LUND UNIVERSITY • SWEDEN
INSTITUTE OF TECHNOLOGY
DEPARTMENT OF FIRE SAFETY ENGINEERING
REPORT LUTVDG/TVBB-1025-SE

The Operational Problem of Fire Control

Stefan Svensson

Lund 2002

The Operational Problem Of Fire Control

Stefan Svensson

The Operational Problem of Fire Control

Stefan Svensson

Report 1025

ISSN: 14002-3504

ISRN: LUTVDG/TVBB—1025—SE

Number of pages: 231

Cover photos by Peter Lundgren, Swedish Rescue Services Agency. Top left: fire attack training in a fire simulator. Top right: kitchen in a burn building. Bottom: commanding officer in front of a burn building.

Figure 1 originally by Roy Bäckbom.

Figures 2 – 5 originally by Per Hardestam.

Keywords: firefighting, procedure, operation, tactics, control

Abstract

The operational core of firefighting operations was examined. The effects of various firefighting procedures on the fire ground, their impact upon conditions on the fire ground in which decisions by commanding officers are made and the effects of allocating resources in time and space on the fire ground were explored. In addition, various approaches for modelling firefighting operations were discussed. The purpose of the underlying work includes gaining knowledge on how firefighting operations are built-up and how the initiation, execution and coordination of procedures affect the course of events at the scene of a fire. The work was mainly based on experiments with fires in small apartments and with fires in large halls where fire spread is restricted. The firefighting procedures used in the experimental work were restricted to fire suppression and fire ventilation. The main contributions to the development of theory on fire and rescue operations were to bring about a better understanding of the inherent dynamics of firefighting operations, and an approach to modelling of firefighting operations based on the analysis of data from experiments on tactical patterns, was suggested. Suggestions for continued work included investigations of the effects of procedures used by the fire and rescue service, and investigating effects of various tactical patterns. In addition, emphasis should be put on modelling of firefighting operations.

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

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

Preface

When I started this work in 1994, my intention was to find methodology in how fire protection design and fire safety measures in buildings can be used as tactical assets during firefighting operations.

As the work proceeded, I soon identified a lack of fundamental knowledge on how firefighting operations actually work and how the dynamics of firefighting operations affect the course of events. Questions arose, such as

- Why is a specific task chosen during a firefighting operation?
- What happens when this task is executed?
- What would have happened if some other task were to be executed?
- What would have happened if the task were to be executed at some other point in time or space?

Also, what is the crux of the matter,

- What is it that we are trying to achieve by sending firefighters and commanding officers to the scene of a fire and into buildings on fire, and how do we achieve this?

To get answers to such questions, I had to look further into what firefighting operations are, what they are affected by, what triggers different tasks and actions, and especially at how actions taken, allocated in time and space, affect the development of the accident.

What I found was thrilling and I believe it opened up a new, but simple, perspective on firefighting operations. I also believe that I have found a way to further advance our view on the work performed by firefighters and commanding officers at the scene of a fire. In other words: now I understand the dynamics of firefighting operations better.

When I started writing this thesis, a colleague and a fellow hunter said to me that he believed that a thesis should be a pleasant journey to the reader in the understanding of my world.

This is it – so far!

Table of contents

List of papers

This thesis is based on six papers, published, accepted for publication or submitted for publication in international journals or presented at international symposiums. These papers are appended to the thesis, and they are listed below together with other publications related to this work but not included in the thesis.

Papers included in the thesis

<u>Paper I</u>

Live fire tests on suppression of post-flashover fires using manually applied high and low pressure water sprays

Stefan Svensson and Sören Lundström

Paper presented at Interflam'99, 8th International Fire Science & Engineering Conference, Edinburgh, 29th June – 1st July 1999.

<u>Paper II</u>

Fire tests in a large hall, using manually applied high- and low pressure water sprays

Stefan Svensson and Stefan Särdqvist

Fire Science and Technology, vol. 21, No. 1, 2001.

<u>Paper III</u>

Developing a command structure within the fire services – from enlistment to a viable system

Stefan Svensson

Jennings, Charles (Ed.). Improving Firefighter Safety: Human Behavior and Organizational Aspects. An International Conference. Alexandria Virginia: Institution of Fire Engineers, United States Branch. 2001.

<u>Paper IV</u>

Experimental study of fire ventilation actions during firefighting operations

Stefan Svensson

Fire Technology, vol. 37, No. 1, 2001.

Paper V

Experimental study of fire ventilation procedures in a large hall

Stefan Svensson and Per Werling

Paper presented at Interflam'01, 9th International Fire Science & Engineering Conference, Edinburgh, 17th – 19th September 2001.

Paper VI

A Study of Tactical Patterns During Firefighting Operations

Stefan Svensson

Fire Safety Journal. Vol. 37, no. 7, pp 673 – 695, 2002.

Other related publications not included in the thesis

Svensson, S. A concept for tactical analysis of firefighting operations. In Proceedings: *3rd International Conference on Emergency Planning and Disaster Management*, Lancaster, UK, 2nd – 6th July 1995.

Svensson, S. *Brandförsök med sprängram samt övertrycksventilation (Live fire tests using explosive cutting frame and positive pressure ventilation, in Swedish)* (rapport R53-132/96). Räddningsverket. 1996.

Svensson, S. *Brandförebyggande åtgärder som taktisk resurs vid räddningsinsatser (Fire protection measures as tactical resource during firefighting operations, in Swedish)* (rapport R53-134/96). Räddningsverket. 1996.

Svensson, S. *Försök med brandgasventilation i en liten lägenhet (Live fire tests with fire and smoke ventilation in a small flat, in Swedish)* (rapport R53-159/96). Räddningsverket. 1996.

Svensson, S. *Taktisk utformning av räddningsinsatser – en simuleringsmodell (Tactical outlining of firefighting operations – a simulation model, in Swedish)* (rapport R53-161/96). Räddningsverket. 1996.

Lundström, S. & Svensson, S. *Försök med högtrycksbrandsläckning (Firefighting using high-pressure water flows, in Swedish)* (rapport P21-196/97). Räddningsverket. 1997.

Svensson, S. Simulation of firefighting operations. Poster presented at: *2nd International Conference on Fire Research and Engineering*, 3rd – 8th August 1997, Gaithersburg, Maryland USA

Svensson, S. *Solving tactical problems using control engineering: systems identification and modeling* (report 1017), Lund University: Department of Fire Safety Science. 1998.

Svensson, S. Numerical modeling of suppression of post-flashover fires. Poster presented at: *6th International Symposium on Fire Safety Science (IAFSS'99)*, 5th – 7th July 1999, Poitier, France

Svensson, S. *Räddningstaktiska grunder, förslag till definitioner och kommentarer därtill (Basic tactical principles – proposals for definitions and comments to them, in Swedish)* (rapport P21-291/99). Räddningsverket. 1999.

Svensson, S. Fire service actions as part of the fire safety design. In Proceedings: *3rd International Conference on Performance-Based Codes and Fire Safety Design Methods*, Lund, Sweden, 15th – 17th June, 2000.

Lundström, S., Svensson, S. & Särdqvist, S. *Släckförsök vid brand i stor lokal (Experiments on fire suppression in a large hall, in Swedish)* (rapport P21-328/00). Räddningsverket. 2000.

Svensson, S. *Att fatta etiska beslut under stress (Ethics in decision making under stress, in Swedish)*, Kungliga Krigsvetenskapsakademiens Handlingar och Tidskrift, nr 5/2000.

Svensson, S. *Brandgasventilation (Fire ventilation, in Swedish)* (U30-602/00). Räddningsverket. 2000.

Davidsson, Å. & Svensson, S. *Modell för bedömning av riskavstånd vid olyckor med giftiga eller brännbara ämnen (Model for estimating safety distances when responding to accidental release of toxic or flammable substances, In Swedish)* (rapport P21-396/01). Räddningsverket. 2001.

Kylefors, M. & Svensson, S. *Insatsplanering – att planera för insats baserat på riskanalys och räddningstaktik (Planning of firefighting operations based on risk analysis and firefighting tactics, in Swedish)*. In press.

Svensson, S. *Responding to Malfunctions of the Complex World*. Submitted to Cognition, Technology & Work. 2002.

Svensson, S. A Shift in Focus. In Proceedings: *International Conference on Fire Service Deployment: Meeting the Standards of Cover Performance Criteria*, Indianapolis, Indiana, USA, 12th – 13th April, 2002.

Summary

This thesis examines the operational core of firefighting operations. It explores the effects of various firefighting procedures on a fireground, their impact upon conditions on the fireground in which decisions by commanding officers are made, and the effects of allocating resources in time and space on the fireground. It draws conclusions upon the operational problem of fire control.

The main contributions by this thesis to the development of theory on fire and rescue operations are that it brings a better understanding of the inherent dynamics of firefighting operations, and that it suggests an approach to modelling of firefighting operations based on the analysis of empirical data.

The purpose of the work underlying this thesis includes gaining knowledge on how firefighting operations are built-up and how the initiation, execution and coordination of procedures affects the course of events at a fire scene. The thesis is mainly based on experiments. The theoretical work and the design of experiments evolved through observations, during participation, in fire and rescue work as well as in the training of fire and rescue personnel. Conclusions in the thesis are restricted, by assumptions in the experimental work upon which the thesis is based: to fires in small apartments and to fires in large halls where fire spread is restricted, such as in mechanical workshops. In addition, the firefighting procedures used in the experimental work were restricted to fire suppression and fire ventilation.

A procedure is the smallest unit of which a larger entirety consists. An in-depth knowledge of how various procedures affect the course of events on the fireground, serves as a basis for any fire and rescue operation. When one or several procedures are initiated, coordinated and executed, an operation is created. Then, an operation is a comprehensive concept for the activity of coordinating a number of procedures, performed by a commander, in some cases with an organized staff or by several command levels. The procedures form the inherent dynamics of the operation, and it is within this dynamic context that tactics are created.

Tactics are about describing the dynamics of the process instead of the structure of the process. The initiation, coordination and execution of procedures, combined into an operation, are key elements in tactics. On

this matter, tactical patterns are defined as combinations of procedures, varying in time and space. In addition, basic tactical principals were defined, based on experiments. Also, for the operation to be efficient, there is a need for a comprehensive objective, represented by control.

Control is the overall, comprehensive objective of a fire and rescue operation. It is only through control that the course of events on the fireground can be directed in an intended direction, and it is through the initiation, coordination and execution of procedures that control is obtained and maintained.

A perspective on the response of the fire and rescue service to emergencies is represented by the succession; procedure – (tactical patterns) – operations – control. Procedures are the smallest parts in an operation, the means by which to achieve something. Operations are the entirety, consisting of procedures arranged in tactical patterns. Tactics are the glue that keeps the operation together. Control is the objective of the operation, i.e. what we are trying to achieve by initiating an operation. Incidentally, command may be considered as the tool for managing the operation. Through this perspective, there is a connection between procedures, operations, tactics, control, and command.

The inherent dynamics of fire and rescue operations may be very complex, also for operations restricted in time and space. In order to further advance the knowledge of this inherent dynamic, it is desirable to develop mathematical models of fire and rescue operations. It is suggested that modelling of firefighting operations should be based on the analysis of empirical data, as opposed to physical modelling. The objective of such modelling should, amongst others, be to try out various tactical patterns, to develop tools for the pre-planning of firefighting operations and to develop simulators for firefighting operations. In addition, understanding the dynamics of fire and rescue operations, together with stringent perspectives on and models for such operations, is crucial to post-analysis and evaluation of fire and rescue operations.

The results in the thesis serve, a great deal, as a basis for continued work. Through the presented perspective on procedures, tactical patterns, operations and control, it should be possible to further advance knowledge on fire and rescue operations.

Suggestions for continued work include investigating the effects of individual procedures used by the fire and rescue service as well as investigating the effects of various tactical patterns. Experimental works as well as the further advancement of theoretical conceptions are important in this effort. Based on existing experimental data as well as experimental data to come, emphasis should be put on development of models. Continued experimental as well as theoretical and modelling work should include emergencies such as fires in various geometries, fires of various sizes, accidents in transportation systems and accidents involving chemical substances.

Also, based on the findings in this thesis, efforts in finding methodology in how fire protections design and fire safety measures in buildings can be used as tactical assets during firefighting operations, should be made.

In addition, a command and control structure for the fire and rescue service should be developed. Such a command and control structure should include aspects on the management of organisations and on leadership.

Sammanfattning (Summary in Swedish)

Denna avhandling undersöker den operativa kärnan i räddningsinsatser. Vidare undersöker den effekten av olika åtgärder som används vid räddningsinsatser mot brand i byggnad, effekten av sådana åtgärder till följd av beslut som fattas av befäl samt effekten av att allokera resurser i tiden och rummet vid en räddningsinsats mot brand i byggnad. Avhandlingen drar slutsatser kring operativ problematik där kontroll är ett centralt begrepp.

Avhandlingens huvudsakliga bidrag är att den bygger upp en bättre kunskap kring räddningsinsatsers inneboende dynamik samt att den föreslår en ansats till modellering av räddningsinsatser baserat på analyser av empiriska data, till skillnad från att fysikaliskt försöka modellera räddningsinsatser.

Det bakomliggande syftet med arbetet omfattar att bygga upp kunskaper kring hur räddningsinsatser byggs upp och fungerar samt hur initiering, utförande och koordinering av åtgärder påverkar händelseutvecklingen på en skadeplats. Avhandlingen är huvudsakligen baserad på experiment. Genom deltagande observation vid räddningsinsatser såväl som vid utbildning och övning av räddningspersonal, har teoretisk bakgrund och experiment grundlagts och utvecklats. Slutsatser i avhandlingen är avgränsade till de antaganden som gjorts i genomförda experiment: till bränder i mindre lägenheter samt i stora lokaler där brandspridning normalt är begränsad, som till exempel i mekaniska verkstäder. Dessutom är de åtgärder som undersökts genom experiment varit avgränsade till brandsläckning och brandgasventilation.

I denna avhandling är räddningstjänstens åtgärder de minsta delarna som skapar en större helhet, en räddningsinsats. En ingående kunskap om hur olika åtgärder påverkar händelseutvecklingen är basen för räddningsinsatsers genomförande. När en eller flera åtgärder initieras, utförs och koordineras, skapas en insats. En insats är således ett begrepp som omfattar aktiviteten att koordinera ett antal åtgärder, under ledning av ett befäl, i vissa fall tillsammans med en stab eller flera befälsnivåer. Åtgärderna skapar en inneboende dynamik i insatser, och det är denna dynamik som benämns taktik.

Taktik handlar om att beskriva dynamiken i processen och inte strukturen i processen. Initieringen, koordinering och utförandet av åtgärder, kombinerade till en insats, är de grundläggande elementen i

taktiken. Taktiska mönster definieras som kombinationer av åtgärder, varierade i tiden och rummet. Genom experiment drogs slutsatser om vissa grundläggande taktiska principer. För att insatsen ska vara effektiv måste det dessutom finnas ett övergripande mål med insatsen, där kontroll är ett centralt begrepp.

Kontroll är det övergripande målet för insatser. Det är endast genom kontroll som händelseutvecklingen på en skadeplats kan styras i avsedd riktning, och det är genom initiering, utförande och koordinering av åtgärder som kontroll erhålls och bibehålls.

Genom detta resonemang presenteras ett synsätt på räddningsinsatser som kan representeras med följden: åtgärder - (taktiska mönster) - insats - kontroll. I detta perspektiv kan åtgärder betraktas som de minsta delarna. Insatsen är helheten, bestående av åtgärder arrangerade i taktiska mönster. Taktiken är "limmet" som håller samman delarna till en helhet (åtgärderna i en insats). Kontroll är det övergripande målet med insatser, det som insatspersonalen (representerat av ett eller flera befäl) avser att åstadkomma. Följaktligen kan ledning betraktas som ett verktyg för att hantera insatsen. Det finns således ett tydligt samband mellan åtgärder, insats, taktik, kontroll och ledning.

Den inneboende dynamiken i räddningsinsatser kan vara mycket komplex, även för insatser som är begränsade i tiden och rummet. För att bygga upp ytterligare kunskaper kring insatsers dynamik, är det önskvärt att utveckla matematiska modeller för räddningsinsatser. Sådana modeller bör baseras på analyser av data från experiment, till motsats från fysikalisk modellering, och basen för ett sådant modellarbete presenteras. Syftet med ett sådant modellarbete är bland annat att undersöka olika taktiska mönster, att utveckla verktyg för planeringen av räddningsinsatser genomförande samt att utveckla simulatorer för utbildning och övning. Dessutom är kunskaper om insatsers dynamik tillsammans med ett stringent synsätt på räddningsinsatser och modeller av insatser nödvändiga för att kunna analysera och utvärdera genomförda räddningsinsatser.

Resultaten i avhandlingen är viktiga för fortsatt arbete. Genom det presenterade synsättet på åtgärder, taktiska mönster, insatser och kontroll, bör det vara möjligt att ytterligare utveckla kunskaper kring räddningsinsatser.

Förslag till fortsatt arbete omfattar att undersöka effekten av olika åtgärder som används vid räddningsinsatser samt att undersöka effekten av olika taktiska mönster. Fortsatta experiment samt fortsatt utveckling av den teoretiska basen kring räddningsinsatser är viktigt i detta arbete. Baserat på analyser av data från såväl genomförda experiment som ytterligare experiment bör ansträngningar läggas på att utveckla modeller över räddningsinsatser. Fortsatt arbete bör omfatta, förutom bränder med olika förutsättningar, även olyckor i transportsystem och kemikalieolyckor.

Baserat på avhandlingens slutsatser bör också fortsatta ansträngningar göras för att finna metoder och modeller för hur byggnadstekniskt brandskydd kan användas som resurser i samband med räddningsinsatser.

Dessutom bör ett övergripande system, omfattande taktik, ledning och ledarskap, skapas för svensk räddningstjänst.

Introduction

The primary objective of the fire and rescue service is to save and protect people in the event of emergencies. In addition, the saving of property and environment are important in the work performed by the fire and rescue service. In recent years, environmental aspects of procedures used by the fire and rescue service have gained an increasing interest. Although the types of emergencies have increased and changed in accordance with the development of technology within society, fires are still a major cause of turnouts. During the period 1990 – 2000, approximately 40% of all turnouts in Sweden were related to fires (Räddningsverket, 2001a). Also, the number of fire deaths has been relatively constant for the last ten years, around 100 deaths per year, and the majority of fires are small at the point when the fire and rescue service arrives on scene. However, major fires still occur and the number of fatalities may in some cases significantly exceed any reasonable predictions (e.g. Statens Haverikommission, 1998).

Focus should of course be on fire prevention. Nevertheless, many fires are hard to prevent, and it is important that conditions under which the fire and rescue service manage fires are explored. Conditions for using available resources in the best possible way must be given, and due to the never-ending development of technology within society, understanding of the impact of the fire and rescue service to emergencies must be constantly improved.

This thesis is a study of the response of the fire and rescue service to buildings on fire, based on experiments. The theoretical work and the design of experiments evolved through observations, during participation, of fire and rescue work as well as in the training of fire and rescue personnel. In addition, the writing of this thesis is a result of an increased understanding of firefighter operations, as the experimental work advanced. Conclusions in the thesis are mainly but not exclusively based on analysis of experimental data. Also, conclusions are restricted, by assumptions in the experimental work upon which the thesis is based: to fires in small apartments and to fires in large halls where fire spread is restricted, such as in mechanical workshops. The work is based on Swedish conditions.

The experimental fires represent a large portion of the total number of real fires in Sweden. Statistics show that more than 50 % of all fires in buildings are in residential buildings and that 60 % of those can be related to a single burning item at time of arrival of the fire and rescue service (Räddningsverket, 2001a). Also, more than 60 % of fires in industrial facilities can be related to single objects (machinery, refuse, etc).

The firefighting procedures used in the experimental work were restricted to fire suppression and fire ventilation. Other procedures, well known by the firefighting community, are of course at hand in a real situation, procedures such as forcible entry, search and rescue, and overhaul. Although considered during this work, the use of such procedures was excluded from the experiments, mainly due to practical problems of considering them in the experimental set-up and experimental procedure. An important aspect that has been excluded from the experimental work is life saving, i.e. physically removing victims from a hostile environment. However, the saving of life is the primary task of any firefighting crew and is especially pointed out in the legislation (1986:1102, 1986:1107).

Table 1. Main differences between military and firefighting operations.

Military operations		**Firefighting operations**
Characterized by the use of force or by threats of force	↔	Physiological and psychological threats to personnel as well as to third parties, but no inflicted violence
Dynamics in the situation are mainly controlled by humans (by two opposing forces)	↔	Dynamics of the fire are controlled by physical aspects such as type of fuel, the geometry of the building, properties of materials, etc.
Two opposing forces, consisting of humans, and usually with similar objectives	↔	A "single-sided" operation, where people interfere with a physical/chemical process

A general assumption in the work is that characteristics of firefighting operations are similar to those of military operations, with the exception of the objective for the operation and for the settings of the operation, as exemplified in table 1. These differences are mainly based on the definition of war, as postulated by Clausewitz (1968),

"*…war therefore is an act of violence intended to compel our opponent to fulfil our will.*"

In the military scenario, the opponent will not necessarily respond in a predictable manner to actions and procedures taken. Physical processes on the other hand, such as a fire, do not have any inherent intention. Also, physical laws govern physical processes and predictions can be made based on such laws.

Similarities between firefighting operations and military operations are assumed in a number of studies. Artman (1999) uses empirical material from a full-scale simulated military command and control unit, an authentic emergency co-ordination centre and computer-aided microworlds. The purpose was, amongst others, to get a broad basis for examining control in dynamic situations. From the material, he examines a perspective of distributed cognition and he draws conclusions on co-ordination of resources and on situation awareness. In addition, Worm (1998) describes a mission efficiency analysis technique and concludes that further development and refinement of the technique could be of vital importance in several areas. Besides military applications such areas include emergency response training and development of future non-military tactical units, procedures, and systems.

On the problem of decision-making, Brehmer (2000) makes a clear connection between military command and control situations and those situations dealt with by the fire service. Command and control is strongly linked to decision-making, which is further treated in this thesis.

Command work has been described as pragmatic and opportunistic (Persson, 2000). In the absence of war, armies have had to build their command practices on a theoretical conception of war and battle management rather than on first-hand experience. To the fire service, conditions are quite the opposite. Theoretical conceptions are regarded as unnecessary due to the numerous opportunities for command practice – fires are fought each and every day. The problem is well known within the firefighting community, and Paul (1994) describes it as that fire has scientific properties, but firefighters do not always have the time or the group coordination to be scientific. This thesis can be viewed as an attempt to change this state.

In addition, there is a historical perspective on similarities between firefighting and military operations. The organising of the original fire brigades, in the 19^{th} century, was done in military fashion, and commanding officers were enlisted from amongst military officers. Unfortunately, these arrangements still have an impact on the Swedish fire and rescue service, especially on problems related to fire inspection and administrative tasks. Operational abilities have been, and are still, recognized before administrative abilities (Räddningsverket, 1992a).

As complexity in society grows and with a changing structure in the fire and rescue service, its recruiting and training of personnel, and of course with a perpetual changing technological structure, there is a growing need for a scientific approach to the problems faced by the fire and rescue service at the scenes of fires.

This thesis examines the operational core of firefighting operations. It explores the effects of various firefighting procedures on a fireground, their impact upon conditions on the fireground in which decisions by commanding officers are made, and the effects of allocating resources in time and space on the fireground. It draws conclusions upon the operational problem of fire control. The purpose of the work underlying this thesis includes gaining knowledge on how firefighting operations are built-up and how the initiation, execution and coordination of procedures affects the course of events at the scene of a fire.

The thesis is divided in sections (dealing with background, procedures, operations, tactics, and control) in which the experimental work is illustrated and reviewed. At the end of the thesis, the collected works are discussed, conclusions are made and the general outline of and suggestions for future work are laid down.

Background

It is well known within the firefighting community that experience is the foundation for all activity in the fire and rescue service. Resistance to change is tough, and the introduction of new technology as well as new theories is a laborious and time-consuming process. However, as society changes, the need for changes within the fire and rescue service becomes imminent. Accidents that occur in new as well as in the existing infrastructure must be met with knowledge and efficiency.

As was indicated in the previous section, a variety of procedures, methods and resources are available to and used by the fire and rescue service. Such procedures, methods, and resources include: fire suppression – using pumps, hoses and nozzles; fire ventilation – using fans and power saws; forcible entry – using crowbars and axes; search and rescue – using flashlights, infrared cameras, and ropes; and overhaul – using dehumidifiers and priming pumps. However, this thesis and the experiments related to it, is restricted to the use of fire suppression and fire ventilation.

The reasons for this restriction are twofold. Firstly, statistics indicate that Swedish fire and rescue brigades are small (Räddningsverket, 2001a). Consequently, the numbers of procedures that can be initiated, executed and coordinated simultaneously are restricted. A recently initiated research project, aimed at obtaining a scientific basis of the physical demands on firefighters, identifies nine standard operations (Räddningsverket, 2001b). Four of these standard operations include interior fire attack, and one includes fire ventilation procedures. The other four include forest firefighting, stretcher carrying, marine rescue, and extricating victims after car accidents. In addition, experience tells us that fire suppression and fire ventilation form the basis of all firefighting operations when responding to fires in buildings. Fire suppression and fire ventilation have been subjected to research and the theoretical background is known, although the applicability of this theoretical background to real firefighting problems is restricted. This is further dealt with below.

Secondly, using only two procedures makes the experimental set-up easily manageable. The addition of procedures will entail an exponential increase in the number of possible combinations. Two different procedures give five possible combinations. Adding another procedure give another twenty possible combinations. Such combinations are exemplified in table 2. In addition, by varying the time between initiations of procedures an infinite number of combinations can be created.

Table 2. Possible sequences of procedures.

Available procedures	**A**	**B**	
Possible combinations	*only* **A**	*first* **A** *then* **B**	**A** *and* **B**
	only **B**	*first* **B** *then* **A**	

The saving of life from fires is often connected to the physical removal of victims from a hostile environment. Although the physical removal of victims was excluded in the experimental work, it is assumed that fire suppression and fire ventilation have a large impact on the saving of life as well as on the prevention of damage to property and the environment.

Suppression

Firefighting using manually applied water sprays is generally considered to be the basic concept of the fire service. Problems encountered during firefighting include minimizing water application rates to minimize secondary damage, speeding up the firefighters work when stretching hoses or when attaching the pump to a fire hydrant. In addition, it includes the actual firefighting, i.e. the use of various types of nozzles to get the water onto the fire, and the effects of such nozzles.

A large number of fire suppression tests have been reported in the literature. Examples of such tests can be found in Dunn (1998), Milke et.al. (1988), Rimen (1990) and Stroup et.al. (1991). However, fire suppression tests reported do not, in general, deal with manual fire suppression but rather suppression by sprinkler systems.

Extensive work has been done in order to theoretically solve the problem of suppression of post-flashover compartment fires using manually applied water sprays. In firefighting, the surface cooling effect of water sprays is commonly used, and when needed the cooling of hot smoke is carried out to make it possible for the firefighters to approach the fire. The Fire Point Theory, suggested by Rasbach (1976) and developed by Beyler (1992), predicts the critical water flow rate for extinction.

According to this theory, the burning rate of a solid fuel can be described by an energy balance at the fuel surface. The extinction condition is defined by the conditions under which the gaseous flame above the surface can no longer be sustained. According to Delichatsios et.al. (1997), the dynamics of the gaseous reactions can be separated from the energy balance in the solid material. The extinction condition is then determined by the critical mass pyrolysis rate below which the flame no longer can be sustained. This theory has been validated for the extinction of fires using manually applied sprays, by Särdqvist et.al. (2001), who report that the critical flow rate does not give the best use of resources, as it requires a more or less infinite time. By increasing the flow rate above the critical value causes a decrease in the total mass of water required to control the fire. There is an optimum flow giving the smallest total water mass. Above this flow, the total mass of water increases again. In addition, Särdqvist reports that the minimum water application rate for extinguishing based on experiments on wooden fuels is 0.02 kg/m^2s, and that firefighters, during the extinguishing of real fires use 0.2 kg/m^2s, based on statistics.

The spray generates a decrease in rate of heat release due to the evaporation of droplets moving through a hot gas. According to Andersson et.al. (1996), evaporation depends to a great deal on the diameter, temperature, and transport properties of the droplet. In addition, McCaffrey (1983) reports that the effect of flame temperature reduction due to water sprays correlates with a single spray parameter, the median drop diameter. Also, the drop size has an impact on the velocity of the drops and consequently their ability to penetrate the fire plume, which was reported by Bishop et.al. (1997). Large drops penetrate the fire plume easier than smaller drops. In addition, smaller drops have a larger surface area in relation to their volume and so heat up and evaporate faster, consequently absorbing more heat. When the water spray passes through the hot gases, heat transfers to the droplets, which then starts to evaporate. Heat is transferred to small droplets ($D < 1$ mm) mainly through natural convection. Larger droplets ($D \geq 0.5$ mm) are mainly affected by forced convection due to the vertical velocity induced by their weight. Small droplets will evaporate very quickly and will mainly have a gas phase effect on suppression. Large droplets will not entirely evaporate when passing through flames and hot gases, unless the flames are very deep, which is not usually the case in apartment fires. Instead, these droplets will largely pass through the flames and hit the burning material, causing a decrease in pyrolysis.

The droplets from a nozzle cover a wide range of sizes and velocities, which means that the Reynolds number will vary throughout the spray. According to Gardiner (1988), the Reynolds number of a droplet defines the following conditions:

- The physical behaviour of the fluid within a drop.
- The heat and mass transfer between a drop and hot gas.
- The drag force and trajectory of a droplet.

In manually applied water sprays the Reynolds number is very large, much larger than the boundary for turbulent conditions ($Re > 2100$). The water spray breaks up, representing a variety of velocities and sizes.

When the water spray hits the burning surface, it absorbs heat by heating and by evaporation. The maximum rate of heat absorption can be determined by using water application rate (i.e. the water that hits the wall), heat of evaporation, heat capacity and temperature of the water at initial and final state. However, the heat transfer between the burning surface and the individual droplets also determines the rate of heat absorption, described by Holmstedt (1998). Velocity of individual droplets, their diameter and the temperature of the wall in turn determine heat transfer. On this matter, Webers number (We) can be used for describing relations at the collision. Webers number describes the relation between inertial force and surface tension force. For $We > 80$ it can be shown through tests that droplets that hits polished surfaces breaks up into smaller droplets. Film forming also has a large impact on heat transfer. When the droplet hits the surface, it spreads out to a uniform film. It then contracts due to surface tension. The longer the droplet stays on the surface, the larger the heat transfer. This infers that the evaporation of the droplet at the surface is mainly determined by surface temperature. At large surface temperatures (approximately > 400°C) the evaporation starts under the centre of the droplet and spreads rapidly as the droplet forms a film on the hot surface. This makes the droplet “isolated” from the hot surface by steam. Heat transfer from the surface to the droplet is small and the droplet “lives” a long time. At lower temperatures (~ 300°C), most of the droplet stays in contact with the surface for a longer time. The cooling is here larger than for surfaces with temperatures over 400°C. At even lower surface temperatures (approximately <200°C), the droplet stays in contact with the hot surface until it has completely evaporated.

Manually applied water sprays have two extinction effects that can be identified and observed visually through experiments:

- They generate a decrease in the rate of pyrolysis mainly induced by a decrease in radiation from flames and hot gases back, i.e. they reduce the externally applied heat flux.
- They penetrate through the flames, hit the burning surface and cause a decrease in the rate of pyrolysis, induced by a cooling of the surface, i.e. they increase the rate of heat loss from the surface.

Practical consequences of this are that it is very hard to reach a high degree of evaporation (and consequently suppression) when applying water on surfaces, especially when using manually applied water sprays. The purpose of the jet or the spray is, amongst others, in addition to the strictly practical reasons to increase the surface of the extinguishing media. According to Svensson et.al. (1999) (paper I), extinguishing mechanisms, how water is applied to fires, and how the jet or the spray affects the fire can be summarized as:

- The momentum in the spray is transferred to a stream of air, which increases turbulence and stirring. This will usually increase the rate of heat release in the initial stage.
- The effect of the spray on the gases generates a decrease in the rate of heat release and radiation from the flames.
- The jet or the spray penetrates through the flames, hits the burning surface and causes a decrease in the rate of pyrolysis.

All of these effects can be observed during real firefighting, although they are very hard to physically model. In addition, adding human aspects of fighting fires, variations in application rates, water spray cone angles and drop diameters (depending on e.g. settings and wear of the nozzle), the situation becomes very complex.

Ventilation

An important type of procedure used by the fire and rescue service is fire ventilation, including the opening or closing of doors and windows, the making of holes in roofs and the use of fans. Changing the ventilation conditions of a fire changes the flow pattern of hot gases inside the building and channels them out of the building. The purpose of using fire ventilation procedures is to facilitate access to fires and searching for trapped victims.

During the last decade, systems for venting of smoke and hot gases, so called smoke management systems, have been in focus for research and development. The theoretical background for the venting of smoke and hot gases out of rooms and buildings on fire is well known and established in textbooks. Generally, the flow of smoke and hot gases occurs from a place of high pressure to a place of lower pressure. In a building on fire, the flow of smoke and hot gases is driven by the pressure difference between the enclosure containing the fire and its surroundings. Karlsson et.al. (1999), split the driving pressure differences into two categories. The generated pressure differences are similar in both categories, but they apply to different time scales. In the first category the pressure differences are caused by normal conditions. This includes pressure differences due to density (temperature), differences inside and outside of the building, pressure differences caused by atmospheric conditions, and pressure differences due to ventilating systems (for comfort). In the second category the pressure differences are caused by the fire. This includes pressure differences caused by thermal expansion, and pressure differences due to buoyancy caused by density differences between the hot and cold gases.

However, theoretical conceptions of fire ventilation procedures from a firefighting point of view are less described in the literature. And existing descriptions are in many cases from a pragmatic point of view. Hay (1994) investigates ventilation of heat and smoke from buildings with the focus on the application of tactical ventilation prior to control and extinction of the fire. Conclusions are that the theory on the venting of hot gases from a stratified smoke layer is generally well established but the theory of cross ventilation and forced ventilation, such as during fire and rescue operations where considerable mixing is likely to occur, is not well understood. In addition, in terms of time required for venting there is a considerable difference between using roof vents (shutters) and cutting holes in roofs to form vents. Cutting a hole in a roof requires a lot more time and physical work than do shutters. Nevertheless, the subsequent flow of hot gases and smoke is similar in both cases.

In recent years, there has been a growing interest in positive pressure ventilation. This is a procedure used to allow for the fast removal of smoke and hot gases from buildings, and implemented in training by, for example, IFSTA (1992), Home Office (1997), and Svensson (2000a). The flow from fans used in this type of procedure is generally in the range of 2 – 15 m^3/s, and the chances of a successful operation are good when combined with a fast interior fire attack. Experiments reported by

Ziesler et.al. (1994), Rimen (1996) and by Svensson (2001) (paper IV), show that positive pressure ventilation rapidly reduces temperatures for firefighters and victims and improves air quality and visibility within the premises that are on fire.

The use of positive pressure ventilation is not a ready-made solution or a generally safe solution for manually fighting fires in buildings. Based on experiments, Svensson (2001) (paper IV) discusses problems encountered when using positive pressure ventilation. Due to the large flow of air, which pushes heat and smoke through the compartment on fire, a rapid spread of the fire may occur. The flow may also increase risks for the firefighters as well as for possible victims trapped in adjacent rooms. Nevertheless, if the effects of different fire ventilation procedures, including positive pressure ventilation, are thoroughly investigated, after the results of such investigations are implemented, and after training for firefighters, then the chances of success are still good.

A simplified model for estimating pressure, flow rate and time to evacuate smoke in a room with one supply opening and one exhaust opening and by the use of positive pressure ventilation has been suggested by Ingason et.al. (1998). The model assumes no influence on pressure and flow from the fire. Still, it indicates that the effectiveness of using positive pressure ventilation can be estimated using simple physical relations.

The main criticism of positive pressure ventilation brought up by fire and rescue personnel in Sweden is that using a fan blowing fresh air into the fire will make the fire increase and spread throughout the building. However, firefighters gaining access to a fire, e.g. by opening a door or a window, will change the ventilation conditions of the fire anyway. Using a fan will bring a degree of control to this change in the ventilation condition. In addition, in a real fire situation the effects of wind should also be taken into consideration. As reported by Svensson et.al. (2001) (paper IV), there is a possibility of static wind pressure dominating the pressure generated by a fan. This problem may be substantial, especially if the wind is directed towards an opening where smoke is intended to flow out (e.g. by use of positive pressure ventilation). The choice of positioning of outlets in relation to the wind is crucial to the successful use of fans during firefighting operations.

Human factors

An important aspect regarding procedures used by the fire and rescue service is that they include human activity. This human activity includes cognitive activity as well as physical work. Cognition is further treated in the section on operations, in terms of decision-making and command functions. However, it should be noted that decision-making and cognitive activity are not exclusive to the command functions during a firefighting operation. The activity performed by firefighters in the execution of procedures, in many cases puts severe tests to the cognitive abilities of firefighters. Nevertheless, physical work during firefighting operations will be briefly treated here.

It is well known that firefighting activities involve hard physical work. Davis et al. (1986) report that the workload during firefighting is very high, especially when using breathing apparatus. Based on investigations among Swedish firefighters, Kilbom (1980) suggests that firefighters over the age of 50 should not perform firefighting using breathing apparatus, due to the increased risk of physical exhaustion, orthostatic responses and cardiac complications.

A number of tests on the physiological aspects of firefighting have been reported by Romet et.al. (1987), Sköldström (1987) and Bennett et.al. (1995). In these tests, the workload as well as heat stress was high. The tests indicated that increases in heart rate and body temperature were related to both physical and environmental stress. However, tests in which heat stress on firefighters equipped with breathing apparatus – BA teams – has been measured under real firefighting conditions and where the workload was low, are rare.

In large-scale experiments involving manually applied water sprays, reported by Svensson et.al. (2001) (paper II), the increase in pulse rates of the firefighters appeared to be triggered by mental stress and further increased due to increasing skin temperature, induced during the test. In addition, working conditions for firefighters may be unbearable due to heat stress, although the workload is low.

A lot of effort is put into finding methods for the testing and recruiting of personnel for the Swedish fire and rescue service (Räddningsverket, 2001b). However, cognitive abilities are important in decision-making situations. The problem of focusing on physical aspects is that cognitive abilities may be set aside. The benefit of studies of the physical aspects of firefighting is that it may serve as a basis for the development of models of firefighting situations.

The firefighter often has to entrust his or her safety to other people, such as a commanding officer, to his or her own knowledge and experience or to the equipment that is available. In firefighting situations physical threats may be reduced by the use of protective clothing, breathing apparatus, harnesses (to prevent falls), helmets, and gloves. In recent years, major efforts have been made to improve personal protective equipment (see, for example, Mell and Lawson, 2000). However, threats to mental health may be harder to reduce and the problem may be summarized by the notion of stress (Orasanu, 1997). Such threats include working in the proximity of mutilated people or fatalities, under conditions with no visibility, with inadequate knowledge about the situation and the feeling of insufficiency in such working environments.

From a safety point of view, commanding officers should be regarded as firefighters, especially when situated on the fireground. The tragic events of 11th September 2001, when a large number of rescuers including commanding officers were killed, is a reminder of this problem. During a firefighting operation, dangerous situations may occur when they are least expected. Procedural aspects must be well recognized at a command level during a firefighting operation, not least from a strict safety point of view.

Models

The purpose of the work in this thesis, includes investigating the possibility to model and to simulate fire and rescue operations. Through this, further knowledge about how firefighting operations are built-up and how the initiation, execution and coordination of procedures affect the course of events at the scene of a fire can be obtained.

As was described above, the theoretical background to procedures used by the fire and rescue service is well known, especially regarding suppression. However, modelling firefighting situations including combinations of procedures and human performance becomes very complex, time consuming, and its applicability on a fireground as well as in a training situation is limited.

The simulation of firefighting operations is a complex problem and attempts have been made to tackle it. One of the more extensive works on the subject is the Fire Demand Model (FDM) (Pietrzak, 1993). The model simulates the suppression of post flashover fires in compartments using water sprays from nozzles used by firefighters. The output of FDM shows the extinguishing effects of water spray at various flow rates and droplet sizes. The calculations are based on a heat and mass balance accounting for gas and surface cooling, steam-induced smothering, water-spray induced air entrainment, direct extinguishment of the fire by water, and the energy transport via inflow and outflow of heat and the products of combustion. The FDM is capable of simulating fires in compartments with single or multiple vents of different sizes and in different locations, including changes in venting conditions in time due to firefighting activities. However, the model is limited to post-flashover fires in single rooms of a limited size and with a uniform temperature, which is a situation containing a low firefighting complexity. The applicability of FDM in the sense of studying practical problems faced by the fire and rescue service is limited.

Also, models for determining the fire growth rate and the flow of smoke and hot gases inside and out of buildings on fire have been developed. Such models are available and well known within the fire engineering community, including software and software packages such as CFAST, FPETool, FASTLITE, CCFM (Consolidated Compartment Fire Model version VENTS) and FIRST (FIRe Simulation Technique). In addition, pressure, flow rate and ratio of air change when using positive pressure ventilation can be determined using simple models based on basic physical relations, as suggested by Ingason et.al. (1998) and described in the previous subsection. The model can be used for determining the efficiency of using positive pressure ventilation. However, such models usually calculate conditions for steady state and they don't generally take into account the dynamics of initiating, executing and coordinating various firefighting procedures.

In recent years, there has been a considerable growth in the development and application of Computational Fluid Dynamics (CFD) to all aspects of fluid dynamics and heat transfer. The application of CFD to fires has become well established, often referred to as field modelling, and typical applications include smoke movement and heat transfer. A number of journal papers and conference presentations have been made over the last few years, either directly reporting simulations using software such as SOFIE (Simulation Of Fires in Enclosures) or physical model development of direct relevance to fire modelling. As an example, SOFIE includes detailed physical models of fire specific features to enable predictions of more complex fire phenomena, such as fire growth, toxic emissions and smoke production (see e.g. Rubini, 1997).

However, up to this point firefighting using manually applied water sprays or ventilation procedures at various stages of the fire development has not been considered in the development of field modelling. Field modelling is already at this stage very complex and adding firefighting procedures into such models will most certainly make them even more complex and harder to grasp.

Considering the number of available options for initiating, executing and coordinating various procedures during firefighting operations, as indicated in table 2, the physical modelling of such operations becomes very complex. In addition, firefighting operations include human performances, which make the problem even more complex. The performance of humans may be treated as stochastic variables. But on the fireground, the initiating, executing and coordinating of various procedures must be based on consciously made decisions, in time and in space, with the focus on the result of the operation.

On the matter of modelling combinations of procedures, Hay (1994) reports that theories to describe the interaction between venting and water attack is not well established. Especially, the potential implications of such theories in backdraft and flashover situations, has not been considered. However, such research has been initiated, as reported by Gojkovic et.al. (2001).

Another approach to the modelling of firefighting situations is served by control theory. Control theory brings systematic in how a process controls another process. Worm (1998) uses control theory as a metaphor for bringing clarity in military command and to further advancing knowledge about military command and control science. In the case of firefighting, control theory should indicate ways of using the firefighting process to control the fire (the physical process of an accident). However, the mathematical theory in control theory may be of less value, in that it requires measured signals as input. But in a simulated situation, such as during training or for the pre-planning of fire and rescue operations, it may very well be useful. Svensson (1998) uses control theory to simulate a simple firefighting situation. However, the only aspect that could be modelled at this point was controlling fire temperature by regulating water pressure. But still, the approach showed that control theory might be a useful tool for the further modelling of firefighting situations.

Fire modelling is in many cases aimed at finding exact solutions to problems related to fires. Variables such as temperature, optical density and levels of carbon monoxide are calculated with accuracy in the range of a few percent, when comparing them with results from well-defined experiments. However, from a firefighting point of view, it is in many cases sufficient to have knowledge about trends in the development of a fire. From a fire science point of view these types of rough results from modelling are in many cases considered being less valuable and the development of rough models is generally not subject to any greater interest.

Problem

In this section, a theoretical background to firefighting activity and the modelling of such activity was presented. Based on this presentation, the problem falls into two categories. Firstly, there is a need to advance the modelling of firefighting activity. Fire and rescue personnel and fire and rescue activities are important elements for the saving and protection of people, property and the environment when accidents occur. In view of the increasing complexity of society and the increasing number of engineered solutions to fire safety problems, it would be desirable to find methodology in engineered solutions to firefighting activity, as well.

Secondly, we need to advance the theoretical conception of firefighting activities. The dynamics of firefighting operations are in many cases very complex. On the fireground procedures are initiated, executed and coordinated, operations are performed and in that way we try to bring control to unwanted events. It is desirable to bring knowledge into how firefighting operations are built-up, how the dynamics of such operations work and to thereby find suitable models of this dynamics.

Procedures

In this thesis, a procedure is considered to be the smallest unit in a larger entirety. Examples of notions used in other contexts are methods, tasks, assignments, and techniques. Examples of procedures are a single firefighter using a fire extinguisher, or a group of firefighters advancing a hose line into a building on fire.

Jenvald (1999) defines three organizational activities: assignment, task and operation. Here, a team or an individual performs an assignment at one geographical location during a shorter period of time. A task is an assignment given to a large organization, a taskforce, consisting of multiple smaller organizations coordinated by a commander with an organized staff. Jenvald's terminology is chosen in order to describe activities in the military domain as well as in the domain of emergency management and response.

During firefighting operations the period of time during which the operation is performed is restricted. Also, the geographical extension is limited. The term "procedure" is used in this dissertation as a comprehensive concept for those activities performed primarily by firefighters on the fireground. In Jenvald's definition this should be similar to an assignment.

Jones (1993) defines procedures as the formalized heuristics and algorithms employed to execute the functions of a problem solving system. Here, a problem solving system is defined as a set of actors performing interdependent activities engaged in solving a problem. Procedures are the processes used in a problem solving system to obtain a solution. A problem solving system operates in the presence of uncertainty, ambiguity and equivocality. Uncertainty refers to the lack of complete information, ambiguity to the existence of alternative hypotheses, and equivocality to the need to make sense out of the situation.

Procedures often follow standard operating procedures, which are written procedures aimed at standardizing general activities (Cook, 1998). Standard operating procedures are primarily a means to getting the firefighting operation started (IFSTA, 1992). They don't replace decisions based on professional judgments, evaluation or command. There may be a variety of standard operating procedures from which to choose depending on the situation at hand. In addition, standard operating procedures should be locally developed, adapted and implemented, although the basic training of firefighters and commanding officers has a large impact on such standard operating procedures. This is especially noteworthy in the Swedish case, where the basic training of firefighters and commanding officers is centralized (1986:1107), and consequently the impact of knowledge gained through basic training is large.

In this thesis, the term "procedures" is used for all kinds of procedures, formally approved as well as informally accepted. The definition of a procedure is based on the performed activity itself rather than on its appropriateness within a context.

It should be noted that the activity known as command and control, performed by one or several commanding officers, a staff, etc., is also referred to as a procedure. Notwithstanding, command and control is further treated in later sections.

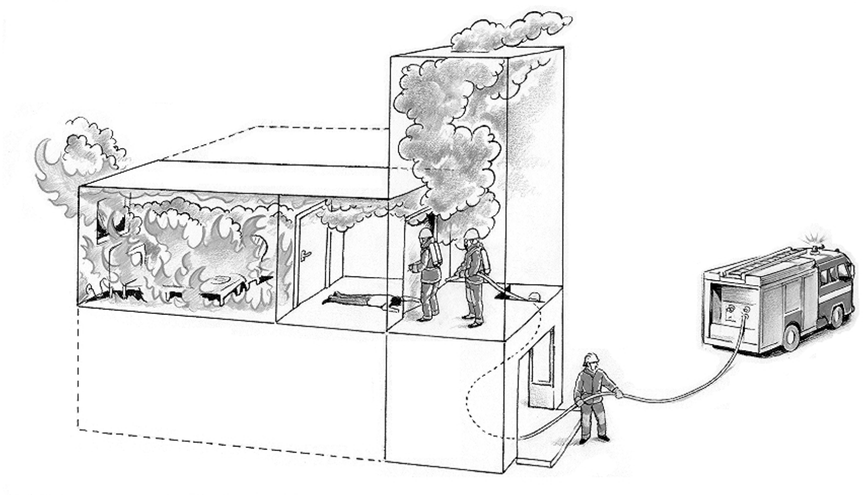

Figure 1. Procedures are based on resources (equipment and knowledge) and firefighters (Svensson, 1998).

There are two important elements on which procedures are based: resources, basically in the form of equipment but also in the form of knowledge, i.e. knowledge held by the second element, firefighters.

Procedures arise when firefighters on the fireground use resources in order to fulfil some assigned or identified objectives, figure 1. The resources as well as the firefighters create boundaries within which the procedures must be performed. Such boundaries must be well recognized by the problem solving system. Otherwise, the system will not function properly due to, for example, the inefficient use of procedures. Crossing boundaries may even create dangerous situations.

Resources on the fireground include: nozzles, pumps, hoses, fans, hand tools, such as cutting machines and chain saws, vehicles, and ladders. Such resources are usually developed through experience and pragmatic needs. However, the capacity of resources in applications such as manual fire suppression systems and in fire ventilation procedures has been investigated, mainly by way of their effects on fires. In order for the problem solving system to function properly, the results from such investigations are important from a command perspective, and it must be well recognized by commanders as well as firefighters.

Svensson et.al (1999) (paper I) report differences between manual high and low pressure fire suppression systems, thus indicating differences in technology as well as in procedures. Also, high-pressure systems have the advantage over low-pressure systems in that they use a rigid hose mounted on a hose reel, which generally decreases the attack time, i.e. the time from arriving on the fireground until the moment when it is possible to apply water to the fire. Attack time may have a large impact on available options when arriving at a fire scene.

In addition, Svensson et.al (2001) (paper II) report that the capability of the fire service to fight fires in large spaces is related to their ability to reach the fuel. The coordination of various procedures at the scene of a fire may have a large impact on the ability to reach the fuel. Also, the use of and availability of water may in some situations be critical to the coordination of the operation. The initiation and execution of such critical procedures creates conditions for the initiation and execution of other procedures. This relates to the dynamics of the operation, further treated in the sections on tactics and control.

On the matter of fire ventilation procedures, Svensson (2001) (paper IV) reports that positive pressure ventilation increases the mass loss rate of the fuel, consequently increasing the burning rate of the fire. Also, working conditions for firefighters are improved by positive pressure ventilation, but the lives of any victims trapped in an apartment on fire are jeopardised. In addition, the risk of fire spread to adjacent rooms will increase. Problems of an increasing or decreasing burning rate as well as the risk of fire spread are important issues to a commanding officer, especially if the initiation and execution of a procedure contributes to such problems. Also, Svensson et.al (2001) (paper V) report that the use of positive pressure ventilation in large halls jeopardizes safety and working conditions for firefighters. Also, the experiments showed the importance of coordination when using fire ventilation procedures, a problem that is directly connected to the command and control of firefighting operations.

An important constrain during firefighting operations is the individual firefighter, and the capacity of firefighters must be well recognized by the system. It is generally well known and even accepted that firefighting is in many cases equal to hard and dangerous work. However, safety during firefighting operations must be considered. This was treated in the background section of this thesis.

In this section, various aspects on procedures were treated. The results from experiments on various procedures were included. In conclusion, there is a need for an in-depth knowledge of how various procedures effect the course of events on the fireground. When one or several procedures are initiated, coordinated and executed, an operation is created.

Operations

In this thesis, the term "operation" is used as a comprehensive concept for the activity of coordinating a number of procedures, performed by a commander, in some cases with an organized staff or by several command levels. Of course, it also includes the initiation and execution of procedures in a dynamic context.

Operations are, generally speaking, considered to be the conception of the collective work at the scene of an incident. An operation is a planned activity that involves many actions or many people doing different things (Collins COBUILD English Dictionary, 2001). According to the Home Office (1994), the operational level is the level at which work at the scene of an incident is undertaken. On a fireground, operations are undertaken in order to fulfil some overriding objective of the organization. Resources, people and equipment are allocated in time and space; they are used as “tools” in order to fulfil this overriding objective.

Jenvald (1999) defines an operation as the coordination of a number of task forces over a long period of time. It involves multiple levels of command and extends geographically over large areas. Logistics are of great importance.

Results from the work by Artman (1999) highlight that coordination is dependent upon resources as well as the individual's knowledge and the goals of the system. Situation awareness and coordination work should be regarded as interdependent.

During an operation, various actions and procedures are initiated, coordinated and executed. The initiation and coordination of such actions and procedures are connected to decision-making. Of course, decision-making involves all individuals on the fireground, although at some tactical level decision-making is applied to one or several commanding officers. The situation on the fireground where decisions are taken is referred to as naturalistic settings. Such settings are defined by Orasanu & Connolly (1992) and they include:

- Ill-structured problems;
- Incomplete, ambiguous, or changing information;
- Shifting, ill-defined or competing goals;
- Time constraints; and

- High stakes.

According to Orasanu & Connolly (1992), research on decision-making in naturalistic settings, as opposed to classical decision-making research, has yielded findings such as that experts in naturalistic settings generate and evaluate single options rather than analyse multiple options concurrently; experts are distinguished from novices mainly by their situation assessment abilities, not their general reasoning skills; decision-makers choose an option that is good enough, though not necessarily the best; reasoning to search and assess information and to build causal models of events is guided by the decision-maker's knowledge, and especially; deciding and acting are interleaved. In addition, Rasmussen (1992) points out that decision-making is intimately connected to action.

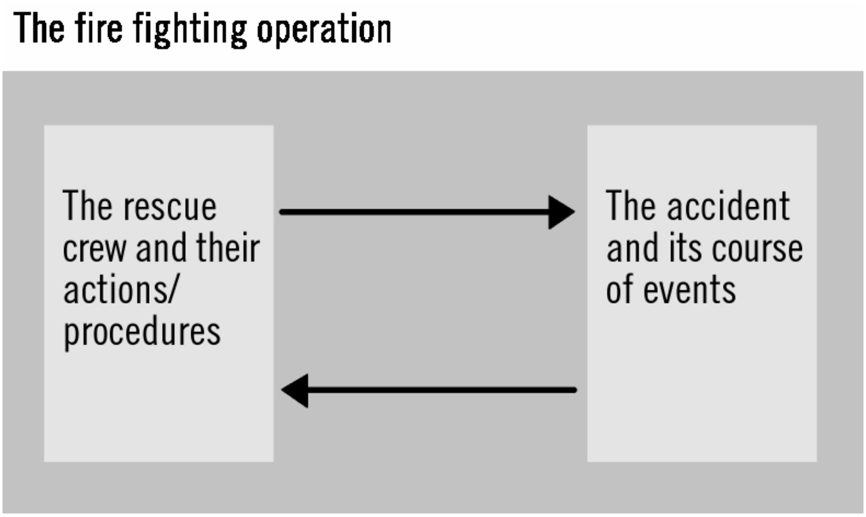

Figure 2. There is a causal relation between the rescue crew and their procedures, and the accident and how it develops (Svensson, 1999).

Results from research on decision-making in naturalistic settings applies well to firefighting operations and to the initiation, execution and coordination of procedures. Procedures are initiated and coordinated through decisions in naturalistic settings, i.e. on the fireground.

In the case of firefighting, Brehmer (2000) identifies three types of temporal constraints for the decision-making problem:

- Decisions must be made as the need arises.
- Temporal processes must manage the fire, which is a temporal process itself.
- Differences in time scales must be recognized and accommodated.

This indicates that there is a dynamic relationship between, on one hand the rescue crew and their procedures, and on the other hand the accident and its development, figure 2.

Also, decision making on the fireground is connected to command. In military applications, the term C3I, which stands for Command, Control, Communications and Intelligence, is commonly used.

The term "operational" is used to describe actions, situations, or problems that occur when a plan or system is being carried out in practice (Collins COBUILD English Dictionary, 2001). Operational problems become situations that one or several procedures are allocated to solve.

According to Fredholm (1991), the operational problem (of a military operation) can be summarized by three basic questions:

1. Comprehension: how does one create a conception of settlement (an operational idea)?
2. Command: how can the operational idea be realized by cooperation between individuals and units?
3. Control: how can feedback from the course of events be related to the operational idea?

Various aspects on control and feedback are treated in the section on control. Comprehension and command will be dealt with here.

Comprehension relates to the understanding of the situation at hand, here: the situation on the fireground. Jones (1993) describes this as equivocality, i.e. the need to make sense out of the situation. At the scene of an accident comprehension includes knowledge of the physics of the fireground; fire dynamics, spread and effects of chemical substances, and effects of initiated and executed procedures. Effects of procedures were examined in Svensson et.al. (1999) (paper I), Svensson et.al. (2001) (paper II), Svensson (2001) (paper IV), and Svensson et.al. (2001) (paper V), and were treated in the section on procedures. In addition, the effects of combinations of procedures were investigated by Svensson (2002) (paper VI), which is further described in the next section (on tactics). Such knowledge is crucial to command work during any fire and rescue operation.

Persson (2000) describes command work as a kind of design work, dynamic, and hard to define and control. It is knowledge-intensive work which designs and produces symbols. In the modern military command structure, experts manage an operational environment by transformation and they control the operational environment through controlling actions. Also, design work may be considered as a situation where prediction is crucial (Svensson, 2000b).

Brunacini (1985) defines a number of command functions, which include the development of an effective fireground organization. This organization is the link between the command level of the fireground commander and the action level of the firefighters. The development must begin at some procedural level, i.e. the activities required to stabilize a situation, placing the emphasis on the action level (where procedures and actions are carried out). The fireground commander must create the correct arrangement (structure) and the correct amount (scale) for each operational level (strategic, tactical and task) in order to balance management with action. The command system must match and reinforce the action, not the reverse.

In this section, various aspects on operations were treated. At the core of an operation are the initiation, coordination and execution of various procedures, and emphasis during an operation should be put on procedures. The procedures form the inherent dynamics of the operation, and it is within this dynamic context that tactics are created.

Tactics

So far, procedures and operations, including some general aspects on decision-making, have been discussed. In this section, the focus will be on the tactical level of command. Several definitions of such a level exist. However, the term tactics is often used in a military context. According to the Swedish Army Regulations (Chefen för armén, 1995), tactics are defined as the capacity to utilize units for carrying out or to support combat. From an emergency management point of view, the Home Office (1994) defines the command objective at a tactical level as to determine priority in allocating resources, to plan and to co-ordinate actions when a task will be undertaken, and to obtain other resources as required. Norman (1998) defines tactics as the actual hands-on operations that must be performed in the right time and place. The challenge here is to recognize the appropriate means and to properly and expeditiously employ them. Similarly, Dunn (1999) defines tactics as the operations that a fire company performs at a fire. Tactical decisions involve forcible entry, ground-ladder placement, hose line placement, window ventilation, and search and rescue.

On the fireground tactics include a mixture of tasks (procedures) performed under the supervision and coordination of one or several commanding officers (Routley, 1991). Such tasks (procedures) have one or several functions, such as: search and rescue, exposure protection, confinement, suppression, ventilation, property conservation, and overhaul. In addition, firefighter safety must be considered.

According to Brunacini (1985), a complex incident includes three basic operational levels, strategic, tactical and task. Sector officers, assigned to specific areas and tasks by the fireground commander in order to meet operational objectives, operate the tactical level. This level is responsible for the tactical deployment of resources assigned, evaluation, and communication with the fireground commander.

Fredholm (1991) defines rescue tactics, i.e. tactics related to rescue and firefighting operations, as ways of thinking and behaving to obtain the best results at an incident according to the overriding aim to save life and prevent or limit damage to property and the environment. The choice of tactics is influenced by a number of general conditions, which are independent of the particular incident in question. These conditions include tactical problems, idealistic solutions, classification of situations, structural basis for operations, routines, skills, tacit knowledge, codes of practice, and textbooks. In addition, Fredholm identifies training opportunities and research as important conditions for tactics.

Also, Fredholm (1991) suggests incidents are either static or dynamic. A dynamic incident develops and changes in time, as a result of inherent dynamics or due to procedures initiated, coordinated, and executed by the fire and rescue service. A fire is a typical dynamic incident. A static incident does not change once the initial event has taken place (except from a medical point of view, but this is outside the scope of the thesis). A traffic accident can be seen as an example of such a static incident.

Also, Fredholm (1991 and 1997) discusses the decision problem during fire and rescue operations. He categorizes the problem into four basic tactical situations, table 3.

Table 3. Categories for tactical problem alternatives (Fredholm, 1997).

Denomination	Characteristics	Tactical demands	Examples
Situation 1	Limited situation, strong recourses	Less demanding tactically	Car fire, “normal” apartment fire
Situation 2	Limited situation, critical resources	Large demands on tactical judgement	Apartment fire with high probability of spread
Situation 3	Limited situation, weak resources	Less demanding tactically	Fire in a barn
Situation 4	Unlimited situation, weak resources	Large demands on tactical judgement	Fire-storm, gas leak

Two additional situations can be identified: strong resources in unlimited situations, and critical resources in unlimited situations. However, these two situations are without practical validity.

According to Fredholm (1995), the accident as a tactical problem represents different kinds of situations depending on the degree of the danger, the type of dynamics in the development of the accident, and the degree of manageability.

In tactics, the initiation, coordination, and execution of procedures in relation to a specific situation is a key element. Svensson (1999) points out that there is a causal relation between on one hand the rescue crew and their procedures, and on the other hand the accident and how it develops, figure 2. Also, a linkage between tactics and decision-making is identified.

Tactics on the fireground are developed based on pragmatic needs, and there is a general lack of any scientific approach to tactics. Individual procedures, in relation to fire service operations, have been the subject of research. Such procedures include ventilation procedures as well as suppression activities by the fire service. However, research on individual procedures does not consider the effects of synergy, when various procedures are combined. The various combinations of available personnel, equipment and procedures can be referred to as tactical patterns. An example of a tactical pattern is shown in figure 3.

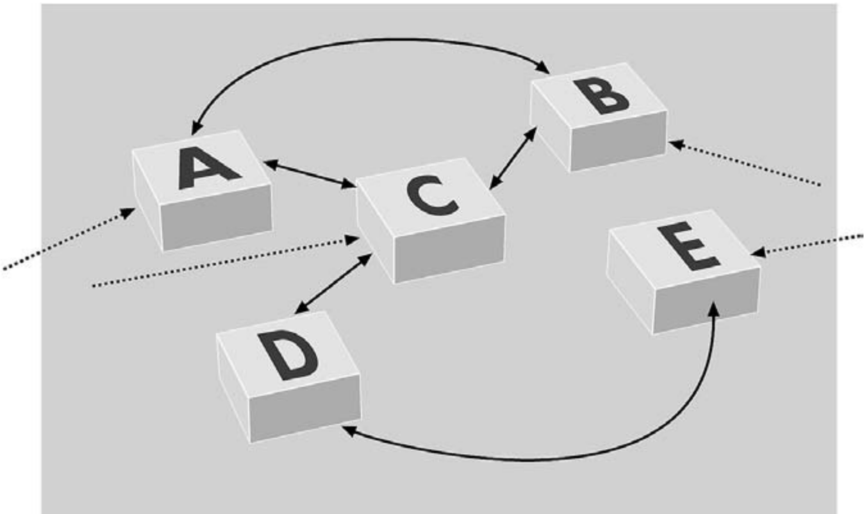

Figure 3. A combination of various procedures, varying in time and space, is defined as a tactical pattern (Svensson, 1999).

As a result of the tactical pattern used during a firefighting operation the outcome of will vary. Tacit knowledge within the fire & rescue service asserts that there are "correct" patterns and "incorrect" patterns. The choice of tactical pattern is also dependent on the objectives of the individual operation and its expected outcome. However, scientific knowledge on how firefighting operations work and on how the inherent dynamics of operations affect outcomes is inadequate. There are no traditions in bringing science into a fire station. Consequently, the determination of such "correct" and "incorrect" patterns is arbitrary.

Svensson (2002) (paper VI) investigates various tactical patterns experimentally. The purpose of the experiments was to investigate how various tactical patterns interact with a fire in an apartment, and to thereby examine and draw conclusions from the course of events during operations and on their outcomes, using various tactical patterns. In a wider perspective, the experiments constitute a basis for further treatment of command and control problems. The experiments included fire attack to at fire in a three-room apartment, on the first floor of a three-storey apartment building with an attached staircase.

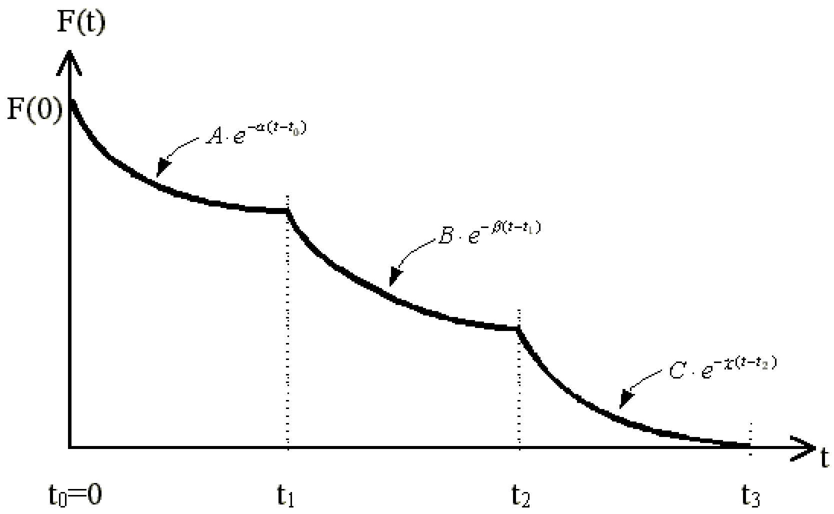

Figure 4. The operation as a sum of exponential functions, with amplitudes A – C and frequencies α – χ varying, due to choice of tactical pattern. Svensson (2002) (paper VI).

The results included data from temperature measurements as well as measurement of fuel load and visual observations. However, due to practical aspects when performing large-scale experiments including manual firefighting operations, the data contained irregularities. The most important irregularity being varying time intervals, but also the variations in maximum/minimum temperatures between tests made the material hard to compare. In order to draw any more extensive conclusions, the material was converted into a more comparable form. The conversion and analysis of data was based on the assumption that effects of various firefighting procedures can be treated as a sum of exponential functions, as in equation 1 and figure 4. In addition, due to irregularities in time to onset of procedures between various tactical patterns tested, the material was resampled using fast Fourier transform.

$$F(t) = \begin{cases} A \cdot e^{-\alpha t}, & 0 \le t < t_1 \\ B \cdot e^{-\beta(t-t_1)}, & t_1 \le t < t_2 \\ C \cdot e^{-\chi(t-t_2)}, & t_2 \le t < t_3 \\ 0, & t > t_3 \end{cases} \qquad \text{Equation 1}$$

As a result, frequencies α, β and χ for various combinations of procedures was obtained. Higher frequency indicates a better combination of procedures, i.e. a better tactical pattern, in that the temperature is reduced faster with larger frequency.

Figure 5 shows the frequencies of the last procedure added, i.e. for tests with onset of procedures at times t_0 and t_1, β is shown, and for tests with onset of procedures at times t_0, t_1 and t_2, χ is shown. Notations in the figure includes opening of window (W), opening of door (D), use of positive pressure ventilation (PPV), suppression using full flow (F), suppression using half flow (0.5F) and suppression using 30% above full flow (1.3F). Slash ("/") indicates simultaneous onset of procedures, and a plus sign ("+") indicates the adding of procedure or procedures at time steps $t = t_1$ and at time step $t = t_2$.

As an example, the diagram indicates that simultaneous opening of window and door, simultaneously using positive pressure ventilation and also using an appropriate flow rate, as in tests 2, 3 and 9, is a better combination than using only the door in combination with positive pressure ventilation and too small a flow rate, as in test 19.

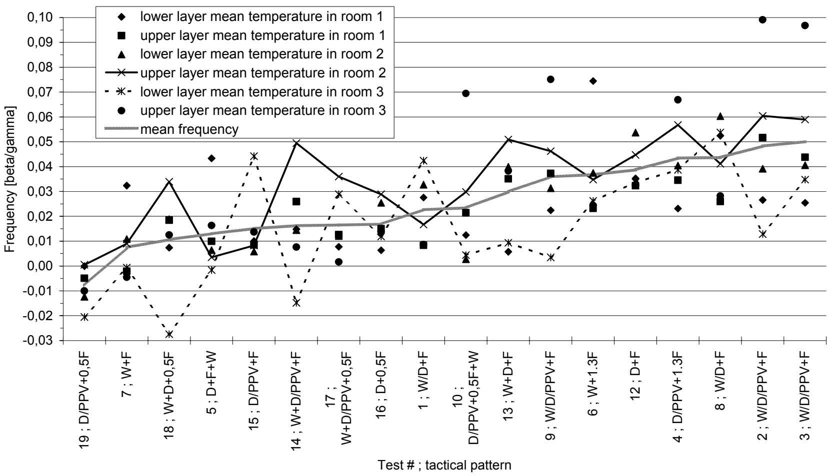

Figure 5. Frequencies at last added procedure in each test, ranked by mean value for each test. Notation for tactical pattern includes window (W), door (D), use of positive pressure ventilation (PPV), full flow (F), half flow (0.5F) and 30% above full flow (1.3F). Slash ("/") indicates simultaneous onset of procedures, and a plus sign ("+") indicates additional procedure or procedures taken at time steps $t = t_1$ and at time step $t = t_2$. From Svensson (2002) (paper VI).

Based on the analysis of the experiments, conclusions were drawn on basic tactical principles, such as that the outcome of a firefighting operation is dependent on the individual procedures as well as on their sequence of implementation. Also, the choice of tactical pattern is dependent on the situation as well as on the objectives of the firefighting operation and that the importance of command and control during firefighting operations is vital. In addition, the analysis showed that certain tactical patterns have an inherent indulgence towards defective or inappropriate procedures. But, defective or inappropriate procedures or tactical patterns can be corrected during a firefighting operation.

Also, the experiments showed how various combinations of procedures can be experimentally investigated and analysed. Based on this type of analysis, mathematical models for firefighting operations can be developed. This will be further treated in the discussion section of this thesis.

In this section, various aspects on tactics were presented. The results from experiments on combinations of procedures (paper VI) were included. In these experiments, various procedures were put into the context of an operation, and the investigated combinations were defined as tactical patterns. As a conclusion from this section, it can be stated that tactics are about describing the dynamics of the process as opposed to the structure of the process. The initiation, coordination, and execution of procedures, combined into an operation, are key elements of tactics. However, for the operation to be efficient, there is a need for a comprehensive objective for an operation, which will be treated in the next section.

Control

Various aspects of procedures, operations and tactics have been illustrated in previous sections. A concept that these illustrations fall back on is control. In this section, various aspects of control will be explored.

The term "fire control" is widely used in the fire protection community. It represents a wide composition of our efforts to use knowledge and artefacts in order to protect people, property and the environment from the consequences of fire. In many cases, it is linked to some operational level of protection against fire (Routley, 1991), and tactical (operational) activities are based on three priorities: safety of the public, fire control, and property conservation.

Also, “fire control” is widely used in forest firefighting (Pyne et.al. 1996). It involves the process by which a fire is systematically contained, its spread halted, and its perimeter secured (Pyne, 1997). According to Heikkilä et.al (1993), wildfire fire control refers to all activities to protect an area from fire, and that the term "fire control" is similar to the general term "fire protection". A wildfire is reported "under control" when it no longer threatens to yield additional destruction and has reached the phase in which mop-up (final extinguishing and removal of burning material) can begin.

On the fireground, primarily when responding to fires in buildings, two basic interwoven activities that involve fire control are identified by Brunacini (1985): stopping forward progress of the fire (confinement) and bringing the fire under control (extinguishing). When reporting "fire under control" on the fireground, this means that the forward progress of the fire has been stopped, and the remaining fire can be extinguished using existing on-scene resources. It does not mean that the fire is completely out but it does indicate that the major hazards have been eliminated.

Control is the ability to make something behave exactly as you want it to behave (Collins COBUILD English Dictionary, 2001). Similarly, to control something dangerous, generally means to prevent it from becoming worse or from spreading.

There are two aspects to control, of which the first was indicated and outlined above. This aspect on control focuses on the accident and on the physical development of the course of events, as in the right hand side of figure 2 (in the section on operations). The second aspect of control relates to the resources and the firefighters on scene, which is illustrated by the left hand side of figure 2. Here, control focuses on the ability to manage on-scene resources and firefighters and to develop and implement objectives. This is usually referred to as coordination (of resources). Clearly, there is a causal relationship between these two aspects of control, indicated by the two arrows in figure 2.

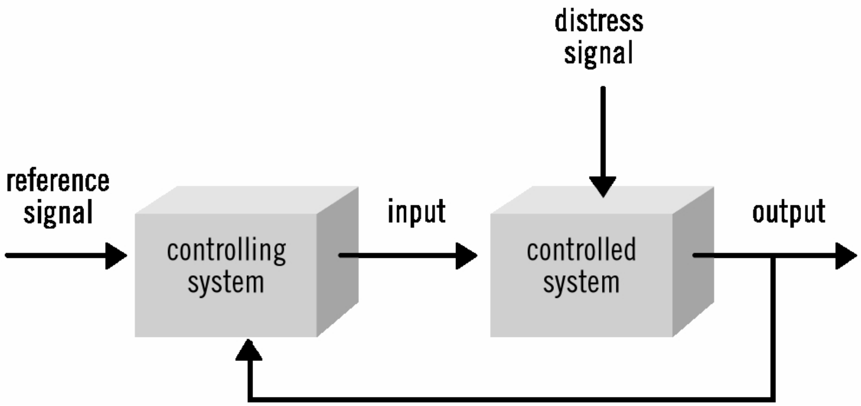

Figure 6. Control theory as a metaphor for understanding the inherent dynamics of a fire and rescue operation.

In control theory, the general problem is to determine input, based on output, such that the tracking of the reference signal is maintained, figure 6. According to Svensson (1998), a firefighting operation is a process with the purpose of controlling another process. Control theory may serve as a useful metaphor for further analysis of the functionality of firefighting operations. In the military case, this has also been suggested by e.g. Worm (1998) and Brehmer (2000). Based on this assumption and on a discussion on firefighting tactics, Svensson (1999) defines the primary objective of a firefighting operation as being to obtain and to maintain control.

By the initiation, coordination, and execution of procedures the course of events on the fireground is affected. In the majority of fire and rescue operations, combinations of procedures are used. Svensson (2002) (paper VI) defines such combinations of procedures as tactical patterns, figure 3. An operation may consist of one or several tactical patterns.

In order to obtain and to maintain control, by the onset of tactical patterns, there is a major need for knowledge on the effects of various procedures. Such effects were investigated by Svensson et.al. (1999) (paper I), Svensson et.al. (2001) (paper II), Svensson (2001) (paper IV), and Svensson et.al. (2001) (paper V), and were treated in the section on procedures. Also, the effects of various tactical patterns were investigated by Svensson (2002) (paper VI), which was treated in the section on tactics.

Also, control problems have been treated in experimental work. Svensson et.al. (1999) (paper I) discusses the problem of establishing criteria for starting water application and for extinguishing. Here, the criteria for control was linked to temperature. At a defined highest temperature level water application started, and at a defined lowest temperature level the fire was considered under control. A similar treatment was chosen in Svensson et.al. (2001) (paper II), although the final decision criteria for the control criteria was left to the firefighter operating the nozzle. However, in either case, when the fire was considered to be within some temperature criteria for control ("under control"), this was not similar to having the fire completely extinguished. At this stage in the experiments the fire was considered to be such that final extinguishing could have been reached by mop-up (final extinguishing and removal of burning material).

Similarly, in the experiments on fire ventilation, Svensson (2001) (paper IV) and Svensson et.al. (2001) (paper V), temperature was chosen as a criteria for control and for comparison between individual tests during post-analyses of the results from the experiments. In addition, in Svensson (2001) (paper IV), the burning rate was used to compare the effects of various ventilation procedures. Here, it was shown that the burning rate is an important aspect when considering problems of fire control. In addition, criteria for control, based on temperature as well as on burning rate, were used in the experiments on combinations of procedures, Svensson (2002) (paper VI). In Svensson (2001) (paper IV), as well as in Svensson (2002) (paper VI), temperature was used as the primary control criteria and burning rate was used as an indicator on the risk of fire spread.

Brehmer (2000) defines four general conditions for control to be met:

- There must be a goal (goal condition).

- It must be possible to ascertain the state of the system to be controlled (observability condition).
- It must be possible to change the state of the system (change condition).
- There must be a model of the system to be controlled (model condition).

Tengblad (2000) shows that a vital condition for control is access to information about the controlled object, which is similar to the observability condition (above). In the centre of this control aspect, is the human, here represented by a commanding officer at some tactical level, i.e. a commanding officer engaged in the initiation and coordination of various procedures during an operation. On the fireground, as well as on the way to the fireground, this human is heaped with information. The commanding officer uses his or her cognitive abilities to transform this information. This is the process usually referred to as decision-making. In this aspect, information, knowledge and cognition are essential elements.

Hollnagel and Woods (1983) present an approach to the description and analysis of complex man-machine systems. This approach introduces the concept of a cognitive system: an adaptive system, incorporating humans as well as technology, that functions using knowledge about itself and the environment in the planning and modification of actions.

Hollnagel (1993) introduces an integrated model of cognitive control, named COCOM – Contextual Control Model. The model is based on three main concepts: competence**,** control**,** and constructs. Here, control describes how things are done and how actions are chosen and executed, and it can be described in a number of ways where the granularity of the description and the mode of functioning are important issues. The model identifies four basic control modes as characteristic performance regions. The modes are:

a) Scrambled control
   in this mode the event horizon is confined to the present and there is no consideration of preceding events or prediction of the outcome of future events. The choice of next action is seemingly random and only one basic goal is considered at a time.

b) Opportunistic control
   here, the event horizon includes only one action that is chosen to

match the current context with minimal consideration given to long-term effects. Some effect of preceding actions is considered; the next action may be chosen to fit the previous one. Also, feedback is not properly utilized.

c) Tactical control
during the tactical control mode the effects of an action are viewed in the light of what went before. Choices for the next action are considered in some detail and their potential effects are taken into effect and plans are used as a basis for choosing action. This mode may pursue more than one goal at a time.

d) Strategic control
in this mode the person, such as a commanding officer, is fully aware of what is happening and is deliberately making plans to deal with the situation which requires the selection and execution of particular controlling actions. The event horizon of this mode involves preceding events as well as future developments, although the number of steps one can plan ahead is rather small even for experts.

Scrambled and strategic control represents two extremes, while opportunistic and tactical control are the two most frequent performance regions. The purpose of the COCOM model is to describe how performance switches between various control modes dependent upon the outcome of previous action as well as upon consideration of available time. Other parameters that can influence the modes are the number of simultaneous goals, the availability of plans (which are part of competence), the perceived event horizon, and the mode of execution.

The control modes, above, are theoretical constructions. In reality, control will vary continuously. According to Hollnagel (1993), important issues are:

- Transition between control modes and causes of changes from one mode to another.

- Characteristic performance in a given control mode.

- Interaction between competence and control.

Concepts such as feedback and feed forward, figure 7, may be important in the interaction between competence and control. Typically, opportunistic control is driven by feedback. This makes the design of feedback indicators crucial. Also, higher competence (i.e. having more knowledge and better skill) makes it more likely that control is maintained. In addition, in the model by Hollnagel, there is a clear link between control and available time.

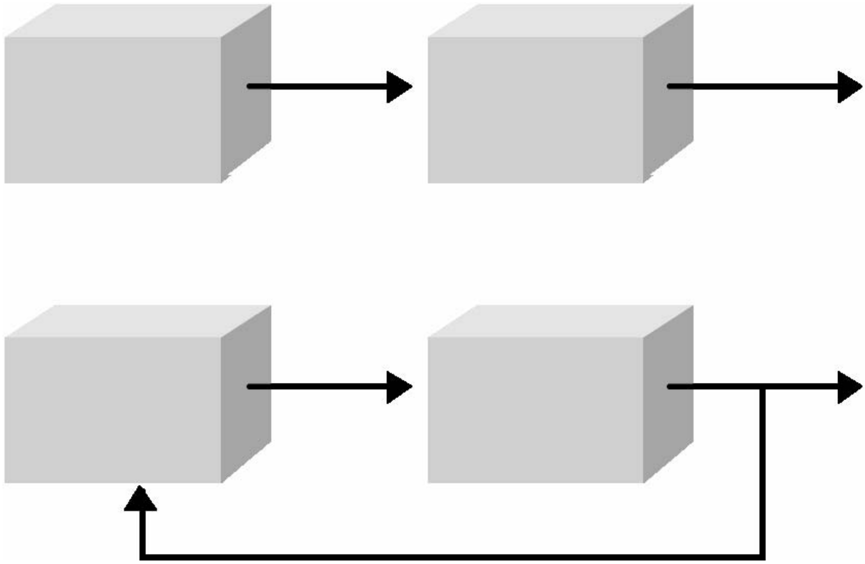

Figure 7. Feed forward control (top) and feedback control (bottom).

Sarter and Woods (1995) lay out multiple cognitive demands involved in maintaining mode awareness in supervisory control. They conclude that new technology is flexible in the sense that it provides practitioners with a large number of functions and options for carrying out a given task under different circumstances. Practitioners must know more than they did before about how the system works in each different mode and about how to manage the new set of options in different operational contexts. This points out the need for knowledge on the effects of various procedures.

Control is connected to decision-making through the cognitive processing of information, especially in an operational context. Work by Klein (1998), recognizes the importance of expertise and skill of decision-making in naturalistic settings. In addition, Orasanu & Connolly (1992) focus on the decision-making process, including how decision-makers cope with naturalistic settings. Important aspects of decision-making in naturalistic settings, are the understanding of the dynamics and also understanding the characteristics of this setting. In addition, the importance of understanding the situation is recognized by Tengblad (2000), who discusses potential drawbacks of obtaining control by the use of decision-making. He concludes that chief executive officers exercise control primarily by being “influencers” and that exercising control is strongly related to the ability of establish consent for a certain agenda.

Rasmussen (1983 and 1992) introduces a model for cognitive control, which includes three levels; skill-based, rule-based and knowledge-based. Skill-based control is characterized by the ability to subconsciously interact with a familiar environment by means of an internal dynamic world model. This type of performance is typical to an expert. Rule-based control includes the conscious use of rules in familiar situations. This rule may have been empirically derived during previous, similar, occasions. This type of behaviour can be viewed as similar to feed forward control, figure 7 (top). Knowledge-based control involves the transformation of knowledge of, in this case, the effect of various procedures, especially in relation to the development of the course of events on a fireground (the physical appearance of e.g. a fire). In such a situation, a useful plan is developed from explicitly formulated goals, based on an analysis of the situation at hand. This type of behaviour can be viewed as similar to feedback control, figure 7 (bottom).

Also, Brehmer (2000) proposes a view on command and control, saying that the form of control changes once planning of an operation meets reality. It then changes from feed forward control (by means of a plan) to feedback control, where the onset of various procedures must respond to the effects on the course of events due to previous procedures. Then, the initiating, coordinating and executing multiple procedures become dynamic.

On the matter of control problems linked to a command aspect of firefighting operations, Svensson (2001) (paper III) suggests a command structure for the Swedish fire and rescue service. The structure is based on a few important elements, the so-called viable systems model, the concept of control, and also leadership. According to Svensson, control aspects, including safety issues, are treated effectively within the framework of this suggested command structure, and the conclusion is that by transforming these elements into a command structure this will lead to efficient management of fire and rescue operations, including safety issues. Redundancy within the system will increase, thus creating necessary conditions for maintaining a high level of safety.

In this section on control, a theoretical background to control was given. In addition, various control problems encountered in experimental work were shown. It is concluded that the problem of control is an important aspect that has to be considered during firefighting operations.

Discussion

The title of this thesis, "The operational problem of fire control", is intended to reflect the core of the work and it is based on two key elements, operations and control, which have been treated in this thesis. The operational element includes the initiation, coordination and execution of procedures. The control element includes the objective of the collective work at the scene of a fire and the ability to achieve and arrive at a desired objective. The intention of this section is to discuss the previous sections on procedures, operations, tactics and control, to put the illustrations given in the previous sections in context to each other and in relation to the background, and to create a basis for conclusions and suggestions for continued work.

The concrete form of the objective given to the fire and rescue service is to save and protect life, property and the environment. In doing so, various procedures are initiated, coordinated and executed. In the section on procedures a problem solving system was defined. In such a system procedures are the processes used to obtain a solution to problems facing the system. Various procedures bring different, and in some cases also the same or similar, effects to such problems. As a consequence, it is only by the initiation and execution of one or several procedures that the course of events at the scene of a fire can be affected. This relates to the change condition for control, treated in the section on control. Each of the initiated, executed and coordinated procedures has its boundaries, within which they must operate in order to arrive at a desired objective. Such boundaries must be well recognized by the problem solving system. An in-depth knowledge of how various procedures affect the course of events on the fireground, serves as a basis for all the work performed at a fireground, including decision-making at command level during an operation.

In the experimental work, temperature was generally used as an indicator of the effects of initiated and executed procedures. It is reasonable to assume that temperature is an indicator of the ability to survive in a hostile environment as well as to the damage to property. Hot gases from the fire include toxic products from combustion. By removing hot gases, toxic gases will also be removed. In addition, time to control may be used as an indicator on environmental conditions. The length of time exposed to hot gases and toxic combustion products have an impact on victims' survivability and damage to property. Here, it is assumed that exposure time can be determined by time to control.

Tactical patterns were defined as combinations of procedures, varying in time and space. From the experiments reported by Svensson (2002) (paper VI) it was clear that tactical patterns were the link between procedures and operations. As a consequence of the illustrations of tactics, if only a single procedure is initiated and executed during an operation, the degree of tactical complexity will be very low. However, there will still be a tactical element due to the need to initiate and execute a single procedure at the right time and in the right place. Similarly, if procedures are, by necessity, initiated and executed in sequence, the degree of tactical complexity will be very low. An example of the former case is a fire in a small waste container located in the open, where a fire extinguisher can be used. An example of the latter case is a traffic accident involving only one vehicle. In such a situation, procedures by the fire and rescue service must be initiated and executed in sequence, in order to support medical treatment of victims.

On this matter, there is also a clear distinction between a dynamic and a static accident. During a static accident, procedures may often be initiated and executed in sequence. During a dynamic accident, the initiation and execution of procedures must be made in relation to the development of the accident. Consequently, the degree of tactical complexity will be very low during static accidents.

The illustrations in the section on tactics show that there is a lack of theory on fire and rescue operations. In these illustrations, the need for planning and the necessity of coordination is pointed out, a rather high level of abstraction is adhered to, or else, pragmatic needs of various procedures are entered deeply into. Svensson (1999) discusses tactical training in Sweden and points out a basic problem in this training. The work on tactics by Fredholm (1991), described in the section on tactics, mainly includes suggestions for future research activities. However, this work has been incorporated into a textbook for the Swedish fire and rescue service (Räddningsverket, 1992b). The result of this direct transfer of suggestions for future research activities to instructions for the fire and rescue service is a rather confused situation regarding tactical knowledge and comprehension. In addition, ideas from Brunacini (1985) have been incorporated into the training of Swedish fire officers. However, the work by Brunacini is based on Northern American building traditions and on Northern American firefighting traditions. There may be large differences between Swedish and Northern American firefighting procedures. Tactical training in Sweden today is evidently a result of such mix-ups.

In table 3 in the section on tactics, four basic tactical situations were defined. Objections to table 3 are that it is of less interest if resources are strong or weak or if the situation is limited or unlimited. It must be the growth in resources and situation that must be of primary interest. Also, a situation may never be unlimited. Due to the fact that accidents (fires, releases of toxic substances etc.) are governed by physical laws, prognostications may be based on such laws, and it should be easy to realise that an accident has its boundaries. The reasoning on strong or weak resources may be applied only as a tool for post-analysis and the evaluation of accidents and operations. Instead, as is illustrated through the discussion in this thesis, tactics are about using resources in the best possible way in relation to the course of events on a fireground. Experimental research on tactical problems has been initiated and results from this work, reported in Svensson (2002) (paper VI), were shown in the section on tactics. An interesting and important aspect from these results is that they have opened up the possibility to perform experiments on tactics and on combinations of procedures.

In the section on control, four general conditions for control were defined: a goal condition, an observability condition, a change condition, and a model condition. The goal condition includes overarching goals for an operation as well as broken down goals for procedures or tactical patterns. An overarching goal may be to save and to protect the public. A broken down goal may be to raise a ladder and evacuate a victim standing in a window within some specified time. The observability condition relates to the ability to establish the state of the system, whether this state is high or low, increasing or decreasing, or, which in many cases may be desirable, if possible, to quantify the state of the system, in terms of temperature or litres of available water. Establishing the state of the system may include observations such as water available for fire suppression; and if the fire is spreading or if it is confined. Physical barriers, geographical conditions and the fact that a commanding officer or a firefighter can only observe and utilize a certain amount of information are impediments for fulfilling this condition. However, opposed to the problem of military operations described in the introduction, conditions on a fireground may in many cases be prognosticated, in that physical laws govern the course of events on a fireground.

Also, there must be a realistic possibility for changing the state of the system, implied by the change condition. The use of procedures combined into tactical patterns is crucial to this possibility and the knowledge of effects of various procedures and tactical patterns is of vital importance. However, due to the inherent dynamics of the system, changes in the system may occur rapidly or they may be delayed in time. From being a part of a plan – feed forward control – on the fireground the operation becomes a system with feedback control.

In order to obtain and maintain control, the model condition needs to be fulfilled. A model of the system may consist of mental models with various degrees of abstraction for describing relations within the system, or it may consist of physical models describing the actual relations between procedures. Consequently, the model condition implies a great deal of knowledge of the effects of various procedures and tactical patterns.

As was described in the section on control, during experimental work the control problem can be related to pre-defined criteria for temperature and rate of mass loss. At a certain level of temperature, the fire can be considered to be under control. In a real firefighting situation, it is not realistic to base decisions upon measurements of temperature or rate of mass loss. However, in a real firefighting situation it is in many cases possible to, based on visual observations, make assumptions as to whether the temperature in a building on fire is high or low, or if it is increasing or decreasing. This may be sufficient for making decisions on initiation, execution, and coordination of procedures.

Based on the illustrations and discussion in this thesis, a perspective on the response of the fire and rescue service to emergencies, is suggested. This perspective is represented by the succession: procedure – (tactical patterns) – operations – control. In this perspective, the initiation, coordination, and execution of procedures is the key element. From a pragmatic point of view, procedures may be considered as the smallest parts smallest parts of the operation, the means by which to achieve something. Operations are the entirety, consisting of procedures arranged in tactical patterns. Tactics are the glue that keep the operation together. Control is the objective of the operation, what we are trying to achieve. Incidentally, command may be considered as the tool for managing the operation. Through this perspective there is a clear connection between procedures, operations, tactics, control and command.

The purpose of using procedures is to obtain and to maintain control over the course of events on the fireground. In order to obtain and to maintain control of a firefighting operation, procedures must be initiated, coordinated, and executed. In addition, procedures are initiated, coordinated, and executed in a context, i.e. at the scene of a fire. To be in control of a process includes the ability to make the process behave as predicted. If this process is an accident, then control becomes activities to prevent the accident from deteriorating or from spreading, and to make the course of events follow an intended direction. If this control of the process is strictly based on predictions, it becomes a form of feed forward control. On the other hand, if the control is based on the actual behaviour of the system, it becomes a form of feedback control. During a real firefighting operation, the type of control will vary continuously.

Control involves knowledge – knowledge about what goal to fulfil, what means we have to fulfil it, and how the controlled system (the accident) as well as the controlling system (the fire and rescue service) work. Also, the understanding of the dynamics of the system is of vital importance for control. The general objective of the fire and rescue service becomes one of obtaining and to maintaining control.

When initiating, coordination and execution procedures, it is evident that the choice of procedure as well as the actual execution and coordination should be the best possible, in relation to the situation at hand. For this purpose we may use the term optimisation, and optimisation becomes an important element in tactics. The problem is then transformed to an optimisation problem in a given situation, which should be considered in further work on modelling. In addition, the view of tactical problems as optimisation problems may be a useful metaphor on the fireground.

The theoretical background to individual procedures used by the fire and rescue service is rather well known, although with a varying degree of precision. However, theory to describe the interaction between various procedures is not established, although, in the majority of firefighting operations, combinations of procedures are used. An approach to the analysis of firefighting operations described in the section on tactics and by Svensson (2002) (paper VI), might contribute to the development of such theory. The suggested approach is based on the assumption that procedures and combinations of procedures can be assigned a value (frequency), indicating their effectiveness ratio to control a fire or a course of events. At this stage, the identified values on the frequencies α, β and χ are applicable to the experimental set-up only or possibly to situations very similar to the experimental set-up. However, further investigation on frequencies of procedures and combinations of procedures (tactical patterns) might to classification of tactical patterns and their usefulness in various situations. Such classification might be a useful tool for the testing of various tactical patterns, for post-examination of appropriateness and effectiveness of real firefighting scenarios, and also to develop simulators for firefighting operations.

In the background section of this thesis, it was concluded that there is a need to advance the modelling of firefighting activity. The effects of single procedures taken have been investigated and physical modelling can be used in most cases. However, effects of synergy when combining procedures into tactical patterns have not been investigated and work on modelling such tactical patterns is lacking. Based on empirical data and through classifications of tactical patterns it should be possible to advance modelling of firefighting operations.

In work by Svensson (1998), control theory was used to simulate a simple firefighting situation. Here, a linear differential equation transformed into a state-space form, equation 2, was used in a grey-box model, similar to the right hand box in figure 6, together with sample data.

$$\begin{aligned} \dot{x} &= f(x,u) \\ y &= h(x,u) \end{aligned} \qquad \text{Equation 2}$$

As a controlling system, the left hand box in figure 6, a PID regulator was used, and various values on the proportional, integrating and derivative coefficients were tested in the simulations. It was assumed that the controlling system, the firefighting operation, had proportional, integrating and derivative effects on the controlled system, the fire. The assumption included aspects on the control problem such that the proportional component represented obtaining control of the situation, the integrating component represented maintaining control, and the derivative component represented preparedness for the development of the situation (forecasting). However, due to lack of data and to lack of basic understanding of the inherent dynamics of firefighting operations, combinations of procedures were not considered.

Through the investigations on tactical patterns in Svensson (2002) (paper VI), it should be possible, together with the general problem of control engineering, as in figure 6, to further advance the modelling of firefighting operations.

However, since the dynamics of a firefighting operation include the initiation, execution and coordination of procedures, as well as the development of the accident, as indicated in figure 2, more work is necessary. Besides investigating the effects of individual procedures and on tactical patterns and frequencies of such procedures and tactical patterns, it includes investigating how the development of the accident, under various conditions such as changes in geometry, contributes to the description of tactical patterns through frequencies.

This thesis has two main contributions to the development of theory on fire and rescue operations. Firstly, it brings a better understanding of the inherent dynamics of firefighting operations. In addition, it suggests a qualitative model for how these dynamics can be viewed, represented by the succession: procedure – (tactical patterns) – operations – control. Based on this qualitative model further advancement, in bringing knowledge to firefighters on the initiation, execution and coordination of firefighting procedures, can be achieved. Secondly, the thesis advances the knowledge on how firefighting operations can be modelled based on the analysis of empirical data, as opposed to physical modelling.

At the outset of this work the intention was to find methodology in how fire protection design and fire safety measures in buildings can be used as tactical assets during firefighting operations. Due to a general lack of knowledge of the dynamics of firefighting operations this approach was revised. Now, when arriving at a greater understanding of the inherent dynamics of fire and rescue operations it should be possible to bring focus to this initial problem. Suggestions are that fire protection and fire safety measures can be viewed either as a boundary condition to procedures used by the fire and rescue service, or such measures can be viewed as procedures themselves.

Procedures are the key element to the success of any operation, and the development of command and control structure should be based on the effects of procedures and on tactical patterns.

Conclusions

This thesis examines the operational core of firefighting operations. The papers, upon which the thesis is based, explore the effects of various firefighting procedures, and the effects of combinations of procedures varying in time and space. Such a combination of procedures is defined as a tactical pattern.

The main contributions by this thesis to the development of theory on fire and rescue operations are that it brings a better understanding of the inherent dynamics of firefighting operations, and that it suggests an approach to the modelling of firefighting operations based on the analysis of empirical data.

A perspective on the response of the fire and rescue service to emergencies, represented by the succession: procedure – (tactical patterns) – operations – control, is presented. In addition, a firefighting operation is a problem solving system, based on the initiation, coordination and execution of procedures.

The general solution that this problem solving system works towards is control. Consequently, control is the overall objective of a fire and rescue operation. It is only through control that the course of events on the fireground can be directed in an intended direction, and it is through the initiation, coordination, and execution of procedures that control is obtained and maintained. Consequently, the operational problem of fire control consists of taking advantage of the available resources in the best possible way (as an optimum), in order to obtain and maintain control.

Although firefighting operations often have very complex inherent dynamics, mathematical modelling of such operations may be accomplished. Such modelling is, together with an increasing understanding of the dynamics of fire and rescue operations, crucial to post-analysis and evaluation of fire and rescue operations.

Additional results can be found in the papers enclosed in this thesis.

Continued work

This thesis serves, a great deal, as a basis for continued work. Through the presented perspective on procedures, tactical patterns, operations and control, it should be possible to further advance knowledge on fire and rescue operations.

Efforts should be put into investigating the effects of the individual procedures used by the fire and rescue service as well as on investigating the effects of various tactical patterns. Experimental work, as well as the further advancement of theoretical conceptions, is important in this work.

Also, emphasis should be placed on the development of models, using existing experimental data as well as data from experiments to come. In addition, the suggested approach to the modelling of firefighting operations, based on the analysis of various tactical patterns, needs verification. Theoretical work in the further advancement of the understanding of the inherent dynamics of firefighting operations is greatly needed.

Based on the findings in this thesis, efforts should be made to find methodology in how fire protection design and fire safety measures in buildings can be used as tactical assets during firefighting operations.

A command and control structure for the fire and rescue service should be developed. In addition, such a command and control structure should include aspects on the management of organisations and human factors, such as leadership.

Also, continued experimental as well as theoretical and modelling work should include emergencies such as fires in various geometries, fires of various sizes, accidents in transportation systems and accidents involving chemical substances.

Acknowledgements

I would like to express my gratitude to my supervisor, Professor Göran Holmstedt. He has with kindness and with great interest placed his expertise at my disposal.

Also, I would like to specially thank Professor Lars Fredholm for offering me his advice and kind support. Especially, our occasional discussions on command and control during firefighting operations and on methodology in science have helped me to gain insight in the world of science.

My research has been conducted within my employment at the Swedish Rescue Services Agency, and they have provided me with financial and benevolent support during my work. I am very grateful to the agency for giving me this opportunity.

Dr. Åke Davidsson has offered me great support and encouraging thoughts in finalizing the thesis and he is gratefully acknowledged.

All the people who I have met during the years have contributed in various ways, and all of you have your share in this thesis. Especially, Sören Lundström, Claes Nicklasson and Ivar Rönnbäck who have offered me great support during the experimental work and when I by necessity have been engaged in administrative work. Also, the firefighters who have put their lives at stake during my experiments should be acknowledged. Thank you all for your kind and engaging support!

I am very grateful to the staff at the Department of Fire Safety Engineering at Lund University. They have always offered me their kind support and a seat at the coffee table.

A very special thanks to my family, Annika, Tova, Ella and to our pets, past and present. The children are the future.

I realize that I have on occasion been a real pain in the XXX to my fellow beings, therefore – to all I love and care about: Forgive me for being absent, even when present!

Thank you people, thank you!

References

Andersson, P., Arvidsson, M., Holmstedt, G. *Small scale experiments and theoretical aspects of flame extinguishment with water mist* (report 3080). Lund: Lund Institute of Technology. 1996.

Artman, H. *Fördelade kunskapsprocesser i ledningscentraler vid nödsituationer – koordination och situationsmedvetenhet* (Thesis). Linköping University: Department of Communication Studies. 1999.

Bennett, B. L., Hagan, R. D., Banta, G. & Williams, F., Physiological responses during shipboard firefighting, *Aviat. Space Environ. Med*., 66. 1995.

Beyler, C., A Unified Model of Fire Suppression, *Journal of Fire Protection Engineering*, 4 (1). 1992.

Bishop, M. J. & Stroup, D. W. (1997) Impact of Firefighting Agents on Drop Size. In Proceedings: *2nd International Conference. Fire Research and Engineering*. National Institute of Standards and Technology and Society of Fire Protection Engineers. August 10-15, 1997, Gaithersburg, MD, 1997.

Brehmer, B. Dynamic Decision Making in Command and Control. In McCann, C & Pigeau, R. (Eds.), *The Human in Command: Exploring the Modern Military Experience*, New York: Kluwer Academic/Plenum Publishers. 2000.

Brunacini, A.V. *Fire Command.* NFPA: Quincy, MA. 1985.

Chefen för armén. *Arméreglemente del 2 Taktik (AR2)*. (M7741-100612). Stockholm: Försvarsmakten. 1995.

Clausewitz Von, C. *On War*. Penguin Books. 1968.

Collins COBUILD English Dictionary. (3rd edition). London: Collins. 2001.

Cook, Jr.J.L. *Standard Operating Procedures and Guidelines*. Saddle Brook, NJ: PennWell Publishing Company. 1998.

Davis, P. O. & Dotson C. O. Physiological aspects of firefighting, *Fire Technology*. 1986.

Delichatsios, M & Delichatsios M.M. Critical Mass Pyrolysis Rate for Extinction of Fires over Solid Materials. In *Proceedings of The Fifth*

International Symposium on Fire Safety Science. Melbourne, Australia. 1997.

Dunn, M. J., *Full-Scale Testing of Fire Suppression Agents on Unshielded Fires*. School of Engineering, University of Canterbury, New Zealand, 98/2. 1998.

Dunn, V. *Command and control of fires and emergencies*. Saddle Brook, NJ: PennWell Publishing Company. 1999.

Fire Service Manual; Fire service Operations (Volume 2), *Compartment Fires and Tactical Ventilation*. London: Home Office. 1997.

Fredholm, L. Decision making patterns in major firefighting and rescue operations. In Flin, R., Salas, E., Strub, M. & Martin, L. (Eds.). *Decision Making Under Stress: Emerging Themes and Applications*. Ashgate Publishing Ltd. 1997.

Fredholm, L. *Det operativa problemet* (In Swedish). Unpublished manuscript. Karlstad: National Defense Research Establishment, Department of Human Studies. 1992.

Fredholm, L. *Firefighting and rescue tactics, analyses and development of concepts*. (FOA report R-95-00128-5.3-SE). Stockholm: National Defense Research Establishment, Department of Human Studies. 1995.

Fredholm, L. *The development of rescue tactics, Analysis and proposed methods*. (FOA report C50089 - 5.3). Sundbyberg: National Defense Research Establishment, Department of Human Studies. 1991.

Gardiner, A.J. *The mathematical modeling of the interaction between sprinkler sprays and the thermally buoyant layers of gases from fires*. London: The Fire an Explosion Group. Hertfordshire: Fire Research Station. 1988.

Gojkovic, D. & Bengtsson, L. Some Theoretical and Practical Aspects on Firefighting Tactics in a Backdraft Situation. In Proceedings: *9th International Fire Science & Engineering Conference (Interflam'01).* Edinburgh, 17th – 19th September 2001. Interscience communications, London, 2001.

Hay, A.. *A Survey of Fire Ventilation* (Home Office, Publication No 6/94). London: Home Office Fire Research and Development Group. 1994.

Heikkilä Timo V, Grönqvist Roy, Jurvélius Mike. *Handbook on Forest Fire Control : A guide for trainers*. National Board of Education of the Government of Finland. 1993.

Hollnagel, E. & Woods, D.D. Cognitive Systems Engineering: New wine in new bottles. *International Journal of Man-Machine Studies*, 18, pp 583 – 600. 1983.

Hollnagel, E. *Human reliability analysis, Context and Control*. London: Academic Press. 1993.

Holmstedt, G. *Kompendium i släckmedel - släckverkan* (In Swedish). Lund: Institutionen för brandteknik. 1998.

Home Office. *Dealing With Disasters*. 3rd edition. London. 2000.

IFSTA. The International Fire Service Association. *Essentials of Firefighting*, *3rd ed*. Oklahoma State University: Fire Protection Publications. 1992.

Ingason, H. & Fallberg, R. *Övertrycksventilation i medelstora lokaler* (Postitive pressure ventilation in large compartments, in Swedish) (SP-report 1998:41). Borås: SP – Swedish National Testing and Research Institute. 1998.

Jenvald, J. *Methods and Tools in Computer-Supported Taskforce Training*. Linköping University: Department of Computer and Information Science. 1999.

Jones, C.R. Problem Solving Systems: A New Concept for a Science of C2. In Jones, C.R. (Ed.) *Toward a Science of Command, Control, and Communications*, volume 156, Progress in Astronautics and Areonautics. The American Institute of Astronautics and Areonautics. 1993.

Karlsson, B. & Quintiere, J.G. *Enclosure Fire Dynamics*. Florida: CRC Press. 1999.

Kilbom, Å. Physical work capacity of firemen with special reference to demands during firefighting. *Scandinavian Journal of Work Environ Health* 1980:6, pp 48 - 57.

Klein, G. *Sources of Power – How People Make Decisions*. MIT Press. 1998.

McCaffrey, B.J. Jet Diffusion Flame Suppression using Water Sprays. *Combustion Science and Technology*, vol 40, no 3 – 4, 1983.

Mell, W.E. & Lawson, J.R. A Heat Transfer Model for Firefighters' Protective Clothing. *Fire Technology*, vol. 36, No. 1, 2000.

Milke, J., Evans, D., Hayes Jr., W., *Water Spray Suppression of Fully-Developed Wood Crib Fires in a Compartment*, U. S. Department of Commerce, National Bureau of Standards, NBSIR 88-3745, 1988

Norman, J. *Fire officer's handbook of tactics*. 2nd edition. Saddle Brook, NJ: PennWell Publishing Company. 1998.

Orasanu, J. Stress and naturalistic decision making: Strengthening the weaks links. In: Flin, R., Salas, E., Strub, M. & Lynne, M. (Eds.) *Decision Making Under Stress, Emerging themes and applications.* Ashgate Publishing Ltd: Hants, England. 1997.

Orasanu, J., & Connolly, T. The Reinvention of decision making. In: Klein, G. A., Orasanu, J., Calderwood, R., & Zsambok, C. E. (Eds.) *Decision making in action, models, and methods*. Ablex Publishing Corporation: Norwood, New Jersey. 1992.

Paul, C. *Fighting Fire*. St. Martins Press: New York, New York. 1998.

Persson, P-A. *Bringing Power and Knowledge Together: Information Systems Design for Autonomy and Control in Command Work.* Linköping University: Department of Computer and Information Science. 2000.

Pietrzak, L.M. (1993). *Recent research and future requirements for modelling fire suppression effectiveness*. Paper prepared for BRANDFORSK (The Swedish Fire Research Board). (Unpublished).

Pyne, S. *World Fire: The Culture of Fire on Earth*. Seattle: University of Washington Press. 1997.

Pyne, S., Andrews, P.L. & Laven, R.D. *Introduction to Wildland Fire*. 2nd edition. Wiley. 1996.

Rasbach, D. J., Theory in the Evaluation of Fire Properties in Combustion Materials, In *Proceedings of the Fifth International Fire Protection Seminar*, Karlsruhe, Germany, 1976.

Rasmussen, J. Deciding and Doing: Decision Making in Natural Contexts. In: Klein, G. A., Orasanu, J., Calderwood, R., & Zsambok, C. E. (Eds.) *Decision making in action, models, and methods*. Ablex Publishing Corporation: Norwood, New Jersey. 1992.

Rasmussen, J. Skill, rules and knowledge: Signals, signs, and symbols, and other distinctions in human performance models. *IEEE Transactions on Systems, Man and Cybernetics*, SMC-13(3), 257-266, 1983.

Rimen, J. G., *The Use of High Pressure and Low Pressure Pumps With Hosereel* Systems, Central Fire Brigades Advisory Council, Scottish Central Fire Brigades Advisory Council, Joint Committee on Fire Research, Research Report Number 36, 1990.

Rimen, J.G. *An Assessment of the Use of Positive Pressure Ventilation in Domestic Properties* (Home Office, Publication No 17/96). London: Home Office Fire Research and Development Group. 1996.

Romet, T. T. & Frim, J., Physiological responses to firefighting activities. *European Journal of Applied Physiology*, 56, pp 633-638. 1987.

Rosenberg, T. Statistics for Prevention in Sweden. *Fire Safety Journal*, vol. 33 (4). 1999.

Routley, J.G. Fire department operations. In Cote, A.E. (Ed.). *Fire Protection Handbook*. 17th edition. Quincy, MA: NFPA. 1991.

Rubini, P,A. SOFIE - Simulation of Fires in Enclosure. In Proceedings: *5th International Symposium on Fire Safety Science*, Melbourne, Australia, March 1997.

Räddningstjänstlag (1986:1102), ändringar till och med SFS 1999:383 (Swedish Rescue Services Act, in Swedish).

Räddningstjänstförordning (1986:1107), ändringar till och med SFS 2000:899 (Swedish Rescue Services Decree, in Swedish).

Räddningsverket. *Brandsyn förr och nu* (Fire inspection of today from a historical perspective, in Swedish). Karlstad. 1992a.

Räddningsverket. *Räddningstaktik, påverkan och utformning*. (Rescue tactics, influences and design, in Swedish). Karlstad. 1992b.

Räddningsverket. *Grunder för ledning, generella principer för ledning av kommunala räddningsinsatser*. (The elements of command and control, general principles for command and control in municipal fire and rescue operations, in Swedish) (report U14-569/98). Karlstad. 1998.

Räddningstjänst i siffror 2000 (Swedish statistics on fires and fire & rescue service operations, in Swedish). Räddningsverket, Karlstad, 2001a.

Räddningsverket. *Brandmannens fysiska förmåga, delrapport 1 – typinsatser*. (Physical ability of the firefighter, report 1 – standard operations, in Swedish). (report P21-379/01). Karlstad. 2001b.

Sarter, N.B. & Woods, D.D. How in the World Did We Ever Get into That Mode? Mode Error and Awareness in Supervisory Control. *Human Factor*, vol. 37(1), pp 5 – 19. 1995.

Sköldström, B. Physiological Responses of Firefighters to Workload and Thermal Stress. *Ergonomics*, 1987;30, 11, pp1589-1597. 1987.

Statens Haverikommission. Brand på Herkulesgatan i Göteborg, O län, den 29 – 30 oktober 1998 (Rapport RO 2001:02, O-07/98). 1998.

Stroup, D. W., Evans, D. D., *Suppression of Post-Flashover Compartment Fires Using Manually Applied Water Sprays*, U. S. Department of Commerce, National Institute of Standards and Technology, NISTIR 4625, 1991.

Svensson, S. *Solving Tactical Problems Using Control Engineering: Systems identification and Modeling*, Report 1017. Department of Fire Safety Engineering, Lund. 1998.

Svensson, S. *Räddningstaktiska grunder, förslag till definitioner och kommentarer därtill*. (In Swedish) (report P21-252/99). Räddningsverket: Karlstad. 1999.

Svensson, S. *Brandgasventilation* (U30-602/00), Räddningsverket, 2000a.

Svensson, S. Fire Service Actions as Part of the Fire Safety Design. In Proceedings: *3rd International Conference on Performance-Based Codes and Fire Safety Design Methods*, Lund, Sweden, 15th – 17th June, 2000b.

Svensson, S. Developing a command structure within the fire services - from enlistment to a viable system. In Jennings, Charles (Ed.). *Improving Firefighter Safety: Human Behavior and Organizational Aspects. An International Conference*. Alexandria Virginia: Institution of Fire Engineers, United States Branch. 2001.

Svensson, S. Experimental Study Of Fire Ventilation Actions During Firefighting Operations. *Fire Technology*, vol. 37, No. 1, 2001.

Svensson, S. A Study of Tactical Patterns During Firefighting Operations. *Fire Safety Journal,* vol. 37, no. 7, pp 673 – 695, 2002.

Svensson, S., Lundström, S. Live Fire Tests on Suppression of Post-flashover Fires Using Manually Applied High and Low Pressure Water Sprays. In Proceedings: *8th International Fire Science & Engineering Conference (Interflam'99)*. Interscience communications, London. 1999.

Svensson, S. & Werling, P. Experimental Study Of Fire Ventilation Procedures In A Large Hall. In Proceedings: *9th International Fire Science & Engineering Conference (Interflam'01).* Edinburgh, 17th – 19th September 2001.Interscience communications, London, 2001.

Svensson, S. & Särdqvist, S. Fire Tests In A Large Hall, Using Manually Applied High- And Low Pressure Water Sprays. *Fire Science and Technology*, vol. 21, No. 1, 2001.

Särdqvist, S, Holmstedt, G, Water for Manual Fire Suppression, *Journal of Fire Protection Engineering*, vol.11 No.4. 2001.

Tengblad, S. *The nature of control, a study of CEO behavior*. (GRI-rapport 2000:10). Göteborg University: Gothenburg Research Institute. 2000.

Worm, A. *Command and Control Sciences: Theory and Tactical Applications* (report Liu-Tek.Lic-1998:49). Linköping University: Institute of Technology. 1998.

Ziesler, P.S., Gunnerson, F.S. & Williams, S.K. "Advances in Positive Pressure Ventilation", *Fire Technology*, Vol. 30, Second quarter, 1994.

Paper I: Live fire tests on suppression of post-flashover fires using manually applied high and low pressure water sprays

Stefan Svensson and Sören Lundström

Interflam'99, 8th International Fire Science & Engineering Conference, Edinburgh, 29th June – 1st July 1999.

Live fire tests on suppression of post-flashover fires using manually applied high and low pressure water sprays

Stefan Svensson & Sören Lundström
Swedish Rescue Services Agency

Abstract

Live fire/suppression tests were performed in a 12 × 5 × 2.5-m steel structure with a 2.5 × 1.1-m opening, using high and low pressure manually applied water sprays. The purpose was to compare a high-pressure (~ 40 bar pump pressure) firefighting system (pump, hose and nozzle) with a normal pressure (~ 10 bar pump pressure) firefighting system, both systems mounted on a fire engine. Appropriate firefighting techniques, respectively, were also considered. One normal-pressure nozzle and two high-pressure nozzles where tested. The tests included water application using a manually oscillated nozzle from a fixed position within the room as well as using actual firefighting techniques, i.e. firefighters advancing from the opening into the room while applying water in an oscillating pattern. The temperature was measured at 18 positions within the room and the total amount of water used as well as the water flow was recorded for each test/nozzle. Also the different techniques used in the tests were recorded. Conclusions from the tests were that high-pressure water sprays reduce the temperature more than low-pressure water sprays, especially when applying water oscillating from a fixed position within the room. When having firefighters advancing through the room, high-pressure water sprays reduced the temperature faster but not significantly to a lower level than when using low-pressure water sprays. The tests also showed that high and low pressure water sprays require different techniques, which could have a dramatic effect on firefighting tactics as well as on the safety of firefighers. The tested high-pressure systems also have the advantage, in relation to low-pressure systems, in that they use a rigid hose mounted on a hose reel, which generally decreases the attack time, i.e. the time from arriving at the fire-scene until the time when it is possible to apply water on the fire.

Introduction

The basic concept of firefighting is putting out fires within buildings or compartments, using manually applied water sprays. In practice, this is not a problem – putting water on the fire generally puts it out. More fire – more water. As long as this activity is restricted to residential fires, one or two nozzles usually are sufficient for firefighting. However, in some situations, such as when the firefighting resources are critical in relation to the fire and its development, the problem becomes how to use the available water in the most efficient way. This includes problems such as minimizing water application rate (which also has a positive influence on salvage) and speeding up the firefighters when stretching a hose or when attaching the pump to a fire hydrant. It also includes the actual firefighting inside a burning room/building, considering type of nozzle, its working pressure and then also the droplet size, in relation to the fire and its development.

The purpose of the work described in this paper was to compare a high-pressure firefighting system (pump, hose and nozzle) with a normal pressure firefighting system. Both systems where mounted on a Swedish standard fire truck. A high-pressure pump delivers water at approximately 40 bars. A low-pressure pump delivers water at approximately 10 – 12 bars. With the tested systems the nozzle pressure were approximately 20 – 30 and 6 – 8 bars, respectively.

Theoretical framework

Many attempts have been made in order to theoretical solve the problem of suppression of post-flashover compartment fires using manually applied water sprays. The minimum water application rate for extinguishing was found to be 96 g/m^{2}min (1.6 g/m^{2}s) fuel area [1]. Also, firefighters during extinguishing of real fires often uses as much as 20 – 100 times more water, i.e. 2 – 10 l/m^{2}min fuel area. This corresponds to using a normal pressure type of nozzle when fighting residential fires. These nozzles generally deliver 100 – 300 l/min (1.67 – 5 l/s), which, from a firefighters point of view, is sufficient for fires in 50 – 150 m^2 apartments.

The effect of flame temperature reduction due to water sprays correlate with a single spray parameter, the median drop diameter [2]. In addition, the drop size also has an impact on the velocity of the drops and consequently their ability to penetrate the fire plume [3]. Large drops penetrate the fire plume easier than smaller drops. In addition, smaller drops have larger surface area in relation to their volume and they therefore heats up and evaporate faster, consequently absorbing more heat.

The effect of the spray generating a decrease in rate of heat release is due to the evaporation of droplets moving through a hot gas. Evaporation depends to a great deal on diameter, temperature, and transport properties of the droplet [4]. When the water spray passes through the hot gases, heat transfers to the droplets, which then starts to evaporate. Heat is transferred to small droplets (D < 0.1 mm) mainly through natural convection. Larger droplets (D ≥ 0.5 mm) are mainly affected by forced convection due to the vertical velocity induced by their weight. Small droplets will evaporate very fast and will mainly have gas phase effect on suppression. Large droplets will not entirely evaporate when passing through flames and hot gases, unless the flames are very deep, which usually not is the case in apartment fires. Instead, these droplets will largely pass through the flames and hit the burning material, causing a decrease in pyrolysis.

Reynolds number (Re) is defined by

$$\mathrm{Re} = \frac{\rho \cdot v \cdot D}{\mu} \qquad \textbf{Equation 1}$$

where	ρ	density
	v	velocity
	D	diameter
	μ	viscosity

The droplets from a nozzle (that similar to a sprinkler) cover a wide range of sizes and velocities, which means that Reynolds number will vary throughout the spray. The Reynolds number of a droplet defines the following conditions [5]:

- the physical behavior of the fluid within a drop
- the heat and mass transfer between a drop and hot gas
- the drag force and trajectory of a droplet

In manually applied water sprays Reynolds number is very large, much larger than boundary for turbulent conditions (Re > 2100). The water spray breaks up, representing a variety of velocities and sizes.

When the water spray hits the burning surface, it absorbs heat by heating and by evaporation. The maximum rate of heat absorption can easily be determined by using water application rate (i.e. the water that hits the wall), heat of evaporation, heat capacity and temperature of the water at initial and final state. However, the heat transfer between the burning surface and the individual droplets [6] also determines the rate of heat absorption. Velocity of individual droplets, their diameter and the temperature of the wall in turn determine heat transfer. Webers number (We) can be used for describing relations at the collision,

$$We = \rho \cdot v^2 \cdot \frac{D}{\delta}$$ **Equation 2**

where	ρ	density of the droplet
	v	velocity of the droplet
	D	diameter of droplet
	δ	surface tension at saturation temperature

For We > 80 it can be shown through tests that droplets that hits polished surfaces breaks up into smaller droplets. Film forming also has a large impact on heat transfer. When the droplet hits the surface, it spreads out to a uniform film. It then contracts due to surface tension. The longer the droplet stays on the surface, the larger the heat transfer.

This infers that the surface temperature mainly determines the evaporation of the droplet at the surface. At large surface temperatures (~> 400°C) the evaporation starts under the center of the droplet and spreads rapidly as the droplet forms a film on the hot surface. This makes the droplet "isolated" from the hot surface by steam. Heat transfer from the surface to the droplet is small and the droplet "lives" a long time. At lower temperatures (~ 300°C), most of the droplet stays in contact with the surface for a longer time. The cooling is here larger than for surfaces with temperatures over 400°C. At even lower surface temperatures (~<200°C), the droplet stays in contact with the hot surface until it has completely evaporated. The cooling will then be very large.

The burning rate of a solid fuel can be describe by an energy balance at the fuel surface [7],

$$\dot{m}'' \cdot L_v = f \cdot \Delta H_c \cdot \dot{m}'' + \dot{Q}''_E - \dot{Q}''_L$$ **Equation 3**

where $\dot{m}''$ burning rate per unit area

L_v heat of gasification

f fraction of heat released transferred back to surface

ΔH_c heat of combustion

$\dot{Q}''_E$ externally applied heat flux

$\dot{Q}''_L$ heat lost from the surface

The extinction condition is defined by the conditions under which the gaseous flame above the surface can no longer be sustained. This can be determined by a critical mass pyrolysis rate below which the flame no longer can be sustained. The dynamics of the gaseous reactions can also be separated from the energy balance in the solid material[8]. The extinction condition is then determined by the critical mass pyrolysis rate.

The water spray also has the purpose to reduce flame and gas temperature, due to heating of the droplets when passing through the flames and hot gases.

As was described earlier, manually applied water sprays therefore have two effects of extinction that can be identified and observed visually through simple experiments:

- It generates a decrease in rate of pyrolysis mainly induced by decrease in radiation from flames and hot gases to the fuel, i.e. it reduces the externally applied heat flux, $\dot{Q}''_E$ (eq. 3).
- It penetrates through the flames, hits the burning surface and causes a decrease in rate of pyrolysis, induced by a cooling of the surface, i.e. it increases the rate of heat loss from the surface, $\dot{Q}''_L$ (eq. 3).

Practical consequences of this are that it is very hard to reach a high degree of evaporation (and consequently suppression) when applying water on surfaces, especially when using manually applied water sprays.

The purpose of the jet or the spray is, in addition to strictly practical reasons, amongst other to increase the surface of the extinguishing media. Extinguish mechanisms, how water is applied to fires, and how the jet or the spray affects the fire can easily be summarized [1]. The jet or the spray affects fires in several ways:

- The momentum in the spray is transferred to a stream of air, which increases turbulence and stirring. This will usually increase the rate of heat release in the initial stage.
- The effect of the spray to the gases generates a decrease in rate of heat release and radiation from the flames.
- The jet or the spray penetrates through the flames, hits the burning surface and causes a decrease in rate of pyrolysis.

All of these effects can be observed during real firefighting, although they are very hard to physically model. In addition with human aspects of fighting fires, variations in application rates, water spray cone angles and drop diameter (depending on e.g. settings and wear of the nozzle), this make up a very complex situation.

Experiments

Background

Until the late 1960s and in the beginning of the 1970s, fire brigades in Sweden used high-pressure firefighting systems, i.e. manually applied water sprays with a nozzle pressure of approximately 40 bars. However, this technique fell into oblivion, mainly because of defective technique (pumps, hoses and nozzles) and due to introduction of new efficient low-pressure firefighting equipment and technique in combination with better training. In recent years, the focus has again turned to high-pressure firefighting systems. The reasons are multiple, such as better materials in pumps and hoses, stronger engines on the fire trucks, better protective clothing, and above all, a demand for faster, better and more efficient firefighting. Research on the use of high-pressure pumps with hose reel systems[9], shows that the benefits mainly are the ability to increase the rate at which water can be applied to the fire, i.e. the speeding up the operation. It also increases the throw of the water. However, research also shows that a high-pressure system reduces the time to extinction as well as the total requirement of water [10]. Previous research on high-pressure systems vs. low-pressure systems does not incorporate the problem of having an actually manually applied water spray, i.e. using firefighters to operate the nozzle, by their own training and experience.

Purpose

The purpose of the tests was to compare a high-pressure (~ 40 bar pump pressure) firefighting system (pump, hose and nozzle) with a normal pressure (~ 10 bar pump pressure) firefighting system, both systems mounted on a fire engine. Appropriate firefighting techniques, respectively, were included in the tests. Temperature and flow rates were measured.

Set-up

A normal-pressure nozzle, FogFighter® [11], and two high-pressure nozzles where tested, Akron Force Style 751™ [12] and Rosenbauer Servo-NePiRo™ [13]. The tests included water application using a manually oscillated nozzle from a fixed position within the room. They also included actual firefighting techniques, i.e. firefighters applying water in an oscillating patter while advancing from the opening into the room.

The droplet sizes for the nozzles vary in the range 0.2 mm (the high-pressure nozzles) to 0.7 mm (the low-pressure nozzle) (mean droplet diameter). This is the very range were large differences can be observed in how droplets behave in a fire situation [4, 5, 6].

The tests were performed in a 12 × 5 × 2.5-m steel structure with a 2.5 × 1.1-m opening, figure 1.

The fuel area was approximately 18 m^2, consisting of 18-mm thick particleboard. The fuel was applied on the walls and in the ceiling at the far end of the room. The temperature was measured at 18 positions within the room. Thermocouples where located at heights 1 and 2 m above floor, at 0.1 m, 2.5 m and 7.5 m from far end wall, respectively. 16 of the thermocouples were grouped in 4×4, table 1, denomination as in figures 3 and 4. This was done for practical reasons and resulted in a mean value of the 4 thermocouples, respectively The total amount of water used as well as the water flow was recorded for each test/nozzle. In addition, the different techniques used in the tests were recorded, by report of the firefighters.

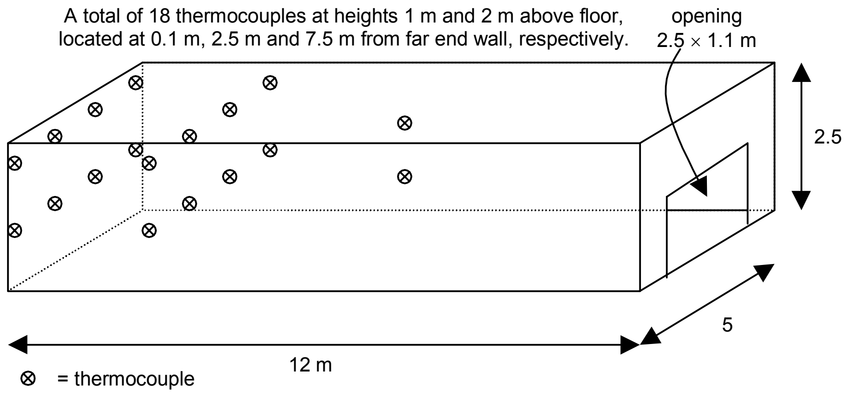

Figure 1. Dimensions and layout of the fire room used during the tests.

8 burns were performed, including 15 tests (2 tests on each burn except the last burn). The tests included different types of nozzles, representing different droplet sizes, different flow rates and also different firefighting technique, table 2. Criteria for starting water application (starting the firefighting) were at a stable upper layer temperature in the fire room. Criteria for extinguishing were at an estimated leveling minimum temperature in the upper layer of the room.

The last test, # 8, was performed for reference reasons, i.e. to relate these tests to a similar set-up.

Results

The results from the tests are summarized in table 2. Tests #4, 7a and 3a are shown in figures 2 – 4 below.

During test #1a, 2a and 3a, water was applied in 5 s pulses, the spray oscillating in a circular pattern in the room. The firefighters were located 5 m from the far end wall during water application.

During test #1b, 2b, 3b and 4b, water was applied continuously during a period as specified in table 2 columns 6, respectively. The spray oscillated in a circular pattern in the room. The firefighters were located 5 m from the far end wall during water application.

The tests # 5a, 6a, 6b, 7a and 7b were performed using a “correct” firefighting technique, i.e. the firefighters advancing from the opening into the room. In general this technique can be described as

- securing attack and retreat route by cooling hot gases just inside opening,
- continuously cooling (by short pulses, ~0.5 – 2 s, of water sprays in an oscillating circular pattern) of hot gases, flames, walls and ceiling during advancement into the room, and finally
- cooling of the fuel.

Test # 4a was performed using a "correct" firefighting technique, i.e. by using short pulses, ~0.5 – 2 s, of water sprays, but from a fixed position at 5 m from far end wall.

Table 1. Placing and denomination of thermocouples

Denomination	**Height above floor**	**Distance from wall**	**Placing**
Upper wall	2 m	0.1 m	Upper part of compartment
Lower wall	1 m	0.1 m	Lower part of compartment
Upper mid	2 m	2.5 m	Upper part of compartment
Lower mid	1 m	2.5 m	Lower part of compartment
Upper outer	2 m	7.5 m	Upper part of compartment
Lower outer	1 m	7.5 m	Lower part of compartment

Test # 5b was interrupted due to high levels of heat exposure to firefighters. One of the firefighters received first-degree burns on arms, shoulders and neck. This was probably due to the generated steam.

Table 2. Descriptions and results from the tests.

Test #	Nozzle	Mean drop diameter, mm	Flow, l/s	Total water used, l	Time to extinguishing criteria, s	Used firefighting technique
1a	Fog-Fighter ®	0.7	1.67	87	73	Pulsating (~5 s pulses), oscillating flow, fixed position at 5 m from far end wall
1b	Fog-Fighter ®	0.7	1.67	138	83	Continuous, oscillating flow, fixed position at 5 m from far end wall
2a	Akron™	0.2	2	97	81	Pulsating (~5 s pulses), oscillating flow, fixed position at 5 m from far end wall
2b	Akron™	0.2	2	286	143	Continuous, oscillating flow, fixed position at 5 m from far end wall
3a	Akron™	0.2	2	69	64	Pulsating (~1 s pulses), oscillating flow, fixed position at 5 m from far end wall
3b	Akron™	0.2	2	218	109	Continuous, oscillating flow, fixed position at 5 m from far end wall
4a	Akron™	0.2	2.83	153	181	Pulsating (~0.5 – 2 s pulses), oscillating flow, fixed position at 5 m from far end wall
4b	Akron™	0.2	2.83	158	56	Continuous, oscillating flow, fixed position at 5 m from far end wall
5a	Akron™	0.2	2.83	48	202 (?)	Pulsating (~0.5 – 2 s pulses), oscillating flow, advancing from the opening into the room

Table 2, continued.

5b	Akron™	0.2	2.83	26	87 (?)	Pulsating (~0.5 – 2 s pulses), oscillating flow, advancing (test interrupted due to injured firefighter)
6a	Rosen-bauer™	0.2	2.93	26	186	Pulsating (~0.5 – 2 s pulses), oscillating flow, advancing from the opening into the room
6b	Rosen-bauer™	0.2	2.93	62	298	Pulsating (~0.5 – 2 s pulses), oscillating flow, advancing from the opening into the room
7a	Fog-Fighter ®	0.7	5	26	165	Pulsating (~0.5 – 2 s pulses), oscillating flow, advancing from the opening into the room
7b	Fog-Fighter ®	0.7	5	28	78	Pulsating (~0.5 – 2 s pulses), oscillating flow, advancing from the opening into the room
8	Akron™	0.2	2.12	394	186	Continuous, non-oscillating flow, fixed position at 5 m from far end wall

Discussion

One of the major problems during tests was to establish criterions for starting water application (starting firefighting) and for extinguishing. Calculations were made in advance in order to get an apprehension of the test set up and also to establish criteria for starting water application. However, it was early realized that such calculations needed to be supplemented with expert judgments during the tests. Therefore this criterion simply was set at a stable upper layer temperature in the fire room. A criterion for extinguishing is even harder, since it is very hard to estimate an extinguishing temperature by calculations. By using expert judgments of the measured temperature in combination with visual observations made by the firefighters, the criteria could be set at an estimated leveling temperature in the upper layer of the room. Figure 2 shows a representative case of the measured temperature during one of the tests (test # 4). These criterions turned out to be sufficient, since the purpose of the tests were comparative and not to establish any absolute extinguishing capacity of the different systems.

During these tests the estimation of when extinguishing criteria was reached was entrust to the firefighters. This included visual observations as well as their sensation of temperature. In combination with on-line monitoring of the room temperature, this gave was ascertained as a fairly good estimate. Expert judgment is an important aspect when it comes to real firefighting.

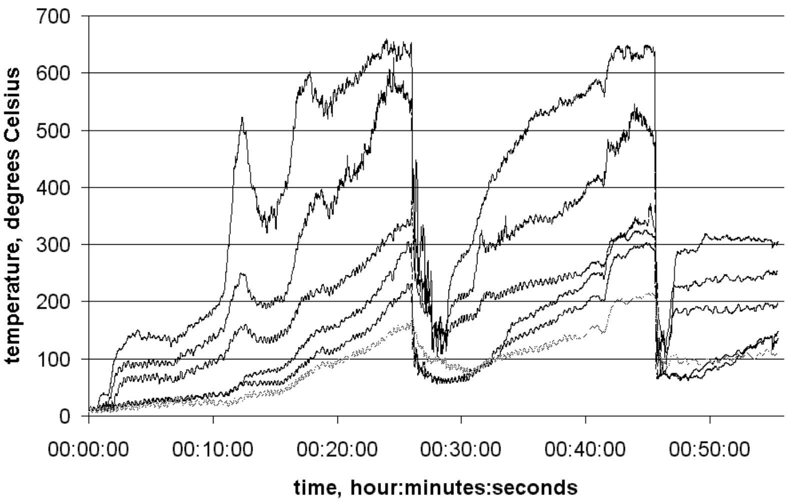

Figure 2. Test # 4 in table 2, using an Akron Force Style 751™ high-pressure nozzle at 2.83 l/s.

Smaller droplets generated by the high-pressure nozzles (Akron Force Style 751™ [12] and Rosenbauer Servo-NePiRo™ [13]), evaporates more or less completely in the burning gases. This generates a decrease in rate of pyrolysis mainly induced by decrease in radiation from flames and hot gases to the fuel. It also generates a faster re-ignition of the fuel. This can be observed by comparing figures 3 and 4, above. The faster re-ignition in figure 4 is due to the lack of cooling of the fuel. Larger droplets generated by the low-pressure nozzle (FogFighter® [11]), penetrate the flames and hit the fuel. This causes a decrease in rate of pyrolysis, induced by cooling of the surface.

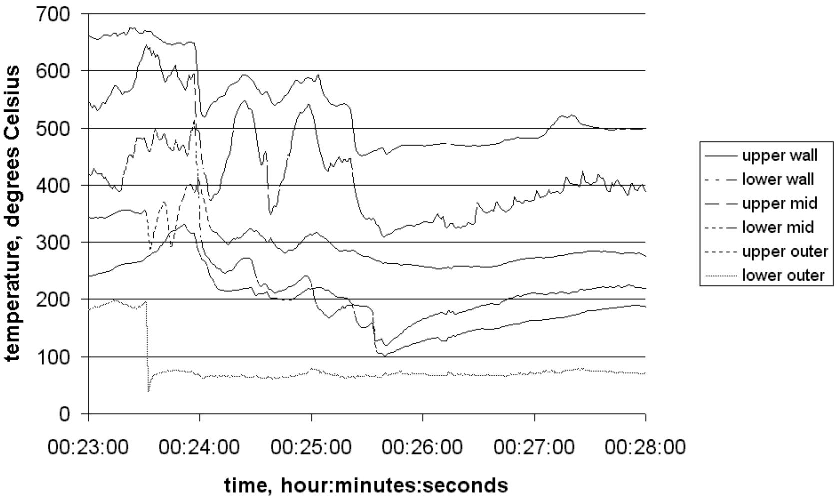

Figure 3. Test # 7a in table 2, using a FogFighter® low-pressure nozzle, at 5 l/s.

When using high-pressure water sprays the firefighters made the observation that it seemed as if the nozzle generated more steam than when using a low-pressure nozzle. This is probably due to the fact that smaller droplets from the high-pressure nozzle evaporate faster, thus generating more steam closer to the firefighters. This shows importance of using appropriate technique for the nozzles, respectively. A high-pressure nozzle needs to be used closer to fire and also in a higher angle, i.e. aiming at the ceiling. Using inappropriate technique increases the risk of burn injuries to the firefighters.

A comparison of figures 3 and 4 (using appropriate firefighting technique, i.e. advancing through the room) also show that high-pressure water sprays reduces the temperature faster but not significantly to a lower level than when using low-pressure water sprays. When applying water from a fixed position in the room, high-pressure water sprays reduced the temperature more than low-pressure water sprays.

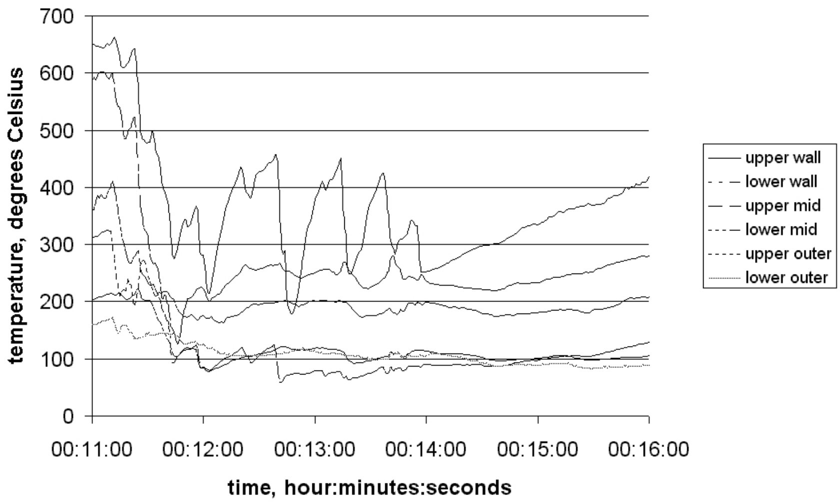

Figure 4. Test # 6a in table 2, using a Rosenbauer Servo-NePiRo™ high-pressure nozzle, at 2.93 l/s.

It was also observed by the firefighters that the momentum in the spray was transferred to a stream of air, which increased turbulence and stirring and also brought air into the burning gases. This increased the rate of heat release during a very short period in the initial stage when applying water. The period was very short and is hard to observe through the measured temperature.

Besides having differences in droplet size and trajectory of the spray, and therefore differences in extinguishing, high- and low-pressure systems also showed more pragmatic differences. In relation to low-pressure systems, high-pressure systems generally have the advantage, in that they use a rigid hose mounted on a hose reel, which generally decreases the attack time, i.e. the time from arriving at the fire-scene until the time when it is possible to apply water on the fire. However, this reduces the applicability of high-pressure systems, to fires within an approximately 50 m-radius from the fire engine.

Conclusions

It is hard to draw any too extensive conclusions, due to the set up of the tests, where flow as well as pressure varied between the tests. The purpose was mainly to compare different systems for manual applied water sprays. The nozzles were used at their working pressure and therefore also at appropriate water flows, respectively.

Comparing the results from tests 1 – 7, an evident conformity with the theoretical framework described above was observed.

The main conclusions from the tests were that high-pressure water sprays reduce the temperature more than low-pressure water sprays, especially when applying water oscillating from a fixed position within the room. When having firefighters advancing through the room, high-pressure water sprays reduced the temperature faster but not significantly to a lower level than when using low-pressure water sprays. The tests also showed that high and low pressure water sprays require different techniques, which could have a dramatic effect on firefighting tactics as well as on the safety of firefighers. The tested high-pressure systems also have the advantage, in relation to low-pressure (normal) systems in that they use a rigid hose mounted on a hose reel, which generally decreases the attack time, i.e. the time from arriving at the fire-scene until the time when it is possible to apply water on the fire.

References

1. Holmstedt, G., Persson, H., Ryderman, A. (1984). Släckmedel och släckverkan (SP-rapport 1984:35). Statens Provningsanstalt: Borås.
2. McCaffrey, B.J. (1983). Jet Diffusion Flame Suppression using Water Sprays. Combustion Science and Technology, vol 40, no 3 – 4, pp 107 – 136.
3. Bishop, M. J. & Stroup, D. W. (1997) Impact of Firefighting Agents on Drop Size. Second (2nd) International Conference. (ICFRE2), Proceedings. National Institute of Standards and Technology and Society of Fire Protection Engineers. August 10-15, 1997, Gaithersburg, MD, 63 pp, 1997.
4. Andersson, P., Arvidsson, M., Holmstedt, G. (1996). Small scale experiments and theoretical aspects of flame extinguishment with water mist (report 3080). Lund: Lund Institute of Technology.
5. Gardiner, A.J. (1988). The mathematical modeling of the interaction between sprinkler sprays and the thermally buoyant layers of gases from fires (Ph.D. thesis). London: The Fire an Explosion Group. and Hertfordshire: Fire Research Station.

6. Holmstedt, G. (1998). Kompendium i släckmedel - släckverkan. (In Swedish) Lund: Institutionen för brandteknik.

7. Beyler, C. (1992). A Unified Model of Fire Suppression. Journal of Fire Protection Engineering, 4(1), 5 – 16.

8. Delichatsios, M & Delichatsios M.M. (1997). Critical Mass Pyrolysis Rate for Extinction of Fires over Solid Materials. In Proceedings of The Fifth International Symposium on Fire Safety Science (pp. 153 – 164).Melbourne, Australia.

9. Rimen, J.G. (1990). The Use of High Pressure and Low Pressure Pumps with Hosereel Systems (Research report No.36). Home Office Scientific Research and Development Branch, Fire Experimental Unit: Moreton-in-Marsh.

10. Lundström, S. & Svensson, S. (1997). Firefighting Using High-pressure Water Flows (in Swedish) (report P21-196/97). Karlstad: Räddningsverket.

11. Fogfighter® (normal-pressure nozzle), data sheet. Ljung, Sweden: Tour & Andersson Inc.

12. Akron Force™ (high-pressure nozzle), data sheet. Wooster, Ohio: Akron Brass Company.

13. Rosenbauer NePiRo™ (high-pressure nozzle), data sheet.

Paper II: Fire tests in a large hall, using manually applied high- and low pressure water sprays

Stefan Svensson and Stefan Särdqvist

Fire Science and Technology, vol. 21, No. 1, 2001.

Fire tests in a large hall, using manually applied high- and low-pressure water sprays

Stefan Svensson

Stefan Särdqvist

Swedish Rescue Service Agency, Revingeby, 247 81 Södra Sandby, Sweden

e-mail: stefan.svensson@re.srv.se, stefan.sardqvist@re.srv.se

Abstract

Large-scale firefighting was investigated, including a comparison between high-pressure and low-pressure manual firefighting systems and measurements of heat stress on firefighters. Six tests were performed in a room measuring 14.0 × 7.7 m². The fuel in each test consisted of wooden pallets arranged in 6 stacks with 13 pallets in each stack. Weight loss, gas temperature, heat radiation and room pressure were measured. The nozzle pressures were 7 bar and 25 bar and the flow rates were 1.92, 3.83 and 5.75 kg/s. The tests showed that the ability to reach the burning fuel with water limits the capacity of the firefighting attack. The high-pressure system proved more efficient than the low-pressure system. It gave a faster response and required a lower flow to attain the same extinction effect as the low-pressure system.

Keywords: large-scale extinguishing tests, fire suppression, firefighting, water, high-pressure, BA team.

Introduction

Firefighting using manually applied water sprays is generally considered to be the basic concept of the fire service. In some situations, the question is raised, as to use the available water in the most efficient way. This includes problems such as minimising water application rate to minimise secondary damage, speeding up the firefighters work when stretching hoses or when attaching the pump to a fire hydrant. It also includes the actual firefighting. Apart from organisational matters, for example the required number of firefighters, regulations prescribe that a safe supply of water should be available to the firefighters. There is, however, no definition of what is a safe supply. There is also a wide variation in existing recommendations, as has previously been shown [1].

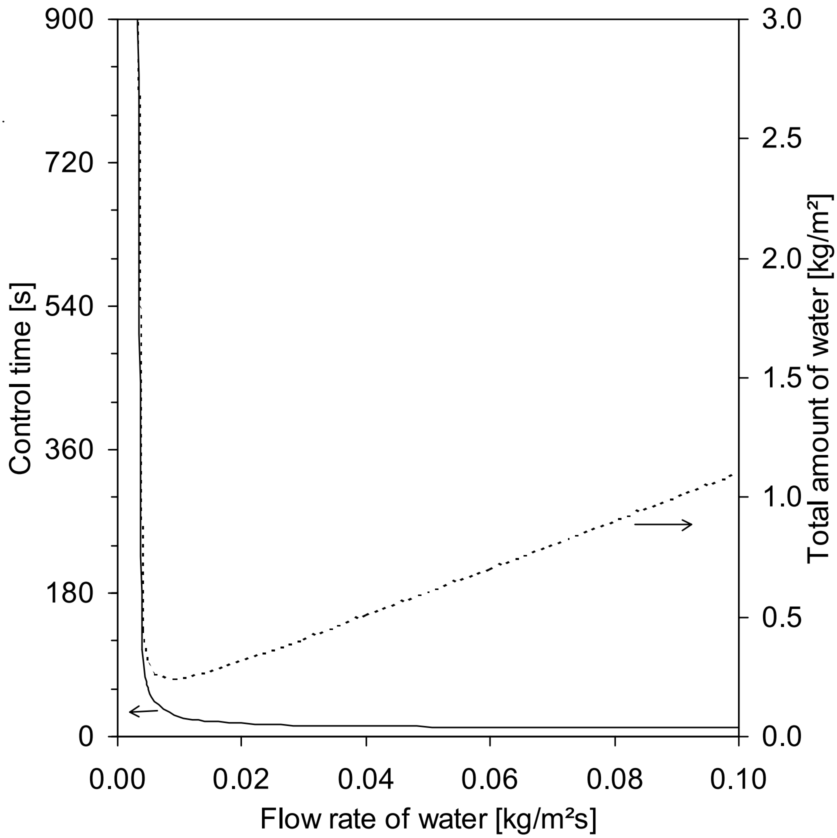

Figure 1. The control time (solid) and the total amount of water (dotted) as a function of the water flow rate. (Figure from ref. [4].)

In firefighting, the surface cooling effect of water sprays is commonly used, and when needed, cooling of hot smoke is employed to make it possible for the firefighters to approach the fire. The Fire Point Theory, suggested by Rasbach [2] and developed by Beyler [3], predicts the critical water flow rate for extinction. This theory has been validated for the extinction of fires using manually applied sprays [4]. However, the critical flow rate does not give the best use of resources, as it requires a more or less infinite time. Increasing the flow rate above the critical value causes the total mass of water required to control the fire to decrease, as is shown in Figure 1 [4]. There is an optimum flow giving the smallest total water mass. Above this flow, the total mass of water increases again.

Many fire suppression tests have been reported in the literature. Unfortunately, most of them do not fulfil scientific demands on reproducibility and documentation, due to poorly defined fire scenarios or lack of measurements. The limited number of scientific fire suppression tests reported do not, in general, consider manual fire suppression but rather suppression using sprinkler systems. Also, manual fire suppression tests in which both the rate of mass loss of fuel and gas temperatures are recorded, are usually concerned with set-ups on a small scale or a medium scale, where the fire is relatively small in comparison with the water flow from the nozzle [5], [6], [7], [8] and [9].

As reported by Dotson et al. [10], the workload during firefighting is very high, especially when using breathing apparatus. This has also been pointed out by Kilbom [11] who, based on investigations among Swedish firefighters, suggested that firemen over the age of 50 should not perform firefighting using breathing apparatus, due to an increased risk of physical exhaustion, orthostatic responses and cardiac complications.

A number of tests on physiological aspects of firefighting have been reported. In these tests, the workload was high in combination with heat stress. The tests indicated that increases in heart rate and body temperature were related to both physical and environmental stress [12], [13], [14]. However, no tests have been found in which heat stress on firefighters equipped with breathing apparatus, BA teams, has been measured under real firefighting conditions and where the workload was low.

This paper describes a series of tests performed in a large-scale structure, using manually applied high- and low-pressure water sprays. The experimental set-up and test procedures were chosen to provide a firefighting attack close to the critical capacity of the firefighters and their equipment. The set-up and details regarding the results are described in greater depth in another report [15]. The purpose of the tests was

- to investigate the capacity of the fire service to fight fires in large spaces,
- to obtain data with the purpose of quantifying this capacity,
- to compare a high-pressure with a low-pressure firefighting system (pump, hose and nozzle) and
- to measure the heat stress on BA-equipped firefighters during fire attack.

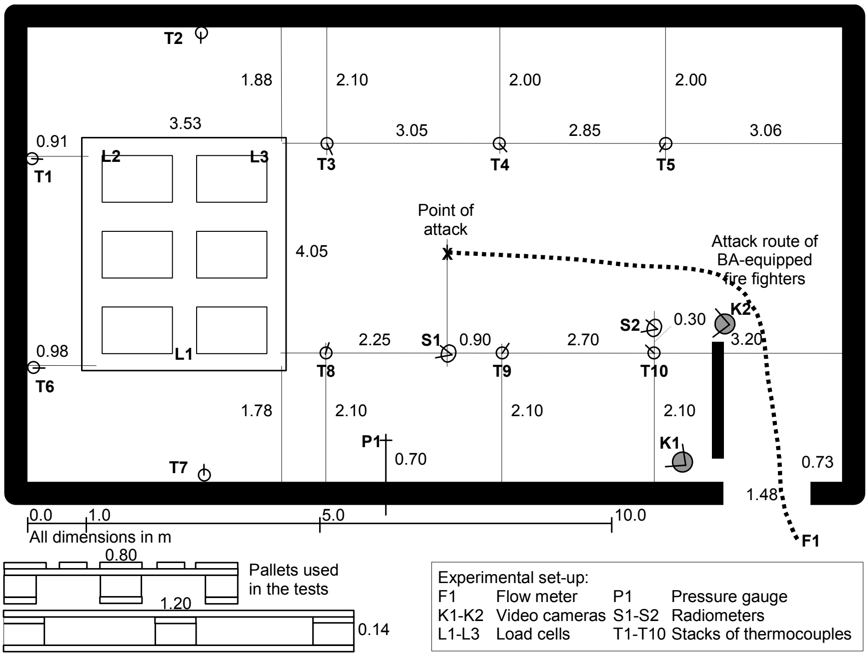

Figure 2. Experimental set-up used for the tests.

Experimental set-up

The tests were performed in a room measuring 14.0 × 7.7 m^2, 6.3 m in height, constructed with 0.4 m thick walls of concrete. The door used for firefighter access, measured 1.48 × 2.98 m^2 (width × height). Inside the room, perpendicular to one side and beside the left side of the door opening was a 2.00 m wide, 1.95 m high radiation shield of lightweight concrete. The distance between the shield and the wall was 0.5 m. See Figure 2 for details.

The fire was similar in all six tests, and is shown in its early stages in Figure 3. The fuel consisted of standard wood pallets arranged in 6 stacks with 13 pallets in each stack. The mean distance between the stacks was 0.4 m. Two different types of pallets were used, measuring 1.2×0.8 m² and 1.2×1.0 m². The exposed fuel surface was calculated as the surface area exposed to the fire, i.e. all surfaces of the pallets except the surfaces covered by stacking. The moisture content of the fuel was approximately 13%. The pallet arrangement was placed on a load platform in order to measure the weight loss. The load platform was a steel structure, 4.05×3.53 m² and 0.25 m high, resting on three load cells, L1 – L3 (see Figure 2 and Table 1). As an ignition source, a 0.035 m² porous fiberboard soaked in diesel fuel was placed at the bottom of each stack of pallets. All six stacks were ignited manually within a period of 30 s. Times given in this paper are the time from which the first pallet was ignited.

Table 1. Measuring range and accuracy of measurements as stated by the manufacturer. Item numbers are in accordance with Figure 2.

Item #	Measurement (number of devices)	Device denomination	Measuring range	Accuracy of instrument
S1-S2	Radiation (2)	Gunner's radiometer	0 - 100 kW/m^2	± 5%
L1	Mass (1)	Load cell, TML CLP-2000KA	0 - 2000 kg	± 0.5%
L2-L3	Mass (2)	Load cell, TML CLP-1000KA	0 - 1000 kg	± 0.5%
T1-T10	Temperature (60)	Thermocouple type K, 0.25 mm	0 - 1300°C	± 0.4%
	Temperature on load cell (1)	Thermocouple type K, 0.25 mm	0 - 1300°C	± 0.4%
P1	Pressure gauge (1)	Pressure gauge, SI Digima LP	0 - 20 mbar	± 0.5%
F1	Flow rate (1)	GPI turbine flow meter	1.67 – 16.7 kg/s	± 1%
	Skin & clothing temperature (8)	Thermistor gauge AT31/40	-40 - +120°C	± 0.4°C
	Body temperature	Thermometer, Terumo C402®		± 0.1°C

Figure 3. Photographs from the interior of the fire room at 90 s, 120 s and 180 s after ignition. The column in front of the fire is 1.4 m high and the stacks of pallets reach 2.1 m from the floor. The tall columns are 6.0 m high and bear the thermocouples.

Figure 3. Continued.

The temperature was measured at 60 points in the fire room. Thermocouples were arranged in 10 stacks containing 6 thermocouples equidistant from ceiling to floor, starting 0.30 m from the ceiling and ending 1.00 m above floor (T1 – T10 in Figure 2 and Table 1). The thermocouples in stacks T1, T2, T6 and T7 were located 0.25 m from the walls. The radiation was measured at 2 locations in the room, S1 and S2, using Gunner's radiometers [16]. S1 was placed at the same distance from the fire as the point of fire attack by the firefighters and S2 was located close to the point where the fire first affected the firefighters. Both radiometers were located 1.35 m above the floor, pointing 10° upwards towards the longitudinal center of the fire. The pressure difference between the fire room and the surroundings was also measured 1.10 m above the floor, using a pressure gauge connected to a copper tube (P1). The measurements of the conditions in the fire room were made at a sampling rate of 0.1 Hz.

Measurements on the two firefighters engaged in firefighting were also performed of body temperature, weight and fluid balance before and after the attack, and pulse rate during the attack. The skin temperature was measured on one of the firefighters during the attack. These measurements were registered with a rate of 1 Hz. The firefighters were dressed in a Rescue Suit 90®, Swedish turnout gear, and they were using Interspiro Spiromatic breathing apparatus.

The tests were documented using an external video camera pointing towards the entrance to the fire room. The firefighters continuously reported their actions by radio, and the radio traffic was recorded using the microphone on the external video camera. After each test, the firefighters gave statements regarding their work, and on how the situation felt during the test. The interior of the fire room was documented using a small video camera (K1), with a water-cooled housing. This camera was located 0.5 m above floor, just inside the entrance to the fire room, pointing towards the center of the fire. During tests 4 and 5, a hand-held infrared camera was used to document the actions of the firefighters at position K2. Infrared photography proved to give an excellent view of the actions of the firefighters through the smoke-filled room, as shown in Figure 4.

Weather conditions, wind and temperature were recorded at the time of each test. The wind speed was measured on the roof of the building, 10 m above the ground, and also just outside the entrance of the fire room, which was protected by surrounding buildings. The temperature was measured in the shade. The wind speed was less than 4 m/s on the roof and less than 1 m/s at the opening during all tests. The weather was sunny and the ambient temperature 17 – 23°C during the tests.

Test procedure

Two different nozzles were used at three different water flow rates. A Protek style #366 low-pressure nozzle and an Akron Force style 751 high-pressure nozzle were used at flow rates of 1.92 and 3.83 kg/s and the Protek nozzle was also used at 5.75 kg/s. The high-pressure pump used during the tests delivered water at approximately 40 bar, giving nozzle pressures of approximately 25 bar. The low-pressure pump delivered water at approximately 11 bar, giving nozzle pressures of approximately 7 bar, see Table 1. The flow rate was registered once per second.

The arithmetic mean water droplet size using the low-pressure nozzle was approximately 0.30 mm at 3.83 kg/s and 7 bar nozzle pressure [17]. The Sauter means diameter of the droplets from the high-pressure nozzle was 0.4873 mm, and the arithmetic mean 0.2122 mm at 6.9 bar and 2.73 kg/s [18].

Six tests were performed. Two parameters were varied, the type of nozzle and the flow rate, while employing a similar extinguishing procedure during all six tests (see Table 3 for details).

Figure 4. Photograph taken through smoke during the attack in test 4, using an infra-camera (from position K2 in Figure 2).

Firefighting commenced when the temperature had reached its peak and stabilised. At this time, the temperature was approximately 700°C at the left-hand end of the room (at T1 and T6) 5 m above the floor. The temperature at the sides (position T2 and T7) was about 600°C and in the rest of the room (T3 – T5 and T8 – T10), the temperature was 450-500°C, at the same height. The pre-burn time was between 6.0 and 7.5 minutes for all tests. Firefighting was performed at a location 3.0 m from the fuel, see Figure 2. At this location, there was no protection for the firefighters against radiation from the fire or from water vapor.

Firefighting was performed manually, and the firefighters were instructed to act in the same way during the different tests. The same two firefighters, both of them well-trained professionals, took part in all tests. They had the same assignment in all tests. The attack route was through the doorway, advancing into the room parallel to the radiation shield, and then turning left and advancing straight towards the fire along the centerline of the room. On a level with the first radiometer (S2), a short sweep was made with the water spray, 45° upwards, in order to cool the hot gases. Three meters from the fire, on a level with the second radiometer (S1), the firefighter with the nozzle halted and started to work on the fire. He used sweeping movements of the water spray alternately towards the fuel in order to cool the fuel surface and reduce the pyrolysis rate, and towards the flames and smoke in order to decrease the temperature to ameliorate the environment in the room and to make it possible to continue the attack.

Table 2. Amount of fuel used during the tests.

	Fire load			**Fire characteristics at the start of extinction**			
Test	**Net load [kg]**	**Number of pallets***	**Exposed fuel surface [m²]**	**Pre-burn time [s]**	**Mass loss rate [kg/s]**	**Average burning rate [g/m²s]**	**Estim. rate of heat release [MW]**
1	1269	52+26	185	533	-0.99	5.4	16.8
2	1234	26+52	198	398	-1.20	6.1	20.4
3	1435	63+15	179	422	-0.93	5.2	15.8
4	1159	78+0	172	472	-0.76	4.4	12.9
5	1411	77+1	172	438	-0.86	5.0	14.6
6	1294	78+0	172	426	-0.86	5.0	14.6

* Pallets with widths of 1.2 · 0.8 m² and 1.2 · 1.0 m² were used.

The test supervisor terminated the firefighting in tests 2, 3 and 6 when the temperature stabilized at a low level. Tests 4 and 5 were cut short by the firefighters due to heat penetration. Test 1 was interrupted after the initial attack. This test was much shorter than the others were and is therefore excluded from the results.

Results

Figure 5 shows the rate of loss of fuel mass up to the initiation of firefighting for the six tests. The growth phases of the fires in the individual tests do not show significant differences, which are noteworthy, considering the scale of the tests. When the firefighting started, the average rate of mass loss was 0.93 kg/s. Standard wooden pallets proved to be a good fire source in a large-scale experiment such as this. As pallets collapse during fire, however, some kind of support is necessary for high stacks. Porous fibreboard soaked in diesel fuel proved to be a very safe and highly reproducible ignition source.

Table 3. Amount of water used during the tests.

	Water spray characteristics			**Water required to control the fire**			
Test	**Pump pressure [bar]**	**Nozzle pressure [bar]**	**Nominal flow [kg/s]**	**Time [s]**	**Total mass [kg]**	**Norm. Mean flow [kg/m²s]**	**Norm. total mass [kg/m²]**
1	7.0	6.0 ± 0.5	3.83	*	*	*	*
2	39	25 ± 5	3.83	210	253	0.00608	1.28
3	7.0	6.0 ± 0.5	3.83	240	286	0.00693	1.66
4	5.2	4.5 ± 0.5	1.92	360 **	303 **	0.00479	1.76 **
5	35	23 ± 5	1.92	360 **	255 **	0.00404	1.48 **
6	8.0	7.0 ± 0.5	5.75	130	152	0.00680	0.88

	Water used overall during attack				
Test	**Total mass [kg]**	**Mean flow [kg/s]**	**Number of sweeps [-]**	**Mass per sweep [kg]**	**Capacity used [-]**
1	83	1.52	8	10.4	0.40
2	694	1.46	62	11.2	0.38
3	692	1.26	42	16.5	0.33
4	298	0.843	26	11.5	0.44
5	284	0.708	28	10.2	0.37
6	755	1.50	35	21.6	0.26

* Test halted after initial attack.

** Did not reach the control criterion within six minutes.

The rate of heat release can be estimated using measurements of the rate of mass loss and the equation:

$$\dot{q} = \dot{m} \cdot \Delta h_T$$

where $\dot{q}$ is the rate of heat release [MW], $\dot{m}$ [kg/s] is the rate of mass loss and Δh_T [MJ/kg] is the total heat of combustion, which was based on the value for wood, 17.0 MJ/kg [19]. This method of calculation, which does not consider the limitation in energy release due to the restricted access of air, gives heat release rates according to Table 2. On average, the heat release rate was 15.9 MW when firefighting was initiated. The chemical heat release can be lower, in small-scale tests, 12.4 MJ/kg [19].

The average burning rate of the fuel, i.e. the rate of mass loss divided by the exposed fuel area, is also given in Table 2. At the commencement of extinction, the burning rate was approximately 5.2 g/m^2s. The average burning rate is low, probably due to non-complete involvement of the pallets, especially the pallets at the bottom of the stacks. For comparison, it can be mentioned that the rate of mass loss during the extinction of particleboard was determined to be 5.5 g/m^2s, using a flammability apparatus [20].

The mean flow rate was calculated from the measurements of the flow rates. The number of sweeps of the nozzle was also counted and the mass of water per sweep was calculated. See Table 3 for details. It can be seen that the mean flow was considerably lower than the nominal flow. It can also be seen that the mass of water per sweep is slightly lower for the high-pressure nozzle (tests 2 and 5) than for the low-pressure nozzle (tests 3, 4 and 6).

The firefighters were able to extinguish the fire in the front row of wood pallets, thereby reaching the control criterion, while the back row of pallets continued to burn more or less unaffected. This was illustrated by the load cell measurements in the tests. One row of wood pallets is thus a sufficient obstacle to conceal a fire and to prevent successful extinction.

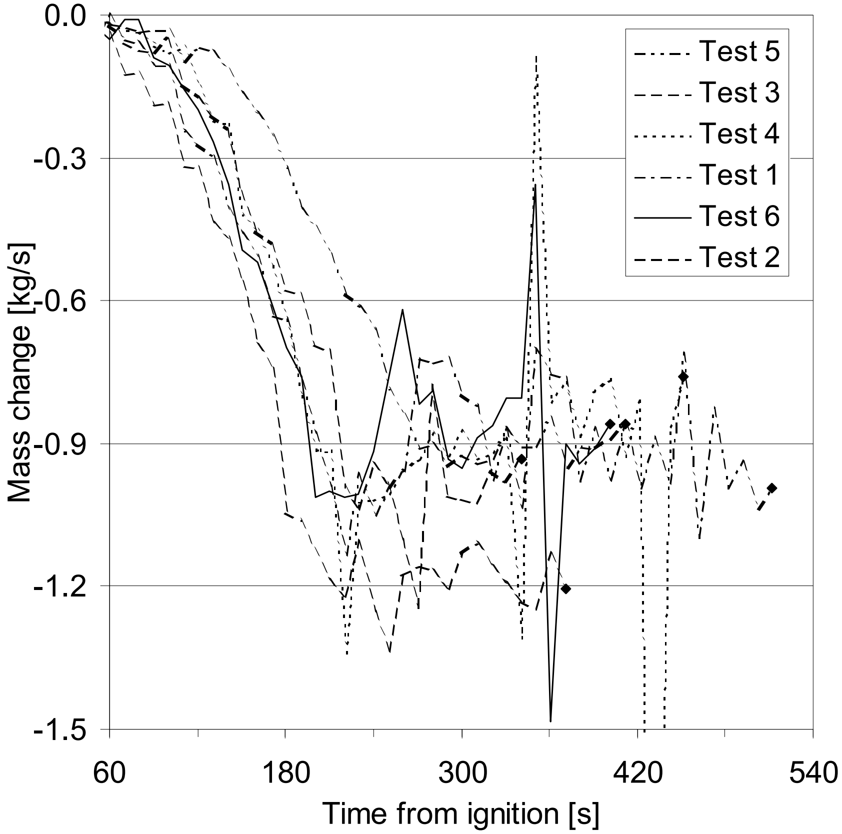

Figure 5. Rate of mass loss up to the time when extinguishing was initiated, represented by the symbols ♦.

Load cell 1 is located on the centerline of the platform. Therefore, it registers approximately half the total mass. Load cell 2 is located at the back of the platform, thus measuring primarily the part of the fuel that was not reached by the water. Load cell 3, finally, was located at the front, and registered an increase in weight due to the application of water.

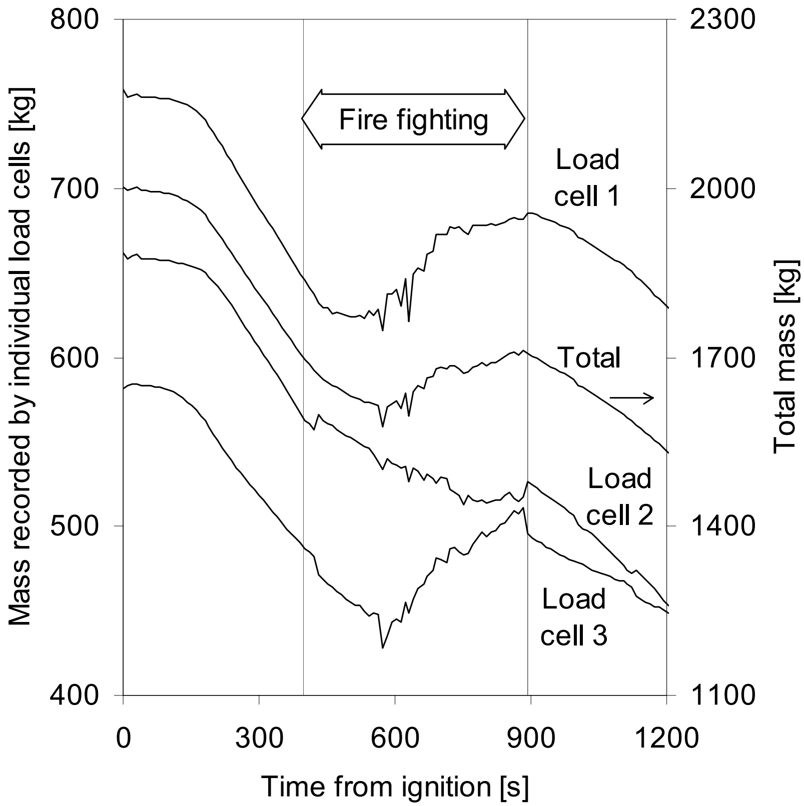

Figure 6. Mass recorded by individual load cells and total mass of fuel in test 2.

There are also some singularities, which can be seen in Figure 6 showing the mass on individual load cells and the total mass in test 2. At 750 s, one of the pallet stacks near load cell 1 collapsed, and some of the pallets slid off the load platform, causing a discontinuity in the load signal. At about 450 s a stack of pallets collapsed. This cannot be seen in the total mass curve, but load cell 3 indicated a weight loss while load cell 2 showed a similar increase in weight at that time.

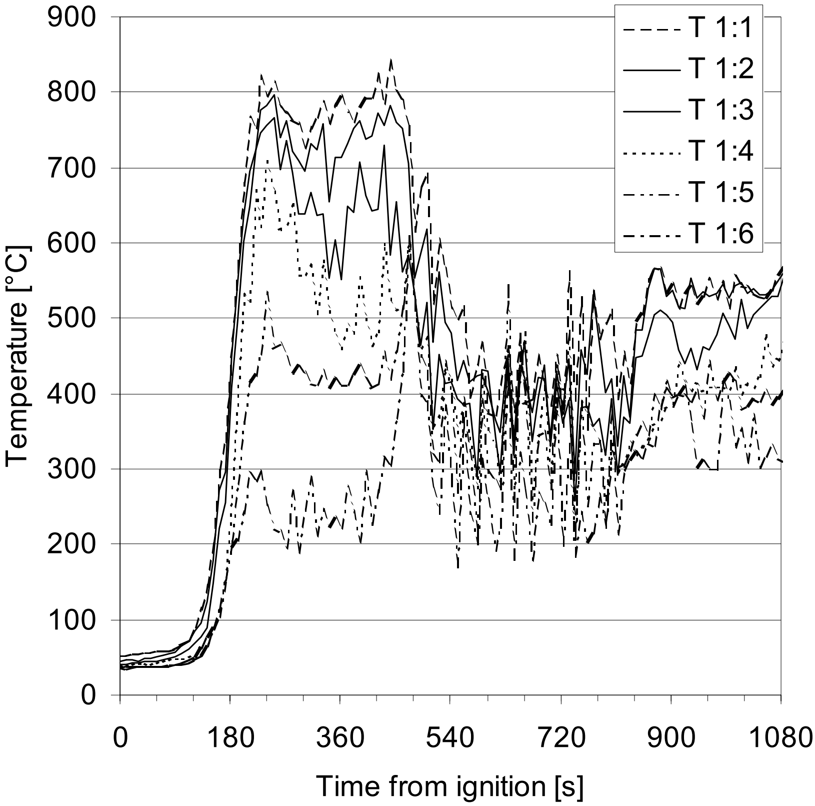

Figure 7. Temperature in the fire room registered by thermocouple stack T1 (see Figure 2), during test 4, using the low-pressure system at a flow rate of 1.92 kg/s.

Figure 7 shows individual temperature measurements from thermocouple stack T1. The diagram shows measurements from test 4, using a low-pressure nozzle at water flow rate of 1.92 kg/s. The extinction period in this test was between 475 and 830 s from the start of the fire. Figure 8 shows the mean temperature of all thermocouples, together with the mean temperature for groups of thermocouples, the upper four and lower two thermocouples, in the front and back of the room, for the same test. In the test report [15], similar diagrams are available for all thermocouple stacks and for all tests.

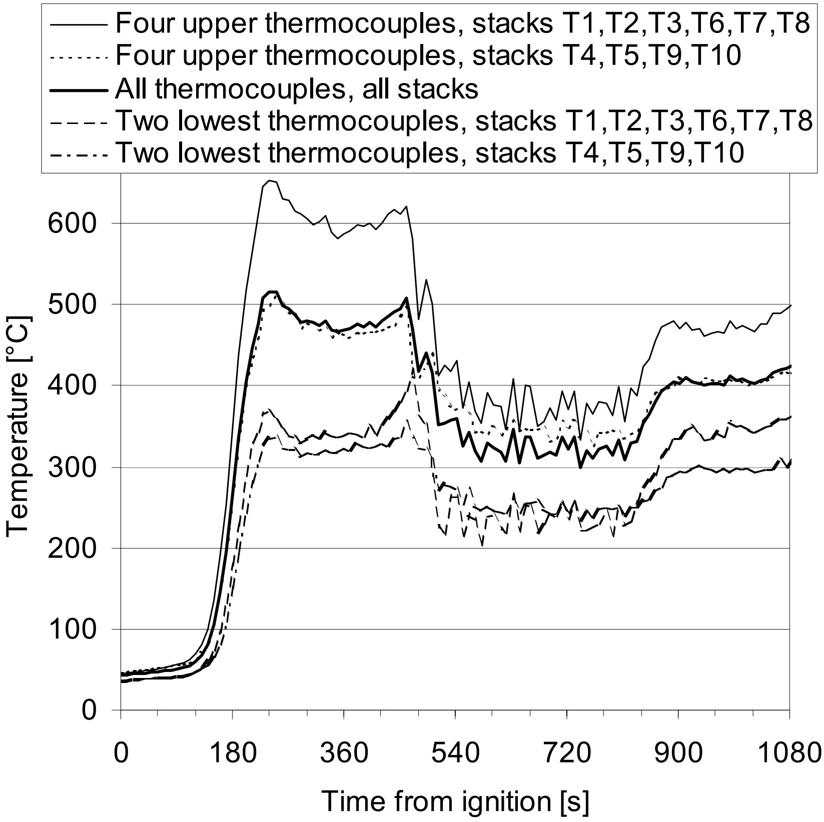

Figure 8. Mean temperatures for clusters of thermocouples in test 4, using the low-pressure system at a flow rate of 1.92 kg/s.

In Figure 9, mean gas temperatures during the extinction phase are plotted for the completed tests. The mean gas temperature was calculated as an average of the measurements from the 60 thermocouples. The figure shows that the high-pressure system at flow rates of both 3.83 and 1.92 kg/s (tests 2 and 5) reduces the gas temperature faster and to a lower level, than the low-pressure system. The high-pressure system reduces the temperature to its minimum within one minute. Thereafter, the temperature remains constant or increases slowly. The low-pressure system, on the other hand (tests 3, 4 and 6), gives a much slower decrease in gas temperature, reaching a minimum after about three minutes. The final temperatures were not as low as that achieved with the high-pressure system.

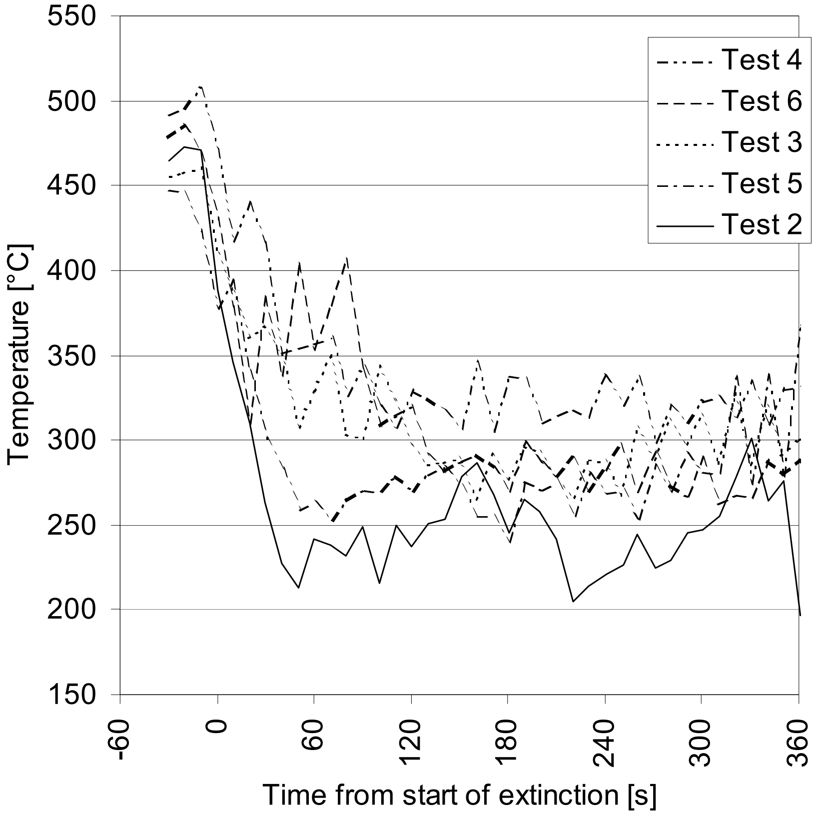

Figure 9. Mean gas temperatures during extinction for all completed tests.

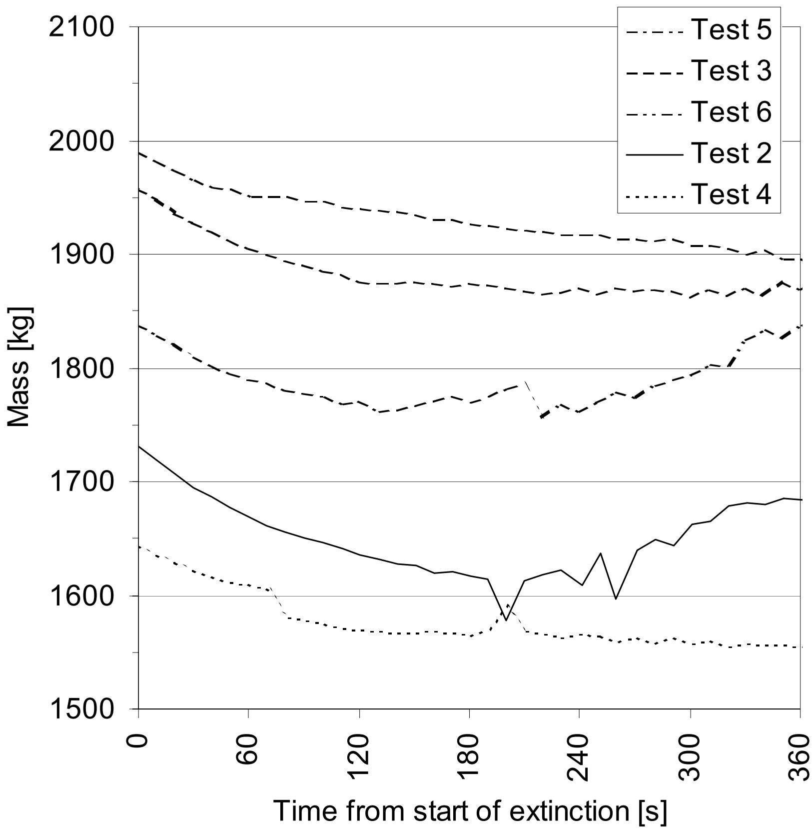

Figure 10. Fuel mass during extinction for all completed tests.

The control time can be defined as the time at which the derivative of the mass loss curve is zero, i.e. the time at which the fuel starts to gain weight due to water application. Using this definition, the flow of 1.92 kg/s was not sufficient to gain control of the fire within 360 s using either high or low pressure nozzles (tests 4 and 5), which can be seen in Figure 10. At 3.83 kg/s, the low-pressure system just reached extinction at 240 s (test 3). High-pressure sprays at 3.83 kg/s (test 2) and low-pressure sprays at 4.75 kg/s (test 6) clearly reached the control criterion within 130 s and 210 s, respectively. This is in accordance with the assessment of the firefighters performing the tests, indicating that the definition of control time is reasonable although the rate of heat release may still be large when control is reached.

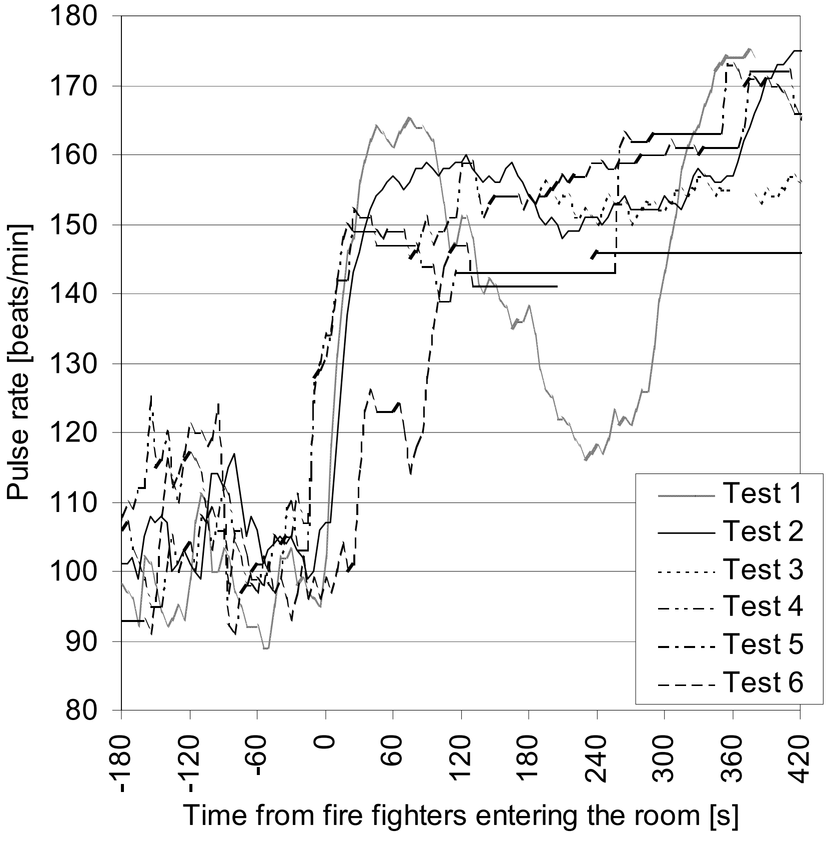

Figure 11. Pulse rate of the firefighter operating the nozzle during all tests.

The physical workload during the tests was low, involving only movement from the doorway to the point of attack (see Figure 1). Figure 11 shows the pulse rate for the firefighter operating the nozzle. In test 6, the firefighter wore a cooling vest. The use of a cooling vest slows down the rise in pulse rate and gave a pulse rate approximately 10 beats per minute lower than in tests 2 - 5. The figure also indicates that the pulse rate increases further after 240 s.

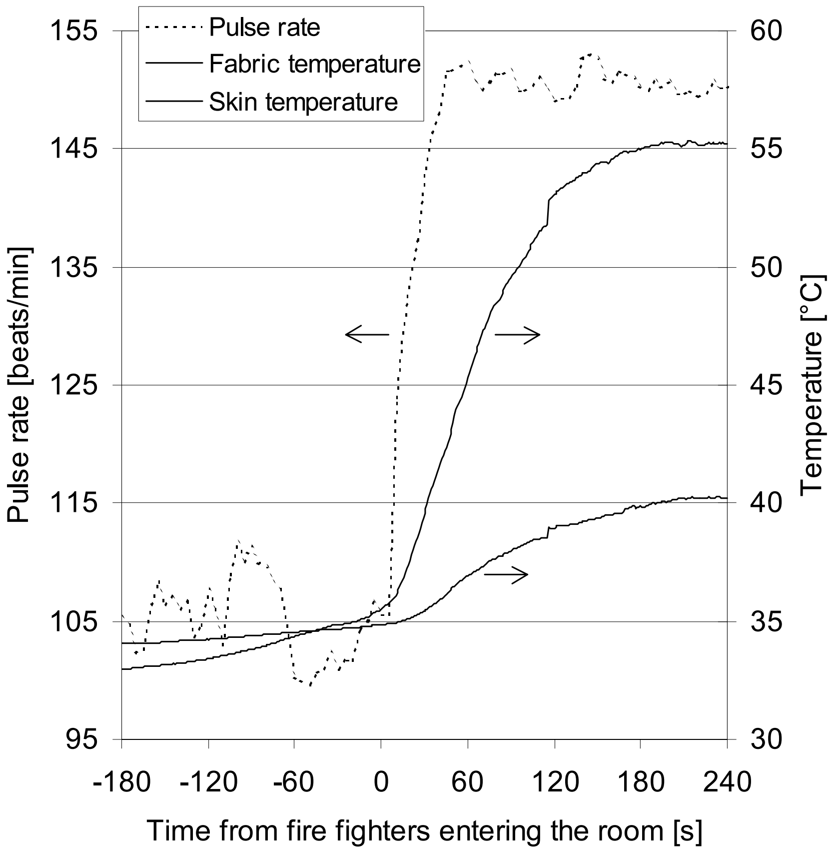

Figure 12. Mean pulse rate and mean temperature on skin and on fabric for the upper arms of the firefighter operating the nozzle at tests 2-5

Figure 12 shows the mean pulse rate for tests 2 - 5, the skin temperature and the temperature of the fabric between the inner and outer garment on the firefighter operating the nozzle. The temperatures are the mean of measurements from both upper arms. The increase in mean pulse rate during tests 2 - 5 is approximately 45 beats per minute 30 seconds from the time when the firefighters entered the room. The mean skin temperature is approximately 40°C after 240 seconds. This skin temperature is not high enough to cause pain. Pain occurs when the skin temperature exceed 44°C [21]. The mean fabric temperature is approximately 55°C after 240 seconds.

After leaving the room, the firefighters also reported their protective clothing to be too hot to touch with bare hands for a few minutes.

A complete set of diagrams for each test is available in the test report [15]. This includes measurements of skin and fabric temperatures on the firefighter operating the nozzle, the pulse rate of each firefighter, water flow, change in mass of the fuel, radiation from the fire, room pressure, gas temperatures measured by individual thermocouples and mean gas temperatures. Tables of body mass for firefighters are also available. Although written in Swedish, the diagrams are universally understandable.

Discussion

During large-scale experiments such as these, especially those involving human performance, a large number of problems, questions and potential errors occur. Problems that arise are primarily associated with the geometry of the fire room, the characteristics of the fuel, firefigher performance and the performance characteristics of the measuring equipment. Large-scale experiments are also very time-consuming. The planning process prior to the experiments was, to a great degree concerned with solving these problems.

One of the purposes of the tests was to investigate capability of the fire service to fight fires in large spaces, which strongly influenced the choice of location and fire room. The influence of weather and wind are other factors that must be considered when performing large-scale experiments, to get reproducible results. The time of year and also the time of day for performing such tests can be of vital importance for the results. During the tests described in this paper, the weather was excellent.

The large amount of fuel required for these tests led to the choice of standard sized wooden pallets as fuel. The advantages of this type of fuel are, amongst others, that the pallets are standardized in size, cheap, accessible and manageable. Pallets are also frequently used in industry and their response to fire is predictable. The development of the fire is greatly influenced by the moisture content. The pallets were therefore stored on the same location for a relatively long period of time and the moisture content was uniform in all the fuel.

Due to the purpose of the experiments, which was to compare a high-pressure, manual firefighting system (pump, hose and nozzle) with a low-pressure, manual firefighting system, a human operator was chosen to apply water to the fire. A professional firefighter handled the nozzle and worked the water spray at his own discretion. This type of procedure can, of course, jeopardize the reproducibility of the tests, complicate the comparison between tests and also comparisons with other tests. These problems were minimized by restrictions on the firefighter regarding his choice of attack route/point of attack, and the flow rate and cone angle of the water spray. The firefighters were also given instructions and were monitored continuously during the tests. Continuous monitoring is also an important safety feature when using human operators in large-scale experiments, as the risk of injury is high.

Measurements in the field, as opposed to measurements in a laboratory, place special demands on the set-up and choice of measuring equipment. The set-up must be adapted to the fire room and the equipment must have adequate resistance to wind, weather and particles. The performance characteristics of the measuring equipment are summarized in Table 2. The accuracy of measurements during large-scale experiments can be questioned. Based on the information presented in Table 2 and comparisons of the results from the six tests, the accuracy is within acceptable limits. Some data from measurements of the skin temperature of the firefighter were lost due to moisture and poor contact between the skin and the sensor in combination with the firefighter's movements.

The following estimates of heat release rate, gas temperature and water demand, made using available models, support the assessment of the accuracy of the tests. Using the mean rate of mass loss, the rate of heat release was estimated to be 15.9 MW. The rate of heat release from burning wooden pallets can also be estimated using the expression [22]:

$$\dot{q} = A \cdot 0.97(1 + 2.14 \cdot h_c)(1 - 0.027M)$$

where A [m²] is the floor area of the burning wood pallets, h_c [m] is the height of the pallet stack and M [%] is the moisture content. This expression was generated empirically using data from free-burning stacks of wooden pallets. Using representative values, the rate of heat released in the tests carried out here can be estimated:

$$\dot{q} = 6 \cdot (1.2 \cdot 0.8) \cdot 0.97(1 + 2.14 \cdot 1.85)(1 - 0.027 \cdot 14)\,\mathrm{MW} = 17\,MW$$

This expression gives a result in accordance with the values in Table 3 based on the rate of mass loss of fuel.

Figure 13 shows the results from a comparable simulation using HazardI [23]. This model can be used until the start of extinction, and until this time, it predicts the descent of the smoke layer interface and the temperature in the upper and lower parts of the room. This can be compared, for example, with the photographs in Figure 3, from camera position K1 in Figure 2. The photographs show how smoke fills the room at 90 s, 120 s and 180 s after ignition. Provided that the two-zone approach of HazardI is accepted, the prediction of the descent of the smoke layer interface is good. However, HazardI predicts, a smoke-free layer of one meter. In our tests, the smoke completely filled the room at about 390 s, mainly due to re-circulation. In fact, the visibility was so poor in some tests that it was difficult to find the correct position for the firefighters. When the firefighters approached the fire, they reported the flames to be just barely visible in spite of being close to the fire and the flames being high, from floor to ceiling. Nevertheless, the fire had grown so large at this stage, that the two-zone concept of HazardI can be questioned.

Figure 13 also shows the gas temperatures calculated using HazardI, which can be compared with the gas temperature in the room, shown in Figure 8. The model gives quite good agreement, although the temperature increase in the tests is slower during the first stage and faster in the later stage of increase than predicted by HazardI. One problem lies in selecting suitable thermocouples with which to calculate a representative mean gas temperature in the upper and lower gas layers for comparison with temperatures predicted by HazardI.

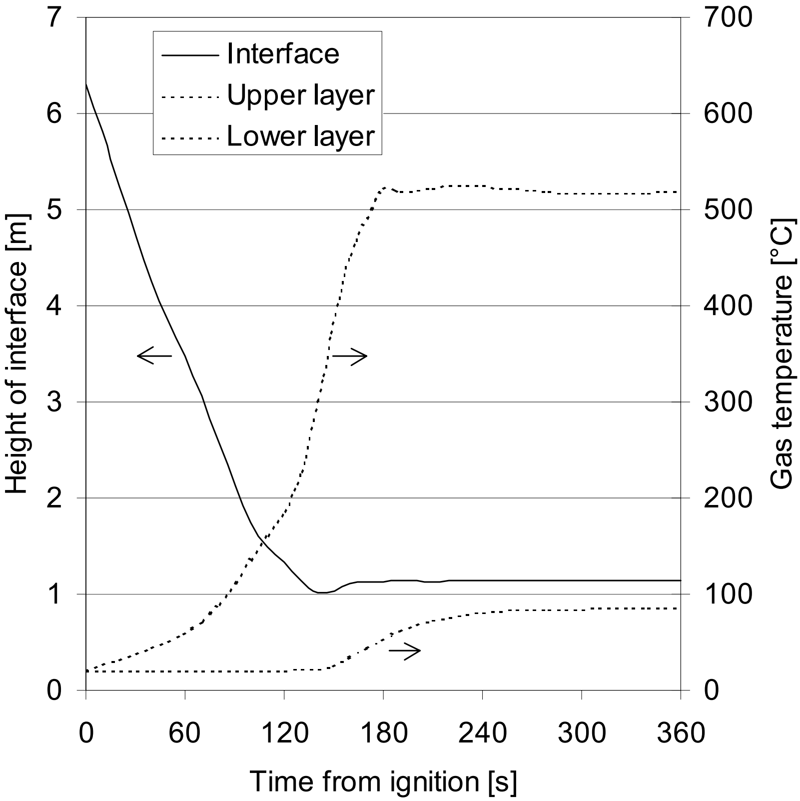

Figure 13. Interface height and gas temperatures as predicted by HazardI.

The extinction phase can be modeled using the Fire Demand Model (FDM) [24]. This is a one-zone model for the prediction of the water demand when fighting post-flashover fires, by calculating the temperature of the gas and of the walls. Although the model has been developed for external firefighting, it gives the right trend for the scenario studied here. The water flows required for control are, however, over-predicted. Figure 14 shows the gas temperature predicted by the FDM with input data according to the conditions in our tests. Figure 15 shows the correlation between water droplet size and the water flow required for control.

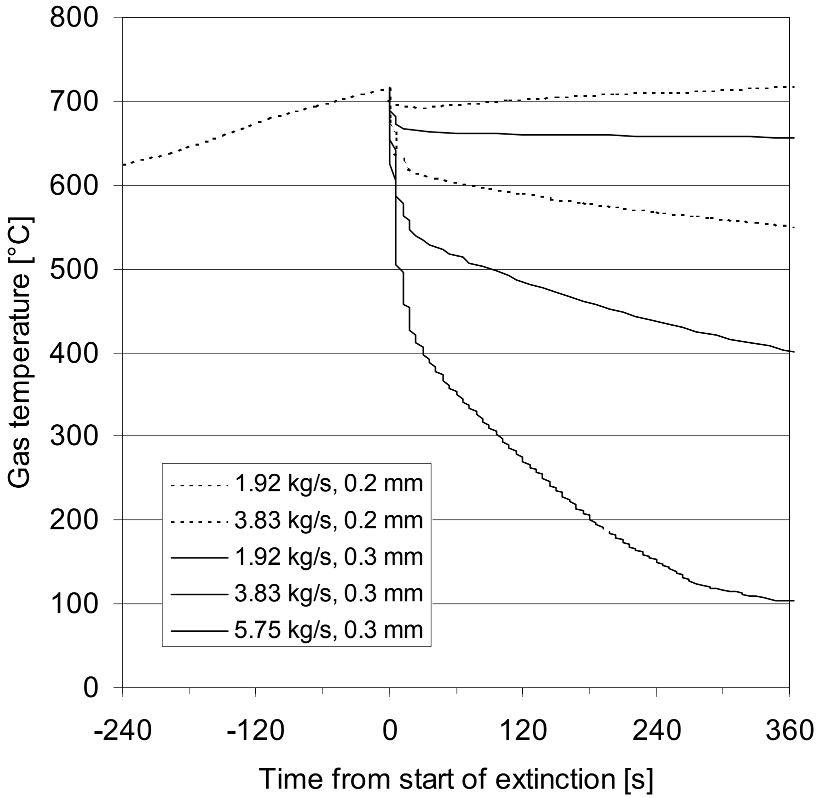

Figure 14. Gas temperature at different flows and droplet sizes as simulated by the Fire Demand Model.

The result of extinction attempts depends on the coverage of the water spray, which is governed by the nozzle movement, the position of the nozzle and the cone angle. Normally, the nozzle has to be moved and the position varied to cover the whole fuel area. Therefore, the larger the nozzle, the lower the mobility and the lower the efficiency. However, a larger nozzle generally delivers more water, and it can be located a greater distance from the fire, thus covering a larger area.

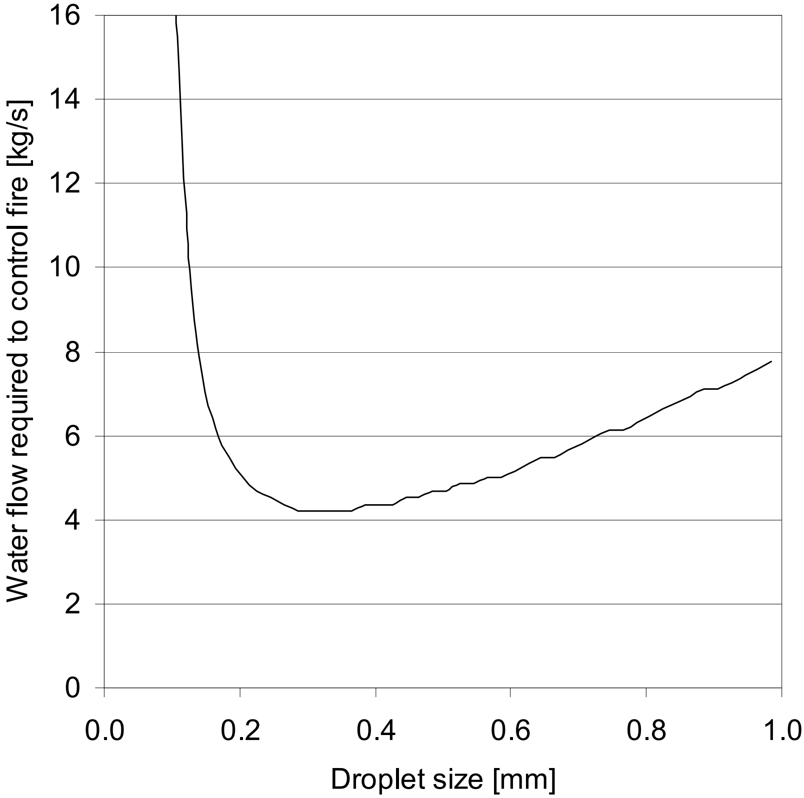

Figure 15. Relation between the water demand and water droplet size for the test scenario.

The cone angle of the water sprays was kept constant during the tests, see Figure 16. If the spray is idealized by a cone and gravity is neglected, the flow density of the cone [kg/m²s] can be estimated by elementary geometry:

$$v''_{mean} = \frac{v}{\pi(L \cdot \tan\alpha / 2)^2}$$

where v [kg/s] is flow rate from the nozzle, L [m] is the distance from the nozzle and α [°] is the cone angle. For ordinary nozzles (such as the nozzle used during the tests) the throw of the water L_{max} [m] can be estimated by [25]:

$$L_{max} = \frac{18 \cdot v^{0.36} \cdot P^{0.28}}{\alpha^{0.57}}$$

where P [bar] is the nozzle pressure. The correlation was developed using visual observations from photographs of water sprays. Estimates of the applied water densities, using the two equations, are shown in Figure 17. During the tests, the firefighters were positioned 3 m from the fire, giving a distance of 6 m to the far corner of the pallet arrangement.

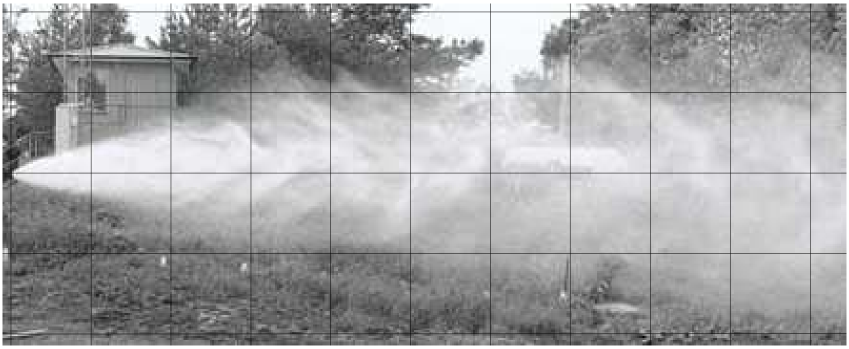

Figure 16. The cone of water spray from the high-pressure nozzle at 3.83 kg/s (test 2), with a one-metre grid.

If the distance between the nozzle and the fire is long, a nozzle with a high flow rate and a small cone angle must be used to obtain the desired throw. This has the further implication that the water density will be high where the water hits the fuel and that the nozzle must be moved vigorously to cover the large area that the amount of water enables. This is also accentuated by non-uniformity of the sprays. A long-distance stream is thus oversized where it hits the fire leading to ineffective use of the extinction capacity of the water.

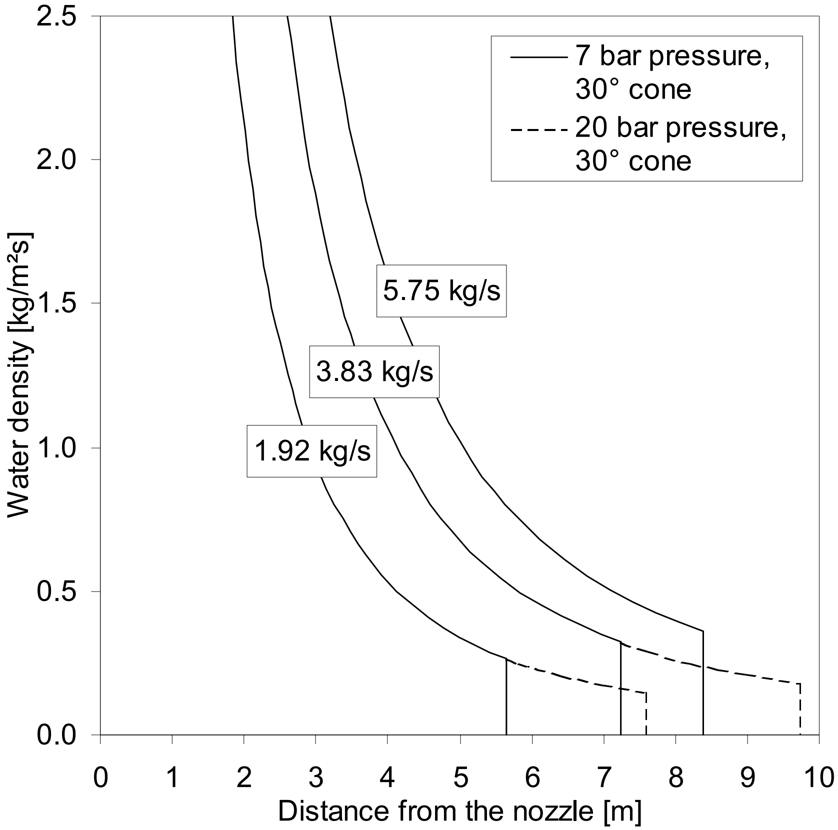

Figure 17. Estimates of the water density at various distances from the nozzle.

This problem of distributing the water can be seen in fire tests where the nozzle is fixed in one place, either by mechanical means or by instructing the firefighter to hold the nozzle stationary. The water flow rate may be sufficient to control the fire, but due to restrictions in nozzle movement, the water flow cannot penetrate the fire or reach the edges of the fuel exposed to fire.

Fire in wooden fuels cannot normally be extinguished unless the fuel surface is cooled down. This cooling is achieved by spraying the surface with water and in some cases by stopping re-radiation from the flames back to the fuel. This explains why fires, for example, in storage facilities pose considerable problems, as outlined below:

- Knowing where the seat of the fire is. The fire must be located, both on the macro-level (the right street, building and room) and on the micro-level (finding the seat of the fire in a smoke-filled room).
- Approaching the fire. The most efficient way to fight fires is, in many cases, to get a firefighter with a nozzle close to the fire. There may be physical barriers stopping the firefighters, or hazards, such as high levels of heat radiation.
- Getting water onto the fuel surfaces. The water from the nozzle must hit the fuel surface to enable cooling. Physical objects can conceal fires although the flames are highly visible, or the fire can be concealed by smoke.

If the firefighters maintain their positions and do not reposition or by other means redirect their attack, the attack may no longer be regarded as offensive. The aim of an offensive attack is to extinguish the fire. By not repositioning the nozzle (for whatever reason), steady state is established and the aim changes to simply maintaining the current position, strategically speaking. The aim is no longer offensive but rather defensive. So, in spite of the firefighters working in an extremely vulnerable situation, the aim has implicitly changed to defensive, and the firefighters will not be able to extinguish the fire. It will instead burn out due to lack of fuel.

The total water flow was sufficient to control the fire in some of the tests. The problem was in applying the water locally and in sufficient amounts to all parts of the fire. There is no point in soaking the front row of pallets, if no water reaches the back row. This was clearly illustrated by the firefighters when they were allowed freedom of movement, after the final measurements. When they were able to move freely, they extinguished the remaining fire in test 6 within one minute using the low-pressure system at a flow rate of 5.75 kg/s.

The tests were performed in an enclosed environment with only one opening. Due to the high gas temperatures in the room, the evaporation of water in the gas phase contributed to the extinction. Evaporation lowered the gas temperature thus decreasing the rate of heat release due to decreasing re-radiation back to the fuel.

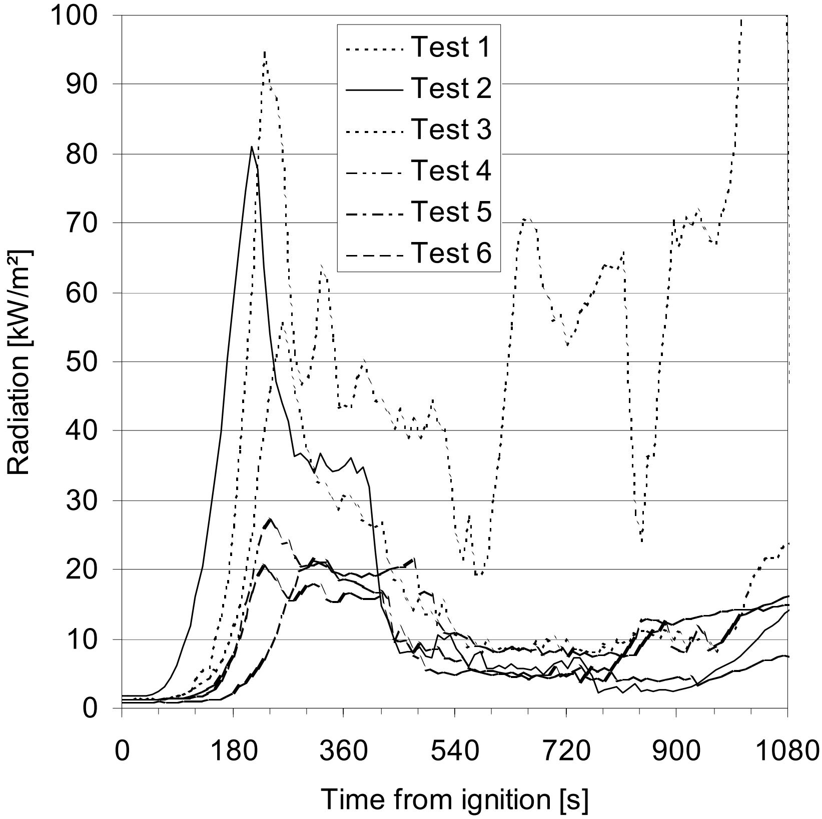

Figure 18. Heat radiation in all tests, measured by radiometer S1.

Figure 1 shows the principle relation between the control time and the flow rate of water applied to a fire. It can be seen that the tests employing 1.92 kg/s flow of water finished below the critical application rate. A higher flow rate allowed the tests to be controlled. It would, however, be possible to control the fire using a smaller amount of water, if the flow rate were increased. On the other hand, the nozzle is not open continuously, which can be seen in Table 3. Due to the heat and steam generation, it was not possible for the firefighter to apply a continuous spray.

Considering both fuel surface cooling effects and gas phase extinction effects, the high-pressure system proved to have a better extinguishing capacity per unit mass of water than the low-pressure system with this test set-up. Regarding fuel surface cooling effects, the high-pressure system at a flow rate of 3.83 kg/s was equally efficient as the low-pressure system at 4.75 kg/s, as shown in Figure 10. The gas cooling effect of the high-pressure system at its lowest flow rate was higher than the low-pressure system at all flow rates. When steady state was reached, the high-pressure system at 1.92 kg/s stabilized the gas temperature in the room at the same temperature as when the low-pressure system was employed at both 3.83 and 5.75 kg/s. This is illustrated in Figure 9. Under these test conditions, the high-pressure system only required approximately two-thirds of the water of the low-pressure system for the same extinction capacity.

A likely reason for the increase in the pulse rate of the firefighters is that the body is trying to compensate for the increasing body temperature by increasing the blood flow. However, the increase in pulse rates during the test was faster than the increase in skin and textile temperature, which increased much more slowly (Figure 12). The pulse rate stabilises at a high level, and it also seems to increase slowly, as indicated in Figure 11. This may be due to the increase in pulse rate being triggered by (mental) stress, in combination with heat stress and body compensation for skin temperature by pulse rate.

The mental stress on the firefighter was probably greatest in the first test, even though the first test was stopped early, giving a less representative result. The mental stress was probably also lowest in the final test (test 6) than during tests 2 - 5. Although the workload was low, the movements and work carried out by the firefighters could have an effect on their pulse rate. However, the results from tests 1 and 6, compared with those from tests 2 - 5, indicate that mental stress has great effect on pulse rate.

Tests 4 and 5 were curtailed by the firefighters due to heat stress and heat penetration through their protective clothing. This shows that the combination of high pulse rate and high skin temperature makes working conditions unbearable after only a few minutes, although the workload is low.

Conclusions

The tests presented in this paper show that good reproducibility and reliability can be achieved in fire suppression tests on a large scale, employing a human firefighter.

The capability of the fire service to fight fires in large spaces is related to their ability to reach the burning area of the fuel. One row of wood pallets proved to be a sufficient obstacle to "protect" objects behind from the firefighting attack. The length of the throw of the water spray may limit the possibility of reaching the fire, regardless of whether the water pressure is high or low, thereby limiting the surface cooling effect.

A comparison between the results obtained when using the high-pressure and the low-pressure firefighting systems indicates that the high-pressure system has a better extinguishing effect regarding gas phase extinction. The high-pressure system at flow rates of 1.92 and 3.83 kg/s reduced the temperature more rapidly and to a lower level, than the low-pressure system at the same flow rates.

The flow rate of 1.92 kg/s was, however, not sufficient to attain the control criterion based on mass loss rate. At 3.83 kg/s, both systems attained the control criterion, but the low-pressure system attained it faster than the high-pressure system.

When both surface cooling effects and gas phase effects are considered, the high-pressure system requires only approximately two-thirds of the water required by the low-pressure system to achieve the same extinction capacity in this scenario.

The increase in pulse rate of the firefighters appeared to be triggered by mental stress and increased due to increasing skin temperature. Working conditions for firefighters may be unbearable due to heat stress, although the workload is low.

A great deal of data was collected during these tests, which can be used for further work on quantifying the capacity of firefighters and their equipment.

Acknowledgement

The Swedish Rescue Services Agency and Brandforsk, the Swedish Fire Research Board supported the work presented in this paper financially.

References

1. Särdqvist, S. "Fire Brigade Use of Water" *Conference Proceedings of the Eighth International Interflam Conference*. Interscience communications, London, 1999, pp. 675-683.
2. Rasbach, D. J., *Theory in the Evaluation of Fire Properties in Combustion Materials*, Proceedings of the Fifth International Fire Protection Seminar, Karlsruhe, Germany, 1976, pp 113-130.
3. Beyler, C., *A Unified Model of Fire Suppression*, Journal of Fire Protection Engineering, 4 (1), 1992, pp 5-16
4. Särdqvist, S, Holmstedt, G, *Water for Manual Fire Suppression*, submitted to Journal of Fire Protection Engineering, 2000.
5. Svensson, S., Lundström, S., "Live fire tests on suppression of post-flashover fires using manually applied high and low pressure water sprays" *Conference Proceedings of the Eighth International Interflam Conference*. Interscience communications, London, 1999, pp 47 - 57.
6. Dunn, M. J., *Full-Scale Testing of Fire Suppression Agents on Unshielded Fires*. School of Engineering, University of Canterbury, New Zealand, 98/2, 1998.
7. Stroup, D. W., Evans, D. D., *Suppression of Post-Flashover Compartment Fires Using Manually Applied Water Sprays*, U. S. Department of Commerce, National Institute of Standards and Technology, NISTIR 4625, 1991.
8. Rimen, J. G., *The Use of High Pressure and Low Pressure Pumps With Hosereel* Systems, Central Fire Brigades Advisory Council, Scottish Central Fire Brigades Advisory Council, Joint Committee on Fire Research, Research Report Number 36, 1990.
9. Milke, J., Evans, D., Hayes Jr., W., *Water Spray Suppression of Fully-Developed Wood Crib Fires in a Compartment*, U. S. Department of Commerce, National Bureau of Standards, NBSIR 88-3745, 1988
10. Davis, P. O. & Dotson C. O., *Physiological aspects of firefighting*, Fire Technology pp 280-291, 1986.
11. Kilbom, Å., *Physical work capacity of firemen with special reference to demands during firefighting*, Scandinavian Journal of Work Environ Health 1980:6, pp 48 - 57.

12. Romet, T. T. & Frim, J., Physiological responses to firefighting activities, European Journal of Applied Physiology, 56 (1987), pp 633-638.

13. Bennett, B. L., Hagan, R. D., Banta, G. & Williams, F., Physiological responses during shipboard firefighting, Aviat. Space Environ. Med., 66 (1995), pp 225-231.

14. Sköldström, B., *Physiological Responses of Firefighters to Workload and Thermal Stress*, Ergonomics, 1987;30, 11, pp1589-1597

15. Lundström, S., Svensson, S., Särdqvist, S., *Släckförsök vid brand i stor lokal,* (In Swedish), Räddningsverket, P21-328/00, 2000.

16. Gunners Nils-Erik, *Methods of Measurement and Measuring Equipment for Fire Tests.* Acta Polytechnica Scandinavica, Civil Engineering and Building Construction Series Nr 43. UDC 614.841.12:699.81, National Swedish Institute for Materials Testing, Stockholm 1967

17. Chen, M., Castek, MFG Corporation, personal communication Nov. 19 and Dec. 1 1999.

18. Akron Force data sheet, (Measurement report, Ref 971428-5, 1998), Akron Brass Company, Wooster, Ohio

19. Tewarson, A. "Generation of Heat and Chemical Compounds in Fires", *SFPE Handbook of Fire Protection Engineering 2nd ed.,* ed. P. J. diNenno, NFPA, 1995, ch. 3-4.

20. 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, pp 153-164.

21. Purser, D. A., "Toxicity Assessment of Combustion Products", *SFPE Handbook of Fire Protection Engineering 2nd ed.,* ed. P. J. diNenno, NFPA, 1995, ch. 2-8, p. 2-113.

22. Babrauskas, V. "Burning Rates", *SFPE Handbook of Fire Protection Engineering 2nd ed.,* ed. P. J. diNenno, NFPA, 1995, ch. 3-1.

23. Peacock, R. D. et al., *Technical Reference Guide for the Hazard I Fire Hazard Assessment Method*, United States Department of Commerce, National Institute of Standards and Technology, NIST Handbook 146, vol. II, 1991.

24. 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*, United States Department of Commerce, National Institute of Standards and Technology, NIST-GCR-92-612, 1992.

25. HMSO, *Fire Research 1955, Report of the Fire Research Board with the report of the director of fire research for the year 1955*, Department of Scientific and Industrial Research and Fire Offices' Committee, Her Majesty's Stationary Office, London, 1955, pp 38-39.

Paper III: Developing a command structure within the fire services - from enlistment to a viable system

Stefan Svensson

Jennings, Charles (Ed.). Improving Firefighter Safety: Human Behavior and Organizational Aspects. An International Conference. Alexandria Virginia: Institution of Fire Engineers, United States Branch. 2001.

Developing a command structure within the fire services - from enlistment to a viable system

Stefan Svensson
Swedish Rescue Services Agency
S – 247 81 Sodra Sandby
Sweden
Phone: +46 46 23 35 76
Fax: +46 46 620 17
E-mail: stefan.svensson@re.srv.se

Abstract

This paper deals with the development of a command structure that is being introduced in the Swedish fire services. Control aspects including safety issues are treated effectively within the framework of this command structure. The structure is based on a few important elements. The general idea is that by transforming the viable systems model together with the concept of control and leadership into a command structure, this will lead to efficient management of fire and rescue operations, including safety issues. Redundancy within the system will increase, thus creating necessary conditions for keeping a high level of safety. The work so far has mainly been on developing and introducing the viable systems model to the Swedish fire services. Still, the concept of control is an important aspect that has to be developed and introduced. Future research should aim at further investigating of the concept of control and at investigating firefighting operations as joint systems of cognition and technology. Priority should also be given to finding models for tactical and strategic design and management of firefighting operations.

Introduction

This paper deals with the development of a command structure that is being brought to use by the Swedish fire services. Control aspects including safety issues are treated effectively within the framework of this command structure. It should be noted that the paper and any comments in it are based on Swedish conditions, although some aspects and phenomena may be recognizable as universal.

Casualties are very rare in the Swedish fire services. Sweden holds approximately 1000 full-time firefighters and 3000 part-time firefighters in readiness, which makes a total employment of approximately 4000 full-time and 12000 part-time firefighters [1]. As a representative example, in 1998 no firefighters were killed on duty [2]. Approximately 130 were injured due to occupational accidents. During the period 1989 - 1994, 2 firefighters were killed on duty. However, the risk of accidents and deaths is still high and efforts should be made in order to reduce the risks. Safety also includes minimizing long-term effects such as chronic exposure to smoke and toxic substances.

Safety at a fire scene of course depends to a great deal on how the actual firefighting is performed, including the handling of equipment. Safety is also affected by the competence of the firefighters and of the commanding officers, which affects how they assess a situation and deal with it. The construction of buildings is another important aspect that greatly affects safety to firefighting personnel. Buildings in Sweden are generally considered as “fire safe”, although exceptions can be found, such as in very old city centers. Material properties of structural elements as well as interior decoration and furniture are effectively controlled by legislation so that the risk of fire is kept low. In addition, development of performance-based building codes should further encourage fire safety and firefighter safety.

However, firefighter safety is also to a very great deal affected by organizational aspects. In particular, how tasks and responsibilities are distributed amongst firefighters and commanding officers and on in-depth knowledge on how different actions taken affect the outcome of an incident.

Background

One of the reasons for humankind to join and to form communities and societies was to protect themselves from enemies, including fire. As complexity grew in these societies, consequently the need for an organized protection against fire grew. Regulations for fire protection and measures in case of fire are very old in Sweden, approximately thousand years old. In the late nineteenth century, the first building code for the municipalities in Sweden was formed, which included nationwide regulations on fire protection. At the same time, the first fire law for Swedish municipal fire brigades was established. The regulations included stipulations for chimney sweeping, fire inspection, firewatchers, water supply in case of fire, fire-fighting equipment,

equipment for life saving in case of fire, fire brigades and others measures in case of fire [3].

The arrangement of the original fire brigades was done in a military fashion, and commanding officers were enlisted among military officers. Unfortunately, these arrangements still have an impact on the Swedish fire services [4]. One example of this is the role and responsibilities of the on-scene commander at an accident site. He/she has up to now been regarded as almost despotic, with unlimited possibilities to make any thinkable decision. This is of course not the case, although the conception permeates organizational and safety aspects of fire fighting operations. Also, fire safety as well as the organization of the fire services is still very pragmatic, and it is not until recent years that academic skill and scientifically-based knowledge has been introduced to the fire safety and fire fighting community.

During the post Second World War period, the need for an altered command structure within the Swedish fire services emerged. Due to a few very complex accidents in the seventies, from an organizational as well as from a technical point of view, the need became obvious. These accidents pointed out lack of cooperation between organizations as well as in safety of firefighters during the rescue work. The intention of the makers of the Swedish Fire Services Act currently in force was never that each municipality should handle all kinds of accidents themselves [5]. Cooperation is of vital importance in any fire and rescue operation. Unfortunately, some Swedish fire chiefs consider cooperation, especially across municipal borders, to be a sign of weakness. Although, susceptibility to boundless cooperation between municipalities is far greater today than ten years ago. In addition, the trend of merger of municipal fire brigades into large federations further increases the need of an organizational structure that makes use of the available resources in a safe and efficient manner.

A structure for safe and efficient handling of fire and rescue operations has been developed during the last few years. It provides a safe manner for conduct of fire-fighting operations, although a lot of work remains. Due to the autonomy of the municipalities it is a slow process to introduce the structure to the Swedish fire brigades. Efforts are mainly on education and training, where the nationwide training system of firefighters and commanding officers has a large impact on the introduction of new theories and ideas.

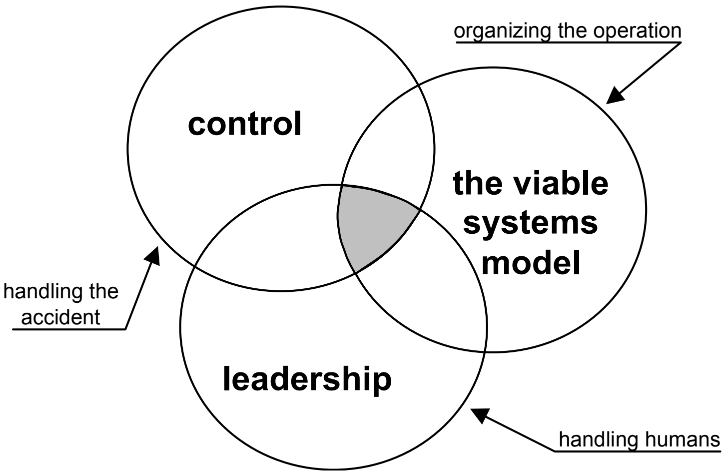

Figure 1. An organizational structure based upon the concept of control, leadership and the viable systems model.

The organizational structure which has been introduced, and which has the capability of overcoming a large number of problems, is mainly based upon the so-called viable systems model. However, the concept of control as well as leadership has to be put in relation to the viable systems model in order to get the big picture and to understand the advantages of this structure and in order to develop it further, figure 1. Finding an organizational structure that function in all types of fire and rescue operations is an important aspect when dealing with safety issues.

Leadership

There is a fundamental difference between being a commanding officer, which is the formal appointment of being in charge of an operation, and being a leader. The leader is the person that is accepted by a group of people to direct them and to make them give up any personal goals in favour of the overriding goal of an operation or a task. The impact of leadership on safety during a fire fighting operation is large and well known by Swedish fire officers.

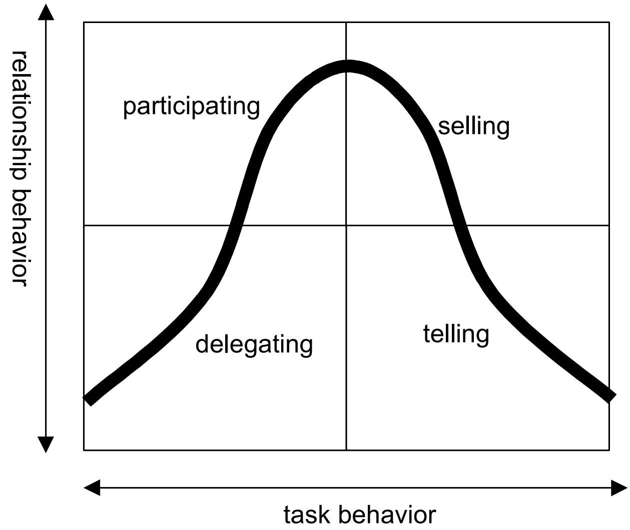

Figure 2. Situational leadership, from [8].

A large quantity of literature describes theories on leadership as well as leadership practices. Leadership is about persuasion and not about domination. People who must rely on their formal position or to force people to act for them are no leaders [6]. Leadership arises only when other people take part in and comply with goals within a group of people. There is by definition, a causal relationship between leadership and the achievement of a group. The criterion of a leader is said to be "performance of teams." The ability of a leader appears in the achievement of the team. Leadership may also be defined as the psychological process that is initiated by one or more people within a group, often by an appointed leader and that aims at commanding, coordinating and targeting the actions of the group [7].

The concept of situational leadership offers another approach to leadership [8]. A combination of task behavior and relationship behavior forms the basis of situational leadership and it incorporates ability and willingness of the adherent (Figure 2). It may seem obvious that leadership should be adapted to the specific situation. The difficulty lies in finding a model that works in all or at least in a large number of situations.

As a summary, the leader should exercise command through actions in order to coordinate the team members to solve a task. Incentives for actions come from the leader, from others (team members) or from the situation. The choice of actions depends on the assessment of the situation. The effectiveness of the team reflects quality of the leadership. An individual does not take the leadership within a group. Rather, the team gives the trust and responsibility that belongs to leadership to an individual within a team.

The concept of control

In order to perform fire-fighting operations in a safe manner, establishment of primary objectives of the operation is vital. Such an objective must be abstract enough to include all kinds of fire fighting and rescue operations, but it must still be possible to easily transform this objective into practice on the fire ground.

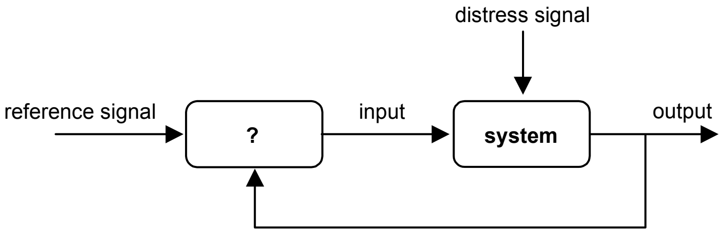

Figure 3. Control theory as a metaphor for understanding the inherent dynamics in a fire and rescue operation.

A fire-fighting operation is a process with the purpose of controlling another process [9]. Therefore, control theory may serve as a useful metaphor for further analysis of the functionality of fire-fighting operations, figure 3. Based on this assumption and on a discussion on fire fighting tactics [10], the primary objective of a fire-fighting operation is to obtain and maintain control. Control requires four general conditions to be met [9]:

- There must be a goal.
- It must be possible to ascertain the state of the system to be controlled.

- It must be possible to change the state of the system.
- There must be a model of the system to be controlled.

The goal condition is obvious. It involves directing the operation towards a common goal, which is in congruity with legal as well as moral rules and regulations. It is also of great importance that the goal is realistic as well as feasible. In addition, if correctly formulated the goal condition and consequently the goal can easily be adapted to the different levels within a viable system. In order to determine the course of action and distribution of resources between tasks, the observability condition ensures that the controlling system uses the actual state of the system to be controlled. The condition of changing the state of the system involves ensuring that the controlling system is actually able to change the state of the system to be controlled. Finally, the model condition tells the controller how to accomplish a desired change in the state of the system and how different parts of the system interact.

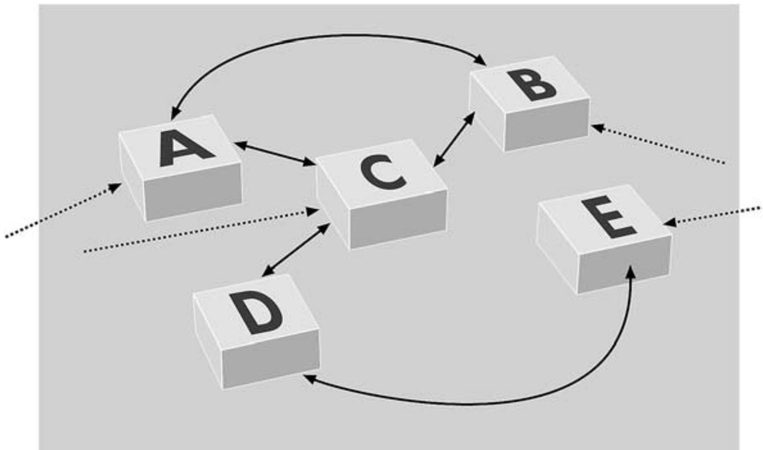

Figure 4. The inherent dynamics of a firefighting operation affects in such a way that actions taken during firefighting operations affects other actions taken in a nonlinear and opaque fashion [10].

Here, the model condition may be the most important condition that has to be met, and it requires a few comments. The model condition involves knowing or being aware of how (in time and space) different parts of the system affects other parts of the system, and how decisions made and measures taken affects (in time and space) different parts of the system, (see Figure 4). Traditionally, this knowledge has mainly been based on experience and skills acquired through participation in firefighting. However, as complexity in society grows and, consequently, when complexity in those breakdowns of systems that the fire services respond to grows, the need for an altered approach also has emerged. The course of events during accidents and incidents and during fire fighting or rescue operations are no longer linear, and actions taken - or not taken - may have long-term effects or impact on people, environment and property which is impossible to identify by experience only. In many complex situations there is simply a lack in experience. This is often obvious when dealing with hazardous materials, but also characteristics of fires have changed dramatically over the years in many ways. For example, fire spread may be difficult to predict. Also, environmental impacts of accidents can be very hard to assess during firefighting operations. These aspects turn the accident and the firefighting operation into a very opaque system. This opaqueness refers to a lack of transparency about the situation of two kinds [9]: the first is due to a lack of information about the system's current state, and the second results from lack of information about the system's current state and the relationships among various sub-processes.

The change in the conditions for the fire services calls for a differentiated approach in knowledge and skills and, not the least, it requires a more academic approach toward fires and accidents. Academic training serves well as a basis for the abstract thinking required when dealing with dynamic systems.

In recent years, the interest by the scientific community for manual fire fighting and related problems has been growing. A large number of research areas that relate to fire fighting can be identified [11]. Such areas include human behavior in fire, physiological aspects of fire fighting, firefighter protective clothing, and aspects of firefighter training. They also include manual suppression using water, foam or dry chemicals, fire testing involving actual firefighting methods such as positive pressure ventilation and additives to water.

In addition, performance-based building codes is an area of applied science and where humans including firefighters, have been identified as an integral part of fire safety in buildings. It is reasonable to assume that the growing interest in performance-based codes is a cause for the growing interest in manual fire fighting and related problems. On this matter, disciplines of statistics, costbenefit and risk analysis are of great importance. There is also substantial research on fire detection systems and sprinkler systems. Here, it should be noted that one of the purposes of such systems is to bring the fire services to the scene of the fire.

It is of great importance to any commanding officer within the fire service to have knowledge of results from such research, especially for the understanding of how fires and accidents can be brought under control. During the last ten years the recruiting of Swedish fire officers is based on academic skills, which inter alia has enabled this flow of results from research into practice useful for the fire service.

The viable systems model

The need for an altered command structure within the fire service emerged in the seventies. Incidentally, a framework for an organization was developed, based on the so-called viable systems model [12, 13, 14]. The basic viable systems model is applicable to a large number of organizations, systems and organisms, in that it explains basic properties and important features of a viable system. The model was found interesting, further development was made [15], and it is now being introduced into the fire services throughout Sweden.

Two essential concepts for the model are dealing with complexity and recursivity. Organizations comprising these key concepts are, by definition, autonomous, i.e. they contain within them the capacity to adapt to change in their environment and to deal with the complexity that is relevant to them. Five essential functions form the basis for the viable systems model:

- Implementation.
- Co-ordination.
- Control.
- Intelligence.
- Policy.

It should be noted that these functions do not represent any hierarchical structure of an organization. The model simply distributes tasks and responsibilities within, in this case, an organization.

At the core of the model are the primary activities, responsible for producing the services implied by the identity of the fire services, i.e.

implementation of the objectives by performing tasks. This is the work carried out by teams of firefighters, the task forces. At a fire scene, the implementation function comprises commanding a task force (a small group of firefighters) in performing an assigned task.

The viable system also has functions in place to co-ordinate its primary sub-units (the task forces). Coordination is necessary between the value-adding functions as well as between the embedded primary activities. At a fire scene, co-ordination, comprises managing different task forces in fulfilling common objectives.

In addition, a two-way communication between sub-unit and meta-level unit is a prerequisite for viability. This is the function where resources are negotiated, direct line management instructions are issued and accountability reports flow upwards to keep the meta-level management in touch with events. At the fire scene, this function, control, comprises management of the operation within the scope of the current operation.

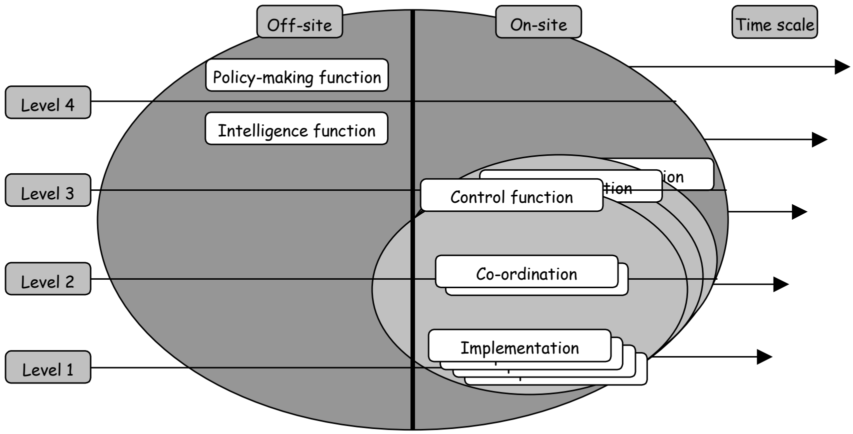

Figure 5. The viable systems model adapted to a firefighting organization. Several simultaneously operations are treated within the system [15].

The intelligence function is the two-way link between the primary activity and its external environment. It provides the primary activity with continuous feedback on all external factors that are likely to be relevant to it in the future. It also projects the identity and message of the organization into its environment. The intelligence function is strongly focused on the future. At a fire scene, the intelligence function comprises assessing and determination of scope of operations.

The last function is the policy-making function. Its main roles are to provide clarity about the overall direction, values and purposes of the organizational units; and to design, at the highest level, the conditions for organizational effectiveness. The decisions that the policy function makes are rare and they constitute, in the main, a final "sanity check" against the direction, values and purposes within and between the intelligence and control functions. At a fire scene, the policy function provides roles and purposes of the organization as a whole.

The original viable systems model is a general model of any viable system. Before introducing the model to the fire services, it was adapted in such a way that it recognized important characteristics of the fire fighting system [15] (Figure 5). Such characteristics included differentiation of commanding levels, positioning of commanding officers depending on command level, time scales of decisions made, time scales in long-term planning and handling of several simultaneous operations.

Discussion

The viable systems model is the core of the commanding structure. It comprises leadership as well as the concept of control. However, no element itself has the sole potential of increasing safety or making fire and rescue operations more efficient, although they all are of equal importance to a command structure. Therefore, it is necessary to discuss the elements separately as well as in conjunction. In addition, safety is the key, which also requires a few comments.

Leadership

Leadership is an important aspect of managing people. However, as was indicated above, the appointed commanding officer is not always the leader. The trust and responsibility may very well be given to another individual. Also, there may be a great difference in demands on commanding officers and leaders between an everyday situation at a fire station and a highly specialized situation at a fire scene. The cooperation between commanding officers and their team is set in the everyday situation at the fire station but put on test during fire and rescue operations. If such operations are to be run smoothly, the everyday situation must run equally smoothly within a group. Conflicts induced during the non-emergency situation can not be allowed to affect performance during fire fighting operations.

Also, the fire service is a very traditional organization and organizational heritage can be very difficult to handle. It should be noted that the viable systems model is not a hierarchical model and that the model doesn't attach any values to assignments and functions as humans often do. The different functions within the model are all equally necessary in order to make the system/organization viable and to fulfill the two essential concepts of the model - dealing with complexity and recursivity. The problem encountered when introducing the model to the fire services is that it often has been taken as a justification of a chain of command already approved. As it usually is commanding officers that introduce the model to the organization, the resistance against the introduction has varied in some municipalities, especially if there is already a lack of leadership. This lack may grow even deeper in such cases and conflicts are bound to arise.

The viable systems model is not a model for leadership, but leadership must be considered when introducing an organizational model, not at least from a safety point of view.

Obtaining and maintaining control

As noted above, the fire service is a very traditional organization. Knowledge is usually based on pragmatic needs, and it has not been until recently that academic skill and scientific knowledge has been introduced to the fire services. The ability to think and reason in abstract terms is still limited and the concept of control requires a rather high degree of ability to think in abstract terms. In addition, it requires an ability to transform an abstract plan and an overarching objective into a tangible and realizable plan of action.

However, due to the growing complexity in society and consequently in the accidents that the fire service respond to, there is no shortcut. Practicable knowledge and academic skills must be combined in order to reach the primary objective of firefighting operations, to obtain and maintain control. Academic skill and pragmatic needs and skills must be allowed to exist simultaneously.

The concept of control seems to be an important aspect of fire fighting operations. However, in order to put the concept into practice there is a need for much more development. Especially, the criteria of control and how to achieve some state of control during fire fighting operations needs further investigation.

In addition, control theory has shown to be an interesting approach, especially for mathematical modeling and thorough investigation of features and characteristics of fire fighting operations. Such work has up to now included topics such as flow rates of water and droplet sizes of water for fire fighting, and decision making during fire fighting operations. However, studies have been initiated on physical modeling of fire fighting operations. So far, the only aspect of fire fighting that has been successfully modeled is the relation between rate of water flow and room temperature [16]. However, the technique of computational fluid dynamics, where the basic partial differential equations for the physical relations and properties in a system are solved, is starting to show its strength. With increasing computer capacity it should be possible to further expound such modeling and simulations. Mathematical modeling and simulations, in combination with testing, are important tools for in-depth studies of fire fighting operation and for identifying criteria for control, among others.

The viable systems model

Introducing the viable systems model to the Swedish fire services, or rather, introducing a modified version of the viable systems model, has not been free of conflicts. As was discussed above on leadership, the model in some cases has been used as a justification for an already approved but in most cases non-working chain of command. An existing organization often tries to "squeeze" their organization into the viable systems model, which effectively stops any improvement in the existing organization.

The reason for this can be the same as was discussed above on obtaining and maintaining control, i.e. a lack in ability to think in abstract terms. As in the case of understanding the concept of control, the viable systems model requires a high degree of ability to think in abstract terms. In addition, the model doesn't attach value to functions, tasks and responsibilities. Each function within the system is of equal value in order to attain a viable system, and it is important that all personnel are familiar with the basic properties of the model.

Getting the operation together

The general idea is that by transforming the viable systems model together with the concept of control and leadership into a command structure for the Swedish fire services, we may come to a point where control features and safety issues of operations can be managed in an efficient way. As indicated above, the general solution to any fire fighting operation consists of obtaining and maintaining control. By means of the viable system model, commanders within different functions can identify factors that affect obtaining and maintaining control of the fire fighting operation early in the process of command. Redundancy within the system becomes high, thus creating necessary conditions for keeping a high level of safety. Each function aims at a defined sphere of interest, objectives are set and the roles and tasks of commanders and teams associated with different functions are stated within the model. In addition, management by objectives plays an important role in creating redundancy. Management by objectives also requires a well-developed and accepted leadership within the organization.

Safety may be jeopardized in situations where the appointed commanding officer not is the actual leader, i.e. he/she is not the person given trust and responsibilities by the team. Lack in leadership may lead to breakdown in the feedback chain, thus causing a discontinuity in the flow of information. Without information, the observability condition for control cannot be fulfilled and there is a great risk of breakdown in the command structure.

The command structure consists of three main elements. However, if one of the elements is not functional, the command structure will not be functional. A functional structure is a great asset for enhancing efficiency and safety during a firefighting operation, but a dysfunctional command structure will most likely be a great burden. It may therefore seem as if the command structure being developed and introduced in Sweden is very sensitive. But still, a fully developed, introduced and implemented command structure based on the viable systems model, the concept of control and leadership, implies more safe and efficient fire fighting operations.

Implications for safety

The primary objective for introducing an altered command structure is to enhance safety and efficiency during fire and rescue operations. Due to the low number of casualties and accidents in the Swedish fire services, it will be hard to show any improvement by way of statistics. However, safety and efficiency can often be assumed to show through other factors.

One such factor is time to control and another may be the cost of fire fighting operations and in salvage. A decrease in time to control, decrease in cost of fire fighting operations and an increase in salvage may indicate more efficient fire fighting operations. In turn, this may imply safer fire fighting operations, although conclusions on safety through observations in efficiency shouldn't be taken for granted.

The concept of control and especially the criteria for control needs further research. By defining and establishing general control criteria for dealing with accidents it may be possible to find the key factors to describe efficiency and then also safety. In a similar way the concept of mission efficiency measures have been defined for military operations [17]. These measures are based on the key factors i) initial mission state, ii) information processing during the mission, iii) utilization of available resources during the mission, iv) decision making and actions during the mission, and v) mission course of events. The problem here is mainly to find an objective assessment of efficiency [18].

Conclusion and continued work

A fully developed, introduced and implemented command structure based on the viable systems model, and the concepts of control and leadership, will lead to safer and more efficient firefighting operations.

The work so far has mainly been focused on developing and introducing the viable systems model to the Swedish fire services. Still, the concept of control is a new but important aspect of performing firefighting operations safely, which has to be brought into the fire services.

Continued work is mainly focused on the concept of control, where two main problems can be identified:

- Criteria for control.
  This problem includes finding relevant criteria for control, which requires in-depth understanding of characteristics of accidents.

- State of control.
  This problem includes studies of how accidents are brought to some state of control. It requires in-depth knowledge of how actions taken

influence the accident as well as other actions taken. The dynamics in the system is important and has to be taken into account.

In addition, it should be noted that fire and rescue operations consist of humans and machines in cooperative work. Therefore, future work should be based on the concept that fire-fighting operations are joint systems of cognition and technology. Priority should also be given to the finding of models for tactical and strategic design and management of fire fighting operations.

References

1. *Räddningstjänst i siffror 1998*. (*Statistics on the fire services 1998*). (In Swedish). Räddningsverket: Karlstad. 1999.

2. *Arbetssjukdomar och arbetsolyckor 1998* (*Occupational Diseases and Occupational Accidents 1998*). (In Swedish). Arbetarskyddsstyrelsen/Statistiska Centralbyrån. 2000.

3. Nyström, L. *Lagar och ansvarsförhållanden i det svenska brandväsendets historia* (*Regulations and liabilities in the Swedish fire services from a historical perspective*). (In Swedish) Räddningsverket: Karlstad. 1992.

4. *Brandsyn förr och nu* (*Fire inspection of today from a historical perspective*). (In Swedish) Räddningsverket: Karlstad. 1993.

5. *Proposition 1985/86:170, om räddningstjänst mm (Draft law 1985/86:170, on fire service etc).* (In Swedish). Försvarsdepartementet: Stockholm.

6. Hogan, R., Curphy, G.J. & Hogan, J. *What we know about effective leadership: Effectiveness and personality. American Psychologist, June*, 493 - 504. 1994.

7. Jeffmar, C. *Socialpsykologi - människor i samspel* (*Social psychology - people in interaction*) (In Swedish). Studentlitteratur; Lund. 1987.

8. Hersey, P., Blanchard, K.H. &, Johnson, D.E. *Management of organizational behaviour*. New Jersey: Prentice-Hall. 1996.

9. Brehmer, B. Dynamic Decision Making in Command and Control. In McCann, C & pigeau, R. (Eds), *The Human in Command: Exploring the Modern Military Experience*, New York: Kluwer Academic/Plenum Publishers. 2000.

10. Svensson, S. *Räddningstaktiska grunder, förslag till definitioner och kommentarer därtill*. (*Basic tactical principles – proposals for definitions and comments to them*) (In Swedish) (report P21-252/99). Räddningsverket: Karlstad. 1999.

11. Svensson, S. *The firefighting operation - the functioning of a joint system*. Abstract submitted to 9th International Fire Science & Engineering Conference, Interflam'01. 2001.

12. Beer, S. *Diagnosing the System for Organizations*. Wiley: Chichester. 1985.

13. Espejo, R. & Harnden R. *The Viable System Model - Interpretations and Applications of Stafford Beer's VSM*. Wiley: Chichester. 1985.

14. Gomez, P. *Modelle und Methoden des systemorientierten Managements*. Haupt: Bern/Stuttgart. 1981.

15. *Grunder för ledning, generella principer för ledning av kommunala räddningsinsatser*. (*The elements of Command and Control, General principles for Command and Control in municipal fire and rescue operations*) (In Swedish) (report U14-569/98). Räddningsverket: Karlstad. 1998.

16. Svensson, S. *Solving Tactical Problems Using Control Engineering: Systems identification and Modeling*, Report 1017. Department of Fire Safety Engineering, Lund. 1998.

17. Worm, A. *Command and Control Sciences: Theory and Tactical Applications* (report Liu-Tek.Lic-1998:49). Linköping University, Institute of Technology. 1998.

18. Dupuy, T.N. *Numbers, Predictions and War*. Fairfax: HERO Books. 1985.

Paper IV: Experimental study of fire ventilation actions during firefighting operations

Stefan Svensson

Fire Technology, vol. 37, No. 1, 2001.

Experimental study of fire ventilation during firefighting operations

Stefan Svensson
Swedish Rescue Services Agency
Rescue Services College
S – 247 81 Sodra Sandby
Sweden

Abstract

Fire ventilation measures taken by fire & rescue services, including positive pressure ventilation, were investigated. Fifteen tests were performed in a three-room apartment, with an attached staircase, on the first floor of the training facility. The fire source was a 0.5 m diameter pool of heptane. The temperature and pressure in the apartment, the weight of the fire source, and the flow through openings were recorded continuously. The tests showed that the rate of burning was increased by positive pressure ventilation. Also, positive pressure ventilation increases the temperature in rooms on the leeward side of the fire and reduces temperatures in rooms on the windward side of the fire. Safety and working conditions for firefighters are improved by positive pressure ventilation, but it jeopardizes the lives of anyone that might be trapped. The importance of command and control during firefighting operations is prominent.

Keywords: fire tests, fire ventilation, positive pressure ventilation, ppv, firefighting

Introduction

The primary objective of fire & rescue services is to save and protect people in the event of accidents. The fire & rescue service responds to a large variety of accidents. However, fires are still a major cause of turnouts[1, 2]. After arriving at the scene of a fire, a fire & rescue brigade has a number of different techniques and methods at its disposal for dealing with the fire. For example, fire extinguishing, i.e. applying water or some other extinguishing substance to the fire. Another method is fire ventilation i.e. the opening or closing of doors and windows or the making of holes in roofs etc. Changing the ventilation conditions of a fire changes the flow pattern of hot gases inside the building and channels them out of the building. In addition, mechanical fans can be used to increase the flow of smoke and hot gases out of buildings. The purpose of fire ventilation is to facilitate access to fires and to ease searching for trapped victims.

Vertical ventilation of heat and smoke from buildings, i.e. roof venting, has been extensively investigated[3]. However, there is a difference between using roof vents (shutters) and cutting holes in roofs to form vents, but this difference is mainly restricted to the time required for venting. Cutting a hole in a roof requires a lot more time and physical work than do shutters. Nevertheless, the flow of hot gases and smoke is similar in both cases.

During the last few years, there has been a growing interest, within the Swedish fire & rescue services, in positive pressure ventilation. It is a method used by fire & rescue services to allow for the fast removal of smoke and hot gases from buildings[4, 5, 6]. The flow of such fans is generally in the range of 2 – 15 m^3/s.

The chances of a successful operation are good when combined with a fast interior fire attack. Experiments have shown that positive pressure ventilation rapidly reduces temperatures for firefighters and victims and improves air quality and visibility within the premises that are on fire[7, 8].

However, the use of positive pressure ventilation is not a ready-made solution or a generally safe solution for manually fighting fires in buildings. Due to the large flow of air, which pushes heat and smoke through the compartment on fire, a rapid spread of the fire may occur. The flow may also increase risks for the firefighters as well as for possible victims trapped in adjacent rooms. Nevertheless, if the effects of different fire ventilation procedures, including positive pressure ventilation, are thoroughly investigated, after the results of such investigations are implemented, and after training for firefighters then the chances of success are still good.

During the last few years the Swedish Rescue Services Agency has been conducting major work on fire ventilation measures taken by fire & rescue services. The aim has been to thoroughly investigate and describe possibilities, problems and plausible courses of action when using fire ventilation during firefighting operations. The intention has also been to develop a scientifically based method, including theories on fire ventilation, adapted for the fireground. The results from this work have recently been published in a textbook for fire & rescue services[6].

This paper describes an experimental study on the effects of fire ventilation during firefighting operations. The purpose of the tests was to investigate the effect of measures taken by fire & rescue services, including positive pressure ventilation, when responding to a fire in a small apartment with an attached staircase. And also to provide fire & rescue services with qualitative data that can be used as a basis for decision making on the fireground. The full description can be found in the experimental report[9]. Data from the tests can be made available upon request.

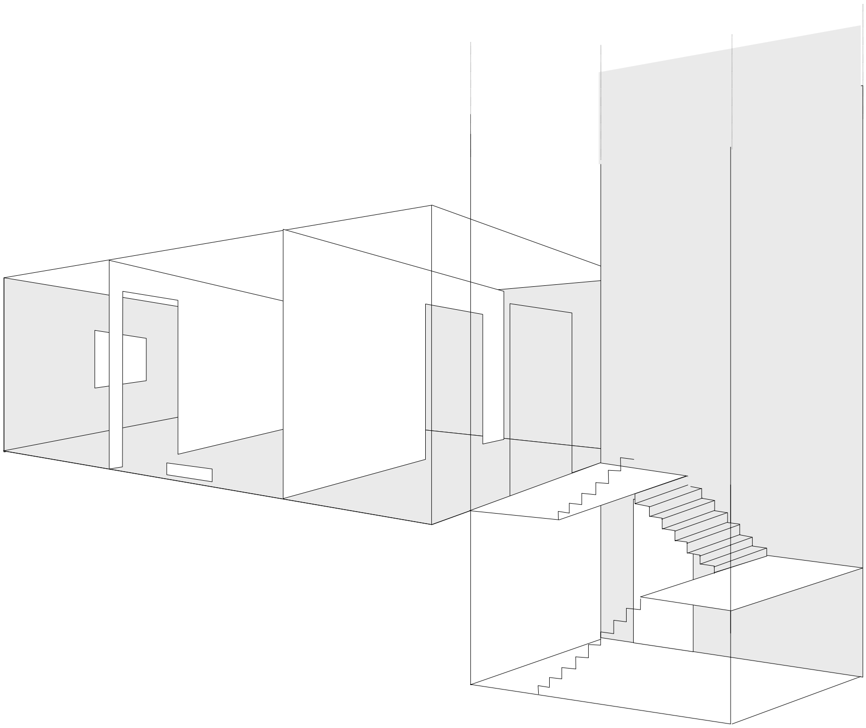

Figure 1. A three-dimensional view of the firefighter training facility used.

Experimental set-up

The tests were performed in a firefighter training facility. Three rooms on the first floor (2.7 m above ground level) were used, measuring (length × width × height) 2.8 × 5.0 × 2.5 m (Room 1), 3.4 × 5.0 × 2.5 m (Room 2), and 1.8 × 5.0 × 2.5 m (Room 3). The attached staircase (Room 4) measured 5.7 × 2.6 × 12 m. The size of the window was 0.88 ×

1.18 m (width × height) (sill at 0.87 m above floor), the size of the doors between rooms 1, 2 and 3 were 1.16 × 1.98 m. The size of the doors between Room 3 and Room 4 and between Room 4 and outdoors were 0.92 × 2.0 m. In rooms 1 and 2 there was a small hatch at floor level, measuring 0.6 × 0.2 m (sill at 0.05 m above floor). See figures 1 and 2 for details.

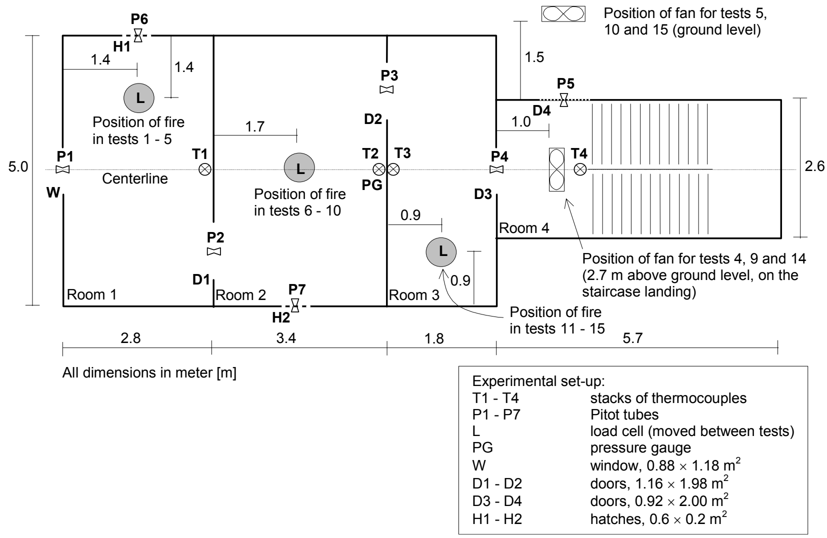

Figure 2. The experimental set-up.

As a fire source, a 0.50 m diameter pool was used. In each test, the fuel was approximately 6.45 litres of heptane floated on approximately 4 litres of water, which correspond to a burn time of 660 - 720 seconds depending on the test scenario. The theoretical mass loss rate was 8.4 g/s, which corresponds to a rate of heat release of 0.37 MW, calculated by[10]

$$\dot{Q} = A \cdot \Delta h_c \cdot \dot{m}''_\infty \cdot \left(1 - e^{-k\beta D}\right)$$

The pool was placed on a loadcell (L in Figure 2) and the weight of the fuel was registered with a rate of 1 Hz. The location of the pool varied between rooms 1 - 3 depending on the scenario for each test. See Figure 2 and Table 1 for details on the different locations in the individual tests.

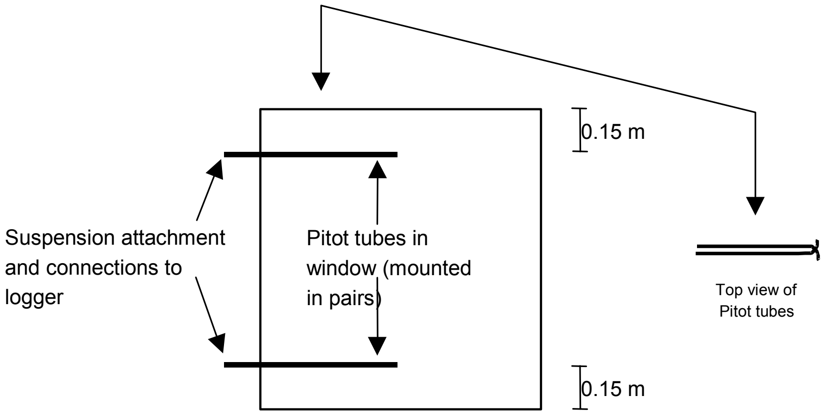

Figure 3. Positioning and assembly of Pitot tubes (mounted in pairs) in the window (W), typical installation.

Temperatures, using type K thermocouples, were registered with a rate of 1 Hz. Thermocouples where mounted at levels 0.25 m, 0.92 m, 1.59 m, and 2.25 m above the floor in rooms 1 – 3 (thermocouple tree T1 - T3). In Room 4 (the staircase) thermocouples were mounted 2.0 m, 5.2 m, 8.3 m, and 11.6 m above ground level (thermocouple tree T4). Pitot tubes were mounted in pairs in all openings, measuring in and outgoing flows, with a rate of 1 Hz. In the window (W), 2 pairs of Pitot tubes were mounted at the height 0.15 m above lower and below upper window frame (along vertical centerline of window) (P1) (Figure 3), respectively. In each door between rooms 1 - 4 (D1 - D3), 3 pairs of Pitot tubes were mounted, at the height 0.2 m above lower and below upper doorframe and horizontally centered in the door (along vertical centerline of door) (P2 - P4), respectively. In the door between Room 4 and the outside (D4), 2 pairs of Pitot tubes were mounted, at the height 0.2 m below upper doorframe and horizontally centered in the door (along vertical centerline of door), respectively (P5). In each hatch (H1 - H2), 1 pair of Pitot tubes were mounted, horizontally and vertically centered in the opening (P6 - P7). Pressure above atmospheric was measured in Room 2 at 2.25 m above floor, using a differential pressure gauge (PG).

The fan used for positive pressure ventilation was a Typhoon 18T5, run by a 5 hp (3.73 kW) gasoline motor[11]. The fan provided a nominal flow of 2.7 m^3/s. The tests were also documented using video and still photography.

Test procedure

The intention of each test was to simulate a firefighting operation, where firefighters gain access to a ventilation-controlled fire in a three-room apartment. The general scenario corresponded to approximately 120 seconds to sound the alarm, 300 seconds time to action and 200 - 400 seconds operational time (depending on actions taken), making a total of 620 - 830 seconds. Based on estimations of equivalence, the pool fire was allowed to burn out within this time. No actual work by firefighters, except the opening of doors/windows and starting of the fan was carried out.

Five different firefighting scenarios were simulated and investigated:

A. Fire attack via staircase (access route through D4, Room 4, D3), window (W) closed.

B. Fire attack via window (W), door between staircase (Room 4) and apartment closed (D3).

C. Fire attack via staircase (access route through D4, Room 4, D3), window (W) open.

D. Fire attack via staircase (access route through D4, Room 4, D3), window (W) open, using positive pressure ventilation, fan positioned in Room 4 on the staircase landing outside the apartment.

E. Fire attack via staircase (access route through D4, Room 4, D3), window (W) open, using positive pressure ventilation, fan positioned outside door to staircase (D4).

In each of the scenarios, the door to the apartment (door D3) and the window (W) remained closed for 420 seconds after ignition. Each of the five scenarios was conducted with the fire source in each of the three rooms. A total of 15 tests were performed. See Table 1 for details on individual tests.

Table 1. Scenarios and results for individual tests.

Test	Location of fire, room no	Scenario	Time to fire out (due to fuel shortage) [s]	Max burning rate during operational time (>400 s from time of ignition) [g/s]
1	1	A) Fire attack via D4 - D3, W closed	620	11.5
2	1	B) Fire attack via W, D3 closed	820	9.6
3	1	C) Fire attack via D4 - D3, W open	750	11.3
4	1	D) Fire attack via D4 - D3, W open using positive pressure ventilation, fan located outside D3	780	10.8
5	1	E) Fire attack via D4 - D3, W open using positive pressure ventilation, fan located outside D4	780	11.6
6	2	A) Fire attack via D4 - D3, W closed		6.2
7	2	B) Fire attack via W, 3 closed	830	7.5
8	2	C) Fire attack via D4 - D3, W open	700	9.2
9	2	D) Fire attack via D4 - D3, W open using positive pressure ventilation, fan located outside D3	690	12.4
10	2	E) Fire attack via D4 - D3, W open using positive pressure ventilation, fan located outside D4	670	14.0
11	3	A) Fire attack via D4 - D3, W closed		6.4
12	3	B) Fire attack via W, door 3 closed	720	12.1
13	3	C) Fire attack via D4 - D3, W open	670	12.8
14	3	D) Fire attack via D4 - D3, W open using positive pressure ventilation, fan located outside D3	700	12.0
15	3	E) Fire attack via D4 - D3, W open using positive pressure ventilation, fan located outside D4	620	15.1

The wind speed during the tests varied between 0 - 2 m/s. No effects on the tests due to wind were observed. The outdoor temperature during the tests varied between 16 and 20°C. The air temperature inside the facility was allowed to cool down to approximately 25 - 50 °C (upper - lower layer, respectively) between tests.

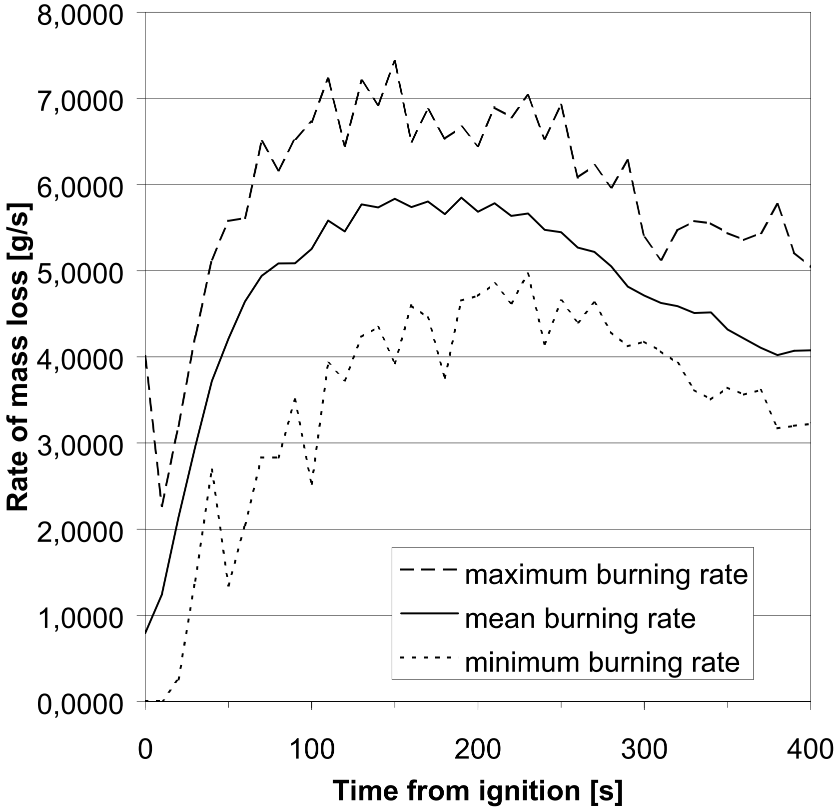

Figure 4. Maximum, mean and minimum burning rate for all the tests, during the first 400 s. The fire is ventilation controlled at 400 s.

Results

Figure 4 shows the mean, maximum and minimum rate of mass loss for all the tests for the first 400 s. The rate of mass loss increased within 100 - 150 s to a maximum of 5 - 7 g/s. After this, it slowly decreased to 3 - 5 g/s at 400 s. The diagram indicates that the fire was ventilation controlled when the simulated fire attack commenced. When ventilation actions were initiated, the ventilation conditions were changed, thus making the fire fuel controlled.

Figure 5 shows the mean burning rate for scenarios with and without positive pressure ventilation (PPV). Maximum rate of mass loss during the period after 400 s is shown in table 1. By using PPV, the burning rate increased by an average of approximately 40 %.

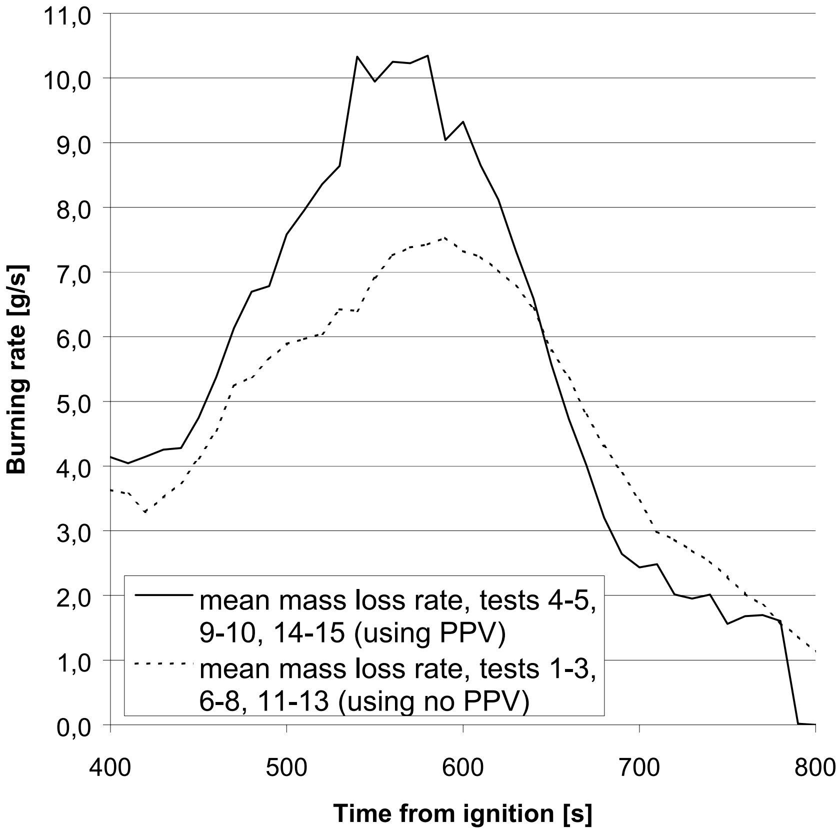

Figure 5. Mean mass loss rates for the scenarios with and without the use of PPV, respectively.

Figure 6 shows the mean pressure above atmospheric at ceiling level of Room 2 (PG), grouped by scenario. In all scenarios, the pressure increased to a maximum of 2 - 5 Pa at 50 - 150 s from ignition. It then slowly decreased to 0 - 1 Pa. In the scenarios without positive pressure ventilation (scenarios A, B and C), the pressure at ceiling level in Room

2 decreased further when D3 and/or W were open. In scenarios using positive pressure ventilation (scenarios D and E), the pressure increased to 5 - 8 Pa, depending on the position of the fan. Positioning the fan outside the staircase (scenario E) the pressure increased more than when the fan was positioned on the staircase landing outside the apartment (scenario D).

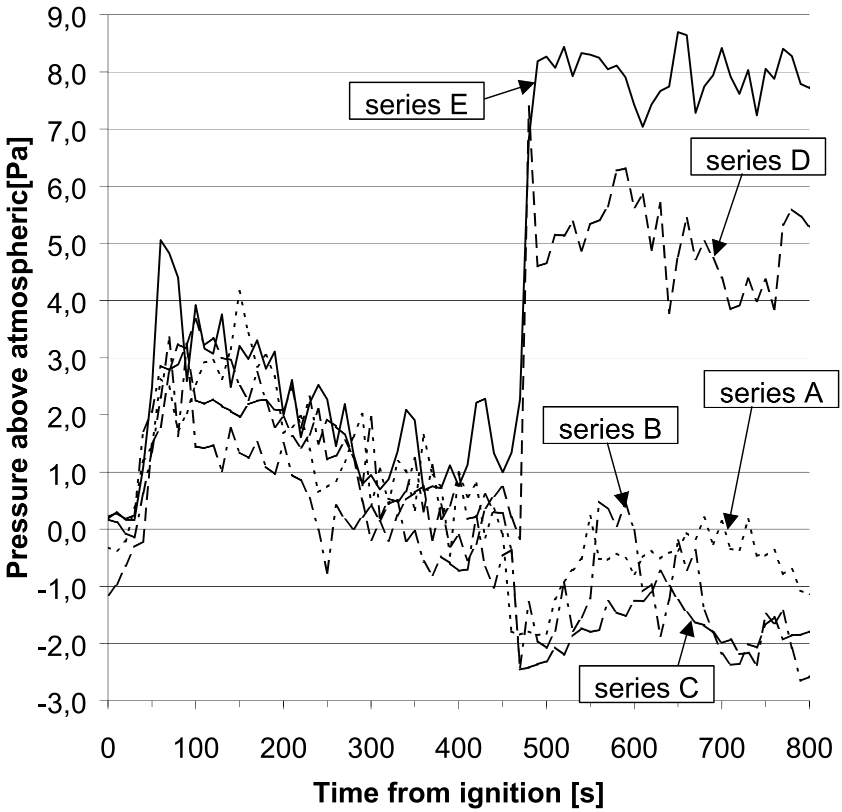

Figure 6. The pressure above atmospheric at ceiling level of Room 2.

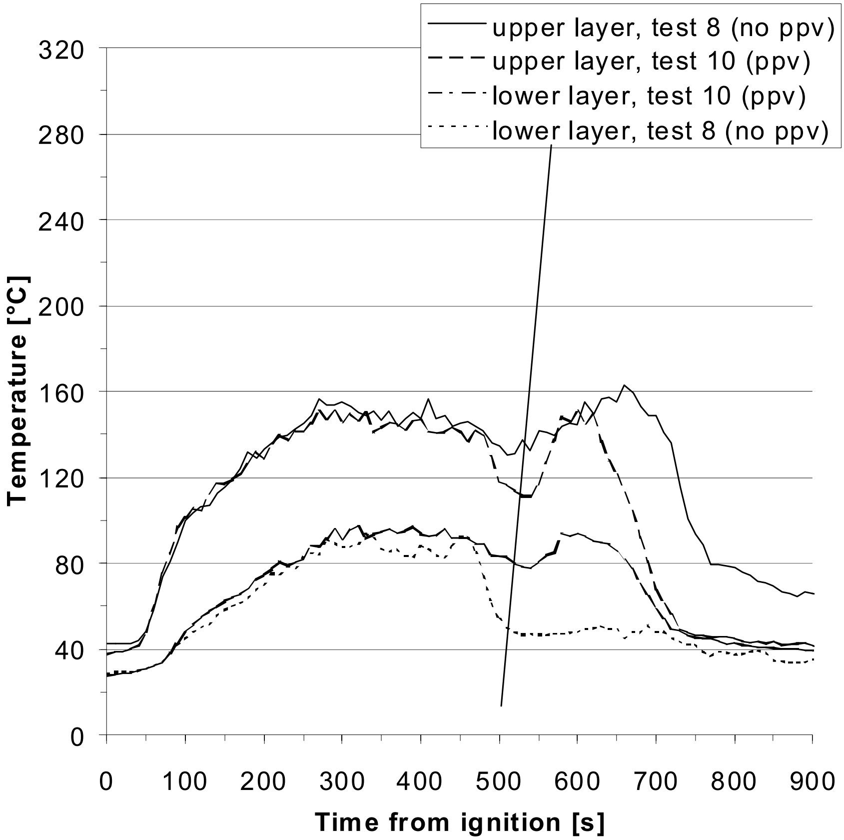

Figure 7. Mean temperatures of the upper and lower layer in Room 1, comparison between test 8 (without PPV) and test 10 (using PPV). The vertical line indicates the order of the tests, as in the legend.

Figures 7 - 9 show upper and lower layer mean temperatures in rooms 1, 2 and 3 for tests 8 and 10, respectively. The lower layer mean temperature in the figures was constructed using data from thermocouples at level 0.25 m and 0.92 m above the floor. The upper layer mean temperature in the figures was constructed using data from thermocouples at level 1.59 m and 2.25 m above floor. When no positive pressure ventilation was applied (test 8), a distinct hot upper layer of out-flowing gases and a cool lower layer of inflowing air through W were formed in Room 1 (Figure 7). When positive pressure ventilation was used, after 450 s from time of ignition (test 10), the fan pushes hot smoke from Room 2 (the room of fire origin) into Room 1 and out through the opening (W). The lower layer temperature remains high and it is increased further at 550 s after time of ignition.

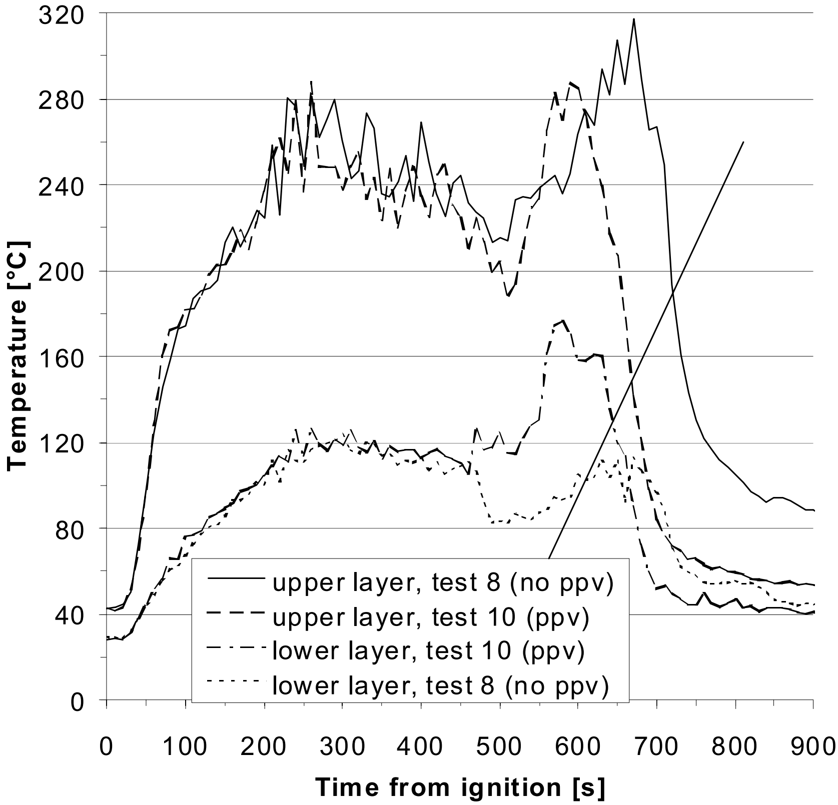

Figure 8. Mean temperatures of the upper and lower layer in Room 2, comparison between test 8 (without PPV) and test 10 (using PPV). The vertical line indicates the order of the tests, as in the legend.

A similar effect can be observed in the upper layer temperature of Room 1. In Room 2, the temperature increases in both the upper and lower layer regardless of positive pressure ventilation being used (Figure 8). However, when positive pressure ventilation was used, the increase in temperature in the lower layer was considerably larger than when positive pressure ventilation was not used. In Room 3, a distinct hot upper layer of out-flowing gases and a cool lower layer of inflowing air through D3 were formed when no pressure ventilation was applied (test 8 in Figure 9). When positive pressure ventilation was used (test 10), the temperatures reduced rapidly in both upper and lower layers as fresh air was pushed into the apartment. However, the temperature in the upper layer of Room 3 increased again after approximately 530 s. This indicates a flow of smoke and hot gases in the upper layer from Room 2 into Room 3, even though positive pressure ventilation was used.

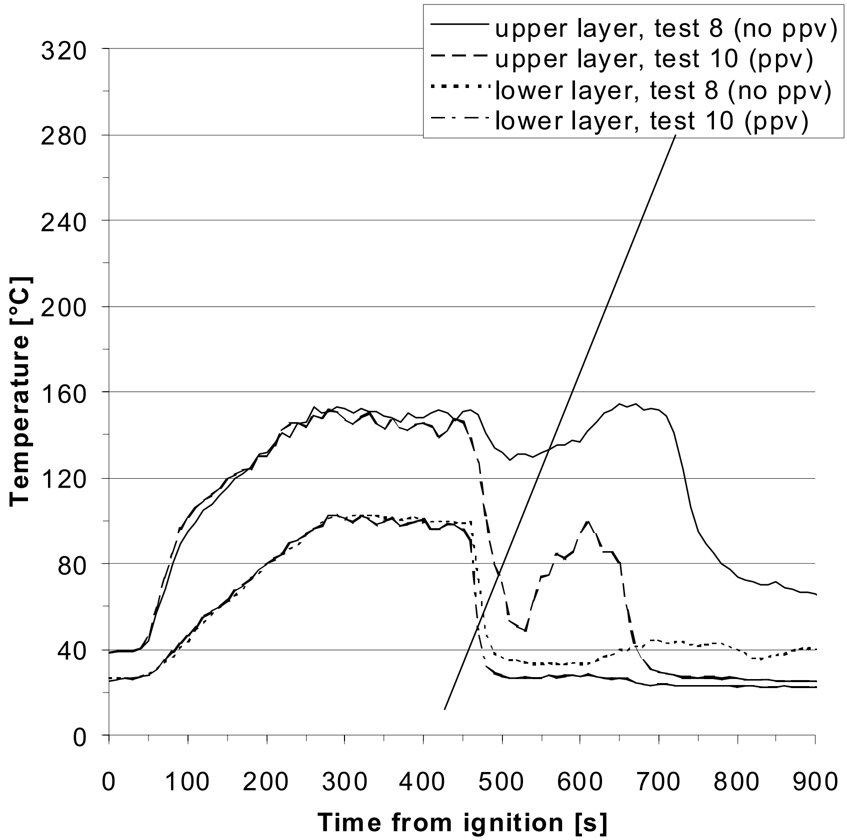

Figure 9. Mean temperatures of the upper and lower layer in Room 3, comparison between test 8 (without PPV) and test 10 (using PPV). The vertical line indicates the order of the tests, as in the legend.

Figure 10 - 12 shows the temperatures in tests 3, 8 and 13, respectively. When D3 and W were opened at approximately 420 s, the mean temperature increased in both upper and lower layers in the room of fire origin. In the adjacent rooms, the temperature was reduced in the lower layer and increased in the upper layer.

Results from flow measurements are still being compiled and are not reviewed in this paper.

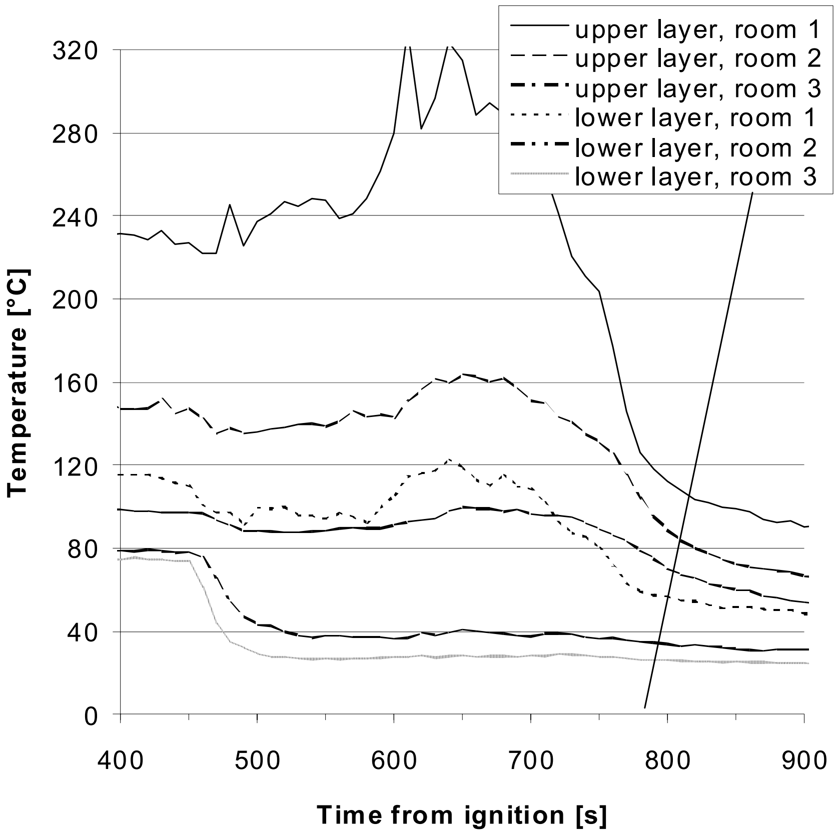

Figure 10. The mean temperatures for the upper and lower layers for test 3. The vertical line indicates the order of the tests, as in the legend.

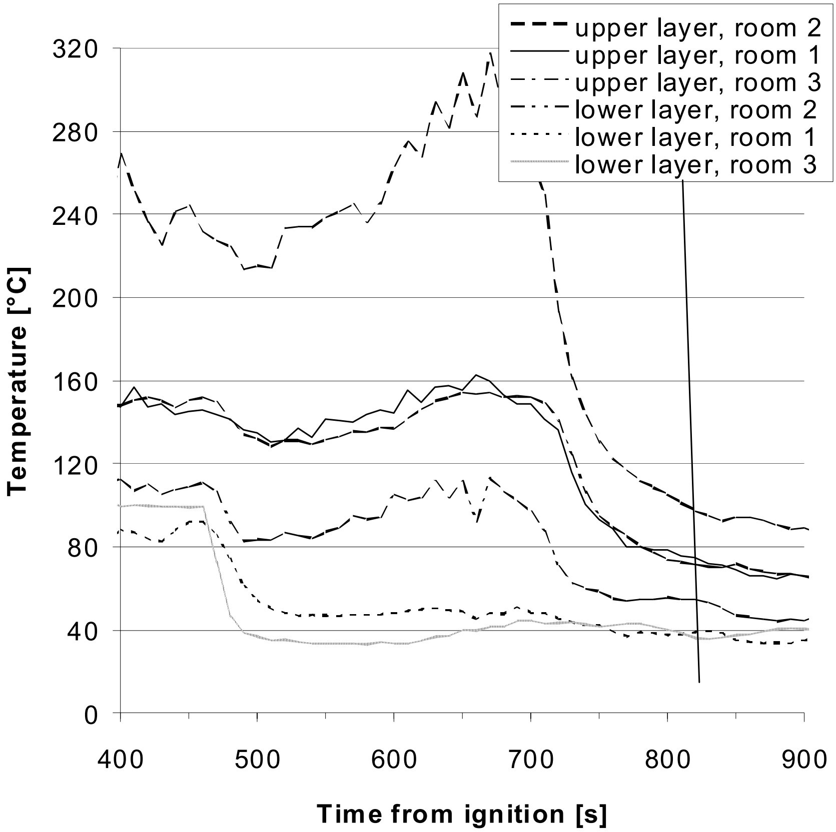

Figure 11. The mean temperatures for the upper and lower layers for test 8. The vertical line indicates the order of the tests, as in the legend.

Discussion

When choosing fire source, several aspects have to be considered. However, when performing large-scale experiments practical aspects always have a large impact. A pool fire is very convenient in that it facilitates easy measurements of weight loss and it makes restoration between tests simple. It is also a safe arrangement, in that the risk of unwanted fire spread during the experiments is very low. Also, the fuel is homogenous and the fire is reproducible, which is harder to achieve using wooden fuel. In addition, statistics show that more than 50 % of all fires are in residential buildings and that 60 % of those fires are related to a single burning item, at the time of the arrival of the fire service[2]. In this setting, a pool fire is a good assumption for a residential fire. However, using a crib fire or equivalent would most likely show a more distinct fire spread, depending on the configuration of the fuel, although the increase in rate of mass loss would not have been as rapid as in the case with a pool fire.

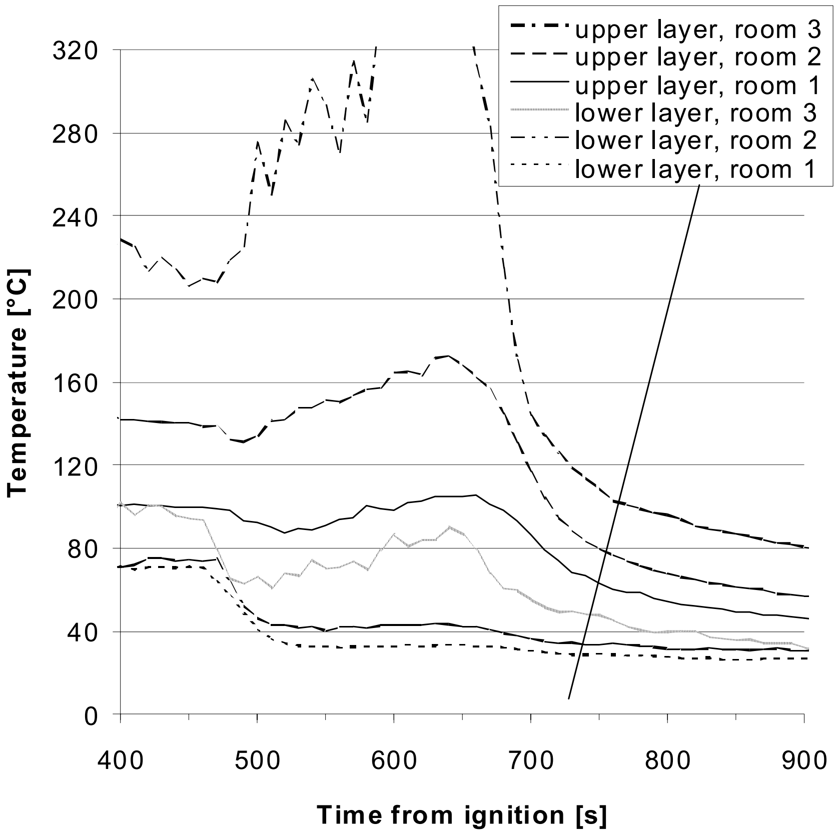

Figure 12. The mean temperatures for the upper and lower layers for test 13. The vertical line indicates the order of the tests, as in the legend.

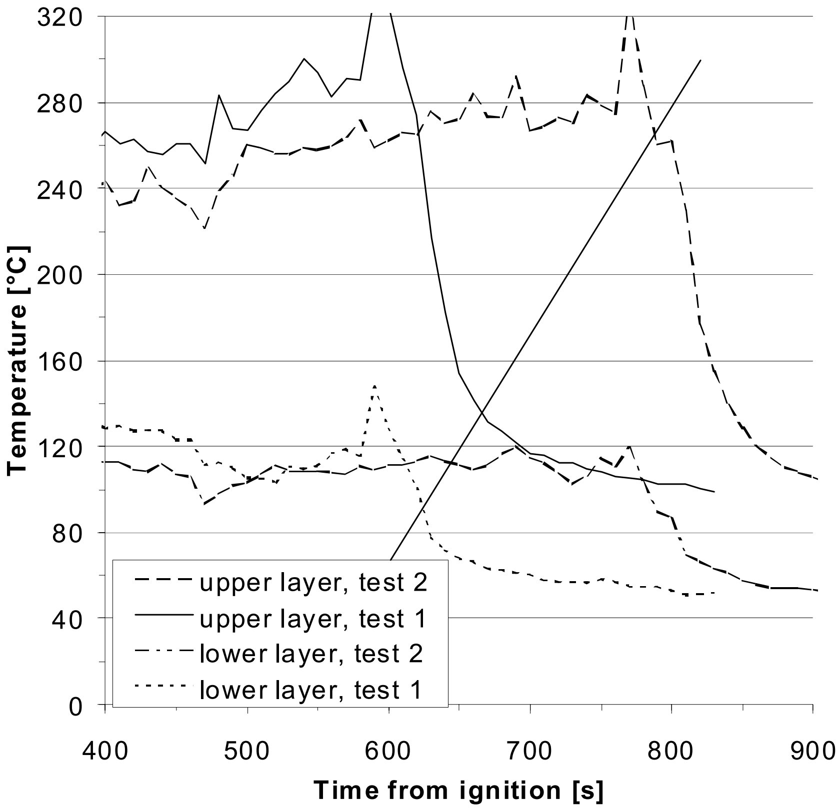

Figure 13. The mean temperatures for the upper and lower layers in the fire origin room for tests 1 and 2. The vertical line indicates the order of the tests, as in the legend.

The number of tests was limited, which often is the case when performing large-scale fire testing. Therefore, the reliability of the tests may be questioned. However, the rate of mass loss during the first 400 s of each test, as in figure 4, shows equivalence between tests. Also, figures 13 - 15 show the upper and lower mean temperatures for the room of fire origin in tests 1, 2, 6, 7, 11 and 12, respectively. The rise in temperature exhibits a striking resemblance in these tests, apart from the mean temperature in the upper layer for test 12, presumably due to the large opening (D3) being close to the fire. Therefore, the reliability of the tests is assumed to be good, especially considering the low wind speed during the tests.

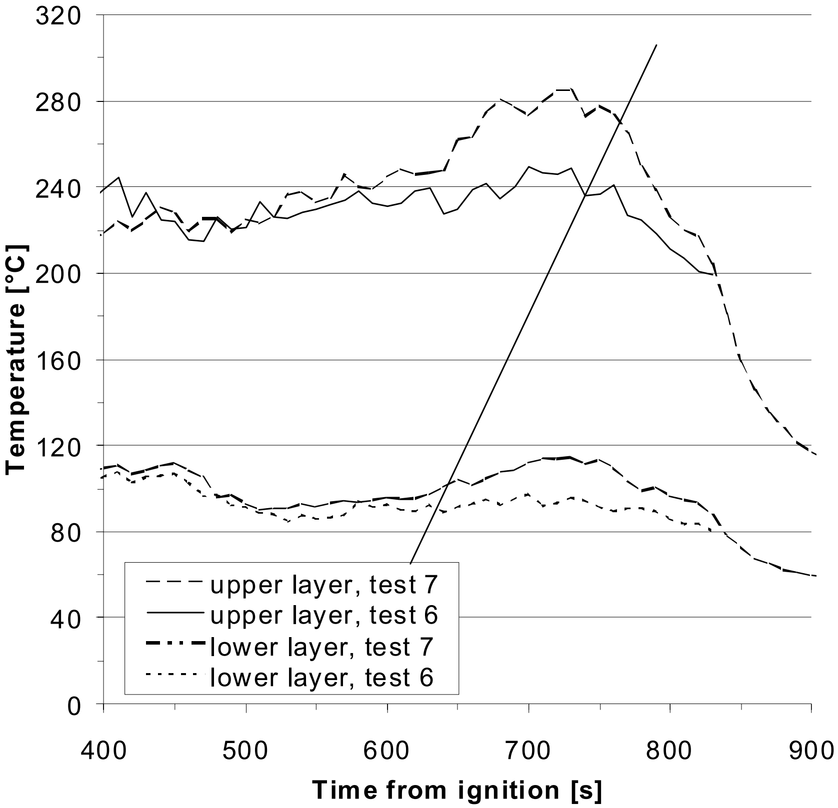

Figure 14. The mean temperatures for the upper and lower layers in the fire origin room for tests 6 and 7. The vertical line indicates the order of the tests, as in the legend.

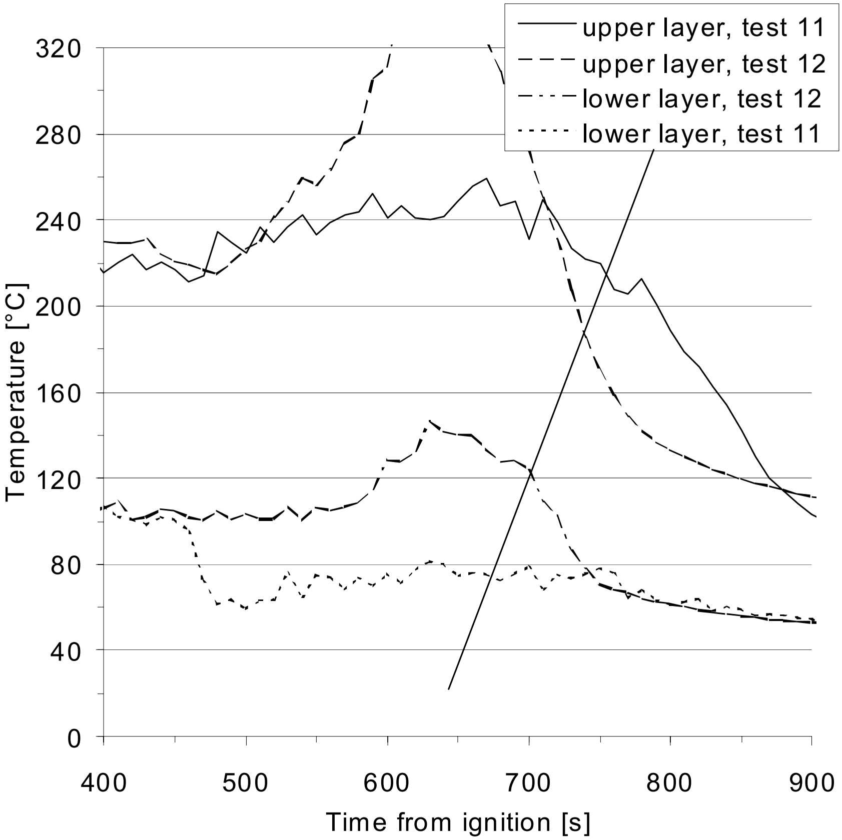

Figure 15. The mean temperatures for the upper and lower layers in the fire origin room for tests 11 and 12. The vertical line indicates the order of the tests, as in the legend.

The purpose was to simulate scenarios reflecting actual firefighting situations and action, and courses of action usually available for the Swedish fire & rescue service. Operational crews in Sweden are generally small, in the general case 4 - 8 firefighters and a commanding officer on scene within 8 - 12 minutes, and possibly another 4 - 8 firefighters within 15 - 30 minutes[2]. For most fires, this is sufficient, but still, the available personnel have to be used in an efficient way and not all the desired measures can be taken. The problem of command and control is to make choices between actions and courses of action. Scenario A is a standard scenario, a fire attack through the main entrance of the apartment, when the window is closed for some reason and cannot be opened. Scenario B is a scenario where the window is used for access to the fire, and where the main entrance cannot be used due to, for example, security doors. In scenarios C to E access is provided through the main entrance and the window is opened by, for example, firefighters on a ladder. In scenario D and E positive pressure ventilation is used, with optional positions in the two scenarios, one in accordance with textbooks[4, 5, 6] (scenario E) and one "incorrect" positioning of the fan (scenario D).

Figure 16. Photo from test 10 showing inclination and turbulence of the flame due to positive pressure ventilation. Photo taken, by author, from door D2 looking into Room 2, without using breathing apparatus.

Fires in apartments are often small at the time of arrival of the fire & rescue service[2]. A common feature is that they are restricted to one or just a few objects, which can be a result of lack of oxygen, i.e. ventilation control. Also larger fires (but still confined within an apartment) quickly become ventilation controlled, unless windows break due to heat stress. The fire source chosen for the tests quickly became ventilation controlled, as is shown in figure 4.

The main criticism of positive pressure ventilation brought up by fire & rescue personnel in Sweden is that using a fan blowing fresh air into the fire will make the fire increase and spread throughout the building. As shown in figure 5, the burning rate is clearly increased by positive pressure ventilation. In addition, the turbulence generated by the flowing air made the flames incline during the tests, see figure 16. This indicates that when using positive pressure ventilation there is a risk of pushing the fire towards unaffected areas of the apartment. However, firefighters making themselves access to a fire, e.g. by opening a door or a window, will change the ventilation conditions to the fire in any case. Using a fan will bring a degree of control to this change in the ventilation condition.

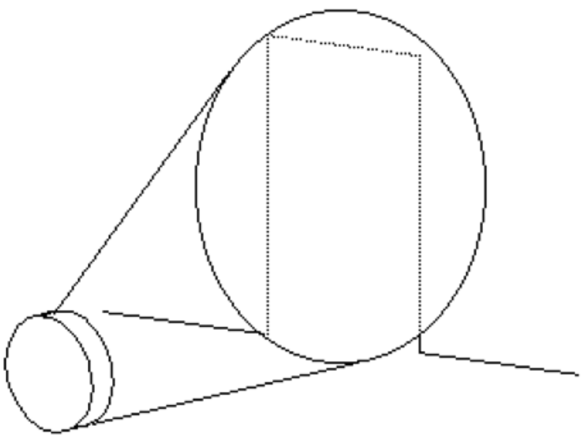

Figure 17. Textbook recommendations on positioning of the fan outside a door when using positive pressure ventilation. The airflow from the fan should cover the opening.

The pressure in the apartment was increased by the use of positive pressure ventilation. Textbooks on positive pressure ventilation practices[4, 5, 6], recommend positioning of the fan outside the staircase having the "air cone" covering the door opening, see figure 17. The result shown in figure 6 confirms such recommendations. The pressure generated by a fan is in the order of 5 - 10 Pa inside the apartment. A larger fan, thus generating a larger airflow, should be able to increase the pressure more. However, in a real fire situation the effects of wind should also be taken into consideration. The static pressure on a building, generated by the wind, can be estimated by[12]:

$$p_w = \frac{C_W \cdot \rho_a \cdot v^2}{2}$$

Even at low wind speeds (2 - 6 m/s), there is a possibility of static wind pressure dominating the pressure generated by a fan. The choice of positioning of outlets in relation to wind is crucial to the successful use of fans during firefighting operations.

The use of positive pressure ventilation pushes hot gases and smoke out from the apartment and replaces it with fresh air. The temperature decreases on the windward side of the fire while it increases on the leeward side. This was clearly observed when comparing test 8 with test 10, see figure 7 - 9. However, this phenomenon was also observed when comparing test 3 with test 5 and test 13 with test 15 (not further described in this paper, see references for details[9]). The variations in temperature and flow patterns due to the use of positive pressure ventilation will improve safety and working conditions for firefighters. Used properly, visibility will increase and temperature will decrease. In addition, putting water on the fire creates steam, thus creating a risk of burn injuries to firefighters. The use of positive pressure ventilation will be of assistance in such a case. Hot steam will be ventilated along with smoke and hot gases away from firefighters, minimizing the risk of burn injuries. However, the use of positive pressure ventilation will jeopardize the life of any victims trapped and increase the risk of the spread of the fire on the leeward side.

As window and door are opened simultaneously without using positive pressure ventilation, shown in figure 10 - 12, the mean temperature increases in both the upper and lower layer in the room of fire origin. This indicates an increase in burning rate due to incoming air. Reduction of temperature in the lower layer of adjacent rooms indicates that fresh air is flowing into the apartment in the lower layer and smoke and hot gases flowing out of the apartment in the upper layer. This improves the conditions for any victims trapped in the apartment, except for the room of fire origin, where the conditions may get worse. In addition, the increase in burning rate, shown in figure 5, and increase in temperature in the room of fire origin, indicate an increasing risk of fire spread. If the firefighting operation is delayed for some reason, the fire will eventually cover the whole apartment, causing a number of problems to the fire & rescue service, such as fire spread to adjacent apartments. Any victims trapped may of course also experience worsened conditions.

The problem of increased burning rate and increased risk of fire spread when using positive pressure ventilation has to be put in relation to the increase in speed at which firefighting personnel can perform search and rescue operations and extinguish the fire. Improvements in working conditions (reduced temperature and improved visibility) will greatly enhance this speed. In addition, the speed at which any trapped victims can be found has to be considered. In order to increase speed, training of personnel and co-ordination of different measures at a fire scene is crucial.

Conclusions

Positive pressure ventilation increases the mass loss rate of fuel, consequently increasing burning rate of the fire. In apartment fires, it is recommended that the fan be positioned outside the staircase, and that the airflow cover the entrance to the staircase.

Working conditions for firefighters are improved by positive pressure ventilation, but the lives of any victims trapped in an apartment on fire are jeopardized. In addition, the risk of fire spread to adjacent rooms will increase.

The entry of firefighters into a building on fire changes the ventilation ratio to the fire and thereby the rate of burning, especially when using positive pressure ventilation. Co-ordination of different measures at a fire scene is crucial and the importance of command and control is prominent.

Nomenclature

A	Area of fire (pool) [m^2]
Δh_c	Heat of combustion [kJ/kg]

$\dot{m}_{\infty}''$	Mass loss rate for infinite-diameter pool [kg/m^{2}s]
D	Pool diameter
k	Extinction-absorption coefficient [m^{-1}]
β	Mean-beam-length corrector [-]
$\dot{Q}$	Rate of heat release [kW]
p_w	Static wind pressure [Pa]
C_W	Pressure coefficient of reactivity, $-1 < C_W < 1$ [-]
ρ_a	Air density [kg/m^2]
v	Wind speed [m/s]

References

1. *Fire in the United States 1987-1996* (11th ed.). Federal Emergency Management Agency, United States Fire Administration, 1999.
2. *Räddningstjänst i siffror 1998* (Swedish statistics on fires and fire & rescue service operations. In Swedish). Räddningsverket, Karlstad, 1999.
3. Hay, A. (1994). *A Survey of Fire Ventilation* (Home Office, Publication No 6/94). London: Home Office Fire Research and Development Group.
4. *Essentials of Firefighting*. 3rd ed. (1992). The International Fire Service Association (IFSTA). Oklahoma State University: Fire Protection Publications.
5. *Fire Service Manual; Fire service Operations (Volume 2), Compartment Fires and Tactical Ventilation*. (1997). London: Home Office.
6. *Brandgasventilation* (In Swedish). (2000). Karlstad: Räddningsverket.
7. Ziesler, P.S., Gunnerson, F.S. & Williams, S.K. "Advances in Positive Pressure Ventilation", *Fire Technology*, Vol. 30, Second quarter, 1994, pp. 269 – 277.

8. Rimen, J.G. (1996). *An Assessment of the Use of Positive Pressure Ventilation in Domestic Properties* (Home Office, Publication No 17/96). London: Home Office Fire Research and Development Group.

9. Svensson, S. (1996). *Försök med brandgasventilation i en liten lägenhet*. (In Swedish) (Report R53-159/96). Karlstad: Räddningsverket.

10. Babrauskas, V., "Burning rates", *The SFPE Handbook of Fire Protection Engineering*, 1st ed., NFPA, Quincy, MA, 1988, pp 2-3 – 2-4.

11. http://haleproducts.com/

12. Magnusson, S-E (1983). *Smoke movement in buildings: a state-of-art review and a program for future Swedish research* (In Swedish with English summary). Lund: Lund Institute of Technology.

Paper V: Experimental study of fire ventilation procedures in a large hall

Stefan Svensson and Per Werling

Interflam'01, 9th International Fire Science & Engineering Conference, Edinburgh, 17th – 19th September 2001.

Experimental study of fire ventilation procedures in a large hall

Stefan Svensson
Swedish Rescue Services Agency
S - 247 81 Sodra Sandby
Sweden
Phone: +46 46 23 35 76
Fax: +46 46 620 17
E-Mail: stefan.svensson@re.srv.se

Per Werling
Swedish Defense Research Establishment
Enköpingsvägen 126
S - 172 90 Stockholm
Sweden
Phone: +46 8 555 041 74
Fax: +46 8 555 041 80
E-Mail: per.werling@foi.se

Abstract

Fire ventilation actions taken by the fire & rescue services, including positive pressure ventilation, when responding to fires in large halls, was investigated. Five tests were performed in a hall measuring 39×11.2×8.1 m. Two lower doors and two upper windows at opposing sides were used to resemble different fire ventilation procedures taken by the fire & rescue service. The fire source was a 2 m^2 pool of methanol. Temperature, weight of the fuel and flow through openings were recorded continuously. The tests were also documented using video cameras. The tests showed that positive pressure ventilation increased the flow rate through openings and that positive pressure ventilation created turbulence, which dissolved the stratification of the upper layer of hot smoke and a lower layer of cool air. The test results were also compared with calculations. Conclusions were that the use of positive pressure ventilation in large halls jeopardizes safety and working conditions to firefighters. Also, the importance of command and control during firefighting operations is prominent.

Introduction

The primary objective of fire & rescue services is to save and protect people in the event of accidents. The fire & rescue service responds to a large variety of accidents, of which fires are a major cause of turnouts[1,2]. After arriving at the scene of a fire, the people seeking for relief expect the fire & rescue service to work efficiently and to use their equipment and their knowledge and skill in the best possible way. Also, fire officers and other decision makers, whose activity is referred to as command and control, must coordinate different actions and measures taken at a fire scene[3,5,5]. The work at a fire scene must be characterized by professionalism and reliability.

In order to fulfill such requirements and expectations, it is of great importance that the fire & rescue service is familiar with effects resulting from actions taken at a fire scene. Such knowledge includes effects of putting water on the fire and effects of ventilation.

During the last few years the Swedish Rescue Services Agency has been conducting major work on fire ventilation measures taken by fire & rescue services. The aim has been to thoroughly investigate and describe possibilities, problems and plausible courses of action when using fire ventilation during firefighting operations. The intention has also been to develop a scientifically based method, including theories on fire ventilation, adapted for the fireground. The results from this work have recently been published in a textbook for fire & rescue services[6]. In order to investigate the effects of fire ventilation, extensive research has been performed. The researches included theoretical studies as well as live fire testing[7,8,9,10,11].

This paper focuses on fire ventilation actions taken by the fire services, including positive pressure ventilation, when responding to fires in large halls. The tests were intended to resemble scenarios where different fire ventilation procedures are taken by the fire service.

Experimental set-up

Five tests were performed in a large hall measuring 39 m long, 11.2 m wide and 8.1 m in ceiling height, see figure 1. Openings to the hall were two 2 m high and 1 m wide openings at floor level (D1 and D2 in figure 1), one in the south wall of the hall and one in the northeast corner, in the east wall. Also, there were two 0.6 m high and 3.3 m wide openings (W1 and W2 in figure 1) with soffit 0.4 m below ceiling, one in the southeast corner (W2) and one in the northeast corner (W1), both in the east wall.

As a fire source, a 1×2 m pool was used, located along longitudinal centerline of the hall 9.75 m from the south wall, 1 m above floor. In test 1 approximately 30 liters of methanol was used and in test 2 – 5 approximately 25 liters of methanol was used. The theoretical mass loss rate was 25 $g/s \times m^2$, which corresponds to a rate of heat release of 1.0 MW, calculated by[12]

$$\dot{Q} = A \cdot \Delta h_c \cdot \dot{m}'' \quad [1]$$

The pool was placed on a loadcell (L in Figure 1).

Type K thermocouples were mounted at levels 1, 2, 3, 3.5, 4, 4.5, 5, 5.5, 6, 6.5, 7, 7.5 m above floor (thermocouple tree T2 – T6 in figure 1). Above the fire (in the plume), thermocouples were mounted at levels 2, 3, 4, 5, 6, 7, 7.5 m above floor (thermocouple tree T1 in figure 1). Bi-directional probes were mounted in all openings, measuring in and outgoing flows (P1 – P6 in figure 1). In door D1, bi-directional probes were mounted 0.1 m below soffit (P1), 0.1 m above sill (P3) and centred in the door (P2). In windows W1, W2 and in door D2, bi-directional probes were mounted centred in the opening (P5, P6 and P4, respectively). Data on weight of the fuel, temperature and flow were registered every 6th second.

The fan used for positive pressure ventilation was a standard type fan used by fire brigades, run by a gasoline motor. The fan provided a nominal flow of 4.5 m^3/s. The fan was located 3 m from D1 (test 4) and D2 (test 5), providing a cone of air covering the doorway in each of the two tests.

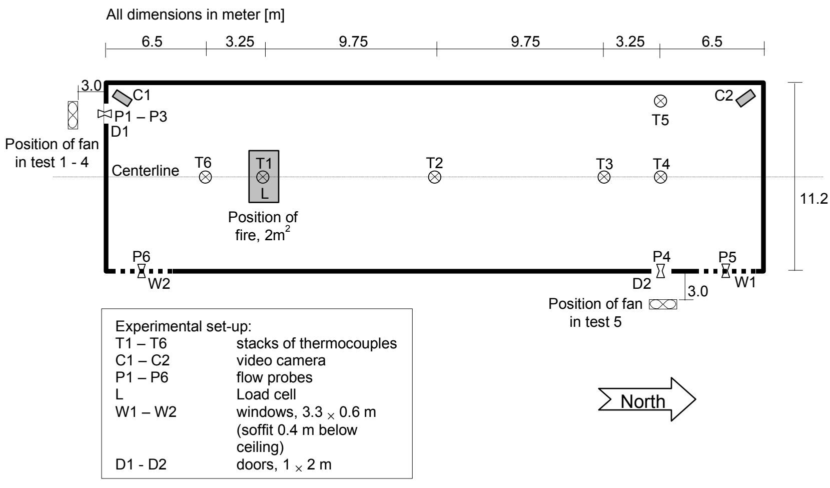

Figure 1. Experimental set-up.

For visual effects and for estimating interface of smoke layer, smoke was produced using propylene glycol from smoke generators of conventional type, located approximately 3 m above the fire source.

The tests were also documented using video (C1 – C2 in figure 1) and still photography.

See table 1 for details on the measuring devices.

Table 1. Details on measuring devices.

Item # (see figure 1)	Measurement	Device denomination	Measuring range	Accuracy
T1 – T6	Temperature	Thermocouple trees, thermocouples type K, ∅0.25 mm	0 - 1300°C	±0.4%
P2, P4	Flow	Bi-directional probes connected to scanner type Furness FCO 11	±200 Pa	±0.3%
P1, P3, P5, P6	Flow	Bi-directional probes connected to scanner type AutoTran series 700	±30 Pa	±2%
L	Load	Load cell, Nobel Elektronik	0 – 400 kg	±10g
C1 – C2	Video	Video cameras		
	Logger	Slumberger datalogger 35951C		

Procedure

In all tests the fire was put out after 600 seconds, by coverage. In all tests the openings were closed during the first 480 s of the burn time. At this time the smoke interface was very close to the floor at the south end of the hall, in all tests. At the north end of the hall, the smoke interface was stable at approximately 1.5 m above floor, in all tests.

At t = 480 s, the ventilation procedures started. Five different procedures were investigated,

1. Door in the south wall, D1 in figure 1.
2. Window at ceiling level in the northeast corner, W1 in figure 1.
3. Door in the south wall, D1 in figure 1, and window at ceiling level in the northeast corner, W1 in figure 1.
4. Door in the south wall, D1 in figure 1, and window at ceiling level in the northeast corner, W1 in figure 1, using positive

pressure ventilation, fan located approximately 3 m outside D1, blowing into the hall.

5. Door in the northeast corner, D2 in figure 1, and window at ceiling level in the southeast corner, W2 in figure 1, using positive pressure ventilation, fan located approximately 3 m outside D2, blowing into the hall.

The main difference between test 4 and 5 was that the intake of air (D1) was closer to the fire in test 4 than in test 5. Also, in test 5 the outlet of air/smoke (W2) was closer to the fire than in test 4.

The wind speed during the tests varied between 0 – 1 m/s. No effects on the tests due to wind were observed. The outdoor temperature during the tests varied between 8 and 14°C (the temperature decreased during the night). The air temperature inside the facility varied between 18 and 21°C (upper layer mean temperature) and between 16 and 19°C (lower layer mean temperature) when the tests commenced.

Results

All denotation of time is in relation to time from ignition. In all tests, the smoke reached the opposing wall at approximately 45 s. The smoke layer interface was at 4 m above floor at approximately 150 s and at 2 m above floor at approximately 240 s. After 480 s the smoke layer interface was very close to the floor in south section of the hall. In the north section the smoke layer interface was approximately 1.5 m above floor. Also, more turbulence in the smoke was observed in the south section of the hall were the fire was located than in the north section.

Results from flow measurements showed the main features of the different scenarios, which also could be confirmed through visual observations. In the main, these measurements and observations showed how air and smoke flowed through openings.

In test 1, D1 was opened after 480 s. Almost no smoke flowed through D1, figure 2.

In test 2, W1 was opened after 480 s. A moderate amount of smoke flowed through W1, figure 3. The tendency of the interface layer was that it was rising. However, the turbulence, induced by the flow through W1, was larger than in test 1. This led to inferior visibility in the hall.

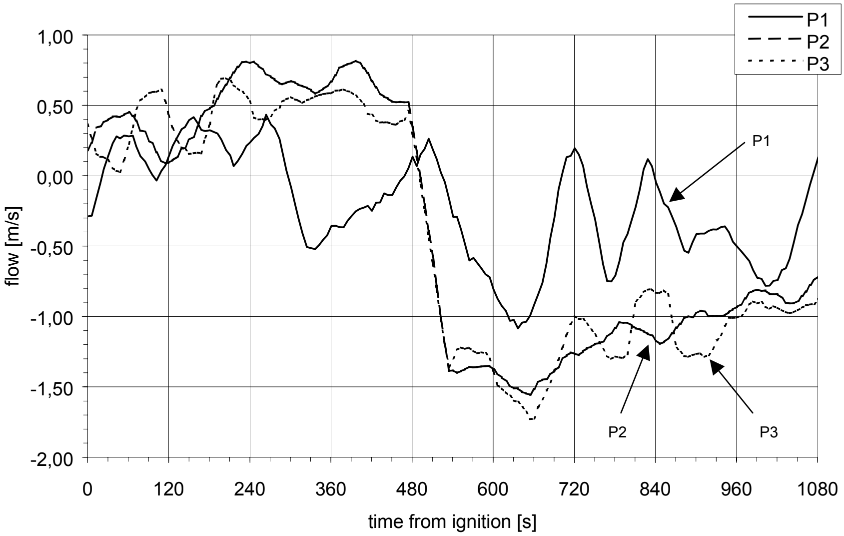

Figure 2. Flow through D1 in test 1. P1 is the upper probe, P2 the middle probe and P3 is the lower probe.

In test 3, D1 and W1 were opened after 480 s. A somewhat larger flow through W1 was observed than in test 2, figure 4. The tendency of the interface layer was that it was rising. The smoke interface at the further short side had risen to approximately 2.5 m above floor after 690 s. At this time, the smoke interface layer was still very close to the floor at the near short side. However, the turbulence, induced by the flow through W1, was larger than in test 1. This led to inferior visibility in the hall.

Test 4 was similar to test 3. The difference was that positive pressure ventilation was used, with a fan placed approximately 3 m outside the D1, blowing into the hall. When the door and window was opened and the fan started, the hall was filled with smoke rapidly. Any smoke interface could not be observed after this point. However, the smoke was seemingly diluted. See figure 5 for details on the flow through openings in test 4.

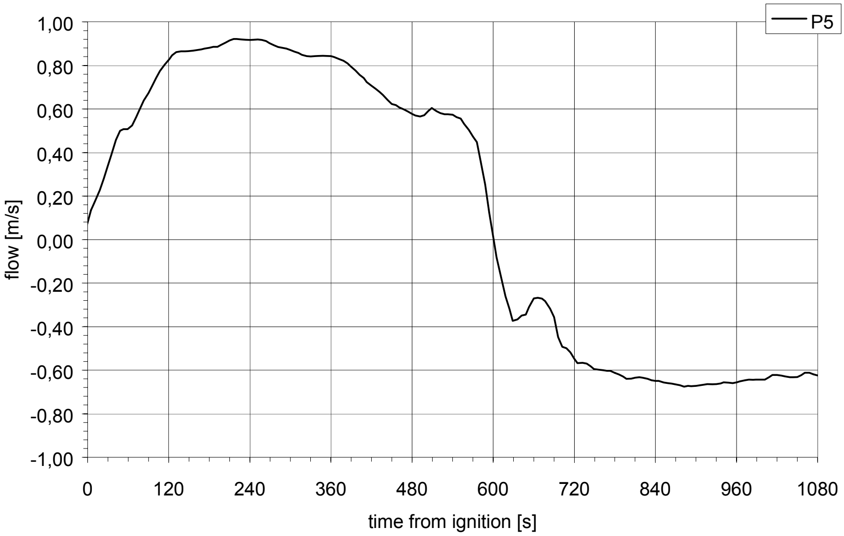

Figure 3. Flow through W1 in test 2. The probe, P5, is mounted in the center of W1.

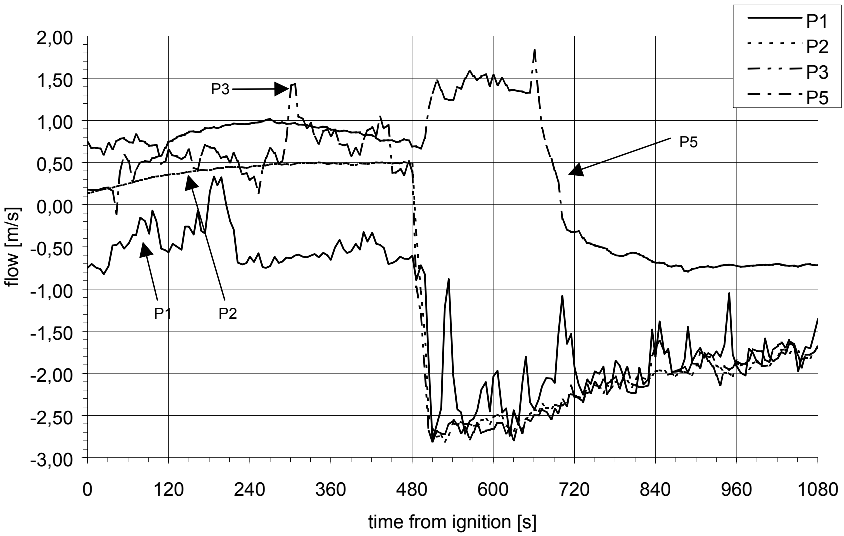

Figure 4. Flow through D1 (P1 – P3) and W1 (P5) in test 3.

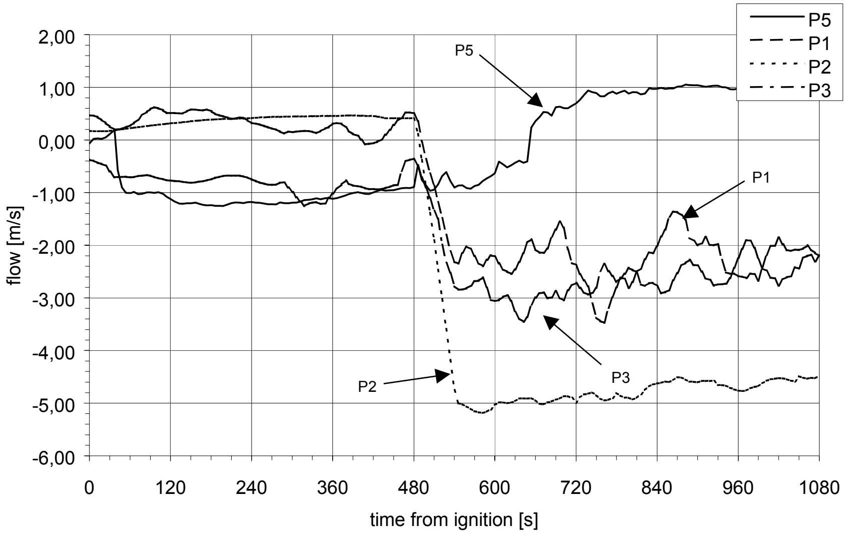

Figure 5. Flow through D1 (P1 – P3) and W1 (P5) in test 4, using positive pressure ventilation.

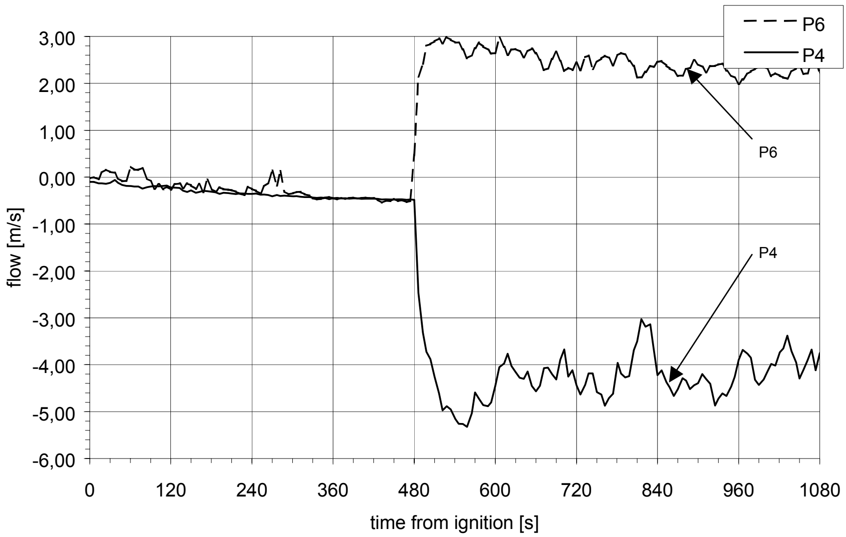

Figure 6. Flow through D2 (P4) and W2 (P6) in test 5, using positive pressure ventilation.

In test 5, D2 and W2 were opened after 480 s. In addition, positive pressure ventilation was used, with a fan placed approximately 3 m outside D2, blowing into the hall. The flow of smoke out of the hall was very slow, considerably slower than in test 4. Also, any smoke interface could not be observed after this point. See figure 6 for details on the flow through openings in test 5.

Measurements of temperature showed, together with visual observations, movement of air and smoke inside the hall.

Figure 7 shows the upper and lower layer mean temperatures for tests 1 – 5. The lower layer mean temperature was created using the six lower thermocouples in each tree T2 – T6. The upper layer mean temperature was created using the six upper thermocouples in each tree T2 – T6.

When using positive pressure ventilation, in test 4 and 5, the curve in figure 7 showing the upper layer mean temperature is slightly steeper, indicating a faster decrease in temperature. However, there is a delay in this decrease in temperature in test 4 and 5 between t = 480 s and t = 600 s. The fire is put out at t = 600 s. At the end of test 4 and 5 (at t = 1080 s) the temperature is slightly lower than in test 1, 2 and 3.

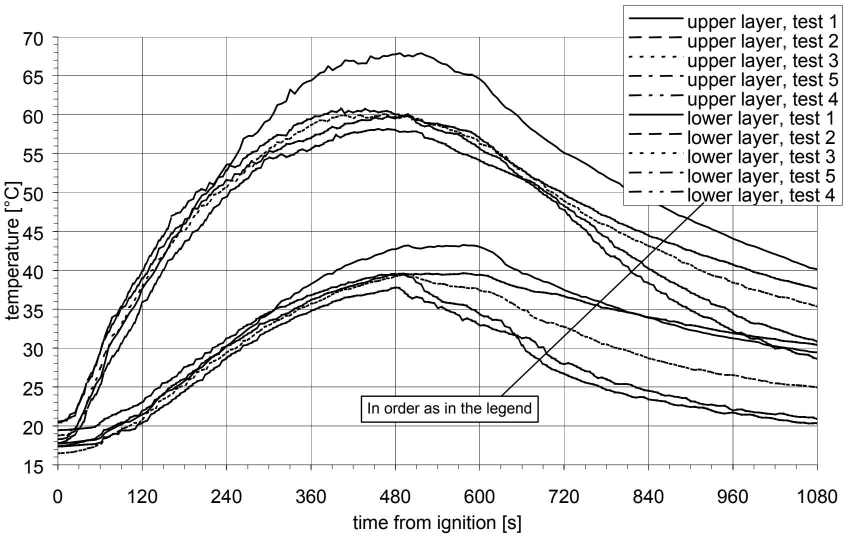

Figure 7. Mean temperature in the upper and lower layer for tests 1 – 5.

In figure 7, the lower layer mean temperature is clearly affected at the onset of positive pressure ventilation, tests 4 and 5 at t = 480 s. when the fire is put out, at t = 600 s, the curve indicating the lower layer mean temperature becomes even steeper, indicating a faster decrease in temperature.

Table 2; Mean temperatures in the upper and lower layer, at t = 480, 600 and 1080 s.

Test	Procedure	Upper layer mean temperature at 480 s	Lower layer mean temperature at 480 s	Upper layer mean temperature at 600 s	Lower layer mean temperature at 600 s	Upper layer mean temperature at 1080 s	Lower layer mean temperature at 1080 s
1	D1	68 °C	43 °C	65 °C	43 °C	40 °C	29 °C
2	W1	60 °C	39 °C	57 °C	39 °C	38 °C	30 °C
3	D1 and W1	60 °C	39 °C	56 °C	37 °C	35 °C	25 °C
4	D1 and W1, using positive pressure ventilation	60 °C	40 °C	56 °C	34 °C	29 °C	20 °C
5	D2 and W2, using positive pressure ventilation	58 °C	38 °C	54 °C	33 °C	31 °C	21 °C

The temperatures at t = 480, 600, 1080 s is compiled in table 2. The results show that there is a difference in mean temperatures in the upper in lower layer, dependent on the chosen ventilation procedure. These differences are more significant when looking at individual thermocouples (due to lack of space, data from individual thermocouples is not showed in this paper).

Comparison with calculations

A simplified model for estimating pressure, flow rate and time to evacuate smoke in a room with one supply opening and one exhaust opening and by the use of positive pressure ventilation has been suggested[10]. The model assumes no influence on pressure and flow from the fire.

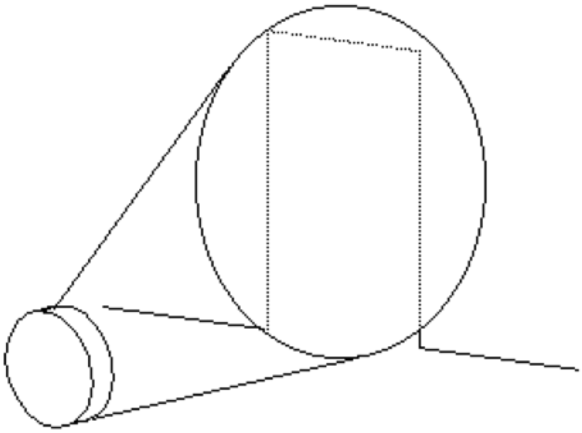

Figure 8. Textbook recommendations on positioning of the fan outside a door when using positive pressure ventilation. The airflow from the fan should cover the opening[5,6].

The exhaust volume flow rate can be calculated by,

$$\dot{V}_f = C_d \cdot v_f \cdot A_f \qquad [2]$$

The model suggest that the velocity of the gases flowing out of an upper opening can be calculated by,

$$v_f = \sqrt{\frac{\Delta p}{\frac{1}{2} \cdot 1.5 \cdot \rho_0 \cdot \left(\left(\frac{A_f}{A_t} \right)^2 + 1 \right)}} \qquad [3]$$

The dynamic pressure in the room can be calculated by,

$$\Delta p = \frac{1}{2} \cdot \rho_0 \cdot v_t^2 \qquad [4]$$

Assuming conservation of momentum along the radial axis of the flow from the fan, the velocity of inflowing air in the supply opening can be estimated by,

$$v_t = \frac{v_0 \cdot D_0}{D_t} \qquad [5]$$

Using data from the tests and assuming that the "cone of air" is covering the entrance, as in figure 8 where D_t equals the diagonal of the opening/door, the velocity of the air flowing into the room becomes, equation [5],

$$v_t = \frac{4.5 \cdot 4}{\pi \cdot D_0^2} \cdot \frac{D_0}{D_t} = \frac{4.5 \cdot 4}{\pi \cdot 0.5334 \cdot \sqrt{5}} = 4.8 \text{ m/s}$$

Figure 5 (P2) and 6 (P4) shows that the flow velocity through D1 and D2 during the test was approximately 4.76 m/s and 4.19 m/s, respectively. However, P1 and P3 in figure 5 shows a lower velocity. This is probably due to the turbulence created by the fan and also due to that the flowing air hits the walls surrounding D1, further increasing the turbulence.

Using equations [3] and [4], with $A_f = 3.3 \times 0.6$ m = 1.98 m^2 and $A_t = 1 \times 2$ m = 2 m^2, the flow through the exhaust vents W1 in test 4 and W in test 5, becomes approximately 2.8 m/s. Figure 6 shows that the exhaust air velocity (P6) is approximately 2.4 m/s. However, figure 5 shows that the exhaust air velocity (P5) is only approximately 0.8 m/s. Any explanations for discrepancy this have not been found.

Still, this shows that the effectiveness of using positive pressure ventilation can be estimated using simple physical relations.

Discussion

When choosing fire source, several aspects have to be considered. However, during large-scale experiments practical aspects always have a large impact. A pool fire is very convenient in that it facilitates easy measurements of weight loss and it makes restoration between tests simple. It is also a safe arrangement, in that the risk of unwanted fire spread during the experiments is very low. In this particular case, the facility used for the tests was an ordinary engineering workshop and it had to be protected from any damage. Also, the fuel is homogenous and the fire is reproducible, which is harder to achieve using wooden fuel.

In test 1, 30 liters of methanol was used as a fire source, and in test 2 - 5, 25 liters were used. Due to this variation, there seemed to be a slightly higher rate of mass loss in test 1, figure 9. This higher rate of mass loss also induced a slightly higher temperature in test 1, figure 7. This variance can be due to the edge effects. However, when comparing the differences in temperature between tests, as in table 2, this phenomenon can be neglected.

The number of tests was limited, which often is the case when performing large-scale fire testing. Therefore, the reliability of the tests may be questioned. However, the weight of the fuel, figure 9, shows equivalence between tests. Also, figure 7 show the upper and lower mean temperatures. The rise in temperature, between t = 0 and 240 s, exhibits a striking resemblance in the tests, apart from test 1 where the mean upper layer temperature is approximately 10° higher at its maximum than in the other tests. Therefore, the reliability of the tests is assumed to be good.

The purpose of the tests was to investigate the effects of fire ventilation procedures when the fire & rescue service responds to fires in large halls. Statistics show that more than one third of fires in large halls, such as in industrial facilities, can be related to single objects (machinery, refuse, etc) and that such fires often are small compared to the size of the room[2]. However, the choice of a small fire source results in small temperature differences thus making it hard to get distinct results.

A larger fire would assumable create more turbulence as well as more smoke and hot air, making it harder to ventilate the smoke and hot gases by using positive pressure ventilation. To ventilate such a scenario using positive pressure ventilation, it would have been necessary to use a larger fan, thus creating more turbulence in the hall. Increased turbulence may induce worsened condition for trapped victims as well as to firefighters.

The main criticism of positive pressure ventilation brought up by fire & rescue personnel in Sweden is that using a fan blowing fresh air into the fire will make the fire increase and spread throughout the building. Any increase in burning rate could not be observed in the tests. However, a larger fan thus generating a larger flow rate of air into the hall may very well contribute to an increased rate of heat release and an increased risk of fire spread. Nevertheless, firefighters making themselves access to a building on fire, e.g. by opening a door or a window, will change the ventilation conditions to the fire in any case. Using a fan will bring a degree of control to this change in the ventilation condition. But if the firefighting operation is delayed for some reason, the fire will eventually spread, causing a number of problems to the fire & rescue service. In order to increase speed, training of personnel and co-ordination of different measures at a fire scene is crucial.

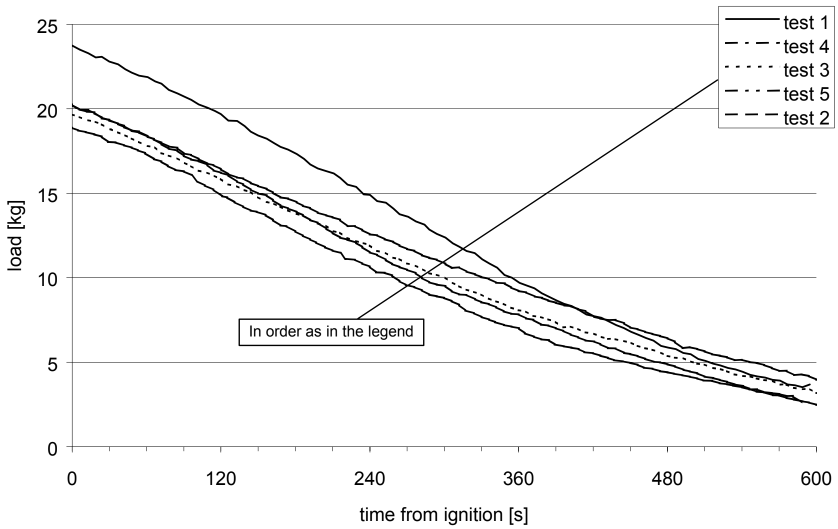

Figure 9; Weight of the fuel in tests 1 – 5.

Conclusions

Positive pressure ventilation pushes fresh air into the hall through an inlet and increases the flow rate of hot smoke out through an outlet.

The use of positive pressure ventilation in a large hall creates turbulence, which dissolves the stratification of an upper layer of hot smoke and a lower layer of clean air. Due to this turbulence, safety and working conditions for firefighters is jeopardized. In addition, the conditions to any trapped victims are worsened.

Burning rate as well as the risk of fire spread may increase when using positive pressure ventilation. This risk becomes larger as a larger fan with a larger flow rate of air is used.

The importance of command and control during firefighting operations is prominent.

Nomenclature

A_f	exhaust vent area [m^2]
A_t	supply vent area [m^2]

C_d	flow coefficient, 0.61 [-]
D_0	diameter of air cone at the fan (diameter of fan) [m]
D_t	diameter of air cone at the supply opening [m]
Δp	dynamic pressure [Pa]
v_0	air velocity at the fan [m/s]
v_f	exhaust air velocity [m/s]
v_t	supply air velocity [m/s]
$\dot{V}_f$	exhaust flow rate [m^3/s]
ρ_0	density [kg/m^3]

References

1. *Fire in the United States 1987-1996* (11th ed.). Federal Emergency Management Agency, United States Fire Administration, 1999.
2. *Räddningstjänst i siffror 1998* (Swedish statistics on fires and fire & rescue service operations. In Swedish). Räddningsverket, Karlstad, 1999.
3. Haurum, G. *Indsatsledelse* (In Danish: Fire Command). Statens Brandskola. 1994.
4. *Fire Service Manual; Fire service Operations (Volume 2), Incident Command*. London: Home Office. 1999.
5. Dunn, V. *Command and Control of Fires and Emergencies*. Fire Engineering/Pennwell Publishing Company. 1999.
6. Svensson, S. *Brandgasventilation* (In Swedish: Fire ventilation). Karlstad: Räddningsverket. 2000.
7. Svensson, S. *Brandförsök med sprängram samt övertrycksventilation*. (In Swedish: report R53-132/96). Karlstad: Räddningsverket. 1996.
8. Bengtsson, L-G., Karlsson, B. & Särdqvist, S. *Brandventilation i teori och praktik*. (In Swedish: report R53-146/96). Karlstad: Räddningsverket. 1996.

9. Svensson, S. *Försök med brandgasventilation i en liten lägenhet*. (In Swedish: report R53-159/96). Karlstad: Räddningsverket. 1996.

10. Ingason, H. & Fallberg, R. *Övertrycksventilation i medelstora lokaler, försök med mobila fläktar*. (SP Report 1998:41). Swedish National Testing and Research Institute. 1998.

11. Svensson, S. *Experimental Study Of Fire Ventilation During Firefighting Operations*. Accepted for publication in Fire Technology. 2001.

12. Karlsson, B. & Quintiere J.G. *Enclosure Fire Dynamics*. CRC Press. 1999.

Paper VI: A study of tactical patterns during firefighting operations

Stefan Svensson

Fire Safety Journal, vol. 37, no. 7, pp 673 – 695, 2002.

A study of tactical patterns during firefighting operations

Stefan Svensson
Swedish Rescue Services Agency's College in Revinge
S – 247 81 Sodra Sandby
Sweden

Abstract

Twenty experiments were performed in a three-room apartment, on the first floor of a three-storey apartment building with an attached staircase. The purpose of the experiments was to investigate various tactical patterns used during fire fighting operations, including suppression and ventilation procedures. As a fire source, eight standard wooden pallets were used. The temperature and pressure in the apartment, the weight of the fire source and the flow rate of water for suppression were recorded continuously. The results showed that positive pressure ventilation is a useful procedure, provided that it is used correct and with caution. In addition, basic tactical principles were experimentally shown and validated.

Keywords: Fire tests; Tactics; Tactical pattern; Firefighting; Modeling

Introduction

In the event of fire we all expect the fire service to attend the fire. After their arrival, they generally have a large number of various techniques and procedures at their disposal for dealing with the fire. For example, fire extinguishing, i.e. applying water or some other extinguishing substance to the fire by the use of pumps, hoses and nozzles. By the opening or closing of doors and windows or the making of holes in roofs or by using mechanical fans. Ventilation conditions of a fire can be changed, thus controlling flow patterns of smoke and hot gases. Examples of other procedures, well known by the fire fighting community, are forcible entry, search and rescue, and overhaul. The main focus of the fire fighting operation is, of course, the protection of people, property and the environment [1].

Individual procedures, in relation to fire service operations, have been the subject of research. Ventilation procedures as well as suppression activities by the fire service have been investigated. Conclusions from this research include, for example, the benefits of using hose reel systems due to their ability to increase the rate at which water can be applied to a fire and the potential to increase the throw of water, especially when considering high-pressure systems [2], [3].

Research has also shown that high-pressure water sprays reduce temperature in the fire room more effectively, and in some cases also faster, than low-pressure water sprays. Also, high and low pressure water sprays require different techniques, which could have a dramatic effect on fire fighting tactics as well as on the safety of fire fighters [3]. In addition, it has been shown that the capability of the fire service to fight fires in large spaces is related to their ability to reach the burning area of the fuel [4]. The length of the throw of the water spray may limit the possibility of reaching the fire, thereby limiting the surface cooling effect. However, manual fire suppression tests are usually set-up on a small or a medium scale, where the fire is relatively small in comparison with the water flow from the nozzle [2], [5], [6].

Conclusions from research on fire ventilation show that the use of positive pressure ventilation improves conditions for fire fighters by rapidly improving visibility and reducing the temperature in the fire compartment [7]. Also, positive pressure ventilation increases the mass loss rate of fuel, consequently increasing the burning rate of the fire [8], [9]. However, the use of positive pressure ventilation in a large hall creates turbulence, which dissolves the stratification of an upper layer of hot smoke and a lower layer of clean air. Due to this turbulence, safety and working conditions for fire fighters are jeopardized. In addition, the conditions for any trapped victims deteriorate [9].

Also, conclusions from the research show that ventilation procedures are not the solution for all problems but simply other tools for use on the fire ground [10]. In addition, the importance of command and control during fire fighting operations has been pointed out [8], [9]. Command and control includes the task of allocating and commanding personnel and equipment in time and space, i.e. designing the operation [11].

Research on individual procedures does not consider the effects of synergy, when various procedures are combined. When combining procedures into various patterns, we use the term tactics. Tactics can be defined as the operations that a fire crew performs at a fire [12]. Tactical decisions involve forcible entry, ground-ladder and hose line placement, search and rescue, exposure protection, confinement, suppression, ventilation, property conservation and overhaul. In addition, fire fighter safety must be considered. An important aspect of tactics is that on the fire ground it involves a mixture of procedures performed under the supervision and coordination of one or several commanding officers [13].

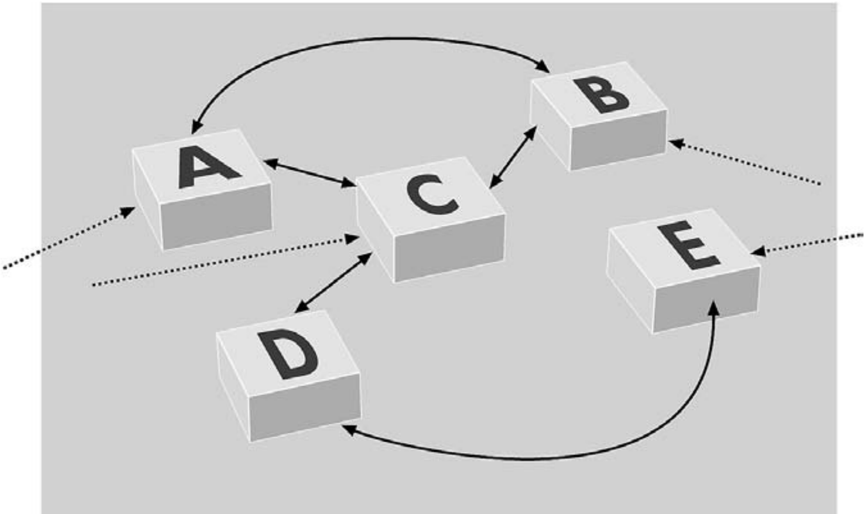

Figure 1. Combining personnel, techniques and methods, represented by boxes A – E, into tactical patterns [14].

The various combinations of available personnel, equipment and procedures can be referred to as tactical patterns [14], Figure 1. As a result of the tactical pattern used during a fire fighting operation the outcome of will vary. Tacit knowledge within the fire & rescue service asserts that there are "correct" patterns and "incorrect" patterns. The choice of tactical pattern is also dependent on the objectives of the individual operation and its expected outcome. However, scientific knowledge on how fire fighting operations work and on how the inherent dynamics of operations affect outcomes is inadequate. There are no traditions in bringing science into a fire station. Consequently, the determination of such "correct" and "incorrect" patterns is arbitrary.

This paper describes experiments with varying tactical patterns. The purpose of the experiments was to investigate how various tactical patterns interact with a fire in an apartment, and to thereby examine and draw conclusions from the course of events during operations and on their outcomes, using various tactical patterns. In a wider perspective, the experiments constitute a basis for further treatment of command and control problems.

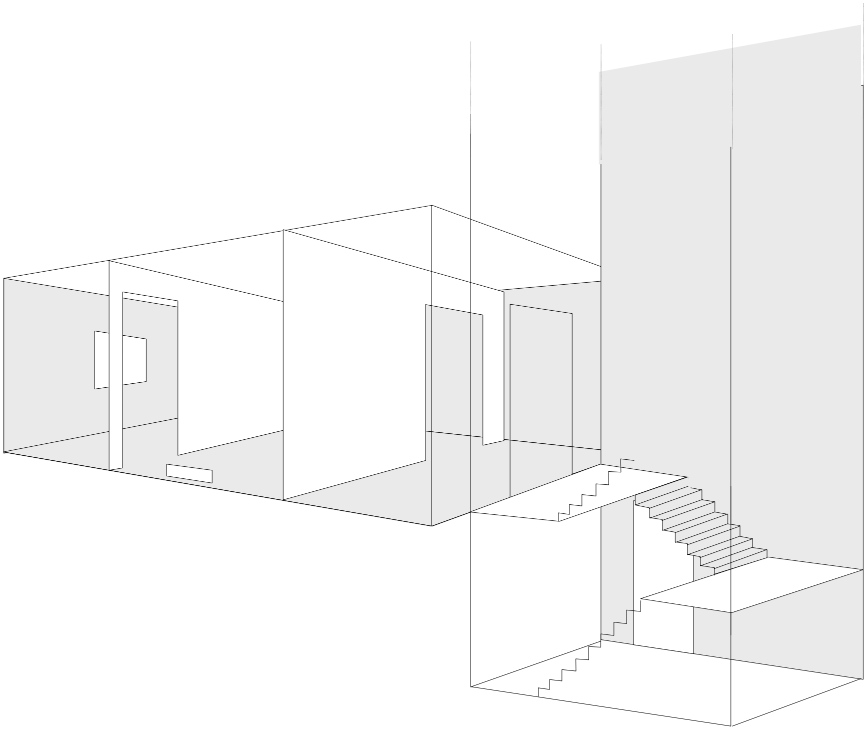

Figure 2. A three-dimensional view of the firefighter training facility that was used.

Experimental set-up

The tests were performed in a fire fighter training facility. The floor and ceiling were constructed from 0.2 m concrete. All the walls were constructed from 0.2 m lightweight concrete. Door and window hatches were of 2 mm sheet steel on a frame of 25 mm square iron. Three rooms on the first floor (2.7 m above ground level) were used, measuring (length × width × height) 2.8 × 5.0 × 2.5 m (Room 1), 3.4 × 5.0 × 2.5 m (Room 2), and 1.8 × 5.0 × 2.5 m (Room 3). The attached staircase (Room 4) measured 5.7 × 2.6 × 12 m. The size of the window was 0.88 × 1.18 m (width × height) (sill at 0.87 m above floor), the size of the doors between rooms 1, 2 and 3 were 1.16 × 1.98 m. The size of the doors between Room 3 and Room 4 and between Room 4 and outdoors were 0.92 × 2.0 m. In rooms 1 and 2 there was a small hatch at floor level, measuring 0.6 × 0.2 m (sill at 0.05 m above floor). See Figures 2 and 3 for details.

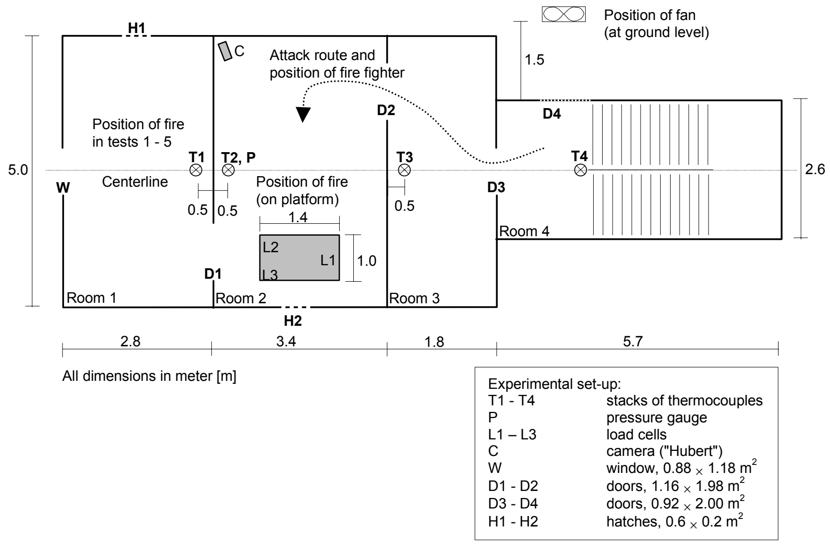

Figure 3. The experimental set-up.

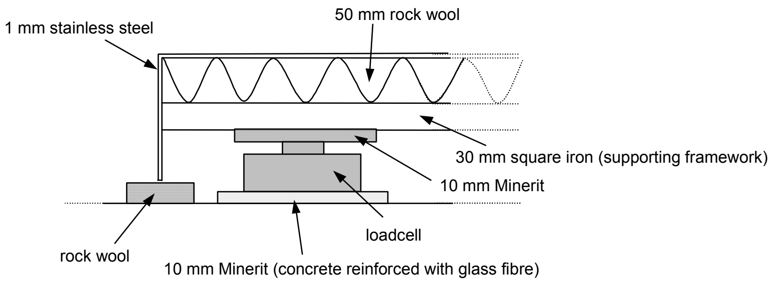

Figure 4. Details of the load platform.

As a fire source, eight standard wooden pallets were used in each test. The fuel was placed on a load platform measuring 1.4 × 1.2 m and 0.15

m high, resting on three load cells, L1 – L3 (see Table 1, Figures 3 and 4 for details on the load platform). The weight of the fuel was registered with a rate of 0.5 Hz. As an ignition source, two 0.15×0.15×0.01 m pieces of porous fibreboard soaked in diesel fuel were placed in the centre of the bottom of the stack and manually ignited using a fusee.

Table 1. Measuring range and accuracy of measurements as stated by the manufacturer. Item numbers are in accordance with Figure 3.

Item #	Measurement (number of devices)	Denomination	Measuring range	Accuracy of instrument
T1 – T4	Temperature (16)	Thermocouple type K, ∅0.52 mm	0 – 1300°C	±0.4%
P	Pressure (1)	Pressure gauge, Testo 0638.1445	-10 – 10 hPa	±0.002 %
L1 (serie 1)	Mass (1)	Loadcell, TML CLP-2000KA	0 – 2000 kg	± 0.5%
L2 – L3 (serie 1)	Mass (2)	Loadcell, TML CLP-1000KA	0 – 1000 kg	± 0.5%
L1 – L3 (serie 2)	Mass (3)	Loadcell, Vetek LPX250	0 – 250 kg	0.1 %
	Flow rate (1)	GPI turbine flow meter	0.17 – 1.67 kg/s	± 1%
	Logger	INTAB AAC-216		± 0.02%[1] ± 0.0034%[2]
	Logger	Testo 454 (pressure measurements only)		

Temperatures, using type K thermocouples, were registered with a rate of 0.5 Hz. Thermocouples where mounted at levels 0.25 m, 0.92 m, 1.59 m, and 2.25 m above the floor in rooms 1 – 3 (thermocouple tree T1 - T3). In Room 4 (the staircase) thermocouples were mounted 2.0 m, 5.2 m, 8.3 m, and 11.6 m above ground level (thermocouple tree T4).

[1] Calibration certificate indicates ±10μV for measuring range 50 mV, which was used for temperature measurements.
[2] Calibration certificate indicates ±340μV for measuring range 10 V, which was used for flow measurements.

Pressure above atmospheric was measured in Room 2 at 2.25 m above floor, using a differential pressure gauge (P).

In all tests, a standard nozzle type Leader Quadra Fog QF150 was used, adjustable between 20 – 150 l/min at 7 bars nozzle pressure. The nozzle was connected to a Swedish standard fire truck (BAS) by 50 m ∅ 42 mm hose. Flow was measured by a GPI turbine flow meter, table 1. In test 1 – 10 and 12 – 15 a flow rate of approximately 1.33 l/s was used. In tests 16 – 19 a flow rate of approximately 0.67 l/s. Due to the characteristics of the system, and to practical aspects generally found on a fire ground, variations in flow rate occurred, table 3 and table 6.

The fan used for positive pressure ventilation was a 24" Swefan run by a 6.5 hp (4.3 kW) petrol motor. The fan provided a nominal flow of 5.8 m^3/s. The tests were also documented using video and still photography.

Test procedure

The purpose of the experiments was to simulate different fire fighting operations, where fire fighters gain access to a ventilation-controlled fire in a three-room apartment, using different tactical patterns. The general scenario corresponded to approximately 60 seconds to sound the alarm and 300 seconds time to action, making a total time to operational interaction of approximately 360 seconds. During this period, the door to the apartment (D3) and the window (W) remained closed.

In all, twenty tests in two different series were performed. Series 1 included tests 1 – 11 and series 2 included tests 12 – 20. The test series are described in tables 2 and 3.

The wind speed during series 1 varied between 0 – 2 m/s, and during series 2 between 1 – 3 m/s. Measures were taken to reduce the influence of the wind, such as windbreaks in front of hatches (H1 – H2 in figure 3). The outdoor temperature during series 1 varied between 5 and 8°C, and during series 2 between 20 and 25°C. Between tests, the air temperature inside the facility was allowed to cool down to approximately 5 – 15°C in series 1 and to approximately 28 – 40°C in series 2. The temperature maintained at a higher level in series 2 was due to the higher outdoor temperature and the intense sun.

Table 2. Specification of the tests. Each test represents a tactical pattern.

Test #	Tactical pattern
1	Attack route through the door to the apartment (D3), door to the apartment (D3) and window (W) opened.
2	Attack route through the door to the apartment (D3), door to the apartment (D3) and window (W) opened, using positive pressure ventilation.
3	Attack route through the door to the apartment (D3), door to the apartment (D3) and window (W) opened, using positive pressure ventilation.
4	Attack route through the door to the apartment (D3), using positive pressure ventilation.
5	Attack route through the door to the apartment (D3), door to the apartment (D3) and window (W) opened.
6	Attack route through the window (W).
7	Attack route through the window (W).
8	Attack route through the door to the apartment (D3), door to the apartment (D3) and window (W) opened.
9	Attack route through the door to the apartment (D3), door to the apartment (D3) and window (W) opened, using positive pressure ventilation.
10	Attack route through the door to the apartment (D3), door to the apartment (D3) and window (W) opened, using positive pressure ventilation.
11	No attack (full-burn), door (D3) and window (W) opened and fire extinguished for safety reasons.
12	Attack route through the door to the apartment (D3).
13	Attack route through the door to the apartment (D3), door to the apartment (D3) and window (W) opened.
14	Attack route through the door to the apartment (D3), door to the apartment (D3) and window (W) opened, using positive pressure ventilation.
15	Attack route through the door to the apartment (D3), using positive pressure ventilation.
16	Attack route through the door to the apartment (D3).
17	Attack route through the door to the apartment (D3), door to the apartment (D3) and window (W) opened, using positive pressure ventilation.
18	Attack route through the door to the apartment (D3), door to the apartment (D3) and window (W) opened.
19	Attack route through the door to the apartment (D3), using positive pressure ventilation.
20	No attack (full-burn), door (D3) and window (W) opened and fire extinguished for safety reasons.

Results

This paper contains the main features and the most important results from the experiments. The full report contains all the results from the measurements [15]. Also, data can be made available upon request.

Measurement results

When using positive pressure ventilation in a "correct" way, i.e. according to text books [6], [20], such as in test 3 (shown in Figure 5), the decrease in temperature is faster and more distinct than when not using positive pressure ventilation, such as in test 1 (shown in Figure 6). It should be noted that in test 3, the temperature is reduced although no water has been applied to the fire (see also table 3). This is not the case in test 1. Also, in test 1 there is a spread of hot smoke to the staircase, room 4, which is not the case in test 3.

Table 3. Results from measurements. D refers to the opening of the door and W refers to the opening of the window.

Test #	Start (first opening) at time [s]	Second opening at time [s]	PPV	Flow onset at time [s]	Flow rate (peak) [l/s]	Total amount of water used [l]
1	368 (W)	368 (D)	No	384	1.59	6.2
2	404 (W)	406 (D)	Yes	422	1.38	6.3
3	360 (W)	368 (D)	Yes	382	1.46	2.9
4	354 (D)		Yes	368	1.78	6.3
5	358 (D)	494 (W)	No	374	1.47	5.6
6	366 (W)		No	392	1.75	6.3
7	362 (W)		No	392	1.32	2.6
8	364 (W)	364 (D)	No	392	1.44	5.5
9	356 (W)	364 (D)	Yes	394	1.41	5.2
10	426 (D)	546 (W)	Yes	450	0.38	2.8
11	> 400 (D)	> 400 (W)	No	Knock down only		
12	364 (D)		No	414	1.23	7.6
13	354 (W)	382 (D)	No	454	1.32	10.0
14	322 (W)	382 (D)	Yes	438	1.27	10.2
15	330 (D)		Yes	418	1.2	4.9
16	362 (D)		No	414	0.89	8.5
17	356 (W)	384 (D)	Yes	426	0.74	14.1
18	356 (W)	384 (D)	No	450	0.65	10.2
19	360 (D)		Yes	460	0.77	9.0
20	> 600 (D)	> 600 (W)	No	Knock down only		

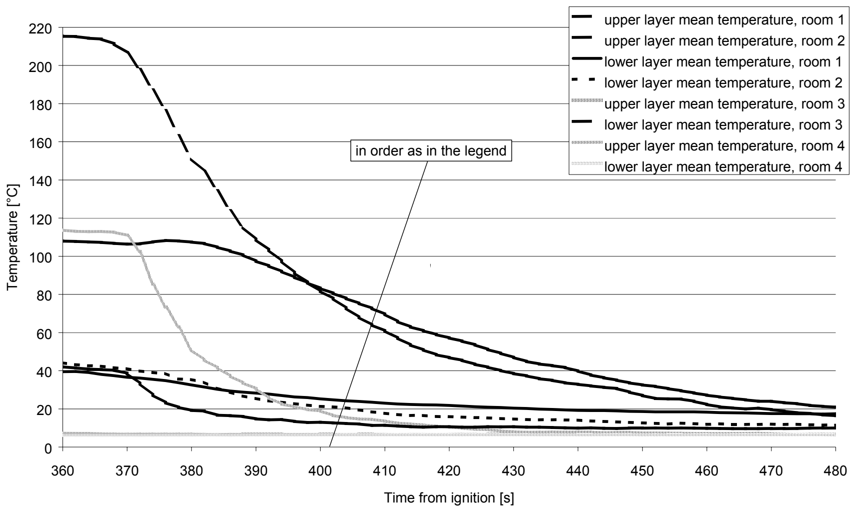

Figure 5. Upper and lower mean layer temperatures in rooms 1 – 4 in test 3.

In test 19, Figure 7, positive pressure ventilation was used but only the door was opened and a flow rate was used corresponding to approximately half of what was used in test 1 and 3. Here, the temperature was only slowly stabilized after the application of water. In some parts of the apartment the temperature increased for a short period of time after the application of water (lower layer of rooms 1 and 3).

Also, the results show that some tactical patterns have an inherent indulgence towards "incorrect" or less appropriate procedures that make up a tactical pattern. The first procedure taken in test 10, shown in Figure 8, included the opening of the door combined with the use of positive pressure ventilation. The second procedure included a flow rate corresponding to approximately half of that used in tests 1 and 3. The third and final procedure in test 10 included the opening of the window. This tactical pattern is similar to the one used in test 19, the only difference being that a third procedure was added, the opening of the window. Figure 8 shows that by adding this third procedure the temperature is rapidly reduced in many parts of the apartment.

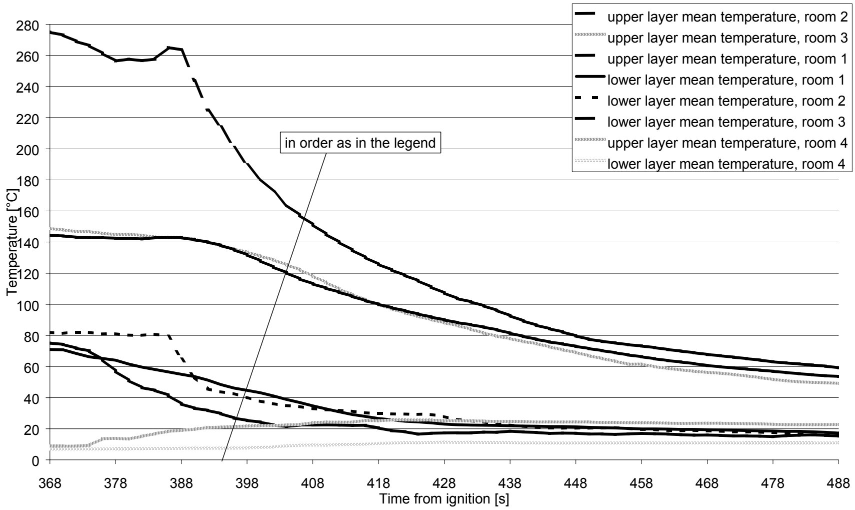

Figure 6. Upper and lower mean layer temperatures in rooms 1 – 4 in test 1.

Visual observations

During the tests visual observations were made by the fire fighter and recorded on video (C in Figure 3).

In tests without the use of positive pressure ventilation there was a clear visual distinction between an upper layer of thick hot smoke and a lower layer of fresh air coming in through the openings. This stratification was only disrupted for a short period right after the application of water, but was regained after a period of 30 – 60 seconds after the water flow was shut off.

In tests where positive pressure ventilation was used in combination with opening of the window in room 1, it was visually clear that smoke and hot gases were pushed out through the window. Also, after the application of water steam was pushed out through the window along with the smoke and hot gases.

However, when using positive pressure ventilation without simultaneous opening of the window, the environment in the apartment became very inhospitable. Visibility disappeared and steam penetrated the protective clothing of the fire fighters making the situation unbearable and difficult to assess and to perceive with the senses. Nevertheless, when the window was opened there was a rapid change in visibility and in the thermal effects to the fire fighter.

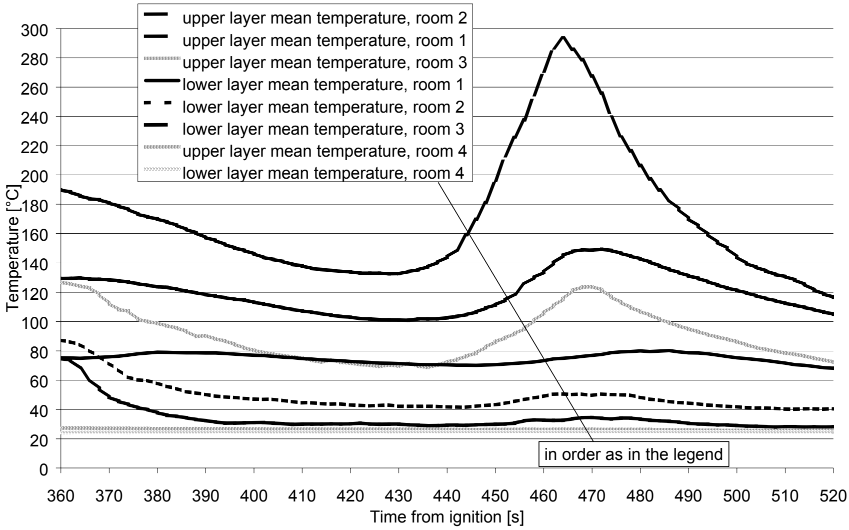

Figure 7. Upper and lower mean layer temperatures in rooms 1 – 4 in test 19.

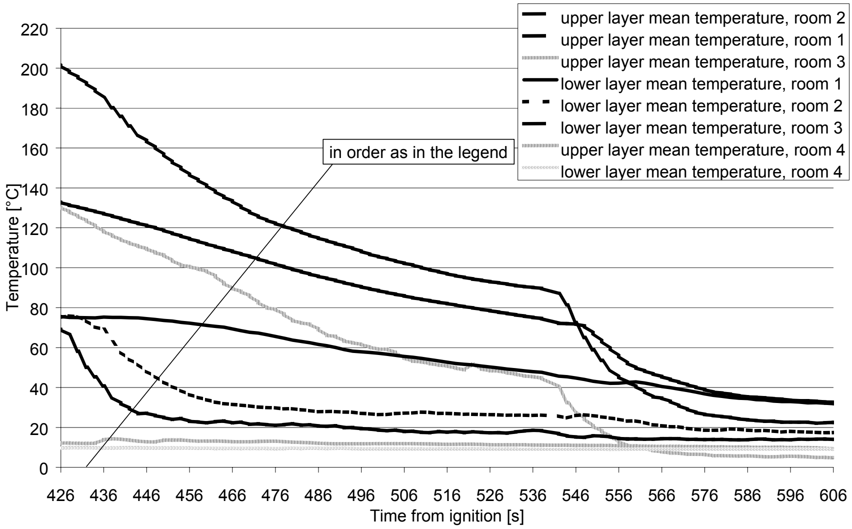

Figure 8. Upper and lower mean layer temperatures in rooms 1 – 4 in test 10.

Analysis of data

Due to practical aspects when performing large-scale experiments including manual operations, the data contained irregularities. The most important irregularity being varying time intervals, but also the variations in maximum/minimum temperatures between tests makes the material hard to compare. In order to draw any more extensive conclusions, it was necessary to convert the material into a more comparable form. The analysis in this section is based on the assumption that effects of various fire fighting procedures can be treated as exponential functions.

Tests 11 and 20 were full burn tests with the primary intention being to achieve visual results from a fire at which no fire fighting measures were taken. Therefore, tests 11 and 20 are excluded from the continued analysis.

Data reduction and resampling

In order to advance the analysis of the data it was standardized both in time and temperature in several steps, as described below.

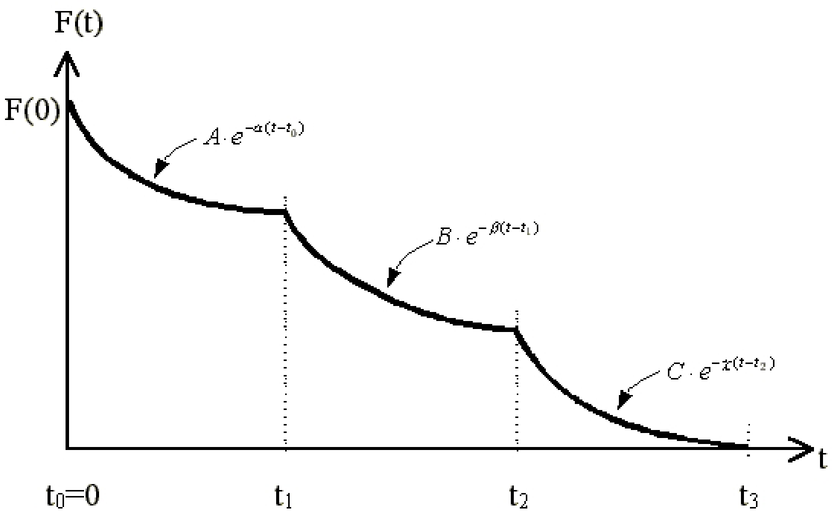

Figure 9. The operation as a series of exponential functions, with amplitudes A – C and frequencies α – χ varying, due to choice of tactical pattern.

In tests 1 – 10 and 12 – 19, it is the "operational" parts that are of interest, i.e. from first opening. Therefore, as a first step, the data was reduced from this time in each test, i.e. setting $t_0 = 0$ at the onset of the operation (second column of table 3).

In order to find a mathematical representation of the data, it was represented by a series of exponential functions, as in Figure 9,

$$F(t)=\begin{cases} A\cdot e^{-\alpha t}, & 0\le t<t_1 \\ B\cdot e^{-\beta(t-t_1)}, & t_1\le t<t_2 \\ C\cdot e^{-\chi(t-t_2)}, & t_2\le t<t_3 \\ 0, & t>t_3 \end{cases} \qquad \text{(Equation 1)}$$

It should be noted that an exponential curve is superimposed a preceding curve. The effect of various procedures, initiated and executed at different instants in time, will be superimposed. This is a key element to the analysis of the various tactical patterns, below.

The time-temperature data from each thermocouple was divided in time steps corresponding to events. These events were triggered at times t_0 and t_1 (for all tests), and also at t_2 for tests 5, 10, 13 – 14 and 17 – 18. Due to long time delays between initiation of procedures and effectuation of the procedure, intervals between onsets of procedures less than 10 s were omitted. In such cases, the procedures were assumed to be simultaneously onset. The material was resampled using fast Fourier transform, Equation 2, and inverse fast Fourier transform, Equation 3, from N (the difference between columns 2 – 3 and 3 – 5 in table 3 corresponding to 2×N) to n = 30 equally spaced points, using Matlab, by

$$g(s)=\sum_{j=1}^{N}F(j)\omega_N^{(j-1)(s-1)} \qquad \text{(Equation 2)}$$

$$F(t)=\left(\frac{1}{n}\right)\sum_{s=1}^{n}g(s)\omega_n^{-(j-1)(s-1)} \qquad \text{(Equation 3)}$$

where

$$\omega_N=e^{-2\pi/N} \qquad \text{(Equation 4)}$$

The result of this transformation is shown in table 4.

From this resampled data, upper and lower mean temperatures were created using the two upper thermocouples in each room for the upper layer mean temperature, and the two lower thermocouples in each room for the lower layer mean temperature. Next, each data set was standardized in two steps, firstly by reducing the temperature to the lowest reached temperature after onset of the final procedure, in each test, and secondly by dividing the data set with the upper layer mean temperature in room 2 at $t = t_0$, which was the highest observed in each test.

An example of the transformation and the standardization processes is shown in Figure 10. The figure shows transformed and standardized data from test 10, and it should be compared with data shown in Figure 8.

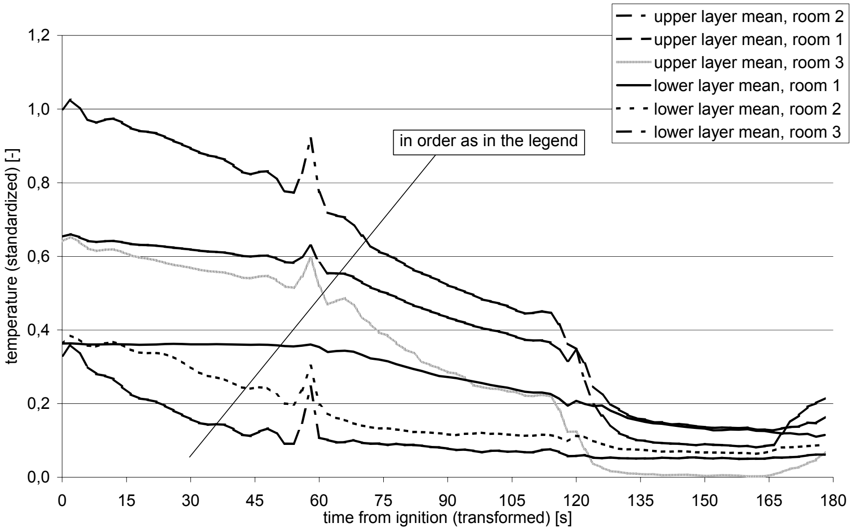

Figure 10. An example of results from the transformation and standardization processes. The diagram shows transformed and standardized data from test 10.

Finally, each interval of the data sets was fitted to the curve in Equation 1, using method of least squares. Values of A – C in Equation 1 were identified for each data set as

$$\begin{cases} A = F(0) \\ B = F(0) \cdot e^{-\alpha t_1} \\ C = F(0) \cdot e^{-\alpha t_1} \cdot e^{-\beta (t_2 - t_1)} \end{cases}$$

As an example taken from test 10 shown in Figure 10, data in the interval t = 0 – 60 was used to obtain values on A and α, data in the interval t = 60 – 120 was used to obtain values on β, data in the interval t = 120 – 180 was used to obtain values on χ.

Obtained values of amplitude A are shown in table 5 and values of frequencies α, β and χ in Figures 11 – 13, respectively.

Table 4. Resampled data using fast Fourier transform. Note that in tests 2, 3, and 9 the first and second openings are assumed to have occurred at the same time (see table 3).

Test #	Start (first opening) at time [s]	Second opening at time [s]	Flow onset at time [s]	Maximum time [s]
1	360 (W)	360 (D)	420	480
2	360 (W)	360 (D)	420	480
3	360 (W)	360 (D)	420	480
4	360 (D)		420	480
5	360 (D)	480 (W)	420	540
6	360 (W)		420	480
7	360 (W)		420	480
8	360 (W)	360 (D)	420	480
9	360 (W)	360 (D)	420	480
10	360 (D)	480 (W)	420	540
12	360 (D)		420	480
13	360 (W)	420 (D)	480	540
14	360 (W)	420 (D)	480	540
15	360 (D)		420	480
16	360 (D)		420	480
17	360 (W)	420 (D)	480	540
18	360 (W)	420 (D)	480	540
19	360 (D)		420	480

Table 5. Amplitudes, A, for procedure/combination of onset of procedures at t_0.

Test	Lower layer mean, room 1	Upper layer mean, room 1	Lower layer mean, room 2	Upper layer mean, room 2	Lower layer mean, room 3	Upper layer mean, room 3
1	0,219167	0,500183	0,260899	1,000000	0,234673	0,516646
2	0,179014	0,601519	0,200796	1,000000	0,173248	0,636114
3	0,158533	0,485930	0,180551	1,000000	0,170500	0,513452
4	0,196225	0,472069	0,236473	1,000000	0,214680	0,500929
5	0,212437	0,512005	0,270733	1,000000	0,221851	0,536611
6	0,182861	0,467340	0,243133	1,000000	0,185900	0,493846
7	0,164192	0,470269	0,226194	1,000000	0,172803	0,494627
8	0,248909	0,524224	0,294004	1,000000	0,264793	0,514913
9	0,309330	0,559783	0,331708	1,000000	0,277106	0,567660
10	0,363043	0,653030	0,361777	1,000000	0,330626	0,640113
12	0,227645	0,560385	0,295511	1,000000	0,233345	0,510331
13	0,234763	0,570468	0,286025	1,000000	0,231246	0,554367
14	0,280309	0,571835	0,341389	1,000000	0,263870	0,527646
15	0,267855	0,574052	0,320412	1,000000	0,258374	0,547274
16	0,205668	0,545953	0,261052	1,000000	0,177727	0,532232
17	0,335939	0,613989	0,357662	1,000000	0,294666	0,578364
18	0,276489	0,596601	0,394298	1,000000	0,288077	0,579461
19	0,290604	0,624365	0,365792	1,000000	0,287547	0,610306

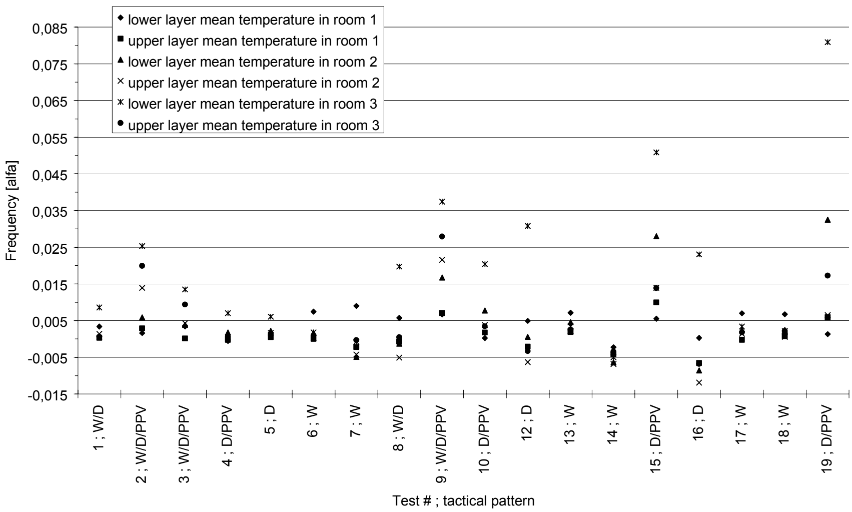

Figure 11. Frequency [α] for each test 1 – 10 and 12 – 19. Notation for tactical pattern includes window (W), door (D) and use of positive pressure ventilation (PPV). Slash ("/") indicates simultaneous onset of procedures, at t = t_0.

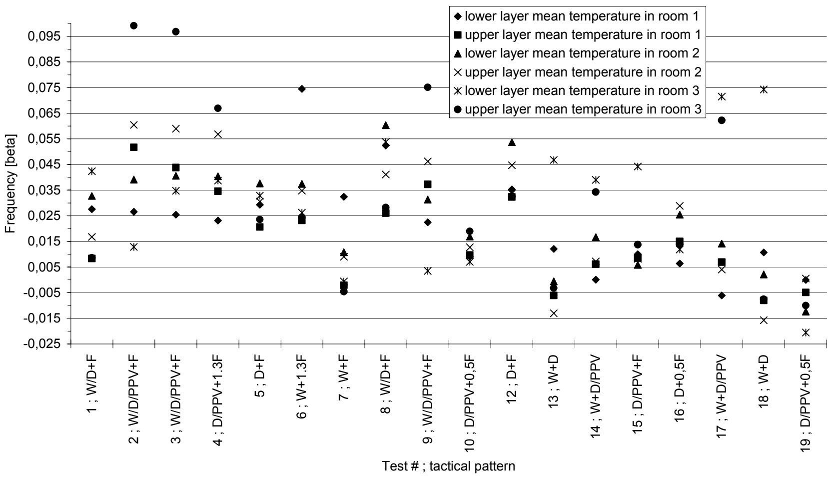

Figure 12. Frequency [β] for each test 1 – 10 and 12 – 19. Notation for tactical pattern includes window (W), door (D), use of positive pressure ventilation (PPV), full flow (F), half flow (0.5F) and 30% above full flow (1.3F). Slash ("/") indicates simultaneous onset of procedures, and a plus sign ("+") indicates additional procedure or procedures taken at time step t = t_1.

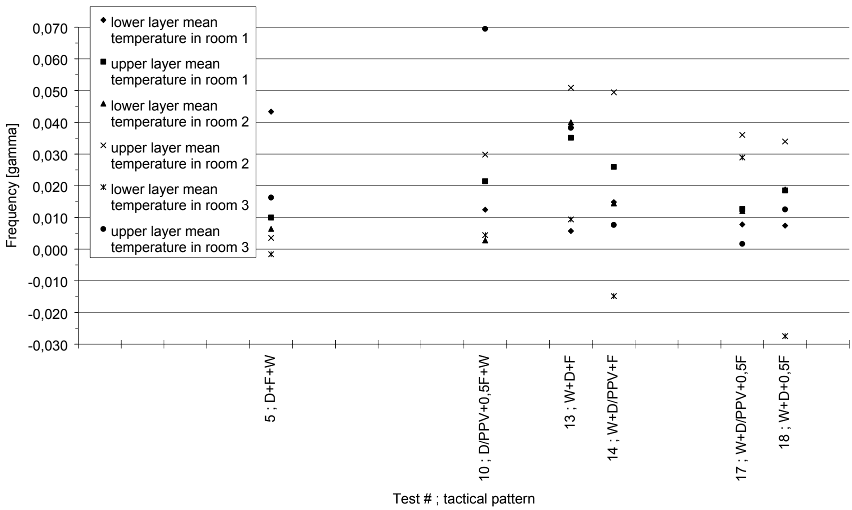

Figure 13. Frequency [χ] for each test 5, 10, 13, 14, 17 and 18. Notation for tactical pattern includes window (W), door (D), use of positive pressure ventilation (PPV), full flow (F) and half flow (0.5F). Slash ("/") indicates simultaneous onset of procedures and a plus sign ("+") indicates additional procedures taken at time steps $t = t_1$ and at time step $t = t_2$.

Comparison of recalculated data

The classification of flow rate was roughly performed in 3 classes. Tests with flow rates exceeding 1.7 l/s were classified as very large flows (tests 4 and 6), tests with flow rates between 1 and 1.7 l/s were classified as large flow (tests 1, 2, 3, 5, 7, 8, 9, 12, 13, 14 and 15) and tests with flow rates below 1 l/s were classified as small flows (tests 10, 16, 17, 18 and 19), see table 3 and 6.

Figure 14 shows the frequencies of the last procedure added, i.e. for tests 1 – 4, 6 – 9, 11, 12, 15, 16 and 19 β is shown and for tests 5, 10, 13, 14, 17 and 18 χ is shown, ranked by mean values for each test. A higher frequency indicates a better combination of procedures, i.e. a better tactical pattern, in that the temperature is reduced faster with larger frequency.

The diagram indicates that simultaneous opening of window and door, simultaneously using positive pressure ventilation and also using an appropriate flow rate, as in tests 2, 3 and 9, is a better combination than using only the door in combination with positive pressure ventilation and too small a flow rate, as in test 19.

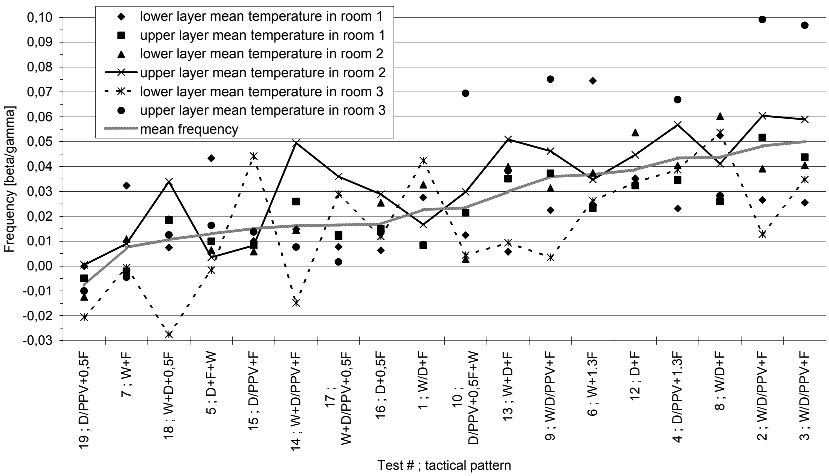

Figure 14. Frequencies at last added procedure in each test, ranked by mean value for each test.

However, the continuous line and the broken line in Figure 14 indicate that attention must be given to the objective of the fire fighting operation. Assume, in a real scenario similar to the experimental set-up, an option between the procedures used in tests 1 and 14, respectively. If the objective is to extinguish the fire efficiently, the procedure used in test 14 may be appropriate. However, if the objective is to save a person located on the floor in room 3, the procedure used in test 1 may be appropriate. Different objectives may influence what tactical patterns are considered as "correct" and what are considered as "incorrect".

For example, consider three representative scenarios with corresponding objectives:

1. Victim trapped on the floor in room 1, objective: reduce temperature in the lower parts of room 1 in order to increase survivability.
2. Victim trapped on the floor in room 3, objective: reduce temperature in the lower parts of room 3 in order to increase survivability.
3. Risk of flame spread from room 2 (room of fire origin), objective: reduce temperature in the upper parts of room 2 in order to lessen the risk of fire spread.

Ranking of the various tactical patterns, represented by tests 1 – 10 and 12 – 19, for frequencies at the end of each test, i.e. β in tests 1, 2, 3, 4, 6, 7, 8, 9, 12, 15, 16 and 19 and χ in tests 5, 10, 13, 14, 17 and 18, Figure 14, indicates that for the first scenario/objective, any tactical pattern where the window is opened but no positive pressure ventilation is used seems superior to other patterns. Similarly, when responding to a fire as in scenario 2, tactical patterns making use of positive pressure ventilation seem to fulfil the desired objective better than patterns without positive pressure ventilation. Also, in the third scenario, Figure 14 indicates that the use of positive pressure ventilation is a better way to prevent the spread of fire in the upper parts of room 2, than other tactical patterns. In addition, in any of these scenarios it is seemingly better to use a large flow.

The primary objective of the fire service is to save lives. In the tests no life saving procedures were explicitly considered. In addition, it is assumed that survivability can be represented by temperature. As indicated by Figure 14 and the examples above, fire suppression may very well be a direct life saving procedure, in that it reduces temperature. From these tests, larger flows have a better impact on the survivability of trapped victims, although the choice of tactical patterns seems to be of greater importance to the outcome of an operation than the procedure of fire suppression itself.

Room 4 was excluded from data reduction and resampling. However, adding it to the analysis would have brought up yet another aspect on responding to fires in multiple-storey apartment houses – the risk of smoke and fire spread to the staircase, to other apartments and to other parts of the building.

Discussion

Working with this type of large-scale experiment, including operator-dependency, introduces a large number of errors that are hard to control. It is of the utmost importance to be aware of the sources of error and, if possible, attempt to minimize their influence on the results. Below, experiments, results and the analysis are discussed, including aspects such as sources of error and applicability of results.

The experiments

Large-scale experiments always bring with them a number of problems. Due to the size of the facility, the experiments had to be performed outside. Exposure to weather and wind may interfere with results in an unwanted fashion. However, during the experiments the weather conditions were such that no interference with the results was detected. Also, the chosen set-up has been used in earlier experiments, on fire ventilation [8].

Table 6. Expected and measured flow rate for each test.

Test	Expected flow rate [l/min]	Measured flow rate [l/min]	Difference
1	80	91	13,8%
2	80	80	0,00%
3	80	87	8,75%
4	80	109	36,2%
5	80	88	10,0%
6	80	107	33,8%
7	80	76	-5,00%
8	80	72	-10,0%
9	80	78	-2,50%
10	80	80	0,00%
12	80	74	-7,50%
13	80	78	-2,50%
14	80	76	-5,00%
15	80	75	-6,25%
16	40	38	-5,00%
17	40	40	0,00%
18	40	38	-5,00%
19	40	35	-12,5%

In order to investigate tactical aspects of fire service operations, considerable assumptions had to be made. Among other things, the experiments leave out the life saving aspect, in the sense of searching and physically removing victims from the scene of a fire. However, there is no contradiction in suppression or ventilation procedures and life saving. Suppression and ventilation procedures may very well be regarded as life saving procedures, on condition that the environment in the room on fire is improved by suppression and/or ventilation procedures. During the experiments temperature was assumed to be an indicator of survivability.

In addition, the experiments were operator-dependent, i.e. the results of the experiments were to some extent dependent on the behaviour of fire fighters. Great demands were placed upon the skill and knowledge of the fire fighters, and their ability to grasp the purpose of the tests.

Due to the characteristics of the water delivery system there was a variance in the flow rate. Unfortunately, in relation to expected flow, the flow rate varied between up to 35 %, table 4. However, this is a common feature in real fire fighting systems and can usually be expected to be much larger in reality than in an experiment [16].

The accuracy of measuring devices is shown in table 1. However, the inherent fluctuations during a large-scale fire experiment are usually very large, and it may be very hard or even impossible to distinguish between natural fluctuations and the accuracy of measurements.

Maximum temperature was higher in tests 12 – 20 than in tests 1 – 11 [15]. Also, the increase in temperature was faster in series 2. These differences may be caused by poor storage of the fuel and higher moisture content of the fuel used in tests 1 – 11 than in tests 12 – 20.

Standardized weight reduction during the first 360 s in tests 12 – 20 is shown in Figure 15. The increasing differences in weight reduction at approximately t = 250 – 300 s may be due to an early increasing degree of ventilation control of the fire. Due to current leakage in the load cells causing loss of data it was not possible to create a corresponding diagram for tests 1 – 11.

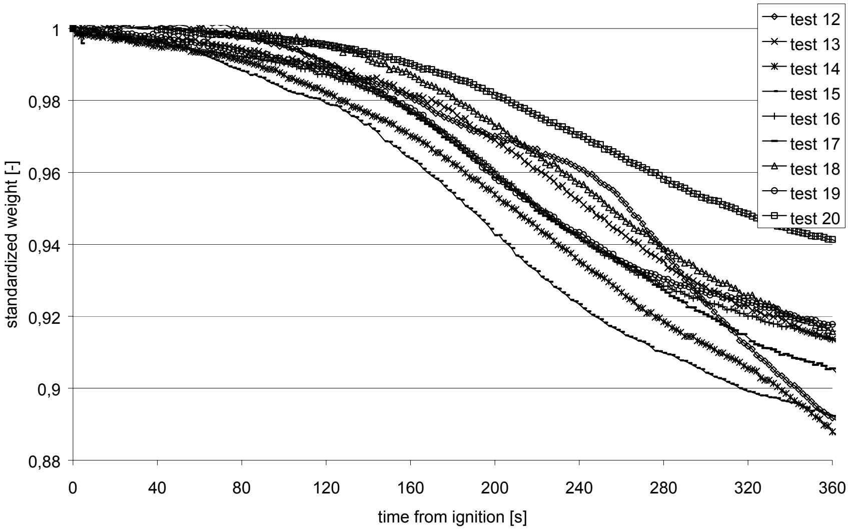

Figure 15. Standardized weight reduction during the first 360 s in tests 12 – 20.

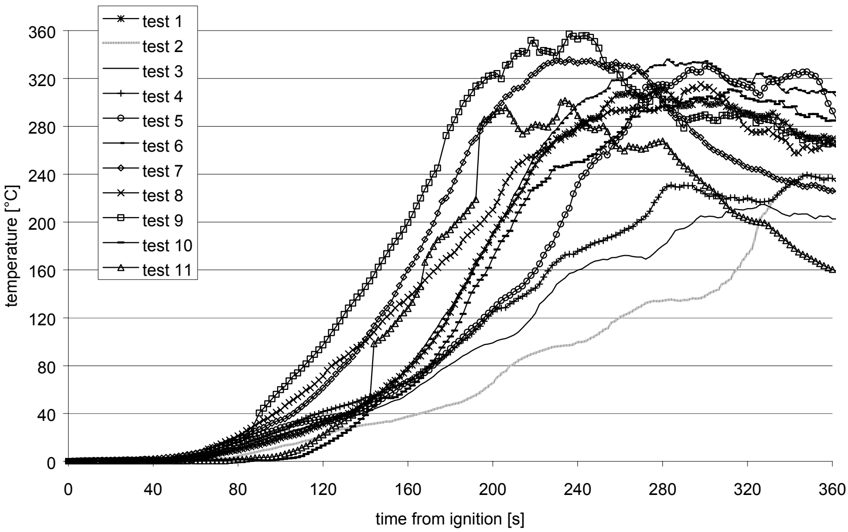

Figure 16. Upper layer mean temperature in the room of fire origin in tests 1 - 11. The temperature scale has been corrected to 0°C.

Upper layer mean temperature in the room of fire origin in tests 1 – 11 is shown in Figure 16 (thermocouple tree T2). The upper mean temperature in series 1 shows large fluctuations, which may be induced by the high moisture content of the fuel. It may also be due to an early increasing degree of ventilation control of the fire, as in tests 12 – 20, see Figure 15.

The chosen scenarios were intended to reflect the procedures that a small crew can accomplish when responding to a fire in an apartment. These procedures include suppression and ventilation and the variations in suppression include variation in flow rate. Variations in ventilation include the opening of various available openings, door (D3) and window (W). This variation also includes the use of positive pressure ventilation. The position of the fan was the same in all the tests where positive pressure ventilation was used.

Results

Measurements indicated important differences, depending on the tactical pattern used. Phenomena similar in character were observed when analogous tactical patterns were used in different tests.

However, the objective of the tests was primarily comparative and the results are valid only in situations similar to the various tests. Comparisons with other experiments and with data from real fire fighting operations should be made only in exceptional cases and then with caution.

Analysis of data

The analysis of data in section 5 was performed in order to advance the possibility to draw more distinct conclusions from it. The analysis was based on the assumption that effects of various fire fighting procedures can be treated as exponential functions. Some other function may be used, but an exponential function is simple to use, from a mathematical point of view. In addition, exponential representation of decay processes as well as other problems is a common and well-known approach in many engineering applications. Therefore, this assumption is assumed reasonable. Also, exponential representation of data equalizes peaks, such as the decay followed by the increase in the temperature shown in the upper layer mean temperatures in figure 7.

By using Fourier transforms, the data becomes a mathematical representation only, although it contains all relevant information from the experiments. However, there is a limit for the extent of this recalculation but it was assumed that the transformation performed was well within its limitations.

Large-scale experiments, especially when procedures are initiated and executed manually, large fluctuation in time and temperature occurs. Standardization and the use of Fourier transform is a way to overcome such fluctuations. The purpose of this process is to draw more extensive conclusions from the data. It should be noted that a similar process could be used on any measured variable. This type of approach could be useful for examining new or alternative fire fighting tactics or when constructing simulation scenarios for e.g. the training of fire officers. Data standardized in the x-coordinate as well as in the y-coordinate could be used as input to simulations and re-calculated into "real" data. Also, this approach could be used for post-examination of appropriateness and effectiveness of real fire fighting scenarios.

The results from this analysis are in many cases well known and certainly recognized by the fire fighting community. This includes the conclusions on the use of and the applicability of positive pressure ventilation. Nevertheless, the analysis also shows the importance of linking procedures and tactical patterns with objectives during a fire fighting operation, i.e. the importance of command and control.

Also, it should be noted that the experiments were performed in a small apartment, with only minor "real" fire fighting or command and control problems. In some other geometry, including greater risks of fire spread, more options and more uncertainties, the conclusions may be different. In addition, these results indicate that the type of standardizing and transformation used may be useful.

At this stage, the identified values on the frequencies α, β and χ are applicable to the experimental set-up only or possibly to situations very similar to the experimental set-up. However, further investigation on frequencies of procedures and combinations of procedures (tactical patterns) might lead to methods or the testing of various tactical patterns, for post-examination of appropriateness and effectiveness of real firefighting scenarios, and also to develop simulators for firefighting operations.

Conclusions

From the results, analysis and modelling work, a number of important conclusions can be made.

Clearly, positive pressure ventilation is a useful procedure, provided that it is used correct (according to recommendations) and with caution. Also, the flow rate can have a dramatic effect on extinguishing effect as well as to the working environment, although the flow rate in some cases should be maintained as low as possible.

Basic tactical principles were experimentally shown and validated, such as that the outcome of a fire fighting operation is dependent on the individual procedures as well as on their sequence of implementation. Such sequences are identified as tactical patterns. Also, the choice of tactical pattern is dependent on the situation as well as on the objectives of the fire fighting operation. The importance of command and control during fire fighting operations is therefore vital.

Certain tactical patterns can have an inherent indulgence towards defective or inappropriate procedures. Also, defective or inappropriate procedures or tactical patterns can be corrected during a fire fighting operation.

Applications of continued work includes finding methods for the testing of various tactical patterns, for post-examination of appropriateness and effectiveness of real firefighting scenarios, and also to develop simulators for firefighting operations.

The processing and treatment of data described needs further validation. Additional experiments are needed from which the applicability of the method used for the analysis must be investigated.

References

1. *Räddningstjänstlag (1986:1102)*, ändringar till och med SFS 1999:383 (Swedish Rescue Services Act).
2. Rimen, J. G., *The Use of High Pressure and Low Pressure Pumps with Hose reel Systems.* Research Report Number 36. Home Office Scientific Research and Development Branch, Fire Experimental Unit: Moreton-in-Marsh. 1990.
3. Lundström, L, Svensson, S. Live Fire Tests On Suppression Of Post-Flashover Fires Using Manually Applied High And Low

Pressure Water Sprays. In *Proceedings of the 8th International Interflam Conference*. Interscience communications, London, 1999.

4. Svensson, S, Särdqvist, S. Fire Tests In A Large Hall, Using Manually Applied High- And Low Pressure Water Sprays. *Fire Science and Technology,* vol. 21, No. 1, 2001.

5. Milke, J., Evans, D., Hayes Jr., W., *Water Spray Suppression of Fully-Developed Wood Crib Fires in a Compartment*, U. S. Department of Commerce, National Bureau of Standards, NBSIR 88-3745, 1988

6. Stroup, D. W., Evans, D. D., *Suppression of Post-Flashover Compartment Fires Using Manually Applied Water Sprays*, U. S. Department of Commerce, National Institute of Standards and Technology, NISTIR 4625, 1991.

7. Rimen, J.G. *An Assessment of the Use of Positive Pressure Ventilation in Domestic Properties* (Home Office, Publication No 17/96). London: Home Office Fire Research and Development Group. 1996.

8. Svensson, S. Experimental Study Of Fire Ventilation Actions During Firefighting Operations. *Fire Technology, vol. 37, No. 2, 2001.*

9. Svensson, S, Werling, P. Experimental Study Of Fire Ventilation Procedures In A Large Hall. In *Proceedings of the 9th International Interflam Fire Science & Engineering Conference,* Interscience communications, London, 2001.

10. Hay, A. *A Survey of Fire Ventilation* (Home Office, Publication No 6/94). London: Home Office Fire Research and Development Group. 1994.

11. Svensson, S. Developing a command structure within the fire services - from enlistment to a viable system. In *Proceedings of International Conference on Improving Firefighter Safety: Human Behavior and Organizational Aspects*, Indianapolis, 3 – 4 March 2001.

12. Dunn, V. *Command and control of fires and emergencies*. Saddle Brook, NJ: PennWell Publishing Company. 1999.

13. Routley, J.G. Fire department operations. In Cote, A.E. (Ed.). *Fire Protection Handbook*. 17th edition. Quincy, MA: NFPA. 1991.

14. Svensson, S. *Räddningstaktiska grunder, förslag till definitioner och kommentarer därtill*. (Basic tactical principles – proposals for definitions and comments on them) (In Swedish) (report P21-252/99). Räddningsverket, Karlstad. 1999.

15. Svensson, S. *Försök med olika taktiska mönster mot brand i en liten* lägenhet (Tests on various tactical patterns when responding to fires in small apartments) (In Swedish) (report P21-380/01). Räddningsverket, Karlstad. 2001.

16. Särdqvist, S. *Real Fire Data, Fires in non-residential premises in London 1994 – 1997* (report 7003). Department of Fire Safety Engineering, Lund University, Sweden. 1998.

17. Magnusson, S.E. *Rökspridning i byggnader: kunskapsöversikt och forskningsbehov* (Rapport LUTVDG/(TVBB-3013), in Swedish). Lund: Lunds Tekniska Högskola. 1983.

18. Särdqvist, S. *Demand for Extinguishing Media in Manual Firefighting* (report 1021). Lund University, Department of Fire Safety Engineering. 2001.

19. Svensson, S. *Brandgasventilation* (In Swedish) Fire ventilation. Räddningsverket, Karlstad 2000.

20. Fire Service Manual; Fire service Operations (Volume 2), Compartment Fires and Tactical Ventilation. London: Home Office. 1999.

LUND UNIVERSITY

KFS AB, Lund 2002