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THE SCIENTIFIC INVESTIGATION OF MARINE FIRES AND EXPLOSIONS

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1. THE PURPOSE OF THE INVESTIGATION

The investigation of an explosion or fire on a vessel, an oil or gas platform, or at a marine terminal may be undertaken with a variety of technical objectives in mind. The most common objective is to establish the circumstances and the cause of the incident. Other areas of concern may include the performance of structural elements of a vessel or rig from a fire or explosion standpoint, the efficacy of fire detection and warning systems and of automatic and manual firefighting arrangements.

The depth, extent and in some cases, the emphasis, of the investigation will be governed by the aforementioned technical objectives and the purpose for which the investigation is undertaken. The purpose may include for example, the gathering of statistics. An investigation may also be undertaken to test compliance with civil or criminal law and in certain cases, particularly those involving hazardous cargoes, the investigation may indicate that additional legislation needs to be promulgated, or that existing legislation requires variation.

An investigation may also be conducted to determine the relevance of an insurance policy to a particular explosion and fire, or the possibility of transferring liability for the event to a third party.

The importance of the consequences of an investigation is readily apparent and in the event of a serious casualty, a detailed analysis of an explosion or fire scene is to be expected. It is likely that a number of investigators will be involved with somewhat different objectives, none of which may be completely disinterested. In the case of a major casualty, it is likely that investigators from the National Transportation Safety Board (NTSB) and United States Coast Guard (USCG) will also be involved and a formal board of inquiry may be convened.

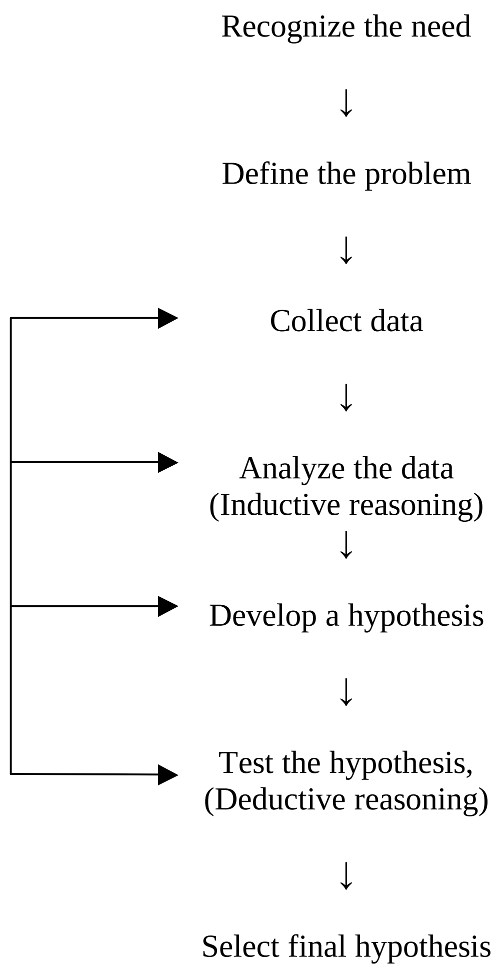
It is clear that bias may develop in individual investigations and analysis. Bias is least likely if the investigation is conducted for the sole purpose of establishing the circumstances and cause of an explosion or fire, perhaps for research purposes. However, whatever the purpose of the investigation, the most satisfactory approach is to treat the investigation as a piece of scientific research, with a defined objective. In treating the investigation as a research project and applying the scientific method to the investigation, a reliable and unbiased set of opinions will likely be produced.

2. <u>THE METHOD OF INVESTIGATION</u>

The investigation and analysis of an explosion or fire is a complex task, requiring the accurate and comprehensive recording of physical data and witness observations and the application of fire science and engineering knowledge. Personnel tasked with the investigation must be knowledgeable about a certain aspect of a wide range of subjects, which include combustion science and engineering, as well as chemistry, materials science, heat transfer, fluid dynamics and electrical matters, to name a few.

An objective investigation requires the application of the scientific method, which involves a process of deduction, induction and validation. The process is set out in detail in the NFPA 921[1]. The steps involved in applying the scientific method to an explosion or fire investigation are set out below.

[1] *NFPA 921, Guide for Fire and Explosion Investigations, 2004 edition,* NFPA, 1 Batterymarch Park, Quincy, MA 02169-7471



In the first two steps of the process, it is recognized that an explosion or fire has occurred and that there is a need to explore the circumstances and cause of the incident and that this need can be satisfied by a detailed scientific investigation into the event.

The third step is to assemble the factual data concerning the incident, which will likely be undertaken in two stages, as set out below.

2.1 Preliminary Investigation

A preliminary inspection of the vessel, platform or terminal will be performed in order to determine the nature, extent and degree of damage. This initial inspection will be carried out without disturbance of the accident scene and will provide the opportunity to identify the areas and aspects of the evidence which are useful from a diagnostic point of view. It will also become apparent at this stage if arrangements need to be made to preserve certain parts of the physical evidence and prevent disturbance or destruction of the evidence by personnel engaged on other tasks at the scene, including for example, salvage work or cargo discharge. The need to alert potential third parties to the casualty and investigation may also arise at this point.

Information from witnesses concerning the circumstances of the explosion or fire and providing background information on events preceding the incident will also be obtained during this preliminary investigation.

General arrangement drawings showing the layout of cargo spaces, accommodation areas and machinery spaces should also be obtained, since these will assist in the questioning of witnesses concerning their observations regarding events surrounding the incident. Detailed plans of the casualty should also be obtained at this stage. These drawings will lead to a closer understanding of the layout of the casualty and will provide structural information on the vessel or structure, which may be required at a later stage in order to consider fire spread routes or to calculate likely explosion overpressures.

The scene should be photographed systematically and the location of each of the photographs carefully recorded. Sketch plans and notes should also be prepared in conjunction with the photographs, so that all relevant areas and features of damage are pictorially preserved for further examination and reference at a later stage.

It will be appreciated that personnel safety is of paramount importance during the investigation and the investigator should carefully consider whether the inspection may expose himself or others to danger and that all appropriate safety precautions have been taken. These precautions may entail taking oxygen and flammable gas readings in confined spaces, the monitoring of atmospheres for potential toxic gases and vapors, and the use of all appropriate personal protective equipment, including respirators, coveralls, helmets, boots, etc.

As indicated above, it is like that several investigators may be present including governmental agencies such as the National Transportation Safety Board (NTSB) and United States Coast Guard (USCG). The investigator may well find that he is working with and under strict guidelines set out by the aforementioned federal agencies. The investigator may also be required to draw up investigation protocols that will satisfy the various federal and state agencies and other interested parties involved in the investigation.

As noted at the outset of this section, the preliminary investigation will identify the area of origin of the explosion or fire without disturbing any of the physical evidence.

2.2 Detailed Examination

The initial investigation of the scene and the questioning of witnesses set out above will likely provide considerable information. In a localized, or well witnessed, explosion or fire, the preliminary investigation may provide sufficient information to determine the circumstances and cause of the event. Depending on the seriousness of the casualty and objectives and purpose of the investigation, no further investigation may be required. However, it will be appreciated that any hypothesis developed from the available evidence must be in accord with the witness observations and all other information garnered in this preliminary investigation. The hypothesis must also be tested and to these ends, it may well be necessary to conduct a more detailed examination of the suspected area of origin of the explosion or fire. This further investigation may require an excavation of the suspected area of origin in the case of a fire, or the collection together of displaced structure and reassembly in the case of an explosion. In addition, samples may be taken for chemical analysis and metallurgical examination and equipment, or machinery may require dismantling for further detailed inspection and testing.

This more detailed investigation will provide further information which must then be combined with the information from the preliminary investigation and considered in the next step of the investigative process.

The data collected in the preliminary and detailed investigation must now be studied and analyzed and a hypothesis, or group of hypotheses, can now be developed to explain the cause of the explosion or fire.

The final step in the process is to test the hypothesis and determine that the proposed mechanism for the explosion or fire is consistent with the physical evidence, the eyewitness testimony, and is supported by the scientific literature and by calculations and experiments performed by the investigator. Hypotheses that do not withstand this testing must be discarded. The investigator may then have to revisit the scene in an attempt to collect further physical data and to revisit the process of analyzing the data and developing hypotheses, until a mechanism for the cause of the explosion and fire is finally developed that will withstand the required testing.

3. THE INVESTIGATON OF MARINE EXPLOSIONS

When an investigator is called to a ship casualty, it is generally clear whether there was an explosion on the vessel, although a question sometimes remains as to whether a fire preceded the explosion. The preliminary investigation described above will likely establish the location of the explosion and determine whether or not there was a fire preceding the event. The primary questions that remain are what was the cause, and in particular, what was the explosive medium that was ignited and what was the source of ignition?

Many explosions in a marine environment involve vessels carrying or handling flammable liquid cargoes, such as crude oil tankers, chemical tankers, and barges and platforms. There have also been a number of cases of vessels carrying coal in bulk which can emit methane gas and which collects in cargo and related spaces.

Explosions also occur on dry cargo vessels, bulkers, and container ships due to the presence of unstable chemicals and chemicals that emit flammable gases in contact with other substances, or when wetted. Examples of such cargoes include calcium hypochlorite, direct reduced iron, and certain forms of metal scrap and slag.

Explosions may also occur in engine rooms and pump rooms and may involve crankcase explosions in diesel engines or the disintegration of high speed rotating machinery, such as compressors and purifiers. In the case of crankcase explosions, overheated components within the engine will give rise to an oil mist, which may occasionally become ignited and cause an explosion within the crankcase of the engine. Such explosions are usually associated with bearing failure and do not generally cause extensive damage to the structure of the vessel, although serious fires in the engine room may follow a crankcase explosion.

Explosions in ships may also be initiated by military ordinance including mines, rockets and sea skimming missiles, together with explosive charges affixed to the external hull of the vessel or in some cases attached to machinery within the vessel.

3.1 Tanker Explosions

Explosions on tankers and tank barges are the most frequent explosions encountered in a marine environment. In determining the circumstances and cause of the explosion, the investigator must determine how and why an explosive mixture of vapor and air developed in the relevant part of the vessel and why this explosive mixture became ignited, bearing in mind that the rules for construction and operation of such vessels are designed to prevent the coexistence of flammable vapor/air mixtures and a potential source of ignition.

The first task is to determine the tank or compartment in which the explosion was initiated. Depending on the nature and size of the vessel, several tanks or compartments may have exploded. In addition, there may have been a long and intense fire following the explosion.

It is necessary to conduct a detailed examination of the explosion damage sustained by the vessel and to determine the nature and direction of failure of all elements of structure, including longitudinal and athwartships bulkheads and deck sections. Sketch plans should be prepared detailing the tanks and compartments that have been subjected to explosion overpressure and the likely direction of propagation of the explosion through the various compartments. In determining the direction of movement of bulkheads in the course of the explosion, care must be taken to note all the damage exhibited by the elements of structure. Large effects and very small effects can be equally important. It is often the case that the initial movement of a bulkhead may be minor and in one direction, and the propagating explosion then reverses the direction of movement of the bulkhead, producing extensive damage to all associated elements of structure. It is clearly essential to note the minor damage and initial direction of movement, as well as the later, more massive damage.

In the course of an explosion, deck sections are likely to be displaced from over cargo tanks. They may become completely detached from the vessel and thrown into the water some distance from the casualty, or they may remain attached to the side shell or some other elements of the vessel. Detached deck sections must be recovered and brought ashore for detailed examination. It is most helpful if all deck sections displaced in the explosion can be brought ashore and reassembled in the appropriate configuration. A detailed examination may then reveal the mode of failure of the steelwork and direction of crack propagation, which may assist in determining the direction of explosion propagation and the compartment in which the explosion originated.

In addition to recovering deck sections and other displaced components for further examination, the location of the debris, post explosion and prior to recovery, must be noted so as to provide an accurate plot for all items ejected from the vessel during the explosion. This information will also assist in determining the progression of the explosion through the vessel and in determining the magnitude of the explosion in the different compartments.

In addition to observing the structural damage in order to determine the compartment in which the explosion originated, studies must be made to determine the nature and extent of the flammable vapor/air mixture that gave rise to the explosion. Explosions within a cargo tank or confined space will only occur if there is flammable vapor/air mixture within the flammable concentration range. This concentration range is bounded by the lower (LFL) and upper (UFL) flammable (or explosive) limits. In the case of crude oil vapors, a flammable mixture in air will be formed when the vapor concentration is between about 2% to 10% by volume in air. Concentrations of vapor below the lower flammable limit cannot be ignited and are said to be “lean”, whereas concentrations above the upper flammable limit cannot be ignited and are said to be “over rich”. Typical combustion properties for a variety of cargoes are given in Tables 1 and 2.

TABLE 1

FLAMMABLE LIMITS OF PETROLEUM COMPOUNDS

Compound			***Flammable Limits* percentage (vol/vol)**	
			Lower	***Upper***
Methane	(gas)	(CH_4)	5.0	15.0
Ethane	(gas)	(C_2H_6)	3.0	12.5
Propane	(gas)	(C_3H_8)	2.1	9.5
Butane	(gas)	(C_4H_{10})	1.6	8.5
Pentane	(liquid)	(C_5H_{12})	1.5	7.8
Hexane	(liquid)	(C_6H_{14})	1.1	7.5
Heptane	(liquid)	(C_7H_{16})	1.05	6.7
Gasoline			1.4	7.6
Naptha			1.1	5.9
Kerosene			0.7	5.0

TABLE 2

FLASH POINTS AND SPONTANEOUS IGNITION TEMPERATURES

	Boiling point/range (°C)	**Flash point (closed cup) (°C)**	**Spontaneous ignition temperature (°C)**
Methane	-162	Gas	537
Ethane	-89	Gas	472
Propane	-42	Gas	432
Butane-Normal	-1	Gas	287
Benzene	80	-11	498
Toluene	110	4	480
Kerosene	151/301	43/72	210
Naptha	100/177	-2/+10	232
Hydrogen	-252	Gas	500
Gasoline	37/200	-43	280
Gas Oil	260/371	66+	338
Atmospheric residues (fuel oil)	>350	>100	350

The ignition of a flammable vapor/air mixture within a tank leads to the development of a flame front which then travels through the flammable vapor/air mixture. The flame front causes a rise in temperature and a concomitant rise in pressure within the tank. The maximum pressure that can be obtained with petroleum vapor/air mixtures in the flammable range is about eight times the initial pressure, or about 8 bar. The bulkheads and deck sections of cargo tanks on tankers and barges are not sufficiently strong to withstand such an internal pressure and will be disrupted well before this maximum pressure can be reached.

In order to explore the nature of potential flammable vapor/air mixtures, the investigator must determine the nature of the cargo. Chemical analysis will likely be required to determine the components of any flammable gas given off by the cargo. Consideration must also be given to the quantity of gas likely to be evolved from the cargo and the rate at which such gas may be produced. These factors will determine the potential spread of the vapor/air mixture and provide important information on the location of ignition sources.

If the nature of the cargo is such that vapor is evolved only very slowly, then the search for potential ignition sources will be concentrated in and immediately around the tank or compartment in which the explosion originated. Conversely, if the nature of the cargo or some operational event on the vessel indicates that significant quantities of flammable vapor/air mixture will be emitted from the cargo tank or compartment, then potential ignition sources may be located some considerable distance from the tank and its vents. The investigator will need to determine the chemical composition of any vapor stream being emitted from the tank and plume dispersion calculations will be required to determine the extent of any flammable vapor/air mixture venting from the tank. It will be appreciated that the investigator needs to be knowledgeable about operational procedures on the vessel and must also have obtained all relevant meteorological data.

The failure of a cargo tank during an explosion releases the products of combustion and a blast wave may develop which travels away from the ship and which is capable of causing damage at a distance from the vessel to surrounding structures. Observations concerning damage to nearby buildings and structures can be useful in determining the amount of flammable vapor/air mixture involved in the explosion.

As noted previously, the explosion may propagate away from the compartment or tank in which it originates, to involve surrounding tanks. Communication of the explosion from one tank to an adjacent tank usually produces turbulence and a higher initial temperature and pressure in the adjacent tank. As a result of this, the violence of the explosion and explosion overpressure generated in the adjacent tank may well be greater than in the tank in which the explosion originated. In the situation where there is a row of adjacent tanks, each containing a flammable atmosphere, the explosion may increase in violence as it passes from one tank to the next through the row of tanks. Great care must be taken in determining the extent and severity of explosion damage and relating this to the tank of origin. There is often a tendency to assume that the tank suffering the most severe damage is the tank of origin, whereas as the above discussion shows, the reverse may be true.

As we have seen, the nature of the flammable vapor/air mixture, together with the quantity and its rate of production, will provide an indication of the likely location of the source of ignition. In the case where very little flammable vapor/air mixture is being released, the source of ignition will likely be within the tank or very close to a tank aperture. Explosion sources within a tank may include for example structural or machinery failure, hot surfaces, self heating, pyrophoric deposits, and electrostatic phenomena. Ignition within a tank may be produced by external events such as lightening strikes and hot work (welding and cutting) on the tank structure. Finally, the investigator must give full consideration to pipe work leading into the ullage space of a tank. Such pipe work may allow the transport of flammable vapor/air mixtures to points remote from the tank, where the mixture may come into contact with a potential source of ignition. Examples of such lines include tank venting lines and inert gas lines.

Certain cargoes and certain cargo operations, such as loading or ballasting, may lead to significant quantities of flammable vapor/air mixture being ejected from tank openings. The fugitive vapors may travel considerable distances before being diluted to the point where they are no longer flammable. Appropriate dispersion calculations coupled with meteorological data will provide an indication of the likely hazard radius and will indicate potential locations for ignition sources.

3.2 Dry Cargo Ships

As noted previously, explosions on dry cargo ships, bulkers or container vessels may involve unstable chemicals, or in very rare cases, high explosives. Explosions produced by unstable chemicals, or cargoes capable of giving rise to flammable gases when wetted or in reaction with other compounds, produce damage similar to that discussed previously in the case of oil tankers. The same diagnostic features will therefore be studied by the investigator, with a view to determining the compartment in which the explosion occurred. Having located the origin of the explosion, the investigator must then determine what materials were present in this location capable of giving rise to explosion overpressure. Clearly the investigator must have access to bills of lading and other records indicating the nature and quantities of cargoes present within the space. In addition, chemical knowledge will be required to determine which of the cargoes have the potential to produce an explosion. Thereafter, sampling, chemical analysis, and testing may well be required to determine the explosive medium.

Explosions on vessels due to the detonation of high explosives carried as a cargo are rare events. Similarly, explosions due to military ordinance or high explosive devices deliberately planted on the vessel are comparatively rare occurrences. The damage produced by such explosions is quite different to the damage produced by the cargo explosions discussed above. In the case of a high explosive device, there will likely be a focus or point source for the explosion, with very high pressures developed close to the focus of the explosion, leading to the shattering of the surrounding structure and the generation of shrapnel. These features will not be found in explosions caused by the ignition of flammable gases or vapors.

3.3 Explosions Involving Machinery

Explosions involving machinery are usually confined to the engine room or pump room of the vessel. A thorough examination of these spaces will usually provide unequivocal evidence of the item of plant involved in the incident. A detailed examination of the machinery will then be required, usually with extensive dismantling, in order to determine the root cause of the event. It is likely that the investigator will require the assistance of an engineer well versed in the operation, maintenance and repair of the equipment in question. Additional expert services, such as that of a metallurgist, may also be required.

4. THE INVESTIGATION OF MARINE FIRES

In general, the investigation of fires utilizes the principle that the natural tendency of a fire is to spread upwards and outwards. It must be remembered, however, that downward spread of fire may occur by falling of burning material and by downward heat transfer, predominantly by radiation and conduction. Outward spread will occur equally in every direction unless influenced by the relative availability of fuel, air movement and presence or absence of physical barriers.

Another general principle that is utilized is that all things being equal, the fire damage will be greatest where the fire has burned longest. Unfortunately, things are seldom equal, and the effect of ventilation, fuel load, firefighting efforts, and the nature of different fuels will all affect the extent of fire damage. In addition, the potential of a fuse, either slow smoldering or rapidly transmitting flame, from a point of origin to a large fuel bed, must be considered. Because of these numerous potential variables, the investigator must make all the appropriate observations on the distribution of fuel and fire damage, including the extent of charring of timber, oxidation and deformation of steel work and indications of temperatures as revealed by the softening, fusion or pyrolysis of various materials. Useful characteristics for a variety of materials commonly found at fire scenes are listed in Table 3. The effects of heat on steels are given in Tables 4 and 5.

TABLE 3

MATERIAL CHARACTERISTICS

MATERIAL	DISCOLORS	MELTS	IGNITES
STEEL	800F	2700F	2750F
ALUMINUM	Varies	1200F	1250F
MAGNESIUM	Varies	1050F	1200F
COPPER	Low heat	2000F	
TITANIUM	1000F	3100F	2500F
BRASS		1600-2000F	
GLASS		1100-2600	
LEAD		621	
PLASTICS			
ABS		190-257	
Nylon		349-509	
Polyethylene		251-275	
Polystyrene		248-320	
PVC		167-221	
RUBBER (blistering) Neoprene 500F Silicone 700F			
Zinc Chromate Paint – tans 450F, brown 500-600F, black 700F			

TABLE 4

CARBON STEEL

TEMPERATURE °C	COLOR
230	Lt. straw
240	Dk. Straw
255	Yellow Brown
265	Red Brown
275	Purple
285	Violet
295	Cornflower Blue
310	Pale blue
330	Grey

TABLE 5

STAINLESS STEEL

Temperature °C	Color
300	Pale straw
350	Brownish straw
400	Brownish Purple
450	Bluish Purple
500	Reddish Purple
550	Purple Blue
600	Light Blue
650	Bluish Violet
700	Greyish Violet
750	Grey

The success or otherwise of the investigator in collecting physical evidence will of course be governed to a large extent by the amount of destruction that has been caused by a fire.

The preliminary investigation will establish the likely area of origin of the fire. The in depth examination that follows will then involve an excavation of the area of origin by the removal of debris in a systematic manner. The removal process should remove the debris layer by layer, uncovering and interpreting the evidence as it comes to light. The aim of this exploration is to identify the materials affected by the early stages of the fire, which in turn will lead to an identification of the material first ignited. This material will represent the earliest stage of the main fire development. However, caution must be exercised at this point since there may yet be an earlier stage of the fire, with fire transference from a smoldering train of material or physical transfer of a small quantity of burning material from a remote source. In addition, it will be appreciated that the first materials involved in the fire may have been destroyed completely and the observations of the witnesses in describing the pre-fire scene are of paramount importance at this stage.

Once the material first ignited has been identified, it is necessary to determine the likely source of ignition. The location of the material first ignited and the circumstances of the fire will often dictate the available sources of ignition. These may include the following.

1. Thermal ignition sources, such as exhaust uptakes and heating equipment
2. Electrical ignition sources, including overload and short circuit faults, static electrification, tracking and arcing, etc.
3. Mechanical ignition sources, including sparks generated by impact and friction heating
4. Chemical ignition sources, including the exothermic decomposition of materials, spontaneous heating, and spontaneous ignition of oil soaked materials, etc.

The extent and nature of the fire damage, together with the fuel and potential ignition sources, will vary significantly depending on the location of the fire on the vessel. The principal areas in which fires may develop include the accommodation section, the engine room and cargo spaces. These are dealt with in turn below.

4.1 Accommodation Section

Fires in the accommodation section are often severe and extensive with much if not all combustible material being consumed. This is particularly true in older vessels in which the bulkheads separating cabins and internal fixtures and fittings are largely combustible. Under these circumstances, there may be very little fire structure evidence. However, in some cases, effective firefighting may have suppressed the fire in the early stages, in which case, good fire structure evidence is often found.

An examination of the electrical wiring for evidence of electrical arcing may also be of assistance in determining the area of origin of the fire and its likely progression. Finally, the observations of the eyewitnesses may be of great assistance in locating the point of origin for the fire.

Fire spread within the accommodation section may occur via open stairwells or by heat transference through steel bulkheads. Again, the age and purpose of the vessel will have a significant effect on the likelihood of fire spread by these different routes.

It is unusual for a fire to spread from the accommodation section of a vessel to the engine room. However, a fire originating within the engine room may well generate sufficient heat to cause fires within the accommodation sections surrounding the engine room casing. Consideration should always be given to the possibility that the fire has spread to the accommodation section from some adjacent space.

4.2 Engine Room

In general, the available fuel in the engine room is limited to fuel oils and lubricants together with stores and packaging materials.

A fire not involving oil will generally be confined to a space such as the work shop or stores area, and will likely be very limited in spread. If the initial fire involves oil, or if the fire is sufficiently prolonged such that it gives rise to an escape of oil, then the fire damage will be much more extensive and may result in fire spread to areas outside of the engine room.

Once again the investigator must record all details of the fire damage, paying particular attention to likely temperatures that have been achieved and likely duration of the fire in different locations. All potential sources of fuel must be identified and in the case of oil leaks, the prime reason for the source of leakage must be identified. In particular, was the leak due to the failure of some component, such as a high pressure fuel line, prior to the fire or was the escape of oil due to fire attack on a fitting or valves or gaskets therein during the course of the fire? Once again, the observations of the witnesses concerning the machinery in operation and the location of the fire in the initial stages will be most important in identifying the area of origin of the fire and the likely fuel.

Once the area of origin of the fire and fuel first ignited have been identified then the source of ignition can be determined.

There are numerous sources of ignition within the engine room and these include hot surfaces such as exhaust assemblies and turbochargers, mechanical failures such as bearings, open flames from boilers and electrical faults. The importance of repair and maintenance work must also be recognized. Such work can often give rise to a spillage or leakage of oil and may also present sources of ignition in the form of grinding, cutting and welding.

4.3 Cargo Holds

In the case of a cargo fire, the preliminary investigation will reveal in which cargo hold the fire has originated. This area of origin will be determined from a combination of the witness observations, the activation of the vessel's fire detection system (if any) and the extent and severity of fire damage sustained by the cargo in the different spaces. Once the space of origin has become identified, it will be necessary to review details of the cargo contained within this space and to examine the various systems and services contained in the cargo space including lighting, ventilation, refrigeration equipment and hatch operating machinery. The history of the cargoes in the hold will need to be determined from bills of lading, the log book and crew testimony. It is important to determine when and where the cargo was loaded and conditions during loading operations. It will also be necessary to obtain all data concerning repair and maintenance in and around the cargo space of origin. It is particularly important to determine if any hot work (cutting, welding and grinding) has been carried out in and around the hold of origin and a review of the vessel's hot work permits should be undertaken.

The more detailed investigation can then be commenced and this will involve the opening of the hatches and the systematic discharge of cargo. During the discharge of cargo, the investigator must be present to record the extent and severity of fire damage as each layer of cargo is removed. This is often a time consuming task and may require the investigator to attend on the vessel during each of several discharge ports. Finally, when all cargo has been removed, the empty cargo hold will be inspected.

The systematic investigation described above will permit the area of origin of the fire within the cargo to be determined, thereby identifying the material first ignited. The source of ignition must then be determined based on the nature of the cargo, the absence or presence of operating machinery in the area of origin and the presence or absence of hot work in and around the area of origin.

Typical causes of ignition include sparks generated during cutting, grinding and welding, heat transmission through steel bulkheads or decks to combustible cargo from hot work operations, carelessly discarded smoker's materials, and contact of cargo with hot surfaces such as cargo lamps, both portable and fixed. In addition, there is always the possibility of self heating, the exothermic reaction of different chemicals, or the exothermic decomposition of unstable chemicals.

Bulk cargoes are also susceptible to fire and the approach undertaken in the investigation is similar to that set out above. The potential fire hazards of bulk cargoes are set out in the IMDG code. Certain cargoes are susceptible to self heating and spontaneous ignition, for example fish meal, coal, and charcoal. The investigator must be fully aware of the potential hazards of various cargoes and of treatments that may be applied pre-shipment to prevent such self heating and spontaneous ignition.

The investigator may also need to obtain samples of the cargo which can then be subjected to testing and analysis in order to determine the propensity of the material to self heat and the efficacy of any pre-shipment treatment that may have been applied.

Similar investigation techniques are used with containerized cargoes, with each container in the hold or area of origin being opened and examined by the investigator. The investigator must also be aware that container contents are sometimes incorrectly described and in some cases certain contents are not disclosed.

5. **CASE STUDIES**

A number of incidents involving fires and explosions on vessels investigated by the author are set out below, with a view to illustrating some of the principles set out in the text of this paper.

CASE ONE

A fire was discovered on a cruise liner involving the aft mooring deck of the vessel. A substantial fire developed on the mooring deck causing significant structural damage and heat transfer to accommodation areas surrounding the mooring deck. Although the fire was initially observed on the mooring deck and the greatest fire damage was sustained in that area, the fire was initiated in a laundry area some two decks below the mooring deck. The fire involved ignition of combustible lint in the laundry area due to hot work and the rapid transmission of fire through a ventilation duct also containing lint. The ventilation duct exhausted to the mooring deck and flames from the fire within the duct were able to impinge on polypropylene ropes stowed on the aft deck. These ropes constituted a substantial fuel load and gave rise to the extensive and severe fire that subsequently damaged the vessel. A number of investigators were convinced that the fire must have originated on the mooring deck due to the extent and severity of the fire at that location and the absence of fire damage in the laundry area. However, a careful examination of the interior of the vessel and full consideration of the alarms presented by the vessel’s fire detection system, and the observations of the vessel’s personnel, revealed that the fire was actually initiated in the laundry area and then transmitted to the mooring deck by the "fuse" of lint contained within the ventilation duct system. The hypothesis that a fire originated on the mooring deck and spread to the laundry was tested by calculation and by consideration of the sequence of events shown by the automatic fire detection system. The mooring deck hypothesis was not tenable. The laundry initiation hypothesis was found to fit all available data and was supported by calculation.

CASE TWO

An explosion occurred in the engine room of a VLCC whilst in dry dock. The explosion occurred in a wing bunker tank at the forward end of the engine room. The explosion overpressure breached the aft bulkhead of the tank and allowed combustion products and burning oil to vent into the engine room. At the time of the explosion, cleaning was underway in the engine room and as a result of the explosion, some 60 people lost their lives. The contents of the bunker tank were analyzed and it was determined that light petroleum fractions were present in the bunker tank. These fractions were consistent with the crude oil being carried onboard the vessel. The investigations onboard the vessel revealed several accidental and deliberate ways in which the crude oil could have been introduced into the bunker tank. The vessel had a practice of carrying reserve bunkers in a tank previously used for cargo and then transferring this bunker oil to the wing bunker tank which would lead to contamination. The vessel also used a shore line for pumping crude oil cargo ashore from the vessel and then used the same line to bunker the vessel. The source of ignition for the explosion was found to be hot work, external to the engine room and bunker tank. A workman was in the process of removing the vent cover on the vent line for the aforementioned bunker tank, using a cutting torch. Vapors within the vent lines were ignited by the hot work and the flame front traveled through the line to the bunker tank.

CASE THREE

A vessel suffered an extensive oil fueled fire which originated in the engine room and subsequently spread to the engine control room and the accommodation. The patterns of fire spread were only consistent with a fire developing at the bottom platform level of the engine room in the vicinity of a main engine. This area of origin was also consistent with the crew testimony. The examination of the main engine revealed a fractured high pressure oil line on the engine. The failed component was removed and subsequently submitted to a metallurgical laboratory for a detailed examination. It was found that the line had suffered from fatigue failure. The failure of the oil line allowed a substantial spray of oil to be emitted from the point of the failure and to splash on and around the turbocharger and exhaust of the aforementioned engine. The fire structure evidence revealed that the oil, which had sprayed onto the turbocharger and exhaust, had become ignited, leading to a substantial oil-fueled fire on top of the engine. A study of likely exhaust temperatures and the auto ignition temperature of the oil in question revealed that the exhaust system constituted a competent source of ignition. Heat generated during the fire had then been transferred to the engine control room and subsequently through higher decks into the accommodation section.

CASE FOUR

Explosions occurred at a marine terminal used for the loading and discharge of oil tankers. At the time of explosion, oil tankers were present on both the seaward and landward side of the jetty and were nearing completion of discharge. One tanker had contained naphtha whilst the second contained gasoline. The explosions caused the sinking of both vessels and the complete destruction of the chicksan loading arms on the jetty between the two vessels. Personnel present on the decks of the vessels and on the terminal at the time of the explosion were killed and no reliable eyewitnesses were present concerning the point of origin of the explosion. The first task was to determine which of the two vessels had exploded first. This was accomplished by a review of the damage sustained by the chicksan loading arms and associated pipe work on the jetty. The directional collapse of the arms and the layering of the debris on the jetty revealed that the original blast had come from the seaward side vessel. The landward side vessel had exploded as a result of the first blast.

Having determined the vessel of origin, the next task was to determine in which of the cargo tanks the explosion had originated. At the time of the explosion, the seaward side vessel was almost completely discharged and substantial quantities of flammable vapor/air mixture were present in all tanks. As a result of this condition, the explosion propogated through most of the vessel's cargo tanks, breaking the vessel's back, setting out the side shell and displacing the majority of the deck sections. The remains of the vessel and all displaced deck sections were subsequently collected in salvage operations and brought ashore for inspection in a nearby dry dock. The inspection of the remaining structure permitted the tank of origin to be identified. The examination of the deck sections from the area of origin then revealed blistering of paint work consistent with a fire on deck prior to the explosion. Further investigation revealed that a temporary system had been set up to handle flammable liquid. Spillage and ignition of this liquid would have provided the observed burning to the deck and constituted a competent source of ignition for the contents of the tank.