealed spaces, e.g. attics, but there are no standards for dimensioning. When applicable, the same principles may be used as for high-expansion foam, i.e. to fill the space with foam before the fire has caused unacceptable damage. The main difference between high-expansion and medium-expansion foam is the foam number, which may be a factor of 10 lower for medium-expansion foam, requiring a flow of water and foam concentrate ten times higher than for high-expansion foam.

High-expansion foam

Empirical models are available for dimensioning of fire-fighting attacks using high-expansion foam. The main difference between these models and models for low- and medium-expansion foam is that when dealing with high-expansion foam, three dimensions are involved, rather than two. Instead of a pool surface area, the volume of the fire room or the volume necessary to cover the highest hazard is the dimensioning parameter. The foam discharge rate is then calculated based on a desired submerging time, e.g. 3-6 min depending on the scenario [15], or a desired height increase, e.g. 1 m/min [16]. High-expansion foam is sensitive to wind and is therefore best used indoors.

The discharge rate is compensated for foam shrinkage, normally about 0.1 m/min for filling rooms not affected by fire, and for foam leakage. The foam will shrink even more in some situations, e.g. in the presence of hot smoke or heat radiation. At 10 kW/m², foam breakdown is about 0.2 m/min and at 20 kW/m² it increases to about 0.4 m/min, depending on, for example, the type of foam concentrate, the expansion ratio and the source of heat affecting the foam layer [17]. As in the case of pool fires, there must be sufficient back-up resources to maintain the foam layer until extinction is assured.

Dry powder

Regarding the effectiveness of portable fire extinguishers, dry powder is the extinguishing agent with the highest extinction capacity. Dry powder is also available in large units. Dry powder is, however, not a single substance. Mixtures of, for example, $NH_4H_2PO_4$, $(NH_4)_2SO_4$, KCl, $KHCO_3$, and $NaHCO_3$ are used, all of them having different extinction efficiencies. The size of the powder grains affects the efficiency; small powder grains having a higher extinction capacity than larger grains [18]. There is also a difference in the degree of protection against re-ignition, depending on the type of powder.

Unlike foam, which interacts with the fire at the fuel surface, dry powder extinguishes flames in the gas phase. Therefore, dimensioning is more complex. An experimentally determined measure of the effectiveness of dry powder is given by the REMP value, the relation between the mass flow of extinguishing medium and the mass flow of fuel gases at extinction [19]. The lower the REMP value, the more efficient the dry powder. For pool fires, the REMP value is commonly of the order of 1.0 to 1.5, depending on the type of powder. If the mass loss rate of fuel is known, it is possible to estimate the required flow rate of dry powder. One problem in using this approach is that the application efficiency must be estimated. When applying dry powder to a fire, a large proportion of the powder does not participate in extinction. Also, dry powder has the disadvantage of giving poor protection against re-ignition. This means that powder can be used to suppress a fire using its superior extinguishing potential, but should be followed by an attack using water or foam to ensure extinction.

Gaseous extinguishing media

As with dry powder, gaseous extinguishing medium is not a single substance, but rather a number of different gases or gas mixtures [20] [10, Ch. 4.6, 4.7]. Many gases are used in permanent extinguishing systems (both local and total flooding) but only a limited number are used in manual fire fighting. Carbon dioxide (CO_2) is common in fire extinguishers and halon 1211 was common before it was banned for environmental reasons. Fire brigades do not often use gaseous extinguishing agents. When they do, it is for special applications, for example, smouldering fires in silos, where no other extinguishing agent has proved efficient.

By using the REMP value in a similar way as for dry powder, dimensioning of the extinction of ventilated fires using gaseous agents is possible. The REMP value is about 10 times higher for most gases than for dry powders. Estimations of the demand for fighting fires in enclosures are possible using the concentration of extinguishing agent necessary to extinguish diffusion flames or premixed flames. This is the same concept as that used when designing a permanent total flooding system. For diffusion flames, the required concentration of extinguishing agent increases with the level of external heat radiation and with the size of the fire, which was demonstrated in Paper VI. A system using gaseous extinguishing medium designed to extinguish a fire in its early stage therefore requires a lower concentration than a manually operated system facing a fire that has developed to give re-radiation from flames and smoke, which is not uncommon when fire brigades are involved in fire fighting.

Water

A survey of existing empirical models for determining the need of water for manual fire fighting was made in Paper III. The differences between the models and the coarseness of their predictions unfortunately mean that any reasonably experienced fire fighter could give a better prediction. In spite of water being the agent most commonly used to fight fires, surprisingly little information is available on the dimensioning of fire fighting using water. One approach is to use the energy released by the fire and the energy required to evaporate water, to calculate the required water flow for extinction [7]. This method has been adopted in a broader concept by the Australian authorities [21].

There are also a small number of theoretical models. The Fire Demand Model, FDM, is based on conservation of energy, mass and momentum in a control volume, the fire room [22]. For some applications it gives a water demand of the right order of magnitude. The model was, however, developed for the situation of a ventilation-controlled fire in one room, with manually applied water sprays through openings, which limits the range of application of the model. In the FDM, defining a mean surface temperature and a mean gas temperature at extinction sets the extinction criterion.

SPLASH models the interaction between sprinkler sprays and the buoyant smoke layer of a fire [23]. This situation is quite different from that encountered in manual fire fighting primarily because the application of water is downwards through the smoke, rather than sideways, and also because the spray is continuous and fixed in space rather than being controlled and moved around by a fire fighter.

Concerning more fundamental models, CFD (Computational Fluid Dynamics) has not yet reached far enough to be able to predict the process of extinction, although attempts have been made, for example, by using a concept of superdrops [24]. This study, however, also concerns sprinkler spray.

This means that there is a lack of quantified and scientifically evaluated models for estimating the demand for resources during manual fire suppression in buildings using water. In fact, knowledge is even lacking regarding the mechanisms behind water as an extinguishing agent. Work was therefore initiated to provide the necessary understanding to develop such models.

Statistically based dimensioning of fire fighting (Papers II and III)

The first step is to ascertain whether current statistical information can be used to determine the demand for extinguishing media. In Paper II, an investigation was presented of fire data collected by fire investigators of the London Fire Brigade. The first observation is that information is mostly available concerning fires fought with water, although this is not always explicitly stated. Other extinguishing agents do not occur often in the statistics, which sets a limit on the statistical approach to dimensioning.

In most cases, the fire-fighting operation did not actually determine the final spread of the fire. The evidence supporting this statement is that no statistically significant correlation was found between the fire area and the time to fire brigade intervention for fires in general. Most fires had already been contained upon the arrival of the fire brigade. The reason for this can be explained as follows. Many small fires are ignited and spread fairly rapidly over the object first ignited. Thereafter, it takes some time for the fire to spread to the next object, or the fire may not spread. If, for example, a waste-paper basket is burning in the corner of a room with non-combustible linings on the walls behind and in the ceiling above, it is of minor importance from a fire spread point of view, if the delay before fire brigade intervention is five or fifteen minutes. Smoke production may cause other damage not included in this study, e.g. injury to people. In another case, there may be combustible lining materials close to the waste-paper basket, leading to a rapid spread of fire. In this case there will be no significant difference whether five or fifteen minutes elapsed before fire brigade intervention, as the fire will already have spread and possibly reached flashover anyway. Only for fires still spreading upon the arrival of the fire brigade will the fire area be correlated with the time to fire brigade intervention. The description of what is actually burning is important and is commonly poorly described in fire brigade statistics.

Real fires may very well lead to flashover, but there are also phases of more or less steady state between the flame spread phases. These phases may be, for example, from the time the first object is involved to the spread to the second object, from fire in single objects to a flashover fire, from fire in one room to the spread of fire to the second room, and so on. This spreading of fire is normally not presented in fire investigations.

In a survey of 1541 Swedish industrial fires [25], using fire brigade data [26], information is available on the involvement in the fire at fire brigade arrival and at fire extinction. This is shown in Figure 2. Fires extinguished upon arrival and fires only producing smoke (39% of all fires) are not included in the material.

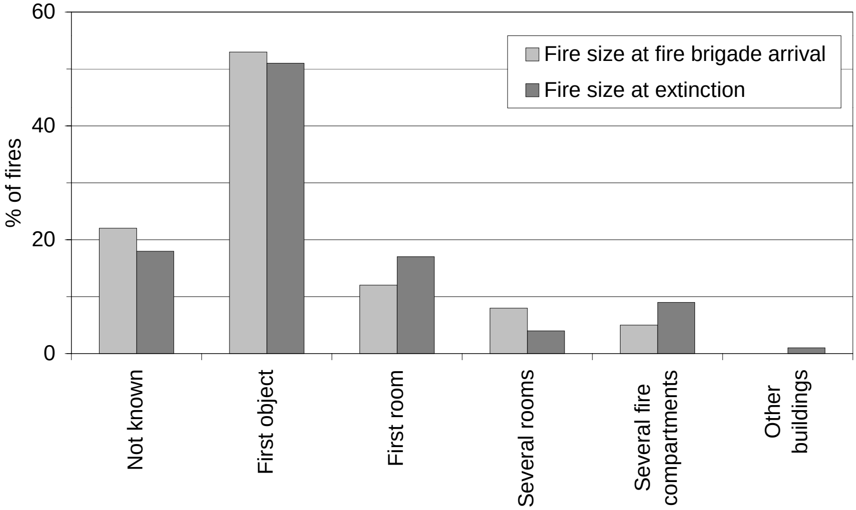

Figure 2. Fire spread at fire brigade arrival and at extinction according to Swedish statistics [25].

The figure illustrates two things, both in accordance with the English data presented in Paper II. First, the majority of fires remain small, actually contained within the first object ignited. Secondly, most fire spread has occurred before the arrival of the fire brigade, which means that most fires are self-contained.

In Paper III, the water required to extinguish fires was compared for actual fires, experiments and dimensioning models. It was concluded that there is a large variation in the water flow rates, regarding both flow rates actually used, and those suggested by dimensioning models. Interestingly, the study revealed that fire tests simulating manual suppression were comparable to real fires in terms of water demand. The use of water is roughly proportional to the square root of the fire area, a relation that was consistent with previous studies.

The interpretation of statistical data is largely dependent on the definition of variables, e.g. the size of the fire. An estimate of the rate of heat release is, in most cases, not possible for real fires. Usually, not even the fuel surface area is known. Some statistics are based on a measure of the horizontal fire area, but the majority of investigations, e.g. [25], give a qualitative rather than a quantitative measure.

One reason for the large variation in flow rates stems from the definition of fire area. See Figure 3. In most statistics and dimensioning models, the fire is expressed in terms of floor area or horizontal fire area. This means that a pile of wooden pallets would require the same amount of extinguishing agent regardless of height, which is of course not correct. In Paper IV, the difference between the fuel area and the floor area was found to be at least a factor of 2 for office buildings. At a lumberyard the difference is much higher.

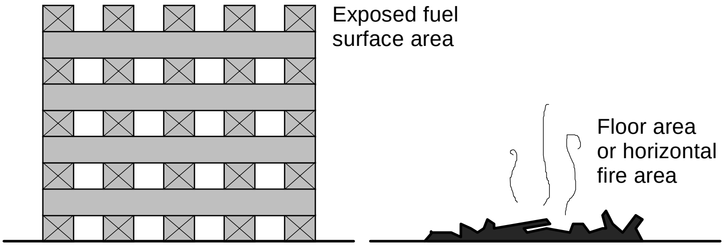

Figure 3. How should the fire area be defined, and how should the fuel be described to make best use of statistics?

The control time or the extinguishing duration is another parameter that must be well defined in order to be able to interpret the data. In Paper IV, it is described why there is a difference of at least a factor of 5 between the control time defined as the time when the fuel starts to gain weight, and the extinguishing duration defined as the time when the fire fighter ceases to apply water to the fire. A fire fighter is not satisfied by controlling the fire, he wants to extinguish it.

Another factor not taken into account in most statistics is the relation between the control time and the flow rate, as shown in Figure 3 in Paper IV. A higher flow rate normally leads to the fire being controlled in a shorter time. Comparing the total mass of water with the flow rate gives the shape of a fishhook. There is an optimum flow rate above and below which the total mass of water increases.

Statistics have the potential to reveal general trends. It is, however, not possible to use statistics in their present form to dimension specific fire-fighting operations. There are some major reasons for this:

- The amount and distribution of fuel, which is not sufficiently described in fire brigade investigations, govern the fire spread and the energy release of the fire.
- There is little information about who is actually doing what at fire scenes and the extinction time is generally obscured by other events.
- There is a large spread in fire brigade statistics, depending on reasons not fully known or investigated.
- Status quo is encouraged when statistics are used, rather than development and improvement.

It should be stressed that this does not mean that statistics are useless. Fire statistics are of great importance in determining, for example, failure frequencies of fire safety systems or in determining ignition sources. Also, in Paper IV, statistics were used to validate extinction theory. If specific types of fires are to be investigated, it is also important to get an overview to identify fires of interest.

Extinction mechanisms
(Paper IV)

Most aspects of extinction can be explained using thermal extinction theory. For example, the extinction of a diffusion flame above a (solid) fuel surface can be explained by using the energy balance at the fuel surface. In Paper IV, this thermal extinction theory is explained and exemplified.

Normally, the energy from a flame re-radiated and convected to a fuel surface is balanced by the evaporation of fuel and heat losses from the surface, as shown in Figure 4. By adding water to the burning fuel surface, the mass loss rate of the volatile fuel decreases below the level required to sustain combustion. The droplet size should be greater than 0.5 mm in this situation, otherwise the droplets may evaporate in the smoke before reaching the fuel surface.

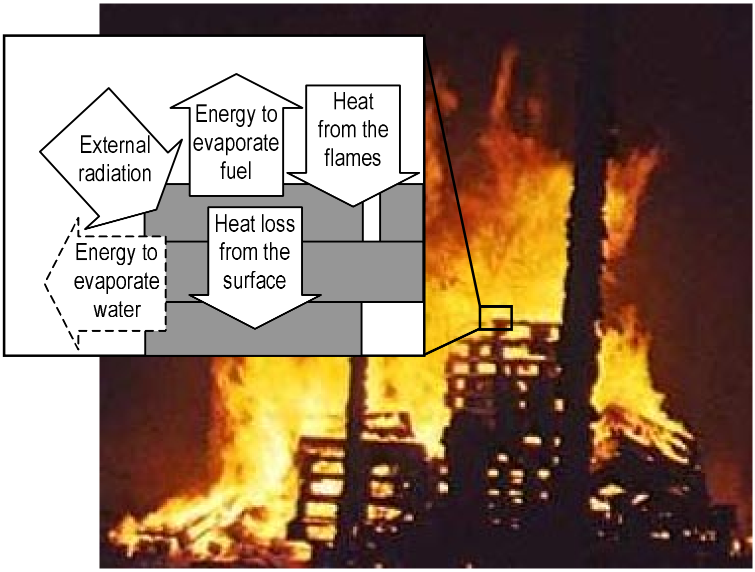

Figure 4. The energy balance at the fuel surface can explain extinction.

The evaporated water also decreases the oxygen content of the gas mixture, thereby changing the combustion limits. In Paper IV, it was shown that the oxygen mass concentration at the extinction limit was reduced from 21% to about 16%, assuming total water evaporation and combustion under stoichiometric conditions. Surface cooling being the dominating extinction effect is the reason behind the well-known instruction on almost every fire extinguisher: *Aim nozzle at base of flames*, or in Swedish: *Rikta strålen mot lågornas bas*.

The consequences of the thermal extinction theory are, for example, that the fuel loss rate, the oxygen concentration and the flame temperature reach a limit at extinction. Concerning wood, the mass loss rate decreases to a level of about 0.0055 kg/m²s at extinction [27] [10, Ch. 3-4]. The oxygen volume concentration falls and at the same time, the adiabatic flame temperature decreases below about 1600 K [8] [28].

This explains to the fire triangle, sometimes used to elucidate the process of extinction. According to the fire triangle, fuel, oxygen and heat are needed to maintain the fire and extinction is achieved by removing one of them. This does not give the whole perspective of extinction, as the required fuel, oxygen and heat is a reflection of other, governing properties. The relation between the velocity of gases, i.e. the mechanical time scale, and the speed of chemical reactions, i.e. the chemical time scale, explains extinction better. At low Froude numbers, the buoyancy or the gravitation primarily governs the velocity of the gases. The concentrations of fuel and oxygen and the presence of thermal ballast or chemical inhibitors, govern the speed of the chemical reaction. A sustained chain reaction is sometimes added to the fire triangle making it into a fire tetrahedron. But, in the end, when the time required for the chemical reactions exceeds the time taken to replenish the reactants, the flame will be extinguished.

Water as extinguishing agent (Papers IV and V)

In previous chapters, and in Paper III, no regard was taken of how the water was applied. In Paper IV, on the other hand, it was assumed that the water hit the fuel surface. To be able to successfully determine the water demand, one must make clear which effect is desired.

Water can be used as an extinguishing agent in many situations, both offensively and defensively, as described in the first part of Paper IV and shown in Figure 5. It can be used directed onto the flames, the hot gases produced, the heated surfaces of the room, the fuel surface or the fuel not yet involved in the fire. The water may be applied in one of these five ways, giving different effects on the fire itself and on the possibility to approach the fire. In some of these cases, the conditions for fire fighters in the room worsen, while in others the conditions improve. What is most effective against the fire is not necessarily best for the fire fighters.

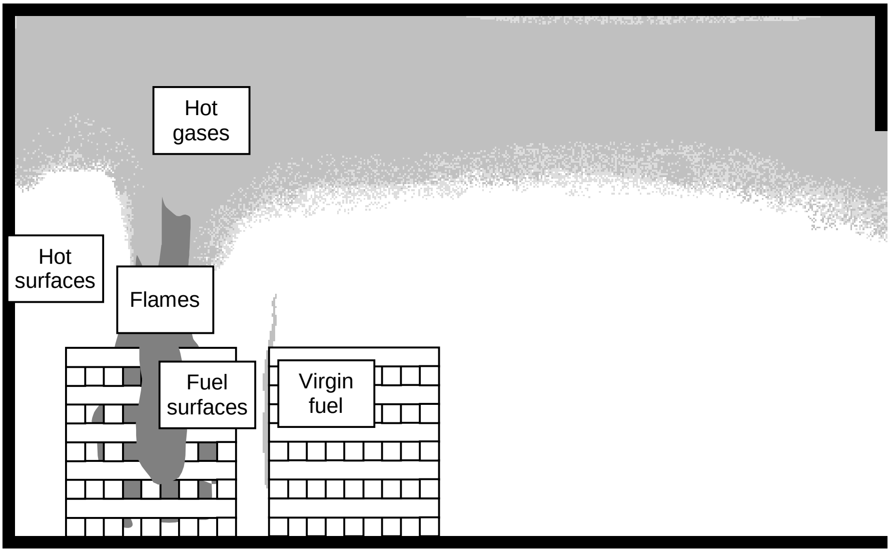

Figure 5. Water can be applied at different places in a room on fire with different effects, depending on the purpose and the options.

Cooling of the flames below the adiabatic flame temperature is the main aim when applying water droplets to flames. Applying the water droplets in the hot smoke does not primarily lead to an interaction with the solid fuel. It may, however, be necessary to cool the smoke to enable the fire fighters to enter the room. If the smoke reaches a temperature and a concentration of combustible gases high enough to ignite when mixed with air, it is also appropriate to apply water droplets to the smoke to lower the temperature and to increase its content of water vapour. The water will act like an inert gas.

Cooling of the fuel, thus preventing fuel gasification and thereby quenching the flame, is the main effect when water is applied to the fuel surface. Charred material is porous and will therefore easily absorb water. The flow rate of water necessary to extinguish a fire when applied in this way was evaluated in Paper IV.

Applying water to fuel surfaces not yet involved in the fire is, in contrary to other measures discussed here, a defensive, rather than an offensive way of using water. It requires a lower flow rate per unit surface area but on the other hand, the water must be applied for a longer period. By preventing other fuels from becoming involved, the fire will eventually run out of fuel.

Finally, by applying the water to hot surfaces, steam will be generated which may under very specific conditions inert the room. Unfortunately, the Leidenfrost effect means that this method of applying water has quite a low efficiency. Leidenfrost discovered and described how water drops on a horizontal metal surface at hundreds of degrees Celsius may survive for several seconds without evaporating, due to the build-up of an insulating layer of water vapour between the drop and the hot metal [29]. The conductivity of the vapour then governs the evaporation rate.

As mentioned above, all these effects are linked together. Water evaporated at a fuel surface can, for example, make the smoke inert. There are also other effects, for example, the stirring of fire gases due to the water flow and to steam generation.

A serious problem during fire fighting in general seems to be the distribution of water. In some cases problems are related to finding the seat of the fire and applying a nozzle, after which the fire can be put out with relative ease.

The distribution of water is a also a question of delivering the required water density at a given distance between the nozzle and the fuel surface, a distribution that may be restricted in various ways. There may be physical obstacles, or the distance of travel through hot smoke may be so long that the droplets evaporate before reaching the target. In Paper V it was concluded that a row of pallets, as shown in Figure 6, is a sufficient obstacle to prevent the water spray from the nozzle from penetrating to the row behind. High levels of radiation, particular hazards or physical barriers can also stop the fire fighters from approaching the fire, leading to a long distance between the nozzle and the fuel surface. These are some of the main reasons why fighting fires in warehouses using water may be compared with trying to put out a fire in a charcoal stack.

Figure 6. Fuel arrangement in the tests described in Paper V. The front row of pallets was sufficient to prevent water from reaching the row of pallets behind.

The amount of water actually reaching the fuel surface governs the extinguishing effect. As shown in Paper IV, there is a correlation between the control time and the water flow rate per unit of the area fuel. There is also a correlation between the total water demand and the flow rate.

Gas phase extinction
(Paper VI)

The thermal extinction theory is valid not only for fuel surface cooling effects, but also for gas phase extinction. In a fire in a room equipped with a total flooding system employing a gaseous extinguishing agent, almost no extinguishing medium reaches the fuel surface. Instead, altering the concentrations of air, fuel vapour and extinguishing medium to the non-flammable region quenches the flame.

Normally, total flooding systems using a gaseous extinguishing agent are dimensioned using concentrations obtained using a cup burner, in combination with a safety factor. In Paper VI, it was shown experimentally that the safety factor obtained is affected by the external heat flux. This is also predicted by the thermal extinction theory. In addition, the safety factor is affected by the size of fire. The increased demand for extinguishing medium when fighting fires affected by external heat radiation is the main reason for the topic being discussed here, in spite of the low frequency of fire-fighting operations using gaseous extinguishing media.

Most gaseous extinguishing agents are inert and chemically stable in flames. However, some of the possible candidates for replacing halons decompose and actually participate in combustion. This can be seen from measurements of the heat release rate, but can also be observed visually. Figure 8 shows tests using methanol and Figure 9 show tests where heptane was burned and where gaseous extinguishing agents were used.

The first photograph in each sequence shows the fuel burning, well ventilated, in pure air. Photographs 2 and 3 show the flame when HFC blend A is added at 80% of the extinction concentration and near extinction. Photographs 4 and 5 show the corresponding case for HFC-227ea. Note, however, that the test using methanol and HFC-227ea ran out of extinguishing medium before extinction. The maximum concentration reached was 8.4%.

No ext. agent	*HFC blend A at 80% of ext. conc.*	*HFC blend A near extinction*	*HFC-227ea at 80% of max. conc.*	*HFC-227ea at max. conc.*

Figure 7. Methanol flames affected by gaseous extinguishing agents. The fuel cup diameter was 0.150 m.

No ext. agent	*HFC blend A at 80% of ext. conc.*	*HFC blend A near extinction*	*HFC-227ea at 80% of ext. conc.*	*HFC-227ea near extinction*

Figure 8. Heptane flames affected by gaseous extinguishing agents. The scale is the same as in the methanol tests above. Photographs 4 and 5 have a slightly different colour due to the settings of the camera.

Conclusions

Through fire pre-planning, the size of possible fires can be estimated in terms of, for example, burning fuel area or heat release rate. It is important to observe that the time-scale of the fire is, to a large extent, determined by the rate of fire spread. Thereafter, an evaluation of the means of suppression can be made in each case. During this process, different fire scenarios are identified which put different demands on the fire brigade, in terms of material resources and in terms of strategy and planning. Scenarios are identified in advance in which the fire brigade will not be able to extinguish the fire in an offensive way, and the owner of the premises should be made aware of this. This process is one way of ensuring that an officer in command understands the context of the fire and can optimise the fire-fighting operation.

Extinction can be largely explained by thermal extinction theory. It is clear that the dominating effect in the suppression of fires using manually applied water sprays, is that of cooling the fuel surface, thereby stopping the mass loss of fuel. Gas-phase extinction does not dominate, except with water mist systems, but cooling and thus contracting the smoke is, in some cases, necessary to enable the fire fighters to approach the fire. It has been shown that one reason, presumably the main one, for extinction not to occur is an uneven distribution of extinguishing medium. Even if all fuel surfaces are not exposed to the cooling effects of the extinguishing medium, it is likely that the fire fighters will prevent the fire from spreading. Steady state may remain until the fire runs out of fuel, or the fire fighters reposition.

The use of water in fire-fighting operations is not adequately described using the present method of collecting statistics. Water flow meters on fire engines will give a much better estimate of the water consumption during extinction of a fire than any subjective judgement of the fire officer. Also, to make the data of greater use, information regarding the type, amount and layout of the fuel can be included.

Thermal extinction theory is a good start towards the understanding of extinction, but there is a need for a deeper theory and also for it to be applied. The computer program *Fire Demand Model* gives a fairly good representation of the effects of water application. It is, however, limited to a one-zone, ventilation-controlled scenario with external fire fighting. The development of CFD based on fundamental physics and chemistry has not yet produced models suitable for manual fire suppression. Besides, none of the models mentioned here deals with the problems concerning the application of suppressants, an area that requires further attention.

Above all, the need is great need for a textbook in the area of fire suppression, as the existing knowledge is fragmented and not easily accessible. By collecting information on different methods of fighting fires and their pros and cons, demands and limitations, comparisons between them will be simplified and the likelihood of fire fighters choosing the optimum method for each specific fire will increase. Training is important, because it is unlikely that the models for estimating the demand for water will be as simple as those for high-expansion foam.

In this work, and indeed in most work carried out on manual fire suppression, the human factor is left out, to a large extent. The suppression capability of fire fighters is likely to depend on their physical fitness, their skill and training. This is a virgin research area and as knowledge accumulates on the more technical aspects of fire suppression, a demand for research on the human aspects will almost certainly arise.

References

1. Shakespeare, W., *King Henry VI*, part 3, act 4, scene 8, first published in 1594.
2. *A Research Agenda for Fire Protection Engineering*, The Society of Fire Protection Engineers, Feb, 2000.
3. *Handbrandsläckare 1986*, SBF Brandförsvarsföreningen, 1986 (in Swedish).
4. *Vatten till brandsläckning, Anordnande av allmänna vattenledningsnät med hänsyn till släckvattenförsörjning och vattenomsättning,* Svenska Vatten- och Avloppsföreningen, Publikation VAV P76, ISSN 0347-1799, 1997 (in Swedish).
5. Svensson, S., *Räddningstaktiska grunder, Förslag till definitioner och kommentarer därtill*, Räddningsverket, P21-291/99, 1999 (in Swedish).
6. Särdqvist, S., *Djupanalys av tre storbränder*, Dept. of Fire Safety Engineering, Lund University, Report 3096, 1998 (in Swedish).
7. Särdqvist, S., *An Engineering Approach to Fire Fighting Tactics*, Dept. of Fire Safety Engineering, Lund University, Report 1014 (Licentiate Dissertation), 1996.
8. Drysdale, D. D., *An Introduction to Fire Dynamics, Second edition,* Wileys, 1999.
9. Karlsson, B., Quintiere, J. G., *Enclosure Fire Dynamics*, CRC press, 1999.
10. ed. DiNenno, P. J., *SFPE Handbook of Fire Protection Engineering*, National Fire Protection Association, 1995.
11. Persson, H., *Basutrustning för skumsläckning - Försöksresultat och rekommendationer som underlag för dimensionering och utförande*, Swedish National Research and Testing Institute, SP rapport 1990:36, Borås, 1990 (in Swedish).
12. NFPA 11, *Low-Expansion Foam*, 1994 ed. National Fire Protection Association, USA, 1994.

13. Persson, H., *Fire Extinguishing Foams Resistance Against Heat Radiation*, Proceedings, First International Conference on Fire Suppression Research, eds. Sjölin, V. et al., Swedish Fire Research Board and National Institute of Standards and Technology, 1992, pp 359-376.

14. Persson, B., Dahlberg, M., *A Simple Model for Predicting Foam Spread Over Liquids,* Fire Safety Science, Proceedings of the Fourth International Symposium, ed. Kashiwagi, T., International Association for Fire Safety Science, 1994, pp 265-276.

15. NFPA 11A, *Medium and High-Expansion Foam Systems,* 1994 ed. National Fire Protection Association, USA, 1994.

16. Rosander, M., Giselsson, K., *Skumboken*, Statens räddningsverk, U14-392/93, Karlstad, 1993 (in Swedish).

17. Holmstedt, G., Persson, H., *Lättskum - förmåga att motstå värmestrålning,* Statens Provningsanstalt Brandteknik, Teknisk rapport SP-rapp 1985:27, ISSN 0280-2503, Borås, 1985 (in Swedish).

18. Holmstedt, G. S., Persson, H., Säwenmark, G., *Släckning av gasdiffusionsflammor med pulver och haloner vid olika Froudes tal,* Statens Provningsanstalt, Brandteknik, SP-rapp 1986:24, 1986 (in Swedish).

19. Persson, H., *A Method for Quantitative Measurements of the Extinguishing Capability of Powders,* Proceedings, First International Conference on Fire Suppression Research, eds. Sjölin, V. et al., Swedish Fire Research Board and National Institute of Standards and Technology, 1992, pp 377-391.

20. Isaksson, S., Simonson, M., Holmstedt, G., *Gasformiga alternativ till halon som släckmedel*, Sveriges Provnings- och Forskningsinstitut, SP rapport 1997:10, 1997 (in Swedish).

21. *Fire Brigade Intervention Model, pre publication draft ver 1.0,* Australasian Fire Authorities Council.

22. Piertzak, L. M., Dale, J. J., *User's Guide for the Fire Demand Model; A Physically Based Computer Simulation of the Suppression of Post-Flashover Compartment Fires,* National Institute of Standards and Technology, NIST-GCR-92-612, 1992.

23. Williams, C., Harisson, R., Holborn, P., *Sprinkler Spray Interaction Studies*, Interflam '99, Proceedings of Eighth International Conference, Vol. 1, Interscience communications ltd. 1999, pp 81-92.

24. Kumar, S., Heywood, G. M., Liew, S. K., *Superdrop Modelling of a Sprinkler Spray in a Two-phase CFD-particle Tracking Model*, Fire Safety Science, Proceedings of the Fifth International Symposium, ed. Hasemi, Y., International Association for Fire Safety Science, 1997, pp 889-900.
25. Statistical database of Swedish Rescue Services Agency, Karlstad, 1998.
26. Johansson, H., *Brandfrekvenser och typbränder i industri-anläggningar*, Dept. of Fire Safety Engineering, Lund University, Report 3100, 1998 (in Swedish), table 3-5 and 3.6, p.29.
27. Delichatsios, M. A, Delichatsios, M. M, *Critical Mass Pyrolysis Rate for Extinction of Fires over Solid Materials*, Fire Safety Science, Proceedings of the Fifth International Symposium, ed. Hasemi, Y., International Association for Fire Safety Science, 1997, pp 153-164.
28. Ewing, C. T., Beyler, C. L., Carhart, H. W., *Extinguishment of Class B Flames by Thermal Mechanisms; Principles Underlying a Comprehensive Theory; Prediction of Flame Extinguishing Effectiveness*, J. of Fire Protection Engineering, 6 (1), 1994, pp 22-54.
29. di Marzo, M., Trehan, A. K., *Transient Cooling of A Hot Surface By Droplets Evaporation*, U.S. Department of Commerce, National Bureau of Standards, NBS-GCR-86-516, 1986.

Paper I:

Särdqvist, Stefan; *An Engineering Approach to Fire Fighting Tactics*, Proceedings, The Second International Conference on Fire Research and Engineering, Society of Fire Protection Engineers, Bethesda, MD, USA, 1998, pp 351-361.

Notes:

In 1996, after the printing of this paper, reference 2 was given the report number 1014.

A poster with a content similar to this paper has also been presented:

Särdqvist, S., *An Engineering Approach to Fire Fighting Tactics*, Fire Safety Science - Proceedings of the Fifth International Symposium, ed. Hasemi, Y., International Association for Fire Safety Science, 1997, p. 1337.

Paper II:

Särdqvist, Stefan & Holmstedt, Göran; *Correlation Between Firefighting Operation and Fire Area: Analysis of Statistics*, Fire Technology, Volume 36, Number 2, 2000, in press.

Paper III:

Särdqvist, Stefan; *Fire Brigade Use of Water*, Interflam, '99, Proceedings of the Eighth International Conference, Vol. 1, Interscience Communications Ltd. 1999, pp 675-683.

Paper IV:

Särdqvist, Stefan & Holmstedt, Göran; *Water for Manual Fire Suppression*, submitted to the Journal of Fire Protection Engineering, 2000.

Paper V:

Särdqvist, Stefan & Svensson, Stefan; *Fire Tests in a Large Hall, Using Manually Applied High- and Low-pressure Water Sprays*, submitted to Fire Science and Technology, 2000.

Paper V

Paper VI:

Särdqvist, Stefan; Andersson, Magnus; Dagneryd, Anders; Skogetun, Pontus & Holmstedt, Göran; *Cup Burner Tests Under the Influence of External Heat Radiation on Normal and Large Scales*, submitted to Fire Technology, 2000.

LUND UNIVERSITY

Report TVBB-1021
ISSN 1102-8246
ISRN LUTVDG/TVBB--1021--SE

KFS AB, Lund 2000