Machinery Space Fire Fighting – Modern Alternatives

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Synopsis

Machinery spaces in the majority of Royal Navy (RN) vessels use carbon dioxide (CO_2) as the primary fire suppressant. While CO_2 is very effective for firefighting, particularly in machinery space application, it is harmful to life in the concentrations required for effective fire suppression; exposure to concentrations greater than 15% can cause death within sixty seconds.

The use of CO_2 and similar fire suppressant systems in machinery spaces presents a risk due to the potential exposure of personnel. This may occur in a fire scenario where personnel are unable to escape the affected compartment, if there is a leak in the system, or due to accidental discharge. These risks are typically mitigated through physical means and procedural controls. However, in the hierarchy of safety controls the primary means should always be the elimination of the hazard.

Babcock Energy & Marine undertook a study for the United Kingdom Ministry of Defence (MoD) into alternative methods of firefighting on Royal Navy minor warship machinery spaces with the safety of personnel considered a key requirement. The study identified five alternatives to CO_2 available on the market. One particular aerosol fire suppression system was found to be superior to the others for application in small craft. This system is not toxic, non-ozone depleting and leaves almost no residue after application to the affected space, enabling re-entry (provided that the space has been ventilated to remove the products of combustion). The study concluded that traditional methods of fire suppression should be reconsidered across all small craft due to the health and safety issues associated with CO_2 and the availability of improved alternatives.

This paper considers the use of traditional firefighting systems on naval vessels in light of 21st century health and safety regulations. An assessment of current fire extinguishing agents is presented followed by a case study to determine the most appropriate solution for a minor warship concept with a particular aerosol system being justified as the preferred option. The paper also considers if the same conclusions would be reached for major warships or if the difference in scale results in an alternative solution.

Keywords: Marine firefighting, fire suppression systems, condensed aerosols

1 Introduction

The ability to extinguish fires is a crucial requirement of all seagoing vessels. Fixed firefighting systems have long been the preferred, even mandated, option as the primary means of firefighting on military and commercial craft with enclosed spaces. This is particularly the case in compartments that are not normally occupied, such as machinery spaces, which typically employ remotely operated and, in the case of some smaller vessels, automated, fire suppressant systems.

In recent decades significant steps have been made to improve the health, safety and environmental impact of fire suppressants. The signing of the Montreal Protocol in 1987 led to the ban of Halon, a chemical commonly used to good effect in fire suppression systems but with significant ozone-depleting properties. Subsequently, other more environmentally friendly fire suppressant agents have been employed with varying degrees of success.

Traditional alternatives suppressants, such as CO_2, are hazardous to life in the quantities required for fire suppression and therefore require full compartment evacuation. A CO_2 system also maintains the latent risk of accidental exposure due to leakage or inadvertent activation. The risk of exposure is typically mitigated through physical means (ease of escape, preventative activation measures and optimisation of system component properties) and procedural controls (fire safety training, operator training and regular leak testing of the system).

Author's Biography
Tim Goode is a chartered Senior Mechanical Design Engineer working for Babcock International Group – Energy and Marine, based in HMNB Devonport, Plymouth, where he began his engineering career in 2009. Since joining the company, he has worked on projects ranging from the design and build of a luxury yacht to the management of the submarine tailshaft inspection programme. Tim is currently part of the mechanical and marine systems analytical group who undertake analysis, design, improvement and optimisation of mechanical systems for the majority of vessels in the Royal Navy's fleet.

However, in the hierarchy of controls, the risk of exposure should be eliminated where reasonably practicable.

In-service naval vessels, such as the Landing Platforms, still predominantly employ CO_2 systems in machinery spaces. There are now many alternative extinguishing agents available, the reputation of which are growing in both commercial and naval marine environments. While currently uncommon, having only been employed in minor naval craft, condensed aerosols present some key benefits that justify consideration for application on larger vessels.

This paper considers how an improved understanding of fire ignition and propagation has led to the development of novel, safer, firefighting techniques. A review of available fire suppression agents is provided with justification for the down-selection of a condensed aerosol system as the preferred option for Royal Navy landing craft. Finally, a case study is presented to compare three of the preferred modern fire suppression methods for fitment to a minor warship concept.

2 Fire initiation and propagation

The ignition of a fire requires three elements known as the 'fire triangle' (Figure 1); a fuel (combustible material), sufficient oxygen and an ignition source. Traditional fire suppressant techniques, such as CO_2 and water, achieve their function by removing one or more of these factors to suppress the fire. While traditional firefighting systems may perform their primary function effectively they can also present inherent drawbacks with regards to through-life cost, safety and reliability.

Conversely, condensed aerosol fire suppressant systems take advantage of the 'fire tetrahedron' principal. This considers the fourth element of the fire – the sustaining exothermic chain reaction produced once the fire is started. Condensed aerosols are designed to react with the 'fire propagation' free radicals (OH, H and O), interfering with the chemical reaction of the fire and extinguishing it. Certain aerosol systems have been proven to successfully extinguish all types of machinery space fire and therefore provide a 'one system fits all' solution. Furthermore, they overcome many of the inherent drawbacks of traditional firefighting methods mentioned previously.

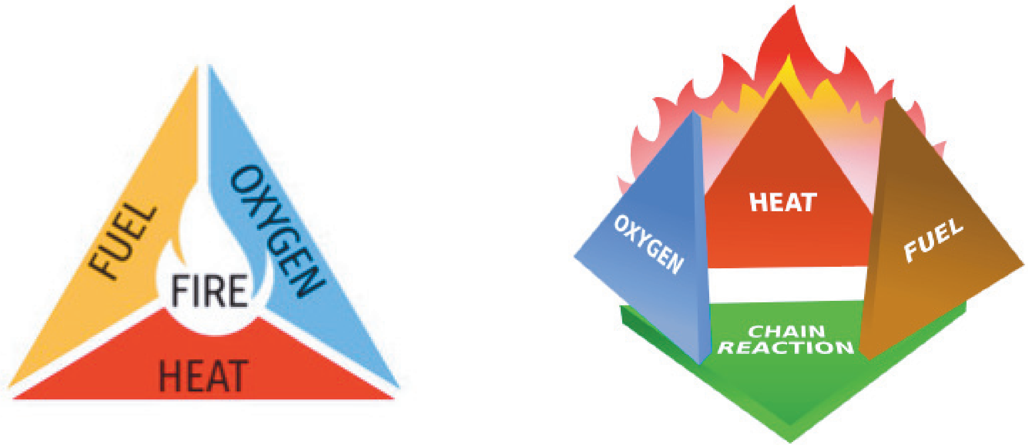

Figure 1 – Fire Triangle and Fire Tetrahedron

3 Regulatory landscape

Chapter II-2 of SOLAS, categorizing the majority of seagoing vessels, details the provisions for fire protection, detection and extinction requiring that fixed firefighting systems conform to the International Code of Fire Safety Systems (FSS Code) IMO Resolution MSC.98(73) (IMO 2000). The FSS Code includes standards and performance criteria for fixed fire-extinguishing systems for machinery spaces. This includes the capability to extinguish a variety of fires that can occur in machinery spaces – typically Class A and Class B fires in accordance with ISO 3941 (2007):

- Class A: fires involving solid, combustible material such as wood, cloth, paper, rubber and many plastics;
- Class B: fires involving liquids or liquefiable solids.

Fixed fire suppression systems are required to extinguish fires and prevent re-ignition of the fire for a given time after extinguishment. This time period is to allow hot surfaces to cool down and for the ship's crew to manage any persistent ignition sources. Class A fires can be the most difficult to extinguish using a gaseous extinguisher as they can smoulder and re-ignite when the compartment is subsequently reopened. Therefore, the

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quantity of fire suppressant required to extinguish a Class A fire is in excess of that required to extinguish a Class B fire.

4 Review of naval fire suppressants

A review of fire suppressant systems was undertaken to understand which would be most suitable for installing on the Royal Navy landing craft. This chapter is a brief overview of the available fire suppressant systems for marine-based machinery space application.

4.1 Carbon Dioxide (CO_2)

Carbon dioxide is widely used for fixed fire extinguishing systems in ship machinery spaces. CO_2 displaces the oxygen in the compartment, thereby suffocating the fire. It is particularly effective on electrical fires where water-based systems cannot be used. CO_2 is an effective fire extinguishing agent that allows for a single central system of bottles serving multiple compartments (Figure 2).

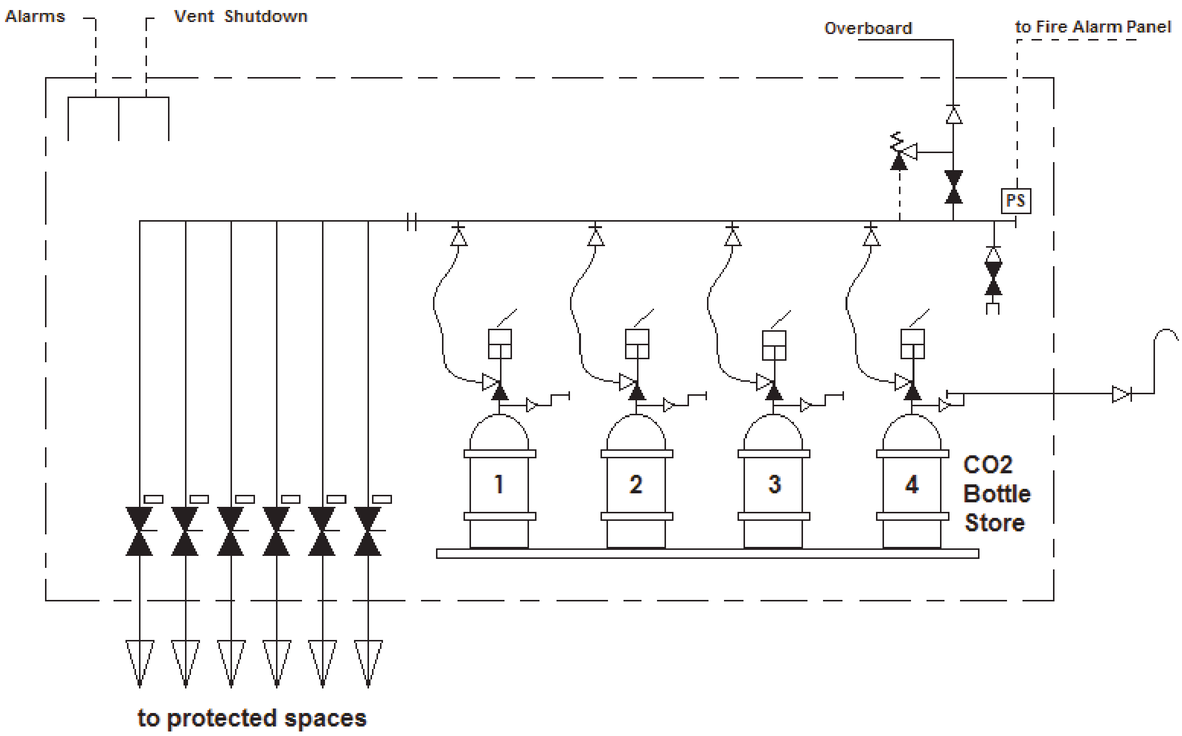

Figure 2 – Example CO_2 fire suppressant system

The concentrations for fire extinguishment are typically in the region of 40%. It is commonly thought that the primary threat to life is caused by the CO_2 displacing oxygen; however, to reduce the oxygen concentration to a level that poses immediate threat to life the CO_2 levels would have to be in the order of 50% by volume. A study by the HSE (Harper, 2011) suggests that the toxicological impact of CO_2 on the body occurs at much lower levels and that inhaling CO_2 at concentrations as low as 15% can cause death within 60 seconds. Furthermore, adverse effects in humans, such as headaches and dizziness can occur at concentrations as low as 3%. Therefore, if a fire is detected the compartment must be evacuated before activation of the CO_2 system. Prior to re-entry the compartment needs to be thoroughly vented and the air composition tested for safety.

A further drawback of CO_2 is the potential for an undetected leak in the system, which could prove fatal.

4.2 Water mist

High pressure water mist fire suppression systems are increasing in popularity with the decline of systems such as CO_2. They are being integrated into parts of the Type 26 design. Pumps or accumulators deliver fresh water, or water and compressed gas, at high pressure to a network of sprinklers which produce ultrafine droplets of water to both cool the fire and displace the oxygen. The ultrafine particles provide a high surface area for optimum cooling. The key benefits to a water mist system are that the agent is harmless to life and provides a significant cooling capability, thereby allowing rapid re-entry.

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The drawbacks of a water mist system include high maintenance due to pressurised cylinders and a reduced effectiveness outside of the direct spray pattern and slower response time on small fires (Figure 3). In these locations water mist systems rely on assistance from the oxygen depletion from the fire and partial vaporization of water by the fire to cause extinguishment. Furthermore, they have the potential to damage electrical equipment. The systems use fresh water, which may need to be conserved in an emergency situation.

Low pressure water mist systems are available but offer reduced efficacy due to the larger droplets providing lower surface area for effective cooling.

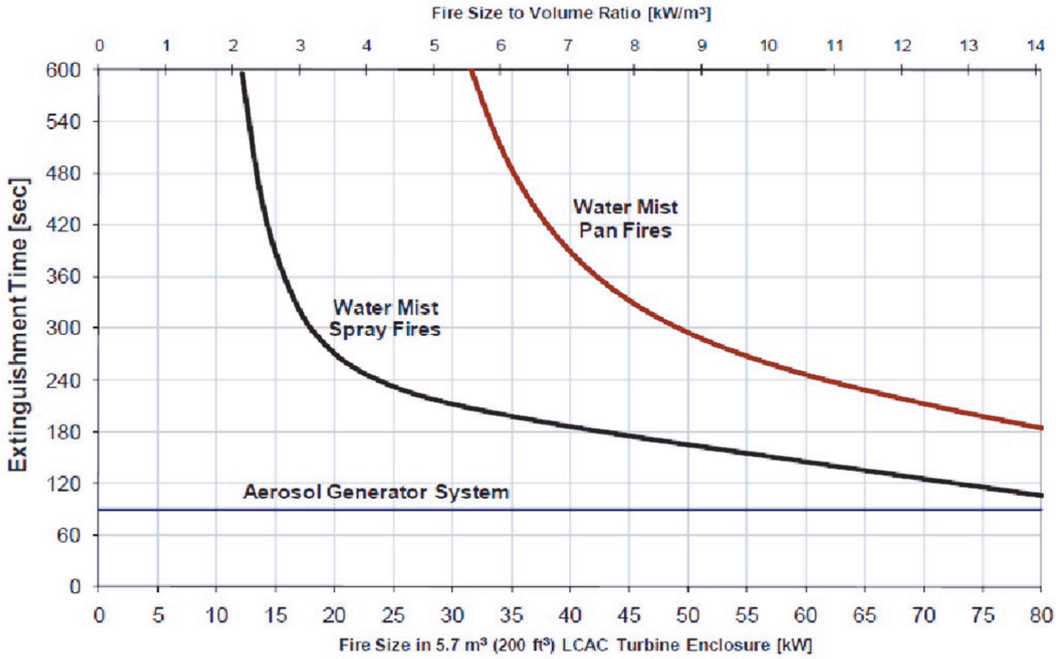

Figure 3 – U.S. Navy extinguishing time requirements of water mist vs. aerosol systems as a function of fire size (provided by Fireaway Inc.)

4.3 FM-200

FM-200 (1,1,1,2,3,3,3-heptafluoropropane) is a compound of carbon, fluorine and hydrogen. It has been widely used for both marine and shore-based applications following a ban on Halon. It suppresses the fire through chemical and physical mechanisms without affecting the available oxygen. The concentrations required to extinguish fires are between 6.25% and 9%; the No Observable Adverse Effect Level (NOAEL) being 9% and the Lowest Observable Adverse Effects Level (LOAEL) 10.5% - United States Environmental Protection Agency (EPA) (NFPA 2001, 2018). Consequently, an FM200 system must be carefully tailored to ensure that the right quantity is delivered to each protected space.

In the high temperatures of a fire, FM-200 decomposes to produce hydrogen fluoride. When it comes into contact with water, including skin tissue, hydrogen fluoride forms hydrofluoric acid which is highly corrosive and toxic. As a result, the compartment needs to be thoroughly vented prior to re-entry and air composition tested for safety.

4.4 Novec 1230

Novec 1230 is a fluorinated ketone (FK-5-1-12 Dodecafluoro-2-methylpentan-3-one) compound of carbon, fluorine and oxygen ($CF_3Cf_2C(O)CF(CF_3)_2$). It has been widely used for both marine and shore-based applications and is appropriate for use on Class A, B & C fires. It suppresses the fire primarily through physical mechanisms, cooling the fire, with minimal effect on the available oxygen. Personnel are still able to see and breathe, permitting them to leave the affected compartment safely. Novec 1230 is considered non-toxic to humans in the concentrations required to effectively to suppress Class A fires (minimum 4.2% by volume in air). Novec 1230 is non-ozone depleting and leaves no residue in the affected space to which it is applied.

At high temperatures, such as those exhibited in a fire, Novec 1230 decomposes to produce Hydrogen Fluoride with the same effects as those described for FM-200.

Novec 1230 is stored in steel containers pressurised with nitrogen to 50 bar aiding discharge of the agent. When the liquid is discharged to atmosphere it evaporates resulting in localised very low temperatures – hence nozzles must be located to avoid direct impingement with personnel.

4.5 Inergen

INERGEN® is a mixture of 52% Nitrogen, 40% Argon and 8% CO_2. Effective fire suppression requires introducing a volumetric concentration of 37.9%. When discharged in the designated concentration, Inergen mixes with the air resulting in a mixture of 67.3% Nitrogen, 12.5% Oxygen, 17% Argon and 3.2% CO_2. The fire is extinguished via oxygen depletion while also providing an atmosphere that is safe to breathe provided the designated volume concentration is applied.

Inergen is non-ozone depleting and leaves no residue in the affected space to which it is applied. Such systems are becoming increasingly more popular in commercial and naval marine applications and have been integrated into the QEC platform design.

The main drawback of Inergen is that it requires steel cylinders pressurised at 300 bar and must therefore be shatterproof in the event of being hit by a projectile. Inergen is delivered to the affected compartment at 20-40bar.

4.6 Argonite

Argonite is a mixture of 50% Argon and 50% Nitrogen. It extinguishes the fire through oxygen depletion, while providing an atmosphere that is safe to breathe, provided the designated volumetric concentration is applied. A concentration of 37.9% Argonite is required to effectively suppress a fire. Argonite is non-ozone depleting and leaves no residue in the effected compartment. Argonite is stored in steel cylinders pressurised at 300 bar and delivered to the affected compartment at 20-40bar.

4.7 Aerosols - Generic

Aerosol fire suppression systems first became available in the 1990's. They required high application densities and the discharge of some was considered to be violent. There are two principal categories for delivering aerosol suppressants to a protected space:

- Condensed aerosols; employ pyrotechnical generators to create a combustion sequence involving the agent charge.
- Dispersed aerosols; stored with an energised carrier agent such as an inert gas or halocarbon and typically released into the space via pipes and nozzles.

Both categories of aerosol are designed to interfere with the chemical reaction of the fire to cause extinguishment. Unlike the other suppressant systems reviewed, no two manufacturers of aerosol use the same design or suppression agent. As a result there are many different systems available providing very similar benefits. Modern 'second generation' systems tend to be of the condensed aerosol variety and much more effective than earlier types.

A review of the available aerosol systems was undertaken, which included: Option 1- the FirePro® FP-range; Option 2 - GreenSol aerosol systems by GreenEx; and Option 3 - Stat-X® fixed aerosol systems by Fireaway Inc. All the aforementioned products provide effective suppression mechanisms, have no ozone depleting potential (ODP) and have no global warming potential (GWP). Furthermore, they do not exhibit the same drawbacks as traditional fixed firefighting systems, such as oxygen depletion, potential for over-pressurisation of the compartment, and do not require fitting of pipework, valves and nozzles, as per the alternatives previously discussed.

While the reviewed aerosols exhibit some similar performance characteristics, Option 3 was chosen as the preferred option for this study for the following reasons:

1. The system is the only condensed aerosol deemed safe for occupied spaces by the US EPA. Other condensed aerosols present a toxicity risk.
2. Competitor products have internal actuation temperatures of close to 2000°C, the preferred system being 1200°C; this has a direct effect on discharge temperature - UL testing placing the largest unit as safe for a proximity to other equipment of 25mm.
3. Smaller particulate size and reduced hygroscopy lead to minimal residue deposit, therefore less clean-up. The smaller particles have the benefit of improving buoyancy within the compartment. Furthermore, the system has been proven to be compatible for use with water mist systems such that the water doesn't 'scrub-out' the aerosol.
4. The system is the only one of its kind with a hermetically sealed body, preventing moisture ingress which can have a detrimental effect on agent efficiency.
5. The system has successfully completed IMO-1270 testing and Marine Equipment Directive (MED) approval is pending;
6. The Royal Navy landing craft are currently undergoing replacement of their CO_2 fire suppression systems with this system.

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4.8 Aerosols – Preferred System

Testing of the preferred aerosol fire suppression system has proven it to be one of the most effective fire suppression systems available. The manufacturer claim the system is five times more effective than Halon on Class B fires and more than ten times as effective as hydrofluorocarbons such as FM-200.

The system uses chemical and physical mechanisms to interfere with the free radicals which are essential elements of fire sustainment and propagation. The extinguishing agent consists of potassium salts with secondary inert gases (primarily nitrogen, CO_2 and water vapour). The system is non-toxic and leaves almost no residue after application to the affected space, enabling re-entry (provided that the space has been ventilated to remove the products of combustion).

Acceptable performance is based on applying the correct design density, typically 58g/m^3 for Class B fires and 72g/m^3 for Class A fires (Stat-X 2017). However, the system is much less sensitive to leakage rates than gaseous systems.

The preferred aerosol system employs 'generators' mounted inside the protected compartment (Figure 4, Figure 5 and Figure 6). A small electrical signal begins a controlled burn that produces an ultra-fine aerosol which passes through an oxidation element, converting carbon monoxide to CO_2, followed by a cooling element to rapidly reduce aerosol temperature before it is ejected at low pressure.

The Maritime Coastguard Agency (MCA) (amongst other organisations and classification societies internationally) has approved the preferred aerosol fire suppression system for small craft in spaces up to 64m^2 floor area and 4m in height. The system has been installed on US Landing Craft Utility (LCU) to replace Halon; the US LPD flammable stores; ACTUV (the US autonomous sub-hunter); and is undergoing installation on UK landing craft; Archer Class and QEC crew transfer vessels.

Figure 4 – Preferred condensed aerosol generator

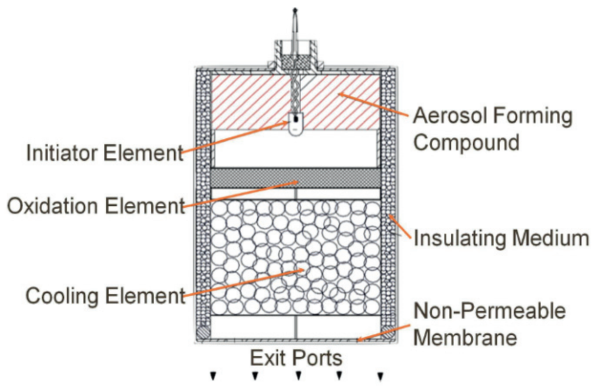

Figure 5 - Cross-section through the generator

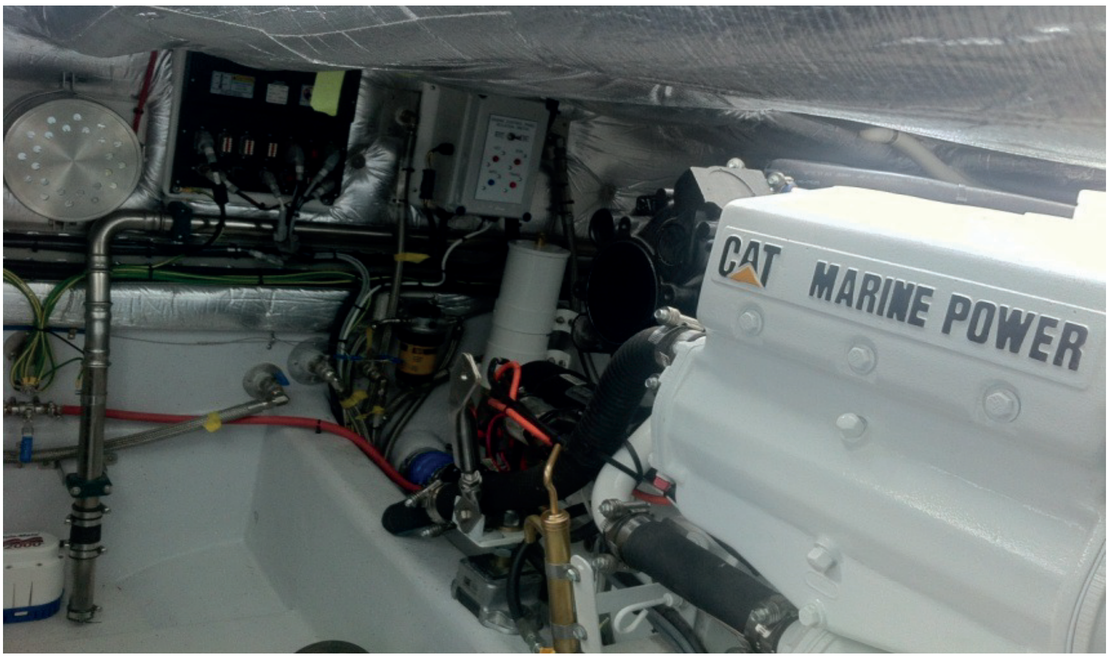

Figure 6 – Aerosol generator fitted in a small craft machinery space (top left of photograph)

Aerosol fire suppression systems are currently limited to small craft. For SOLAS ships, aerosol systems must meet the requirements of the Marine Safety Committee (MSC) publication IMO MSC.1/Circ.1270 (IMO 2008), underwritten by the IMO. At the time of writing, the manufacturer of the preferred aerosol system had successfully completed IMO testing, witnessed by UL. The US Coastguard is reviewing the results and may consider using the system without restriction on compartment size. The results of these tests have been submitted to the relevant organisations and classification societies including Lloyds and DNV GL. IMO approval would provide a strong case for subsequent endorsement by classification societies such as Lloyds Register in due course.

4.9 Summary of fire suppression systems

All of the systems discussed above may have been considered for the Royal Navy landing craft. However, FM-200 and Novec 1230 both have the problem of producing toxic hydrogen fluoride gas and hydrofluoric acid in the heat of a fire. These can be lethal and cause serious corrosion issues, therefore would not be a preferred solution unless it can be guaranteed that they are deployed before a fire gets hot enough for heat decomposition to occur. There has been a reduction in the use of both systems in the UK due to fluorinated gas regulation 517-2014 and therefore such systems are considered undesirable.

Inergen and Argonite are safe to breathe when delivered in the correct concentration and do not decompose to form harmful products. However, the canisters take up 30% more volume than an equivalent CO_2 system and present a weight increase of more than 100%. They are therefore better suited to larger craft. Pressurised systems such as these exhibit significant costs associated with installation and periodic maintenance checks to ensure components are all in a safe, serviceable condition. Furthermore, there is a requirement for specific pressure relief measures to avoid over-pressurisation of the compartment that could lead to structural failure.

Water mist systems are safe to breathe, produce no harmful by-products in a fire scenario and have no global warming or ozone depleting potential. Their size makes them unsuitable for small craft and they may not be rapid or effective on small fires.

Inergen and water mist systems are generally seen as the way forward for mid to large new UK naval marine craft and have been integrated into Type 26 frigate and QEC respectively.

The preferred aerosol system is approved for occupied spaces (limited human exposure), does not decompose to form harmful materials, has a very low space and weight requirement, is non-ozone depleting, leaves almost no residue, and is non-pressurised - therefore does not require compartment overpressure protection. Furthermore, there are no pipe runs and seals to maintain in a vibration/ mechanical shock scenario, a significant benefit in military craft and it does not occupy deck space.

It should be noted that exposure to any agent should be avoided where possible. Most agents, including water mist can obscure vison and therefore evacuation of the affected compartment is always a requirement.

5 Amphibious landing craft installation solution

The CO_2 fire suppression systems on the Royal Navy Landing Craft, Vehicle, Personnel (LCVP) and LCUs were found to have the following shortcomings:

- Expensive maintenance through life;
- CO_2 is toxic to humans at concentrations required for fire extinguishment;
- Potentially difficult to maintain outside of UK;
- Not possible to recover compartment without returning to mothership or base support.

Babcock undertook a design study to determine the most suitable replacement to the CO_2 system, addressing the above shortcomings. The preferred aerosol system was recommended based on the following key benefits over the CO_2 system and other alternatives:

- Similar or better fire extinguishing capabilities;
- Approved for limited human exposure up to 102 g/m^3 (with normal designs being 72g/m^3 or less);
- Does not decompose to produce harmful by-products;
- Non-ozone depleting with no GWP;
- Low-cost, relatively simple integration;
- Compact;
- Weight saving.

The LCVP meets the requirements of MCA approval certification for the preferred aerosol system; specifically, less that 24m load line length and no protected space larger than 64m^2 and 4m in height. The LCU measures larger than the MCA requirement and is therefore non-compliant with MCA requirements.

Despite the preferred aerosol system being approved for use on the US LCU, a similar size vessel, and the Royal Navy LCU qualifying as a non-SOLAS vessel (less than 500 GT), Lloyd's Register of Shipping (LRS) have

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advised that it would have to pass IMO fire tests as defined in MSC.1/Circ.1270. The results of the tests are expected this year. At the time of writing one Royal Navy LCVP has undergone a full aerosol system installation and two LCUs are being prepared for outfitting in anticipation of approval being granted.

An example electrically actuated condensed aerosol fire suppression system schematic for protecting a landing craft compartment is provided in Figure 7.

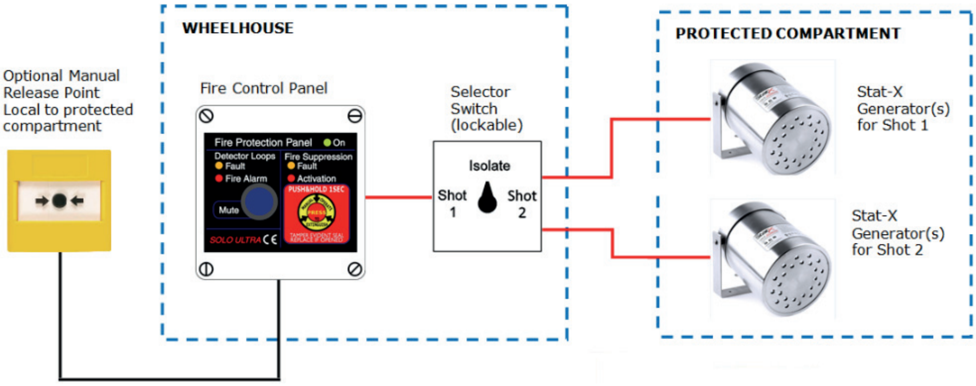

Figure 7 – Example - landing craft aerosol fire suppression system schematic (Hinge, 2014)

6 Case study

Fixed aerosol fire extinguishing systems are currently approved for small craft only. This case study has been undertaken to understand the potential benefits of installing an aerosol-based extinguishing system on larger naval vessels compared to the currently favoured alternatives (namely Inergen and water mist). The subject of the study is a Babcock 70 metre Defender concept for an offshore patrol vessel; details of the protected machinery spaces are provided in

Table 1.

Table 1 – Case study vessel, compartment sizes

Protected Compartment	Volume
Forward Engine Room	561 m^3
Aft Engine Room	525 m^3
AVCAT Space	21 m^3

The benefits of Water Mist, Inergen and aerosols as fire suppressant systems have been discussed previously. It is assumed that all three types of suppression are suitable for the proposed application. This study therefore compares the systems from a cost and integration perspective.

The water mist system is a Marioff HiFog® system dimensioned for the largest (561 m^3) compartment. The system comprises:

- A pump unit comprising five 27kW electric motors (four plus one backup);
- Eight water cylinders;
- 110 sprinkler heads;
- Eight nitrogen cylinders (providing system pressure in case of a complete power outage).

The system is positioned in a central location to serve the protected spaces and capable of delivering up to 576 litres per minute.

The Inergen fire protection system comprises a main and reserve ‘total flooding’ system to achieve an extinguishing concentration of gas within the space. The system comprises:

- 26 Inergen canisters pressurised to 300 bar (13 for main system, 13 for reserve);
- A reducing unit to reduce the pressure to 50-60 bar;
- A matrix of nozzles.

The preferred aerosol system can be provided as a single or two-shot system. It is sized to provide an application density derived from the quantity required for suppression of a Class A fire. The ‘single shot’ system consists of 33 canisters positioned around the space to provide optimum distribution of the extinguishing agent as follows:

- 17 canisters in the FER;
- 16 canisters in the AER;
- 1 canister in the AVCAT space.

All three systems include the associated control panels as recommended by the manufacturer and designed to meet the relevant SOLAS Chapter 2-II classification requirements, noting that the preferred aerosol system does not currently have IMO accreditation. Table 2 provides a direct comparison of the three systems.

Table 2 – Fire Suppression System Comparison

	Water Mist	**Inergen**	**Preferred Aerosol**
Electrical Power Requirement	108 kW (4 x 27kW motors)	None (pneumatic / manual release)	1 Amp (initiation current)
Equipment Total Space Required (Excl. / Incl. Service Space)	8.3 m^3 / 28.3 m^3 (Excludes tanks)	4.1 m^3	0.34 m^3 / 5.3 m^3 (single shot*) 0.68 m^3 / 10.6 m^3 (two shot*)
Equipment Total Weight	7,500 kg (dry system)	4,800 kg	480kg (single shot*) 900kg (two shot*)
Estimated Cost	£220k	£120k	£65k (single shot*) £128k (two shot*)

*A two shot system may be preferred in case of re-ignition.

The benefits of the preferred aerosol system are evident in all categories, being significantly lower weight, requiring less space, lower cost than water mist and comparable to Inergen, and having minimal power requirements.

Initial discussion with the suppliers also suggests that the upkeep costs of the aerosol system would be significantly less than the alternatives systems. This is predominantly due to there being no pressurised components that require frequent test and inspection.

7 Conclusions and further research

In conclusion, this paper has reviewed the available fire suppressant systems for use in marine naval applications, in particular machinery spaces. Improved health, safety and environmental regulations have led to the development of a variety of effective firefighting systems that are not harmful to humans or the environment.

Two firefighting agents, Inergen and water mist, appear to be the preferred technologies in the way forward for medium and larger naval craft (greater than 24m in length). However, the Stat-X fire suppression system has been demonstrated to be effective in small compartments and more recently tests have shown it to be effective in compartments in excess of 500m^3. As a result, it is recommended that condensed aerosols are given consideration as a suitable fire suppression technique on all new naval vessels, should the relevant certification be achieved. Where full compartment protection is not possible using an aerosol technique, it may be practicable to employ them within enclosed cabinets as a primary measure for equipment such as generators and turbines, therefore preventing unnecessary isolation of the whole compartment. The preferred aerosol system may also be employed alongside a water mist system for increased capability or redundancy.

While this paper considers the initial outlay costs for three different fire suppressant systems, further investigation should be undertaken to understand the through life costs for a more informed comparison.

Furthermore, due to the volumetric and weight benefits afforded by condensed aerosol fire suppression, investigation into the potential for its use on submarines should also be considered.

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References

Harper P., 2011. Health and Safety Executive (HSE) Advisers: Wilday J., Bilio M., HSE Document : Assessment of the major hazard potential of carbon dioxide, June 2011.

IMO, 2000. Adoption of the International Code for Fire Safety Systems (FSS Code) IMO Resolution MSC.98(73).

IMO 2008. MSC.1/Circ.1270/Corr.1, Revised guidelines for the approval of fixed aerosol fire-extinguishing systems equivalent to fixed gas fire-extinguishing systems, as referred to in SOLAS 74, for machinery spaces, 29 August 2008.

ISO 3941, 2007. Classification of Fires. September 2007.

NFPA 2001, 2018. Standard on Clean Agent Fire Extinguishing Systems.

R Hinge, 2014. Landing craft fire suppressant gas replacement study and cost benefit analysis, prepared by Design management Services on behalf of DES Ships. Issue 01, October 2014.

Stat-X, 2017. First Responder Part No. 19052 05/17 datasheet. Accessed May 2017.

UL 2018. Underwriters Laboratories Reference: 20180301-E495772 for Class I, Division 2: UL Online Certifications Directory, accessed May 2018.

Nomenclature

GT	Gross Tonne
kg	kilogram
m	metre

Glossary of Terms

AFFF	Aqueous Film Forming Foam
AVCAT	Aviation Fuel
CO_2	Carbon Dioxide
DNV GL	Det Norske Veritas and Germanischer Lloyd (Classification Society)
FK	Fluorinated Ketone
GWP	Global Warming Potential
HSE	Health and Safety Executive
IMO	International Maritime Organisation
IP	Ingress Protection
LCU	Landing Craft Utility
LCVP	Landing Craft, Vehicle & Personnel
LOAEL	Lowest Observable Adverse Effects Level
LRS	Lloyds Register of Shipping (Classification Society)
MCA	Maritime Coastguard Agency
MED	Marine Equipment Directive
MoD	Ministry of Defence (UK)
NOAEL	No Observable Adverse Effects Level
ODP	Ozone Depleting Potential
QEC	Queen Elizabeth Class Aircraft Carrier
RN	Royal Navy
SOLAS	Safety of Life at Sea (International Maritime Treaty)
UK	United Kingdom
UL	Underwriters Laboratories
US	United States (of America)