

Historical Aspects of Fires, after Impact, in Vehicles of War

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ABSTRACT

Bellcose, destructive engagements between land, sea and air vehicles throughout history are reviewed, where fire has been the primary destructive agent or has been a powerful secondary consequence of the mechanical impact of projectiles.

INTRODUCTION

The subject of fire in vehicles of war was strikingly brought to the attention of the people of the U.K., (and indeed elsewhere), by the Falklands War of 1982. News-reel coverage of incidents in which ships were hit and set on fire by Exocet missiles was extensive and the public in Britain engaged in much discussion about the reasons for the vulnerability of their present day naval craft to fire, especially after missile attack.

Studying the effects of fire in, or caused by, vehicles of war, brings about a realisation that fire has long been a deliberately offensive weapon and sometimes an unforeseen horrendous secondary consequence of the use of missiles.

This short paper endeavours to draw together some of the more general but conspicuous features of fire as encountered historically in vehicles of war. There are, necessarily, lacunae in this treatment of the subject because of want of information about weapons' effects and because the topic has not, apparently, been greatly researched *in extenso*.

The review begins with brief historical facts and references to pre-Christian and Roman naval operations in which fire was employed and these are followed by notes, mostly about Greek fire and its use predominantly by the Byzantines, with some interspersed remarks drawn from Needham's writings on firearms and gunpowder in ancient China. Little has been found about fire in vehicles of war at the time of the Middle Ages and indeed up to the relatively modern post-1600 A.D. era. From simple reflection it is easily concluded that until the 20th. century, it is naval vehicles that must be considered the principal topic of interest, since the two large categories, automotive vehicles and aircraft, previously had no existence, whilst railways or locomotives have been operating for but a century and a half. For a survey of the subjects of fires after impact in non-warlike vehicles, see ref. (1).

FIRE IN WAR VEHICLES

I. Pre-Christian Naval Engagements Using Fire

The maximum speed of pre-Christian warships has been estimated at between 6 and 13 knots,² it tending to increase in proportion to the number of super-imposed banks of oars. Phoenician biremes, and Greek triremes and penteconters are known of from several centuries B.C.³, and many illustrations of them appear on ancient vases.

For penetrating the hulls of the ships of their adversaries beneath the water, solidly pointed underwater rams³ were employed. Besides these it was common to throw fire and shoot flammable arrows and the like from towers specially built on warships.

Chapter 2 in refs. (4), notes several conspicuous pre-Christian warlike encounters in which the deliberate promotion of on-board fire was attempted, thus,

1. In the battle of Salamis, 480 B.C., the Greeks placed red-hot coals in kettles on the end of long spars and tipped them into enemy (Persian) ships.
2. In the battle of Actium in 31 B.C., heavy weights and balls of fire were thrown on to Roman ships from wooden towers built on to the vessels in Mark Anthony's fleet.
3. It is recorded that Archelaus in a war (of 87 B.C.) against the Romans, washed a wooden tower with a solution of 'alum' (sic) to render it fire resistant. Apparently however, this alum seems not to have been used to protect ships' timbers against fire and in any case was not present-day alum (see the discussion in ref. (5)). However, Partington⁹ does attribute the use of real alum to Greeks for fire-proofing timber and to Romans for fire-proofing siege engines in 296 A.D.
4. Recall that Archimedes was supposed to have set fire to Roman ships using metal mirrors.

II. Principally on Greek Fire

To convey a sense of proportion about the true importance of fire in the whole of early warfare, it is well to recall an excerpt from Oman's⁶ 'The Art of War in the Middle Ages, A.D. 378-1515.'

"... Greek fire ... though its importance in poliorcetics (siege warfare) and naval fighting was considerable ... was a 'minor engine of war' and not comparable as a cause of Byzantine success to their excellent strategical and tactical system ..."

However, the impression which Greek Fire could have on troops is well instanced by the following extract from a Russian chronicle,⁷

"The Greeks have something which is like lightning from heaven, and, discharging it, they set us on fire; that is why we did not defeat them."

The above quotation refers to a naval attack on the Russians by the Byzantine navy in 941, when a Russian armada was virtually annihilated by the use of Greek fire. Of the year 971 A.D., there is a report of Byzantine fire-shooting ships "capable of turning the very stones to cinders". Greek fire was a notorious 'secret weapon' for which nations from Eastern Europe sought 'samples' of this 'priceless commodity' from the Byzantine Empire. One early 13th. century manuscript⁷ shows an artist's idea of such an encounter. Early occasions as in the 7th. century when "fire ships" were fitted with siphons are noted in ref. (9).

Scoffern in 1858, gave an early and relatively lengthy discussion of the origins of Greek fire, whilst a shorter different survey on Inflammables and Explosives, is to be found in the book published in 1906 by Cowper.⁹ The most significant work of scholarship on this subject is undoubtedly that from Partington⁹ in 1960, entitled "A History of Greek Fire and Gunpowder."

The ingredients of Greek fire, variously stated to be mixtures of any or all of sulphur, resin, quick-lime, pitch and turpentine, or naphtha,[†] Needham categorically states to have been used from the classical period of Greece up to the 14th. century A.D., by which time gun-powder had been developed or invented. This fire was projected by bellows or pumps (from ships or even land vehicles) on to enemy vessels which took fire and caused black smoke which could seldom be suppressed. The projected incendiary material, say the naphtha, was likely to have been thickened by resinous materials and sulphur since the jet would otherwise have been dissipated too quickly by the air.

[†] From "liquid petroleum from oil wells in Iraq", p. 28, ref. (9).

The common idea that the Chinese used gun-powder only for fireworks, Needham holds, is quite false.¹¹ That it was developed solely by artisans he maintains is also untenable; he claims it was the outcome of 'systematic' explorations by Taoist alchemists.

The name 'wet fire' or 'wild fire' has been used to describe the 'fire' ejected from siphons; and yet another variant seems to have been 'sea fire' which probably included salt-petre;¹⁰ the latter went out of use in 1200 A.D.

Needham,¹¹ has described a 'fire lance' of the 10th. century which was used to destroy rigging and woodwork; when first used it was held manually by fire-weapon soldiers. Later it was made of bamboo, (he claims it to be the archetypal gun barrel) and was called an eructor; it is indicated to have been long and nearly one foot in diameter, being mounted on a framework of legs and even wheels for mobility. This device is supposed to have shot flaming projectiles. Edward Gibbon's Chap. LII of his Decline and Fall of the Roman Empire,⁸ contains an interesting reference to the use of copper tubes in the bows of ships, for projecting Greek fire in assaults on Constantinople in the late 8th. century.

Table 1 from ref. (1) seems to show that knowledge of gun-powders, allegedly first used as a 'match' for flame-throwers in 919 A.D., was brought to Europe from Chinese lands in the second half of the 13th. century by Moslem and Christian merchants and adventurers and by proselytizing Nestorian priests. The later forms of gun-powder were brilliant with the nitrate proportion in compositions increased to give destructive explosions.

Greek fire was employed in Western Europe in the Middle Ages for burning towns, the very common roofs of straw or shingle being highly vulnerable to fire. In 1379 at Oudenarde, inhabitants covered their houses with earth to resist fire hurled into the bassee-cour.

Generally, ancient fire extinguishers were water, sand, dry or moist earth and manure or urine (which contain phosphates) and probably salty vinegar.

The same applied in respect of bridges and shipping. A Brabanter wooden bridge over the Meuse was attacked by the Guerlols with 'engins feu' in 1388 and caused to collapse into the river. At Breteuil in 1356, those besieged were provided with 'canons jetant feu...' to deter attackers on advancing towers.¹²

If we include Middle Ages siege engines as early vehicles in our review then notice may be taken of a full description of the use of the Sow or Cat (the ancient Vinea) in the siege of Jerusalem in 1099 which was given by William of Malmesbury. The Sow is essentially a low, mobile covered timber construction protecting advancing engineers engaged in mining the foundations of walls. Mines prepared in about 1200 A.D., were caverns in which pillars of wood, supporting incumbent walls, were smeared with pitch, surrounded with combustibles, and then fired to allow collapse. Also, Belfrelds or moderate-sized towers were employed as a stage for attacking soldiers contesting defenders on ramparts. The defenders it is reported, 'trusted their whole security by pouring down boiling grease and oil upon the Tower'. This was replied to by the Franks by throwing 'faggots flaming with oil on to an adjoining wall tower'. Wet animal hides were frequently draped over wooden walls to protect structures.

Cowper⁸ notes the wide and early use of inflammable propellants for projecting rockets and fire pots from tubes in 'early India' by the Siamese, at Delhi by Mahoud V against Timur Beg and their throwing by catapult in 1290 by Ala-ed-din. He quotes too, examples of projected ignited moss on to burning villages by South American Indians. Cowper's summary that "Inflammables for war derive from Assyria which bequeathed it as Median fire to Byzantium - the Arabs stole (sic!) it from the Greeks - and the Europeans learned (sic!) it in the Crusades", may well be as true as Needham's line of suggestion in imputing to it a unique origin in China. Partington,⁹ again, devotes whole Chapters to this subject. It is not all improbable that many pyro-jetting practices were developed in several societies independently of one another, much as is sometimes the case with scientific discoveries.

Partington devotes a chapter to incendiaries of war and especially mentions several Muslim fire books which show among other things recipe proportions for gunpowder and the use of naphtha.

III. Fire Ships and Hot Shot

Wooden naval ships have always feared incendiary attack - an increasing threat onward from the time of the introduction of Greek fire. Cowper says that Procopius in his history of the wars of the Goths of Africa describes the use of Median fire and Genserik is said to have used fire ships against the Greeks in the 5th. century A.D.

Fire ships were used, successfully, against Drake at Cadix in 1490 by the Spaniards, and the Dutch filled ships with explosives to cause explosions in the Duke of Parma's fleet which was besieging Antwerp in 1585. In battles against the British in the latter half of the 17th. century, the Dutch always had on hand a number of specially combustible craft. Fire was used to great advantage in a Dutch raid (on English ships) up the river Medway in 1667.*

Fire ships consisting of fishing smacks of faggots and pitch were apparently to be used by the English to attack the Spanish armada in 1492 in the Calais Roads but as they could not be assembled rapidly enough, eight small ships of the fleet, probably victualers, were prepared. A Spanish screen of protective patrol boats mostly fled as tide and wind bore the fired ships into the assembled armada. These fire ships had 'shotted' guns and their explosions added to the panic induced. The starting of ship fires in the armada apparently failed completely but they were successful in as far as they induced the 120 Spanish ships to slip or cut their cables to escape in terror.

It has often been observed that, certainly in the late 18th. century, it was rare for ships-of-the-line to be sunk by gun fire: burning or capture[†] was the rule. In a Dutch-English naval battle of 1794, the Dutch had at least seven and the British two ships burnt or blown-up. In the battle of Trafalgar no ship was sunk on either side as a direct consequence of enemy action.¹⁴ Though fire ships were included in most large fleets there is little evidence that they directly caused fire disasters. But fires in wooden ships were a terrible threat and their menace generally led to the British Navy taking thorough precautions against them.

Fire ships were used as recently as the first quarter of the 19th. century, for example in 1809 by an English fleet under Lord Cochrane against French ships at anchor in the Basque Roads, and in the War of Greek Independence the Greek fireships used successfully against the Ottoman navy led to their command of the sea.

Notwithstanding the panic which tended to be induced by fire ships hampering the movements and dispersal of a fleet, they could be easily sunk by enemy fire or towed away by enemy boats. Also, experience showed that premature explosion by those putting fire ships into position could often be fatal. Typically, fire ships of later times consisted of building 'a fire chamber' between decks from the forecabin to a bulkhead constructed abaft of the mainmast. This was fulfilled with resin, pitch, tallow and tar and with gunpowder in iron vessels. The gunpowder and the combustibles were connected by powder trains and by bundles of brushwood ('bavins'). Service with these fire ships was so dangerous that the reward of £100, or in lieu of it a gold chain, was given by the British Navy!

It was long the practice when wooden naval ships were in vogue to exchange hot shot or cannon balls in the hope that fires would be started or ammunition caused to explode on the enemy's ships. It was infrequent for shot to penetrate the sides of ships

* Interestingly, it is recorded that Newton heard the noise of this raid from as far away as Cambridge and was able to pinpoint the time of day and deduce that serious losses had been incurred.

† Firing à ricochet to demast ships and thus leave them to be boarded later or at the mercy of the weather was a serious 18th./19th. century tactic, of the British Navy. See W. Johnson and S.R. Reid, 'Ricochet of Spheres Off Water', *J. Mech. Eng. Sci.*, 17, 71-81, 1975.

of a fleet which were often three feet thick in hard woods such as oak, teak and mahogany. In ref. (13) it is implied that it took a close range 32 lb. shot from a 10 ft. long cannon to do so. In a long siege of Gibraltar by wooden French ships in the 1780's, red hot shot was apparently fired from the land fortress.¹⁴ Many reports exist of ships exploding after gunpowder carried in magazines had been heated by unintentional ship fires or penetration by missile fragments.

The invention of red hot shot, in 1579, is attributed by Brigadier O.F.G. Hogg in his foreword (page v) to the book, Great Art of Artillery[†] (Artis Magnoe Artillerioe) by Polish General C. Simlenowicz, to the King of Poland. The book itself is a fascinating text book for would-be pyrobolists rather than artilleryists; it was originally published in Latin in 1650, then translated into French and from French into English in 1729. The variety of fire projectiles treated by him exceeds at least twenty. Simlenowicz says in his Chap. XVII that red hot shot was "far from being modern" and refers to Diodorus Siculus testifying that the Tyrians projected it into the "works of Alexander the Great". Also an occasion is mentioned when in a war of 1598 a red hot ball penetrated a tower, fell into a barrel of gun powder and destroyed the entire structure. Gibbon (see above) in his Chap. LII refers to the launching of red hot balls of stone and iron in the 8th. century as well as to inflammable oil deposited in fire ships.

Under this heading brief mention needs to be made of incendiary shells first introduced in 1480 and variously developed since. In the main these were spherical carcasses or shells containing ignitable compositions which were vented radially to allow the egress of flame. Martin's shell (c. 1860) was filled with molten iron and used against shipping by the British whilst another design due to Hodgkinson (c. 1914) was used against Zeppelins (See O.F.G. Hogg, Artillery, Archon Books, 1970, p. 171).

Firing fleets at anchor as described above merely underlines the perennial risk from fire in any gathering together of vehicles, e.g. of buses and coaches, see ref. (23). We may mention that the biggest naval holocaust of the 19th. century occurred in the U.S.A. at the Norfolk Naval Base when Southern sympathizers torched warships on the occasion of Virginia's secession from the Union in 1861.

The effects on wooden ships of a lightning strike, namely 'rigging set on fire, masts split and severed to pieces...' was reported in writing in 1775 by Bathae.³ The reason for the latter was probably due in part to the anisotropic character of the grain of the wood; its moisture when instantaneously vapourised 'explodes' the wood whilst axially in the flow of electricity leads to severing or 'chivvering'. Early references to this (end of the 17th. century), and closely related work on fulgerite* formation is given in ref. (24).

Lightning conductors had been introduced and were nearly universal in British naval vessels by the beginning of the 19th. century.

IV. Armoured Fighting Vehicles and Fire in the 20th. Century

In all military fighting vehicles fire poses a huge and constant threat. Not only does it destroy expensive structures and equipment but the personnel, aside from purely humane considerations, are frequently expensively equipped and costly to train. The flame-thrower has already been mentioned in an historical context[‡] as an ancient

[†] Republished by S.R. Publishers Ltd., 1971, Wakefield, England and Scholar Press Ltd., Menston, Yorkshire, U.K.

* Fulgerites: tubes of vitrified sand found in the earth after a lightning strike, so-called after the Roman god of lightning, Fulger.

[‡] Compare Gibbon (Chap. LIII) who refers to the use in (probably) the 8th. century of a "mischievous engine that discharged a torrent of the Greek fire, the feu Gregois ..." In a footnote he says that Joinville described something as "like a winged long-tailed dragon...with the report of thunder and the velocity of lightning..." "It was shot with a javelin from an engine that acted like a sling", seemingly a mangonel, but more likely a balista.

naphtha projector which was certainly in use according to Needham[†] in 919 A.D., when gun-powder of a kind was first identified as being a 'match' for naphtha. A British origin and development for napalm has been claimed in ref. (15). Flame Fougasse as a one-shot weapon was apparently developed in about 1940 to project onto advancing tanks about one ton of burning petroleum.[†] The mobile Churchill flame-throwing tank was later developed to assist in clearing operations and a slightly fictionalised account of this Crocodile as used operationally in World War II is given in 'Flame Thrower' by A. Wilson.¹⁶ Some details as outlined by him follow.

The flame-projector was mounted in the front of a Churchill Mark VII tank with the flame-gunner alongside the driver. Four hundred gallons of heavy viscous flame fuel, (of petrol, naphtha and rubber - a crude form of napalm) was carried in a seven-ton trailer connected to the tank by an armoured link containing the fuel pipe. The fuel was projected from the nozzle gun by means of 350 p.s.i. of nitrogen, - actually reduced from 5000 p.s.i., as stored in five steel 'bottles' carried in the trailer. The 'rod' of fuel was ignited by a jet of burning petrol that passed between two electrodes. The gun had a range of 90 yards and could flame continuously for two minutes.

In 'The Secret War' by Gerald Pawle,¹⁷ a 'Cockatrice' is described in chapter 4 as designed mainly by the Lagonda Car Company. It fired diesel oil and used 8 gallons of fuel per second. Later models fired 200 yards; these were developed by the Army and the Anglo-Iranian Oil Company. The Cockatrice consisted of a 2½ ton lorry, "Invulnerable" to fire, possessing a tank holding 2 tons of fuel with the flame thrower itself mounted in a turret behind the cab and operated by a gunner in the turret. The all-up weight was 12 tons.

It was tried at sea after installing it on a trawler, by firing it vertically against low-flying aircraft: the pillar of flame was over 400 ft. high, its height being enhanced by the heat of the fuel. However, in tests with even up to one half an aircraft wing being driven through the flame, no serious damage to the plane ensued. A few naval flame-throwers were produced and installed on sea-coasters but their maintenance was difficult; very high pressures had to be maintained and unless well handled, ships and their crews were liable to be smothered in tar and oil.

It seems that German experience after testing a somewhat similar device which projected ignited fuel from a pipe and nozzle which ran up a ship's mast, showed it to be a failure.

Tests of the ability of assault landing-craft to enter a harbour with the infantry passing through the fire of any flame-thrower mounted on a breakwater, showed they needed no canopy. To fire a flame along a straight trajectory when slightly depressed was said to be very difficult. Tests showed that dummies, paper and mice in the bottom of craft, emerged without scorching or poisoning.

Impact leading to fire and/or explosion is promoted when some modern tank armours are penetrated by copper-lined shaped-charges; the temperature of local target material is raised but particularly it has been noted that hot spall particles are ejected through tank compartments. If they are small (mainly aluminium), they may burn so rapidly that effectively an explosion occurs and they may have a lethal effect on a tank crew. Suppression is provided by plastic liners.

A shaped-charge passing through a partially filled container of gasoline, or volatile hydraulic fluid, renders it rapidly combustible when heated and atomised. Diesel fuel thus tends to be used and its tank container located outside the crew compartment armour. Shaped-charge jets may also penetrate ammunition, but steps are now taken to quench explosion propagated through propellant charges by surrounding them with an extinguishing agent.

[†] Hogg, op. cit., p. 174, refers to an engine tested for projecting liquid fire at Woolwich, near London, in 1709.

V. Airships

Fire sources in airships and catastrophic experiences with them are outlined in refs. 18 and 19; also many references are quoted therein which detail well known disasters, for example Delighton and Schwartzmans' 'Airshipwreck'.²⁰ Because the risk of fire aboard airships has been so heavily reduced, mainly due to ceasing to use hydrogen as the lifting gas - and for several other reasons²¹ - many governments have become interested in developing them for off-shore patrolling work such as protecting oil installations and fisheries, etc., and as having anti-submarine capability. They have been thought of as capable of carrying air-to-air and other missiles and torpedoes, all both cheaper and faster (at up to about 100 knots) than conventional surface ships, able to have light armour and being easily maintained with a small crew. It has been stated that such airships have a lower radar profile and little infra red and noise emission, which makes them less attractive targets for homing missiles.

Stepping back into history, the Britannica Encyclopaedia (1947) gives a detailed historical account of air balloon development in which instances of disastrous fires occur, many similar in result to contemporary disasters typified by a 1983 report in the Sunday Times of a 140,000 ft³ hot air balloon being projected 200 ft in the air after a propane cylinder had exploded.

By contrast, 'My Airships' is an interesting but little known book,²⁴ by A. Santos-Dumont (1873-1937) about his airship development and flying activities between 1900 and 1905. Among many of his observations, this pioneer thought that the first practical use of airships would be found in war, (p. 80). He recorded that he had no fear of fire (p. 45), and that he could see but one dangerous possibility of it (p. 48), namely, "that of the petroleum reservoir taking fire by a retour de flamme from the motor" - (a sucking back of flame). This innovator, contrary to the subsequent experience of others, appears to have suffered no fire disasters despite his large number of journeys.

VI. 20th. Century Naval Ship Fire Safety²⁵

"Naval ships are often floating ammunition farms and fuel dumps housing multi-million dollar (equipments)... and densely packed with personnel..."

"The most common feature of modern naval warfare is internal fire caused by shells bursting among combustibles and explosives."

This topic is reputed to have received much attention from about the time of the Russo-Japanese war (1904-1905) when fire, smoke and burning paint on the Russian ships, together with acrid gas from Japanese gun powder ('shimosa'), had devastating effects.

In about 1880 the coal bunkers of battleships were deliberately placed between the outer skin of a vessel and its vital organs. It was noted from tests in 1878 that 2 ft of coal had the resisting power of 1 inch of iron (ref. 26, p. 412) and was not set on fire by shell (i.e. gun fire) explosion. However, tests in 1904 using torpedoes showed that similar protection was not available against them.

From World War II to the mid-1970's, major fire disasters aboard naval ships and aircraft carriers especially, hardly diminished.

H.M.S. Hood, a 41,000 ton British capital ship, (having a deck only 3 inches thick and turret roofs only 5 inches), apparently never modified for the containment of powder flash from burning powder magazines after experience in World War I, suffered a direct hit from The Blismark which caused a great fire that quickly led to the explosion of the magazines. The German ship suffered nearly 400 direct shell hits and 6 torpedoes and only sank after being scuttled. Oscar Parkes²⁶ in his huge and authoritative volume on British Battleships, 1860-1950, notes that propellant cordite which exploded when exposed to flash in the magazines, explains the loss of battle cruisers at The Battle of Jutland. A different treatment of cordite (separation into two sections) by the Germans did not give rise to explosion despite being fired. Parker notes that among the German battle cruisers associated with nine penetrations there were eight fires but no explosions (p. 641 and p. 679).

World War II 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 attack by bomb and Kamikaze attacks. This reflects the fact that a new, essential and far reaching lesson for sea power (after the battle for Midway) was that centuries of dependance on big ships carrying big guns was ended and their place was to be taken by aircraft carriers. Many battery explosions and electrical fires in U.S. submarines occurred between 1949-1955, whilst in the late 1960's, three carriers were the subjects of conflagrations due to 'burning pyrotechnics' and deck fires fed by aircraft ordnance and fuel ignitions.

The 1970's saw in fires on the U.S.S. Forrestal and U.S.S. Saratoga, impassable passage-ways affording fire spread and fire propagation along wire and cable-ways. Most traumatic was the fire resulting from the collision of cruiser U.S.S. Belknap and carrier U.S.S. J.F. Kennedy in 1975. The mast and aluminium superstructure of the former were sheared off by the overhang of the Kennedy's angle deck sponson; most damage resulted from the melting of aluminium structure due to fire,[†] fed early on by JP-5 fuel pouring from the sheared flight-deck fuel risers on the U.S.S. Kennedy.

Hydro-carbon fires are combated best by excluding air and reducing the vapourisation rate of applied liquid Aqueous Film-Forming Foam (AFFF) concentrate (mixed with sea water to give 6% solution). Halon gases in machinery spaces extinguish fires by interfering with the combustion chain reaction.

Fire protection design against present-day fire threats to ships are outlined in ref. 4.

Oil fire extinguishment it is held, may be possible by using pressurised containers of water and very fine mist nozzles; the water spray droplets become steam which absorbs thermal energy and cools the fire.

A Flight-Deck Washdown System was introduced after the unfortunate experiences with the U.S.S. Forrestal (1967) and U.S.S. Enterprise (1969). The system can deluge all or part of a flight deck with AFFF through spray nozzles on a flight deck or along a deck edge.

Items for upgraded fire protection on naval ships include, among other things, luminescent markers to make clear escape routes to weather decks, refractory felt for the protection of aluminium superstructure, improved magazine sprinkler systems and fire spots for cable ways.

For detailed papers about missile magazine protection, see refs. (29) and (30); Halon Expansion foam fire protection systems for ships, are discussed in the Naval Engineers Journal of recent years.

VII. Mainly About the Use of Aluminium in Naval Vessels^{31,32}

Aluminium has wide use in modern naval craft, especially in the hull and superstructure in order to reduce weight, improve stability and to help conserve fuel. Unfortunately, the relatively low temperatures vis-a-vis steel at which aluminium loses its strength, renders fire threat of enhanced importance. Thus, alongside the use of aluminium it has become necessary to develop light weight thermal mitigation systems. This leads to trade-offs as between fire resistance (or time to structural failure under fire conditions) and weight, in the design of high performance craft.

[†] The ability of metals when sliding, cutting or dragged under pressure against another surface to reach a high flash temperature and thus to be an energy source sufficiently high to ignite available vapourised fuel is empirically addressed in ref. (27). Ref. (28) seems to be the most recent scientific paper in which junction growth and heat due to the work of plastic deformation, are incorporated into the heat-transfer equations of the Jaeger-Archard theory and provide results which compare well with those of experiment for estimating flash temperatures.

Aluminium is about one third the density of steel but has about the same ultimate strength, which impressively contrasts the strength of these two materials over a large range of temperatures. Whilst the various aluminium alloys do perform differently, they do not do so significantly over the temperature range of interest; certainly at 700 °F all aluminium strength has effectively disappeared. When active systems are inadequate, malfunction or by human error are not released, then passive systems are relied on. Particularly this means minimising serious fire threat where aluminium is concerned; time is purchased prior to active fire protection systems being operated, by adding thermal insulation. Fire prevention, early fire detection and rapid fire extinguishment are essential active features, especially on aluminium craft. Examples exist of aluminium bulk heads, aluminium hulls and indeed whole ships being melted down; in contrast these items in steel do not.

Fire insulation materials currently used are mineral wool, refractory felt or blanket polyisocyanurate foams, polyimide foam and fibre glass, all with densities in the range 2.5 to 7 lb/ft³. With a temperature of 450 °F as a failure level, one hour of protection is given by about 1³/₄ inches of 4 lb/ft³ refractory felt. Note however that heated and ignited isocyanurate foams give off large amounts of HCN gas.

VIII. Naval Vessels in the Falklands' War* of 1982^{21,19}

Fire and its consequences in fighting ships in the Falklands' War highlighted the subject's enormous importance and underlined the cost of taking, or neglecting to take, its likelihood seriously enough. Especially, a lesson of the Falklands' War of 1982 was the need to reduce smoke in battle damaged warships; this was made clear when the destroyer, HMS Sheffield was hit at 8-15 ft. above the water-line, and set on fire by a Super-Etendard 600 mph Exocet missile of 658 kg weight, which carried a 164 kg warhead. It is reported that within minutes of it striking the ship, smoke poured from deck openings at 100 ft and more from the point of impact. The ship was set on fire and burning solid propellant was scattered, as well as the missile's own fuel; these in part created the massive smoke pall. Doubtlessly the ship's ventilating systems contributed to the rapid spread of fire as well as the ship's own materials and the availability of cable ways.[#] Paint on the ship's side came off around the zone near to the missile and close to the region of penetration the hull glowed red. Though fought for several hours it was eventually abandoned out of fear that the magazine might explode.

H.M.S. Coventry was hit by several bombs which caused flooding beyond the design limits of the ship. Smoke rendered the operations room unusable, as much as anything because of disorientation effects.

Of torpedoes which helped sink the Argentine troop carrier Belgrano, one was reported by the Captain to have created 'a fireball', (compare and see the references in (34)), and another 'a cloud of dirty smoke'. A huge hole was created in her bottom, amidships, and her bow broke off.

H.M.S. Antelope suffered from an unexploded bomb that detonated when defusing was in progress. The ship burned for many hours apparently with the aluminium superstructure remaining intact and not being responsible for her loss.

The Atlantic Conveyor received one or two Exocet missiles and burned for two to three days, but the superstructure on this occasion distorted without collapsing.

* Evidence and sources for many remarks in this section will be found interspersed among two references stated.

[#] Remarks concerning pre-routing ventilation systems to permit smoke removal and for improving ventilation fans for de-smoking have been made. Existing fans apparently cannot remove hot gases since the fan motors cannot withstand the temperatures. Eductors from exhaust systems have been recommended for investigation.

The New Scientist catalogued the following explosion-fire 'errors' as contributing to the H.M.S. Sheffield 'fire trap', though the £85 million ship (commissioned in 1980) had the usual sprinkler systems, fireproof doors and hatches, etc.

1. Generators providing power to fire-fighting pumps were out of action: the missile knocked-out the aft main generator and the forward one failed minutes later.
2. Fire-fighting pumps did not work because vital parts were missing: the ship was deficient in small fire extinguishers since only a small number was available and not rechargeable.
3. In some cases, breathing equipment containing compressed air was almost empty.
4. Foam mattresses burnt easily, giving off clouds of toxic smoke. It is reported that in the latest U.K. battleships, these have been dispensed with in favour of horse hair, which only smoulders and gives off smoke less rapidly than synthetic materials.*
5. Hydraulic fluid sprayed uncontrollably from burst pipes feeding the fires.
6. Sailors were wearing polyester[†] uniforms that melted on to their skins. Anti-flash personnel protective equipment, e.g. hoods and gloves, was a major factor in preventing and limiting injuries from flash and blast.[#] Multiple layers of any clothing served better than one layer; polyester or other synthetic fabrics were counter-productive.

Reports described missile blasts as going "upwards and outwards" - upwards as frequently happens in buildings where ceilings are usually the weakest of a room's containing surfaces - rupturing H.M.S. Sheffield's deck and almost one third of the ship from galley to damage control headquarters, causing it to burst into flames with thick toxic smoke; "...the gaping hole in the ship's side and engines fed the flames, which rapidly turned into an inferno".

Early allegations that in the damaged H.M.Ss Invincible, Sheffield and Ardent, 'aluminium burnt' and contributed to loss have been refuted.* In a recent leaflet, the (British) Aluminium Federation felt it necessary to state that aluminium does not burn under natural conditions, but that it does melt and vent a fire. However, that there was much flammable material aboard ships at the Falklands (and as unnecessary furnishings) was conceded and that it would burn when some critical temperature was reached was unavoidable; but most of it was "fuel and ammunition followed by electrical cabling, deck and bulkhead linings and furnishings". Apparently, 175 miles of cable were then to be found in a British destroyer. With H.M.S. Sheffield it is acknowledged that the smoke and fire were chiefly the products of unspent rocket fuel from the attacking missile motor, and oil from the ship's fuel tanks. Noteworthy, is the little known fact that H.M.S. Glamorgan suffered a hit from a land-based Exocet but that the major fire was extinguished by a large hole in the deck being plated-over and other major equipment repairs being performed.

A possible useful conclusion, valuable for future ship design that has been noted is that control functions (which includes damage control) might be prudently separated from those of internal command. Also that the location of generators and similarly

* Plans to do away with oil for potato chip making are afoot too!

[†] Suits now provided are flame resistant. Partington⁹ (p. 207) mentions fire-suits for men and horses, of felt and compositions of talc and brick dust etc., being used in about the 14th. century by the Arabs!

[#] Interestingly, many World War II bombers had extensive interior hydraulic lines which blew up or burned rapidly when damaged. In prisoner-of-war camps it was observed that the type of aircraft that had been flown by certain in-coming prisoners, (B-24 crews), was known by the kind of bandages for burns which they wore.

* An instance in which metal probably did burn occurred in the Le Mans (French) Grand Prix of 1955, when a Mercedes car containing an engine with a high fraction of magnesium, swerved at 180 mph during the race and ran up an earth safety bank, somersaulted, bounced and "exploded into white-hot component parts", amid spectators, killing 82. ['Great Disasters', Treasure Press, (1976), p. 61.]

'soft' vital auxiliaries might be more thoughtfully distributed around ships in view of likely hits from smart munitions; and that loss of air conditioning, low pressure air and centrally-supplied services can disable weapons and command positions.

In one discussion on the latter topic, it was pointed out that modern engine rooms are in a kind of deep pit with very hot machinery at the bottom and with volatile and combustible fuel oil about. Steam drench was thought preferable for putting out machinery space fires but as noted above, "the ultimate is large quantities of salt water with AFFF foam or some equivalent". Inert gases are generally used in weapon electronics compartments in gas turbine modules and in the engine rooms of gas turbine ships. Nitrogen is used in submarines though halogens are favoured; lower over-pressure is required for fire extinguishers and personnel survive it better. Fire has to be contained for inert gases to be effective and large missile holes in ships preclude this.

The U.S. Navy aircraft carrier U.S.S. Forrestal (1966), already referred to above, was almost totally destroyed by fire after a missile on a plane exploded on the flight deck and many died of carbon monoxide poisoning. A consequence was that a Survival Support Device (S.S.D.) was developed, but regrettably too few of these were available to British Naval personnel in the Falklands' war. (Apparently, emergency life-support apparatus holding air for 8 minutes has since been ordered). About 120,000 such units were with the U.S. fleet in 1978 and now an Emergency Escape Breathing Device (E.E.B.D.), has been developed to provide a 15 minute air supply for the U.S. fleet.

CONCLUSION

It is hoped that some general appreciation of the significance of fire associated with fighting vehicles in a primary or secondary role over the centuries has been conveyed and that in particular some of their vulnerable features have been usefully noted. This significance will be seen to have grown with time and vessel system sophistication.

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