An introduction to the concept of weapon-induced fires

Per Walmerdahl

Department of Fire Safety Engineering
Lund University, Sweden

Brandteknik
Lunds tekniska högskola
Lunds universitet

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Abstract:
The concept of weapon-induced fires on board ships (mainly warships) is introduced in a comprehensive manner. The analysis is based on experiences from military and civilian shipping, statistics, experimental work and literature on the subject. Events following a weapon-induced fire are outlined in a qualitative manner and key hazards and measures of protection and their effects are recognised and discussed. Finally, a few methods and computer codes to assess overall vulnerability of ships are outlined and a few examples of on board fires are given.

Brandteknik
Lunds tekniska högskola
Lunds universitet
Box 118
221 00 Lund

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

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

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

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

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

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SUMMARY

Mainly during the Falklands and Gulf Wars, fire on board warships after weapons effects proved to be a complex problem, which under some circumstances could come to severe consequences. Many questions have been raised in this area and the main purposes of this paper have therefore been to:

- outline the events following a weapon-induced fire in a qualitative manner, and
- recognise key hazards and measures of protection and their effects.

The study has been performed as an “outline qualitative hazard analysis”, where the whole concept of weapon-induced fires has been grasped in an overview manner. The initial literature study concluded that warship design is a complicated task, which has to satisfy a number of contradictory needs. Potential hazards are preferably identified already at the design stage and at this point the use of ship fire modelling techniques and vulnerability assessment codes can be a valuable aid. Still, “trade-offs” between different types of systems are needed in the overall process of accomplishing a low vulnerability. A few of the more important factors in warship construction are watertight subdivision and zoning of a ship’s services. The design of a warship is not bound by SOLAS (Safety Of Life At Sea), even though the construction in practise follows many of these guidelines.

Statistics on military as well as civilian shipping, reveal that no real decline in the total number of fires on board ships in peacetime can be concluded, and that nearly half of all ship fires originate in the machinery room, many times due to human error, negligence or lack of maintenance of the ship and equipment. Most fires on board warships seem to be relatively minor and are extinguished within the first few minutes, creating little damage. Relatively little statistics on peacetime incidents on board warships is available, but still electricity appears as one of the main sources of ignition. In wartime conditions, fires as a result of weapons effects are much more likely to occur in present day ships, due to the nature of weapons as well as the amount of combustible material and other hazards on board.

The fire protection should consist of a balanced mix of both active and passive systems to limit the consequences of a weapon attack with ensuing fire. The actions taken in the early stages of the fire are crucial and effort should be placed on developing an effective approach to early fire-fighting, either by means of fully automatic fire suppression, which will work without manual intervention, or manual actions. Shipboard fires often prove hard to fight due to the rapid spread of fire and dense smoke. The need for enough, properly trained manpower with the necessary equipment is an important point to make.

Tests and experiences show that eventually most ship compartment fires will reach the stage of ventilation-control. In addition, tests simulating fire conditions after a missile impact suggest that no more than ten minutes will be available for fire-fighting before conditions will be too severe. After about 10-15 minutes, the air temperature in above compartment will be high enough to spontaneously ignite other flammable material. The fire spread to adjacent compartments is usually somewhat slower. Another great concern to any fire-fighting activities on board, is the generation and spread of smoke. Low visibility, problems in finding the seat of the fire and toxic effects are a few of the problems that follow.

To summarise the events, a few factors have been identified as crucial to the outcome of a fire on board. These are of a more “generic” kind and involves two factors of protection and mitigation and three hazard factors as follows:

⇒ **Initial fire-fighting efforts or the use of active suppression systems**.
⇒ **Damage control and fire-fighting measures**.
⇒ **The type of fuel in the affected compartments**.
⇒ **The fuel load of the affected compartments**.
⇒ **The level of integrity of passive systems**.

Even though there has been and to some extent still is, a lot of work put into an increased knowledge and understanding of fire behaviour in highly confined and densely packed spaces, to some extent these are still poorly understood. Fires vented mainly from above represents another scenario, which is hard to predict. Maybe some additional insight can be gained in the field of ship fires from the extensive efforts made analysing fire and smoke behaviour in tunnels and underground facilities, since these have some similarities to conditions on board ships.

Another problem area is represented by the lack of distinct procedures for smoke management on board. There is a need for developing a well functioning approach to these issues and a good way seems to be through experimental studies. More generally, it can be concluded that no matter how expensive and problematic, small- and full-scale experiments are extremely important to increase the understanding of fire behaviour under different ventilation conditions, effectiveness of suppression systems etc. These results are needed in order to build sophisticated fire models to help assess the overall vulnerability of different ships already at the design stage.

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1. INTRODUCTION

1.1 Background

Fire on board warships after weapons effects is a complex problem, which under some circumstances could come to severe consequences, as was proved during the Falklands and Gulf Wars. The effects of fires aboard vessels in general have mainly been demonstrated as experiences of fires on board civilian ships such as passenger and cargo ships and as a result of collisions between ships during peacetime.

In most navies there are relatively few ships of any one type, individually very valuable and which would take many years to replace. In consequence, there is a far greater emphasis on preventing the loss of an asset, while merchant practice focuses on minimising loss of life. It has been suggested that the safety is “philosophically” more complex than that of a commercial vessel (Brown *et al.*, 1990). Legislation exists covering most aspects of merchant ship safety and the value of ship and cargo is insured and the loss of a ship will not usually have a great effect on the ship owner, who can hire a replacement. Although there are safety rules for warships, there is a need for a flexible interpretation of these in order for these vessels to carry out dangerous missions and exercises. Naval vessels demand a high level of general safety and also the ability to remain operational at all times in the most extreme and adverse conditions. In any event, fire is an ever present risk in a ship and at sea with no where else to go it must be dealt with by people on board.

Today several approaches are used in order to analyse the events following a weapon-induced fire. Computer models ranging from deterministic to purely probabilistic are used for assessing vulnerability in general and fire behaviour in particular. Unfortunately, several of the models commercially available are not transparent enough for the user to relate input data to output results. The Swedish National Defence Research Establishment (FOA) has developed a code (LIBRA) for vulnerability assessment of weapons effects in ship targets as well as armoured vehicles and aeroplanes. Efforts have been made to develop a model for implementing the effects of fire as well and for this purpose the paper serves primarily as a study of aspects that might need further consideration.

1.2 Purpose

The main purposes of this paper can be summarised as follows:

⇒ outline the events following a weapon-induced fire in a qualitative manner, and
⇒ recognise key hazards and measures of protection and their effects.

Conclusions should include identification and characterisation of the more important aspects of these as well as recognition of areas, where future work is needed. Of great importance for this work is an inclusion of lessons learned from wartime as well as peacetime incidents. Hopefully, the work will in the end contribute to the introduction of valuable aspects to be considered in the future development of vulnerability assessment codes such as LIBRA mentioned above. Finally, it is the wish of the author that this paper be seen mainly as a compilation of existing literature, complemented with some important conclusions, and used as introductory reading for personnel wishing to get an overview of the matters surrounding weapon-induced fires.

1.3 Method

In order to achieve the main objectives of this study (i.e. description of the events following a weapon-induced fire and the main hazards associated with this), a literature study is initially performed in order to review current literature on the subject. This gives the author a valuable possibility to develop an understanding for special problems concerning ship-related fires. Several visits have been done during the course of the work. Examples of this are the Royal Navy's Training School (HMS Excellent) in Portsmouth, Maritime Operations Division within DSTO (Defence Science and Technology Organisation) in Melbourne, FRS (Fire Research Station) in Watford and Karlskronavarvet. These have been very helpful in providing well-needed information. Participation during smoke spread tests on board a Swedish Navy minesweeper can also be mentioned.

The literature study is based mainly on information extracted from accident reports, available results from research and development, commercial and military statistics, articles and information on a few different assessment codes for vulnerability modelling. Since weapon-induced fires on board ships in some cases show similarities to offshore experiences of explosions and subsequent fires, some consideration will be given to hazards and experiences associated with these activities.

The study is performed as an "outline qualitative hazard analysis", where the whole concept of weapon-induced fires is grasped in an overview manner, focus being on vulnerability (defined in chapter 3.2.1) aspects. The study is basically divided into five main sections (chapters 2-6), based to some extent on different risk assessment approaches (Chapman *et al.*, 1997 and SRV, 1997). Chapters 2-4 are mainly a result of the literature study, while chapters 5-6 include the analysis, evaluation and conclusions. A short summary of important reflections within each section is given in the beginning of chapters 2-4 as an introduction.

The ship itself will be dealt with as a *system* and chapter 2 - **System Definition -** brings up general aspects of ship design, rules and regulations and a discussion of different ship types. **Hazard Identification** aims at identifying the hazards concerning fires on board ships and these are divided into primary and secondary, where the primary are related to the direct effects of the weapon impact. A review of available statistics and methods for risk analysis and vulnerability assessment are also presented at this stage. The chapter **Response Identification** further explores the responses available such as fire-fighting measures and active and passive fire protection. In the **Damage Scenario Analysis**, a "generic" fire scenario, evolving given a weapon hit, is identified and described. Initiating events as well as intermediate and accident outcomes are presented in a qualitative manner. Important vulnerability factors are identified and presented in an overview way. The evaluation of the analysis- **Conclusions and Discussion** - is given last and includes a summary and discussion of important hazards and responses as well as where future work within this area is needed.

The contents and working procedure for the report is illustrated in figure 1-1. Except for the introduction and reference list, found last is also a number of appendices, of which the last one (referred to as appendix C in the report) is of a restricted nature and therefore only can be added to the report separately.

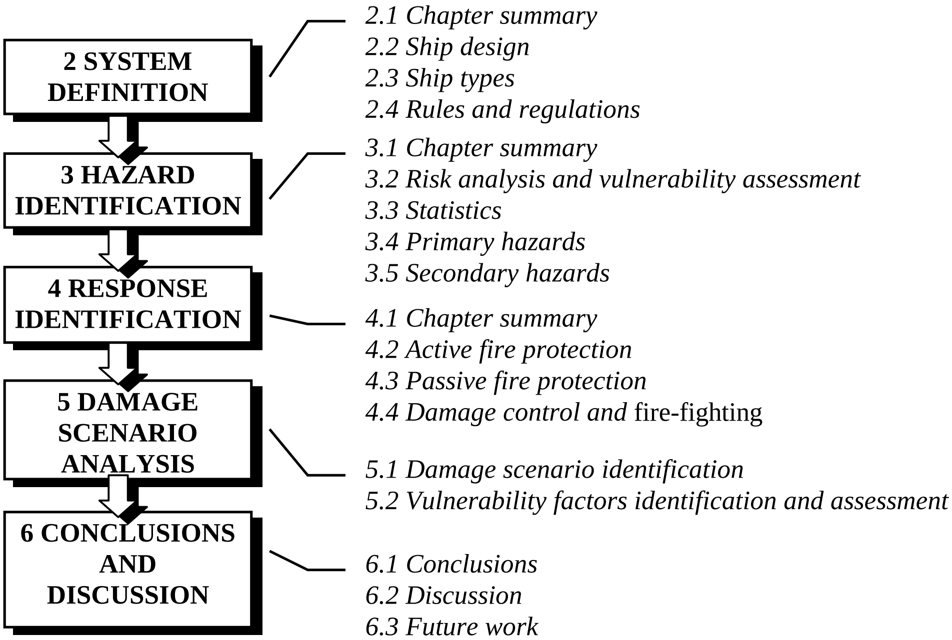

Figure 1-1 *Contents and working procedure for the paper.*

1.4 Limitations

Fire on board warships is a broad subject covering a lot of different areas, all of which can not be covered in this paper. The objective to present a broad analysis will naturally be on the extent of the depth of it. As one of the underlying purposes is to bring up aspects of weapon-induced fires that might be interesting, when considering the possibility to model the events through computer assessment codes, the analysis has to deal with general and broad conclusions prior to details. This is also a result of the author’s lack of background in shipping, which will bring focus to fire related issues prior to details on ship design etc. The key word could to a large extent be said to be simplicity, since modelling fire behaviour is not a science involving pinpoint accuracy.

One of the major limitations is that even though general events are analysed and key hazards and measures of protection are recognised, no real recommendations of more direct preferred actions are given except in an overview manner. Another example of the limitations following the above is that no deeper analysis of problems concerning stability will be presented (apart from those arising from excess use of water during fire-fighting). Very little will also be said regarding the defence and protective weapon systems of modern warships and how these are designed, since it is felt that this would fall under susceptibility (defined in chapter 3.2.1) studies. A ship’s possible lack of adequate, modern close-defences will therefore not be looked into any further. No consideration will be taken to nuclear, chemical or biological warheads and how these might effect the ship and its crew. In addition, the paper focuses on above water weapons and therefore will make no attempts to describe the events after impact of torpedoes and mines other than the general effects of fire initiation and behaviour with reference to particular cases.

To some extent human behaviour (e.g. irrational behaviour) and how fire will affect humans will be discussed, but no attempt will be made in order to evaluate certain aspects of protection for personnel, for example the effectiveness and risks associated with lifesaving systems. A further probabilistic approach on this particular matter has been presented (Alexandrov, 1970).

The study will not attempt to evaluate all different ship types, but mainly focus on frigate-sized ships and therefore to some extent include corvettes and destroyers. Submarines will not be dealt with at all, since they involve some very specific aspects of fire-fighting and fire protection measures.

Besides the fact that the studied *systems* are bigger than other, the situation is further complicated by the necessity for assessing the contribution to ship vulnerability of carried weapons, systems, equipment and vehicles such as amphibious vehicles and aircraft and their ability to function after weapons impact. This will be considered only to the extent to which this kind of equipment may pose a threat to the vessel itself.

Finally can be said that the following approach will be mainly deterministic, which means little will be said about event probabilities. In chapter 3.2.3 a review of methods and approaches used for risk assessment of warships and similar systems is done.

1.5 History

The following section is mainly to be seen as a background to fires on board warships based on information mainly gathered from three sources of information (Johnson; Pohler *et al.*, 1978 and Villar, 1984).

Almost every war has seen the destruction of warships by fire. In the era of sail, the losing ship was almost always engulfed in flames beyond the most ambitious fire-fighting efforts prior to sinking. It was not until much later that the nature of conflagration aboard heavily armed and armoured steel ships was first realised.

By World War I (WWI), the capital ships had become larger and their armament more capable. Despite this, the ships were now more vulnerable than ever before, much due to the large main battery rifles, together with their armour-piercing projectiles, that penetrated the magazines and initiated large fires. The Germans made the most progress in the direction of flash-proof scuttles during WWII, which proved when the *Bismarck* absorbed nearly 400 direct shell hits and about 6 torpedo hits before finally sinking. During WWII aircraft carriers were introduced to a new kind of conflagration involving the burning of high-octane aviation gasoline initially caused by bombs and Kamikaze attacks.

The British capital ship *HMS Hood*, which was never modified for the containment of powder flash from burning powder magazines after WWI experiences, suffered a direct hit from the *Bismarck* quickly leading to the explosion of the magazines. WWII made clear the vulnerability to conflagration from oil, aviation gasoline and explosives of many Japanese and American aircraft carriers, which had only lightly armoured decks. Many ships were lost due to these and after bomb and Kamikaze attacks.

The USN has experienced a few major fire disasters since WWII of which the major aircraft carrier fires have been the most severe considering loss and lessons learned. Other warships have also experienced fire losses, such as a number of serious fires on minesweepers that resulted in the total or near loss of several of these wooden hulled ships. Battery explosions and subsequent electrical fires onboard the diesel submarines *USS Cochino* in 1949 and *USS Pomodon* in 1955 (while in dry-dock), led to the sinking of the former and internal gutting of the latter. The most traumatic shipboard fires were by far those that occurred in the late 1960´s aboard the carriers *USS Oriskany*, *USS Forrestal* and *USS Enterprise*. The *Oriskany* fire was initiated by burning pyrotechnics, whereas the *Forrestal* and *Enterprise* fires originated on the flight deck during flight operations. All fires were characterised by hangar-deck and flight deck conflagrations fed by aircraft ordnance.

Several lessons were learned from these events. From the *Oriskany* fire in 1966 it was learned that a personnel Survival Support Device (SSD) was needed to permit crewmen to escape from smoke-filled environments to weather deck. A device was later developed containing an 8-minute supply of oxygen, which has many similarities to Escape Life Saving Apparatus (ELSA) currently in us in the Royal Navy (Great Britain) and by the Swedish Navy for example. The fires aboard *Forrestal* in 1967 and *Enterprise* in 1969 highlighted the inadequacy of fire protection on the flight decks of carriers. This was later addressed with the introduction of a flight-deck wash down system, which originally was an installation for removing contamination from chemical or biological attack now converted to a AFFF (see further chapter 4.2.2) system with spray nozzles.

Further lessons were to be learned in the early 1970´s when fires were experienced in the vital spaces beneath the heavily armoured flight deck on *USS Forrestal* and *USS Saratoga*. The intense heat and smoke in the narrow fore and aft passageways held off the fire-fighting parties for hours, thereby permitting extensive spread of fire damage. Later it was discovered that the fires had propagated along wire and cableways, passing through the non-watertight bulkhead openings. On the *Forrestal*, the furnishings and decorations, most of which were polymers, were sufficiently flammable to propagate an intense fire.

The most devastating shipboard fire before the Gulf War was aboard the *cruiser USS Belknap* following her collision with the carrier *USS J.F. Kennedy* in 1975 during an exercise. Most of the damage done to the superstructure resulted from melting of the aluminium structure above the steel 01-deck level during the topside conflagration. In the early stages the fire was fed by an estimated 4000 litres of jet fuel pouring from a fractured pipe on the sheared flight-deck fuel risers on the *Kennedy*. In 1977 the British frigate *Amazon*, lead ship of the Type 21 ships, had a narrow escape when an electrical fire started under the floor of her Operations Room. Fire-parties found that aluminium ladders had melted in the heat, making it impossible to get to the heart of the fire. Luckily the sprinkler system put the fire out.

2. SYSTEM DEFINITION

The first phase is concerned with describing the system (i.e. the ship) and shed some light on a few of the more important aspects of basic ship design, different ship types and rules and regulations. The flow chart below illustrates the contents and working procedure for chapter 2.

The deliverable from this phase is an overview understanding of key aspects of ship design regarding fire-related issues. The chapter starts with a short summary, introducing a few of the more important aspects brought up within this section.

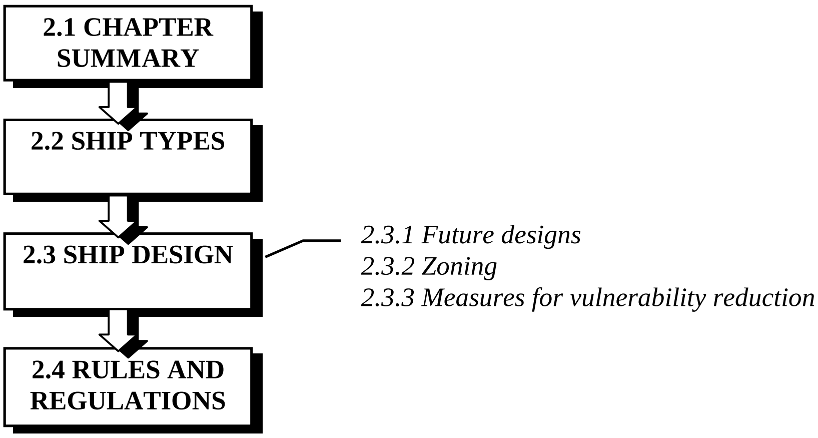

Figure 2-1 *Contents and working procedure for chapter 2.*

2.1 Chapter summary

The main objective of this chapter is to point out a few important aspects of ship design and especially fire-related issues. Warship design is a complicated task, which has to satisfy a number of contradictory needs. “Trade-offs” between different types of suppression and passive systems, the use of fire insulation etc. are needed in the overall process. The design of a warship is not bound by SOLAS (Safety Of Life At Sea), even though the construction in practise follows many of these guidelines.

Watertight subdivision and zoning (compare to the MVZs in SOLAS) of a ship’s services are a few of the more important factors in warship construction when considering the vulnerability of the ship. In the end, this should provide a way to practise the principles of concentration, separation, duplication and protection to reduce the vulnerability. Finally is concluded that measures for vulnerability reduction is best identified as early as possible at the design stage, and not backfitted as a result of after-thought.

2.2 Ship types

There are several different types of warships even though they have many similarities. The propulsion is usually by diesel engines, steam turbine, gas turbine, diesel electric or nuclear power. Other systems such as transmission, safety systems and other vital systems are solved very differently depending on where and how it is supposed to be able to operate and which navy it is used in. The modern warship, designed post Falklands, comprises a balance between optimised fighting capability, protection, safety and the need to provide suitable accommodation often for prolonged periods (Peacock *et al.*, 1989).

The largest ships are the **aircraft carriers**, which can carry up to about 80 aircraft. **Cruisers** are long-range reconnaissance and escort, lightly armoured covering for example the magazines, machinery and communications equipment. They have helicopter landing and hangar facilities. **Submarines** are large missile carrying nuclear powered or smaller hunter/killer (nuclear or diesel electric). **Destroyers** facilitate missile launchers, anti-aircraft and anti-submarine systems and usually have little armour protection and some classes make use of aluminium for superstructure and internal divisions to save weight. **Frigates** are ocean escort vessels for convoy protection and anti-submarine patrol with additional strike capacity. It is a sophisticated weapon, thin skinned and heavily armed for the size of ship. Anti-aircraft and anti-missile to larger vessels, support in landings, helicopters are carried gives anti-submarine capability and also anti-ship weapons and missile launchers. For propulsion, diesel, diesel electric or gas turbine is usually used. **Corvettes** are small, fast and heavily armed strike craft (60-90m) used for coastal defence. They carry surface-to-surface missiles, anti-aircraft and missile defences and some anti-submarine weaponry. These are lightly constructed and considering the relatively small crews, hold a considerable load of weapons. High-speed diesel, gas turbine or a combination usually manages propulsion. **Minesweepers** have wooden or GRP (fibreglass) hulls and a minimal of ferrous metal. These are lightly protected with self-defence capability and also carry anti-aircraft and missile defences. **Coastal defence and strike craft** (15-55m) are quick and facilitate fixed firing guns and missiles. These have small crews and a relatively large armament. **Fleet auxiliaries** are often larger supply craft (bunker oil in tanks, ammunition stocks, food supplies and spare parts) (Cox, 1997). The use of merchant ships in a wartime role has been showed in two World Wars, the Korean and Vietnam Wars, in the Falklands, where 55 vessels were used, and in the Gulf. However, these ships need additional vulnerability reducing measures such as improvements to the watertight sub-division and the addition of fireproof curtains Ro-Ro (Roll-on/Roll-off) vehicle decks.

2.3 Ship design

Warships are complex systems containing sophisticated weapons systems, advanced equipment and large amounts of ammunition and different fuels. Also, during wartime the ship and its crew are subjected to the constant threat of being hit by an enemy weapon and facing the consequences of this. Up until the events during the Falkland and Gulf War, design of shipboard fire protection systems has been evolutionary. After the ship was built and a hazard noted, a remedy was developed and backfitted if possible. This approach has since these events changed somewhat and substituted with a more proactive risk assessment in order to clarify the foreseeable mishaps already at the design stage. This is considered a positive development, since such studies performed should be considered an aid to design rather than an assessment of it.

The usual approach to ship design is to start by dividing the ship into fire zones, deciding on the damage control deck (lowest deck with fore and aft access), size the firemain system, locate the fire pumps and special fire extinguishing features such as magazine sprinklers, hangar bay foam systems and machinery space protection. After this, local and remote controls for various fire-fighting systems are selected and located, usually while the ship design is still fluid and spaces are being moved around. At this stage, efforts are made to provide two means of egress (at least from living and working areas) as widely separated in the compartment as possible, leading to areas that are separated by smoke tight divisions where possible.

When it comes to fire protection, there is no such thing as a fire-proof ship (unless extreme resources can be grasped) even though good warship design accompanied by correct training in fire-fighting and damage repair obviously are essential in minimising the dangers from fire. Cost and weight restraints also play an important part in reaching a compromise. A warship contains a number of high risk compartments such as magazines, machinery spaces, fuel tanks, control and operations room, where a hit could severely affect the ship's ability to fight or even move (Dimmer, 1986).

In order to accomplish a balanced ship design, there is a need for technical personnel representing a lot of different disciplines to be involved depending on the scope of the effort and ship under design such as (Said, 1995):

- Threat assessment
- Fragmentation and ballistic protection
- Shock
- Human factors and systems safety
- Fire-fighting
- Combat and communication systems
- Structural integrity
- Stability
- Signatures (radar, infrared, acoustics, magnetic)
- Weights
- Cost and producibility
- Survivability research and development

2.3.1 Future designs

A quick look at possible designs reveals several different innovative solutions for future warships. For instance, most ships today have a mono-hull construction, but feasibility studies are being carried out to find alternative designs. Twin-hull ships could for example be fast, quiet and very good in a seaway. However, they would have poor tolerance to minor flooding and be more costly than mono-hulls. Catamarans provide a very wide and stable working deck and they have good stability qualities in both intact and damaged condition (Sadden *et al.*, 1998; Jorde *et al.*, 1998). The main disadvantage is the penalty, which has to be paid on structural weight, which in turn means an increase of the power required.

SWATH (Small Waterplane Area Twin Hull) vessels were explored in the 1980's and are believed to have potential for very high survivability and better damage protection than mono-hulls from splinter damage and small projectiles, much because piping and cable systems can be protected according to figure 2-2.

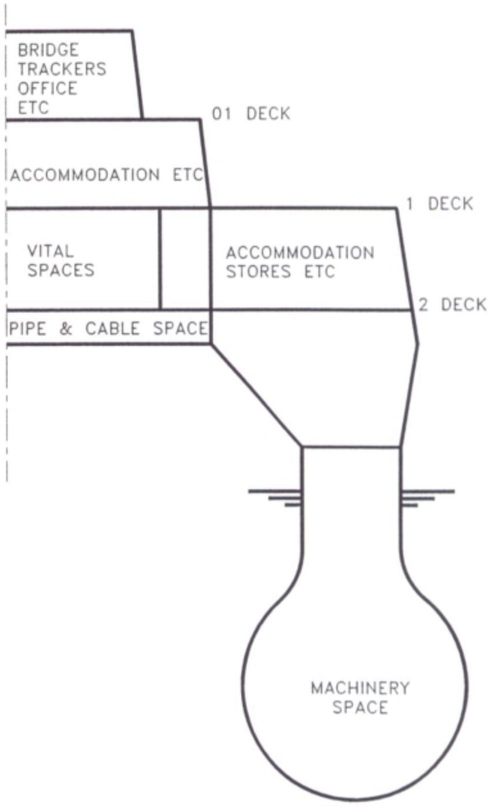

Figure 2-2 *SWATH arrangement principles showing half of the construction in a longitudinal view (Sadden et al., 1998).*

One of the great advantages of SWATH design is that even if the machinery arrangements in one hull is destroyed, the other hull can continue to operate effectively. In the middle of the "box", the magazines will be situated protected by double walls to reduce effects of an explosion. During the 1990's the focus is on trimarans, which are also believed to have good damage stability.

The Swedish Material Administration (FMV) and Karlskronavarvet shipyard in co-operation have developed an example of ship design using carbon fibre. The new so called YS 2000 is a 70 m, 35 kt design displacing around 600 tons, the specification for which includes especially stringent requirements on weight, shock resistance, strength and reduced signatures.

The vessel is built using composite materials and it has been shown that adequately designed FRP sandwich hulls with cross-linked PVC foam cores have a very high level of survivability due to their structural strength and inherent damping properties, which reduces the effects of shock on men and equipment. (Composite fire behaviour will be outlined further in chapter 3.5.4.)

YS 2000 was conceived as a flexible design, with top performance at both high and low speeds and capable of undertaking mine countermeasures, anti-submarine warfare, minelaying, surveillance and surface combat missions.

2.3.2 Zoning

In warship design, survival after damage is a fundamental objective. As a result, watertight subdivision and zoning are much more rigorous than in merchant ships and a greater measure of simplicity is accepted in living and working spaces in accomplishing fire resistance (Dawson, 1990).

Where practical, a ship should be divided into a number of smoke zones separated by water tight/smoke tight boundary bulkheads, which extend to the uppermost deck of their respective positions. The number of zones will depend on the size of the vessel, which could mean 4-5 zones on an average frigate (Brown *et al.*, 1990). The zones will be equipped with a number of separate systems such as air conditioning system and air filtration system. Smoke extraction fans are also installed in each zone. Ventilation trunking is not permitted to cross the zone boundaries in order to keep a fire limited to where it started. The main ventilation system fitted in *HMS Sheffield* (appendix C), for example, was not designed in fire zones, which led to smoke penetrating boundaries making smoke control impossible.

Access to and from the upper deck is provided in each zone to avoid necessity of crossing zone boundaries within the ship in the event of an incident on board. Where ventilation trunking passes through main watertight bulkheads within a smoke zone, locally operated watertight steel valves are provided in the trunking to enable those bulkheads to be made both fully water- and smoketight. Smoke curtains can also be provided at main watertight doors in passageways below the weather deck to limit the spread of smoke. In order to keep the different systems working in one zone, there is also need for independent power supplies and hydraulic systems as well as autonomous fire-fighting installations (piping, pumps etc.) for every compartment (principals see figure 2-3). The accommodation can also be split between the different zones to minimise the loss of life in the event of a direct hit and also to reduce the need for passage between zones (Peacock *et al.*, 1989).

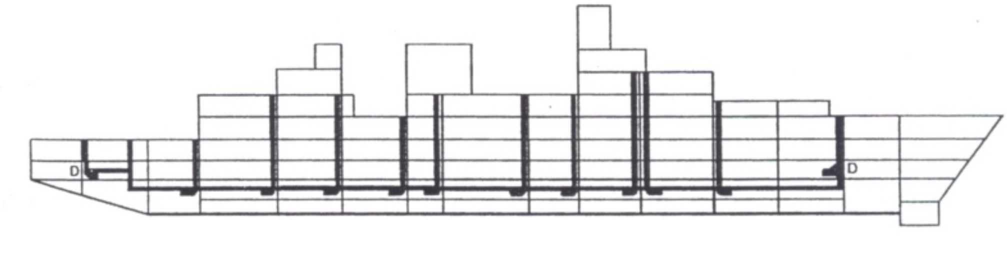

Figure 2-3 Fire-fighting *installations in separate zones (Ronken et al., 1998).*

A number of changes have been made to the design of for example the HPSW (High Pressure Sea Water) systems based on war experiences. Among the most important are the introduction of additional pumps, the provision of a low level cross connection and the remote operation of valves to isolate the system into sections prior to action or to reconfigure in the event of damage. Ideally, in terms of operational efficiency and vulnerability, pumps should be located as low down and as close to the ship centreline as possible. Furthermore, pumps in adjacent compartments should be sited well away from their dividing bulkhead. The prime objective should be to locate one HPSW pump in each fire zone. Of course, without power these measures will be no good. Electrically driven pumps within the system are now provided with alternative electrical supplies from the emergency diesel generator with facilities for local starting as well as operation from the ship control centre (Peacock *et al.*, 1989).

2.3.3 Measures for vulnerability reduction

This section will merely point out a few general aspects of vulnerability reduction associated with basic ship design (these measures will be discussed further in chapter 4). Essentially these can be divided into the following main categories:

1) those built into ship design (e.g. location of equipment and passive fire protection), and
2) those added to the ship as additional protection (e.g. active fire protection and equipment for manual fire-fighting).

When it comes to warship vulnerability, there are a few basic principles to be considered as to the location of equipment.

Concentration is when there is only one means to achieve a certain function, then all the components, linked in series, should be concentrated into the smallest possible space in order to reduce the probability of the system being hit. For instance, there is an increased recognition of the need to co-locate all the equipment and ship systems required to operate each weapon or propulsion system in warships and this has been reinforced by the events in the South Atlantic. Zoning of ship's services, to ensure that all weapons are not put out of action by one single hit, has also been recognised for a long time, but the increase in sophistication of weapon systems has made it almost impossible to retain this feature in modern ship designs.

Duplicate items of equipment are often installed in a parallel arrangement in a ship for availability, reliability and maintenance. This can have important implications for survivability if care is taken to ensure that both items cannot be made to fail by the same incident. This action helps providing some kind of redundancy. Therefore duplicate equipment or equipment performing similar functions should be **separated** to maximise survivability benefits.

Minimising the vulnerability (to blast, fragmentation, fire etc.) can therefore be accomplished by separating parallel systems and concentrating series systems as shown in figure 2-4. The opposite approach will generate very vulnerable system linked in series and a risk for loss of more than one parallel system, given a hit at a particular location.

Protection can be used to complement or replace the above measures. Examples are blast resistant structures, armouring and layered Kevlar sheets to protect whole compartments.

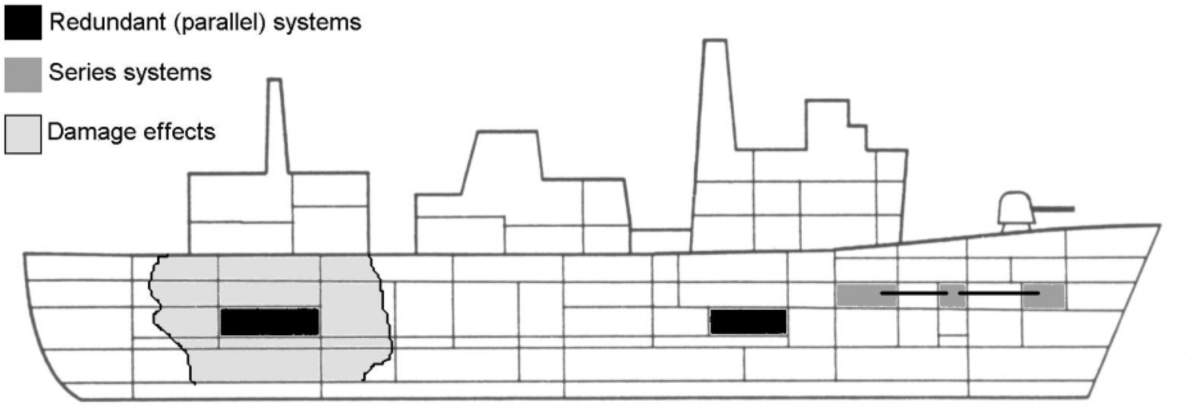

__Figure 2-4__ Concentration, duplication and separation as means to decrease vulnerability (reproduced from Martin, 1998 and Tozer, 1993).

Additional risk reducing measures are of course different types of active fire protection such as sprinkler and carbon dioxide systems added to high risk/high value compartments. These could be operated manually or automatically depending on many factors such as system type, location and design. There is no way concluding that one solution is better than another and system design differs from one navy to the next. It would seem that automatic systems in many cases are needed to fight a fire in its incipient stage and not let it grow out of control, while manual systems sometimes takes to longer to operate and therefore do not fill their intended function. Passive measures of protection are also used for both short term and long term protection purposes. Initially there is a need to keep the affected compartments intact so that a fire will not be able to spread to adjacent compartments. The long-term effects are mainly to keep the fire from spreading from one compartment to the next by means of heat conduction.

Fire detection systems are used to detect the fire at an early stage and to be able to fight the fire as soon as possible. “Trade-offs” between detection systems, extinguishing systems and fire insulation materials are frequently made, which in the end alters the safety parameters including fire load, time, manning requirements, space, weight and cost.

2.4 Rules and regulations

Warships are not bound by the legislation in SOLAS (Safety of Life At Sea), since military vessels and troop carriers along with a few other ship categories such as wooden and fishing vessels are excluded. In practice, however, the construction will broadly follow the similar guidelines with some exceptions such as the location of weapons magazines, accommodation spaces and ventilation systems. Smaller warships generally lack armour protection of any substance, while larger ships such as destroyers have armour plating over vital areas and much more extensive compartmentation than merchant ships. Also, sometimes the alternative can be double, triple or multiple “inner” hulls instead of the armour (Cox, 1997). The purpose of SOLAS is not that it should be referred to as an afterthought, but rather woven throughout the concept and design phases of the ship’s plans.

Main principles of the SOLAS convention are (Croquette, 1992):

- Division of the vessel vertically into main sections using bulkheads with mechanical and heat resistance (MVZs - Main Vertical Zones,). The vertical escape route for each MVZ (which was introduced in 1948 in the SOLAS convention in order to sub-divide passenger ships and the enclosure of main staircases to restrict internal spread of fire) is a key element in the means of escape. The stairwell is considered a safe place and here the passengers should be safe until reaching the lifeboats. Public spaces that contain a large number of people (restaurants, atria etc.) should have direct access to stairwells, while cabins, lockers and storerooms should not. MVZs are the foundation on which all structural fire protection for passenger ships is built (Murtagh, 1990). They serve several purposes such as limiting the spread of fire and smoke, facilitating fire-fighting management and limiting the travel distance to safety.

- Separation of living quarters from the rest of the vessel using bulkheads, which have mechanical and heat resistance.
- Restricted use of combustible materials.
- Protection of exits and entrances for the purpose of fire-fighting.

To some extent merchant ships are used in military operations as well, mostly as fleet auxiliaries. Merchant ships are different types of ships such as tankers and container ships. The fire protection measures on board these ships varies from protecting only the machinery room spaces, corridors and stairwells to covering all spaces with at least heat detectors. When it comes to passenger ships, the safety has increased after the accident aboard *Scandinavian Star* and includes for instance that all spaces need to be covered with smoke detectors. This includes all newly built ships from 971001 (Idestrand, 1992).

At present, SOLAS regulates details of the fire protection on board such as the number of fire pumps, hoses, equipment, requirements for emergency power supplies etc. available on a ship of a certain type. Also regulated is the need for fixed fire-fighting installations on vehicle decks on passenger vessels, machinery spaces of all ships and cargo areas of tankers. CO_2 or halon alternative is the most common one in machinery spaces, not 1301 but instead for instance FM200 (see 4.2.5). Release warnings and shut down of ventilation has to be completed before releasing a CO_2 system due to the toxic effects. After 1994 sprinkler systems are compulsory on passenger vessels in the accommodation spaces, public and service spaces (retroactively done by 2005). High-speed passenger carrying craft must also have sprinklers in special category spaces (manual or automatic). SOLAS also makes provision for structural protection of ships, requirements for compartmentation and subdivision to create fire barriers and reduce risk of uncontrolled fire spread. The MVZs, for example, require A60 division and atria must be located in one MVZ, be fully sprinkled and have two means of escape. A few spaces such as machinery spaces and car decks are required to be separated by class A divisions (welded steel construction, suitably stiffened). When it comes to ventilation, it is important that the ducts and dampers designed to close automatically, have the same integrity as the bulkheads. Smoke detection or air sampling controls the ventilation system, which brings the system to exhaust or shut-off mode. Automatic fire detection and alarm is required in the cargo areas of Ro-Ro vessels and also in all corridors and stairway enclosures (Cox, 1997).

SOLAS is now developing towards being more functionally based in order to let new solutions and materials being let forward that will still meet certain demands in safety. The basis for this should then be some form of risk analysis. Eriksson (1998) gives an example of how this could be performed (coupled to the High Speed Code).

3. HAZARD IDENTIFICATION

The second phase is concerned with identifying major fire hazards associated with weapons effects. These hazards are divided into **primary** and **secondary** hazards, where primary are those directly related to weapons effects and secondary related to particular equipment and materials on board. However, this section will start with an overview of methods and approaches for risk assessment of warships and offshore installations, which have some similarities when it comes to the hazards for fire and explosion. A review of available statistics and peacetime incidents is also included.

The deliverable from this phase is an understanding of key hazards (threats) to the system when considering fire as a result of weapon impact.

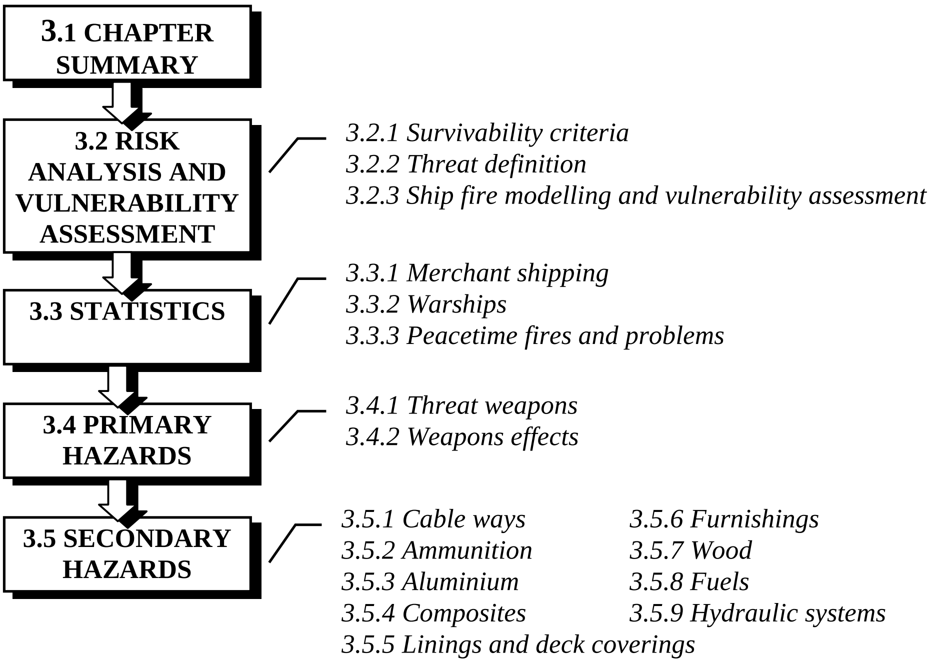

Figure 3-1 *Contents and working procedure for chapter 3.*

3.1 Chapter summary

Chapter 3 is mainly concerned with introducing a few of the main hazards associated with ship fires in general and weapon-induced fires in particular. These potential hazards, in order to enhance overall survivability, need to be identified already at the design stage. Important in evaluating vulnerability, is the definition of suitable survivability criteria and a realistic threat, to which the vessel might fall victim and be expected to survive. The use of ship fire modelling and vulnerability assessment codes can be a valuable aid not only to design, but also in the evaluation of vulnerability of existing ships.

Statistics reveal that no decline in the total number of fires on board ships can be concluded, and that nearly half of all ship fires originate in the machinery room. Human error, negligence, lack of maintenance of the ship and equipment, failure to follow the lessons of past experience and carefully drawn up procedures are a few of the factors which contribute to the losses sustained. Most fires on board warships seem to be relatively minor and are extinguished within the first few minutes, creating little damage. Electricity appears as one of the main sources of ignition on board warships in peacetime. However, more detailed incident reports from peacetime fires are desired, since studying and learning from incidents is usually a good approach to accident prevention.

Finally, fires as a result of weapons effects are much more likely to occur in present day ships, due to the nature of weapons as well as the amount of combustible material and other hazards on board. Merchant ships in a wartime role have proven to be considerably more vulnerable to attack weapons than warships, mainly due to the lack of watertight bulkheads.

3.2 Risk analysis and vulnerability assessment

Since one of the main objectives of this paper is to identify the major hazards associated with fires on board warships in general and weapon-induced fires in particular, this will give rise to several simplifying assumptions and limitations. A more accurate approach would be to perform some form of risk analysis of a single ship or class of ships, since the risks could then be analysed further than here. This kind of approach is getting more common and there are many advantages in identifying potential risks already at the design stage, instead of back-fitting equipment after a hazard is noted. Performing risk analysis at this early stage, will provide a cost effective method for hazard identification when only the basic ship system is defined, and provide a good overview of the problems which might arise from particular design. The preliminary design stage is also the most appropriate time for the analysis of a ship’s proposed fire protection systems, because the ship is defined enough to conduct a meaningful fire safety analysis. If some hazards (or means of protection) require further examination, attention can be readily focused upon areas where the greatest hazards exist.

Risk assessment first found wide-scale application in the nuclear industry, from where usage spread to the general process industries. Today it is found in a growing number of areas including offshore and shipping. One way of characterising the different methods used are as qualitative or quantitative (further outlined in SRV, 1997)(there are semi-quantitative methods as well such as rapid risk ranking).

Qualitative methods are used mainly to identify the most hazardous events and examples are HAZOP (HAZard and OPerability analysis), What-if analysis, FMEA (Failure Mode and Effects Analysis) and checklists. These methods contribute to the identification of deviations from a system’s standard performance and are usually part of a larger risk analysis, i.e. it will be a step on the way to a more quantitative consequence and probability analysis. They could, however, be used as analyses in their own right. The HAZOP study, for example, has been developed to identify operability problems that, even though not hazardous, could compromise a system’s ability to achieve design productivity. Finally, search in accident data bases and locating relevant statistics are usually obligatory parts of the hazard identification procedure as well.

Quantitative methods such as QRA (quantitative risk analysis) are strongly recommended on for instance offshore installations. After the disaster involving Piper Alpha (see further appendix B) and the subsequent Cullen report (The Hon Lord Cullen, 1990), the Safety Case was introduced. This included a full description of the system, systematic identification of all major hazards and risk assessment to demonstrate that risk levels had been reduced to as low as reasonably practicable, known as the ALARP principle. The Safety Case is a key feature of the offshore safety policy and has similarities to the Seveso Directive[1] and the Safety Report, which has to be included in the Safety Case. The main purpose of this directive is the prevention of major accidents and limitation of potential consequences. This approach differs from the compliance with a set of prescribed standards, as is typical of regulatory documents (Squires *et al.*, 1998). Parts of the offshore Safety Case could be applied to shipboard risk analyses as well.

In practice, it would be almost impossible to carry out a rigorous risk assessment of all explosion and fire events on ships and offshore platforms due to the lack of knowledge of event probability and determination of consequences of an event. The analysis would then have to be limited to certain conditions. Examples of methods to use are the following:

1) *Worst Case Analysis* can be performed on critical systems or parts of the structure without any attempt to estimate the probability that such an event will occur. The advantage of this approach is that the method concentrates on identifying the vulnerable parts of the structure, which would then be designed to provide adequate protection regardless of the probability of the event.
2) *Identified Event Analysis* is an identification of critical scenarios that need to be considered and evaluated in order to improve conceptual design. Again, this method avoids the complexities of considering the overall consequences in probabilistic terms.
3) *QRA* (Quantified Risk Assessment) is a method that recognises the probabilistic nature of events and event sequences. There are four basic concepts in the QRA:
    - identification of the likely accidental events,
    - the consequences of the event,
    - the frequency of occurrence, and
    - the acceptability criteria.

Quantitative methods can then in turn be either **deterministic** or **probabilistic**, where the prior focuses on describing the hazards in terms of consequences and the latter takes the frequency of occurrence into consideration when determining the risk.

In performing a QRA, there are a few additional tools the analyst can use. Event Tree Analysis evaluates potential accident outcomes that might result following an incident known as an initiating event. These provide a precise way of recording the accident sequences and defining the relationships between the initiating events and the subsequent events that combine to result in an accident. Event trees are well-suited for analysing events that could result in a variety of effects (e.g. effects of weapon impact (example in figure 5-6), and events following a release of flammable oil and gas on an offshore platform) and it is possible to consider the consequences as well as probabilities of an accident outcome (chapter 3.2.3).

Fault Tree Analysis is in many ways a similar technique to event trees and is useful in identifying the causes of critical system conditions. Working from the top event, the analyst uses the fault tree structure to trace the possible causes down to basic events, usually equipment failure modes. Human failures can also be included. The disadvantage of the

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[1] The Seveso II-Directive has now replaced the previous directive, but no major changes have been done except there is a greater emphasis on environmental issues in the new directive (SRV, 1998).

technique is that the quality of the results are much dependent upon the skill of the analyst and in particular his understanding of the system (Jones *et al.*, 1993).

Finally, the conclusions drawn from an assessment will need to be justified and should reference all the sources of evidence or record the principal assumptions made so that they can be challenged if it emerges that they are critical to the outcome. Different actions to reduce hazards on board and improve safety are no better than to the extent hazards have been recognised in the first place. No single procedure can ever be best for all cases (Jones *et al.*, 1993).

3.2.1 Survivability criteria

Before initiating a risk analysis or any kind of vulnerability assessment, there is a need for setting of acceptable and realistic survivability criteria for the system. These criteria for a warship's systems and different vital spaces should be based on a defined "design threat" (chapter 3.2.2).

Historically, ship survivability has been defined as: "The capability of a ship and its shipboard systems to withstand a weapons effects environment without sustaining impairment of their ability to accomplish designated missions." However, **survivability** can better be described as the product of three major elements, which are susceptibility, vulnerability and recoverability (Squires *et al.*, 1998).

Susceptibility refers to the inability of a ship to avoid being damaged and to its probability of being hit. This in turn could be said to deal with three factors; the operating condition, the threat and the ship itself (the capability to delay discovery, weapon decoy and weapon interception and destruction).

Vulnerability refers to the inability to withstand damage effects from one or more hits, to its vincibility and to its liability to serious damage or loss when hit by threat weapons. Factors such as ship size, compartmentation and separation of vital systems will affect the performance. Minimising vulnerability is all about countering the instantaneous effects of a hit. Minimising the effects of a hit on systems may be achieved by either minimising the damage to the equipment itself by hardening or protecting the equipment, or, accepting the damage may still occur, the effect of the damage may be mitigated against by duplication or redundancy.

Recoverability refers to the ability of a ship and its crew to prevent loss and restore essential functions given a hit by one or more threat weapons. This is a function of damage control features built into the ship, shipboard allowance of damage control equipment (quantity and type) and crew training and abilities. Maximising the recoverability of a warship is somewhat difficult. The key issues are being able to recover from the longer term effects of the hit, these being mainly flood, fire, smoke and damage to essential services, particularly electrical power and firemain.

3.2.2 Threat definition

In the author's view, an important step on the way of setting suitable survivability criteria, is a definition of the threat (and subsequent consequences) the system as a whole is supposed to withstand (figure 3-2). First after this has been done is it possible to determine requirements for matters such as manning (damage control and fire-fighting) and level of protection of the vessel. The conflict of the future is likely to be one where naval ships are constrained in the use of force but still required to face a real threat. Winning this war may not be a matter of overcoming the enemy with superior force; it may simply be surviving an unprovoked or unexpected attack (Squires *et al.*, 1994).

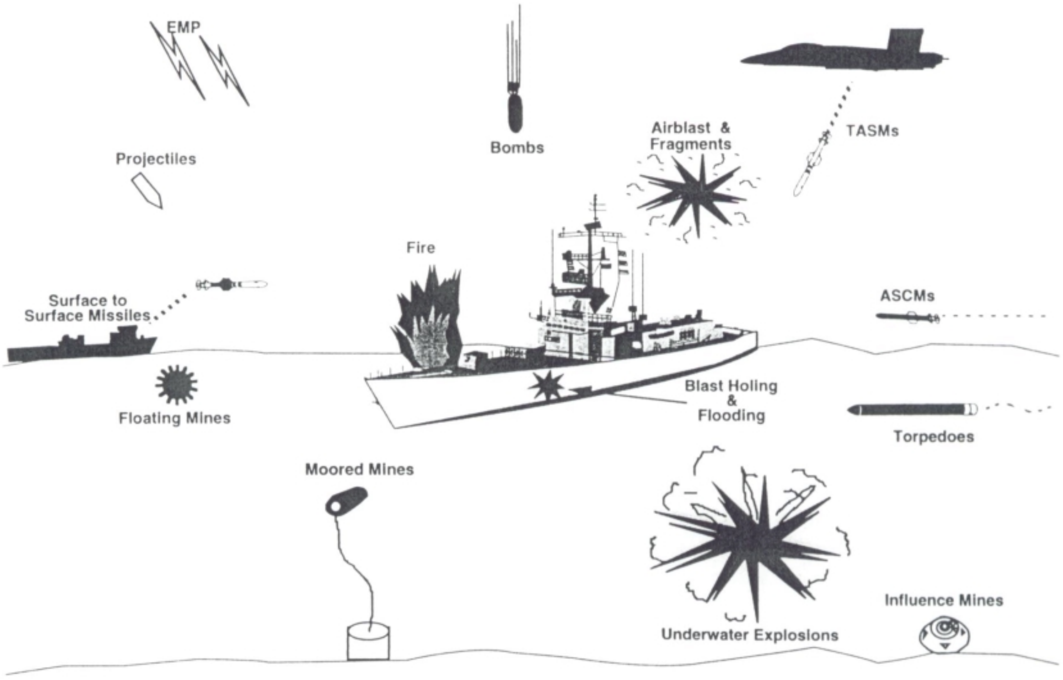

Figure 3-2 *Anti-ship threat weapons and effects (Said, 1995).*

It would seem that relatively little that can be done to guarantee the survival of a relatively small ship, say a frigate of under 5000 tons displacement, from multiple hits by modern anti-ship missiles (Smit, 1998). It is therefore important to define a realistic threat to which the ship might fall victim and the aim must be to maximise the ability of the ship to survive that attack. The "design threat" should summarise the overall data (e.g. air delivered, proximity bursting) and technical details (e.g. TNT equivalent charge weight, warhead type, type and quantity of fuel carried) for each threat weapon. The design threat may for example take the form of a single or perhaps double hit by sea-skimming missiles such as the *Exocet*. Designing ships for action damage is assessed to be more than adequate to cater for peacetime incidents such as collision, grounding and accidental fires. For most countries this is also a natural consequence of a prolonged period of peace and stability. (Martin, 1998).

3.2.3 Ship fire modelling and vulnerability assessment codes

Ship fire modelling and vulnerability assessment codes are good ways of evaluating the future vulnerability of a certain design. The problems of predicting fire behaviour aboard ships can be found in other sectors of society as well, and constitute but one part of evaluating overall vulnerability of a ship type or class. When it comes to weapon-induced fires, these are often considered a secondary effect (such as flooding), even though it is not unusual that they are more severe than the primary effects of blast and fragmentation. Several different models have been developed over the years and a few of these are briefly presented in appendix A along with a further discussion.

There are two major classes of computer models for analysing enclosure fire development and the first, **probabilistic or stochastic models**, generally treat fire growth as a series of sequential events or states. Mathematical rules are established to govern the transition from one event to another. Probabilities are assigned to each transfer point based on analysis of relevant experimental data, historical fire incident data and computer model results. In contrast, **deterministic models** represent the processes encountered in a compartment fire by interrelated mathematical expressions based on physics and chemistry. The deterministic approach has the advantage that the results are more easily assimilated (temperatures etc. rather than possibilities) and answers the question “What are the consequences of such a scenario?”.

In using different approaches to fire modelling, it should be noted that some factors are more suitable to a deterministic approach, while others would benefit from a probabilistic. When considering weapon-induced fires in particular, it is the author’s opinion that well-established models to predict damage due to blast and fragmentation effects exist today. When it comes to modelling fire growth (within the compartment) and spread (to adjoining compartments), reliable deterministic models can also be relied on. However, in order to describe factors such as fire ignition and effects of active systems and fire-fighting measures, a more probabilistic approach is preferred. This could mean finding suitable probabilities for fire ignition, where the probability depends on factors such as type of weapon used, fire load in the affected compartment etc. Another factor where a probabilistic view could be used is the effects of actions, which can not be modelled easily or an area where the knowledge is not good enough to use deterministic models. An example already mentioned is the activation and efficiency of suppression systems and manual fire-fighting actions. Of course, a well-trained and motivated team will have better chances of fighting a fire than a lesser well organised team with unreliable equipment, and these are matters that need to be considered. When considering suppression systems for example, it might be a good solution to solve the problems with a mix of deterministic and probabilistic approaches. The former could be used to define where for example splinters have ruptured vital parts of a sprinkler system, something that in the end will lead to a low probability of activation and suppression.

Finally is recognised that modelling the vulnerability (and to some extent the recoverability) of a warship, will depend on the ability to model fire and smoke itself as well as many other factors such as the actions taken by the ship’s staff under extreme conditions. One of the greatest advantages of assessment codes is that the computer predictions can show up unexpected results and highlight vulnerable or critical points, which are sometimes overlooked by other types of analyses.

3.3 Statistics

In order to establish a background to the concept of war-related fires, which fortunately enough are rather infrequent, the following includes a review of peacetime and wartime statistics as well as incidents in warships and commercial vessels during peacetime operation. It is felt that an important background in many cases is made up by well documented and structured statistics. This is an aspect to consider in most risk analyses no matter what area.

When it comes to finding relevant statistics of fires on board warships, this has proved quite difficult to accomplish. It seems that relatively few of the peacetime incidents that occur on board warships are actually being reported in more than an overview manner, even though some wartime experiences are documented in a more extensive manner. However, if fires on board ships in general (e.g. merchant and passenger vessels) are considered, more information is available.

3.3.1 Merchant shipping

Looking at statistics from Institute of London Underwriters shows no real reduction of the number or gt (gross tonnage) of ships lost to fire and explosion. According to Harvey (1990), the total gt losses by fire and explosion from 1959 to 1988 indicates no decline in the fire loss percentage of merchant ships, but instead a continuing similarity in that ratio.

More recent statistics (Institute of London Underwriters, 1994) verify that fire and explosion accounts for about 21% of the total number of vessels lost for the period 1990-1994 (see figure 3-3).

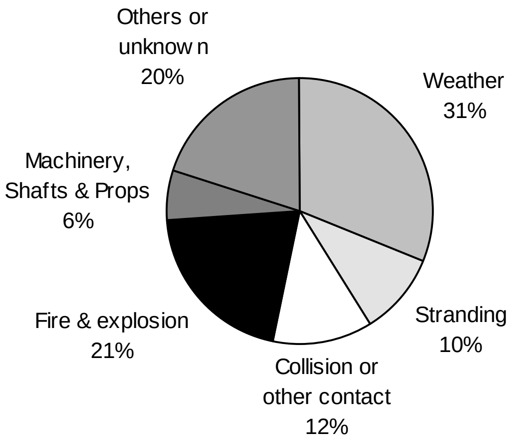

Figure 3-3 *Number of total vessels lost 1990-1994 (Institute of London Underwriters, 1994).*

When it comes to identifying the location of fire outbreaks, statistics from the period 1984-1988 point out machinery spaces as being the place of outbreak for most fires that occur (Institute of London Underwriters, 1988) (see figure 3-4).

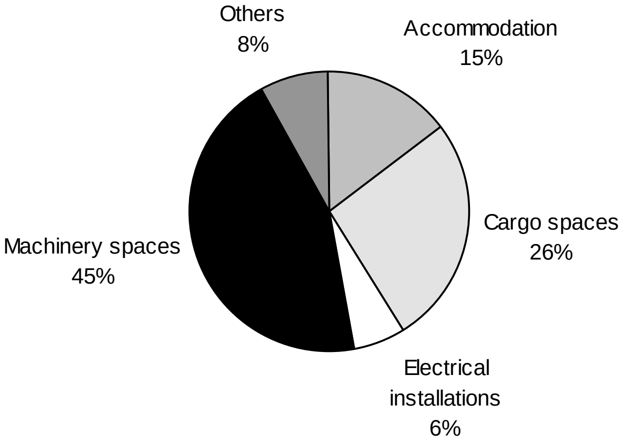

Figure 3-4 *Location of fire outbreak (Institute of London Underwriters, 1988).*

Swedish incidents reported during the period 1990-1997[2] (Sjöfartsverket,1998) verify the above statistics in the sense that out of a total of 93 reported incidents involving fire and/or explosion, 47% occur in machinery spaces with accommodation and cargo spaces as second and third. Flammable material (e.g. fuels, lubrication oil) igniting upon contact with hot surfaces is by far the most frequent cause for fire initiation. This was the case in one third of the cases. Most of the fire incidents remaining in the statistics can be considered caused by human behaviour (e.g. arson, smoking and welding). Electrical failures account for about 12% of the total number of fires.

Similar conclusions can be drawn from statistics the Japanese classification society Nippon Kyokai presents (Iwamoto, 1994). From 1980 to 1992, engine room fires damaged 73 ships classed by the society. Human error was the dominant cause due to maloperation or incorrect repair. There was found no correlation between the number of fires and a ship's age, tonnage or nationality.

There is a difference to be seen where vessels are well manned and maintained. As seen from the above, more outbreaks of fire occur in the machinery spaces than anywhere else, caused in most cases by spray of fuel or lubrication oil, impinging on a hot surface and igniting. Another frequent cause of very expensive fires is burning or welding on a bulkhead/deckhead/deck adjacent to a space containing flammable material or gas, or doing the same thing close to a vent pipe of a tank which is gaseous.

When it comes to the loss of life, about 90% of all people killed in shipboard fires are due to smoke inhalation and only 10% from heat exposure (Jensen, 1994). The total figure for deaths on board ship due to fire and explosion, compared to other types of incidents, is 39% (average over the years 87-92) (Hesler, 1995).

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[2] At the time of presentation of this paper, not all incidents (8 out of 21) from 1998 had been investigated and summarised. However, nothing indicates a major change in the trend described. 6 out of 8 fires originated in the machinery space, mainly as a result of fuel igniting upon contact with a hot surface.

Finally a few words about fire detection and suppression. It is not really possible to draw any far reaching conclusions on how fires are fought on board and the effectiveness of different measures of suppression, since statistics provide only limited information on this matter. Most of the fires reported by Nippon Kyokai were detected by the staff and only 19% by fire alarms (Iwamoto, 1994). About 40% of the fires were extinguished by portable extinguishers (mostly within 15 minutes) and about 18% by fixed CO_2 systems. Roughly 20% were put out by seawater which increased damage to electrical equipment, while 20% were extinguished by a fire-fighting vessel or burnt themselves out naturally. These numbers are hard to verify by means of other statistics since it generally contains very limited information of fire behaviour and methods of suppression.

3.3.2 Warships

Even though it would have been convenient to assume that fire onboard warships always would come as a result of hostile fire, peacetime incidents frequently occur and are far from always a result of explosions. Similar to the statistics for merchant vessels, the record of for instance the USN (United States Navy) regarding peacetime fires has not necessarily improved with the years. Up until 1978 it appeared to have worsened since WWII, as measured by the frequency of fires and subsequent losses. No attempt is made here to try and validate this statement, since data on peacetime incidents regarding naval ships both the for the Swedish and other navies seldom is well documented and accessible.

	Total numbers	**Losses**
Explosion	27	1 submarine
Fire	Approx. 10/year	3 minesweepers
Collision	115	1 submarine, 1 minesweeper
Grounding	50	1 frigate
Flooding	1	1 submarine
Docking accident (storm)	2	1 frigate, 1 submarine

Table 3-1 *Accidents to HM ships - 1945-1984 (Brown et al, 1990).*

From the above table can be seen that losses have been rather infrequent in the RN (Royal Navy, United Kingdom) since the earlier part of the century. However, fire is by far the greatest cause of reported accidents as well as total losses and some of the ships in the above table were so severely damaged that repair was uneconomic. The inquiries of some of these disasters have sometimes (at least in the UK) led to calls for improving particular aspects of design, but no overall verdict that the standards are too low has been made (Brown *et al.*, 1990).

The MoD’s (Ministry of Defence) Naval Support Command (NSC) manages a fire reporting system on behalf of the Royal Navy and from this a few important lessons can be learned (Blackmore, 1994):

- On average, 130 fires are reported each year of which 90% are relatively small and extinguished within the first few minutes.
- Approximately 50% originate in machinery spaces with a further 20% in electrical spaces. In about 30% the ignition source is electrical.
- Relatively high success rate in small fires not developing into major conflagrations.

During WWII the RN had about 1,000 incidents, 140 involving involved fires of which 50 were large (Blackmore, 1994). These attacks resulted in the loss of 250 ships, 58 of which involved fires, and of these 37 were large. A large number of serious fires were caused by shells or bombs exploding in the vicinity of the boiler room, causing fuel fires and loss of electrical power and pumping capability. Another common cause was the ignition of cordite by fragments penetrating magazines. Bombs caused 44% of the fires, shells 24% and torpedoes 22%.

In the Falklands, fire was the main cause of five ships out of six being lost. There were 20 incidents in which RN ships and ships taken from trade were attacked. Three attacks were cannon shells causing minor material damage and no fires. 14 attacks were by bombs, in some cases accompanied by cannon fire. In some of these cases the bombs did not explode, although the direct hits on the ships caused structural and equipment damage. One minor fire occurred and an unexploded bomb igniting the ship ammunition caused one major fire. In incidents where one or more bombs exploded or deflagrated within the ships, fires occurred and developed into extensive major fires. The ships were abandoned when the reduced fire-fighting capabilities could not contain them. In one case the bombs caused such severe damage to the hull that flooding and capsize was the primary cause of loss. One ship was subsequently recovered. Three attacks by *Exocet* missile caused major fires, which in one case was contained but in the other two cases the fires became uncontrollable when fuel and ammunition ignited and fire-fighting degraded.

Comparing this campaign with WWII, out of 20 incidents, eight involved fires, of which seven were large. Six ships were lost, five of them as a direct result of fire. Apart from bombs, the attack weapons were different. There were no attacks by underwater weapons and the effects of guided missiles are not directly comparable with those of WWII weapons. However, the Falklands War shows that fire is much more likely in present day ships as a result of weapon attack than in earlier ships. Fires caused by weapon effects differ from peace-time fires in that the exploding weapon produces a fire ball of very high temperature. Combustible material in the vicinity is caused to ignite, thereby increasing the heat in a very short time. Large quantities of smoke are produced. Combined with this are the damaging effects of blast and fragments. Not only does this degrade the fire-fighting systems but may cause rupture of fuel tanks or ignite ammunition, adding to severity of the fire. The behaviour of weapon-induced fires will be further investigated in chapter 5.

As part of an examination of the need for passive protection measures, an analysis of large peacetime fires between 1969-1984 was performed (Akhurst, 1985). The overall result is presented in table 3-2 below.

Space of fire origin	Number of fires
Machinery spaces	54
Stowage	38
Electrical spaces	10
Electronic spaces	8
Accommodation	3
Galley	3

Table 3-2 *Spaces of origin for large fires in Royal Navy ships 1969-1984 (Akhurst, 1985).*

It is concluded from the above table as well that fires in machinery spaces are the most common peacetime fires aboard warships (in the RN) as well, with about 47% of the fires originating here. A slight difference from fires in for example passenger vessels is that accommodation fires are infrequent and the reason is most likely that the occupants, who usually "create" the fire, are able to extinguish it before a major fire develops. On a passenger vessel this type of fire is normally lit intentionally (arson) and therefore harder to suppress in its incipient stage. The fires in electrical and electronical spaces are normally due to short circuiting or overheating. The relatively large number of fire outbreaks in stowage rooms is due to a variety of reasons, most frequently exhaust heat or electrical failures.

Finally statistics from the Naval Safety Center (1998) has been analysed and a few differences can be shown when compared to statistics on civilian vessels. A number of 932 fire incidents has been evaluated in the following (no weapon-induced fires). First of all, it can be concluded that the number of mishaps involving fire on board US Navy warships has decreased during the period 1990-1997 (reported incidents) as illustrated in figure 3-5.

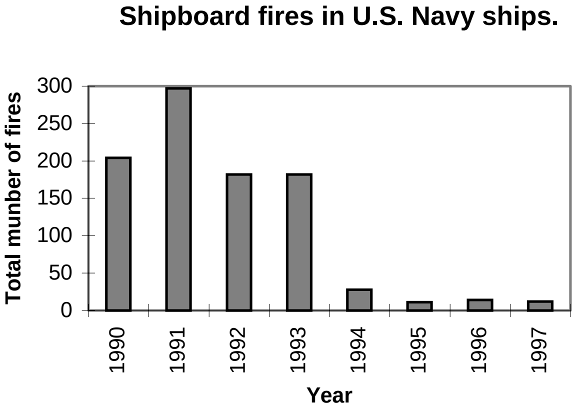

Figure 3-5 *Reported shipboard fires in US Navy ships 1990-1997 (Naval Safety Center, 1998).*

This indicates that the fire safety has improved over the last couple of years in the US Navy or that the crew is more aware of the present hazards. The location of fire outbreak is not given in the statistics, but the source of ignition is and this is shown in figure 3-6, pointing out electricity as the main source of ignition e.g. (electronic control and guidance systems and high voltages). About one third of the category "Other" consists of causes that could not be determined at the time of the incident, and nearly as much in the same category is caused by activities in the galley (e.g. overheated grease).

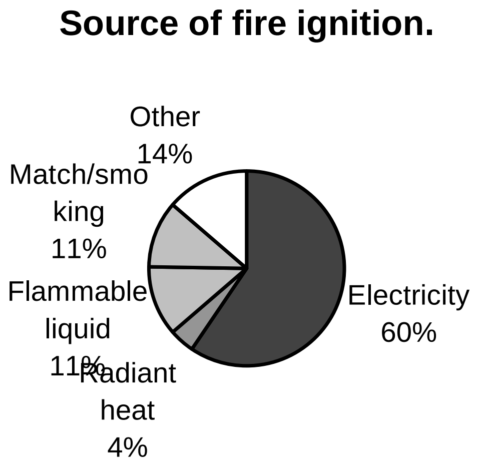

Figure 3-6 *Source of fire ignition on board US Navy ships 1990-1997 (Naval Safety Center, 1998).*

Finally, the fire mishaps can be classified after event severity and depending on what material was burned (table 3-3). The fire classification used is according to the NFPA[3] (National Fire Protection Association) and the classification of event severity will not be penetrated in detail. However, "A" is the most severe event generating considerable financial loss or loss of life and "D" is a mishap in which the resulting total cost of property damage, injury or occupational illness is relatively minor. "B" and "C" identify intermediate event outcomes.

	Fire classification					
Severity	A	B	C	D	Other	**Total**
A	3	5	0	0	0	**8**
B	2	8	14	0	0	**24**
C	35	18	87	2	4	**146**
D	167	106	477	1	3	**754**
Total	**207**	**137**	**578**	**3**	**7**	**932**

Table 3-3 *Fire mishap severity and types of fires in the U.S. Navy 1990-1997 (Naval Safety Center, 1998).*

Table 3-3 concludes that most mishaps become incidents and not many cases end up major accidents. Above table (as well as figure 3-6) illustrate that fires caused by electrical systems are rather frequent and also that of the more severe cases, burning of petroleum products play an important role. Finally, statistics from the New Zealand Navy can be used to verify certain aspects of these results (NZ Navy, 1998). The statistics involve 20 incidents and electrical causes of ignition are the single most common cause of fire ignition here as well.

3.3.3 Peacetime fires and problems

As available statistics clearly show, there has been no real decline in the total losses of ships due to fire and incidents involving fire (except in the US Navy). Since weapon-induced fires luckily enough are rather infrequent, there is need to consider peacetime fires in order to shed

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[3] A -burning of rubbish, trash, paper etc.
B - burning of any petroleum product, gas, oil grease etc.
C - fire caused by energising/operating electrical systems/equipment.
D - burning radioactive material or metals producing toxic fumes/gas.

some light on fire behaviour and suppression of ship fires in general. The next step involves a characterisation of peacetime incidents into a number of categories, where particular hazards and subsequent fire behaviour are identified as well as possible weaknesses in design. The different categories are illustrated with examples where applicable. The study is found in appendix B, but the more important conclusions will be given in the following.

After the initial literature study, following categories of interest were identified and categorised:

1) *Arson*
    - These fires are less likely to be discovered and fought in its incipient stages, since ignition is often initiated in secrecy, and
    - they are associated with a number of different locations on board.

2) *Accommodation fires*
    - These are often characterised by rapid fire and smoke spread, many times due to the open plan design of a ship accommodation (comparable to hotel fires).

3) *Vehicle deck fires*
    - These are often rather violent in their behaviour, and
    - on vehicle decks of for instance Ro-Ro ships, fire growth could be fast generating a massive production of toxic smoke due to the fact that usually no sub-division is applied here.

4) *Engine room fires*
    - Most likely of all fires to lead to total loss of a ship due to the rapid fire development (often flash fires), intense heat and large amounts of smoke produced, causing low visibility.

5) *Galley fires*
    - These are considered rather infrequent, and
    - the spaces are usually well protected.

Several categories could be added to the list such as cargo fires, but in some of these cases to little information was found to be able to come to any conclusions. Other cases might be of little or no relevance when considering the purpose of this study.

The fire scenarios studied involve some very different assumptions in regards to factors such as fire and smoke spread, fire severity and possibilities for fire-fighting to mention a few. The high temperatures (up to 1,100°C) experienced in some cases show similarities to basement and underground fires. Some ships, while in dock, have proven even more vulnerable since the fire protection measures often are disconnected and welding and flame cutting are the most common causes leading to fires.

Anyway, a few of the more interesting contributing factors to the magnitude of the incident can be concluded to be:

- ⇒ The failure to extinguish the fire in its incipient stage by either automatic or manual suppression. In a few cases the automatic fire detection system was out of commission because of misuse and this in turn slowed down any fire-fighting efforts.
- ⇒ The fuel loading of the cabins in the area of initial fire involvement.
- ⇒ The failure of fire station hoses on board the ship when fire crews attempted to place these lines in service.
- ⇒ The low availability and poor reliability of portable fire-fighting equipment was in a few cases considered contributing to accident outcome.
- ⇒ Manual actions such as ventilation system shut down, have sometimes proved to take a long time before being taken, generating an increased smoke spread to other areas of the ship. In machinery room fires, a delay in emergency fuel shut-off or failure in closing watertight doors for example, is likely to increase the fire severity as a result of the large fuel load introduced and quick fire spread throughout the machinery spaces.
- ⇒ The rapid horizontal and vertical spread of products of combustion throughout the ship caused mainly by open fire doors.
- ⇒ The presence of combustible interior finish materials in passageways and in the stairwell.

A few actions and circumstances, where fires did not become conflagrations, can be identified and summarised as follows:

- ⇒ Resolute action by fire-fighters in the incipient stages of the fire has dealt with fires successfully in a few cases on the condition the water pressure was maintained.
- ⇒ The value of sprinklers and other suppression systems (both manual and automatic) can be clearly demonstrated.

3.4 Primary hazards

The primary hazards described in the following, are those directly related to the weapons effects. The main threat considered in this paper is defined as weapon impact and subsequent fire and therefore the effects of this is looked into a little further in the following. First an introduction to some of the more common threat weapons is given.

3.4.1 Threat weapons

Today almost every nation with a navy possesses modern anti-shipping weapons such as anti-shipping cruise missiles (ASCMs), tactical air-to-surface missiles (TASMs), surface-to-surface missiles, bombs, projectiles, torpedoes and mines. The damage potential of modern anti-shipping weapons was demonstrated by the varying experiences of *HMS Sheffield, USS Stark* (missiles) and *USS Samuel B. Roberts*; *USS Tripoli* and *USS Princeton* (mines) to mention a few (Said, 1995).

Ships are generally larger in size and complexity than other weapon systems and must be prepared to deal with a different mix of threats. They are also subject to significant secondary damage such as fire and smoke, the extent and duration of which frequently depend on crew actions. As previously mentioned, a major consideration for ships is the time required after damage to return the ship to a war-fighting capability. Navy ship primary missions include for example anti-air warfare (AAW), anti-surface ship warfare (ASU), antisubmarine warfare

(ASW), strike warfare (STW) and mine warfare (MIW), all of which could bring the ship into positions in which it may encounter attacks by threat weapons.

A significant difference in ships with respect to aircraft and land based systems is that secondary and cascading damage is more likely to comprise a greater part of the total damage than for other systems. Examples are again the missile hits of *HMS Sheffield* and *USS Stark* (appendix C). As previously discussed, the terms "primary" and "secondary" refer to when the damage occurs, not the significance or extent of the damage. **Primary damage** results from the immediate effects of threat weapons and includes damage resulting from warhead penetration, blast, shock, hull whipping, fragments and heat. **Secondary damage** occurs after primary damage and includes for example fire and smoke spread and progressive flooding by free communication with the sea.

3.4.2 Weapons effects

Weapons effects can be divided mainly into two kinds:

- **Primary weapons effects** that include kinetic energy, blast, fragmentation, shock and whipping (depending on weapon type).
- **Secondary weapons effects**, which include spread of fire, smoke and flooding.

Typically, an anti-ship missile relies on a combination of blast and fragmentation to inflict damage, where blast is the dominant internal damage and fragmentation external after a detonation. Blast loading occurs when during an explosive event the burning gas or vapour expands, creating a flow of gas ahead of the flame. The overpressure created by such an event depends on whether the blast is confined or vented and in the geometry of the structure which can magnify the blast effects (Dow *et al.*, 1994(2)).

A stand-off mine or torpedo, if detonated close to a ship's hull, could generate bubble jetting into ship or localised shock damage to smash a small portion of the hull, therefore initiating flooding. If detonated further away, the effects of whipping (the pulsating bubble can excite the whole hull at its natural frequency) could give rise to plastic deformation or even the ship's backbone being broken and the ship sunk.

Fragmentation, blast and spread of decomposition products (nitrous gases) occurs in a matter of milliseconds, while the effects of fire and smoke are a matter of anything from seconds to minutes or hours in duration. There is a need to consider both long-term and short-term effects of the fire and smoke problem. Short-term effects can be reduced by passive measures, like improvement of the ship's structure for example. Also automatic measures are possible, like installing sprinkler systems, but crew actions are usually ruled out. However, the consequences of fire and smoke spread can generally only be considered in view of time. The fire can develop rapidly, especially after a missile impact, but the spread to adjacent compartments takes time and can, therefore, be influenced by the behaviour of the crew. The main threat considered in this paper is the above water threat, in particular the penetration (and possible detonation) of a missile-delivered warhead inside a frigate. It is felt that this is one of the major threats to frigate sized ships (Smit, 1998).

Fragmentation can itself present a serious threat to the ship. When designing offshore structures for explosion, there is a need to consider projectiles, that can lead to further structural damage and escalation of the initial event (Dow, 1994(2)). These are primarily of two types; primary projectiles and secondary projectiles, where the secondary represent the unsecured and other shattered objects. These usually possess enough kinetic energy to rupture piping or parts of hydraulic or fuel systems, which in turn could initiate fires.

For offshore installations, it is worth noticing that the interaction between explosion and fire effects will depend on whether the explosion precedes the fire or occurs during a fire. For structures designed for passive fire protection and sited in high explosion risk areas, consideration must be given to ensure that the fire protection capability is not compromised due to the effects of the blast loading. If the firewater main is ruptured during an explosion then there would be a reduction in both pressure and volume to the distribution system. The firewater main should therefore be designed to withstand the effects of blast and projectile damage and to resist the effects of blast wind loading. Temperature increases due to fire effects can severely reduce the material properties of the structure. This reduction when subjected to explosion loading could result in excessive plastic deformation of the structure and a reduction in buckling and collapse loads for structural members.

Weapons effects will naturally affect the personnel on board as well as the different systems. Therefore a quick review of the major factors affecting personnel from fire and blast loading is given (Dow *et al.*, 1994(2)).:

1) *Blast overpressure* (the blast wave generated by the explosion),
2) *blast wind* (this can cause damage by knocking people off balance, hot burning gases in the blast wind can also cause severe injuries and projectiles in the blast wind can also cause severe injury),
3) *combustion products* (inhalation of toxic gases, CO_2, CO, HCN, low level oxygen levels),
4) *hot objects*,
5) *hot air* (convection processes can lead to burns),
6) *radiation* (can lead to skin burns), and
7) *fire protection systems* (halons, which decompose upon contact with hot surfaces or flames, to produce toxic gases).

3.5 Secondary hazards

Earlier fire was characterised as a secondary weapon effect (damage), which could follow in the event of a weapon impact. In the following, when characterising some of the hazards surrounding fires on board, the term secondary hazards is used. These are intended to include fire hazards associated with particular materials and systems of a modern warship, which of course holds a lot of flammable material, by far the largest being the fuel and ammunition followed by electrical cabling, deck and bulkhead linings and furnishings. A ship compartment fire is severe due to the large number of fuel sources, small areas with restricted air movement and the presence of steel bulkheads, which radiate a portion of the heat back into the compartment. Temperatures near the top of the compartment can reach over 1,100°C.

The trend to replace steel as structural material with lighter substitutes such as aluminium and composites, which are less fire tolerant, has created the need for increased fire protection. Today’s ships use considerably larger quantities of organic polymeric materials, which are more susceptible to fire than metals are. Fire safety requirements have also increased due to reduced manpower and increased sensitivity of today’s advanced weapons and electronic systems to damage by fire. The multitude of material on board also adds to the complexity of establishing a good fire protection. Everything from plastic, rubber, thermal/electrical insulation, upholstery, wood, paper and clothing to flammable liquids such as gasoline, diesel and cooking oils, compressed gases and explosives are found on board. Selection of fire safe material for ships must be accomplished in consideration of things such as overall ship vulnerability to fire, new ship design concepts, fire spread and damage scenarios, fire detection, fire-fighting and smoke suppression technology. These improved materials can be used for a variety of shipboard applications. Structural materials that will reduce the fire damage without serious weight penalty, non-burning deck coverings, high temperature exhaust and blast resistant materials, lightweight and fire protective sheathing for aluminium structures and fire resistant material for cables and wires are just a few of the application areas. Consideration should also be given to the use of commercial items in the manufacture of military material (De Marco, 1991).

The following sections bring up a few of the more important (in the author’s view) secondary hazards found on modern warships today. The points made reflect a mix of previous experiences, research & development and design considerations.

3.5.1 Cable ways

January 1984 on the *USS Tattnall*, a fire originating in a locked compartment spread through electrical cable ways. Before being contained, this fire caused loss of life, extensive damage to critical systems and prevented the ship from completing her assigned mission. An investigation revealed that the fire started as a result of cable way discrepancies (e.g. sparks or short-circuit) (Hendricks *et al.*, 1989).

Due to the large amount of sophisticated electronic systems aboard ships today (about 280 km of cables on a destroyer), the integrity of the electrical cables is vital. These cables can be a critical issue for a ship in either a combat or non-combat situation if a fire occurs. For example, one of the more important conclusions from the *Stark* report was that after the initial burning of the propellant, the fire was fed primarily by the high fuel load of the PVC (poly-vinyl chloride) jacketing of the electrical cables plus normal combustibles present in the berthing compartment. The PVC has a high flame spread when ignited. The cable ways can become the routes of fire propagation from compartment to compartment throughout the ship. The heat release of the burning PVC is substantial enough to ignite other materials in the ship. The resultant heat build-up can also be lethal to a ship’s personnel. Burning the PVC releases dark, dense smoke, which makes it hard for fire-fighters attempting to locate the fire and slows the egress of evacuating personnel. Burning PVC releases hydrogen chloride (HCL) gas, which is very acidic in the presence of moisture. The HCL poses a health threat and along with the smoke, can be transported to other areas of the ship through the ventilation system. The acidic HCL will corrode electronic equipment, further hampering critical functions.

The Naval Research Laboratory (NRL) conducted large scale cable fire tests in 1985 on the decommissioned tanker *Albert E. Watts*. These tests showed that after the fire was ignited, smoke filled the passageway outside the test compartment within two minutes (Ward *et al.*, 1990). The cables became totally involved within minutes and burned for 3.5 hours, the PVC also produced flaming drips. The stuffing putty was blown out of the collar due to over-pressurisation allowing the fire to travel into the forward compartment and consume the entire cable run.

The US Coast Guard also performed fire tests on uncoated PVC cables while monitoring the oxygen, carbon monoxide and carbon dioxide levels. The tests concluded that protected cables burned less and only generated a slight O_2 depletion.

3.5.2 Ammunition

Explosives are unpredictable and sometimes generate sufficient oxygen in the combustion to be self-sustaining. Missiles, for instance, usually contain two forms of explosive charges. The propellant is a “low” explosive which may detonate under some circumstances, but will usually burn with some intensity. The warhead is filled with high explosive, which may be expected to detonate if involved in or subjected to a fire.

One problem is that large fires in compartments adjoining storage rooms or magazines could generate slow cook-off of explosives. In order not to let too much heat penetrate the surrounding walls of the magazine, there is a need for some form of isolation to be applied. Usually these compartments are also equipped with some kind of protection system such as a sprinkler or deluge system. It is in general recognised that a fire close to a ship’s ammunition magazine will constitute a high risk for total ship destruction.

3.5.3 Aluminium

Aluminium has been used for many years on naval ships, particularly for superstructure, in order to reduce weight and improve ship stability. Aluminium is a high strength-to-weight ratio material with a density one-third that of steel and a corrosion resistance, which actually takes place some ten times faster in steel under corresponding conditions. When exposed to fire, it loses its strength very rapidly (compared to steel under the same temperature conditions) as shown in figure 3-7. Steel suffers metallurgical changes as well as simple thermal expansion, if heated to a temperature of 650°C. Aluminium suffers deleterious metallurgical changes at about 200°C (can be assumed to have lost all of its strength) and melts at about 650°C. Protection of structures of this kind should normally be supplemented by sprinkler systems or with a greater depth of insulation (Cavenagh, 1992 and West, 1982). Some degree of caution should be taken when applying thermal (and acoustic as well) insulation, since this in itself may provide a fire propagation path.

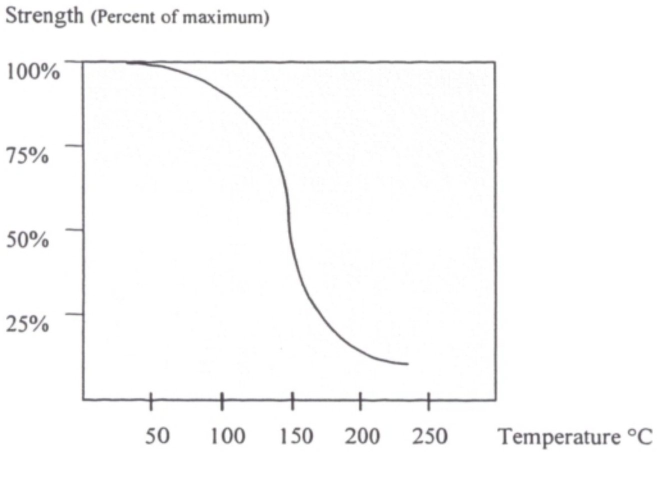

Figure 3-7 *Effect on temperature on ultimate strength in aluminium (Eriksson, 1998).*

The application of aluminium was highlighted by the fires, which raged on *Sheffield*, *Invincible* and *Ardent* as results of weapon hits (see appendix C). There was a lot of talk in the media about “firetrap ships” where aluminium burnt and contributed to the loss. The truth was that the ships had steel hulls and superstructure and aluminium contributed in no way to *HMS Sheffield’s* (destroyer) loss for example. The loss of *HMS Sheffield* was mainly due to the burning of oil (Horlick, 1983).The frigate *HMS Ardent* was also lost as a result of fire and her aluminium superstructure did not contribute to this at all. However, the advantage in using steel over aluminium and light alloys in a ship’s superstructure, is not that the steel will stop a missile (as the sinking of *Sheffield* and *Coventry* showed), but it may at least localise a fire once the ship is hit (Villar, 1984).

Aluminium does not burn under natural conditions since the melting point is considerably lower than the ignition point. This means that aluminium melts away from the heat source before the ignition point is reached and could therefore vent a fire in the case structural parts melts away. This also means that aluminium will not contribute to the production of toxic gases. However, aluminium does burn at a temperature of about 2000-3000°C and has an intensive blue/white flame and leaves behind a powered grey/white ash.

Another problem with aluminium is the increased splinter effects in the event of a weapon hit. This was experienced by the cruiser *USS Worden*, which was hit by an anti-radiation missile while cruising off Vietnam. The missile exploded about 25 m overhead, showering the ship’s superstructure with fragments, destroying electrical cables and radar equipment. After analysing the event it showed that some 60% of the damage had been done by fragments of aluminium - it was estimated later that for every fragment of warhead the aluminium panels had generated two more and assisted in the ship’s destruction (Villar, 1984).

3.5.4 Composites

Composite materials have been used in the marine industry for over 50 years and their use is increasing as their burning behaviour is better understood and regulations evolve to reflect current technology. The application of fibre-reinforced polymer matrix composites offers the potential for significant weight, cost, signature and maintenance reductions as well as improved corrosion control and lower thermal conductivity. Composite components can be up to 80% lighter than steel and 40% lighter than aluminium (Gagorik *et al.*, 1991) Composite materials are being seriously considered as replacements for marine aluminium alloys currently used for ship superstructures. Seaborne applications for these materials include for example mine countermeasure vessels, much due to the low magnetic signature this will give rise to because of the non-magnetic, non-conducting hull structure. Consideration is given to the construction of machinery components (e.g. piping, valves and heat exchangers) as well as auxiliary items such as ventilation ducts. Primary and secondary load bearing structures such as lightweight foundations, deckhouses, masts etc. are also considered.

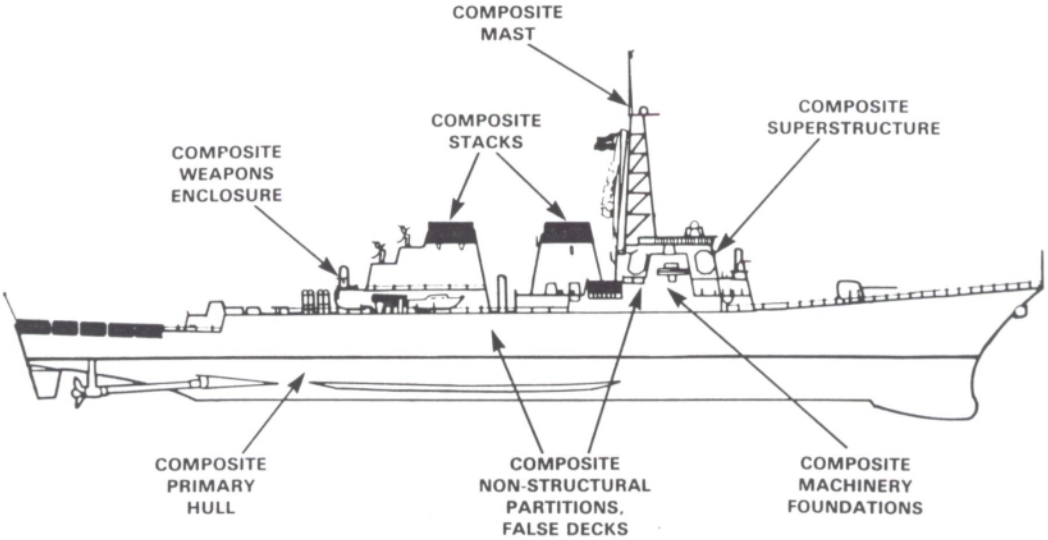

Figure 3-8 *Potential composite ship structures (Gagorik et al., 1991).*

The inherent chemical nature and complexity of these materials makes analytical prediction of their behaviour when exposed to a high heat flux from a fire source hard to predict, since they selectively burn, produce smoke, release heat, chemically degrade, produce char and delaminate. This could mean that the use of composite materials also can introduce the potential for increased hazards associated with fires aboard ships and submarines.

Two guiding criteria have been established earlier (by the U.S. Navy) regarding the use of composite systems aboard naval vessels. The composite system will *not be the fire source*, i.e. it will be sufficiently resistant to fire ignition not to be the source of spontaneous combustion. This is also an important factor to ensure adequate response time and to minimise the spread of the fire. Also, secondary ignition of the composite system will be delayed until the crew can respond to the primary fire source, i.e. *the composite system will not result in rapid spreading of the fire* (Sorathia *et al.*, 1997 and Caplan *et al.*, 1996). Generally speaking, fire performance of materials can be categorised using the following factors (Dow *et al.*, 1994(1)):

1) *Fire growth* (ignitability, flame spread, heat release and flashover),
2) *habitability* (smoke and toxicity), and
3) *residual strength and structural integrity*.

Suppression of fire growth potential calls for measures which either preclude the heat from an external fire getting to the surface of a composite or which dampen the inherent response of the resin to this heat. Water sprinkling or oxygen exclusion readily extinguishes most composites, and provided woven reinforcement is used, provide a partially effective flame barrier in the form of exposed glass fibres. However, emission of smoke and fumes by burning resin (mainly poly- and vinylester) presents a serious problem which may require special ventilation and fire-fighting facilities. Intumescent and other fire resistant coatings (see chapter 4.3.1) can provide effective protection. At one extreme is total fire insulation of the composite. This has been suggested as a solution for both hazard of fire involvement and for the threat of structural collapse. Developments in fire research and understanding of fire dynamics have highlighted the importance of heat release rate (HRR) as one of the primary fire hazard indicators. Fire hazard under a given set of conditions of fuel load, geometric configurations and ventilation conditions can be expressed in terms of HRR and the fire hazard analysis should include the relevant fire response parameters of a material. If HRR during a fire is low, the ability of the fire to spread or act as a source is greatly limited.

Heat weakens the polymer binder and functioning of the binder is therefore diminished and the composite loses strength. The second problem is that the binder may ignite and support the flame spread on the composite surface and also release heat and generate potentially toxic smoke. Thus the localised, external fire may cause a larger structural fire involving the composite which now becomes the fuel for the growing fire. In confined or enclosed spaces such as ships, the growing fire could lead to flashover condition in which all combustible materials within the enclosure begin to burn. Compared to many flammable materials, composites have a built-in advantage that helps resist the extensive fire involvement. This is a result of their high fibre content, which displace polymer resin, making less fuel available to the fire. When the outermost layers of a composite lose their resin due to heat induced gasification, they act as an insulating layer, slowing heat penetration into and evolution of gases from the depth of the composite. The process could be described as the three stages of degradation, delamination and pyrolysation not further investigated here. All these effects contribute to a loss of strength in the laminate.

Naturally composites, as a organic material, will actually burn when exposed to sufficiently high temperatures. However, the low thermal conductivity of composites assists by slowing the damage progression. This means it can be a good thermal barrier, providing a period of grace for response or evacuation and a protection against spread of fire (figure 3-9). This can be compared to the large temperature rises that will occur on the unexposed faces of steel bulkheads and can cause rapid propagation of fire (Allison *et al.*, 1991).

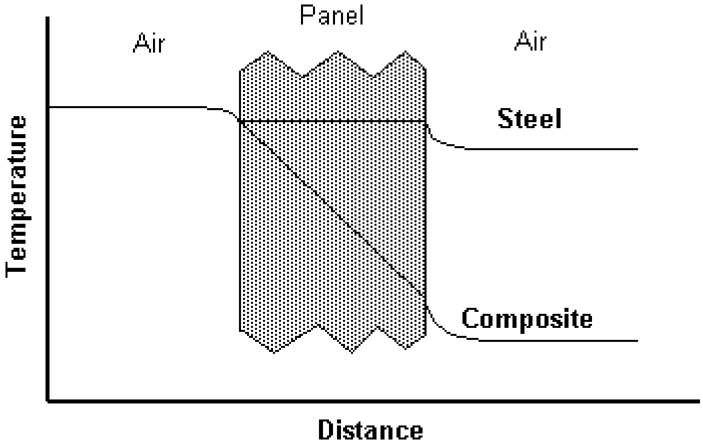

Figure 3-9 *Temperature gradient across panels (reproduced from Dow et al., 1994(1)).*

Structural composites for naval, commercial marine and infrastructure applications are typically glass reinforced with polyester, vinyl ester, epoxy or phenolic resins and these all offer different properties, which the following section briefly will show.

Epoxy resin offers superior mechanical properties, while phenolic resins has the main advantage possessing good fire resistance (high flammability resistance - longer ignition times), and has low smoke emission in comparison to vinyl- and polyester laminates. Nevertheless this must be balanced against their inferior mechanical properties when compared to polyester for example.

To improve the low flammability protection offered by poly- or vinylester resins, additives are incorporated either by chemical modification of the resin or as fillers. Most commercially available fire-retardant polyester or vinylester resins are modified by the attachment of suitable halogen to the polymeric backbone of the resin. Although the halogen effectively alters the burning characteristic of the resin, it produces toxic decomposition products. This is not considered acceptable, especially in confined areas such as ship bulkheads.

To summarise these events, polymeric composite systems will ignite and flame will spread when subjected to high enough heat fluxes. In most systems tested, the fire did not seem to propagate without additional external source of radiant heat (Sorathia *et al.*, 1991). However, all composite rooms could be driven to flashover by small fires over a period of time, even though insulated composites did not flashover in similar tests. Even bare composites provide thermal penetration resistance. There were no unusual requirements for fire extinguishment and in most cases water sprinkling was adequate, also where re-flash occurred. In the tests, a combination of insulation and fire-hardened beams delayed the composite’s involvement in the fires and prevented structural failure for approximately 90 minutes (Caplan et al, 1996).

There was a major fire in the engine room on a RN GRP (glass reinforced plastic) vessel, *HMS Ledbury* (a mine counter measure vessel), which started as a diesel oil fire in a machinery space. Very high temperatures arose fast within the compartment, well in excess of 600°C. Apart from some burn-through via a gland into an adjacent compartment, the low thermal conductivity of the GRP prevented the fire from spreading to adjacent compartments. Adequate cooling of the structure was difficult and re-ignition occurred in several instances. The repair of the damaged structure, however, was not difficult. This put together points at the fact that GRP laminate has the ability to act as a thermal barrier and to contain a major fire. In turn, this could allow for increased application of these materials (Allison *et al.*, 1994).

3.5.5 Linings and deck coverings

Generally speaking, experiences have shown that linings for bulkheads are best omitted when possible. Unsupported plastic laminate forms a splinter hazard if not backed by for example aluminium. Lightweight metallic honeycomb removable linings are also recommended.

What kind of linings are chosen for different compartments is important when considering whether flashover is reached or not (Kokkala *et al.*, 1991). Experiments (large scale) with different linings show that even a textile wall covering on gypsum board in fact comes very close to flashover with a little help from external radiation. The tests were performed in a high and large room (9.00*6.75*4.90m) with a small ignition source, which left the potential for flashover to a great extend to depend on the processes related to so called upward flame spread on the wall and ceiling surfaces. In smaller compartments within a ship, the effects linings have on the time to flashover conditions are bound to be significant.

Deck coverings were found to be a significant fire hazard in the Falklands and a policy for their removal from passageways in non accommodation areas was subsequently introduced.

3.5.6 Furnishings

Another category of hazardous material includes plastic furnishings etc., weighing some 100 tonnes a frigate (Dimmer, 1986). Furniture should be constructed from metal with a minimum of other materials, since this will otherwise contribute to increased fuel loads of the different compartments. Another important note to make, is the fact that fire-retardant materials often give off more smoke than materials that burn easily.

3.5.7 Wood

Wood has always played an essential role in ship construction. However, the hazards associated with it, namely flammability and splintering, were confirmed as being unacceptable in the Falklands War. Thus, a directive was issued soon after Falklands that the amount of wood on board should be reduced to the absolute minimum. Steel furniture has already become the norm in modern warships. Wooden ladders have been replaced by steel, supports for linings and other internal fittings and storage racks in store rooms are manufactured from steel or light alloy. Some of the changes have also reduced the need for maintenance.

3.5.8 Fuels

For fundamental design reasons, bulk fuel has always been carried deep in the ship. In addition to this, ready use supplies are provided in tanks convenient to their point of use relatively high in the ship in vulnerable spaces. Efforts should be done to keep all fuels as deep as possible in the ship (Peacock *et al.*, 1989), thus reducing the probability of contact with missile fragments, unburned missile propellant or the resultant fire following an attack. A typical frigate will hold about 700 tonnes of fuel and stowing the fuel below the waterline can significantly reduce the fire hazard.

As identified earlier, another area of great hazard is the engine room, where large amounts of fuel might be released and ignited onto hot surfaces. Due to the often violent nature of these fires they, as fires close to ammunition stores, constitute a high probability of ship destruction.

3.5.9 Hydraulic systems

The use of hydraulic power systems is decreasing and is being replaced by the use of air or electric power where possible and otherwise the less flammable water-based hydraulic fluids are used (Peacock *et al.*, 1989).

Even so, because of its high power density, flexibility of application and arrangement and ability to respond quickly and accurately to mechanical, electrical or manual signals, hydraulic power is widely employed for marine application. Therefore several hundred miles of hydraulic piping can be found aboard a warship, even though the trend seems to go towards self-sustaining units in less need of a larger pipework, which also helps reducing the vulnerability of the system. Networks of rigid and flexible pipes interconnect power units, control devices and actuators in machinery compartments, ring mains provide hydraulic power to winches and lifts and the transfer and handling of shells and missiles involves numerous control valves and actuators with extensive interconnecting pipework. Ships steering stabilisation and other systems also rely for their operation upon hydraulic power. These systems operate at pressures of anything from 10-300 bar. When this equipment is sited close to the heated surfaces of other equipment the fire hazard is greatly increased, fires have for example resulted from the auto-ignition of oil-soaked thermal lagging situated below leaking hydraulic fittings. The first components of a hydraulic system to fail in the event of fire are rubber joints seals and hoses. Simple laboratory tests using a gas-burner to increase the surface temperature to between 400-500°C, indicated that the endurance of this equipment will be in the order of 10 minutes before fluid is ejected as a jet or spray (Easthaugh *et al.*, 1983).

Under more hostile conditions, shock and explosions may displace pipework and components, leading to the discharge of hydraulic fluid. Since many systems store fluid gas in pressurised accumulators, ejection is likely to be in the form of a sustained jet or spray, which in the end gives a high probability of local fires resulting from enemy attack. With this combination of circumstances, a minor and relatively easily contained fire could therefore rapidly escalate into something far more serious and difficult to control.

As mentioned above, a number of so-called “fire-resistant” hydraulic fluids are available commercially. They will burn under certain conditions, but are less flammable than mineral oils. They do not offer the same performance as the mineral oils and in some cases (synthetic fluids) they can produce toxic products of combustion. Most of these fluids contain a lot of water and are not very good lubricants and can not be used to the same low temperatures as mineral oils. Not very many accidents have happened with hydraulic equipment, but in cases where this has been involved, the consequences have been severe (Easthaugh *et al.*, 1983).

4. RESPONSE IDENTIFICATION

The third phase is concerned with identifying and describing the different response actions that could come to use in the event of a fire on board. It will focus mainly on three aspects of this, namely active and passive fire protection and fire-fighting measures and damage control.

The deliverable from this phase is an understanding of key responses and their applicability.

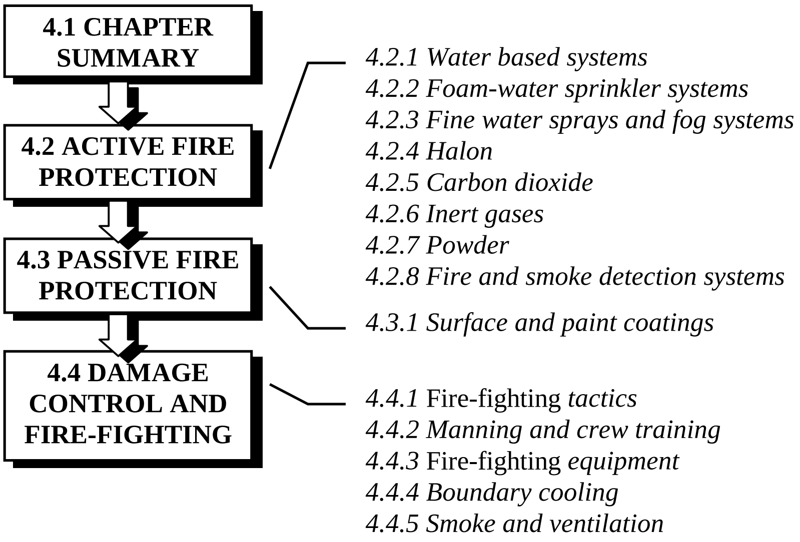

Figure 4-1 *Contents and working procedure for chapter 4.*

Initially, it is important to develop an approach to fire protection through passive features such as fire zones and thermal insulation as well as active features (e.g. detection and extinguishing systems). It is recognised that particularly on a naval ship a blend of both active and passive systems of protection is needed. However, too much emphasis should not be placed on the active systems alone since, from case histories of shipboard fires, it has been the passive system that has protected the ship where the active system was not sufficient, malfunctioned or by human error not released. A mix of active and passive fire protection is needed to satisfy safety requirements within a given ship design’s weight, space and cost constraint. It is however necessary to avoid adding so much passive fire protection that the combined weight of for example the insulation and aluminium will either approach or equal the weight for an unprotected steel structure.

Design for fire resistance should be verified by testing and fire protection systems should not be considered as substitutes for good design practise, warning and detection systems. However, passive and active fire protection systems can protect the structure and systems, limit damage and prevent escalation of the fire.

4.1 Chapter summary

A presentation of important responses and their applicability is being done in chapter 4. A balanced mix of both active and passive systems of protection is needed to limit the consequences of a weapon attack with ensuing fire. The actions taken in the early stages of the fire are crucial and effort should be placed on developing an effective approach to early fire-fighting, either by means of fully automatic fire suppression, which will work without manual intervention, or manual actions.

Fire suppression systems can generally be described and assessed by evaluating their availability, reliability and effectiveness. Fire detection is the first stage of overall fire extinguishing processes and the speed at which fire is detected is an important feature. Several well documented cases point out the importance of early warning systems of fire outbreaks, and the need for quick response fire-fighting actions. Passive fire protection systems are designed to minimise the overall degrading effects that action damage or fire will have on the ship from both a long- and short-term perspective. They include design considerations such as zoning, selection of materials and the use of fire insulation for example.

Shipboard fires often prove to be hard to fight due to the rapid spread of fire and dense smoke. The need for enough, properly trained manpower with the necessary equipment is an important point to make. The tendency of reduced manning should be considered in light of the need for DC&FF (Damage Control and Fire-fighting) measures, such as boundary cooling etc. A recognition of available and reliable fire-fighting equipment and a well-protected system for the supply of fire-fighting water are considered of great importance.

4.2 Active fire protection

Active fire protection includes a mix of manual and automatic suppression and detection systems. One of the major problems with non-automatic suppression systems is that since these are not released directly in the event of a fire, there is an increased possibility to reach flashover conditions and this in turn will make the suppression more complicated.

It is interesting to note that not all ships hit by *Exocet* missiles during Operation Corporate had their fighting capabilities seriously damaged, and more ships might have survived the fires better if these had been extinguished within seconds of ignition. Good warship design and thorough crew training are therefore considered essential ingredients in minimising the dangers of fire but the right equipment, with capability matched to the threat, is also vital to improving ship survivability. Naval fire-fighting using gaseous total flooding systems has been developed largely on knowledge gained in the industrial field, where they are in everyday use and perform in a reliable way. When similar systems are installed in warships, there is a need for confirmation of performance under combat conditions.

Two things can be said about fire-fighting with for example halons (even though these are being phased out at the moment). The products of combustion and the fire itself are far more deadly to crew than halons and a rapid attack on the fire offers the best chance of survival of crew and ship. Usually, the problem with these systems is not the operation time, which is around ten seconds and after this the fire is extinguished. Instead, the problem is the activation, which is done manually only after warnings from fire detectors, stopping of machinery space ventilation fans and closure of vents to prevent the escape of gas, a procedure taking about five to seven minutes in an average destroyer (Dimmer, 1986). This shut-down time includes evacuation of crew and has several fundamental disadvantages - explosive fuel fires cannot be contained, running fires gain hold and may become deep-seated and large quantities of toxic smoke and fumes can be generated.

As was evident during the South Atlantic conflict, hits on fighting ships by a variety of weapons cause extensive damage and liberate large quantities of hot hydrocarbons. Fast running fires, flash fires and fuel explosions are likely to be encountered and can result in burns on the crew, rapid smoke spread and increase in toxic gases. In other words, ships can be totally disabled with only one hit. To be effective against anti-ship missiles the old concept of fire-fighting needs to be reviewed and to some extent replaced by fully automatic fire suppression, which will work without manual intervention and consist of an integrated detection and extinguishing capability. Also, with the drive for leaner manning of warships, there is an implicit need to employ more automatic systems. This could to some extent be compared to the use of Close In Weapon Systems (CIWS), which out of automatic mode simply would not possess enough accurate or be fast enough. However, these aspects consider wartime conditions and since the normal case involves mainly peacetime incidents, where interference of automatic systems generally is unwanted, there is a need to consider different aspects of the problem.

Initially some systems designed for rapid detection and suppression were made to meet specific needs for military vehicle crew protection against penetration of vehicles by HEAT (High Explosive Anti-Tank) weapons. The criteria for survivability is in the order of 200 ms. The performance of these systems has been verified over many hundreds of trial fires, most of which have been initiated by live anti-tank warheads. The trials also showed that the system was virtually unaffected by air flow, since the trial was carried out in very windy conditions. The second series of tests was designed to test the system response to explosive fuel fires and these were actually knocked down by the halon before they had a chance to spread. The overall requirements are high immunity to false alarms and rapid establishments are the most needed. Sufficient data exists on closed compartment trials to confirm that rapid attack on an explosive fire leaves enough oxygen to support life, limits carbon monoxide formation to a survivable level and produces only small amounts of halon pyrolysis products. There is a clear need for integrating the systems concerning the safety in the same way as weapons fit, propulsion etc. in the design process, not left to be added as an after-thought (Davies, 1987).

When considering offshore installations, the active fire protection is commonly provided by water spray systems although foam and halon gas (replacements) are sometimes used in special cases. The regulation available for offshore structures does not take account of passive protection methods. National legislation for the UK and Norway, require that active water spray systems be installed on all platforms in the North Sea. Foam systems are required for helicopter decks from aviation fuel fires and similar. Halon replacements can be used where electrical fires need to be fought.

To summarise, fire suppression system assessment involves evaluation of three main factors:

1) *Availability,*
2) *reliability,* and
3) *effectiveness*.

The reliability of the system is a measure of the ability of an item to perform its required function in the desired manner under all the relevant conditions, and on the occasions or during the time intervals when it is required so to perform. Reliability is normally expressed as a probability. Availability is the proportion of the total time that a device is performing in the desired manner. When it comes to considering the reliability of any device, various factors have to be taken into account. For example, the quality of the components used in the device, their suitability for their particular application, the stress imposed on these components by the surrounding environment in which the device is installed etc. It is not possible to apply reliability statistics for active systems from different industrial activities to those experienced during wartime conditions. Reasons for an active system not working can be many after a weapon attack. It could relate to faults experienced on impact or human failures such as the water being shut off, the system not working adequately etc. (Finucane *et al.*, 1989). There is also very limited data on the effectiveness of a system following a weapon attack and this is best evaluated using realistic tests.

4.2.1 Water based systems

These systems are totally environmentally friendly. However, whilst fires can be extinguished quickly, the secondary damage caused by the water itself can be considerable, since both corrosion and stability problems might occur due to excess use. Also, traditional water-based systems tend to be heavy and bulky and care is needed when fighting hydrocarbon fires.

Most major surface vessels have a high pressure sea water system supplying large volumes of sea water throughout at a pressure of around 7 bar. This serves water or foam based systems in high risk compartments, but also fire-fighting equipment such as hose lines. The systems used are mainly of two different types, either automatic (sprinkler) or remotely operated (deluge). The advantage of a sprinkler system is that it admits the activation of only a number of the sprinkler heads, since these are controlled by bulbs that melt away (activates) at a certain temperature. These systems are at present not as common as deluge systems. Problems that might occur after the activation of a deluge system is mainly the need to drain the fire-fighting water not to experience stability problems.

A sprinkler system based on plain water only has a very limited extinguishing effect on pool fires in low flash point flammable liquids such as gasoline. However, the system might cool exposed surfaces and protect the construction of the ship, thereby to some extent limit the fire spread to adjacent compartments. For high flash point flammable liquids such as lubrication oil, the fire intensity might be reduced as the fuel surface is cooled. However, the probably most important disadvantage is that burning fuel will be carried by the water. The major advantage of water sprinkler is its ability to control and suppress fires in ordinary combustibles.

Problems releasing water sprinkler systems on board after weapons effects can occur. The failures could for example be associated with inadequate water supplies, defective valves, inadequate maintenance, low mains pressure or water supply failure. Splinter effects can also cause severe damage to piping etc.

4.2.2 Foam-water sprinkler systems

This type of system eliminates the disadvantage of a water sprinkler system against pool fires. The foam layer controls and extinguishes a pool fire and prevents the fuel to be carried on the water layer. Against fires in ordinary combustibles, foam-water sprinklers will have qualities comparable to standard sprinklers.

There are several different kinds of foam to access. Perhaps one of the most significant improvements in fire-fighting on all classes of ships is the replacement of protein foam by AFFF (aqueous film forming foam). It has been estimated that this improvement alone has increased fire-fighting efficiency alone by 300% when introduced (Pohler *et al.*, 1978). With the addition of gel-forming substances, the foam can be made alcohol-resistant and fight fires in different fuels (SRV, 1994). AFFF has gained wide acceptance within the fire industry due to its fast knockdown capability with the minimum amount of agent. FFFP (film forming fluoro protein) is claimed to have better heat burn-back resistance and fuel tolerance properties. (Heat burn-back resistance refers to the ability of the foam to resist heat and burn-back prior to extinguishment. Fuel tolerance is the resistance of the foam to mixing with the fuel and hence preserving its effectiveness.)

Existing fixed spray systems utilise about a 6% concentration to be employed, whilst flight deck monitors use about 1% due to the large quantities of water used.

Medium expansion foam is the most commonly used because of the light equipment (portable) and its ability to fill large spaces, while low expansion foam is best used for decks and for covering engine rooms, since it gives rapid cover. High expansion foam systems have the ability to control and extinguish pool fires the same way as foam-water sprinkler systems. However, due to the expansion, the flow properties of the foam is reduced and there might be problems for the foam to flow between narrow obstructions (e.g. cargo areas). Other concerns when using these systems are the possibilities to evacuate people and manual fire-fighting (Arvidsson *et al.*, 1997). Hi-expansion foam is not suitable for machinery rooms, since there is a difficulty in injecting the foam against the pressure generated by the usually large fires and that the foam burns off at high temperatures. Other problems experienced during trials are difficulties of removing the foam after injected and the fact that the foam provides an efficient thermal barrier, which resists penetration by thermal imaging cameras (Blackmore, 1994).

4.2.3 Fine water sprays and fog systems

Fine water spray or fog technology is not new, but until the demise of halon and concerns regarding the environment appeared, there was little or no reason for manufactures to develop alternatives. Fine water spray technology using only water and air, has resulted in a fire extinguishing technology which has most of the advantages of traditional water based systems and few of the disadvantages. The amount of water used in these systems to extinguish a fire is considerably less when compared to traditional sprinkler systems. During initial trials, a fire created by 10 litres of gasoline burning at peak flame temperature was extinguished in four seconds using only 0.5 litres of water. A very fine water mist ideally has the capability to extinguish fires with only two-thirds the weight of Halon 1301 (Baturin, 1994), which will limit stability problems occurring as a result of excess use of fire-fighting water. Crucial to the technology is droplet size, direction and throw. The spray extinguishes by delivering droplets of water to the heart of the fire, drawing in heat and then turning to steam, which in turn blankets the fire excluding oxygen to the level at which combustion no longer can be supported. Extinguishment is reached by absorbing energy in the combustion zone and by cooling down the surrounding gases (principles are shown in figure 4-2). If the droplets were too small they would vaporise before reaching the heart of the fire and if too large they would risk splashing, which can actually accelerate the spread of fire, particularly with liquid hydrocarbons. The action of the spray significantly attenuates heat and radiation produced by a fire and knocks down surrounding temperatures rapidly. The spray also to some extent strips particles and smoke from the atmosphere and absorbs toxic gases. This reduces toxicity of the atmosphere and improves visibility, which could be essential for a safe evacuation. Watermist systems have the potential to allow early re-entry by fire-fighters, which means saving valuable time in resuming naval operations. Disadvantages are mainly that it conducts electricity, it could reduce the visibility and that it mostly limits the fire and can not extinguish the fire completely. It could also be difficult for the water drops to sufficiently penetrate (Isaksson *et al.*, 1997).

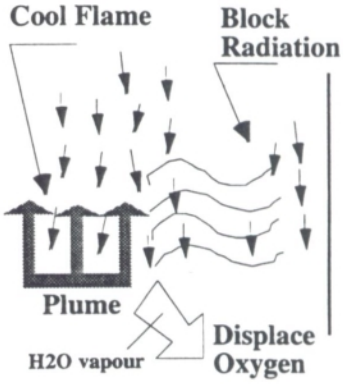

Figure 4-2 *Principals for suppression using water mist (Mawhinney, 1994).*

The systems have proved efficient especially for fires in small enclosed spaces but also for extinguishing fires in flammable liquids, both pool and spray fires, in simulated small engine rooms. When the volume increases, the installation and system design becomes important. It has for instance been demonstrated that that water mist will extinguish fires in open, freely ventilated spaces, provided that the spray application rate is sufficient. However, enclosure effects tend to be important to consider. One example is that confinement of heat leads to increased evaporation of mist, with consequent steam expansion, which displaces air from the compartment and further reduces oxygen concentration. Problems are likely to occur with smaller, well-ventilated hidden fires if applying water mist before the temperature has reached about 100°C. When the fire has grown larger, extinction will depend to a lesser extent on direct cooling of the flame and more to cooling and more on oxygen displacement. It is at this point important to consider if a fire in the compartment will be “ventilation limited” or not.

The systems available can be either low, intermediate or high pressure nozzles operating at pressures between 3-300 bar. The larger systems tend to rely on a series of pumps to maintain and deliver spray to the nozzles. Very small systems may be pre-pressurised. Low pressure twin fluid systems are generally self-contained and comprise of a dedicated air or nitrogen cylinder and water storage vessel, complete with associate controls. The stored air or nitrogen pressure is used as both the propellant for the water supply and for atomisation of the water at the nozzles. The advantage of this type of system is that it can be recharged at sea. These systems are in service in the marine market and also offshore, protecting high value equipment like gas turbines.

Tests with these systems have been performed in mock-ups of machinery compartments by amongst others the Danish Institute of Technology in 1993 (McKay, 1994) and for the Canadian Navy by NRCC (National Research Council of Canada) (Mawhinney, 1994). These tests show that fires up to 20 MW can be extinguished within 30 seconds and with an oxygen concentration never dropping below 18%. It is however proposed that the maximum size of the protected compartment should be $200m^3$ and each zone would have to be suitably engineered to protect the defined area or object. This will require sophisticated detection/actuation equipment and could require more pipework/equipment, which in turn might increase the vulnerability to action damage.

Watermist has the potential for application in other areas such as high risk/high value compartments, accommodation spaces, gas turbine enclosures and electrical cabinets. Final reflections include the potential use of new sprinkler systems using only 2-4 litres per minute compared to the 75-100 litres that the conventional systems use. However, the best fires are still those that do not occur and therefore the preventive protection on board is highly important.

4.2.4 Halon

Since halon at the moment is being phased out (the production of halon came to a stop from January 1994 (Baturin, 1994)) as the premier fire extinguishing agent mainly due to the environmental issues surrounding its use, this has necessitated a review by both industry and the military as to the future fire protection requirements. Most modern warships use gas turbines or a combination of gas turbines and high speed diesel engines for their main propulsion. Traditionally, these and associated equipment have been protected by Halon 1301. There are now a multitude of halon alternatives commercially available, including fine water spray or fog systems, inert gases, chemical agents and various types of foam systems.

The halons extinguish the fires by interfering with the chain reaction involved in combustion in a very effective manner. The full extinguishing concentration of halon (about 5% by volume) is discharged into the protected space in less than 10 seconds after fans have been stopped and vents closed. Explosion systems originally developed for military vehicles, provide protection against a high explosive strike on a fuel tank. The system is designed to detect, actuate and suppress the incipient explosion within 100 ms, employing infra-red detectors and a very rapid injection of halon.

Halon 1301 has been used to protect machinery spaces in ships due to its extinguishing capabilities, minimum space requirements and cost effectiveness. The phase out of halons has to some extent seen a return to CO_2 total flooding systems. Whilst halon may be considered less dangerous to personnel, this is not the case with carbon dioxide. Both agents require an air tight enclosure and offer little if any cooling effects. This means that it is critical for protected spaces to remain tightly closed until sufficient natural cooling takes place after the fire has been extinguished, not to experience re-flash. The above may present problems, since preceding weapons effects are probable to tear up holes in the exterior and keeping the compartment sealed may prove hard to accomplish when studying previous war experiences. A peacetime fire in the deep fryer on board the German destroyer *Moelders* in December of 1987 illustrates the problems of re-flash further. The fire was extinguished by the use of Halon 1301, which is not really a cooling agent. This made the fire re-flash after the space was abandoned and went right up through the ventilation ducts causing extensive damage.

4.2.5 Carbon dioxide

Carbon dioxide is stored as a condensed gas, does not conduct electricity and has good ability to penetrate. However, the concentrations needed for fire suppression are lethal to humans and therefore protective measures are needed before release of the system.

Machinery spaces were usually equipped with halon and backed up by water spray/AFFF systems. Today carbon dioxide and the halon replacement FM 200 could be alternative replacements even though they have some disadvantages. For example the CO_2 requires 4-5 times the storage capacity of halon and FM200 about 2 times. FM200 can also produce HF hydrogen fluoride), which with water can form highly corrosive hydrofluoric acid. Of greater concern is the potential for fatalities if there are lapses in maintenance procedures or personnel training when considering CO_2. Exposure of casualties or trapped personnel to CO_2 in an action damage situation may also prove fatal (Blackmore, 1994). Before releasing a carbon dioxide system in a machinery space for example, there are a few things to consider:

- Control has to be made that no people are in the area. This will naturally take time but has to be done.
- The space has to be sealed and ventilation stopped in order to seal off the compartment properly .
- Oil supply needs to be shut and the engines turned off.

Depending on source of reference, the concentration of CO_2 that needs to be maintained varies greatly. It seems a concentration of about 35% should be maintained and the marginal is not great. If it comes down to about 30% there is a possibility that re-ignition will occur. This was the case with the *Cunard Ambassador*, who in September of 1974 experienced an engine room fire and CO_2 was discharged into the room. However, an improperly closed ventilation flap and leaky funnel vent closure plate, reduced the effects of the complete charge of CO_2 and it took 8 h for the fire to burn out (Cowley, 1994). These machinery spaces need to be sealed in order to sustain the high concentration of gas. In the case of long pre-burntimes, the temperature raises and the increased thermal powers can remove the extinguishing gas through leakage. The concentration will therefore decrease and the heat may spread the fire to adjacent compartments. Another problem with CO_2 is the fact that the cooling effects of CO_2 sometimes are insufficient. This was illustrated by the engine room fire on board *Capitaine Tasman* in April of 1993, where the fire re-ignited several times after the CO_2 system had been activated.

Generally, not a lot of data is available on the effectiveness of different suppression systems. However, a study of experiences from shipboard fires in merchant shipping (machinery installations) and the use of CO_2 has been done (Cowley, 1994) and summary results are presented in table 4-1.

CO_2 released	
Fire extinguished	14
Fire controlled	8
Extra CO_2 used	2
CO_2 system unavailable	
System defects	3
Controls not approachable	1
Operational problem	1
Other appliances preferred	
With success	9
Without success	1
Total	**39**

Table 4-1 *Analysis of 39 cases, where CO_2 systems were fitted (Cowley, 1994).*

The “CO_2 released” refers to where CO_2 systems have been used and the outcome of it. “Fire controlled” basically means that the fire was not extinguished, but merely controlled. In a few cases under this heading the fire in the compartment of origin was controlled, but had earlier spread to adjacent compartments. The “CO_2 system unavailable” concludes that attempts were made releasing it, but it could not be done. In a few cases other appliances were used instead of the CO_2 system with or without success. Even though these different cases analysed here differ in many ways (different ship types, conditions, manning etc.), it gives some indication to the effectiveness of CO_2 systems under normal working conditions. Roughly it can be concluded that fires have been extinguished in about 50% of the cases, where efforts were made to release the system and the fire is at least controlled in 75% of the cases. It is however emphasised that these are peacetime conditions and the addition of any weapon effects will most certainly alter these numbers.

The fire on board HMS Älvsborg in November of 1987 demonstrated an example of the problems that might occur when applying carbon dioxide. Due to a handling error, one of the oil leads started to leak and diesel oil sprayed onto the hot exhaust pipe and immediately ignited. The quickly growing fire forced the personnel in the machinery space to retreat after having started the fire pump, stopped the fans and the main engines. After these events took place, carbon dioxide was released in the machinery room. Since it was not possible to determine whether the fire was extinguished or not, high expansion foam was released into this compartment and the air intakes filled with low expansion foam. Growing secondary fires started in the adjacent compartment, but were extinguished rather quickly. The measure to start the electrical fire pump did not have any effect, since the carbon dioxide, which was released within short, stopped the plugged-in generator and with that the supply of electricity. This release was done first after all personnel had evacuated the area and took about 2-3 minutes from the fire started. The effects of the carbon dioxide have not been evaluated for certain. The flow of smoke is believed to have been powerful enough to blow out the carbon dioxide through the chimney. After this high expansion foam was used to bring the fire under control (Marinens Haverikommission, 1987 - see also appendix B).

4.2.6 Inert gases

Inert gases are stored as compressed gases and generally used in weapon electronics compartments, in gas turbine modules and in the engine rooms of gas turbine ships due to the fact that they do not conduct electricity and are considered clean. Also, they do not contribute to decreased visibility when released and they are non-polluting and non-toxic. The problem with inert gases is that the fire has to be effectively contained for these to be effective. In addition, corresponding system needs 10-15 times the storage space compared to halon and it takes longer time to reach concentrations of suppression (Isaksson *et al.*, 1997).

Inert gases are , as mentioned above, clean and do not react with the products of combustion, as is the case with halons. One gaseous mixture of 50% argon and 50% nitrogen is ARGONITE. Inert gases extinguish fires in enclosed spaces by reducing the oxygen from the normal 21% down to 12-13%, where combustion usually cannot be sustained. Systems are designed on a total flooding basis for machinery space applications. The gas is stored in high pressure cylinders at 200 bar, although the actual working pressure in the distribution pipework may be as low as 12 bar depending on the application and installation. These systems may be automatically or manually released and have been accepted for marine use in machinery spaces by various certifying authorities including Lloyds and Det Norske Veritas. A number of systems are already in service with commercial vessels and whilst the military currently has a dispensation to continue to use halon, it is reviewing the options, including inert gases.

When these gases are used after action damage they might not be successful, since the air-tightness of the compartment might be affected (compare to halon and CO_2 in section 4.2.4). This in turn will prevent the concentration build-up of the gas and suppression will not be reached. The most likely reasons for failure of a gas extinguishing system are generally not the hardware, but inadequate air-tightness of enclosure or failure of interfaces with other systems such as close down of the ventilation. The air-tightness of enclosure is particularly important for halon gas systems (Finucane *et al.*, 1989).

The submarine is one of the environments that offers unique approaches to fire protection. Here it is possible to pressurise the sealed compartment with an inert gas, such as nitrogen, in order to reduce the *concentration* of oxygen to a value below that needed to support combustion, but still maintain the *partial pressure* of oxygen so that the atmosphere is habitable for humans.

4.2.7 Powder

Powder extinguishing systems consist of a source of the powder with a compressed gas propellant, to blow the powder out of the container through the associated pipework and discharge nozzles. Such systems have a poor record for reliability; the two main reasons being that the powder tends to compact in its storage container or the pipework blocks upon discharge (Finucane *et al.*, 1989). Also, the systems are not clean, do not have the same ability as halon to penetrate and problems with limited visibility when released might occur. Other than this, powder can be very effective on flaming fires and is non-toxic at suppression concentrations. For example, gas vessels use fixed dry powder fire-fighting systems for fighting cargo fires on-deck. In pool or torch type fires likely to be encountered onboard ship, sustained (and relatively high) powder application rate available from such units is generally required.

4.2.8 Fire and smoke detection systems

Traditionally, fire detection in many navies has been done by personal observation combined with alarm sensors to detect threshold values of temperature and smoke in critical compartments. Information was passed to officers over a manual information system to assure absolute reliability. The primary limitation of this system has been slow time response. In one of the latest destroyer designs for the US Navy is included nearly 800 fire/smoke and flooding sensors of the threshold type (Whitesel, 1994). There is a need to detect damage, characterise the extent and predict its progression. To meet this need, damage control sensors are required that can measure more parameters on a continuos basis in all compartments of the ship. A well monitored shipboard environment will reduce the response time to casualties, allow control of certain casualty actions and support the reduction in manning requirements.

Fire detection is the first stage of overall fire extinguishing processes and as such the speed at which fire is detected is very important. The faster the fire is detected, the better are the chances of extinguishing it and lowering the extent and cost of damage caused. Another important point for the fire detection system is its reliability. With conventional systems it is very difficult to monitor and control any fire incident on warships and to do this, intelligent fire detection systems are necessary. A fire detection system, which will be self-monitoring and which will initiate both audible and visual warning signals in the ship’s control station are required on warships. In a conventional system the detection and monitoring of fire and co-ordination of fire-fighting activities are performed by an organisation of manpower, which undertakes all damage control and surveillance functions. One of the major disadvantages with this system is the need for manpower, which goes badly with the reductions in manning on warships and also the long time to process information and make assessments. The intelligent systems are primarily based on microprocessors and is considered to have a few main advantages:

- Identification of exact location of fire,
- automatic testing of associated circuitry,
- ease of maintenance,
- historical events log,
- reduction of wiring installation costs, and
- reduction of false alarm.

The search for this kind of system has been primarily to accomplish the following (Pati *et al.*, 1989):

- Limited manpower,
- speed of fire detection,
- efficient operation,
- the storage and presentation of data, and
- expert systems (recommend courses of action).

The detectors used in these systems are primarily smoke detectors (optical or ionisation type), heat detectors (fixed temperature or rate of rise) or flame detectors (infrared or ultraviolet).

Generally, the optical smoke detector will detect a fire far quicker than the ion smoke detector, which is also in many cases affected by air speed, dust, steam etc. This shows the importance to consider the environment when designing a system, in order to avoid an unacceptable high rate of false alarms from the system. The optical detector is sensitive to visible smoke with large particles, which is the type of smoke expected from a smouldering or glowing fire. Since the detector is not affected by air speed and tends to be the best choice in environments with relatively high humidity. The ion chamber detector will respond to small particles or invisible fumes, normally generated by a flaming fire. As the smoke cools it will coagulate and build larger visible smoke particles containing less energy. This type of smoke is more efficiently detected by the optical detector. It is further possible that ion chamber detectors may not respond to some special kinds of smouldering.

Optical smoke detectors are best used in stairs, cabins, small lockers and stores in accommodation areas, cargo holds and car decks. These should also be found in machinery spaces and in spaces with a ceiling height over 4.5 m. Ion chamber detectors can be used in all technical rooms, in accommodation, AC-rooms and generally in spaces where a hot flame may be expected. It is recommended to install 50% ion chamber and 50% optical smoke detectors in the engine room.

Smoke sensors alone can however be misleading and do not provide sufficient information on the extent of a fire, which means there is a need for personnel to inspect compartments in order to clarify the situation.

There is little scope for heat-sensitive detectors as early warning devices, since heat detectors react to temperature rise and takes relatively long time to rise the alarm, especially in high, well ventilated areas. An example of these problems is the experience on board the *Universe Explorer* in July 1996 after a fire broke out in the laundry room. Due to the late response of the heat detectors and the delay until the master sounded the general alarm, the dense smoke and heat spread up two decks and killed five crew members of smoke inhalation. If there is a need for a quicker reaction time, the differential heat detector can be used. However, they may continue to be useful as triggers for fire-fighting measures, e.g. application of water spray.

In machinery spaces a good solution can be the flame detector, which reacts to the radiation of a flaming fire. The line detector could also be a complement to smoke detectors in machinery spaces and consists of a light source and a photo cell. When the beam is broken, the alarm is sounded.

Finally, information on the reliability and effectiveness of fire and smoke detection systems on board warships is rather limited. For instance, a smoke detection system was fitted to *Sheffield*, but no information on its performance is available.

4.3 Passive fire protection

Passive fire protection systems are designed to minimise the overall degrading effects that action damage or fire will have on the ship both in a hostile environment and in peacetime. Passive fire protection features include design considerations such as zoning, selection of materials used in ship construction, selection of materials used in furnishings and fittings, vital space protection, provision of escape routes from compartments, fire insulation and fire alarms.

Sub-division (or zoning - see chapter 2.3.2) is required to separate compartments with different functions or environments such as machinery spaces, tanks for stowage of fluids, stores and living spaces.

To a large degree sub-division is fitted for physical separation, environmental control and flood limitation. The additions for fire and smoke containment are that the tops of the bulkheads are watertight and ventilation trunks and air return openings are fitted with valves. Ideally every main compartment should have its own self-contained ventilation and air-conditioning system. This is hardly practical, but 4-6 treatment plants throughout the ship's length is not unreasonable, giving 4-6 groups of compartments or "zones" with no passing air trunks. The hazard of fire transmission through pipe systems passing zone bulkheads is not high, although fire hazard is increased by oil pipes, i.e. fuel or hydraulic oil systems, and compressed air.

Insulation is sometimes used in bulk- and deckheads in order to slow down the rapid fire spread between compartments, which is otherwise common in ship fires. However, a few experiences have showed that insulation can be a fire propagation path.

On board warships, some special solutions regarding passive protection of certain pieces of equipment can be found. An example are the turbines, which are generally housed in fireproof modules, so if the fire starts inside this outer casing, it can be contained after the engines have been shut down. However, if the fire is outside the turbine module, the build-up of heat will threaten the oil pipes that, once ruptured, will spray diesel fuel around the room.

4.3.1 Surface and paint coatings

In naval vessel interiors, chlorine-containing surface coatings are candidate replacement materials for traditional coatings such as alkyds and epoxies because of their superior fire performance as well as their excellent durability properties. However, because these materials contain chlorine which may be converted into toxic products during combustion, it is important to consider the nature and concentration of these gases against the inherently low flammability of these coatings in assessing their overall suitability for interior applications (Brown *et al.*, 1995).

Fire-retardant polymers, commonly known as intumescent paint coatings, refer to the class of insulate materials that provide temporary protection against fire by delaying the heat penetration into the objects to which they have been applied. They do so by undergoing endothermic chemical decomposition followed by charring and considerable thermochemical expansion (see figure 4-3).

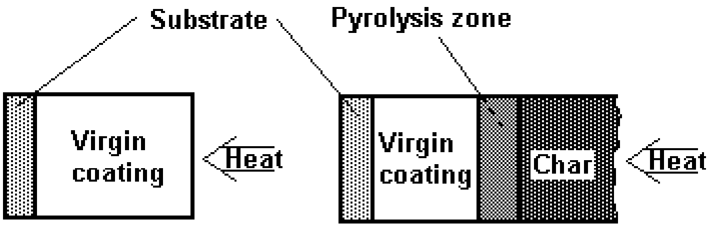

Figure 4-3 *Intumescent coating under heating conditions (reproduced from Chaboki et al., 1991).*

These paints have found applications in various industries. For example, they are widely used to protect construction elements such as structural steel components and emergency exit doors. One suggestion has also been to use these coatings to protect various weapons such as bombs, mines and missiles from any accidental fire. The importance of such coatings has been apparent to the US Navy for several years. In 1969, fire on the aircraft carrier *USS Forrestal* resulted in the death of 133 men and damage amounting to 72 million dollars. In 1981, fire on the *USS Nimitz* resulted in the death of 14 men and 60 million dollars worth of damage. It was realised that the loss of life and the extent of damage could be reduced if detonation of ordnance due to fire could be delayed by even a few minutes (Chaboki *et al.*, 1991).

Comparable to the intumescent coatings are the fire retardant coatings used for protecting flammable substrates from reaching ignition temperatures and for preventing non-flammable substrates from reaching softening temperatures and compromising their structural integrity during fires. However, these coatings can contribute to the production of toxic combustion products, the more common being carbon monoxide (CO) and hydrogen cyanide (HCN) (De Marco, 1991).

4.4 Damage control and fire-fighting

Advances in damage control and fire-fighting (DC&FF) technology have tended to be more evolutionary and usually occurred as a result of lessons learned. Following a weapon hit, the primary goal of the DC&FF must be to deal with the effects of fire, smoke and flooding and damage to essential equipment.

4.4.1 Fire-fighting tactics

Initially there is a need to consider that different navies do not use similar approaches to fire-fighting. However, there are a few (mainly war-related) experiences worth noticing and these are discussed further in the following.

Since the Falklands war, great improvements have been made in locating fires (thermal imaging cameras) and in communication (internal radio) for example. New fire suppression techniques have been tried with encouraging results. Smoke extraction fans are fitted to remove smoke once the fire is out and evacuation routes are planned and marked (Brown *et al.*, 1990).

In order to fight a fire successfully, it is essential to locate the source quickly, assemble the fire-fighting teams and achieve good overall control. In most cases the critical part of fighting any fire is in the early stages of the incident - particularly when resources are limited.

It is generally recognised that a direct straight-stream attack is preferred for an incipient or growing, unobstructed fire, whereas an indirect attack is preferred for the post-flashover/fully developed fire scenario. The situations in which a fog attack could be considered include a horizontal approach to a free-burning fire, where (1) the overhead gases are burning, (2) the seat of the fire is obstructed and water streams cannot be applied directly to the fire seat, or (3) multiple fire seats are growing within the fire space such that one fire seat could grow out of control while water is being applied to another fire seat (Farley, 1996).

Problem experienced on several occasions, are the ones concerning the introduction of large quantities of fire-fighting water and subsequent stability problems. One conclusion is that the fire should be fought as low in the ship as possible. This should be done in order to lower the centre of gravity or at least minimising the rise. Access is usually easier if the fire is located above weatherdeck.

Fixed fire-fighting systems should not be turned off until the fire is out, but instead stability problems force solutions for draining off the water (e.g. deck drains in selected areas) not to experience free surface effects. A good working knowledge and the effects of flooding damage or fire-fighting water upon it, is vital to controlling any damage situation. *Sheffield* and *Stark* (appendix C) experienced similar problems concerning the accumulation of fire-fighting water high in the ship. This type of problems can be accentuated on board car decks of Ro-Ro ships for example, where absence of vertical bulkheads will create a large free water surface. This was the case with the *Herald of Free Enterprise*, which is alleged to have sailed with its bow doors open - allowing water to flood the car-deck and quickly capsize the vessel. These risks can also be generated or amplified by the movements of cargo. One of the additional problems of Ro-Ro ferries concerns the often rapid spread of violent fires on car decks (Crook, 1990).

A final example is the Italian-built M/F *Deledda*, which experienced a fire that began on the pier-side and it was localised in the crew quarter zone in the aft area of the upper deck over the garage. The zone was equipped sprinklers that started to flood water as soon as the fire began. The sprinklers flooded 2.2 tons of water per minute over the full 370m^2 fire-fighting zone. In addition, shoreside fire-fighting support introduced large amounts of water. Because moored to the shore and anchored, the *Deledda* only had a list of nearly 12 degrees, but it was later calculated that without constraints the listing would have been close to 28 degrees. This because of the about 720 tons of free water on board. In this particular case,16 degrees was evaluated as being the critical point, where more water could start flooding in through the stern port (Balestrieri *et al.*, 1990).

4.4.2 Manning and crew training

Ships can be considered very crew intensive and require more crew members than other weapon systems to operate its systems. Aircraft and land vehicles often depend on land-based support to restore war fighting capabilities, something the ship has to handle itself in order to for example respond to a second enemy attack.

The conditions for carrying out fire-fighting activities are very different when comparing civilian and military vessels. In the civilian case, the main effort is to evacuate the passengers and in the military case, the interesting parameter is often the battleworthiness. Crew training should include theoretical/practical fire-fighting, behaviour of cargo/humans, leadership/team building, risk assessment and incident planning as well as realistic exercises (Hesler, 1995). The training programmes should be applicable to the risks that might occur and it is essential that ships' personnel have experience of fire awareness during training and are able to see how quickly a fire can develop and the amount of smoke that can be produced in a relatively short space of time.

Fire-fighters are often forced to enter fire compartments from above (engine room fire temperatures can be up to 1,100-1,200°C), which can create difficulties. In the use of boundary cooling, there is a need to weigh the advantages of this against the creation of a free surface from the run-off water. Boundary starvation might be an alternative, preventing the fire spread by removing all combustible material from contact with the bulkhead (Cox, 1997).

Many factors influence the effectiveness of damage control. There must be enough, properly trained manpower with the necessary equipment. These human and technical resources must be properly deployed, with efforts concentrated on priorities. After having identified “design threats” and survivability criteria for a ship (chapter 3.2.1-3.2.2), it should here be possible to define the need for manpower, depending on which tasks are carried out by humans or are fully or partially automatic. The increasing use of automation and remote operation in more recent designs together with reducing maintenance requirements has resulted in leaner manning with the attendant risk that some emergency situations will stretch personnel beyond their capacity to maintain control of the incident and repair battle damage and fight fires.

Damage reports from WWII reveal that at several occasions, US destroyers took more than three hits at one time. The problem that occurred was that it proved difficult to fight several fires at one time with the personnel available. It is also clear that simply adding more technology, rather than reducing the workload, can potentially increase it. Improvements can only be made where the technology complements the man by performing functions that man finds difficult or time-consuming. Principally, ways are needed to assess the impact of design options on manning, in order to inform reasoned decisions about the trade-off between costs of automation and cost savings delivered through manning reduction. The best thing would be to have methods, which allow assessments to be made at the earliest stages of design (Edwards *et al.*, 1998).

As technical components are becoming more and more reliable, the human factors’ relative importance is increasing, and man is becoming the critical part of the system. Since the human failure probability is affected by several factors such as motivation, stress and working conditions, no further analysis of this will be done in this paper. It is, however, hardly adequate to compare crew reactions during the events on board a passenger ship to those following a weapon impact and subsequent fire on board a warship. One reason for this can be that the former case is mainly focused on safety to personnel and passengers and in the latter, focus could be on the battleworthiness of the ship, which of course would be very dependant on situation.

Finally a look at possible future methods. The intelligent systems discussed in chapter 4.2.8 could prove to be an important aid if future fire-fighting. In multiple fire incident scenarios (e.g. weapon-induced fires), with limited fire-fighting resources available, knowledge of air temperatures near the deck head in fire compartments and surrounding spaces can be used to aid effective decision making. Such information would permit optimal decision making, which could prove to be crucial as the manning of ships today are constantly being reduced. This could also affect other areas. For instance, it is suggested that knowledge of air temperatures in a compartment and surrounding spaces during a fire can be utilised such that extraction and positive pressure ventilation techniques can be used in an optimal way without increasing the severity of the fire. The use of such techniques could significantly improve the environment in which naval fire-fighters operate by reducing the some of the hazard factors such as low visibility and high air temperatures.

4.4.3 Fire-fighting equipment

Experiences gained in the Gulf and during the Falklands emphasise the need for available and reliable fire-fighting equipment and a well-protected system for the supply of fire-fighting water. Using the statement made by the safety superintendent of the *Piper Alpha* before the incident (The Hon Lord Cullen, 1990):

“We certainly concur with you that the fire-water system is critical to platform safety and must be maintained in a peak operating state at all times.”

Another important matter is that the total number of fire pumps must be able to provide the full sea water load while fighting a major fire, plus two additional spare pumps. In order to ensure against total loss of HPSW system (as was the case with *Sheffield*), pumps should be distributed throughout the ship with at least one in each zone. Two pumps should not be immediately adjacent to either side of a bulkhead in the event of a localised damage eliminating both at once. Installed pumps should not depend upon a single source of power, but should have alternative electric supply as well as back-up diesel driven pumps. Control of all pumps should be both local and from the ship control centre, since several experiences have shown difficulties accessing some equipment or different controls. A hit above the waterline can severely damage vital systems such as the horizontal ring main system. Therefore, it is suggested this system be complemented with an additional low level forward-to-aft loop as close to the centre line as possible.

If the firewater main is ruptured during an explosion there would be a reduction in both pressure and volume to the distribution system. The firewater main should therefore be designed to withstand certain effects of blast and projectile damage as well as effects of blast wind loading.

Portable extinguishers are sometimes used in order to accomplish a quick knock-down of a fire in the early stages. The AFFF extinguisher is the main general purpose portable type. CO_2 extinguishers can be used where electronic cabinets and computers are at risk and dry powder extinguishers are used for quick knock-down of flammable liquid fires, in main machinery spaces and on the flight deck and have proved to be rather effective.

A further look at possible future fire-fighting equipment is summarised in chapter 5.2.2.

4.4.4 Boundary cooling

An important means of limiting the extent of damage after a fire is experienced is boundary cooling. Boundary cooling of compartments, where a major fire is raging, will protect adjacent compartments of high value/risk from spontaneous combustion mainly through the effects of heat transfer through the bulkheads. An increased use of boundary insulation can reduce the need for these actions.

4.4.5 Smoke and ventilation

The traditional response is to batten down a fire, switch of the ventilation, cool the boundaries with water sprays and remove combustible material, which is adjacent to the six sides of the fire compartment. The SOLAS Convention was amended in 1994, declaring that public spaces spanning three or more open decks containing varying combustibles, must be equipped with a smoke extraction system activated manually or by the smoke detection system and be able to exhaust the entire space in less than ten minutes. If extraction fans are left on to allow escape or during the initial fire-fighting attempt, the increased visibility and lowering of heat and humidity levels will be considerably advantageous to the fire-fighters. The general philosophy in fighting fires in machinery spaces is to have one good attempt with portable equipment after the alarm has been raised or by a fast response by a BA (Breathing Apparatus) wearing emergency team. If the situation deteriorates then there is no question that there must be an immediate withdrawal, a muster, closing of ventilation flaps and release of the fixed installations. Air-conditioning systems on ships will vary considerably and on commercial vessels it may be on partial re-circulation where a certain percentage is supplied from fresh air and the rest continuos to re-circulate. Unless this system is switched off immediately the smoke in the space will quickly spread to other areas. This was one of the reasons for the tragedy aboard *Scandinavian Star*. Finally, early detection is essential so that the fire can be contained and the steps taken in these first few minutes are crucial (Abell, 1994). Two mechanisms of smoke transport are important and these are mainly (Rockett, 1986):

- Smoke entering the ship's ventilating system and being carried by the system to non-fire involved spaces, and
- smoke transported, by natural convection generated by the fire, through openings of the fire compartment into adjacent spaces and thence to more distant locations.

Shipboard fires are among the most difficult fires to fight primarily because of the amount of smoke. The dense smoke generated can reduce the visibility for crew members and cause confusion and disorientation. In addition, inhalation of the smoke, which usually contains carbon monoxide and other toxic gases, tends to hinder the escape and fire-fighting activities. In the course of a confined, poorly ventilated fire, many materials are not burned completely, but constrained to smouldering. This produces an atmosphere with low oxygen content and vapours, gases and smokes that are chemically different and therefore physiologically different than those produced when the material burns freely. The reduction of ventilation intensifies this problem. In building fires, one solution to the smoke problem is ventilating the smoke through making suitable openings in the structure, so called “fire-axing”. For obvious reasons, this procedure is not as easily done in shipboard fire-fighting.

A continuing challenge is the protection of personnel, since for example, the human brain can be affected by carbon monoxide at much lower levels than that needed to be lethal. A decrement in mental acuity due to a fire during a battle can be very important to the safety of a ship and fulfilment of its mission. As mentioned in chapter 2, statistics on this matter from the shipping industry clearly point out that most casualties die from smoke inhalation (Jensen, 1994). However, war experiences such as that of *USS Stark* show that blast and thermal injury are the more common causes here.

Obscuration by smoke continues to be one of the major problems in confined spaces mainly for two reasons:

- The fire-fighter has problems in locating the seat of the fire, and
- trapped personnel have a hard time in trying to find their way up to weather-deck.

One example pointing out the problems of locating the seat of the fire, was the fire on board the passenger vessel *Yarmouth Castle* in November of 1965. It caught fire and sank 5h later and 87 passengers and crew members lost their lives in the process. Initially there was a smell coming from the engine room, which was mistakenly thought to be coming from the galley via the ventilation system. After some time it was realised that the smoke came from a storage room below main deck. and this impeded fire-fighting activities. The sprinkler system is also believed to be partly responsible for the magnitude of the incident, because of the late response and the ineffectivity to fight fires in concealed spaces.

5. DAMAGE SCENARIO ANALYSIS

The following chapter is mainly an attempt to describe the overall events following initiation of a weapon-induced fire and identify key hazard and response factors.

Deliverable from this phase is an understanding of which risks/responses are important for the incident outcome.

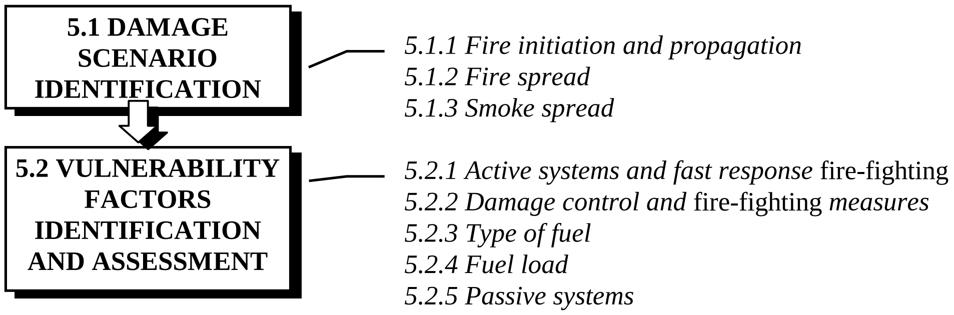

Figure 5-1 *Contents and working procedure for chapter 5.*

5.1 Damage scenario identification

Initially an outline damage scenario will be identified and characterised, with particular reference to the events of *fire initiation and propagation*, *fire spread* and *smoke spread*.

5.1.1 Fire initiation and propagation

The particular scenario at interest is that a fire initiates by an explosive projectile strike to a ship above its water line. This can be conceptualised as a projectile penetrating the steel hull, entering a compartment(s), possibly detonating and destroying some structural portion of the ship. Even if the weapon (e.g. missile) does not detonate, previous war experiences have shown that residual missile fuel can be the cause of very violent fires.

Fire initiation as a result of weapon impact can be caused in several different ways. If the weapon explodes, the following fireball could be more than sufficient to ignite combustibles in the compartment directly. Secondary damage effects caused by for example splinter, could also be the cause of a fire initiating and subsequently developing. The presence of liquid fuel (e.g. gasoline) or residual missile propellant, has proved to increase the probability of ignition. One important issue is whether the blast of a fuel rich explosive will ignite the combustibles affected, particularly when they are solids. Of course, temperatures will rise to decomposition levels, but in the absence of sufficient oxygen, which might be depleted by the explosion, ignition might not occur.

Experiences and tests have shown that fires can be initiated in adjacent compartments as well. The events surrounding the destruction of *Piper Alpha* (appendix B) serve as one example of this. Most probably the initial explosion on the platform generated small projectiles by the disintegration of the firewall between the two modules affected. These in turn had enough energy to rupture some of the surrounding pipework, releasing and igniting condensate and after this crude oil, which is believed to have been the fuel of the subsequent poolfire.

An example directly related to the effects of weapon impact is the hit on the gas tanker *Gaz Fountain* in the Persian Gulf in October of 1985 (Carter, 1985; see also appendix B). This was the first occasion that a liquefied gas carrier has been breached with ensuing fire and then successfully salvaged. The *Gaz Fountain* was attacked with Maverick TV guided air to ground armour piercing rockets. Three rockets are reported to have hit the vessel and one of these exploded on-deck above the fore end of one of the tanks near the centreline. The tank was not ruptured since the main explosive blast from this missile appears to have gone upwards and outwards above the deck. Instead, all service pipework and electric cabling carried on the overhead walkway above the blast was blown upwards. Much of the piping was ruptured or badly bent and the electric cabling destroyed. Escaping gas from the ruptured pipework caught fire and a heavy steel-ladder leading down from the walkway to the deck at this position was blown off and landed on the pipework. Possibly as a result of this shock a valve failed on one of the other tanks and propane was released, under pressure into the line. The released gas exited through the damaged pipework over one of the tanks, where a sustained torch fire was established. These two examples sustain the assumption that a release of flammable liquid would most certainly ignite onto a hot surface or in contact with the hot splinters in case of an explosion.

A number of different fire scenarios may be encountered when considering both long-term and short-term fire effects. To a large extent the following cases are similar to those considered hazardous within offshore and in chemical process industries as well:

- *Fireball*: The rapid turbulent combustion of fuel as an expanding, rising ball of flame is usually very intense and has in many ways similarities to an explosion. They can (as was the case with the Ro-Ro ship *Kukawa*, described in appendix B), be a contributing part of rapid fire spread through ventilation ducts and uptakes. After the initial explosion on *Piper Alpha*, a fireball created from an estimated 100 kg of fuel was reported. In several cases of weapon-induced fires, fireballs have been experienced as well. One example is the incident on board *USS Samuel B. Roberts* in April of 1988 when the ship struck a contact fused mine (Heine, 1988). A 6-7 m hole in the hull was created beneath the engine room disabling both gas turbine engines, knocking the reduction gear off on its mount and rupturing two 40 m^3 fuel tanks. Machinery in the engine room lower level was propelled a few metres up into the engine room upper level. The spewing fuel oil which was pushed up onto the gas turbine, immediately ignited, shooting a fireball through the stack 45 m into the air. Flames and smoke spread rapidly and sea water rushed into the ruptured hull. Four sailors were manning the main engine room at the time of the explosion and the gas turbine module halon could not be activated. Serious damage was done to the keel and the superstructure cracked. The main engine room was flooded and seriously blast damaged to vital equipment and uptakes.
- *BLEVE* (Boiling Liquid Expanding Vapour Explosion): BLEVE can result from the sudden failure of a vessel containing a pressurised liquid at a temperature well above its normal boiling point. No example has however been found in the literature exemplifying this phenomena related to weapons effects.
- *Pool fire*: Pool fires are often the subsequent result following explosions, where liquid fuel of some kind is involved. A boiling pool fire is very difficult to control and may accompany a jet of fire where liquid rains out of the jet. Basically, this consists of a turbulent diffusion fire burning above a nearly static pool of vaporising fuel.

- *Running fire*: These fires basically consist of a burning liquid fuel that flows by gravity over surfaces. It became evident during the South Atlantic conflict, hits on fighting ships by a variety of weapons cause extensive damage and liberate large quantities of hot hydrocarbons and fast running fires are likely to be encountered. They can be very hard to control and in these cases resulted in burns to the crew, assisted in the rapid smoke spread and increase in production of toxic gases.
- *Jet or spray fire*: This is a turbulent diffusion flame resulting from the combustion of a fuel continuously released with some significant momentum in a particular direction. As mentioned above, these are often accompanied by subsequent pool fires created by rained out liquid. They have the potential to assist in fast fire spread.

The fire ball and BLEVE have a typical duration of a few seconds, while the other types of fires often involves much longer processes if not extinguished somehow.

Only a short period (seconds) after an explosion, the blast effects will have decayed and the fire growth environment will revert to that generally experienced by natural fires (normal temperature and pressure - the environment in a compartment immediately following an explosion is characterised by extremely high pressures). This means the fire can be treated as any freely burning fire until the “air” flow induced by the fire becomes vitiated (reduced in O_2 due to contamination by re-circulating combustion products), or the fire pyrolysing region grows extensively in size so that all the air supplied is reacted and the fire becomes “ventilation-controlled”. Although only a thin combustible surface coating may exist, it should be realised that under typical fire heating conditions roughly only 1 mm of the depth into the surface controls its ignition and flame spread. Even retarded materials burn under realistic conditions. The most concentrated quantity of combustibles, excluding munitions, is most likely the liquid fuels - diesel oils, hydraulic fluids, aviation fuels - stored in tanks and pumped through pipe lines. Pool fires of contained liquid spills or spray fires from line and tank ruptures are also possibilities.

For the fully-developed compartment fires, temperatures will depend more on the size and thermal properties of the compartment, on the ventilation factor ($A \times H^{1/2}$) and to a lesser extent on the mass of fuel (fuel load). This variation of mass burning rate can be conceptualised in an overview manner by stoichiometric lines (figure 5-2). On the left side of these, the fire is ventilation-controlled and all the air entering the compartment is consumed (i.e. the rate at which air enters the compartment is insufficient to burn all the volatiles and the excess will be carried through the ventilation opening with the outflowing combustion products). Fire duration is then given by the mass loss rate and the mass available. The fuel’s mass loss rate will in the ventilation-controlled case, tend to be reduced from the freely burning state, hereby extending the fire duration.

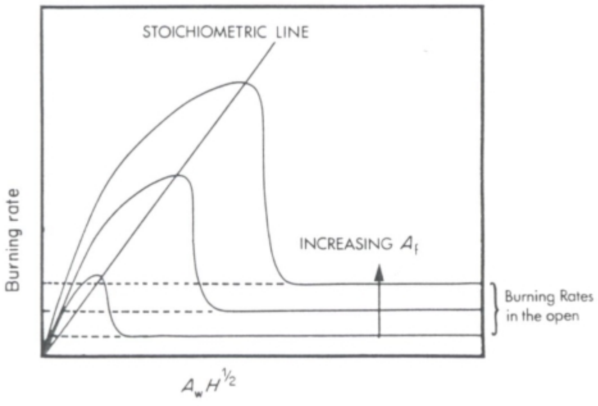

Figure 5-2 *Variation of mass burning rate with the ventilation parameter ($A_W H^{1/2}$) and fuel bed area (A_f) (Drysdale, 1985).*

A particular problem is the prediction of ventilation conditions during a shipboard fire. A ship is a sealed vessel with inter-connecting internal decks (horizontal "floors"), compartments and passages. The openings to the external atmosphere are at the upper decks, internal decks are connected by floor and ceiling hatches and stair accesses. The only natural openings are usually at the exterior deck levels. As a vertical section of the ship fills with smoke, the availability of new ambient air becomes possible only through open deck hatches, where the air and combustion products are transported through the openings without mixing. In both cases the growth of the fire beyond a critical early size will thereafter be controlled by the available air flow supply rate to the burning-pyrolysing fuel region. Few studies have been made on the burning of fuels in a compartment with only a top opening in contrast to the building case with a side opening, even though results would be of great interest. Fires vented from above are also hard to predict. Model equations can for example be developed for the steady burning case, where the fire is relatively small compared to air supply capability of the ventilating hole. The unsteady case, however, with the larger fire/smaller hole, is likely to occur and will be more difficult to predict as well as present a more difficult fire-fighting problem. Some small scale tests claim that the pyrolysis rate was 2-8 times compared to open tank burning conditions (Quintiere, 1985).

A compartment fire can generally be described using the phases in figure 5-3, where the conditions when reaching flashover are considered of special interest. Ignition is directly followed by the growth stage, where the fire grows primarily as a function of the fuel itself and with little or no influence from the compartment. Flashover is generally defined as the transition from a growing fire to a fully developed fire in which all combustibles in the compartment are involved in fire. At this point the radiation from the hot gases in the compartment will ignite all combustible materials. Temperatures for this to occur is considered to lye between 500-600 °C and the radiation at floor-level at this time is about 20 kW/m^2. If enough fuel is present, the fire becomes fully developed, which means the HRR (heat release rate) is greatest. Most likely a fire within a ship compartment reaching this stage will be ventilation-controlled, since more fuel is likely to be pyrolysed than can be burned with the oxygen available. The final stage of the fire (unless extinguished earlier) is the decay stage, which occurs when the fuel is consumed and the HRR declines. At this point (if not sooner), the fire is likely to go from ventilation to fuel-controlled. Many factors can influence the duration of the fire and when the decay stage is reached, at which the compartment temperatures start to drop. One important factor to consider for shipboard fires is the amount of boundary insulation for example. Tests in large compartments with restricted ventilation (Cooke, 1994) show that the duration of a fully developed fire can be large for a compartment having boundaries of high thermal insulation, a large fire load and restricted ventilation. The thin line in figure 5-3 represents fuel depletion or lack of oxygen to the fire, which is a possible scenario if compartment boundaries are intact ("closed room" conditions). An introduction of new air at this point (opening, ventilation etc.) might cause re-ignition of the pyrolysed gases and in case this occurs as a deflagration, it is referred to as a "backdraft" (Bengtsson, 1999).

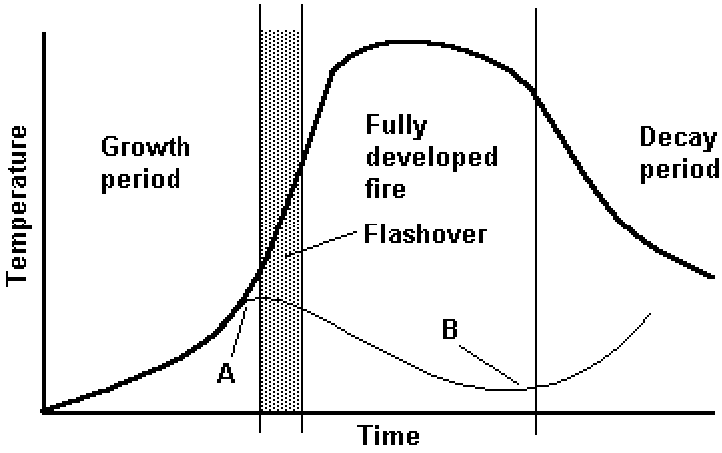

Figure 5-3 *The general temperature-time curve for a compartment fire (the thin line represents depletion of fuel before flashover is reached or lack of oxygen (A), and possible re-ignition (B) as new air is introduced to the fire.)*

Tests were conducted as part of the Ship Survivability Enhancement Program (SSEP) on a destroyer escort, the former *HMAS Derwent*, at the Royal Australian Navy Fleet Base in Cockburn Sound, Western Australia (Gamble *et al.*, 1998). The aim was to investigate the effect of residual missile fuel on the growth and duration of missile-induced fires and also to study the effectiveness of current fire-fighting techniques. Three large compartment fires were set which simulated missile hits with no subsequent warhead explosion. The resulting fires established similar temperature histories. After the explosive initiation (fireball), a rapid rise in temperature is observed as the dispersed fuel is consumed. The temperature at this point is about 800°C until the residual fuel is consumed and the temperature drops and a convection dominated fire is established, eventually consuming the flammable materials within the compartment. In the post flashover compartment, the temperatures within the compartment were essentially the same - 800°C. The time for the fire to consume the fuel was about three minutes and the total time until flashover was about ten minutes. To summarise the experiments, the results matched those predicted very well (simple calculations based on standard fire curves, the ventilation and the fuel load predicted the average fire behaviour) and the longer the fire was let to burn, the harder it became to fight. It is concluded that no more than ten minutes are available for fire-fighting before the conditions become to extreme (i.e. flashover).

The fire was initiated by detonating a 2.95 kg charge, coupled with four base fragments, to spread and ignite 20 litres of fuel (JP-5) in the compartment. All hatches and openings from the compartment were closed from the outset of the experiment (except for a hole cut in the ship's side to simulate the opening made by the weapon penetration). It proved that the initial blast was sufficient to open the hatch to the compartment above and fragmentation also pierced through the boundaries in different directions. The effects of the fire in other compartments than that of origin also showed clearly. Most of the paint of the bulkheads of adjacent compartments had peeled off the bulkhead and even though there was very little combustible material in these compartments, an electrical junction box had caught fire from the heat transmitted through the bulkhead. Due to the initiating blast and fragments, an opening to the above compartment was established and even though most of the combustible material had been removed, the fire was such that the fire-fighters could not enter the section for a considerable period. The intumescent paints proved effective in reducing the damage in adjacent compartments. The compartment protected by the paint had very little heat damage after an exposure of two hours whereas the unprotected compartment adjacent to the opposite side of the fire had the paint burnt from the walls and spot fires in components attached to the wall.

There were a few other important conclusions drawn from these fire experiments. In all experiments the construction of the hatches proved inadequate to contain the blast. These were sprung open and in one case this contributed to an unwanted fire spread to the compartment above. Also, it was noted that aluminium ladders melted and access between decks was made difficult. The final conclusion is that the time after the initial impact of a missile until flashover conditions is a critical time for the crew of a naval vessel. These experiments indicate a period of about ten minutes is available for fire-fighting before the conditions become extreme. Within this period a fire-fighting team could consider fighting the fire directly.

5.1.2 Fire spread

Fire spread between compartments is a major concern for the ship designer as well as the on board fire-fighters and can be divided into two main categories:

1) The fire spread, which is due to hot gas and flame transport through openings to the adjacent compartments (mainly convection and radiation), and
2) that which is due to heat transfer through bulkheads etc.

The former involves mainly fluid dynamics and radiant heat transfer, the latter primarily heat conduction. Earlier in chapter 3.3.3, a characterisation of different types of fires was made and examples given. In the following, a few examples and experiences gathered from war- and peacetime incidents are used along with results from several experiments with the purpose of illustrating the different ways fire may spread.

A number of tests have been performed on the decommissioned *USS Shadwell* (the US Navy's fire test ship in Mobile, Alabama). Two sets of tests were completed, one in March 1992 and the second in April/May 1993. The fire tests in March 1992 simulated conditions experienced when two missiles hit the USS Stark. The fires that were generated reached temperatures of nearly 1,100°C. These tests were made in order to evaluate the use of different temperature sensors. Fire detection information is generally considered very important on board ships, since quick response is required to minimise casualties and damage. Problems experienced were that some sensors stop operating permanently above 400°C, meaning the monitoring system is blind when the system cools below this temperature and for safety reasons it is important to know the cool down temperature (Whitesel, 1994).

Other tests performed on the same test ship from 1989 to 1993 were made for the purpose of comparing the vertical heat conduction of real-scale fire tests with those from an algorithm developed for CFAST (Consolidate Fire And Smoke Transport - zone model for calculation of smoke spread, compartment temperatures etc.). The ability to account correctly for conductive heat transfer through metal decks and bulkheads is especially important aboard ship, since fire can spread as a result of rising temperatures in adjacent compartments that reach ignition levels even when there is no breach in the compartment of fire origin. One of the objectives was to develop ship design criteria that would address devastation of the type that occurred on the *USS Stark* as the result of fires caused by a missile.

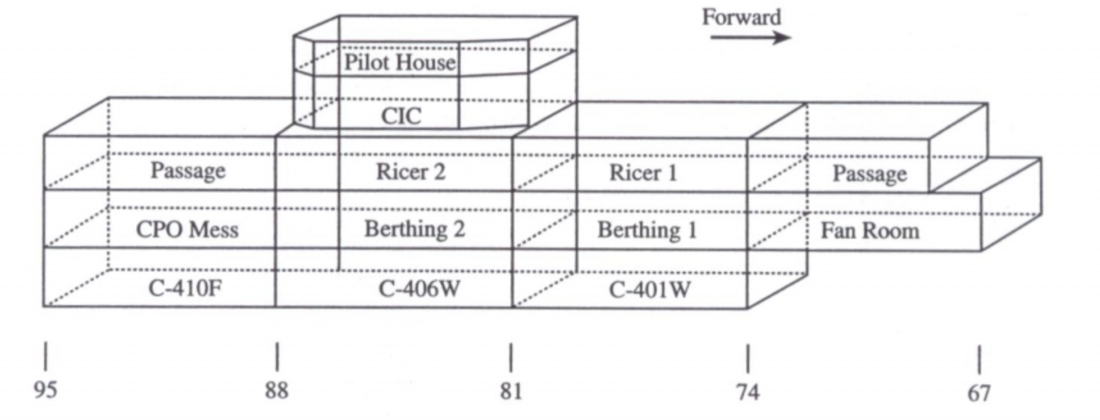

Figure 5-4 *Section view of the test ship USS Shadwell (Bailey et al., 1998).*

The test configuration consisted of three compartments vertically aligned above a fire compartment (“Berthing 2” in figure 5-4). Results of the tests were several and mainly concerned modelling of compartment temperatures. Before the new algorithm was added, the model predicted that the temperatures in the compartments above the compartment of fire origin would remain essentially at ambient. After the algorithm was incorporated, however, the model’s predictions were much more realistic. The comparison between the predicted and measured temperatures in this series of experiments showed good agreement. The comparison indicates that during the early stages of the fire, the far-side temperatures - that is, those on the unexposed surface - were underpredicted. This indicates an effective heat capacity that is too high and/or effective conductivity that is too low (Bailey *et al.*, 1998). The addition of the new algorithm resulted in much more realistic predictions.

Other conclusions extracted from these tests are in short the following:

- The average compartment temperature in “Ricer2” (above the compartment of fire - see figure 5-4) reached about 200°C after 10 minutes, while in the “CIC” the rise in average temperature is very small.
- The deck temperature of “Ricer2” is close to 400°C after 5 minutes and 600°C after 10 minutes. In “CIC”, the rise in temperature of the deck is again very small.

The above results can be compared to other fire tests on the same test-ship and using the same compartment as fire compartment. In these tests a diesel spray fire of about 10MW was simulated, which led to almost instantaneous flashover. Large ventilation openings were present in the side of the compartment not to limit the effect of the fire. However, no holes or openings could directly spread flame or smoke and the steel was not isolated (0.48 cm). The heat transfer was solely due to the thermal conductivity of the steel. This represents a very different case from the heat transfer through concrete structures found in most buildings for example. Empirical values compared to analytical from standard thermodynamic formulae, energy balance calculations and heat transfer coefficients gave the following results:

- Temperature values were in good agreement, and
- the heat flux calculated was greater than the measured and give rise to "worst case".

As might be expected, the conditions in adjacent compartments were less severe than in the overhead compartment, particularly with regard to air temperature (figure 5-5). For the overhead compartment, these temperatures seem to match the results of above tests well. Radiant heat is also a problem that needs consideration. In the overhead compartment, the radiant heat flux after 10 minutes, measured 0.3 m from the floor to about 50 kW/m^2, which would be more than enough to create pilotless ignition of wood for instance. In the adjacent compartment, the measured fluxes were notably lower and after 10 minutes measured nearly 10 kW/m^2.

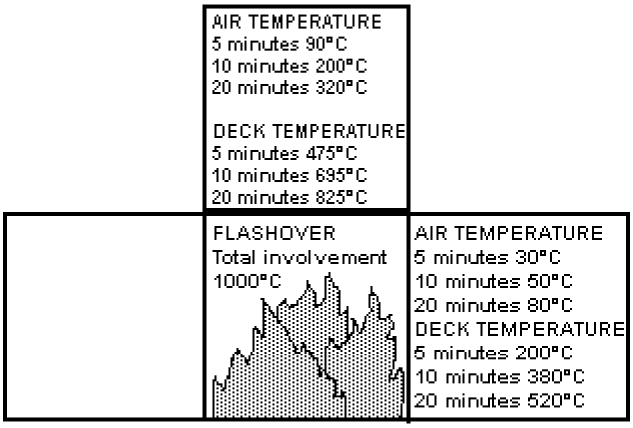

Figure 5-5 *Air, deck and bulkhead temperatures in overhead and adjacent compartments (reproduced from Darwin et al., 1994).*

To summarise the tests, it can be assumed that fire will start to spread to adjacent but mainly overhead compartments in about 10 minutes for an unisolated steel construction (the deck temperature in above compartment reached 475 °C in just 5 minutes) after flashover is reached. In these tests flashover was experienced very quickly, basically at the time of fire ignition. Weapon-induced fires involving residual missile propellant are likely to present similar scenarios.

5.1.3 Smoke spread

Of great concern to any fire-fighting activities on board is the problem of smoke spread. Low visibility, problems in finding the seat of the fire and the toxicity of the smoke are just a few of the difficulties encountered.

Experiments to gain further information on smoke spread on board has been done both on civilian and military vessels. However, some of these tests show contradictory results from the use of similar ventilation techniques and it therefore becomes hard to come to any far reaching conclusions on the design of a well functioning smoke extraction system. The results seem to a large extent depend on the type and size of ship.

For example, experiments were made on the mine vessel *HMS Visborg*, where smoke of a temperature of 200°C was generated and measurements made. One experiment included the ventilation being used as normal, but without any re-circulation and the second test was made without any ventilation (shut off after 1min45sec). Conclusions from the experiments are mainly (Jansson *et al.*, 1991(1)):

- The rise in temperature were close to identical for the two tests.
- Having the ventilation running proved to give rise to the best results as far as smoke spread is concerned, the smoke spread was minor .
- The ventilation being shut off showed increased smoke spread and smoke also spread through leaks in doors and walls and through ventilation ducts.
- Important for these results is that no re-circulation can be allowed.

With a number of experiments, fire was simulated and the smoke spread was evaluated aboard the corvette *Göteborg*. In short, the results are in agreement with those above and say that the best conditions were obtained when the ventilation was left on but with the re-circulation shut off (Jansson *et al.*, 1992).

Some experiments have also been performed on passenger ships. During the winter of 1991, experiments of full scale were carried out on the *M/S Wasa King* under the guidance of the Swedish National Defence Research Establishment (FOA). Results concerning the effects of ventilation are the following (Jansson *et al.*, 1991(2)):

- When the ventilation plant was running normally, meaning that both supply and exhaust fans were in operation, the smoke spread was quicker. The ventilation system created turbulence that destroyed the buoyant smoke layer. This mechanism created the smoke layer to be built up more homogeneously and the escape of people in this simulation will be more difficult. Despite the air renewal effect of the ventilation plant the smoke conditions of the stairway were not improved.
- Only using the supply fan naturally caused turbulence and the effects of creating over-pressure were not reached.
- Running of the exhaust fan in the cabin ventilation system as smoke evacuation fan was tested with a positive result. The experiment was made from a situation where corridors and stairway was extensively smoke filled and the smoke simulator was still in operation. As the ventilation capacity of exhaust fans in these systems are large due to extensive area served, in intense ventilation effect was obtained.

Experiments were also carried out aboard *Wasa King* in Åbo in 1987 to see how well the practical smoke spread correlated with the calculations made in FAST. The theoretical calculations proved to be very accurate and the smoke spread from the fire in a compartment could therefore be simulated in a good way. Further conclusions were that without the ventilation on, a smoke free layer was created and the ventilation created more diffusion of the smoke and time to critical conditions would be much shorter (Sjöborg, 1991).

In conclusion, the above results regarding the use or non-use of running ventilation for the purpose of smoke clearance, are contradictory when comparing some of the tests performed on warships and passenger vessels. It is, however, important to note that the warships tested are much smaller and differ in basic ship design in many ways. Generally speaking, it seems accurate to assume that warships (at least up to corvette-sized ships) would benefit from active use of running ventilation.

An examination of the spread of both hot and cold smoke (Gamble *et al.*, 1998) was also done on board *HMAS Derwent* mentioned earlier. During the tests a number of ventilation conditions and smoke clearance procedures were used. Many navies have had a policy of crash stopping all ventilation upon report of a fire and seal off all bulkhead and inter deck connections if not already closed. Ventilation is then only restarted in those areas of the vessel which are unaffected by the fire. The reason for this is that limiting the amount of oxygen available to the fire will make it more easily contained and knocked down. It could, however, be shown that using both positive pressure ventilation techniques and smoke extraction did not increase the severity of the fire, provided the temperature in the compartment is well below 400°C. Again, one experience from the Gulf and *USS Samuel B. Roberts* will serve as example. After hitting the mine, smoke was initially a problem in fighting the fire in the gas turbine and keeping the progressive flooding under control. This was brought under control by setting positive ventilation in the fire compartment and later by setting negative ventilation in two of the adjacent compartments.

The advantages associated with the use of active smoke extraction techniques in such situations are that visibility is dramatically increased. This also increases the speed and effectiveness of any search activities undertaken by naval fire-fighters, whether this be for locating the seat of the fire or for the location of unaccounted personnel. In addition, the temperatures in adjacent spaces, particularly passageways in the direct smoke clearance path, are reduced significantly therefore reducing heat hazards for fire-fighters while temperatures within the fire compartment remain essentially unaffected. Furthermore, the ability to locate the seat of the fire as early as possible is of great importance and in general this means that fewer resources, both human and equipment, are needed to defeat such fires. The primary disadvantage of using active smoke clearance procedures is that, in a ventilation limited fire or a fire approaching a compartment air temperature of about 400°C, the additional oxygen so introduced can “fan” the fire and accelerate the onset of flashover.

It must, however, be considered that the advantages of clearing the smoke and increasing the visibility, may in certain circumstances such as search and rescue operations, outweigh the risk of increased fire severity. One “rule of thumb” based on the results of the experiments seems to be that if the active smoke clearance techniques are utilised within the first five to eight minutes, the severity of the fire should not increase (Gamble *et al.*, 1998).

Another series of tests were conducted within a test chamber comparable to a ship accommodation quarters. One of the objectives was to gather data on the behaviour of a fire in a compartment with ventilation conditions similar to those on ships, with different types of materials, but also to determine the effect of the ignition intensity on materials found difficult to ignite. Besides the specific results including fire behaviour of polyurethane versus the less ignitable chloroprene, some interesting general results regarding the effects of ventilation on the intensity of the fire can be found. It seems that for the more easily combustible polyurethane, "closed" ventilation conditions severely limited the rate of heat release shortly after the fire started, while the "forced" ventilation fire was somewhat more intense than the "free" ventilation fire. In the final test, burning of chloroprene under "forced" ventilation conditions, makes the fire develop more rapidly than for the "closed" and "free" ventilation conditions even though the intensity fluctuates (Steward *et al.*, 1992).

5.2 Vulnerability factors identification and assessment

After a review of literature and an attempt to describe the events surrounding the behaviour of weapon-induced fires in a overview manner, the final stop is an identification of the more important factors (in the author's view) influencing the outcome and severity of a fire. Simply put, these can be identified as two "protection factors" and three "hazard factors", which in turn consider several aspects previously discussed in chapters 3-4.

The response actions can be illustrated using the event tree in figure 5-6. Taking this type of analysis further, could result in a more or less complete identification of probable accident outcomes depending on a number of factors. Since this is not within the scope of this paper, this is merely done in a qualitative manner.

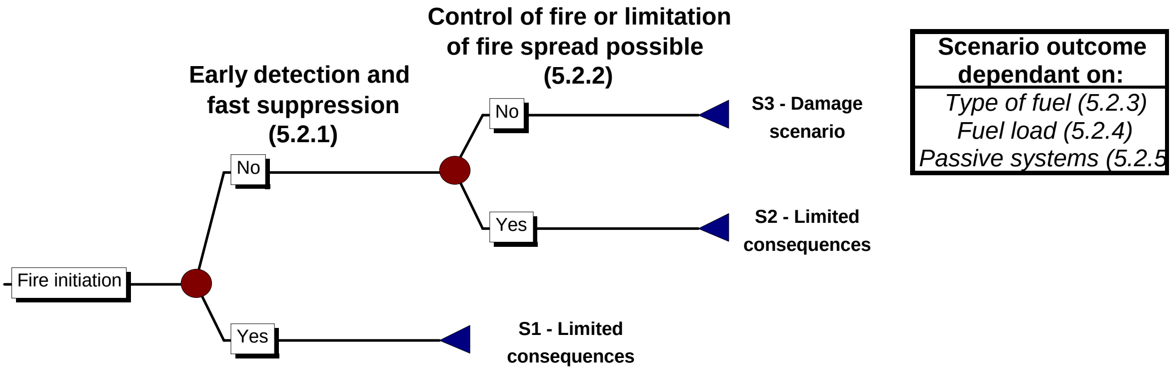

Figure 5-6 *Initial part of event tree showing* fire-fighting *actions.*

5.2.1 Active systems and fast response fire-fighting measures

Previous war experiences have identified early fire-fighting measures as crucial in several cases during military operations (appendix C) as well as in peacetime(appendix B). Full-scale experiments such as those on *HMAS Derwent* also emphasise the need to fight fires in the incipient stage in order to achieve suppression or at least a quick knock-down of the fire (S1 in the event tree above). If this can be done, this will limit the damage done to the ship as well. The need for early fire-fighting is an important point to make, even though a rather obvious one. It would seem a lot is gained if flashover conditions are not reached, since this will increase the probability for rapid fire spread to adjacent and overhead compartments as well as limit the possibilities for successful fire-fighting. The fact that weapon-induced fires with residual missile propellant often prove to be rather violent might limit the possibilities even further. Actions should then be focused on limiting the fire spread using techniques such as boundary cooling and starvation (removal of combustible material from adjacent compartments).

Direct actions to fight the fire in its early stages range from automatic active measures such as sprinkler systems to quick manual fire-fighting by designated teams and portable equipment (centre fed hose reels, extinguishers etc.) or manually released suppression systems (deluge, CO_2 etc.). It is important to ensure that all gaseous drench and deluge systems are fitted with local, remote and upper deck operating stations, since damage effects might limit access to control and availability of fitted suppression systems. These tactical matters are of course solved differently from one navy to the next, but it would seem in an age of decreased manning on board ships, automatic systems is a good way to accomplish fast effective fire-fighting. Then again, during peacetime conditions and accidental fires, the release of these systems could easily be a nuisance best avoided. Also, there would be a need for increased maintenance of this kind of equipment to always be in best condition possible. A well trained and motivated crew along with a planned fire-fighting organisation will of course also play an important role in the effective fighting of a fire.

To summarise the more important aspects from above discussion, figure 5-7 provides a good way of approaching the problem. This illustrates the effects failure of initial fire-fighting actions, such as active systems and quick manual fire-fighting, will have on the ability to fight the fire before it grows out of control. In order to control the fire, initial fire-fighting should be focused on suppressing or at least "knocking down" the fire before Q_{CRIT} (critical heat release rate for the suppression system or the manual fire-fighting actions taken) is reached, since hereafter the fire will need more extensive fire-fighting efforts in order to successfully be brought under control (S2 in the event tree). Preferably, Q_{CRIT} should be determined experimentally somehow.

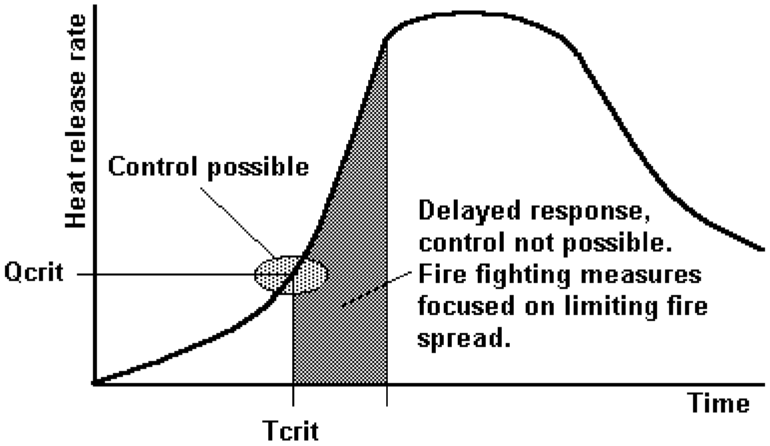

Figure 5-7 *The systems fails to suppress the fire prior to the critical heat release rate is reached.*

While there is no certainty that an extinguishing system, although operating correctly, will always put out or even contain any specific fire, the reliability of the system can be related to its ability to perform to design specification when required. Little information is generally available on the performance of foam, gas and powder extinguishing systems. Some data on the performance of water sprinkler systems is available mainly from insurance organisations and tests. In some cases it might also be necessary to consider different interaction effects. One example is the interaction between sprinklers and fire vents, which is not well understood at present (a summary of present knowledge is given by Persson *et al.*, 1996). It is never the less the authors view that the only way to really evaluate the effectiveness and reliability of different measures of suppression for warships is by realistic tests.

5.2.2 Damage control and fire-fighting measures

In the case initial fire-fighting efforts and the use of active systems are not successful in suppression or accomplishing a quick knock-down of the fire, the severity of the outcome will depend considerably on whether the damage control and additional fire-fighting efforts taken are successful or not (outcomes S2 and S3 in the event tree).

There are many aspects of damage control and fire-fighting (DC&FF) measures that in some way contribute to the outcome of a fire and this section is mainly focused on a discussion of fire-fighting measures in a more long-term perspective than the previous. Assuming that the initial response actions were not effective, there is a need to look at additional measures that might at least limit the spread of fire to other compartments.

First of all is the matter of manning that has been previously discussed. The constant reduction in available manpower for coping with DC&FF could pose a threat to the survival of a ship in the event it is struck by a weapon of some kind. There are several other aspects on available fire-fighting equipment and how it is used. Experiences of weapon-induced fires have pointed out that the lack of adequate equipment as well as the sudden loss of main water pressure can be limiting in many ways. The latter case could lead to the incapability of using for instance boundary cooling as a means of minimising the spread of fire. Below follows a summary of some of the more important overall lessons learned from peace- and wartime fire-fighting on board warships as well as other vessels. These are not given in any specific order of importance, but just as an aid in developing an understanding for the sometimes special conditions and problems occurring during fire-fighting on board:

- Lack of training and preparedness of the crew has been identified at several occasions as a contributing factor in both success and failure in fire-fighting.
- The often rapid fire growth and spread experienced on board ships in general, but weapon-induces fires in particular, when residual missile fuel is present. Improved procedures for dealing with these intense fires and the attendant possibility of vertical fire spread are needed.
- Portable extinguishers have in several cases proved ineffective and usually the reason for this has been established as poor maintenance.
- Lack of adequacy in fire main water pressure is a serious problem, that on several occasions caused major problems in performing effective fire-fighting after weapons effects and subsequent fire (as was the case with *Sheffield* for instance - appendix C).
- Smoke problems. On several occasions problems in locating and fighting fires have been experienced. Worth mentioning in this context is the fire on *HMNZS Canterbury* (appendix B) in January of 1997, where large amounts of smoke led to confusion in isolating the scene of the fire. A need for improved smoke removal equipment has been identified, portable and/or installed. Smoke curtains and other means of protective measures could be considered as well. A thermal imaging camera for naval fire-fighting can provide the discovery of a fire at an early stage.

- Some examples from fires on board both warships and commercial vessels show that low availability of equipment can present a serious problem. The ability to rapidly deploy additional physical resources also depends on the distance to those resources. Several times, equipment has either been impossible to access or non-functioning when brought to bear. Many examples (*Stark*, *Sheffield*, *Waikato* and *Piper Alpha* - appendix B and C) show the crucial effects that rupture of fire-main piping or loss of the HPSW system may have on the possibilities to effectively fight the fires.
- Problems with re-flash, both after active systems have been released and during subsequent fire-fighting entry, has presented difficulties. The reason is often that the suppression agent used (mainly halon, CO_2 or inert gases) offers little or no cooling effects.
- Improved procedures for rapid removal of fire-fighting water from the ship has been accentuated at a few incidents in peacetime as well as in wartime. Instead of having to shut off the water supply to deluge systems for example, solutions should be worked out for removal of the large amounts of water. The future use of water spray and fog systems could prove helpful in limiting these problems, since they would introduce much smaller amounts of water.
- Improvements and additions to some areas of portable fire-fighting and damage control equipment has also been identified. Examples are the need for wireless communications equipment for internal damage control management efforts, equipment for cutting access through bulkheads and decks (for cutting access routes, water drainage and venting holes and clearing battle damage), improved fire-fighting protective clothing (e.g. anti-flash hoods) and more portable fire-fighting/de-watering pumps. Another example is the need for a higher availability of Emergency Escape Breathing Device (EEBD), mainly for making escape from smoke filled compartments easier. An increased number of BAs and BA canisters should also be considered. Machinery rooms of large ships can give rise to problems with BA duration, since it could be 20 m down.

In order to come clear with some problems identified above, several “new” technologies are considered for the future. These are for example watermist, which is considered as one of the possible new additions to warship protection. Another one of the more recent additions to the means of protection, are the so called Platform Management Systems (PMS), which basically is an integrated platform control and surveillance system with a wide range of possibilities (Squires *et al.*, 1998). One important aspect from a fire-fighting perspective is the decision support and surveillance this can provide. Other ways of increasing the level of protection is the addition of new equipment such as centre fed hose reels for example. These are bulkier but less manpower intensive than traditional hoses and has the potential to allow a rapid response with fewer fire team members. Further pieces of equipment are fog lances, which can be inserted into smaller less complicated compartment to release a water fog. Automatically operated (solenoid valves controlled by measured temperatures) fixed boundary cooling systems is another example, as well as an increased use of boundary insulation, longer endurance breathing apparatus, thermal imaging cameras, improved ventilation systems and use of smoke clearance techniques, of what is being considered.

It will prove hard to rank the different technologies, but somehow this has to be done before deciding on the different protection measures needed. One way to accomplish this is by using some kind of measures of effectiveness analysis. These measures of effectiveness could be for example (Squires *et al.*, 1998):

1) *Military effectiveness*. Contribution to platform survivability by increasing the ability to maintain fighting effectiveness.
2) *Risk*. Overall risk, including development, installation and through life (reliability) risks.
3) *Cost*. Procurement and installation cost, through life cost and potential for manpower reduction.
4) *Statutory requirements*. Potential impact of future legislation.

In the above analysis, the most effective technologies for the future are likely to be simple portable equipment such as extended duration breathing apparatus and improving the zoning and control of ventilation. Technologies that rely heavily on sensors and actuators did not perform well in the measures of effectiveness analysis. This was because the sensors, actuators and associated systems were perceived to be expensive to develop, purchase, install and there were fears that they could lead to an increased maintenance burden.

5.2.3 Type of fuel

In the case where actions to fight and limit the extent of a growing fire are insufficient, mainly three “hazard factors” are identified here as contributing to the accident outcome (figure 5-6). The first one is the actual fuel type, which is looked into a little further in the following.

The type of fuel present in the compartments affected by the fire has proved as an important factor, since the fire will spread more rapidly in a compartment dominated by easily ignited material with a low flash point compared with less ignitable material such as lubrication oil (i.e. the type of fuel present in the compartment of fire (can naturally be a mix) will dictate the growth rate of the fire).

Based on the previous, different materials can be divided into four categories (Kennett *et al.*, 1991), depending on ease of ignition:

1) *Low ease of ignition* (e.g. lubrication oil)
2) *Medium ease of ignition* (e.g. wood)
3) *High ease of ignition* (e.g. paper)
4) *Very high ease of ignition* (e.g. petrol, gas, missile propellant)

In short, the fire growth rate (HRR) can generally be described using the following equation:

$$\dot{Q} = \alpha \times t^2$$

where α is the growth factor (given in kW/s^2) and t is the time from ignition in seconds. The above categories correspond to different values of the growth factor, given in table 5-1.

Growth rate	**α (kW/s^2)**
Ultra fast (4)	0.19
Fast (3)	0.047
Medium (2)	0.012
Slow (1)	0.003

***Table 5-1** Values of α for different growth rates according to NFPA.*

As has been pointed out earlier, fires involving residual missile fuel have a tendency of developing very fast and the fire growth rate of such a fire could be faster than “ultra fast” and has to be handled separately. The incident on board *USS Stark* (appendix C) serves as an example of this. The frigate was hit by two missiles, of which only the second one detonated. However, burning missile propellant (is self-oxidising and cannot be easily extinguished with water or AFFF) was spread in the affected compartments and created intense heat, which in turn ignited all combustibles in the compartment initially affected. Heat and smoke caused by the ignition of combustibles, including PVC jacketing on electrical cables, impeded fire-fighting efforts, blocked normal entry routes to compartments and heated deck temperatures enough to cause vertical fire spread. Intense heat caused by the residual propellant burning at about 1,650°C, combined with dense smoke and an immediate loss of firemain pressure impeded initial attempts to control the fire. The heat caused an almost immediate flashover of all the combustibles in the compartment. After initial burning of the propellant, primarily the high fuel load of the polyvinyl-chloride lacquering of the electrical cables fed the fire, plus combustibles normally found in the berthing compartment.

A similar scenario was experienced by the destroyer *HMS Sheffield* in 1982 during the Falklands War. The missile, which was air-launched, entered the ship on the starboard side amidships, creating a hole 4.5 m long by 1 m high in the ship side, roughly 2.5 m above the waterline, but did not detonate. However, rupture of the missile motor caused considerable blast effects and unspent diesel oil fuel caused immediate fires centred in the forward auxiliary machine room.

These events and other experiences coupled to different tests, identify the fuel type as a major hazard that has to be considered in the overall process of vulnerability assessment.

5.2.4 Fuel load

Another important aspect of threat definition is concerned with the ship itself and relates to the fire load on board. To put things in perspective, a 4000 tonne frigate will carry about 700 tonnes of fuel, 45 tonnes of ammunition and some 100 tonnes of other flammable materials. The safety of fuel depends on secure stowage, low in the ship where it is least likely to be ignited by enemy attack and where it is more easily extinguished by a foam blanket. Other flammable materials can mainly be divided into (Dimmer, 1986):

- those designed and built into the ship,
- furniture and fittings,
- stores, paper and books,
- personal effects, and
- unofficial improvements.

A crucial point when considering overall vulnerability is obviously the actual fuel load of the affected compartments. A high fuel load will increase the probability that the fire will reach flashover conditions and continue burning for a considerable time. This will also mean increasing the risk for fire spread to adjacent compartments mainly due to the effects of heat conduction. An attempt to divide different fuel loads into a number of categories is done by Kennett *et al.* (1991) (based primarily on experimentation described in Pettersson *et al.*, 1976) and the following is to some extent based on a similar approach. One main conclusion of the extensive experimentation is that for fuel loads around 60 MJ/m^2, flashover and complete combustion does not occur (Pettersson *et al.*, 1976). Fuel load is defined as the total heat of combustion of materials in the compartment divided by the compartment floor area. These values are of course to a large extent dependent on ventilation conditions in general and the ventilation factor ($A \times H^{1/2}$ - see chapter 5.1.1) in particular. A relatively small fuel load can create a long duration fire in case of ventilation control. However, this will be a less severe fire, since flashover is not likely to occur and temperatures are therefore bound to be lower. Based on the previous and for the purpose of simplicity, following overall classification can be done (no effort has been made to evaluate the different categories in numerical terms):

- *Low fuel load*. If the fuel load is considered low, flashover and complete combustion are not likely to occur and fire spread due to the effects of heat conduction are bound to be relatively small. Of course, large openings to adjacent compartments or other unfortunate conditions can make the fire spread quickly anyway.
- *Moderate fuel load*. If the fuel load is a moderate one the fire will probably be able to support itself until flashover conditions and assist the fire spread mainly due to heat conduction and the spread of hot combustion gases.
- *High fuel load*. In case of a high fuel load, there is enough potential for a fire to flashover and create a long duration fire (Kennett *et al.*, 1991) with a high probability for fire spread to adjoining compartments.

All the ships lost during the Falklands were said to have experienced a very rapid spread of fire. It was argued that *Sheffield* might well have survived if the fire had not taken hold so fiercely. Two ships, the frigate *Plymouth* and the destroyer *Glamorgan*, caught fire (in *Glamorgan's* case there were two fires). In both ships the fires were put out very quickly and there seemed little reason to suspect furnishings as the main cause of the fires in *Sheffield, Ardent, Antelope* and *Coventry*. Most of the burning items was, except for the unspent rocket fuel, fuel from the ship's fuel tanks and ammunition followed by electrical cabling, deck and bulkhead linings and furnishings. However, as a result of mainly the Falklands conflict, it was concluded that too much flammable material had crept into the warships in order to mitigate the inherent discomfort.

There was a lot of flammable material aboard ships in the Falklands in general and that it would burn when reaching some critical temperature seemed unavoidable. Another example is the merchant ship *Atlantic Conveyor*, which was hit by two air-launched *Exocet* missiles. They penetrated her main cargo deck on the port side aft causing explosions and a fireball. The ensuing fires were catastrophic as the ship was carrying a large amount of highly inflammable cargo including many tons of canvas tentage and 500 bottles each of oxygen and acetylene gases. Despite the efforts to save her, she sank three days later.

Finally it is recognised that determination of the actual fuel load in a compartment is a difficult task, especially since residual missile fuel seems likely to be present after a weapon impact. Another fact is that shipboard fires almost always get to the stage of ventilation control. As a general result, the fire duration may be considered proportional to the fuel load factor and fire intensity proportional to ventilation conditions (Kennett *et al.*, 1991).

In the end, there is a need to develop a list of approved materials aboard ship, hereby characterising the different compartments and their potential hazard in the event of a fire. Consideration should also be taken to flammability, toxicity and smoke characteristics and the fact that for example polymers constitute a higher fuel load in compartments compared to wood. One methodology for accomplishing this could be something similar to the one given in Kennett *et al.* (1991) ("Fire risk assessment methodology for naval vessels"), which is presented briefly in appendix A.

5.2.5 Passive systems

The passive systems are important in the prevention of fire and smoke spread from the affected compartment to other sections of the ship. As mentioned earlier (chapter 2), zoning is one of the corner stones of warship construction. The division of a ship into a number of independent zones is a means of limiting damage to one zone and protect the ones adjoining.

The first thing to consider in the event of weapon impact is the structural damage done by the weapon whether exploding or not. The integrity of the compartment after being affected by blast, fragmentation etc. can be predicted in ways not discussed here. These openings are important when considering several effects such as ventilation conditions, fire and smoke spread to mention a few. It is also an important aspect to consider, since it is intimately related to both fuel load and type, described in the previous sections. The intervention and effectiveness of active extinguishing systems might also be affected.

In the authors view it is not possible to distinguish the level of integrity from ventilation effects and subsequent fire behaviour. The ventilation factor discussed in chapter 5.1.1 is important in predicting mainly the intensity, but also the duration of the fire. It would appear that after full involvement, compartment temperatures are more dependant on ventilation than on fuel type or mass, while fire duration depends on both ventilation and fuel mass (Quintiere *et al.*, 1985). The burning of combustibles in a compartment with limited ventilation can go on for a very long time. Flashover seldom lasts very long in a ship compartment, due to the often limited ventilation.

Two mechanisms of smoke transport are important - smoke entering the ship's ventilation system and being carried by the system to non-fire involved spaces, and smoke transported, by natural convection generated by the fire, through openings of the fire compartment into adjacent spaces and then further to other locations (Tozer, 1993). As far as possible, it should therefore be ensured that all ventilation systems in each zone are independent and that trunkings do not violate zone boundaries.

Disregarding ventilation effects for a while, there are many factors influencing the level of integrity of the compartments affected by effects of weapons effects. History has shown several examples of unexploded bombs and missiles, which helps preserving larger portions of the passive fire protection. On the other hand, these fires have on several occasions shown a tendency to be violent as a result of burning missile fuel. Either way, effects of blast and fragmentation are important to predict in order to create a sound basis for the subsequent fire behaviour. The following generic categories of level of passive protection are identified:

1) *High level of integrity*. In the event of an unexploded bomb or missile, historic events show a high probability of only a small portion of the outer hull or surrounding bulk- and deckheads being damaged and openings created. In a compartment with a high or moderate fuel load, the fire is most likely going to be “ventilation-controlled” at some stage, whilst a low fuel load probably will introduce a “fuel-controlled” fire. Naturally, the type of fuel will be a factor to consider as well. In the event of quick fire-fighting actions being taken, there is a good chance of limiting the fire to the compartment of origin. Suppression systems would also be more likely to be released successfully than if more damage has been done to the them. The higher level of integrity will also assist in sustaining a suppressing concentration of agent if using a gas drench system such as halon or CO_2.
2) *Medium level of integrity*. Basically this case is considered as the most likely one and comprises a mix of the two extreme cases of high and low level of integrity. Whether the weapon is detonated or not, parts of the integrity of the compartment is considered lost due to blast and fragmentation.
3) *Low level of integrity*. The explosion of a bomb or missile can create major blast and fragmentation damage, which in turn means large openings to the open or adjacent and overhead compartments. The fire growth rate and behaviour is likely to depend mainly on the type of fuel and fuel load. The potential for fast and extensive fire and smoke spread is considered great in this case.

In the subsequent evaluation of the disaster on board Piper Alpha for example, it was concluded that when it comes to protection against fire and explosion, a lot of things could have been better. The initial explosion knocked out the Control Room and disabled power supplies, communications and the fire-water deluge system and caused severe vibration which may have affected several systems. The passive systems prove to play an important role. It had the great advantage that it gave immediate protection without the need for specific initiation and was less dependent on systems, which might be disabled by an explosion such as power supplies. Moreover, it has a relatively low maintenance requirement.

6. CONCLUSIONS AND DISCUSSION

6.1 Conclusions

The purposes of this paper were mainly to outline the events following a weapon-induced fire and recognise key factors leading up to disasters as well as important mitigation measures and their effects. The literature study has been the foundation on which the outline analysis has been built and important aspects of weapon-induced fires identified. Along the way, several other aspects of shipboard fires in general have been brought up as well.

There are many hazards on board a warship of today such as large varieties and amounts of different fuels, ammunition and advanced weapons systems. In order to create a ship of low vulnerability (where fire protection is one part), there is a need to identify and evaluate the different risks/hazards as soon as possible and preferably during the early stages of design, when major measures for vulnerability reduction can be integrated. Before further analysis and subsequent changes to design are done, there is a need to define a “design threat” the vessel is supposed to withstand. Only after this has been done, is it possible to consider aspects of manning, level of protection of vessel etc. At this point, computer modelling can be a helpful tool.

Fire initiation is a probable effect following weapon impact, whether the weapon explodes or not. War experiences and tests show that the frequently occurring fireballs of very high temperatures (in excess of 1,100°C are not unusual) are likely to ignite combustible material in the vicinity, hereby initiating intense fires. If residual missile propellant is present (like in the *Stark* and *Sheffield* incidents), quickly growing (almost instantaneous flashover), violent fires followed by large quantities of smoke might be expected. This will limit the possibilities for effective fire-fighting and increase the risk for fire spread. Running fires or jet-and spray fires initiated, have also proved to contribute to a rapid spread of fire. Fires involving fuel of some kind have a tendency to become pool fires at some stage.

If not intervened somehow, the fire will become fully-developed and eventually most ship compartment fires will reach the stage of ventilation-control. At this point, the temperatures (and intensity) will depend more on the size and thermal properties of the compartment, on the ventilation factor ($A_W H^{1/2}$) and to a lesser extent on the fuel load. Fire duration is mainly dictated by the mass loss rate and the mass available. However, one important factor to consider for shipboard fires is the amount of boundary insulation used. As well as the use of this can help slowing down the spread of fire from one compartment to the next, tests have shown that in compartments with restricted ventilation, the duration of a fully developed fire can be large for a compartment having boundaries of high thermal insulation and a large fire load.

The time the fire reaches flashover conditions are considered of special interest from a fire spread point of view. From a number of experiments, it can be concluded that fire spread from a compartment (steel with no insulation) is likely to start soon after flashover is reached. From hereafter, effective fire-fighting will also be difficult due to the intense heat. Tests simulating fire conditions after a missile impact, suggest that no more than ten minutes will be available for fire-fighting before conditions will be too severe.

Intumescent paints can prove effective in reducing the damage in adjacent compartments and delay fire spread. Experiments have shown that the upward fire spread can be very rapid and within a period of five minutes, flammable material directly in contact with the above deck (unisolated) could ignite. After about 10-15 minutes, the air temperature in above compartment will be high enough to spontaneously ignite other flammable material. The fire spread to adjacent compartments is usually somewhat slower.

Another great concern to any fire-fighting activities on board, is the generation and spread of smoke. Low visibility, problems in finding the seat of the fire and toxic effects are just a few of the problems. Despite many tests and several experiences, no one solution seems appropriate for all cases in limiting the consequences of smoke spread. There are many advantages associated with the use of active smoke extraction techniques in order to increase visibility and the speed and effectiveness of any search activities undertaken by naval fire-fighters. The primary disadvantage of using clearance procedures is that, in some cases, the additional oxygen introduced can “fan” the fire and accelerate the onset of flashover. However, in the early stages of the fire, when it is likely to be fuel controlled, it seems as if the advantages of active smoke clearance procedures outweigh the problems and therefore if possible should be used (at least for ships up to corvette size). This will necessitate a further review of crash stopping fans to prevent the spread of smoke.

A few factors have been identified as being crucial to the outcome of the fire. These are of the more “generic” kind and involves two factors of protection and mitigation and three hazard factors:

Initial fire-fighting efforts or the use of active suppression systems. Many fires as results of weapons effects, have recognised the importance of fast response actions to limit the consequences. In case these immediate actions (automatic or manual) are unsuccessful, the fire is likely to reach flashover conditions, which will lead to fast spread of the fire to adjacent and overhead compartments as well as an increased production of smoke.

Damage control and fire-fighting measures. In case initial fire-fighting efforts are unsuccessful, the DC&FF efforts further taken, will to a large extent dictate the severity and outcome of the fire. A well organised and motivated crew with the proper equipment and training, stand a good chance of limiting the consequences and spread of the fire, using boundary cooling and starvation for example. However, the constant reduction in manning for coping with DC&FF actions, could pose a threat to the survival of a ship. Another factor that might have a devastating effect on the possibilities of effective fire-fighting, is the rupture of the fire-main piping or loss of the HPSW system.

The type of fuel in the affected compartments. It can easily be concluded that the fire behaviour will depend heavily on the fuel type in the compartments involved in a fire. A more easily ignited fuel such as gasoline, will lead to a more quickly developing fire than for instance lubrication oil. The type of smoke generated will naturally depend on the type of fuel as well.

The fuel load of the affected compartments. Another factor to consider is the fuel load of the compartments. If a high fuel load is present, this will mainly have a bearing on fire duration, and therefore be an important factor when considering the probability for flashover at some stage and subsequent fire spread. For example, a fire close to a magazine, will probably constitute a high probability of total ship destruction. If feasible, sprinkler systems or other means of protection, should be installed in accommodation spaces and other high fire load compartments in close proximity to especially vital or vulnerable spaces.

The level of integrity of passive systems. This last factor involves a number of aspects in need of consideration. First, the short-term effects of fire spread will be affected by the initiating effects of blast and fragmentation, which are likely to create openings to adjoining compartments, hereby speeding up the process of fire and smoke spread. Ventilation conditions will be changed as well, limiting the possibilities of quick suppression by means of automatic systems dependant on a high and sustained concentration build-up (e.g. CO_2 and inert gases). Compartment temperatures are also more dependent on ventilation, in the case of full involvement, than for example on fuel type or mass. Fire duration depends on both ventilation and fuel mass.

6.2 Discussion

Of course, several other factors have to be considered as well in the overall evaluation of ship vulnerability in general and fire protection in particular. It is hard to come to any far reaching conclusions regarding the question whether a certain scenario stops as an incident or ends up a disaster. Many factors and circumstances influence this, even though the factors identified above are considered highly contributing. Interactions between risks and responses have not really been explored further in this study. Both experiences and tests conclude that fighting the fire in its incipient stages is one of the main concerns. Tests evaluating both fire initiation and spread suggest an available time of ten minutes for initially suppressing or at least knocking down the fire. If this is not accomplished within this time, the fire will take hold and spread throughout the ship.

6.3 Future work

Even though there has been and to some extent still is, a lot of work put into an increased knowledge and understanding of fire behaviour in highly confined and densely packed spaces, fire dynamics and characterisation of ships etc., to some extent these are still poorly understood. Fires vented mainly from above are not unlikely to occur on board ships and represent another area, which is hard to predict. No matter how expensive and problematic, full-scale experiments aboard test ships such as the decommissioned *USS Shadwell* (USA) and *HMAS Derwent* (Australia) are extremely important in order to increase the understanding of fire behaviour under different ventilation conditions, effectiveness of suppression systems etc. In due time these experiments can be scaled down and finally the results integrated in sophisticated fire models to help assess the overall vulnerability of different ships preferably at the design stage.

Another matter is the availability of statistics. In performing risk analyses in general, reliable statistics is of great importance. Basically, in order to increase overall survivability and prevent disasters, there is a need to study and prevent the incidents. This is applicable for these matters as well, and in order to limit the consequences of fire subsequent to weapon impact, there is a need to be able to study incidents from wartime (rather few) as well as peacetime incidents.

The lack of distinct procedures for smoke management on board has become obvious during the course of this study. There is a need for developing a well functioning approach to these problems and a good way seems to be through experimental studies.

A final issue worth mentioning is the poor understanding of suppression system effectiveness and how this can be predicted. Work is being undertaken, but this is still an area that needs much work. Another side of this problem is how, in fact, to cope with weapon-induced fires and especially when residual missile fuel is present. Different types of explosion suppression systems can be used in order to extinguish a fire in the order of 100 ms, but there is still a need to develop ways to attack these fires using manual fire-fighting efforts. Hopefully some insight can be gained in this field from the extensive efforts made today analysing fire and smoke behaviour in tunnels and underground facilities, since these have some similarities to conditions on board ships.

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Appendix A METHODS AND CODES FOR VULNERABILITY ASSESSMENT

As part of the initial literature study, some effort was put into a brief description of a few vulnerability assessment codes and fire modelling techniques, for the purpose of gaining some perspective on different approaches and develop an understanding for what aspects of overall survivability are generally considered important. The objective of applying codes is generally to provide the analyst and ship designer with a valid estimation of the vulnerability of the vessel and its primary systems. An assessment can be made at various times, but it would seem there are many advantages in assessing vulnerability early in design in order to address reduction measures. These should be balanced against the perceived weapon threat (Tozer, 1993). The different codes will be described in an overview manner and no comments will be made in regards to applicability etc.

Worth mentioning are a number of other methods and programs used for the purpose of accomplishing reduced vulnerability. A few of these methodologies are also briefly described.

A.1 Vulnerability assessment codes

The approach to assessment of a ship's vulnerability can be done in several different ways as described in chapter 3.2.3, ranging from deterministic to probabilistic or a combination. Some models focus on describing primary weapons effects (chapter 3.4.2), while others further penetrate secondary effects such as fire and smoke. Again, combinations are possible. The following is just a brief overview of a few of the codes available, but will still illustrate the number of approaches to modelling and predicting vulnerability.

A.1.1 SURVIVE

After basic design, computer assessments can be used to determine if the designs are compliant and where further improvements can be made. Two examples of the codes used are:

1) REVS (Rapid Evaluation of the Vulnerability of Ships) is used to investigate primary effects of above water explosions. It is based on a series of algorithms, which model some of the fundamental weapons effects caused by the detonation of a high explosive missile or shell warhead.
2) SSVUL (Surface Ship Vulnerability Code) is used in a similar way to predict shock, whipping and flooding damage caused by underwater attacks such as torpedoes or mines.

Both these codes use a ship model comprising structural and systems information and they both consider vulnerability assessment and therefore address the effects on a ship or its systems following a weapon hit. They do not consider aspects prior to weapon detonation (e.g. weapon guidance and decoy systems) since these are considered to be matters for susceptibility studies. The vessel is described in terms of its physical geometry, the equipment which support the primary roles such as anti submarine warfare, anti air warfare, propulsion etc. and the way which they interrelate, i.e. dependency information. Each equipment is also allocated a failure criterion. Damage probabilities are calculated using "Monte Carlo"-technique. A large number of attacks, by a given weapon, are simulated and damage probabilities calculated from damage recorded for each attack.

SURVIVE is under development at DERA Rosyth since 1995 and has been designed to replace REVS and SSVUL (and also SUBVUL, which is a code for evaluating submarine vulnerability) with a view to the provision of a single vulnerability code. The damage algorithms have been reviewed in the light of full-scale explosive tests on warships. The model has ability to predict effects of above and underwater weapons (missiles, bombs, mines and torpedoes) and simulates the cumulative damage caused by multiple hits. There is an ability to model novel hullforms such as the trimaran and the model also includes “hooks” for future attachment of new damage algorithms, including fire and smoke spread, which have not yet been integrated.

A.1.2 SAVIUS

SAVIUS (Italian acronym of Integrated System for the Vulnerability Analysis of Surface Vessels) is another one of these tools (Cataldi *et al.*, 1998), jointly developed by the Italian Navy and CETENA for the vulnerability assessment of naval surface vessels at the preliminary design stage. The whole SAVIUS system has been conceptually and physically subdivided into four modules:

1) the SHIP module, for definition and management of the geometrical and non-geometrical characteristics of the ship,
2) the SYSTEM module, for description of the different ship systems on the basis of the vital components characteristics,
3) the DAMAGE module dedicated to the definition of offensive weapons and the deterministic propagation of their damage effects on board. This module is based on some damage modules and is available to treat effects on the vessel due to internal and external air blast, fragmentation, shock and gas bubble due to underwater explosions, and
4) the ANALYSIS module, for the study of hit probabilistic distribution associated to each weapon and the processing of the results coming from the calculations performed by previous modules. This will also allow assessment of the feasibility of a defined mission and the general vulnerability characteristics of an examined vessel.

The future developments of the system (1998) will be addressing the modification of the DAMAGE module in mainly two directions: the introduction of fire propagation effects and a general improvement in existing damage algorithms.

The leading criterion was to follow the philosophy of creating the ship model based on very early information on the vessel (preliminary design phase), in order to allow the user to perform a vulnerability analysis on the basis of rough data, susceptible of modifications and improvements.

The four modules correspond, for the user, to three distinct work phases:

1) *The input definition*: This phase includes the SHIP and SYSTEM modules and the modelling of the whole ship with a suitable degree of detail, i.e. the vessel's structural description and the on board vital components and systems definition and placements. The SHIP module allows the generation and management of geometrical and physical characteristics of the naval vessel for which the analysis has to be carried out, i.e. the building of the structural model of the ship. Through this module the user defines and generates the shell, the superstructure decks and plating, internal bulkheads and compartment. As far as the SYSTEM module is concerned, it allows definition, management and subsequent storing of all the necessary information to characterise the Vital Components and their assembly into Sub-Systems and Systems in order to identify their link with missions the vessel is designed to perform. The module is used for the definition of the Vital Components, Systems and Sub-Systems. A Vital Component can be defined as any device belonging to a System or Sub-System, whose non-working entails the inefficiency or degradation of the System (Sub-System) it belongs to. System or Sub-System in this context means any on board plant (mechanical, electrical, electronic etc.) whose correct working is necessary for the performance of a certain mission of the vessel. The only formal difference between these is that a Sub-System is a system belonging to a more complex one.
2) *The damage propagation*: This phase involves the DAMAGE module in order to define the beginning of the damage phenomena and their deterministic propagation through the ship model. The DAMAGE module is the core of the whole system; in fact it allows the analysis of on board propagation of damages deriving from a defined set of threats corresponding to different types of weapons. In SAVIUS these weapons are naval missile, naval gun, torpedo and submarine mine. Five different effects related to the above mentioned weapons have been considered in addition to the possible penetration inside the hull and superstructures: internal blast, external blast, fragmentation, underwater shock pressure wave and underwater gas bubble pressure pulse. One or more of these effects can be simulated.
3) *The analysis and presentation of results*: The ANALYSIS module is involved here and this phase includes a semi-probabilistic evaluation of the capability of the ship to complete its missions. During this phase the software enables the user to visualise and compare obtained results. Graphical presentation of results, three-dimensional views and colours are used to help the naval designer in the task of minimising the overall vulnerability of the ship. The duties of this phase are mainly the following: (1) definition of the topology of attack, i.e. the probabilistic hit distribution according to the user's need and complying with the defined weapon; (2) evaluation of the probabilistic effect of a weapon attack; this value is obtained by collecting the deterministic results of a certain number of single shots, obtained running the DAMAGE module, whose distribution has been defined in the previous step; (3) graphical and alphanumeric analysis of results. By this module it is also possible to evaluate the cumulative effects of two or more hits in order to evaluate the minimum number of hits of a particular weapon able to completely deactivate a defined system or the whole ship operability.

The SHIP and SYSTEM modules are mainly related to the definition and building of the model upon which the vulnerability analysis has to be carried out.

The future fire model is supposed to be kept as simple as possible, the intention being to evaluate the rise in temperature inside the compartments affected by the spread of fire. Computational algorithms will include an elementary combustion model able to evaluate the different phases associated with a fire: ignition, growth, flash over, fully developed fire, post-flash over and decay. Then, a simple propagation model able to compute the spread of the fire from one room to another will be activated. The main hypotheses of the code are:

- in each compartment there is a homogenous gas mixture with air and a percentage of combustion smoke, with a medium temperature and a medium mass at constant temperature, and
- in each room there is a specific fire load expressed in wood kilogram equivalent to the heat energy of the material present in the room.

As regards the development of the fire within a room, the fire is represented by a two zone model, which means that in the room where the fire begins, two zones are distinguished - a hot gas layer and a cold gas layer - in order to guarantee that flames and relevant hot combustion smoke go correctly upwards. Fire propagation to the adjacent compartments occurs if the plating is damaged or if the room has any connection with the others. In any case, propagation takes place after the fire has reached a post-flash over state. It is also planned to introduce evaluation of propagation in the case of intervention of fire-fighting systems.

A.1.3 LUCIFER

This tool was designed to simulate the spread of fire on board a ship and to give the probabilities of fire for given spaces and equipment. LUCIFER was specified and developed by the DSA/Service des Programmes Navals, and is primarily employed by DCN Ingénierie, responsible for aircraft design.

LUCIFER enables a deterministic appreciation of the step-by-step propagation of a fire after a set time ‘t’. It also enables the identification of vital functions and important zones that will be partially or totally destroyed by the fire. LUCIFER does not calculate the fire duration through to its extinction by either lack of combustible material or through the action of fixed or mobile fire-fighting equipment. Instead, fire propagation within a space is broken down into two phases:

1) **The latency period** is a function of:
    - its type, generally characterised by the nature and concentration of the combustible material that it contains. The various types of space studied, under which all ship’s spaces may be classified without major problems, are as follows: living quarters, operational power plant, stores, gangways, workshop, airlock, ammunitions magazine, fuel tank, water bunker and coffer dam.
    - the air flow that is available (access[4] open or shut, ventilation air flow), and
    - the origin of the fire: combustion originated within the space or propagating through a bulkhead, the door, the floor, the ceiling or through the ventilation system.

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[4] Door, deck panel or manhole.

2) The latency period is followed by the **established** (or **flash over**) **phase** characterised by a rise in temperature following the appropriate fire curve. This is:
   - the ‘hydrocarbon’ curve for spaces classified as power and fuel tank,
   - the ‘SOLAS’ curve for living quarters, operational, stores, gangways, workshop and airlock, and
   - a zero curve for water bunkers and cofferdam.

The ability to propagate starts once the fire in the space becomes established (since flash over). The propagation time from one space to another is equal to the propagation delay afforded by the connection between these spaces. The link between two spaces is either a bulkhead, which results in a ‘bulkhead delay’, or a ventilation or air conditioning duct, which results in a ‘ventilation delay’ associated with a propagation distance. When two links exist, LUCIFER takes the shortest delay time. The ‘bulkhead delay’ is a time period, which corresponds to the fire resistance of the bulkhead and depends on the type of bulkhead defined. The fire propagation delay where access is open is nil. Propagation through the ventilation system is quantified using two parameters: the propagation time, called ‘ventilation delay’, and the propagation distance.

Essential functions are described in the form of a functional/location tree structure further outlined in (Le Garsmeur *et al.*, 1998). This representation enables those spaces housing equipment essential to the ship’s operation to be identified, at the same time revealing any redundancy.

LUCIFER automatically implements the fire development and propagation mechanisms, starting in the space where the fire originated. Thereafter, it continues for a time ’t’ equal to the sum of the detection delay determined for the first space and the fire crew intervention time that has been entered by the user of the programme. For each space where a fire originates, LUCIFER provides the following results:

1) extent of the fire,
2) essential spaces affected, and
3) essential functions that are partially or totally destroyed.

LUCIFER contains two components. The first, termed the ‘core’, contains the formulas and algorithms for fire development, fire propagation mechanisms and analysis of essential functions. Defined in the 'core' are also different types of space, latency times, types of bulkhead, ‘bulkhead delays’, types of ventilation, ‘ventilation delays’ and propagation distances. The core of LUCIFER can only be modified in its source version.

The second part includes the ship’s database that contains the description of the ship’s layout, bulkheads, ventilation systems architecture, automatic fire detection system, essential functions and the status of space access openings. This part can be modified by the user.

LUCIFER software works out the spheres of fire for every space of the ship, i.e. a list of spaces, which are reached, by a fire initiated in the space of origin. A sphere of fire is identified by:

1) a space of origin,
2) the water- and airtightness situation of the ship (three situations are taken into account: at sea, in combat situation, berthed) - these situations impose conditions of closing for determined doors, and
3) an intervention period: how long is it going to be until the fire-fighters intervene?

A sphere of fire lists not only the spaces attacked by a fire of a given origin but also all the important functions for safety, which are destroyed. It works from different sources of information:

1) The files of results worked out from LUCIFER, and
2) the probability databases which give:
    - the probability of a fire initiation in a given type of space (information taken from the French Navy fire databases),
    - the probability of being in the three airtightness situations (at sea, in combat situation, berthed), and
    - the probability of containing the fire in a given period (5, 10 and 15 minutes).

LUCIFER was originally developed for the *Charles de Gaulle* program, because of the complexity of the fire safety studies that had to be carried out. The fire safety studies for the *Charles de Gaulle* include classical fire scenarios and the analysis of spread of fire on the ship's scale. Conventional scenario studies concern critical spaces from a ship's security and availability point of view. However, a full size ship fire propagation study is needed to:

1) analyse the losses in redundancy for essential functions that are divided between several spaces,
2) reveal any fires of an unacceptable size, and
3) analyse the risk of essential areas being affected by a fire originating at any location within the ship.

This study is considered easier by LUCIFER. It is not designed to demonstrate the ship's safety, which is still the engineer's role. LUCIFER was developed with a concern for cautiousness and gives overestimated results. These results underline a possible weakness in the ship's safety design and highlight ways for the fire to spread.

A.2 Additional models and methodologies

There are several other models in use, all of which can not be described in detail here. However, this section is ended with recognising a few additional models and methodologies found in the literature.

One possible way of accomplishing computer-based ship vulnerability assessment is by using the **SVM** - Ship Vulnerability Model- analysis program. The SVM is capable of performing total ship, probabilistic damage determinations for one or more hits for a number of anti-shipping threat weapons. An assessment using the SVM requires that a high level of detail for ship equipment and systems be developed to complete a ship description (ship geometry, compartment functions, vital components etc.). The blast-structural effects are assumed to occur instantaneously and are estimated deterministically. The Fire Damage Model (**FDM**) of the Ship Vulnerability Model is essentially a probabilistic analysis of the blast and fire consequences of a missile penetration and explosion within a ship. The fire damage estimates involve more aspects and are evaluated using a combined deterministic and probabilistic approach along with empirical judgement. Crewmembers can also be modelled for casualty considerations. By conducting a variety of weapon hit and damage determinations for a particular ship description, using a baseline design or one that incorporates protection features, it is possible to compute probabilities of kill for each mission area and overall combat readiness.

Other ways to assess the fire and smoke spread are by using **NAVFIRE** or **NAVSMOKE** developed by Navware Canada Inc. NAVFIRE predicts the probability of fire propagation in ship structures (multiple compartments), but not the smoke spread, which is further evaluated in NAVSMOKE. In NAVFIRE it is possible to consider and model things such as influence of manual fire-fighting on the probabilities of fire spread and the level of training of the crew. When it comes to active fire protection, the presence of suppression systems will affect the probabilities of fire spread. For example, automatic fire-fighting means are considered far more effective than manual ones primarily because of the minimum of reaction time required. While for instance the influence the compartment type will have on the probability of fire spread is considerable, the effects the fire load will have are relatively small.

Finally, there is a need to recognise the potential use of the more sophisticated field models instead of zone models, in order to properly account for thermal buoyancy effects, which drive smoke within the ship. However, these models need expertise in **CFD** (Computational Fluid Dynamics) and require considerable computing power.

A.2.1 Fire risk assessment methodology for naval vessels

One way of evaluating the risk of a certain compartment on board a warship is called "**Fire risk assessment methodology for naval vessels**" and was worked out by DSTO (Kennett *et al.*, 1991). Simply put, this method assigns numerical values to hazard factors (positive) and to protection factors (negative) which are assumed to be additive. Thereafter the risk is evaluated as "hazard minus protection". The ranking scales established were mainly based on the knowledge base of typical fires in naval systems and on discussions with naval personnel on manning and operational requirements. The methodology is mainly applicable when assessing the severity of accidental fires, but some parts of the approach seem appropriate in evaluating fires after weapon impact as well.

Four hazard factors are considered for every compartment when it comes to the survival of the ship:

1) **Vital space**. Here a distinction is made between vital and non-vital compartments when it comes to the ship objectives such as fighting, moving or floating. These compartments may very well depend on the tactical situation. For example, no compartment above the weather deck is considered vital to float and all of the machinery spaces were considered vital to float.
2) **Relative probability of accidental ignition**. For example, the probability of ignition in engine compartments and food preparation areas is higher than in storage areas.
3) **Fuel load**. The higher the factor the greater the likelihood that a fire, once started will reach flash over and continue burning for a considerable time. Knowledge of the fuel load and the ventilation conditions can be used to estimate the duration of a fire within the compartment.
4) **Fuel type**. A fire will spread more rapidly in a compartment dominated by a material that is easily ignited than in a compartment, which is dominated, by a less easily ignitable material.

When it comes to protection factors, five factors were considered important and these are:

1) **Sensing**. Fire sensing systems that respond to heat or smoke enable the detection of fires in otherwise unoccupied compartments.
2) **Compartment occupancy**. An ignition source in an occupied compartment has a high probability of being detected before a fire becomes established.
3) **Fire suppression system**. The installation of fixed fire-fighting systems (e.g. halon, CO_2 etc.) that are triggered in the event of a compartment fire can give excellent fire protection.
4) **Barrier passive protection**. The relative probability of fire spread from an adjacent compartment depends on the nature of the fire in that adjacent compartment and on the boundary between the two compartments. It is assumed that all vents and openings are shut. If they cannot be shut then the boundary in which the opening or vent exists will be assigned the highest boundary value. If special fire retardant coatings have been used on a boundary, the level of protection is considered higher.
5) **Distance to repair base**. The ability to rapidly deploy additional physical resources depends on the distance to those resources.

A.2.2 Live Fire Test and Evaluation

Another example is the Ship LFT&E (Live Fire Test and Evaluation), which is a generic program to accomplish a higher level of overall survivability (US Navy). This type of ship-specific LFT&E program should consist of the appropriate combination of testing and engineering analysis required to address each of its LFT&E issues. The method includes several elements further discussed in Bloom *et al.* (1994). Ship LFT&E requires a combination of testing and analysis in order to evaluate the vulnerability of a new acquisition ship class to the threat weapons it is likely to encounter in combat. Also data from wartime damage incidents and peacetime accidents are used and there is a strong need for vulnerability assessment models and prediction tools in order to analyse secondary damage such as fire and smoke.

LFT&E supports the ship acquisition process by identifying vulnerability weaknesses early in a development program and enabling timely, well informed decisions regarding ship vulnerability reduction features. Since it is generally not feasible to conduct ship LFT&E by firing threat weapons at a completed ship, alternative approaches to assess the vulnerability of the ship have to be developed. These approaches utilise a combination of component, system and full-scale testing and demonstrations together with test-based engineering analyses to perform comprehensive assessments of ship vulnerability.

The minimum ship's operational value, at any time after impact, could for instance be formulated so that the ship should be able to move at a certain speed and have some form of self-defence. In order to set realistic survivability criteria, there is a need to define the type of threat the system is supposed to withstand (chapter 3.2.1).

The objective of LFT&E is to provide a timely and reasonable assessment of the vulnerability of a system as it progresses through its development and prior to fullrate production, since it is at the early design stage major vulnerabilities reduction features may be integrated. The intent of LFT&E is also to gain knowledge similar to for instance the *Stark*-incident (appendix C), but in a more systematic and comprehensive way and without the risks to lives.

A.2.3 Ship Fire Safety Engineering Methodology

The Ship Fire Safety Engineering Methodology (SFSEM) provides an integrated framework for analysing fires on ships in comparison to established fire safety objectives (Wikman, 1995). It accounts for all relevant aspects; the behaviour and spread of fire, the effectiveness of passive design features, automated suppression systems, barrier materials, flame spread paths and manual fire-fighting. The Ship Applied Fire Engineering (SAFE) computer programs implement SFSEM and evaluate the probability of spaces and barriers limiting a fire. The evaluation is conducted on a compartment-by-compartment basis. It incorporates the fire growth hazard with the probabilities of ignition, automated fire suppression, manual fire suppression and barrier effectiveness. SAFE calculates the probable paths of fire spread based on time duration.

The philosophy used in the development of this method is fundamentally probabilistic, however deterministic aspects are integrated wherever they are appropriate and experimental data is available to validate the algorithms. In the end, the method produces a numerical value of the fire safety, generating a possibility to compare the relative value of different designs to be evaluated. One of the drawbacks is that the method required some of the input data to be determined by engineering calculations or subjective judgement.

Appendix B PEACETIME FIRES AND INCIDENTS

The following is a further review of a few different categories of ship fires initially brought up in chapter 3.3.3. The different categories are briefly characterised and a few examples are introduced to illustrate the particular problems further.

The examples given cover aspects of peacetime fires in warships as well as merchant and passenger ships. The incidents on board warships are gathered from the Swedish and New Zealand Navies. One problem experienced in the search of incident reports involving fire, is that these are rather few and really only cover the major incidents (at least the Swedish Navy).

It is felt that weapon-induced fires several times have shown similarities to incidents experienced within the offshore industry. Therefore the events surrounding the destruction of *Piper Alpha* is also described in short, for the purpose of taking part in a few lessons learned from offshore experiences and methods of accident prevention.

B.1 Arson

Most incidents are caused by intentional or accidental actions of passengers or staff. Fires started intentionally are by nature less likely to be discovered in its incipient stages due to the fact that the perpetrator will generally initiate ignition in secrecy. The fire on board *Scandinavian Star* was started deliberately and cost the lives of 158 people (Cowley, 1994). Fires broke out simultaneously outside cabins in the aft section of the ship and were thought to have been ignited deliberately. Investigators believe that alcohol was a major contributory factor in the arson. The investigators estimated that within one minute of the corridor walls being ignited, flash over had occurred over the whole cross section of the corridor. From this on the fire spread quickly and large quantities of smoke was produced. Many of the people who died had been trapped below deck in bars or in their cabins. Some people were also said to have slept in their cars. Some problems communicating due to the multi-national composition of the ship’s complement were experienced. A joint commission from Sweden, Norway and Denmark also concluded (Thorell, 1992) that no attempts were made to fight the fire when it was first discovered and the person named as fire chief was unaware of his appointment. Moreover, there was a lack of personnel trained on fire-fighting aboard.

Another example is the *Norrona*, a passenger/freight ferry, which experienced a fire while crossing from Wales to Ireland. The fire led to one fatality and 34 injuries. Many people suffered smoke inhalation, but good emergency planning helped prevent the fire becoming a major catastrophe. It is believed thieves who stole money from a shop first started the fire as a diversion. This since there was discovery of two fires in an unused section of the passenger deck which, was out of bounds (CFPA Europe Arson Working Group, 1993).

B.2 Accommodation fires

On the June 30 1996, *Borrenmill* suffered a fire in the accommodation that destroyed four bridge decks including the navigation bridge (Marine Eng. Review, 1997). Decks below suffered smoke, heat and water damage. The source of ignition could not be established with certainty. Initially a patrolman sighted smoke from a locker, opened it, flames leapt out and the door was left unclosed for the fire to spread. The rapid fire spread was due to the open plan design of the ships accommodation, lack of fire doors between decks, delay in shutting off the accommodation fans and the combustible coatings on the bulk- and deckheads.

Another example is the *Scandinavian Sea*, which in March of 1984 experienced a fire in a crew cabin and even though the ship's fire brigade was mobilised quickly, it was not possible to get close enough to the fire to suppress it. The cause of the fire was not clear at that time. Before it was finally suppressed, with the assistance from land-based fire department, the fire had spread in the MVZ from the deck of origin and to the three decks above. A few of the more interesting contributing factors to the magnitude of the incident were concluded to be (Timoney, 1984):

- the failure to extinguish the fire in its incipient stage,
- the fuel loading of the cabins in the area of initial fire involvement,
- the failure of fire station hoses on board the ship when fire crews attempted to place these lines in service, and
- the lack of training of the land-based fire department units in shipboard fire-fighting tactics.

Accommodation fires on board warships show similarities to those in passenger ships for example. Usually rapid fire and smoke spread is experienced as a result of the high fuel loads and easily ignited materials. This type of fire can be compared to those occurring in laundry rooms and similar.

In January of 1997 *HMNZS Canterbury* experienced a fire, most probably caused by the failure of an electrical fan, which was secured to the wooden seat in cabin. The fan was left with the power on but switched off at the fan operating switch. The switch appears to have failed and caused an electrical fire. At a later stage the fan fell off the wooden seat onto dry washing and a cardboard carton causing an escalation of the fire. Flames have then set fire to the mattress and bedding and at this stage the fire was discovered and extinguished. A lot of brown acrid smoke was generated and lead to understandable confusion in isolating the scene of the fire. Initial attempts to locate the cause of the smoke were unsuccessful as the rapid smoke build up resulted in personnel evacuating the cabin flat unless wearing BA. The spread of smoke was very rapid and caused confusion in determining the scene of the fire. Ventilation was crashed stopped and despite this the smoke quickly spread throughout the ship. Boundary cooling was quickly established and would have assisted in containing the fire if it had escalated further. This was done after hot spots were confirmed in a few of the adjacent compartments. After the source of smoke was discovered, the fire was extinguished using a total of five AFFF extinguishers for extinguishing and cooling of the scene. The fire on board *Canterbury* was the first major fire in the RNZN (Royal New Zealand Navy) for several years and highlighted the dangers of copious amounts of smoke and the difficulties of finding the seat of the fire (NZ Navy, 1997).

B.3 Vehicle deck fires

Tampomas II experienced a vehicle deck fire in January of 1991, where 666 passengers and crewmembers lost their lives. Even though the ship was considered deficient in almost every operational and safety aspect, there are a few important lessons to be learned from this disaster (Cowley, 1994):

- Some portable extinguishers were empty when tried to bring use of.
- It took a long time before the ventilation system was shut down (45 minutes) and smoke spread to cabins and other areas was stopped.
- The automatic fire detection system was out of commission because of misuse.
- Fuel control valves were not closed in the engine room, which led to the fire being fed about 860 tons of fuel after having spread to there.
- Failure in closing the watertight doors made the fire spread to and throughout the machinery spaces.

The emergency generator did not come into action automatically, since the automatic starting arrangements had been out of commission for months and when it was started manually it stopped after 2-3 minutes because the wrong fuel was being used.

These kinds of fires pose a few new threats and have proved to be rather violent in their behaviour. Usually the vehicle decks of for instance Ro-Ro ships do not have any subdivision at all and therefore the fire growth could be rather fast generating a massive production of toxic smoke.

B.4 Engine room fires

Shipboard machinery space fires present serious challenges to crewmembers. Figures suggest that up to 65% of machinery spaces fires are the result of oil mist (Marine Eng. Review, 1997). The usual sources of mist are leaking injectors, fractured flexible hoses, loose or badly fitted pipe couplings and broken welds. Causes of ignition are exhaust pipes, turbochargers, electrical contacts, static electricity and non-flameproof motors. An atmospheric oil mist detection system is recommended to be used alongside a smoke detection system because the latter may respond too late to avoid damage. All three elements of a fire are constantly present, fuel in the form of diesel and lubrication oil, ignition source from hot metal surfaces and oxygen through forced ventilation. Fuel or lubrication oil may be released from a wide variety of sources including high-pressure fuel lines, breaks or leaks in service tanks, transfer pumps, gaskets and flanges. Diesel fuel has a flash point around 60°C and lubrication oil around 220°C. Surface temperatures for exhaust pipes and some moving parts exceed these temperatures. Fires may consist of spray or pool fires, or a combination of both. Some areas in machinery spaces are more prone to spray fire scenarios. High-risk areas include the engine exhaust manifold, cylinder tops, high-pressure fuel injection systems, fuel treatment area, boiler fronts and tops. Lower risk areas are known to be subject to pool fires and include lubrication oil and fuel tanks.

Engine room fires appear most likely of all fires to lead to total loss of a ship. The basic problem is that in most cases the engine room is one single undivided compartment as far as fire is concerned. Although there may be subdivisions for work rooms, store rooms and similar, and although there may be a separate engine control room, the enclosures of these are seldom if ever wholly fire-resistant, so that fire will spread into or out of them quite readily. Large machinery spaces also have high air ventilation rates that will dilute the smoke and combustion products from a fire. One of the key factors is still good housekeeping (Taylor *et al.*, 1982 and Blogg, 1988) and in particular the cleaning of drip trays, correct stowage of materials and equipment, sealing of paint and oil containers etc. Machinery spaces are normally equipped with fixed extinguishing systems such as CO_2 or halon (which is now being phased out). One major cause of engine room fires has now been handled in the amendments of SOLAS from 1 July 1998, which requires all adjacent hot surfaces need to be insulated to prevent the ignition and spread of fire. Machinery room fires often develop rapidly, giving off intense heat. Measures usually taken in the event of an engine room fire are mainly:

- Shut down ventilation and close openings,
- emergency fuel shut-off,
- check the fixed fire-fighting system and activate these, and
- if the ship has an independent fuel separator plantroom, close the watertight door.

There are several documented examples of fires on board ships initiated in the engine room. One is the fire aboard the Ro-Ro ship *Kukawa*, which experienced an engine room fire in December of 1997 after a fuel line ruptured on the starboard engine (Kettle, 1988). This created a fireball, which was sent up through the boiler flat space and funnel uptakes. All dampers and vents were operated by the crew and the engine room was drenched with carbon dioxide from the fire suppression system. These actions extinguished the fire, but the fireball had already spread the fire into the superstructure via cable runs and unprotected openings and destroyed a lot of the superstructure.

In August of 1984, a fire erupted in the auxiliary engine room of M*/V Scandinavian Sun* caused by the ignition of atomised lubricating oil leaking from a diesel engine driving one of the ship's generators. Two people were killed and 57 injured. Products of combustion were able to extend vertically six decks above the main engine and auxiliary machine rooms by way of a ladder access way and through an open passageway and watertight doors. Doors leading to passageways on several of the upper decks were also open during the initial stages of the fire which allowed dense smoke and heat to extend horizontally into crew and passenger cabin areas. The oil sprayed for ½-1 ½ minutes leaving about 140 litres of it collected on other surfaces. The pressure of the line was estimated at 5 bar and the most probable source of ignition was the exhaust manifold to one of the auxiliary engines. Once the ignition occurred, the engine room staff attempted to fight the fire with hose lines for several minutes without success. Once the oil spray had ignited, the fire spread to other fuel sources, many of which had been coated by the deflected oil spray. The forced ventilation of the machinery spaces provided an abundant supply of oxygen to the fire, resulting in an intense fire and also provided the mechanism for the rapid movement of the products of combustion to adjacent areas of the ship. Important was also that the intense fire created strong convection currents, which added to the rapid vertical extension of the fire to adjoining areas of the ship.

Major contributing factors to the loss of life were (Bell, 1986):

- the failure to extinguish the fire in its incipient stage by either automatic or manual suppression,
- the rapid and intense flash fire resulting from the ignition of combustible lubricating oil,
- the rapid horizontal and vertical spread of products of combustion throughout the ship caused mainly by open fire doors, and
- the presence of combustible interior finish materials in passageways and in the stairwell.

From the room of origin, the products of combustion moved both upward and horizontally and caused severe damage seven decks above fire origin. A lot of smoke was also spread through the ventilation system.

In February of 1991 an engine room fire erupted on the LASH (Lighter-Aboard Ship) *Stonewall Jackson* and six members of the crew lost their lives (Butturini, 1993). It is believed to have ignited when lubricating oil circulating through an unsecured oil strainer on the steam-powered generator sprayed onto hot, unisolated steam piping. The fire was short-lived but very intense. The engine room filled with thick oily smoke almost immediately, trapping crewmembers within the compartment. Engine room fires often produce large quantities of thick black smoke. If smoke rapidly fills a multilevel engine room, crew members may not be able to feel their way out before smoke inhalation. A matter of minutes may be critical to survival.

On *Queen Elizabeth 2*, a flexible coupling on a high pressure turbine failed and the turbine was destroyed within seconds. The simultaneous escape and vaporisation of lubrication oil gave rise to an oil mist explosion in the shape of a short-lived fireball of burning gases followed by a serious turbine oil fire. Even though the supply of steam too the turbines and the lubrication oil pump were shut down, the fire spread into an upper deck alleyway through a door probably left open by a crew member. A considerable amount of combustibles was stowed here, but the fire was extinguished by the operation of the sprinklers. A manned attack on the seat of the fire was initiated under very low visibility and the fire was brought under control within 30 minutes even though about 4,500 litres of lubricating oil escaped. This fire was effectively brought under control and the ship could return to port at reduced speed. A few important notices can be made to identify why the outcome of the fire was successful (Cowley, 1994):

- Resolute action by competent fire-fighters dealt with the fire successfully and the water pressure was maintained.
- Machinery spaces should be gastight with an independent ventilation supply.
- Low melting point materials in machinery spaces are vulnerable.
- The value of sprinklers was clearly demonstrated.

In November 1991, the Ro-Ro ship M/S *Stora Korsnäs* experienced a fire in the machinery room, probably due to the ignition of oil onto a hot surface. Within short the extinguishing system (CO_2) was released, but after this was done the fire was thought to have spread to the cargo area. The remote control of the extinguishing system did not work at first, which meant that there was a delay in activation of the system. CO_2-systems in both the cargo area and again in the machinery space were activated. After some time it was realised that the garage level had been affected as well and soon after the ship was abandoned. The ship was on fire for four days and after a few powerful explosions, the ship sank (Statens Haverikommission, 1991).

A review of available cases of documented peacetime fires on board warships, reveal that not many such cases are to be found. However, one incident gathered from the Swedish Navy is worth looking a little further into.

In November of 1987 the *HMS Älvsborg* experienced a fire during transfer. Due to a handling error, one of the oil leads starts leaking and diesel oil sprays onto the hot exhaust pipe and immediately ignites. The quickly growing fire forces the personnel in the machinery space to retreat after having started the fire pump, stopped the fans and main engines. After these events took place, carbon dioxide was released into the machinery room. Since it was not possible to determine whether the fire was extinguished or not, high expansion foam was released into this compartment and the air intakes filled with low expansion foam. Growing secondary fires start in the adjacent compartment, but are extinguished rather quickly.

The measure to start the electrical fire pump does not have any effect, since the carbon dioxide, which was released within short, stops the plugged-in generator and with that the supply of electricity. This release is done first after all personnel have evacuated the area and took about 2-3 minutes from the fire started. The effects of the carbon dioxide have not been evaluated for certain. The flow of smoke is believed to have been powerful enough to blow out the carbon dioxide through the chimney. After this high expansion foam is used to bring the fire under control.

There was no way to shut off the diesel oil supply directly aboard *Älvsborg*, but when the pump was stopped from the loss of power, at least the flow of oil decreased. However, the supply of oil and air to the fire is still enough to create such a major conflagration that aluminium parts and covers melt down. The “chimney effect” from the fire transfers heat through the asbestos isolated bulkheads and ignites paint and electrical cables on mine deck. Later the adjacent compartments are checked for hot spots, but no signs of this are established.

Before the incident, the oil piping was equipped with protective coating to reduce the risks of a fire initiating after a leak. However, at the time of the failure these were removed, since they were considered being mostly in the way. A few measures are recognised that should have been taken and include the closing of valves to stop the flow of oil, which feed the fire. Also, the ventilation should have been stopped early in order to stop the spread of fire. The closing of the machinery room fans probably reduced the effect of the fire, but the continual access to fuel created an intense enough fire to transfer heat through the bulkheads and create hot spots in the above compartment. The fire was after some time brought under control and this was probably due to two things happening at the same time:

- the decision to locate and extinguish secondary fires, and
- to fill the machinery room with high expansion foam.

There is a need to consider that rules created by IMO do not apply to warships, but are still useful to support decisions regarding the following:

- prevent fires to occur,
- prevent fire- and smoke spread within the ship,
- discover fire at an early stage,
- limit and fight fires,
- determine access and egress routes for fire-fighting, and
- limit the use of combustible materials.

Also recognised is the need for personnel to practice fire-fighting aboard under realistic conditions and to do this with continuity. These exercises should primarily be held where the probability of fire is the greatest. During the events on *Älvsborg*, the loss of power after about three minutes had severe impact on the possibility to keep communicating throughout the ship (Marinens Haverikommission, 1987).

A final example is gathered from the RNZN. Like most navies of the world, the RNZN has no first hand experience of action damage caused by modern air launched weapons. However, there are a few parallels to be drawn between the *Stark* and *Sheffield* incidents and the engine room fire on board *HMNZS Waikato* in 1970. This fire led to the evacuation of the ships company onto the upperdeck due to the uncontrollable spread of dense black smoke. Also here, fire-fighting operations were impeded by the lack of breathing apparatus sets. The ones (6) that were actually carried could not be retrieved from inside the ship until other sets from ships in company were made available as well as the emergency use of the divers self contained BA. Neither of the other action damage related problems occurred, but still this incident served as a reminder of the problems fires onboard warships can cause even during peacetime. Much of *Waikato*´s success in dealing with this particular incident was probably due to the recent return from a six month deployment to the Far East.

B.5 Galley fires

Medium and major fires in accommodation spaces and galleys are rather infrequent. Galleys are usually well protected against fire and the occupants are aware of the risks. An example, however, is the fire on board *HMNZS Wellington* in February of 1998, where a fire originated in a deep fat fryer (DFF), probably due to faulty temperature control within the fryer. The cause of the fire can not be clearly determined and there are many factors, which when taken together, may have all contributed to the start of the galley fire, which was contained within the deep fat fryer.

The most likely cause of the fire is that the inboard vat, either through mistakenly setting the temperature to the old dial setting, or through a fault not found, caused the temperature of the inboard vat to raise above 210°C. 210°C is the temperature that the DFF overheat alarm circuit activates at giving a safety margin of approximately 50°C before the flash point of the fat is reached. The disconnection of the overheat alarm bell resulted in the staff being unaware that a problem existed with the unattended DFF, and as such no corrective action was taken to bring the temperature of the fat in the inboard vat to a safe level. The steam kettles situated directly behind the bulkhead induce water into the surrounding bulk- and deckheads. So much water is introduced that it continually seeps from the joints of the bulkheads and running directly into the DFF. Overly heated fat mixed with water seeping from the bulkhead would have caused the fat to bubble and spit. The resultant vapour, next to a vat that was cooking chips may have spontaneously ignited causing the fire to start. The initial attack was beaten back as well as the first BA attack. When the local fire department arrive, the fire in the galley is reported out, but re-flash occurs and the fire burns with greater intensity until it is extinguished for good after a short while. Remarkably there was only superficial damage to the galley with light electrical fittings and ventilation ducts suffered the most from the effect of heating.

No fixed fire-fighting system was fitted to the DFF. It is believed that a potassium carbonate system with local and remote operation may have been more effective than carbon dioxide extinguishers (proved largely ineffective). The system would at least have knocked the fire down to give the attack party a better chance of extinguishing the fire (Neville *et al.*, 1998).

B.6 Offshore experiences

B.6.1 Piper Alpha

On the 6th of July 1988 at about 22.00 hours, the production deck of *Piper Alpha* experienced an explosion. This was followed immediately by a fire at the west end of B module and a fireball, which erupted from its west face. The fire spread rapidly in B module and extended into C module (adjacent to B module) and downwards. From the outset dense black smoke from the fire engulfed the upper parts of the northern end of the platform. The initial explosion was followed by a series of smaller explosions. Most of the emergency systems of the platform, including the fire water system, failed to come into operation. At about 22.20 there was a major explosion which was due to the rupture of one of the gas risers. This caused a massive and prolonged high pressure gas fire, which generated intense heat. This caused several men to jump into the water. By about 22.50 hours about 39 survivors had left the platform. At that point a further massive explosion occurred. This is likely to have been caused by the rupture of yet another gas riser and added to the intensity of the high pressure gas fire. The structural collapse of the platform was hastened by a series of major explosions, one of which was about 22.30 hours and due to the rupture of a third riser. Shortly thereafter the west crane collapsed followed by further events, which led to the platform tilting slightly to the east and within short the pipe deck to the west collapsed. Finally it tipped northward into the sea. Of the total 226 persons on board, 165 men were killed in the incident, mostly due to inhalation of smoke (109 cases).

The first explosion was most probably a deflagration, which occurred in the south-east quadrant of C module and the following fire in B module was due to rupture of a pipe which resulted in a fireball and a large oil leak. The second explosion immediately after was probably the pipe rupture and fireball in B module. The fuel involved here was condensate and the low lying gas cloud probably only filled 25% of the volume, consisting of approximately 30-80 kg of fuel. The location and nature of the ignition source are unknown. The maximum peak over-pressure of the explosion was probably in the range 0.2-0.4 bar.

The leak most probably occurred during the restart of one of the condensate injection pumps. Earlier the pressure safety valve had been removed on the pump, which made it leak after being restarted. The ignition sources have been considered and possibilities are electric arcs and sparks, static electricity, flames and hot gases, hot surfaces, hot particles and chemical energy. One possibility was an electrostatic spark.

It is clear from evidence that the fire in B module started without apparent delay after the initial explosion. It was a significant fire before the fireball occurred and for the first 20 minutes it was the principal fire of the installation. Most probably the initial explosion generated small projectiles by the disintegration of the firewall between B and C module. These in turn had enough energy to rupture the pipework, releasing condensate and after this crude oil, which is believed to have been the fuel of the subsequent poolfire. The following fireball, about 15 seconds after the initial explosion, was probably an event that followed the complete rupture of the condensate and an estimated weight in excess of 100 kg is believed to have created the fireball.

The fire in B module extended through a breach in the B/C firewall into the C module and thereafter appeared on the north face of the platform. As a result of the spillage of crude oil from the pool, which was providing fuel for the fire in B module, the fire extended downwards.

The major explosion at 22.20 hours was caused by a full-bore rupture of one of the risers as a result of the high temperature created by a pool fire beneath it. It is concluded that rupture of the riser could have been delayed by fireproofing for a substantial period, perhaps 1-3 hours, and by a cooling deluge system which came into operation after the initial explosion for an indefinite period.

There was a previous incident on *Piper* on the 24th of March 1984, where there was an equipment failure, explosion and release of gas followed by a fire in the Gas Conservation Module (above module B). The alarms and deluge functioned on demand and the fire pumps came on line and continued to operate. The supply of fuel to the fire was cut off and the fire was put out by fire-fighters in about 2 hours. Essentially, the fire was under control at all times.

As following most major disasters, a number of lessons can be learned. As regards to the fire-water system it is clear that it never came into operation. A mere trickle came out of some of the sprinklers and apart from this no water came out of sprinklers, deluge systems or hoses. As far as concerns explosion, the water deluge pipework also added significantly to the “clutter” effect and might enhance the over-pressure from an explosion. The systems themselves with their small bore pipework were vulnerable to explosion.

Attempts were made to reach the fire pumps in order to start them manually, but due to the fire nobody could get near them. The dieseldriven pumps supplying fire water in an emergency was set on manual mode with no possibility to switch them back to automatic mode from the Control Room. This was a serious deficiency that left the pumps inoperable during the events on board Piper. When it comes to protection against fire and explosion, a lot of things could have been better. The initial explosion knocked out the Control Room and disabled power supplies, communications and the fire-water deluge system and caused severe vibration which may have affected several systems. The passive systems prove to play an important role. It had the great advantage that it gave immediate protection without the need for specific initiation and was less dependent on systems, which might be disabled by an explosion such as power supplies. Moreover, it has a relatively low maintenance requirement. It was later shown that drills and training of personnel with special duties in case of an emergency did not take place with the frequency laid down. In regards to the management of the safety on board the *Piper*, this was generally considered as poor. A few important areas of safety management are especially important to cover and include the reviewing and monitoring of safety procedures, the investigation of previous incidents and equipment failures and applying the lessons of those investigations and finally the examination of the safety implications of changes in equipment and activities.

One adverse effect had been on ventilation. Reference areas were basically defined as the complete floor areas of hydrocarbon processing modules and were enclosed by firewalls. In order to limit the size of reference areas, and hence the water to be delivered, additional firewalls had often been used, so that modules became compartmentalised. This reduced natural ventilation and led to the need for mechanical ventilation and might increase the risk of explosion. Weak points on the accommodation through which smoke might enter included penetrations through external walls, doors, windows, and ventilation intakes and exhausts. Smoke could be prevented from entering if there was a positive pressure in the accommodation, which was maintained by the ventilation system itself. The ventilation air intakes were a weak point through which noxious gases might be drawn into the accommodation. Prevention might include shutting off the ventilation and closing the dampers in the intakes. A necessary complement to the Piper at the time of the disaster would have been escape routes to and from the accommodation, since only within minutes of the initial explosion, these were impassable due to smoke and fire. An alternative could be a temporary safe refuge to which the personnel could go.

The following recommendations were put forward after the incident and are considered important:
- The operator should be required by regulation to submit to the regulatory body a Safety Case in respect of each of its installations.
- The regulatory body should be responsible for maintaining a database with regard to hydrocarbon leaks, spills and ignitions to the industry and for the benefit of the industry. The collection, use and assessment of data should regularly be discussed with the industry and the existence of any trends should be reported. Particularly for the purpose of carrying out quantified risk assessment, these measures are important.
- Operators should be required by regulation to submit a fire risk analysis to the regulatory body for its acceptance.
- The ability of the fire water deluge system, including the fire pump system, to survive severe accident conditions should be a feature of the Safety Case.
- Provisions should continue to be made by regulations supported by guidance notes as to the construction of the accommodation and as to escape routes and embarkation points.
- Each individual on board should be provided with personal survival and escape equipment.(The Hon Lord Cullen, 1990)

There were firewalls (A60) between all modules (A/B, B/C, C/D) and the C/D firewall was a double layer construction. After the explosion an opening between C and D modules could have been created. Flame detectors consisted of UV flame detectors and heat detectors. Detectors were placed in all modules except in D. The water deluge system was designed to activate automatically on detection. The platform was also provided with a fire-water deluge system fed by a main ring. All systems except those in the modules were operated manually. The system as a whole also consisted of a few foam addition systems at particular places where oil fires might appear.