FRDG Publication Number 5/94

HOME OFFICE

A Survey of Backdraught

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FIRE
RESEARCH &
DEVELOPMENT
GROUP

FRDG

Pub No 5/94 A Survey of Backdraught

Home Office
Fire Research and Development Group

A SURVEY OF BACKDRAUGHT

BY

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FRDG Publication Number 5/94
ISBN 1-85893-191-6

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ABSTRACT

The Home Office Fire Research and Development Group have identified flashover and backdraught among several topics where further study may bring benefits in the reduction of financial losses from large fires.

This report describes a survey of current knowledge of backdraught and considers needs for any further research work and the implications for the training of firefighters.

It is important to distinguish the difference between a backdraught and a flashover. Both are sudden events that represent a serious hazard to firefighters. Backdraught is an often explosive consequence of admitting air into a compartment containing a fire deficient in oxygen. It is an event of short duration burning off un-burnt gaseous flammables which have accumulated in a compartment. Flashover is a sudden jump in fire growth from a relatively localised fire to one having a sustained involvement of all combustible surfaces in a compartment.

MANAGEMENT SUMMARY

Introduction

Flashover and backdraught are distinctly different events which occur in different ways. A flashover can occur in a compartment when a small localised fire rapidly develops into a fire involving all the combustible surfaces. In contrast a backdraught occurs after air is admitted to a poorly ventilated compartment and mixes with un-burnt pyrolysis products from the oxygen starved fire. Any ignition source, such as a glowing ember, can ignite the resulting flammable mixture. Expansion due to heat created by combustion can then expel burning gases out through the opening which originally admitted air to the compartment.

In the U.K. "flashover" has often been used as a generic term for any sudden growth in the heat release rate of a fire. To differentiate processes that can cause such a change, various authors have independently introduced further terms, for example "radiation induced flashover" or "hot rich flashover". This can lead to the same physical event being described by several names. It is likely however that in the U.K. any sudden change in heat release rate would be reported by a fire officer or catalogued by a library as a "flashover".

British (BSI) and International (ISO) standards provide definitions of the term flashover which correspond to the specific description given above. Backdraught is not, however defined by BSI or by ISO, but definitions are given by the Institution of Fire Engineers (IFE) and the National Fire Protection Association (NFPA) which correspond to the process described above.

Research

Flashover has been the subject of many studies and a reasonable understanding of the phenomenon has been developed. Research on backdraught is sparse. This study has identified only one active group at the University of California (Berkeley) whose work will provide a base line for further studies. Other research into fires in under-ventilated compartments is ongoing and may provide information on the conditions preceding a potential backdraught.

Fire Fighting and Training

A firefighter needs to be able to identify the conditions which may lead to a backdraught, these are :

A fire in a compartment with few openings that has been burning for some time.

Oily deposits on windows.

Pulsating smoke from openings.

Blue flames in the hot gas layer.

In addition the colour of the smoke can indicate an under-ventilated fire, however this will be difficult to determine under different lighting conditions and is dependent on the type of fuel. This may not always be a reliable warning sign for a potential backdraught scenario.

Another indicator may be the movement of smoke when a door is opened, a rapid inflow at low level and outflow at high level could indicate the mixing processes (a gravity current) which may precede a backdraught (if an ignition source coincides with a flammable gas mixture). This must be considered in the context of any other venting of the compartment.

The roaring noises sometimes reported may be an indication that a backdraught is in progress at which stage there is probably little action that can be taken by a firefighter to prevent it.

There is currently no practical training given to firefighters regarding backdraught in the U.K. Training for Swedish firefighters does, however, include theoretical and practical aspects of flashover and backdraught. This is currently based on the concepts of Giselsson and Rosander whose theories are unfortunately flawed and in some cases misleading. The practical fire fighting tactics appear, however, to be sound, but require significant skill to be performed safely and effectively.

Conclusions

All firefighters need an adequate understanding of the development of fires in both well and under-ventilated states so that they can recognise potential backdraught and flashover conditions. Tactics such as venting, indirect and offensive application of water can then be used effectively and safely.

The terminology used to describe events such as flashover and backdraught should be consistent throughout the fire safety community. Since adequate definitions exist, the generic use of the term flashover should be discouraged. This will facilitate better communication and, since the event can then be readily identified, permit the extent of the problems due to backdraught to be assessed.

Continued research into both flashover and backdraught are required to give the firefighter clearer warning signs of such events and to examine the effect of fire fighting techniques, especially venting. In addition, predictive tools can be developed to enable building design which would mitigate the effects of a backdraught and allow fire fighting strategies to be evaluated. Backdraught in large building spaces presents a special hazard to the firefighter since the explosive event may occur sometime (possibly minutes) after the building has been opened to gain access. Studies so far have only addressed small enclosures; however techniques such as CFD (computational fluid dynamics) are available and could provide a safe and relatively inexpensive method for such investigations.

Safety considerations make the development of realistic training facilities for flashover and backdraught difficult, if not prohibitive. However training programmes reinforcing academic fire science with small scale demonstrations and then full scale fire fighting exercises would provide a good understanding of the basic scientific principles of fire development and how various fire fighting techniques operate.

There is a clear need within the Fire Service for a sound education on all aspects of fire science. A simple book along the lines of Giselsson and Rosander's "Fundamentals of Fire" but which gives a sound introduction of the principles of fire behaviour and the mechanisms of fire fighting techniques to the practising firefighter would be particularly valuable.

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APPENDICES

1. INTRODUCTION

An examination by the Home Office Fire Research and Development Group (FRDG) (Reference 1) identified several topics, including flashover and backdraught, where further study may bring benefits to reducing the financial losses from large fires. A preliminary study by the Fire Experimental Unit (FEU) (Reference 2) concluded that flashover was well enough understood, however backdraught required further consideration. This report describes a survey of the existing knowledge on backdraught. The scope of the survey has been to:

1. Determine the current extent of knowledge of backdraught.
2. Establish what theoretical, scientific and practical work has been carried out and to evaluate the results and conclusions.
3. Explain the physical and chemical processes involved.
4. Determine if backdraught is fully understood and identify where further research is required.
5. Investigate and evaluate advice given to firefighters world-wide with relation to the identification and hazards of backdraught.

The survey is intended to provide the Fire Service with a clear understanding of the mechanisms involved in backdraught and its relationship to flashover. This will assist in an evaluation of training methods to ensure that appliance crews will be better able to recognise a potential backdraught situation.

A literature review has been conducted to establish the current scientific understanding of backdraught, its manifestation in practice and related firefighter training. Research groups currently active in this and related fields in the USA, Japan and Sweden have been consulted. Fire Services in the U.K. and Sweden have also been consulted to provide information on their current training methods.

This report considers definitions of backdraught and flashover, presents an assessment of current knowledge of the phenomena, provides explanations for the processes involved and finally makes recommendations on the needs for further research and training.

Several terms appear to be in use to describe the backdraught phenomenon. The survey has been broadened to include flashover and other sudden fire events so that the particular features of backdraught can be clearly identified. Some recent articles (e.g. Reference 3) based on the book

"Fundamentals of Fire" by Giselsson and Rosander (Reference 4), have suffered from over-simplified descriptions of the various phenomena and the use of terms for events which do not correspond to terms and definitions used elsewhere. The concepts of Giselsson and Rosander relating to backdraught which strongly influence current Swedish Fire Service training are critically appraised in Section 7.

2. REVIEW METHODOLOGY

The survey has combined a literature search with interviews, visits and a direct request for relevant material from Japan. Contact addresses are given in Appendix A.

A search of the published literature was made using the Fire Research Station (FRS) FLAIR and FEU databases. Very few references were found relating directly to backdraught because the generic use of the term flashover to include backdraught has propagated into library indexing of information. Searching using the keywords **flashover** and **smoke explosion** gave over four hundred references between the two databases. There was, however, some duplication. Selection by consulting the abstracts resulted in excess of eighty references having a possible relevance to backdraught. Items not directly referenced in the text are listed as additional material after the references.

Visits have been made to laboratories and fire training centres known to be active in this field. In addition attendance at the 1993 NIST Annual Conference on Fire Research facilitated discussions with US-based research workers regarding backdraught.

3. DEFINITIONS

3.1 General

The first important step is to clarify what the terms flashover and backdraught refer to. Further definitions of terms used in this report are included in a glossary (see page 47).

The Fire Research Station have suggested descriptions of flashover and backdraught (Reference 5). These, with revisions made as a consequence of this survey, are given below.

These descriptions will apply to the subsequent use of the words flashover and backdraught in this report.

3.2 Flashover

In a compartment fire there can come a stage where the total thermal radiation from the fire plume, hot gases and hot compartment boundaries cause the radiative ignition of all exposed combustible surfaces within the compartment. This sudden and sustained transition of a growing fire to a fully developed fire is **flashover.**

3.3 Backdraught

Limited ventilation can lead to a fire in a compartment producing fire gases containing significant proportions of partial combustion products and un-burnt pyrolysis products. If these accumulate then the admission of air when an opening is made to the compartment can lead to a sudden deflagration. This deflagration moving through the compartment and out of the opening is a **backdraught.**

3.4 Definitions from Standards and Texts

3.4.1 Flashover

The definition of flashover is given in a British Standard (Reference 6) as a :

"Sudden transition to a state of total surface involvement in a fire of combustible materials within a compartment".

The International Standards Organisation (ISO) (Reference 7) use a similar wording :

"The rapid transition to a state of total surface involvement in a fire of combustible materials within an enclosure".

These are consistent with the description given in Section 3.2 however it is not emphasised that the transition is sustained which is a significant feature of a flashover. Other descriptions such as those by Walton and Thomas (Reference 8) and Drysdale (Reference 9) refer to the same mechanism.

3.4.2 Backdraught

Backdraught does not appear in any British or ISO Standards. There are however definitions given by the Institution of Fire Engineers (IFE) (Reference 10) and the National Fire Protection Association (NFPA) (using the American spelling - backdraft) (Reference 11).

The IFE definition is :

"An explosion, of greater or lesser degree, caused by the inrush of fresh air from any source or cause, into a burning building, where combustion has been taking place in a shortage of air."

And the NFPA definition :

"The explosive or rapid burning of heated gases that occurs when oxygen is introduced into a building that has not been properly ventilated and has a depleted supply of oxygen due to fire."

Fleischmann, Pagni and Williamson (Reference 12) suggested that "un-burnt pyrolysis products" should be substituted for "heated gases" in this definition. The term backdraught (backdraft) is clearly understood in the USA to be distinct from flashover.

Use of the word backdraught (or backdraft) is not new. The earliest use uncovered during this survey dates from 1914 by Steward (Reference 13) who gives the following description :

'These "smoke explosions" frequently occur in burning buildings and are commonly termed "back draughts" or "hot air explosions". Fire in the lower portion of a building will often fill the entire structure with dense smoke before it is discovered issuing from crevices around the windows. Upon arrival of the firemen openings are made in the building which admit free air, and the mixture of air and heated gases of combustion are ignited with a flash on every floor, sometimes with sufficient force to blow out all the windows, doors of closed rooms where smoke has penetrated, ceilings under attics, etc.'

3.5 Other Related Terminology

3.5.1 General

Despite the definitions in Section 3.4 "flashover" is often used as a generic term to describe any sudden change in behaviour that occurs during a fire, including backdraught. It may also be used to describe any rapid advance of a flame front across a ceiling (Reference 14). To distinguish between the different phenomena several terms have been used by different authors, these are described and attributed individually.

3.5.2 Terms to Describe Flashover

Temperature Induced Flashover : Used by Cooke and Ide (Reference 15).

Lean Flashover : Used by Giselsson and Rosander (Reference 4). Their description has been interpreted here to be the rapid spread of flames across a ceiling occurring at an early stage of the flashover transition (Section 7).

Flame over : Rapid flame spread over one or more surfaces. (Reference 11)

3.5.3 Terms to Describe Backdraught

Smoke Explosion : Explosion of a mixture of flammable fire gases (pyrolysed fuel and partial combustion products) and air. Given in Reference 11 as : "An explosion of heated smoke and gases."

Ventilation Induced Flashover : Used by Cooke and Ide (Reference 15).

Rich Backdraft : Adopted recently by Fleischmann (Reference 16) to describe a backdraught as defined in Section 3.3.

Rich Flashover : Used by Giselsson (Reference 4) to describe a smoke explosion or backdraught.

Hot Rich Flashover : Used by Giselsson (Reference 4) to describe an event when air is added to a hot, fuel rich mixture which then spontaneously ignites.

Lean Backdraft : Used by Fleischmann (Reference 16) to describe a variant of backdraught when an ignition of an accumulation of flammable gases by a pilot flame occurs when the lower flammability limit is reached. This does not require sudden venting, but is the result of a fire burning inefficiently.

Delayed Flashover : Used by Giselsson (Reference 4) to describe an event where the ignition of the flammable mixture is delayed allowing additional mixing either increasing the volume of gases within the flammability limits or diluting a rich mixture closer to its stoichiometric (ideal) concentration. The consequence is a more violent event.

3.5.4 Other Events

Flameover and **Rollover** are used by Grimwood (Reference 17) also to describe the onset of flaming in the hot gas layer.

Flashback : The propagation of flame from an ignition source to a supply of flammable liquid. (Reference 10)

Blow torch : Grimwood (Reference 17) describes this as an effect which may occur in tall buildings. An external window to a room containing a fire breaks, wind blowing through the opening supplies air to the fire and forces the burning gases through the building.

Gas explosion : The deflagration resulting from the ignition of a flammable gas mixture in an enclosure. The source of the flammable gas could be a piped or bottled gas supply (Reference 10).

4. VISITS / CONTACTS

4.1 Building Research Institute, Japan

Dr Yuji Hasemi,
Head, Fire Safety Section.

In response to a request for information, Dr Hasemi provided five research papers and a report (in Japanese) of a Tokyo Fire Agency investigation into a fire that occurred in a warehouse (Shinko Kairiku Transport Warehouse) in 1977. This has been translated by the FEU (Reference 18).

The Shinko Kairiku Transport Warehouse was a temperature controlled building with an internal lining of exposed polyurethane insulation. During construction work a fire occurred which featured several explosions injuring 21 workers and firefighters. A detailed investigation, including small scale experiments, attributed the explosions to the products of the thermal decomposition of the lining material accumulating in the warehouse and encountering an ignition source. Preceding the explosions yellowish smoke was seen swirling around inside the warehouse.

The events correspond to the description of backdraught given in Section 3.3 however the production of un-burnt pyrolyzates was not found to be due to poor ventilation of the compartment but to inefficient combustion of the wall lining material. A similar event has been reported in a disused cold storage warehouse in the U.K. in 1984 (References 19,20).

The other papers supplied by Dr Hasemi are referred to in Section 5 or listed with the additional material.

4.2 National Institute of Standards and Technology, Washington, USA

1993 Annual Conference on Fire Research
18-20 October 1993

The Annual Conference on Fire Research organised by the Building and Fire Research Laboratory (BFRL) of the National Institute of Standards and Technology (NIST) provides an annual forum for the discussion of NIST research, both internal and extra mural. Its emphasis alternates on a two yearly basis between applications and fundamental research. The 1993 conference was directed to the application of research. This was used to assess the current research activity in the USA relating to backdraught and the awareness of researchers to the problem.

Only one NIST funded project is currently active directly concerning backdraught, this is under the supervision of Professor Pagni at the University of California (Berkeley)

(Reference 16, Appendix B). During the course of this survey no reference to any other current research directly addressing backdraught has been encountered.

Other work on incomplete/inefficient combustion and compartment fires is, however, relevant to the conditions that can lead to a potential backdraught scenario (e.g. Reference 21). Positive pressure ventilation (PPV) (Reference 22), a technique that may be employed to reduce or remove the risk of a backdraught, was also presented.

Discussion with delegates revealed a general understanding that the term backdraught referred to the introduction of air to an oxygen starved fire in a compartment and the subsequent violent event if ignition occurs. This is known to be different to flashover.

4.3 University of California, Berkeley, USA

Professor Pat Pagni
Dr Charles Fleischmann
Professor Brady Williamson

Fleischmann has just completed a PhD Study of the phenomenon of backdraught and the details are presented here in Section 5.1.4. Further study awaits new funding. Papers describing the backdraught experiments, a salt water model of the various hydrodynamic processes and some numerical modelling are in preparation and are at various stages of the publication process.

4.4 University of Lund, Sweden

Professor Sven Eric Magnuson
Dr Göran Holmstedt

The Department of Fire Safety Science at the University of Lund are providing a greater scientific content to the courses given to Swedish Fire Service personnel by the National Rescue Service. They have had problems introducing this input to the previously used experienced-based approach, especially that originating from Giselsson whose book, with Rosander "Fundamentals of Fire" (Reference 4) offers pseudo-scientific explanations of some fire events which are misleading. Many of his practical approaches are however sound but poorly described. Section 7 reviews some of these concepts that relate to flashover and backdraught. In addition Appendix C attempts to clarify some of his work relating to indirect fire fighting.

The Department is working closely with the Technical Research Centre of Finland (VTT), to evaluate the proper use of the "flashover training containers" to be described in Section 4.5. This is being done by undertaking experimental measurements in containers and comparing results with predictions from a computer fire simulation model. This model, known as the Fire Demand Model (Reference 23), is a one zone post-flashover, fully developed fire model which enables water demand to be assessed taking into account effects such as evaporation and extra air entrainment due to fire fighting water sprays.

The Department is not conducting research into backdraught and are not aware of any such research in Sweden. It is however conducting work on under ventilated fires similar to that ongoing at the Fire Research Station to improve theoretical modelling treatments of carbon monoxide yield (Reference 24).

4.5 Stockholm Brandförsvar, Sweden

4.5.1 "Flashover" Training

A theoretical foundation, currently based on the work of Giselsson is developed by the Swedish Fire Service using small scale demonstrations and large scale fire fighting exercises conducted in shipping containers. This is intended to explain to firefighters various events which are described as types of flashover. This is included in a 15 week course for new firefighters. The Stockholm Fire Service have access to at least three containers of similar design at different locations. In addition containers are located at each of the four National Rescue Service sites in Sweden.

The small scale laboratory demonstrations begin by heating some small pieces of wood in a flask and igniting the gases given off to illustrate that "smoke can burn". The fire triangle is referred to and it is emphasised that fuel, air and heat must be present in the correct proportions for successful combustion.

The theoretical discussion (Section 7) and demonstration of "flammable smoke" are reinforced (Reference 25) by using a small tank (referred to as a "Giselsson box") to demonstrate the presence of flammability limits of gas/air mixtures. The tank, measuring approximately 0.5m wide, 0.7m long and 0.5m high is constructed from a metal frame holding 6mm thick laminated glass on three sides. The forth side has a opening which can be sealed with a sliding cover. The top of the tank has four opening flaps which act as pressure relief vents. A solid base contains a mixing fan, propane supply and supports electrodes for a spark igniter. The gas supply and ignition spark are controlled remotely by the instructor using a small hand held unit. While gas is being supplied a display at the front of the tank records time. This display is calibrated to show the times to reach the lower and upper flammability limits in the tank.

Four demonstrations are conducted:

1 The tank is filled with propane with the spark operating. An explosion occurs when the lower flammable limit of the mixture is reached. This is said to be a "lean flashover".

2. A much more violent explosion is achieved by filling the tank to an approximately stoichiometric mixture before operating the spark.

3. A "delayed flashover" is achieved by placing a compartment wall around the spark so that lean ignition inside the compartment ignites a much richer mixture outside.

4. A rich mixture is created and the spark started. The vent on the side of the tank opened and air wafted in. The resulting explosion is presented as an illustration of a "rich flashover".

These "flashovers" are related to the behaviour of fires in compartments using the theories of Giselsson and Rosander which are discussed in Section 7.

Realistic, full scale, training is conducted in shipping containers 12m long, 2.5m wide and 2.5m high (Figure 1a). One end has a set of doors. At the closed end a fire is built on a raised platform using scrap timber. Sheet chipboard is used to construct a ceiling and combustible walls next to the fire. There is a ceiling vent (0.5m by 0.5m) which can be operated from inside the container. The exercises are introduced by descriptions of the use of the "Fogfighter" branch (Reference 26) to provide direct, indirect and offensive applications of water (Section 7).

Two lines with "Fogfighter" branches are used, one for the instructor, the other for the trainees. These are supplied by separate pumps. Various exercises can be performed increasing the severity of the fire as the skill of the trainee develops. The fire may be held at the onset of flashover (as defined in Section 3) by using the offensive technique to cool the hot gases and reduce the radiative feedback to the fuel. A potential backdraught scenario, referred to as a "rich flashover", is created by closing the container doors and allowing the fire to become ventilation controlled. The offensive technique is used to cool the gases so that the doors may be safely reopened. No intentional demonstration of "rich flashover" (backdraught) is provided, but there is clearly the potential for a serious accident involving such an event.

These containers are also used in Sweden to build complexes for search, rescue and fire fighting exercises. Several interconnected levels, including vertical shafts and underground sections may be employed. This provides an inexpensive training facility.

During the training the importance of suitable clothing and the maintenance of body fluids is stressed.

4.5.2 Comments

The use of the small scale demonstrations to provide a link between a theoretical understanding of fire behaviour and the mechanism of fire fighting techniques is effective. However there are over-simplifications and omissions due to Giselsson and Rosander's theoretical foundation which must be corrected. The University of Lund is currently undertaking this task. Section 7 examines the concepts of Giselsson and Rosander regarding backdraught and flashover.

When demonstrating that "smoke can burn" no distinction is made between products of pyrolysis and products of combustion. A discussion of diffusion flames, premixed flames and combustion efficiency is required to indicate the proportions of pyrolysed product which are consumed and the different gas mixtures that are found at different locations in a flame. This would lead to a better understanding of the conditions which can lead to a fire burning inefficiently causing an accumulation of un-burnt pyrolisation products and partial combustion products in a compartment.

The tank demonstrations are clearly not flashovers as defined in Section 3.2 but are transient events - gas explosions. The sequence of demonstrations is effective in showing the existence of upper and lower flammability limits and the relative severity of the resulting explosions which could occur with different mixtures. The final demonstration with the rich mixture is similar to the backdraught experiments conducted by Fleischmann to be described in Section 5.1.4.

VTT Finland (Reference 27) have conducted detailed measurements of fires in a similar container system and a reduced scale model. This simulator uses two small containers, one for the fire compartment, the other as an observation room (Figure 1b). The only internal difference to the Stockholm simulators is the height between the base of the fire and the ceiling which is greater in the case of the VTT system. This will lead to greater entrainment in the fire plume and slightly lower gas layer temperatures using the VTT configuration. The VTT simulator is instrumented with thermocouples, heat flux meters and provision for gas analysis. They have concluded that a flashover (as defined in Section 3.2) must be avoided in these systems and that the fire should only be allowed to develop slowly so that it is always under control. The skill of the instructor is critical for safe use.

4.6 Essex County Fire and Rescue Service

Station Officer John Smith

The Essex County Fire and Rescue Service have built a container fire simulator for advanced firefighter training following the Swedish design using a single container. The objective of the training offered is to expose trainees to realistic fire conditions and to demonstrate offensive fire fighting using equipment supplied to the U.K. Fire Services, but not including hose reels. The "Fogfighter" branch is not included.

Trainees lay on silhouettes painted on the floor of the container and watch demonstrations of fire fighting techniques conducted by the instructor and experience realistic fire conditions. Fire fighting by the trainees in the container is being considered as a future development.

The fire is arranged differently to the Swedish systems. Chipboard offcuts are used to form a wall and ceiling centred at the end wall instead of using sheet material in the corner. This is largely due to the availability of fuel. The fire is not built on a platform. Unlike the Stockholm systems, the Essex County Fire and Rescue Service simulator is equipped with some instrumentation. Four thermocouples are located in the container and temperatures logged each time the container is used.

This instrumentation is used to provide those outside the container with an indication of conditions inside so that backup can be provided to the instructor if required. These data are used to assess repeatability between sessions and to provide a record which can be used for subsequent discussion with the trainees.

Thermocouple temperatures (close to the wall) of 500°C at high level and 90°C at low level have been recorded. Flames can extend along the length of the ceiling of the container.

4.7 H.M.S. Phoenix, Portsmouth

Lieutenant Commander Kite
Lieutenant Commander Bamforth

The Royal Navy Fire Fighting School, H.M.S. Phoenix, provides several training courses for all those personnel who go to sea. There is a two day initial course, a three day advanced course and a further five day course. Each vessel should have at least one crew member who has attended the five day course. Each crew member of a Royal Navy vessel is seen as a potential firefighter and on discovering a fire is expected to raise the alarm and, if safe to do so, begin to fight the fire. Raising the alarm will initiate a pre-attack plan which provides suitably dressed crew members as a fire fighting team and additional members to contain the fire and attend to matters such as the removal of excess water.

A booklet (Reference 28) is provided to all personnel on the initial training course which details the techniques, equipment, deployment of personnel and any interaction with a local authority Fire Service.

The Royal Navy employ a technique which involves the use of a "waterwall". This is a 180° spray delivered at high pressure (supplying 27 tonnes/hour, 440 litres/minute) blocking any inflow or outflow from the compartment. This is used as a protective wall by the firefighters. A water jet or foam stream can be applied through the waterwall to fight the fire. Some hatches are equipped with waterwall nozzles which can be put to use while the fire fighting team is being assembled. The leader of the fire fighting team will have access to thermal imaging equipment to locate the fire.

Practical training takes place on structures representing the cross-section of a ship. Exercises may include more than one fire source. The trainees will have to attack the fires either vertically or horizontally.

A "waterwall" would prevent the ingress of air which could create the conditions for a backdraught to occur. Although an attractive fire fighting technique in these circumstances, the high pressure water delivery may damage some forms of building construction and the water supply requirements may be impractical on shore.

4.8 Other Contacts

During the course of this survey the topic of backdraught has been discussed with a variety of workers who have a knowledge in the field. In addition to current and former FRS staff and delegates to the NIST conference, these have included authors of recent contributions. For example, SO John Taylor of the North Yorkshire Fire and Rescue Service and Paul Grimwood of London Fire Brigade and contributor to the journal "Fire".

In addition John DeHaan a fire investigator for the Office of the Attorney General in California USA and author of "Kirk's Fire Investigation" was able to confirm, at an early stage of the project the difference between backdraught and flashover, but felt the difference between a backdraught and smoke explosion was not significant to a firefighter.

5. CURRENT KNOWLEDGE RELATING TO BACKDRAUGHT

5.1 Fire Science

5.1.1 General

To gain an insight into the backdraught phenomena it is necessary to examine how the conditions for a backdraught to occur may be created and the various sudden changes that can happen during the course of a fire. This section describes under-ventilated fires (which can create the atmosphere required for a backdraught) and a quasi steady-state analysis which can show several mechanisms which will lead to a flashover and indicate the potential for a backdraught.

5.1.2 Ventilation Controlled Fires

Under "ideal" conditions, as a fire burns all the pyrolysis products from a fuel surface would be completely oxidised during a chain of exothermic combustion reactions. Some of the heat released will maintain the pyrolysis of the fuel and the rest will be convected away with the combustion products and surplus entrained air or be lost by radiant heat transfer. However these "ideal" conditions of completely efficient combustion cannot be achieved. Some of the pyrolysis products will remain un-burnt and some of the combustion reaction chains may stop before complete oxidation is achieved. The hot gases leaving the fire plume will always contain some un-burnt pyrolysis products and partial combustion products. Reducing the amount of oxygen available to the fire will increase the quantities of these products and limit the heat release rate.

In a compartment the oxygen supply to a fire may be reduced either by restricting the total fresh air supply to the compartment or the local supply to the fire.

The total supply of air will be controlled by the openings to the compartment if these are small then not all of the hot gases will be able to leave the compartment and will be recirculated through the fire. This will dilute any available fresh air and reduce the concentration of oxygen in the gases entrained into the fire. This has been studied for many years and there are well known relationships for such circumstances relating rate of heat release, or burning rate of the fuel to the size and shape of the opening e.g.

$$M_b = 5.5 A\sqrt{H} \text{ kg/min}$$

where M_b is the mass burning rate of the fuel, A the opening area and H the height of the opening. (Reference 9)

A fire against a wall or in a corner entrains less air than it would away from walls because of local restrictions to the availability of oxygen. Flames will lengthen to compensate for this deficiency. If there is insufficient height available for additional entrainment then the excess pyrolysed fuel may accumulate in the hot gas layer.

The accumulation of un-burnt pyrolysis products and partial products of combustion in an under-ventilated compartment can lead to conditions where a backdraught could occur when the compartment is opened.

Both mechanisms to reduce the oxygen supply to a fire and the subsequent accumulation of un-burnt pyrolysis and partially oxidised combustion products are the subject of current research (e.g. at FRS, Reference 24). This research is primarily directed to providing an understanding of the factors affecting the production of carbon monoxide and other partial combustion products to provide a better understanding of various fire tests (Reference 29) and to guide the development of mathematical models (Reference 30). Such research will also assist in providing an insight into how a potential backdraught scenario can occur.

Other studies of poorly ventilated rooms have observed "ghosting" flames (Reference 31). These leave the fuel source to move around the compartment burning where the fuel-air mixture is favourable. Poorly ventilated fires are also known to pulsate (Reference 32). These have been reported as warning signs of a potential backdraught.

5.1.3 Thermal Instabilities - A Quasi-Steady Analysis

Several mechanisms for the sudden change of heat release rate from a fire can be explained in terms of thermal instabilities in a quasi-steady state analysis. For a fire in a compartment containing a ventilation opening, a heat balance may be stated to be : "the heat gained by the gases in the room is equal to the difference between the heat released by the fire and the heat losses through the opening and conducted away through the walls". If any changes can be considered to occur slowly, then the temperature of the gases in the compartment can be considered to be quasi-steady for a short interval of time and the heat balance simply stated by equating the heat loss, $L(T)$, to the heat gain $G(T)$.

$$L(T) = G(T)$$

This quasi-steady approach was considered in detail by Thomas (Reference 33) and others (Reference 34) and has been recently revisited by Beard et al (References 35,36) drawing on modern mathematical developments in non-linear dynamics.

Although the analysis does not directly address any of the transient processes, some insight into the conditions leading to a potential backdraught and its severity can be gained.

i. Heat Release Rate

The heat release rate of a fire in a compartment may be related to the compartment temperature as well as thermal feedback from its flame. A simple model has been described by Thomas (Reference 33) which relates this heat release rate to the compartment temperature through the radiative heat flux incident on the fuel. A further assumption (which is reasonable for liquid fuels) is that all the incident heat at the fuel surface vaporises the fuel which can then be burnt, depending on the availability of oxygen. In such a case the heat release rate, while the fire is fuel controlled, $G(T)_{fuel}$, may be written as :

$$G(T)_{fuel} \propto (T^4 - T_f^4)$$

Where T is the compartment temperature. (K)
and T_f the fuel surface temperature. (K)

Hasemi (Reference 34) uses an exponential expression to relate the reaction rate, and thereby the fire heat release rate, to compartment temperature in his development of this quasi steady analysis. It is sufficient here to show that while the fire remains well ventilated the heat release rate is strongly dependent on the temperature of the compartment.

If the compartment is poorly ventilated then the heat release rate of the fire becomes limited by the amount of air which can react with the fuel. The heat release rate of the ventilation controlled fire, $G(T)_{air}$, is then :

$$G(T)_{air} = \frac{\chi m_a}{r} H_c$$

Where χ	combustion efficiency
m_a	mass flow rate of air to the fire (kg/s)
r	stoichiometric mass ratio
H_c	heat of combustion of the fuel (J/kg)

By using Bernoulli's relationship, the fire-induced flow rate of air into an enclosure through a door or window is often expressed as :

$$m_a = 0.67\, CW\rho_o \sqrt{2g\frac{T_o}{T}\left(1-\frac{T_o}{T}\right)}\ (H-H_n)^{1.5}$$

Where	C	Opening discharge coefficient
	W	Width of opening (m)
	H	Height of opening (m)
	H_n	Height of clear layer in compartment (m)
	T_o	Ambient temperature (K)
	r_o	Ambient air density (kg/m^3)
	g	Acceleration due to gravity (ms^{-2})

The general heat gain rate to the compartment is thus:

$$G(T) = \min\left(G(T)_{fuel} , G(T)_{air} \right) + G_o$$

Where G_o is the heat release rate of the fire at ambient temperature required to provided sustained ignition.

A schematic representation of the heat gain, G(T), is provided on Figure 2.

ii. Heat Loss Rate

The heat lost from the compartment will be conducted through the walls, lost by convection through the opening with the escaping hot gases and radiated out through the opening. Thomas et al (Reference 33) combine these losses and show that they may be approximated as being proportional to the temperature difference between the compartment gas temperature and ambient, i.e. :

$$L(T) \propto (T-T_o)$$

Where To is ambient temperature. (K)

A schematic representation of L(T) is provided on Figure 2.

The constant of proportionality is dependent on the compartment wall temperature, as the wall temperature increases during a fire the slope of L(T) will decrease as indicated on Figure 2.

iii. Thermal Equilibrium and Instabilities

Figure 2 shows three intersections between the heat loss and heat gain curves, **A**, **B** and **C**. These represent solutions of the steady state condition where :

$$L(T) = G(T)$$

The points **A** and **C** are stable solutions and represent fuel and ventilation controlled equilibria respectively. A small increase in compartment temperature while the fire is at state **A** will result in the heat losses exceeding heat gains which will tend to restore the temperature to the value at point **A**, a decrease in temperature would make the gains greater than the losses and also restore the temperature to **A**. Small Temperature changes while the fire is at the ventilation controlled state **C** have a similar effect restoring the temperature to that corresponding to point **C**.

The solution at **B** however, is unstable. A small increase in temperature from point **B** will lead to the heat gains exceeding the heat losses and the temperature increasing until the stability point at **C** is reached. Conversely a small decrease in temperature from **B** will make the losses greater than the gains and the temperature will fall to point **A**.

Point **A** or point **C** will therefore represent the temperature and heat release rate conditions of a fire in a compartment unless the curves change (for example by changing the ventilation) or a large change in temperature can be induced.

Figure 3 provides an illustration of one way in which flashover (as defined in Section 3.2) may occur. The curves L1 to L3 correspond to the heat loss rate function for different (increasing) compartment wall temperatures. As the fire develops the wall temperature increases, the heat losses decrease corresponding to a change in the loss curve from L1 through to L3. The compartment temperature (represented by the stability point **A**) increases and when the loss rate curve reaches L3 the solutions **A** and **B** coincide. This point is unstable and the fire heat release rate will jump to the stable ventilation controlled point **C**. This jump in temperature and heat release rate constitutes a flashover.

A flashover may also be induced by increased ventilation. Figure 4a shows two levels of ventilation control. Initially the lower ventilation, represented by the curve $G(T)_{closed}$ (corresponding to small openings in the room) applies and the fire reaches a ventilation controlled stability point **X**. The ventilation is increased to $G(T)_{open}$ (a door or window is opened) and the heat loss rate will increase to L_{open}, since more heat can be convected through the opening. There will now be a flashover, from **X** to **Y** as indicated by the jump on Figure 4a.

Prior to the change in ventilation the fire will have been pyrolysing more material than can be burnt. This excess pyrolyzate is represented by the unreleased energy associated with the difference between $G(T)_{fuel}$ and $G(T)_{air}$ at the temperature **X**. This production rate of un-burnt pyrolysis products could be used to estimate the concentration in the room and the potential energy release during a backdraught.

It should also be noted from Figure 4b starting from the same closed room stability point **X** as in Figure 4a then if there is a very much larger change in the heat loss rate corresponding to the change of the ventilation condition, say to L_{open}, then the jump on Figure 4b will be to the stability at **Z** resulting in a fall in temperature. This would represent a successful attempt to ventilate the fire. The potential for a backdraught is still present being again represented by the difference between the two energy release curves.

Figure 5 provides a simple illustration of the quasi-steady model applied to a practical problem. Consider a room 3m high, 4m wide and 5m deep with a single door 2m high with an open width of 1.0m. The potential fuel in the room is polyurethane furniture (heat of combustion (H_c) 30MJ/kg, heat of vaporisation (H_v) 0.5MJ/kg, stoichiometric ratio (r) 10) and the heat transfer coefficient for the walls is taken to be $50W/m^2/K$. For five wall temperatures between ambient, 300K, and 500K, corresponding to different times during the development of the fire, heat loss curves, L(T) has been calculated. Figure 5 shows these heat release rate, G(T), and loss rate, L(T), curves. The lower fuel-controlled equilibrium point, **A**, indicates a layer temperature rising to about 700K with increasing wall temperature. At this point an instability condition is reached and there is a transition to a ventilation controlled equilibrium at about 1200K. This represents a flashover. The low temperature in this example is due to the idealised material properties selected.

iv. Potential for Flashover and Backdraught

There have been many studies of the well ventilated fire and its transition to a fully developed, ventilation controlled state involving all the exposed fuel in the compartment (e.g. Reference 37). In addition to the definitions and descriptions given in Section 3.2, flashover is often identified with a hot gas layer temperature of approximately 550°C when a blackbody emitter of infinite area would cause a radiant intensity of 30 Kw/m^2 (Reference 9) at floor level (these values are related by $I=\sigma T^4$ where T is the absolute temperature, σ the Stefan Boltzman constant $5.669x10^{-8}$ W/m^2K^4 and I the radiation intensity). This intensity is sufficient to support ignition of most materials.

The quasi-steady approach does not specifically address how the transition between two of the stable states occurs or any transient events, such as backdraught, which may occur during a fire. However it can assess the possible conditions in a compartment before and after such events as well as estimating the potential energy which can be released in any backdraught.

5.1.4 Backdraught

There is only one group currently conducting direct research into the backdraught phenomena. Fleischmann et al (References 12,38) at the University of California (Berkeley) have adopted a simple compartment scenario so that the phenomenon can be made amenable to scientific study. They have conducted backdraught experiments in a half scale domestic room and supplemented these with both salt-water and computational fluid dynamics (CFD) numerical simulations of the hydrodynamic mixing processes between fuel and air that may occur on the sudden opening of a vent. The inflow of air to a compartment of hot products from an oxygen starved fire is driven by the density difference between the gases inside and outside the compartment. The resulting "gravity current" is well known from studies in other fields such as oceanography and is considered to be important in determining the delay between venting a fire and any subsequent backdraught.

i. Experimental Study

The group use an experimental compartment measuring 1.2m by 1.2m by 2.4m, representing a half scale domestic room, designed to withstand repeated backdraughts. A diagram showing the apparatus and instrumentation is shown in Figure 6. One long side is arranged to act as a pressure relief vent operating at 600Pa. The opposite side is an observation window made of Neoceram (Nippon Electrical Glass Co.), a transparent ceramic capable of enduring continuous exposure to 1000K. The walls, ceiling and floor are made of gypsum wall board covered with 50mm thickness of refractory fibre blanket. One of the short walls contains an opening covered with a computer-activated hatch. This could be configured as a door or window opening of different sizes. Inside the compartment, against the wall opposite the hatch is a 0.3m by 0.3m methane burner. A pilot flame was used to ignite the burner. A small, 0.1m diameter vent was kept open while the burner was lit to prevent the initial pressure pulse at ignition operating the pressure relief vent. A spark igniter for the backdraught was located 0.45m above the floor at the burner location. This provided a continuous spark when operating.

The apparatus is controlled by computer with a remote override system. The operation sequence is to light the burner, close the small vent after 15 seconds, then to supply fuel to the burner for a preset duration. Five seconds after the supply to the burner was stopped the hatch was released. The ignition spark was either left running for the full duration of the experiment or started at a specific time after the hatch is opened.

Data were collected from a thermocouple tree, bi-directional velocity probes with adjacent thermocouples and gas analyzers for concentrations of oxygen, carbon dioxide and total hydrocarbon. A scanning rate of 10 scans per second was used until 20 seconds prior to the hatch opening when it was increased to 50 scans per second. Between 4 and 10 Mbytes of data were collected for each experiment.

Over one hundred experiments have been conducted to characterise the conditions in the compartment prior to the backdraught and to quantify the severity of the event. Much of these data are still to be processed.

As the fire proceeds and oxygen is consumed "dancing flames" were seen in the compartment for a short time and the fire pulsed just before extinction. The "dancing", or "ghosting" flames occurred when the ignition spark was left running throughout the experiment. The backdraught deflagration in the compartment occurs either along the interface or through the whole volume of mixed air and flammable gases. Burning along the interface resulted in the larger external fire ball (approximately 4m diameter compared to approximately 2m diameter). The "dancing" flames were thought to cause large thermal instabilities in the compartment increasing the mixing of fuel and air. For the methane burner it was found that an un-burnt hydrocarbon concentration in excess of 10% was required for a backdraught to occur.

ii. Salt Water Modelling

To help clarify the factors controlling the speed at which the gravity current flowing into the compartment would propagate. A series of experiments using flows of fresh and salt water were conducted (Reference 39). The higher density salt water is used to represent ambient air and lower density fresh water representing hot gases. The fresh water was retained in a compartment inside a larger tank representing a room filled with hot gases. This compartment had an opening of variable geometry. The compartment was 1/8 scale model of the backdraught apparatus. The pH of the salt water was increased by the addition of sodium hydroxide and an indicator (phenolphthalein) added to the fresh water. As the fluids mix the indicator changes to a red colour allowing the flow to be visualised. Since the flow is three dimensional, a 45° mirror was placed above the immersed model compartment so that both plan and elevation views could be recorded simultaneously by a video camera.

iii. Numerical Modelling

A two dimensional, direct simulation computational fluid dynamics model was also used to examine the detailed progress of the gravity current (Reference 40). This model provides a numerical simulation of the salt water model rather than the backdraught experiments since no account was taken of the combustion reaction. Predictions were in good agreement with both the salt water and backdraught experiments both in qualitative behaviour and for the time for the gravity current to reach the far side of the compartment. Some results from the numerical and salt water modelling are shown in Figures 7a and 7b respectively.

iv. Previous Work

An investigation following the 1974 explosion at Chatham Dockyard is often referred to (e.g. Reference 15) when discussing the warning signs of a potential backdraught. A smouldering fire in some latex rubber mattresses filled the building with flammable pyrolysis products. An explosion occurred killing two firefighters as air was introduced into the building while ventilating the smoke. A series of tests showed that the latex rubber material could be made to smoulder and produce a flammable, cool grey smoke (Reference 41).

5.2 Fire Fighting

5.2.1 General

If a backdraught, or other sudden transient event occurs there will be little the firefighter can do to prevent its progress, however there are widely reported warning signs related to the behaviour of a fire in an under-ventilated compartment and actions which may be taken that can reduce the risk of a backdraught or mitigate its effects. Dunn (Reference 42) compares the hazard to that of a potential explosion and discusses containment, quenching, isolation, removal and venting (providing means of relieving the pressure).

Before any action can be taken to prevent a backdraught its potential must be realised.

5.2.2 Warning Signs

The warning signs of a potential backdraught are listed by several authors (References 17,42,43).

Before opening a door or window to the compartment, the firefighter should be aware of :

Fires in securely closed premises: If the building is secured against intruders it may also be poorly ventilated in the event of a fire until the building is opened for access. There is the potential for an accumulation of pyrolysis products. Fires in concealed spaces (e.g. ceiling voids) may also present the same problem.

Oily deposits on windows : Pyrolysis products may condense on cooler surfaces such as windows providing an indication of a ventilation-controlled fire.

Hot doors and door handles : The Manuals of Firemanship (Reference 44) stress the importance of checking whether doors or door handles are hot before a door is opened. This also applies to windows.

Pulsating smoke from openings : The pulsation of smoke through small cracks and openings and rattling of windows can be due to the pulsation mechanisms of an oxygen-starved fire or possibly the turbulent mixing created by ghosting flames.

When inside, or looking into a compartment a potential backdraught may be indicated by :

Blue flames : Grimwood (Reference 17) and Yu (Reference 43) attribute the observation of blue flames to the burning of carbon monoxide from incomplete combustion. They may also be related to the "ghosting" or "dancing" flames reported earlier. Both explanations indicate the presence of un-burnt pyrolysis products and a potential backdraught scenario.

Smoke drawn back through opening : This may be an indication that a gravity current is in progress. Hot smoke will be leaving at high level, possibly through a different opening, and replacement air being drawn in to the compartment will change the local direction of smoke movement. When ventilation of the fire is first instigated, smoke at low level may move toward the fire carried by the gravity current.

Whistling and roaring sounds : These are sometimes referred to as a warning of a backdraught. A roaring sound while the backdraught is in progress has been referred to in several incidents (References 18,19). Although too late for those directly involved to take action it will alert others that something has occurred. Whistling sounds may be due to air moving at high velocity through small gaps.

In addition :

The colour of smoke : This is often referred to, however several colours are mentioned depending on the type of fuel. For example thick black smoke is associated with un-burnt hydrocarbons, yellow smoke with nitrous and sulphurous polymers and cool white smoke with smouldering latex foam. Since the smoke may be viewed at night with a variety of street lighting and other illumination sources it may be difficult to make a reliable assessment based on colour alone. Some knowledge of the building contents would also be required.

These warning signs must be considered in the context of the specific scenario encountered and excessive weighting should not be given to any single sign. Encountering several of these signs together however would give a strong indication of a potential for a backdraught.

5.2.3 Venting

Although venting is intended for removal of smoke and un-burnt pyrolysis products from the compartment, it will also provide pressure relief should a backdraught occur. Venting as a fire fighting tactic to limit fire spread, as distinct from ventilation to clear smoke, is an accepted practice in some fire services (USA, Sweden), but due to differing building construction may not be appropriate in the United Kingdom. This is the subject of a separate survey. A compartment which has been apparently successfully vented should still be treated with caution as pockets of un-burnt pyrolysis products may be retained in concealed spaces such as ceiling voids or other sub-compartments.

5.2.4 Application of Water

Indirect and offensive application of water can be used to cool and reduce the flammability of fire gases.

The indirect technique is outlined by Grimwood (Reference 17). A water spray is applied to hot surfaces where the steam dilutes the atmosphere on evaporation causing the gas mixture to fall below its lower flammability limit. This requires skilled application so that the temperatures of the hot surfaces do not fall below 100°C when the applied water will not vaporise. Caution is required to avoid injury in the scalding environment that is produced. The generation of steam may create a positive pressure inside the compartment and force the hot gases out through the openings made for access of firefighters. Giselsson (References 26,45) presents a calculation to show that an application rate of 0.1 litre per square metre of compartment surface is sufficient and may be achieved with quick sweeps of a wide angle spray branch with a supply rate of 75-100 l/min. This calculation has propagated through several sources in an incomplete form with some errors - a corrected version is given in Appendix C.

The offensive technique is to deliver short bursts of a fine water spray into the gas layer to cool it. The objective is to create a high heat transfer from the hot gases to the very large surface area of water created by the fine spray. The hot gases contract rapidly as they cool. The pressure in the compartment falls and air enters at low level creating a clear layer. This is considered further in Section 7.

It is possible to draw air into a smoke layer using a water spray. If the spray is operated from outside the compartment then oxygen could be "pumped" into the fuel rich atmosphere possibly inducing a backdraught. If the branch is used inside the compartment any air moved by the spray will originate from inside the compartment and no extra oxygen will be entrained endangering backdraught.

6. THE PHYSICAL AND CHEMICAL PROCESSES

6.1 General

This section examines the basic mechanisms which can involve a sudden change in the heat release rate of a fire in an enclosure and then specifically considers the sequence of events which happen during a backdraught and a flashover.

These sudden changes can be divided into step events where the heat release rate of a fire reached during the change is sustained and transient events when the heat release rate returns to (approximately) it original value. This study has identified seven ways in which a sudden change may occur. Four of these are step events representing transitions between fuel and ventilation controlled states and the remaining three are transient events corresponding to one of the components of the fire triangle (oxygen, heat or fuel) suddenly becoming available.

These events may occur relatively slowly and be perceived as simply a phase of fire growth, or under some conditions they may occur explosively. In some cases the heat release rate of the fire may decrease. This condition is valuable when venting a fire.

6.2 The Step Events

The heat release rate of a fire is either controlled by the supply of fuel or the supply of air. Therefore in principle four transitions are possible :

Fuel supply control	to	New fuel supply control
Fuel supply control	to	Air supply control
Air supply control	to	New air supply control
Air supply control	to	Fuel supply control

In each of these cases the new fire size is sustained. The event defined as flashover in Section 3.2 is usually a step from fuel control to air supply control although as presented in Section 5.2.3 it can also occur by increased ventilation. When the change is from an air controlled state (such as a fire in a poorly ventilated room) there is an added hazard created by any accumulated pyrolysis products which may burn during the transition, in some cases this could be manifest as a backdraught.

6.3 The Transient Events

6.3.1 General

These are short, possibly violent, releases of energy from the fire which are not sustained.

6.3.2 Adding Fuel

In a fuel controlled state the sudden addition of fuel to the fire will cause an increase in the overall heat release until that new fuel is consumed. This could, for example, be due to the rupturing of a container containing a flammable liquid or gas and its subsequent ignition by the original fire. If the fire is ventilation controlled, the addition of extra fuel in such a manner may have little noticeable effect. However the concentration of flammable components in the vitiated atmosphere will increase the potential of a backdraught should there be a later sudden addition of air by, for example, venting.

6.3.3 Adding Air/Oxygen

This would usually be caused by the deliberate or accidental opening of a door or window to a room containing a fire. If the fire is fuel controlled then it will already have an adequate supply of air and the additional opening may serve to ventilate the compartment, cool it and thereby reduce the fire size. Conversely if the fire is ventilation controlled, not all the pyrolysis products from the fuel will have been burnt and may have accumulated in the compartment. The addition of air may allow these gases to burn off, possibly explosively. Backdraught is a variant of this mechanism.

6.3.4 Adding Heat

Fuel rich fire gases from a ventilation controlled fire may be able to leave the original compartment and travel through a building to other compartments mixing with 'fresh air' forming a mixture within flammable limits. If the location of this mixture coincides with a source of heat (flame, spark or glowing ember) to provide ignition then an explosion could occur.

6.4 Sequential Events

It is possible for transient and step events to occur sequentially or at the same time. For example opening a door to a room containing a ventilation controlled fire which has been producing volatile gases for some time may result in a backdraught burning off the excess pyrolyzates followed, probably quite rapidly, by the original fire growing over the solid phase fuel surfaces until it is limited by the new ventilation opening.

6.5 Backdraught: A Basic Scenario

6.5.1 General

Backdraught is a special case of the transient event where air is introduced into an enclosure containing an under-ventilated fire.

6.5.2 Creating the Conditions for a Backdraught

Consider a small room, the doors and windows are closed and there is only a small air supply due to leakages, air bricks etc. There is a fire in the room. This scenario may have come about either by an occupant closing a door on discovery of a fire or a fire starting in the closed room. The fire grows and consumes oxygen. At first it burns efficiently, but the products circulate in the room, and after some time the air being drawn into the fire contains these products and is deficient in oxygen. The combustion is less efficient and some of the pyrolysed fuel together with potentially flammable products from the partial combustion (carbon monoxide, un-burnt hydrocarbons) mix into the atmosphere. As time progresses further the atmosphere in the room contains less oxygen and more flammable gases. The original fire will die down and may go out as the combustion reactions cannot be supported by sufficient radiant heat feedback from its own products of combustion. Residual heat in the fuel source may however continue to pyrolyse the fuel increasing the concentration of flammable gases. During this stage smoke will exit from openings due to the positive pressure created by expansion of the gases in the room.

With a reduced heat source the room will begin to cool, this will cause the gases to decrease in density and a negative pressure to occur drawing air in at the openings. It is possible for this to cause the original fire to flare up (depending on its position relative to the opening) and a pulsation cycle to ensue.

Other mechanisms may lead to an accumulation of un-burnt pyrolysis products in an enclosure. For example smouldering or the burning of a fire which, due to the configuration of fuel, cannot entrain enough air to support complete combustion of the pyrolysis products.

6.5.3 Increasing Room Ventilation

Some time later either a door or window is opened, this may be by firefighters entering the room or from the failure of a window due to thermal stress. Hot buoyant gases will leave the room at the top of the opening and cold, fresh air will replace it at the bottom. Initially this flow will be local at the opening but the disturbance will propagate deeper into the compartment, its progress being hindered and mixing enhanced by obstructions in the room. This mixing will create mixtures within the flammable range as the un-burnt pyrolysis products are diluted.

6.5.4 Ignition in the Room

If gases within the flammable range encounter an ignition source of sufficient energy such as a flame, spark or glowing ember then the mixture will ignite. This combustion will heat the gases in the compartment causing them to expand and raise the pressure in the room.

6.5.5 Backdraught

This pressure rise will force the burning gases in the compartment out through the opening with a high velocity, possibly igniting some of the un-burnt pyrolyzate that had already left the compartment. This can create a significant fire-ball outside the compartment.

6.5.6 Post Backdraught

After the backdraught event fire growth in the room may resume until limited by the availability of fuel or supply of air through the increased opening.

6.6 Flashover : A Basic Scenario

6.6.1 Creating the Conditions

Consider again a fire in a small compartment, however this time the door is open and the room well ventilated. The fuel burns freely but heat is retained in the compartment and is fed back to the fuel enhancing the pyrolysis rate and thereby the total rate of energy released. This is an example of positive feedback. In addition other combustible items in the room will be heated by the hot gas layer and begin to pyrolyse. Initially all of the energy released by combustion is either convected through the opening as hot fire gases, absorbed by the compartment walls and contents or radiated through the opening.

6.6.2 Flashover

As the fire grows the energy release increases and at some point more energy is released than can be lost, the temperature rises and the pyrolysis rate of fuel items increases providing more fuel for combustion, increasing the energy release rate and thereby the temperature. The fire grows until the fuel supply is exhausted or the combustion is limited by the amount of air that can be drawn through the opening. This thermal runaway causes a change from a (small) localised fire in the compartment to involvement of the whole room.

6.6.3 Post Flashover

After the flashover transition there will be a fully developed room fire involving all combustible surfaces. In the absence of any fire fighting action this will continue to burn until the fuel supply is exhausted

7. A DISCUSSION OF THE CONCEPTS OF GISELSSON AND ROSANDER

7.1 General

Although not universally accepted in Sweden (Section 4.4) the concepts of Giselsson and Rosander (References 4,26) strongly influence Swedish Fire Service training.

What follows is a brief critique of those aspects of Giselsson and Rosander's book which are especially relevant to this current survey of backdraught. The language used is idiosyncratic to those authors and makes difficult reading for the fire scientist. In order to examine their ideas, some of this language has of necessity had to be used in this section despite its obvious weaknesses. Direct quotations given here are indented and enclosed in quotes "". Sections in their book "Fundamentals of Fire" are referred to here as Section GRn.n, where n.n is Giselsson and Rosander's heading number.

The book is an attempt to provide the firefighter with a text which will give an introduction to the fire science that is required to understand fire development and the principles of fire extinguishing. Unfortunately it is full of confusing attempts to explain phenomena with pseudo-scientific arguments. There are many over-simplifications and omissions. Clearly it is not intended as a comprehensive scientific text (such as Reference 9) however there should be some place for an accurate discussion of the mechanisms of heat transfer (conduction, convection and radiation), principles of energy conservation, laws of thermodynamics and chain combustion reactions. Some simple numerical examples could also be given to support the values given in the text and illustrate the use of data given in the tables. A serious omission is that no bibliography is provided. Some of the figures in the book are cartoons which help create an approachable feel to the subject, however the impact of the photographs is lost because of the lack of captions. The frequent use of graphs with unlabelled axes does not enhance the text and is a poor example to any student. If a student wishes to acquire a deeper understanding of a topic then some explanations would have to be discarded instead of built on.

It is beyond the scope of this survey to provide a comprehensive critique of "Fundamentals of Fire", however the sections on "Indoor Fires" and "Extinguishing Blazing Fires - Extinguishing Mechanisms" have a direct relevance to backdraught and these are summarised and discussed here. The pamphlet "Extinguishing with Fogfighter" (Reference 26) describes the use of offensive fire fighting in situations where a backdraught could occur; this is also discussed.

7.2 "Indoor Fires"

7.2.1 General

Two key stages in Giselsson and Rosander's description of "Indoor fires" are lean and rich "flashovers". (Sections GR6.3 and GR6.4). These seem particularly confused.

7.2.2 "Lean Flashover"

Their description of "lean flashover" is as follows:

> "GR 6.3 **Lean flashover**
>
> When a fire begins in a room, **lean flashover** often occurs.
>
> A fire normally begins as an **initial fire** in the lower part of a room. This initial fire, because of oxygen deficiency, secondary heating etc., generates un-burnt gases which rise and collect under the ceiling. The gases become increasingly flammable as the concentration and temperature rise. Soon the gases' lower limit of flammability is reached, where ignition is immediately possible. The initial fire ignites this "cushion" of combustion gases which has collected in the upper part of the room. Unless the room is very large this is normally short-lived and is over before the fire service arrives.
>
> This lean flashover rises from the initial fire up into the upper part of the room where it spreads out. This takes 5-15 seconds with a moderate pressure rise of 1 kPa.
>
> The lean flashover dies out itself very quickly if no ventilation is present. It is self extinguishing due to its oxygen consumption and simultaneous over-carburating. A great deal of combustion gases are extracted from wall and ceiling materials when heated by the flashover.
>
> Lean flashover happens in a similar way even in large premises, such as industrial buildings. Every stage in the development of the fire takes considerably longer than it does in a house fire. The premises are often leaky and well ventilated which also affects the course of the fire. It can take almost 10 minutes for lean flashover to occur in a large building.
>
> If the room is directly connected to another room, then the combustion gases can cause a flashover in the next room and this can be far more fast than flashover in the original room.
>
> After lean flashover is finished, the mixture in the room becomes quite rich.

> Normally there are a number of smouldering fires left in the room. If there are no easily ignited materials in the room which can smoulder, i.e. only synthetic plastic materials, then the fire dies out by itself after the lean flashover."

It is a little difficult to see how this event would occur suddenly as this suggests. During normal fire growth, flames from the fire will eventually reach the ceiling of the room. Under the ceiling it is not so easy for the un-burnt fuel gases to mix with air because buoyancy forces tend to keep the hot fuel gases above the cool air. The flames will therefore lengthen considerably after they impinge on the ceiling. It is the consequent increase in radiant heat transfer from these now lengthened flames that leads to flashover as described in Section 3.2. The lengthening of flames following their impingement on the ceiling is not a particularly sudden event and is unlikely to generate a sudden pressure increase of 1 kPa. If it did then windows would be blown out more frequently than they are. Of course the details of how a local flammable mixture is formed are strongly influenced by chaotic turbulent mixing processes. It is these processes that may be responsible for the "sudden" ignition of gases under a layer during fire growth.

For a more "explosive" event to occur a flammable mixture must develop remotely from the source of ignition. Such an event could occur if pyrolysis products, from a source unable to sustain flaming combustion, accumulate forming a flammable mixture which is subsequently ignited. For example the ignition by a boiler pilot flame of the products from a smouldering fire. This, of course, could occur anywhere between the upper and lower flammability limits. These possibilities are not described as "lean flashover" by Giselsson and Rosander since they require (Section GR6.3.1) that ignition results from the initial fire.

The demonstration of "lean flashover" provided during the training for Swedish fire service personnel and described here in Section 4.5 does **not** correspond to the mechanism described by Giselsson and Rosander and quoted above. It merely illustrates a lean mixture gas explosion - representative of what may occur as a result of an enclosed gas leak or volatile fuel spillage.

7.2.3 "Rich Flashover"

Giselsson and Rosander continue to develop their model of a compartment fire by considering the events after the point when a "lean flashover" could occur. They argue that if the flammable mixture is not ignited then the concentration of flammable components could continue to increase until a rich mixture is created. If "lean flashover" does occur then the atmosphere will be oxygen depleted and smouldering fuel could continue to produce un-burnt pyrolysation products which will accumulate and create a fuel rich mixture. A rich mixture gives the potential for a "rich flashover" which Giselsson and Rosander describe as follows:

> "GR 6.4 **Rich flashover**
>
> If a room containing an over-rich mixture receives a supply of air, the mixture enters the flammable range. If there is an ignition source in the room then a rich flashover will take place.
>
> GR 6.4.1 **Hot rich flashover**
>
> Often the temperature of the combustion gases is sufficiently high for spontaneous ignition to occur if air is supplied. The ignition takes place at the air opening and rapidly spreads into the room. The increase in pressure is very noticeable, about 2 kPa is normal.
>
> GR 6.4.2 **Delayed flashover**
>
> Sometimes ignition does not take place until an igniting flame flares up from the initial fire. This is similar to a concealed source of ignition where delayed ignition means that the mixture can be well inside the flammable range, the ignition can be violent. This phenomenon is known as a combustion gas explosion. The increase in pressure can reach 10 kPa.
>
> Overall the effect of delayed ignition of combustion gases is explosive. Sometimes the ignition can be caused by the fire service personnel themselves if they expose a concealed ignition source when they enter a room.
>
> GR 6.4.3 **Energy rich combustion gases "in ambush"**
>
> In contrast with normal combustion gases, such as ones from energy rich substances do not ignite immediately if ventilation is provided. This is because they require more air than ordinary combustion gases do, and this air has a cooling effect. The thermal point of ignition of these gases is also usually higher. This failure to ignite immediately means there is a considerable risk of later, delayed ignition with a combustion gas explosion."

These descriptions of "Rich flashover" corresponds to the definition of backdraught as described in Section 3.3.

The tank demonstration of "rich flashover" described in Section 4.5 partially simulates the real event in that air is introduced to a fuel rich atmosphere and is ignited as the mixture reaches the upper flammability limit. However fire gases will usually be buoyant and the tank uses propane (heavier than air) so the gravity wave studied by Fleischmann which is responsible for the time delay between opening the compartment and the backdraught is different and has to be enhanced by the instructor wafting air into the tank (at some personal risk). The design and use of the tank for the backdraught or "rich flashover" demonstration could be improved in the light of Fleischmann's experiments.

7.2.4 Fire Development in a Closed Room

During the instruction by the Stockholm Fire Service the "lean" and "rich" flashovers described above were presented to explain the development of a pulsation cycle that can occur during a fire in a virtually closed room.

"1 A small initial fire begins in a closed room.

2 As the temperature increases, water in the atmosphere is condensed and oxygen consumed, as a consequence the pressure in the room falls and replacement oxygen can enter.

3 The fire continues to grow.

4 Hot gases reach the ceiling.

5 The combustible ceiling material begins to pyrolyse.

6 A "lean flashover" occurs, the room is now oxygen deficient.

7 The temperature in the room is high and more fuel pyrolyses.

8 A fuel rich atmosphere develops and the fire dies back because of over carburation.

9 The temperature falls, as the gases cool the pressure in the room falls and fresh air enters.

10 A "rich flashover" occurs, oxygen is consumed, temperature and pressure in the room increase.

The process then returns to step seven and a pulsating cycle is established."

The assumption of a well mixed gas mixture, which is implied in Giselsson and Rosander's descriptions of "lean" and "rich" flashover is critical here. The "flashovers" and the sequence given above assume a uniform gas mixture in the room. In practice however, immediately above the pyrolysing fuel the concentration of gaseous un-burnt pyrolysation products will be very high whilst near an air inlet they will be very low. Throughout the room a full range of mixtures will be found. Ignition will occur if a mixture within the flammable range coincides, spatially, with an ignition source. The presence of quenching agents such as water vapour and carbon dioxide considerably complicates the determination of the flammability of the gas mixture which are encountered under such conditions (this is discussed by Drysdale, Reference 9). As a consequence the "flashovers" could be small local events rather than involving the whole room. The presence of "ghosting" or "dancing" flames described in Section 5.1.2 could not be explained with a uniform mixing assumption.

7.3 "Extinguishing Blazing Fires - Extinguishing Mechanisms"

Giselsson and Rosander's primary consideration is the extinguishment of the flaming gases rather than attempting to halt the pyrolysis process supplying the fuel to the flames. Their approach to fighting a fire is to reduce the extent of the flaming combustion by cooling or by creating an atmosphere (fuel rich or lean) unfavourable for combustion and then to attack the primary fuel supply. This has the advantage of creating better conditions in which to attack the fuel source, but it requires great skill and if the attack fails then a more dangerous scenario could occur (possibly backdraught). They identify four mechanisms for extinguishment of the flames (Section GR5):

> "1. Too much air or other cooling substance.
>
> 2. Too little fuel **starving** the flame.
>
> 3. Too much fuel to be decomposed.
>
> 4. Too little air, too low oxygen content.
>
> GR 5.1 **Cooling**
>
> A flame can be extinguished by adding an extraneous substance to the fuel/air mixture, in the simplest case excess air.
>
> The additional substance, the **extinguishing agent**, must be heated to the same level as the fuel/air mixture for combustion to take place. The heat required by the additional substance can be so great that the whole mixture becomes non-combustible and the flame goes out. In other words the flame is cooled. This is what happens in fire fighting with carbon dioxide, nitrogen, exhaust gases and water vapour. Solid material and liquids can also cool flames, as can easily be demonstrated by the following experiment :
>
> If a cold article such as a mirror is moved into a flame, it can be observed that the cold object has extinguished the flame in a zone approximately 1 mm thick round the cold surface.
>
> The zone is about 1 mm thick owing to the ability of the molecules to carry cold away from the cold surface. The

> transport of cold is limited by the fact that molecules are always changing direction so the thickness of the zone is fixed by the average collision distance of the molecules. This is to some extent dependent on temperature, but not on the composition of the gases.
>
> Dry powder extinguishment is an application of this form of cooling. Around every grain of powder a zone is formed where the flame cools to death. All zones together put out the whole flame.
>
> A drop of water can also act as a cold particle. If water droplets of sufficiently small diameter can be brought into the flame frequently enough, the flame will go out. In theory it would need 20 million drops per cubic metre of flame to extinguish the flame through the effect described. If the drops move quickly they can cool a greater volume by extinguishing a track through the flame. This extinguishing effect becomes more obvious when the droplet diameter is under 0.3 mm. The effect is comparable with dry powder extinguishing, the flame is beaten down instantaneously.
>
> The most modern nozzles fires used for indoor fires utilise the cooling effect of water droplets directly in the flame. This is often called offensive extinguishment as distinct from indirect extinguishment where larger drops of water must first evaporate on hot surfaces in the room.
>
> In the future, liquids such as water, atomised into droplets smaller than powder grains, i.e. into a fine mist, ULTRA-FOG. will be the most important extinguishing agents in indoor fires."

The zone surrounding a cool object placed in a flame is a visualisation of the boundary layer created by the flow around the object. Because of the energy transfer from the hot gases to the cool object the temperature of the gases is reduced and the flame quenched in the boundary region. This is not so simply related to the mean free path of the molecules as suggested by Giselsson and Rosander. The quenching distance is a function of the gas velocity and temperatures of the gases and object. The transport of "cold" suggested by Giselsson and Rosander does not reinforce any understanding the reader may have of the second law of thermodynamics (energy flows from a high to low temperature).

Although a dry powder may have a cooling effect on the flame, its conventional use is to create a layer over the pyrolysing solid or vaporising liquid surface to isolate the fuel from the air. Thermal degradation of the powder also releases chemical agents which inhibit combustion.

There are several instances in the work of Giselsson and

Rosander where they cite, as in the above quotation, calculated values without indicating their source. The drop density is one of these cases. The value of 20 million drops in "Fundamentals of Fire" is given as 200 million in "Extinguishing with Fogfighter". Since no information is given on the theory used to calculate this number the correct value cannot be determined by the reader.

> "GR 5.2 **Starvation**
>
> If the supply of fuel to a flame is cut off, it has the same effect as an excess of air. A flame can be put out if its fuel supply from a flammable liquid is blocked by an impervious layer. Above the layer there will be a lean mixture which is equivalent to an excess supply of air. This does not have the "strength" to heat the flame. The temperature falls and the fire goes out since no more fuel is available. Foam and film forming liquids use this principle in extinguishing fires."

This explanation complicates a simple process. Removal of the fuel supply simply terminates the combustion process since very soon there is nothing left to burn in the flame.

> "GR 5.3 **Over-carburation (decomposition)**
>
> As mentioned previously, heat energy is consumed decomposing the fuel. So too-high concentrations of fuel are non-combustible through Over-carburation. Supplying excess fuel or an extraneous substance, an extinguishing agent, which needs a great deal of energy to break down and which does not provide extra heat, reduces the temperature of the flame so that it goes out.
>
> The extinguishing efficiency of halons is due to them going through the same decomposition as fuel must do in the first stage of the combustion process. This absorbs heat, a process which causes a loss of energy and puts the flame out.
>
> The action of a fire blanket can also be described as causing over carburation. The fuel mixture under the blanket becomes so over-carburated (rich) that the low heat content from the flame is not enough to decompose the fuel. The effect is the same when a lid is put on a container of burning liquid."

Again a simple process has been over elaborated. When a mixture is fuel rich there is not enough oxygen available to provide a sufficiently high reaction rate to maintain combustion. The explanation of the action of halons is not conventional. Halons act through termination of the chemical chain reactions. Any cooling effect is secondary.

> "GR 5.4 **Smothering**
>
> A reduction in the oxygen concentration in a flame lowers the upper limit of the flammability range. This allows Over-carburation to happen more easily. Such a reduction can occur if the flame is supplied with air with a lower oxygen content. It is, however, more common with an enclosed flame using up surrounding oxygen.
>
> Enclosing a flame is an alternative to using an extinguishing agent. The mechanism is known as smothering, and it brings about an over rich mixture. Fighting fires through enclosing them with, for example a fire blanket, uses smothering and Over-carburation mechanisms together. **NB Enclosing a fire can cause flashover!**"

Although explained in a strange way this gives an essentially accurate description of how a fire might be extinguished by oxygen starvation. It does recognise that closing a door on a fire may extinguish it, but may give rise to a potential backdraught scenario.

7.4 Fire Fighting

"Fundamentals of Fire" only briefly refers to fire fighting tactics. These are discussed at more length in "Extinguishing with Fogfighter" (Reference 26). The use of offensive water application to gain entry to a room and to reduce the flammability of a combustible atmosphere is of relevance to this survey of backdraught. It must be noted that Reference 26 is a "Technical note" produced by the manufacturers of the Fogfighter branch for its promotion. It is beyond the scope of this current survey to assess the performance of fire fighting equipment. Although Giselsson and Rosander only refer to the Fogfighter branch, other equipment may be available which can offer a similar performance.

> "The method is based on the availability of a modern spray nozzle for water mist extinguishing such as the TA FOGFIGHTER with a droplet size of less than 0.3 mm. Apart from all the advantages of indirect extinguishing, there is a direct extinguishing effect on the burning gases. This avoids the indirect route over water vapour formation and indirect extinguishing in order to combat a developed room fire. Instead the finely divided spray can be aimed directly at the inflammable gases.
>
> The room no longer needs to be closed, offensive fire fighting also functions in ventilated spaces as well as outdoors. Ventilation and extinguishing can be carried out at the same time and re-ignition during the ventilation phase easily prevented.

...

When the small droplets pass through hot gases there is a rapid cooling. The water absorbs heat from the gases but since the hot surfaces do not provide water vapour in the same way as in the case of direct extinguishing the amount of water vapour is considerably less. The working environment for fire fighting personnel is both more comfortable and safer. If re-ignition should occur through the inward flow of inflammable gases or through normal flame-up the fireman is not defenceless. A modern spray nozzle for offensive extinguishment can easily combat initial flame up. Continued intensive work is possible if a maximum flow with small droplets is utilised.

Indirect extinguishing, through the formation of water vapour, provides expansion in the parts of the room furthest away. This expansion drives hot gases towards the firemen. Offensive extinguishing provides instead cooling of the gases that are closest. This means that the firemen are not subjected to the wave of heat that is normal in the case of indirect fire fighting.

...

Finally offensive fire fighting means that the transport of air to the fire through the jet has another character. The flow of air does not decrease due to small droplet size but the air is mixed up the whole time with many small droplets which do not separate out due through gravity. The risk of air getting the initial fire to flare-up is considerably less through the mixing in of water.

Rules for offensive fire fighting

...

Try to establish contact with the fire. If necessary use the spray to cool off the gases along the penetration route. For the best cooling effect hold the nozzle low, aim about 45° upwards and move it backwards and forwards towards the fire room. The droplets will then pass the maximum distance through the fire gases. Cool off with short spurts, think of secondary damage but primarily of your own safety.

Fire fighting is carried out in the same way as cooling described. Try to get an attack position in the room and you do not need to be afraid of the wave of heat as you would in the case of indirect extinguishing. A good position is often a metre inwards from the penetration opening. Put the fire out with a few short spurts, maximum flow for 2-4 seconds. Wait then cool off again if necessary."

The objective of both indirect and offensive extinguishing is to prevent combustible gases in the compartment burning, either by cooling and reducing the flammable range gases or by dilution to create a lean mixture. This reduces the risk of, or prevents, a "rich flashover" or backdraught.

During the Swedish firefighter training (Section 4.5.1) a procedure is taught for opening the door to a room which may contain a ventilation-controlled fire, and possibly a risk of backdraught (or "rich flashover"). This principally uses the offensive technique described above by Giselsson and Rosander.

Before opening a door any smoke and hot gases outside the room are cooled and loaded with a suspension of fine droplets using a few pulses from a spray branch. This is to prevent ignition and a possible backdraught of these gases if flames leave the room when the door is opened. The door is now opened and two firefighters enter the room, a third holds the door closed behind them. Remaining close to the door, the firefighters inside the room begin an offensive attack extinguishing flames and cooling the hot gas layer. As the conditions in the room improve, search and rescue and direct fire fighting can take place.

The principles involved are sound, remove any potential for backdraught inside or outside the room, and allow a direct attack of the fire source.

Offensive fire fighting however requires skill and courage for its successful use. It was stated by the Stockholm instructors that ten or more attempts were usually required in the container fire simulator to acquire the basic skills and these were not achieved by all firefighters.

7.5 Summary

The intention of Giselsson and Rosander to produce a small, simple, readable and affordable book (Reference 4) to provide a foundation in fire science for firefighters is commendable. It is unfortunate that the result is misleading because of the many questionable statements and misconceptions. This gives firefighters a poor understanding of the situations they may encounter and the techniques that they are taught to use. The fire fighting techniques proposed by Giselsson and Rosander, in as far as they relate to backdraught, seem to have a sound practical basis and are effectively demonstrated in the fire simulator containers.

8. DISCUSSION AND NEEDS FOR FURTHER RESEARCH

Only the University of California (Berkeley) study has addressed the backdraught phenomenon directly. The Fire Science community has so far primarily concentrated on studies of compartment fires that are well ventilated. As a consequence the thermal instability defined as flashover in Section 3.2 is reasonably well understood. However, although the quasi-steady models give a good insight into the conditions before and after the event there are no comprehensive mathematical models that describe a backdraught or the transition process during a flashover.

Research programmes are under-way to examine the consequences of under-ventilated fires on carbon monoxide yield and burning rate. In addition phenomena such as ghosting or dancing flames and pulsation of under-ventilated fires are now being studied. Such work is relevant to gaining a better understanding of the conditions which may lead to a backdraught.

The evolving mathematical modelling methodology based on computational fluid dynamics (CFD) with appropriate combustion sub-modelling should provide a viable approach which is not dependent on data from experimental studies. The two dimensional, direct simulation by Fleischmann and McGrattan (Reference 40) of the mixing between cool and hot gases shows promise, but does not yet address the ignition and combustion processes required to model the whole backdraught sequence.

Fleischmann, Pagni and Williamson's backdraught studies have so far only considered an idealised scenario, but have provided the base line for more realistic studies, such as the impact of different opening (doors, windows and ceiling vents) compartment geometries (rooms corridors and shafts) and the location of the ignition source relative to the opening. Their data is also valuable validation material to those developing mathematical models.

The conditions where insignificant or no backdraughts occur in experimental studies will have a special relevance to firefighters as these are the conditions they will seek to achieve when entering a compartment with an under ventilated fire.

The impact of multiple openings (especially in the presence of wind), large compartment volumes and obstructions in the path of the gravity current (which would increase turbulent mixing and the consequential severity of the explosive event) will be more practical for study by CFD methods (because of safety considerations and cost) once the technique has been validated against the simpler experimental scenarios.

A firefighter must be able to identify conditions which could lead to a backdraught. The warning conditions discussed in Section 5.2.2 identify the principle features. However, these must be seen in the context of the specific scenario encountered to make a reliable assessment.

The tactics taught to Swedish Firefighters for opening a door and entering a room where a potential backdraught or "rich flashover" has been identified is, in principle, sound. However the current presentation of the mechanisms involved in fire development and extinguishment do not have a sound scientific basis. This could lead a firefighter into a dangerous situation if he has to make a decision based on deduction as opposed to experience.

High rise buildings and the effects of wind may combine to produce variants of the backdraught phenomenon, notably that referred to as a "blowtorch" where an air supply at one opening is able to supply oxygen to a fire and its products are forced out through another opening. This could approach pre-mixed conditions resulting in very severe conditions at the combustion outlet. Opening of any doors in a high rise building can lead to significant changes in pressure across other potential openings such as windows which could in turn lead to their failure and the consequent supply of further air. There are too many variables to make generalised recommendations in such cases. Each building will be different, each time it is entered there will be different combinations of open and closed windows and doors. Wind conditions will vary from day to day and even through the duration of a fire. Firefighters should be aware that if they feel resistance opening a door due to air pressure then once open that pressure difference may transfer elsewhere and possibly lead to a sudden failure of a window for example, with serious consequences. Caution and co-ordination are required.

As has been stated, there is as yet no reliable quantitative treatment for the transient processes involved in a backdraught. Furthermore, despite the basic Berkeley research on the propagation times of gravity currents from vent to ignition source there is little practical research on how best, from the firefighters viewpoint, venting should be achieved.
The impact of internal obstructions on a deflagration wave is known to increase the severity of a gas explosion. There is no information on such interactions with a backdraught.

A substantial contribution to a better understanding of these effects would result from attempts to develop transient theoretical models of backdraught. These, supported by appropriate validatory experiments should provide quantitative tools that can be exercised to examine the consequences of different fire fighting strategies. Such a capability would be valuable not only for examining such alternative strategies but also for providing safe training tools that would complement the hot, but potentially dangerous container fire simulations.

9. CONCLUSIONS

The basic physical mechanisms of both backdraught and flashover are reasonably well understood, however the details associated with the transient processes remain to be adequately described by quantitative analysis. The current understanding should however assist a firefighter to recognise the potential for backdraught and flashover and the difference between the two events. Warning signs indicating a possible backdraught tend to be generalisations. The presence of any of the characteristics listed in Section 5.2.2 does not unreservedly indicate backdraught will occur, nor does their absence guarantee safety.

Current research into under-ventilated compartment fires is exploring the mechanisms of indicators such as pulsating flows of smoke and high level blue flames (ghosting or dancing flames) and should lead to more reliable warning signs.

Research into backdraught is sparse and this survey has identified only one active group at the University of California. Their study has considered the effect of opening doors and windows to a room containing an under ventilated fire. Extending the study to simulate fire venting procedures is of particular relevance to the practising firefighter.

The use of numerical modelling could be especially valuable. Once validated such models can be used to study the numerous variables systematically, reproducibly and safely. This would also lead to practical design and training tools. Backdraught is not a phenomenon readily amenable to the "zone" modelling approach which requires a priori knowledge of the mechanisms involved (although these methods are useful in determining potential backdraught scenarios). The field modelling technique used by Fleischmann to model the gravity current (Section 5.1.4) will need to be extended to include ignition and combustion. These features are available to the modeller (Reference 46), but have not been validated in the context of backdraught.

The absence of generally available realistic training for firefighters where the dangers of backdraught can be presented and demonstrated needs to be addressed. The use in Sweden of small laboratory scale demonstrations to link fire science theory with practical firefighter training has a high educational value. The fire science must be sound and the terminology used should conform to that used by the rest of the fire safety community to achieve the maximum benefit.

The time delay for the gravity current to cross an enclosure and for a flammable mixture to coincide with an ignition source may extend to minutes for very large spaces. Firefighters should be aware of this as a backdraught could occur some time after entering a large compartment.

The intention of Giselsson and Rosander to produce a small, simple, readable and affordable book (Reference 4) to provide a foundation in fire science for firefighters is commendable. It is unfortunate that the result is misleading because of the many questionable statements and misconceptions. There is a clear need for a simple text of this kind which is scientifically sound.

The generic use of the term flashover in the U.K. for both rapid growths in the heat release rate of a fire and transient events makes it difficult to assess from the literature how frequently backdraught is a real hazard to a firefighter. Awareness and use of the definitions given in Section 3 should be encouraged.

ACKNOWLEDGEMENT

The author wishes to thank SO Taylor of North Yorkshire Fire and Rescue Service for facilitating his visit to the Stockholm Fire Service.

GLOSSARY

Dancing or Ghosting Flames: A description of flames which are not attached to the fuel source and move around an enclosure to burn where the fuel air mixture is favourable.

Deflagration: Sudden and rapid combustion in which the flame speed is less than the speed of sound in the gaseous products (Reference 10), and may or may not develop hazardous pressures (Reference 11)

Field Modelling: A technique used to provide a mathematical representation of a fire by dividing the volume of interest into a large number of small volumes and for a series of time steps calculating the temperature, velocity, concentration of gases in each volume. This draws on developments in computational fluid dynamics (CFD) to provide a very detailed simulation (with few intrinsic assumptions) of a problem.

Flammable Limit: The highest or lowest concentration of a flammable gas or vapour in air that will explode or ignite (Reference 11).

Gravity Wave: An opposing flow of two fluids caused by a density difference.

Pyrolysis: Chemical breakdown of a substance due to heat.

Pyrolyzates: Products of pyrolysis.

Stoichiometric Mixture: A balanced mixture of fuel and oxidiser such that no excess of either remains after combustion (Reference 11). The ratio, r, used in Section 5.1.3 is the number of mass units of air required to completely oxidise one mass unit of fuel.

Vitiated Atmosphere: An atmosphere with a reduced concentration of oxygen from that of "fresh" air.

Zone Modelling: A technique used to provide a mathematical representation of a fire by considering the scenario as a number of discrete zones (e.g. plume, hot gas layer, vent flow). Each is treated by semi-empirical mathematical relationships. Since combustion products are usually assumed to be well mixed and have uniform temperature and composition the results are usually averaged quantities.

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Additional Reference Material

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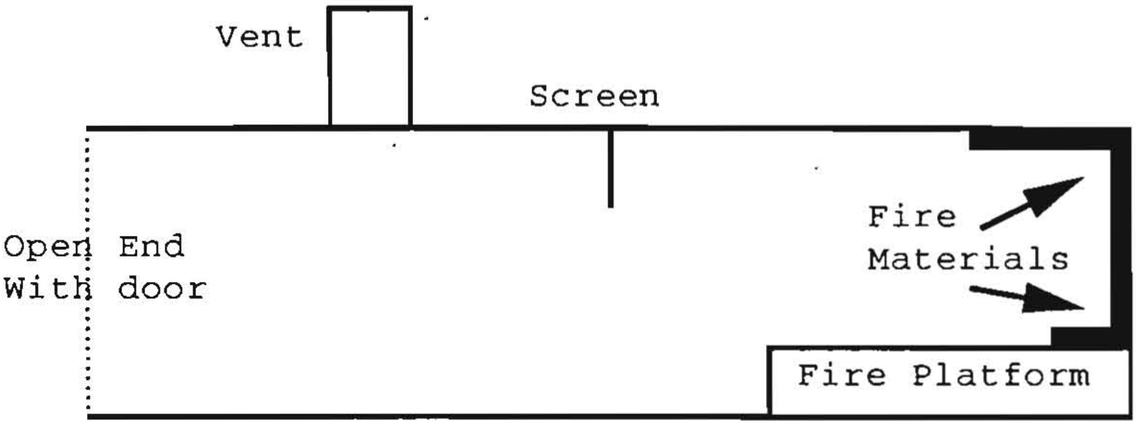
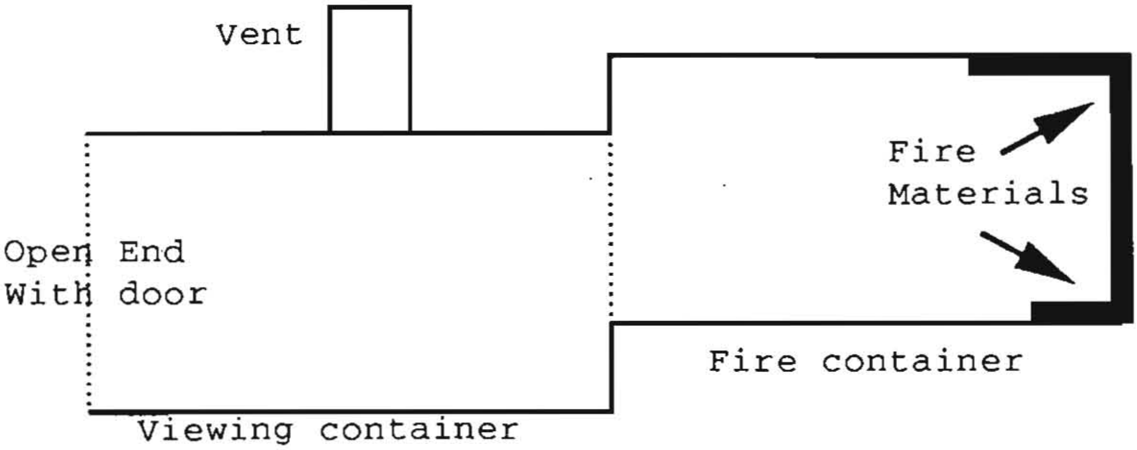


a) Single Container System (Stockholm)



b) Double Container System (VTT)

Figure 1 : Side Elevation of Containers used for Flashover Training in Sweden

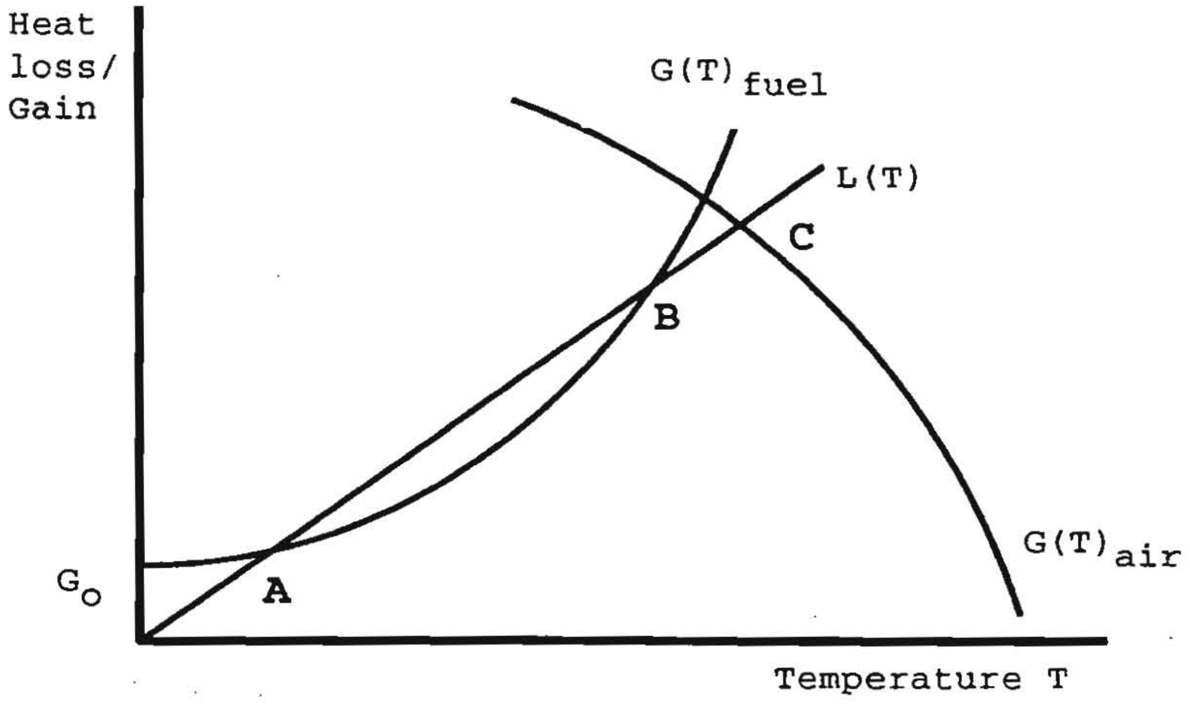


Figure 2 : Fire Stability Curves : General

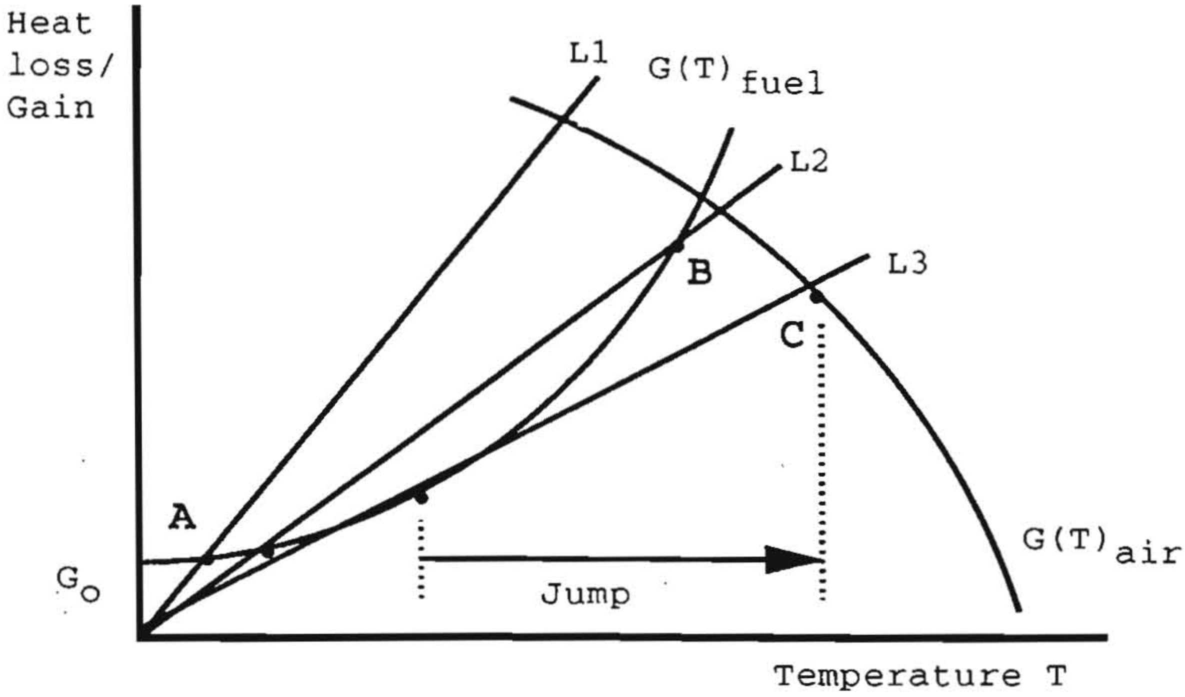
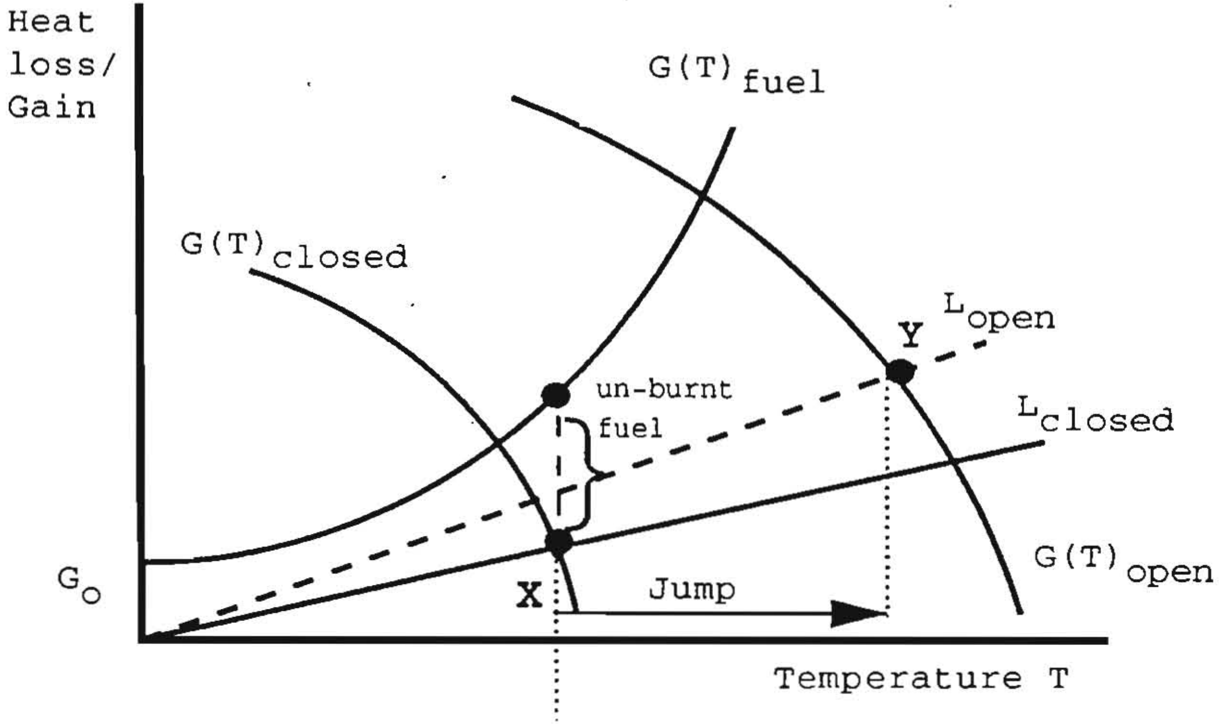
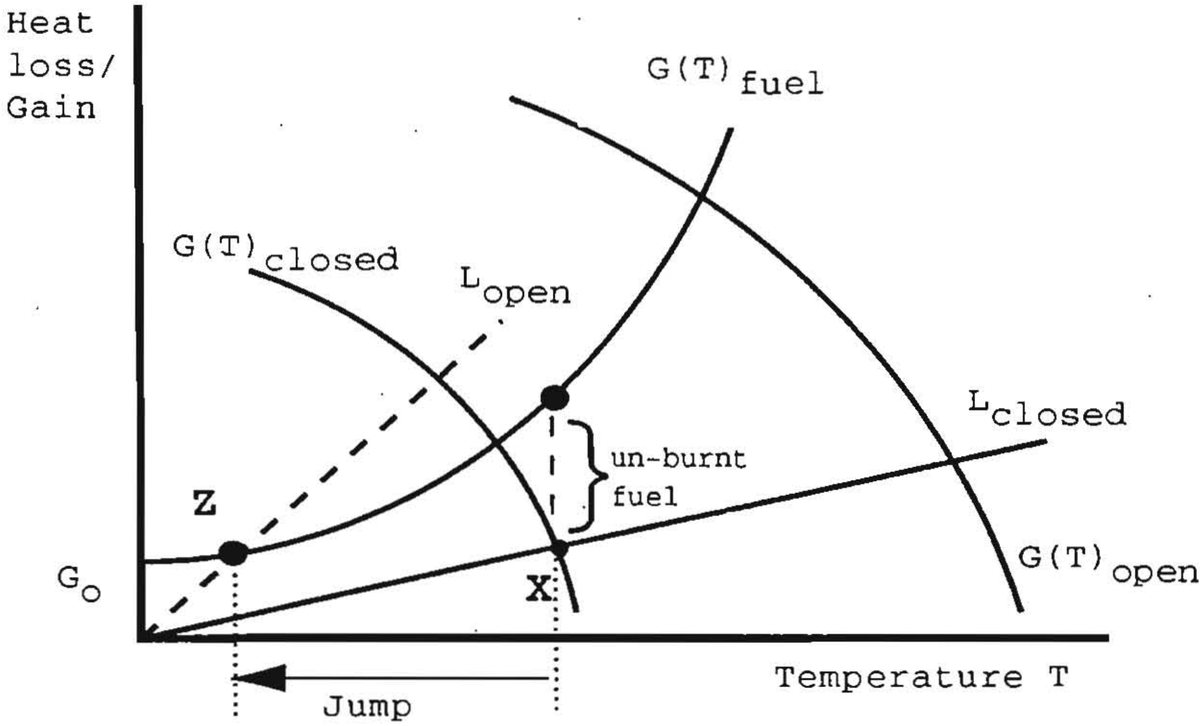


Figure 3 : Fire Stability Curves : Flashover



a) Flashover with Potential for Backdraught



b) Venting with Potential for Backdraught

Figure 4 : Fire Stability Curves : Potential for Backdraught

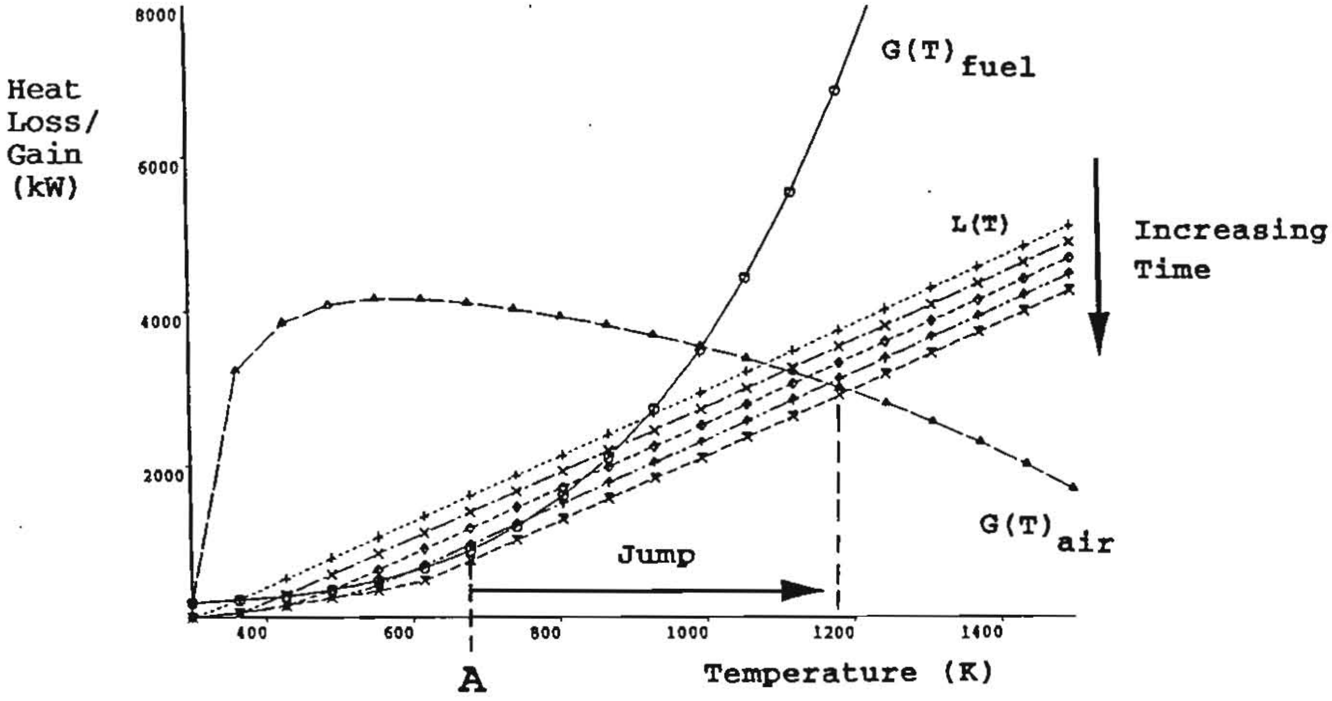


Figure 5 : Fire Stability Curves : An Example

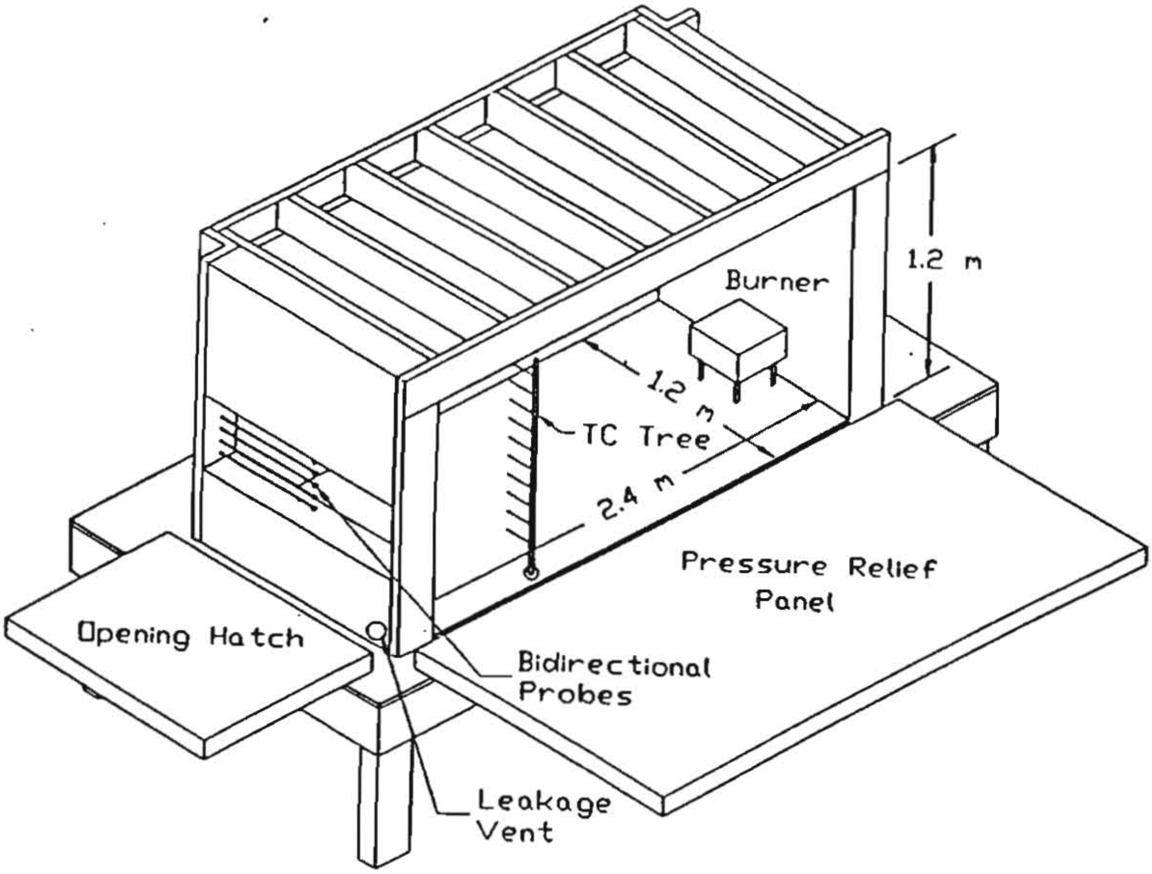
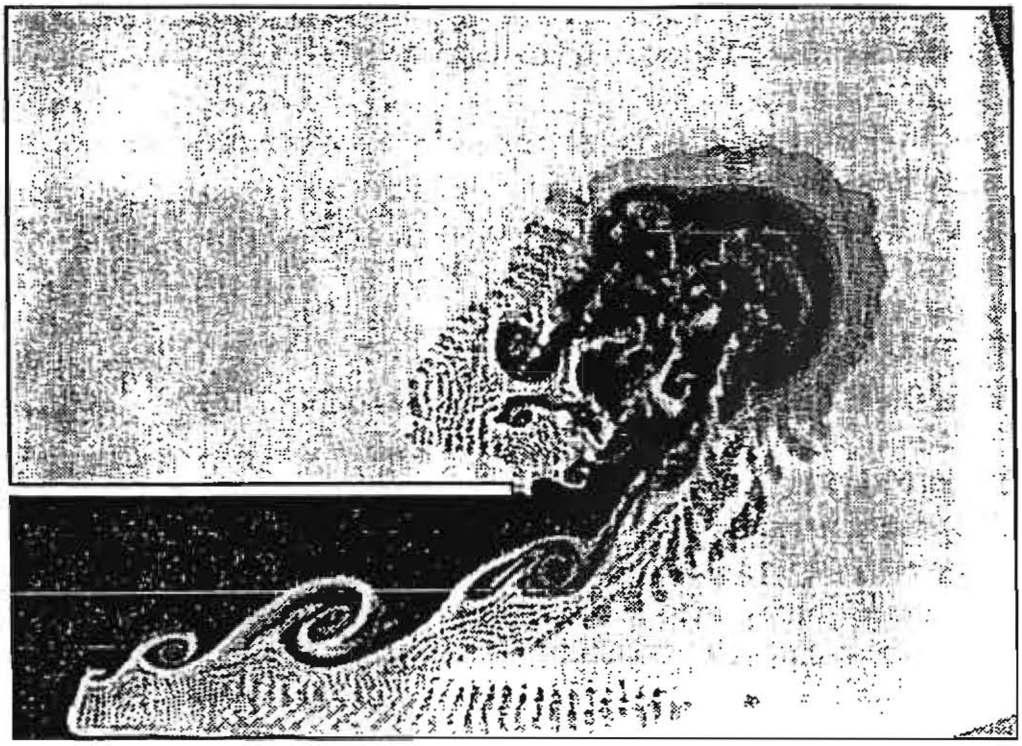
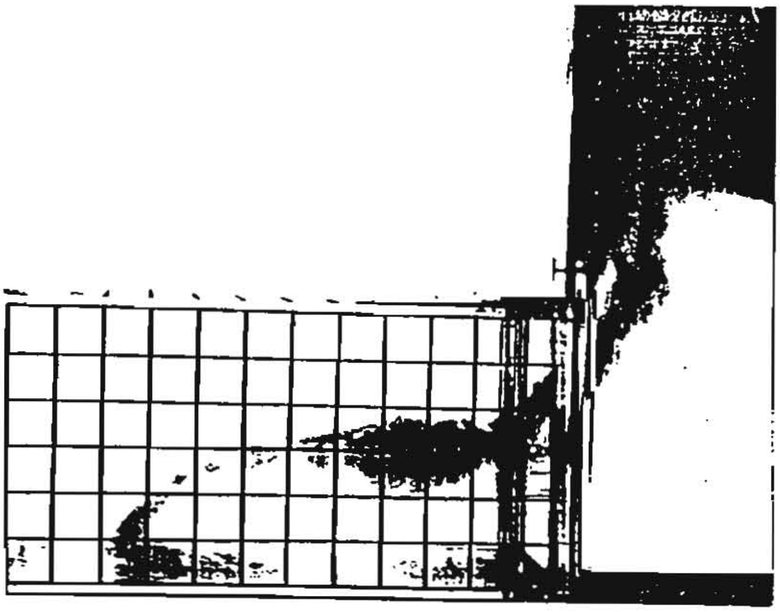


Figure 6 : Sketch of Half Scale Backdraught Compartment used by Fleischmann et al.



a) Numerical Model



b) Salt Water Model

Figure 7 : Numerical / Salt Water Modelling

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APPENDIX B - NIST 1993 Annual Conference on Fire Research
Quantitative Backdraft Experiments

QUANTITATIVE BACKDRAFT EXPERIMENTS

C. M. Fleischmann, P. J. Pagni and R. B. Williamson

University of California, Berkeley, CA 94720

This paper extends our pervious results to provide a quantitative study of backdraft phenomena. Backdraft has been defined as a rapid deflagration following the introduction of oxygen into a compartment filled with accumulated excess pyrolyzates. There are many scenarios which can lead to backdrafts fitting this definition but the physical and chemical fundamentals underlying these phenomena are not well understood. This presentation divides backdrafts into several categories: rich backdrafts with early, middle and late ignition and lean backdrafts. For the rich case sudden compartment venting is required in order for a backdraft to occur. In the less common lean case the compartment upper layer approaches the flammable limit from the lean side with an ignition source constantly present so that sudden venting is not required Videotapes and data illustrating each category will be presented.

A half-scale apparatus[1] was used to obtain data from 52 backdraft experiments. The primary focus of this study was the rich backdraft case where experiments included 40 with early, 5 with middle and 3 with late ignition. Four experiments were also conducted for the lean case. Experimental parameters measured include species concentrations, (HC, CO, CO^2, O^2), layer temperatures, layer height, vent flow, compartment pressure, leakage rate, and fuel flow rate. A gas burner supplied a range (70 - 180 kW) of methane fires in a 1.2 m high, 1.2 m wide, 2.4 m long compartment with two different opening geometries: a centred horizontal slot 0.4 m high by 1.1 m wide and a centred window 0.4 high, by 0.4 m wide, as shown Fig. 1. In the rich case, significant un-burned fuel (18% to 35% by volume) accumulates in the compartment after the oxygen concentration drops below 10% as shown in Fig. 2. At a predetermined time, a hatch covering the front opening was released, simulating a window breaking due to thermal stresses or entry by fire service personnel. Once the compartment is open, a gravity current of cold oxygen rich air enters through the new opening and propagates across the compartment. This gravity current carries a flammable mixed layer to an existing spark located near the burner on the opposite wall (early ignition). Upon ignition, a rapid deflagration moves through the compartment culminating in a large exterior fire ball. Compartment pressure >70 Pa were recorded in these experiments. Middle ignitions were obtained by delaying the spark onset by 4 to 12 s to allow the reflected gravity current to generate a larger mixed region. Late ignitions, with 60 to 600 s delays, occurred in unburnt fuel trapped by the soffit. These rich backdraft scenarios are known to cause firefighter injuries. The lean case is more of an explosion than a backdraft. The upper oxygen concentration remains high (> 15%) and the aggregated flammable species (HC and CO) increase to the lower flammable limit. To investigate this scenario, the gas burner was shrouded with a fine mesh screen that acted to quench the flame and inhibit the combustion efficiency. The upper layer was ignited by a pilot flame left burning in the centre of the compartment at the same height as the burner. A large mushroom shaped flame erupted within the compartment causing significant overpressure, as high as 350 Pa, before the pressure relief panel operated. Additional salt water model experiments of backdraft gravity currents have been compared with NIST computations by McGratten[2]

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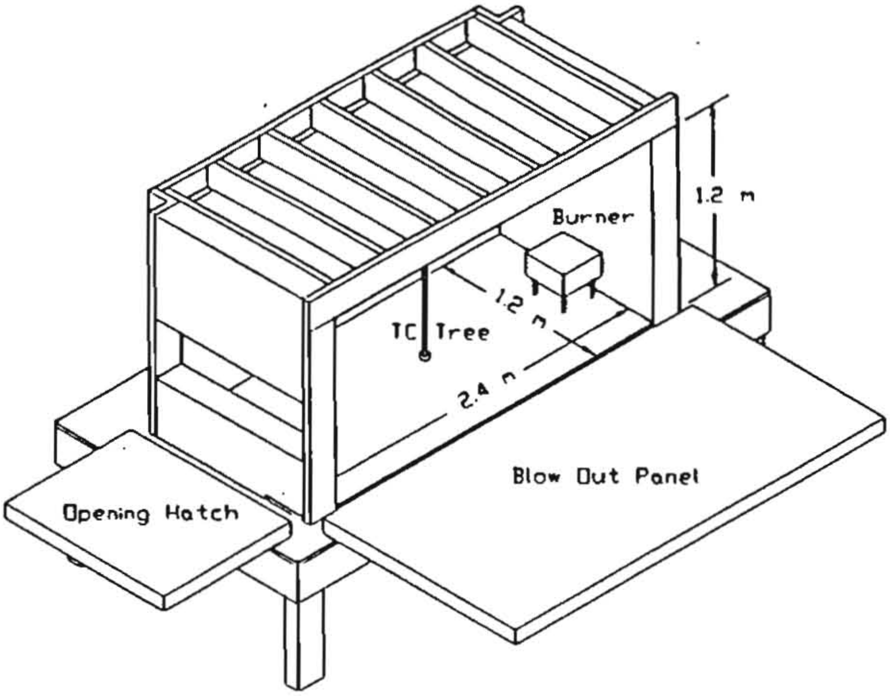

Fig. 1 Schematic of the half-scale backdraft apparatus with original slot opening.

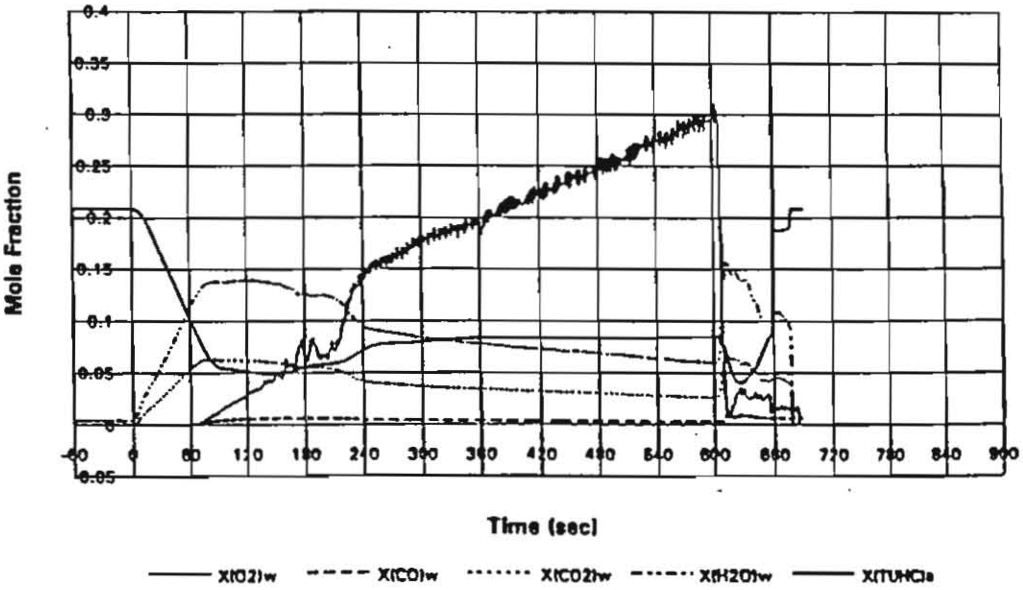

Figure 2 Typical measured upper layer gas species (O_2, CO, CO_2, H_2O, and HC) histories prior to the rich early ignition backdraft at 604 s.

APPENDIX C - Calculation Relating To Indirect Water Attack

CALCULATION RELATING TO INDIRECT WATER ATTACK

A. INTRODUCTION

Giselsson and Rosander present a calculation to explain the action of indirect firefighting attack (the application of water to hot surfaces to create a steam rich atmosphere, displacing oxygen, and controlling a fire), this has been taken up by Grimwood, with a few corrections in his book 'Fog Attack'. The explanation needs some embellishment to aid understanding due to a lack of rigour in the original (for example a statement such as 90°=380kW is nonsensical). In addition some steps in the calculation and associated values are missing. This is an attempt to rewrite the indirect fog attack example calculation clearly.

B. A REVISED CALCULATION

Consider a room with a $40m^2$ floor area, 2.5m high filled with burning gases. Application of water is intended to create an atmosphere of 10% water vapour at 180°C (supply water at 10°C).

Volume of steam at 180°C = $10\ m^3$ (10% of $100m^3$)

Using the ideal gas laws to correct this volume to a temperature of 100° C

$$V_{100} = V_{180}\ (100+273)/(180+273) = 0.823\ V_{180} = 8.23\ m^3$$

This is 8230 litres of steam at 100°C

A litre of water will vaporise to 1700 litres of steam at 100°C. To create the 10% steam atmosphere

8230/1700 = 4.84 litres of water must be vaporised.

To heat 4.84 litres of water from 10°C to steam at 180°C energy must be provided to :

raise the water temperature from 10° to 100°C
provided latent heat of vaporisation
raise steam temperature from 100°C to 180°C

Generally

$$E = m\ (C_{p(water)}\ \Delta\theta_w + L + C_{p(steam)}\ \Delta\theta_s)$$

where

m	Mass of water (kg)
$C_{p(water)}$	Specific heat capacity of water (J/kg/K)
$\Delta\theta_w$	Temperature rise of the water (K)
L	Latent heat of water (J/kg)
$C_{p(steam)}$	Specific heat capacity of steam (J/kg/K)
$\Delta\theta_s$	Temperature rise of the steam (K)

NB. the mass of 1 litre of water is 1kg

Evaluating gives

E = 4.84 (4180*90 + 2260000 + 2020*80) = 13.541 MJ

Giselsson and Rosander assume that in the first instance all this heat is held in the first 1mm of the wall. The available energy in this slab of wall may be found from :

$$E_{wall} = \rho_{wall} A\, d\, c_{pwall}\, \Delta\theta_w \text{ Joules}$$

Where		
	ρ_{wall}	Density of the wall material
	A	Area of wall/ceiling
	d	Depth
	$c_{p(wall)}$	Specific heat capacity of the wall material
	$\Delta\theta_w$	Temperature change of the wall

Assuming an initial wall temperature of 500°C and final temperature of 180°C, density of 1000 kg/m^3 specific heat capacity of 1000 J/kg/K and the depth of 1mm then the area required to provided the required amount of heat is :

$$A=\left(\frac{E_{wall}}{\rho_{wall}c_{pwall}d\Delta\theta_w}\right)=\left(\frac{13.5\times10^6}{1000.0\times1000.0\times0.001\times(500.0-180.0)}\right)$$

= 42.2 m2

Therefore 4.9 litre of water should be applied to 42.0 m^2 of wall to achieve the required concentration of steam, an application of 0.11 litre/m^2 as calculated by Giselsson and Rosander and reproduced by Grimwood.

A transient model for heat losses from the walls could significantly improve this analysis as the reheating time and hence the time between applications and the duration of subsequent applications of the spray could be estimated.

Several fire suppression/control actions have occurred, firstly as stated by Giselsson and Rosander the oxygen concentration in the room is reduced inhibiting combustion reactions. In addition the compartment temperature will have been reduced decreasing thermal feedback to the fuel surface and the heat losses to the boundary increased. These thermal factors may be sufficient for the fire to jump to a lower stable equilibrium (a reverse of the flashover mechanism).

Giselsson and Rosander continue to warn of the effects of over drenching (causing the wall temperature to fall below 100°C) and observing that fuel rich atmospheres will require less water since they will be oxygen depleted already and leaner mixtures will require more. It is then stated that the opening should be kept as small as possible during the fire fighting procedure, presumably to reduce incoming oxygen. The reignition hazard is emphasised.