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Damage Control Technology

A Literature Review

John A. Hiltz
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Defence R&D Canada – Atlantic

Technical Memorandum
DRDC Atlantic TM 2006-045
March 2006

Canada

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Abstract

The costs associated with personnel and maintenance account for approximately 70% of the total operating costs of a ship. Of these costs more than 50% are associated with personnel. As the Canadian Forces have made the reduction of the total operating costs of ships a priority, approaches to the reduction in crewing levels without jeopardizing operational capabilities and safety are being investigated. Of particular concern is how labour intensive tasks, such as damage and fire control, can be carried out on ships with reduced crewing levels.

To aid in addressing the challenges arising from attempts to reduce crewing levels and maintain or enhance damage control, DRDC Atlantic initiated a project entitled Damage Control and Crew Optimization. This project has several objectives including a state-of-the-art review of damage and fire control technologies, modeling and simulation of damage control activities and the evaluation of how automation will affect crewing levels required to maintain damage and fire control capabilities, identification of materials with enhanced damage and fire resistance, and the evaluation and demonstration of wireless condition monitoring systems.

In this memorandum the literature pertinent to developments in damage and fire control technologies that have the potential to allow reduced crewing while maintaining damage control capabilities are reviewed. The technologies include damage control systems, fire and damage sensors, fire suppression agents and techniques such as water mist, gaseous agents and aqueous fire fighting foams, smart valves, ventilation control and fire hardened materials. In addition, specifications for and manufacturers/vendors of fire and damage control systems and hardware are reviewed.

Résumé

Les frais touchant le personnel et l’entretien représentent environ 70 pourcent des coûts d’exploitation totaux d’un navire. Plus de 50 pourcent de ces frais sont associés au personnel. Étant donné que la réduction des coûts d’exploitation totaux des navires est devenue une priorité pour les Forces canadiennes, on est en train d’examiner des moyens de réduire les équipages sans compromettre les capacités opérationnelles et la sécurité. On est particulièrement préoccupé par la façon dont les tâches exigeantes en main-d’œuvre, notamment le contrôle des avaries et la lutte contre les incendies, peuvent être exécutées à bord des navires si les équipages sont réduits.

Pour aider à relever les défis qui découlent des tentatives visant à réduire les équipages et à maintenir ou à accroître le contrôle des avaries, RDDC Atlantique a lancé un projet baptisé Contrôle des avaries et optimisation des équipages. Ce projet comporte plusieurs objectifs, dont un examen des technologies de pointe en matière de contrôle des avaries et de lutte contre les incendies, la modélisation et la simulation des activités de contrôle des avaries, l’évaluation de l’incidence que l’automatisation aura sur les équipages requis pour maintenir

les capacités de contrôle des avaries et de lutte contre les incendies, la détermination des matériaux ayant une meilleure résistance aux avaries et au feu, ainsi que l’évaluation et la démonstration de systèmes de surveillance d’état sans fil.

Dans le présent document, il sera question de la littérature relative aux innovations dans le domaine des technologies de contrôle des avaries et de lutte contre les incendies qui peuvent permettre de réduire les équipages tout en assurant le maintien des capacités de contrôle des avaries. Ces technologies comprennent les systèmes de contrôle des avaries, les détecteurs d’incendies et d’avaries, les agents et les techniques d’extinction des incendies comme la brumisation, les agents chimiques gazeux et les mousses extinctrices à base d’eau, les clapets coupe-feu intelligents, le contrôle de la ventilation et les matériaux ignifugés. Il y est également question des spécifications et des fabricants/fournisseurs des systèmes et du matériel de lutte contre les incendies et de contrôle des avaries.

Executive summary

Introduction

To aid in addressing the challenges arising from attempts to reduce crewing levels and maintain or enhance damage control, DRDC Atlantic initiated a project entitled Damage Control and Crew Optimization. This project has several objectives including a state-of-the-art review of damage and fire control technologies, modeling and simulation of damage control activities and the evaluation of how automation will affect crewing levels required to maintain damage and fire control capabilities, identification of materials with enhanced damage and fire resistance, and the evaluation and demonstration of wireless condition monitoring systems.

Results

The literature pertaining to developments of damage and fire control technologies and systems that enhance or have the potential to enhance damage control capabilities in a reduced crewing environment have been reviewed. The technologies include damage control systems, fire and damage sensors, fire suppression agents and techniques such as water mist and gaseous agents that will replace Halon and aqueous fire fighting foams, smart valves, ventilation control and fire hardened materials. In addition, specifications for and manufacturers/vendors of fire and damage control systems and hardware have been reviewed.

Significance

This review is a starting point to a more critical review of damage and fire control technologies whose goal is to identify research and development opportunities in the area of damage control and crew optimization. The review also supports modeling and simulation work in the Damage Control and Crew Optimization project directed at determining how damage/fire control technologies will impact crewing levels required for damage control onboard new build CF ships. Although the output of the Damage Control and Crew Optimization project is directed at the single class surface combatant (SCSC), the review should also be of interest to personnel responsible for damage control systems and technologies on the Joint Support Ship (JSS).

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Sommaire

Introduction

Pour aider à relever les défis qui découlent des tentatives visant à réduire les équipages et à maintenir ou à accroître le contrôle des avaries, RDDC Atlantique a lancé un projet baptisé Contrôle des avaries et optimisation des équipages. Ce projet comporte plusieurs objectifs, dont un examen des technologies de pointe en matière de contrôle des avaries et de lutte contre les incendies, la modélisation et la simulation des activités de contrôle des avaries, l’évaluation de l’incidence que l’automatisation aura sur les équipages requis pour maintenir les capacités de contrôle des avaries et de lutte contre les incendies, la détermination des matériaux ayant une meilleure résistance aux avaries et au feu, ainsi que l’évaluation et la démonstration de systèmes de surveillance d’état sans fil.

Résultats

Nous avons étudié la littérature relative aux innovations dans le domaine des technologies de contrôle des avaries et de lutte contre les incendies qui améliorent ou peuvent améliorer les capacités de contrôle des avaries dans un environnement où les équipages sont réduits. Ces technologies comprennent les systèmes de contrôle des avaries, les détecteurs d’incendies et d’avaries, les agents et les techniques d’extinction des incendies comme la brumisation et les agents chimiques gazeux qui remplaceront le halon, et les mousses extinctrices à base d’eau, les clapets coupe-feu intelligents, le contrôle de la ventilation et les matériaux ignifugés. Nous avons également examiné les spécifications et les fabricants/fournisseurs des systèmes et du matériel de lutte contre les incendies et de contrôle des avaries.

Importance

Cet examen constitue un point de départ en vue d’un examen plus critique des technologies de contrôle des avaries et de lutte contre les incendies dont le but consiste à cerner les possibilités de recherche et de développement en matière de contrôle des avaries et d’optimisation des équipages. L’examen appuie également les travaux de modélisation et de simulation effectués dans le cadre du projet de contrôle des avaries et d’optimisation des équipages, qui vise à déterminer l’incidence que les technologies de contrôle des avaries et de lutte contre les incendies auront sur les équipages requis pour assurer le contrôle des avaries à bord des nouveaux navires des FC. Bien que le projet de contrôle des avaries et d’optimisation des équipages s’adresse au navire de combat de nouvelle génération (NCNG), l’examen devrait aussi intéresser le personnel responsable des systèmes et des technologies de contrôle des avaries à bord du navire de soutien interarmées (NSI).

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1. Introduction

The Canadian Navy has identified the reduction of the total operating cost (TOC) of new ships as a priority. The major contributors to the TOC of a naval ship are those associated with crewing and maintenance. Of these costs, approximately 35% have been estimated to be due to crewing levels. This has led to an increased interest in how crewing levels can be reduced without jeopardizing the ship's ability to complete its mission. Labour intensive operations, such as fire and damage control, become a major concern when ships are being designed to operate with reduced crewing levels[1].

To aid in addressing the challenges arising from attempts to reduce crewing levels and maintain or enhance fire and damage control, DRDC Atlantic initiated a project entitled Damage Control and Crew Optimization in April 2005. There are several elements of this project. Modeling and simulation in conjunction with functional analysis will be used to study how automation (improved technology) will affect crew requirements for damage control. An assessment of battle damage and fire control systems and sensors and related research and development will be completed. In addition, human factors and human factors research related to the new technologies will be considered. The aim of this is to ensure that new technologies and resulting automation are designed to maximize performance of damage control personnel.

This memorandum reports the results of a literature survey of damage control systems, damage and fire sensors, and fire suppression systems and technologies as they relate to damage/fire control technologies for naval ships.

2. Results

There are a number of technologies applicable to maintaining or enhancing fire and damage control on Naval vessels with reduced crewing levels. These include:

1. Battle Damage (including fire) Control Systems
2. Sensors (Fire and Damage)
3. Fire Suppression Techniques
4. Other Technologies

In this section research and development in the area of these technologies are reviewed

2.1 Battle Damage Control Systems

2.1.1 Commercial systems

In this memorandum a control system is defined as a device or set of devices that manage the operation of other devices. A remote operator uses the control system to gather situational information and take corrective action when necessary. There are a number of suppliers of integrated platform management systems, of which a damage control system is an integral component. These include L3 Communications MAPPS (St. Laurent, Quebec)[2], Siemens AG (Hamburg, Germany)[3], ABB Process Solutions and Systems (Genova, Italy)[4], and Lyngso Marine AS (Hersholm, Denmark)[5]. Rolls-Royce Marine AS (Longva, Norway)[6] and Rockwell Automation[7] are also involved the in the supply of control and automated system components and software.

Practical capabilities of damage control systems include monitoring ship spaces for fire, structural damage, or flood, and taking or recommending corrective actions. These actions may include activating fire suppression systems, modifying fire main and hydronic water piping systems, modifying ventilation systems and opening or closing hatches to control smoke spread and to assist with smoke dispersal. Other capabilities include incident management and plotting, two-dimensional and isometric representation of the ship, closed circuit television and automated kill-cards, ship stability calculations, and management of resources. Damage control systems can automatically log damage control events.

A detailed study of each manufacturer’s control system has not been undertaken in this report.

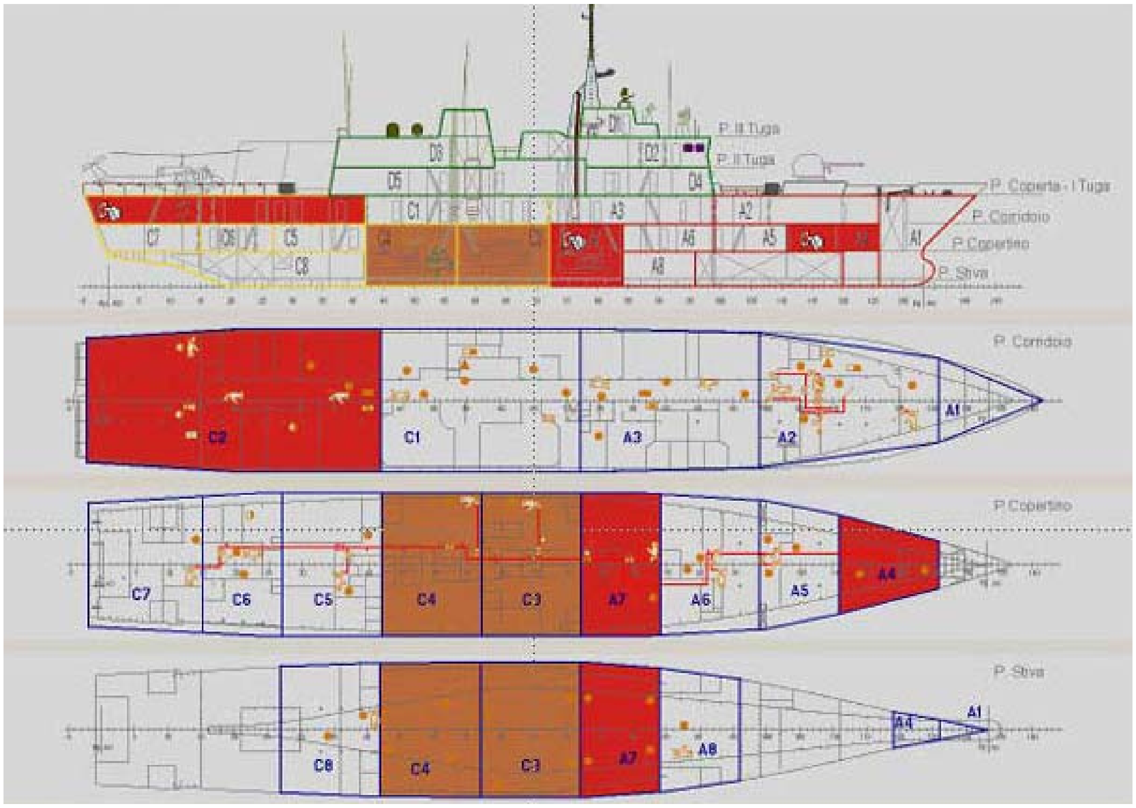

Figure 1. Screen Shot of ABB Damage Control System.

2.1.2 Research and Development

A significant amount of work on the development of a supervisory damage control system has been carried out in the United States under the auspices of the Naval Research Laboratory, Washington, DC as part of the damage control automation for reduced manning (DC-ARM) program. The ex USS Shadwell[8] was used as a test platform for the development of the supervisory control system. The development of this system is described in a series of reports[9-19] that deal with design, scenario development, physical ship simulation of fire, smoke, flooding and rupture, human computer interface, intelligent reasoning, knowledge, experimental measurement, and software architecture. A software user's manual and summary were also produced. The system and the results of a full scale test[20,21] on ex USS Shadwell in 2001 have been described. For the damage scenario used in the test, the firemain was restored in 92% less time, the damaged area was identified in 99% less time and the fire boundaries were set in 98% less time when using the supervisory control system. An instruction manual for the system has recently been published[22].

An advanced damage control automated information system has been described[23]. This system was designed to incorporate desirable features of a large number of automated information systems into a single system and is termed the enhanced damage control action management system (eDCAMS). The systems passed factory acceptance testing in June 2005 and will be installed on LPD 17 USS San Antonio. The developers of this system suggest that it might evolve into an US Navy fleet wide advanced damage control system (ADCS). Developments of subcomponents of this system, such as a casualty power reconfiguration assistant (CPRA)[24], continue.

2.2 Sensors

2.2.1 Fire sensors

Fire sensors can be described as either point or volume sensors. Point sensors monitor parameters such as temperature and rate of temperature change, concentrations of combustion gases such as carbon dioxide or monoxide, and other combustion products such as smoke at one point in a space. The weakness of these sensors is that the parameter they measure may not be representative of the rest of the space and from a fire detection perspective may not represent the worst case existing in that space. Therefore, if these sensors are not in the vicinity of the fire then it can take some time before an alarm is activated. In contrast to point sensors, volume sensors monitor a space using video (closed circuit television (CCTV)) and image analysis technology. Light or smoke released from a burning material allows detection of a fire from a location remote from the fire. Volume sensors promise to decrease the time between the start of a fire and its detection.

2.2.1.1 Point sensors

Thermocouples, carbon monoxide and carbon dioxide monitors, and photoelectric and ionization sensors are the most common point fire sensors. A partial list of manufacturers and performance codes for these sensors are given in Tables 1 and 2. Fibre optic sensors have been evaluated for use as temperature sensors[25] and as part of the DC-ARM program[26].

A significant effort has been made to develop multi-criteria fire detection systems using input from a number of sensors[27-32]. A series of three tests investigated the ability of different point sensors to correctly identify fires and differentiate them from nuisance sources with the goal of improving detection sensitivity, lowering detection times, and reducing the number of false alarms by the system. The final test was carried out using four point sensors; an ionization, a photoelectron, a carbon monoxide and a carbon dioxide sensor.

The results of the three series of tests were used as a training set for the development a probabilistic neural network (PNN)[33-38] as part of an early warning fire detection (EWFD) system. The results of the tests[39,40] indicated that prototype EWFD systems using multi-sensors and a PNN classifier performed better than commercial sensors by reducing nuisance alarms and response times.

Testing of multicriteria fire detectors by the Naval Research Laboratory has continued[41-43]. The program has involved tests in the laboratory and on ex-USS Shadwell.

Table 1. A partial listing of suppliers of point fire sensors.

SENSOR TYPE	MANUFACTURERS
Photoelectric	Yuan Hsun Electric Co., Ltd., Taiwan, ROC Julon Co., Ltd., Taiwan, ROC Hochiki America Corporation, California, USA Telco Sensors Inc., North Carolina, USA Acculex, a Division of HR Technologies, New Hampshire, USA Apprise Technologies Inc., Minnesota, USA
Ionization	Baseline-MOCON corporation, Colorado, USA Hochiki America Corporation, California, USA AC-CAS Group Co. Ltd., Bangkok, Thailand Apollo Fire Detectors, Hempshire, England, UK Compania Panamena de Sistemas, Panama, Panama
Carbon Monoxide	Angeleye Corporation, Richmond Hill, Canada Argos Technology, Paris, France BW Technologies Ltd., Calgary, Canada Rosslare Enterprises Ltd., Kowloon, Hong Kong Kidde Safety, Illinois, USA
Carbon Dioxide	Industrial Scientific Corporation, Pennsylvania, USA ABB Instrumentation, Connecticut, USA BW Technologies Ltd., Alberta, Canada Delta-F Corporation, Massachusetts, USA OI Analytical Instruments, Texas, USA TSI Incorporated, Minnesota, USA
Temperature	Nutech Engineers, Kandivli West, Mumbai, India AJ Thermosensors Ltd., West Sussex, UK AccuTru International, Texas, USA Alloy Engineering, Connecticut, USA ARi Industries, Illinois, USA

Table 2. Performance codes for fire sensors.

SENSOR TYPE	PERFORMANCE CODE
Photoelectric	Underwriter's Laboratory code UL 268
Ionization	Underwriter's Laboratory code UL 268
Carbon Monoxide	ANSI / NFPA 72, National Fire Alarm Code
Carbon Dioxide	Underwriter's Laboratory code UL 913, Class 1, Group C
Temperature	ANSI / NFPA 70, National Fire Alarm Code

2.2.1.2 Volume (video - based) Sensors

The ideal sensor would provide an operator in a position remote from the space with information similar to that which a person in the space would provide based on their sensatory inputs (sight, sound, and smell). The goal of volume sensor research and development is to achieve this.

The technology related to volume sensors is far less mature than for point fire sensors. An initial evaluation of video-based fire detection technologies has been completed[44], and factors such as lighting, camera setting, spectral and acoustic signatures on the effectiveness of volume based sensors have been considered[45]. There has also been some effort in algorithm development for spectral based volume sensors[46] and multi-component prototype evaluation work is planned[47]. At present from a fire detection perspective, smoke detection algorithms are the most mature and video based detection is most effective in large open (uncluttered) spaces. It is expected that this technology will develop to the point where it is effective in smaller and/or cluttered spaces found on ships. In addition, video based sensing has potential for shipboard functions other than fire detection. These include tracking of personnel, damage detection and assessment, and flood detection[44].

Dr. Fred Williams of the Naval Research Laboratory in Washington, DC, feels that the development of volume sensors will be crucial to maintaining or enhancing damage control on ships with reduced manning levels[48].

2.3 Fire Suppression Techniques

Fire suppression agents and systems have been extensively investigated over the past 15 years. There are a number of reasons for this. The most important has been the ban in production of Halon - based fire suppression agents. Halons are volatile halocarbons that cause depletion of stratospheric ozone. As a result of this, they were identified with a number of other halocarbons as chemicals whose production and use should be banned or restricted in an attempt to slow ozone depletion. International regulations, most notably, the Montreal Protocol on Substances that Deplete the Ozone Layer, were developed to formalize the reduction and/or banning of the production and use of these chemicals. The agreement was revised twice (London 1990; Copenhagen 1992) in response to worsening reports of stratospheric ozone depletion and led to the total phase out of the production of Halons (bromofluoro- and bromochlorofluoro-carbons; CF_3Br (Halon 1301), CF_2Cl Br (Halon 1211), and CF_2BrCF_2Br (Halon 2402)) at the end of 1994.

Halon 1301 has been used extensively as a total flooding agent in shipboard spaces where flammable spray and liquid fires were most likely to occur, such as engine rooms and machinery spaces. Halon-based fire extinguishing systems will not be used on new build Canadian Navy ships. This has led to a continuing effort to find effective, environmentally friendly and safe alternatives to Halon total flooding systems.

There has also been concern over the continued production of aqueous film-forming-foam (AFFF) agents. In 2000, 3M voluntarily ceased production of its AFFF product, Light Water™, because of the concern about one of the chemicals, perfluorooctanesulfonyl fluoride, resulting from the process used to produce the fluorosurfactants in Light Water™. The chemical and its derived products are biologically degraded to perfluorooctane sulfonate. Perfluorooctane sulfonate is believed to a persistent, bioaccumulative, and toxic chemical.

A large body of research directed at improved fire suppression techniques has been completed. One of the major goals of this research has been the elucidation of Halon alternatives. In this section fire suppression technologies and developments are reviewed.

2.3.1 Water Mist (Fog)

Water mist (fog) is regarded as an effective fire suppression agent, extinguishing fires by fuel surface cooling, flame cooling, and oxygen depletion and displacement[49]. Water mist was first suggested as a fire extinguishing agent for naval applications in the late 1970s[50,51]. Small scale testing showed the efficacy of water mist as a fire extinguishing agent[52]. Water mists systems were largely forgotten for the next 10 years. In the 1990s, concern about the ozone depleting potential of the Halon fire extinguishing agents led to a ban in their production in 1994. The search for a ‘safe’ alternative to the Halons led to a renewed interest in water mist (fog) systems.

A large volume of literature on the testing of water mist systems exists. The National Research Council of Canada (NRC)[53-70], the Naval Research Laboratory, Washington, DC[71-79], and others[80-81] have been actively involved in research and testing of water mist systems. Early research on water mist systems was directed at finding a non ozone depleting and non toxic replacement for Halon 1301 for total flooding applications.

Liu and Kim[67] prepared an excellent overview of water mist and water mist fire suppression studies. Extinguishing mechanisms including cooling, oxygen displacement, radiant heat attenuation, and the kinetic effect of water mist on flames, water mist characteristics including droplet size distribution, mist flux density, and spray momentum, enclosure effects, dynamic mixing, and the effect of additives on water mist performance are discussed. Water mist refers to fine water sprays in which 99% of the droplets are less than 1000 microns in diameter[82]. The water mist droplet size distributions are defined in the National Fire Protection Association (NFPA) Standard 750 as Class1 (90% of the volume of spray with diameters of 200 microns or less), Class 2 (90% of the volume of spray with diameters of 400 microns or less), and Class 3 (90% of the volume of spray with diameters greater than 400 microns).

For Naval applications enclosure effects are extremely important. In confined spaces with poor ventilation a water mist system can be effective for obstructed fires. However, as the level of ventilation increases or the fire size with respect to the size of the space decreases then the system becomes less effective. Fire size, large or small, is defined in terms of how the fire effects the temperature and oxygen concentration in the space. In a large fire the temperature of the space increases and the oxygen concentration decreases. Both increase the effectiveness of water mist and therefore decrease extinguishment times relative to small fires. The mode of extinguishment for water mist is different for large and small scale fires. In a large fire the primary mechanism is oxygen depletion while for a small fire the primary mechanism is cooling.

Nozzle types for water mist generation have also been reviewed[67]. Impingement nozzles work with a single fluid and consist of a large diameter orifice and a deflector at low (12.0 bar or less) and intermediate (12.0 to 43.0 bar) pressures. Pressure jet nozzles also work with a single fluid and consist of small diameter orifices (0.2mm to 0.3mm) or swirl chambers. Operating pressures can range between low (5.1 bar) and high (272 bar) pressure. Twin fluid nozzles operate with a compressed gas (usually air) and water and consist of a water inlet, a compressed gas inlet and an internal mixing chamber. The pressures of the gas and water inlets are controlled separately and are in the low pressure region (between 3 bar and 12 bar).

Applications of water mist fire suppression systems have also been reviewed[68]. These include the protection of machinery spaces, turbine enclosures, and other spaces where there are flammable liquid hazards. Water mist fire suppression systems have been shown effective in extinguishing a number of exposed and shielded hydrocarbon pool, spray and cascading fires. They have also been shown to be effective for combined Class A (ordinary combustible materials including wood, paper, cloth, rubber and many plastics) and Class B (flammable or combustible liquids and gases, greases and similar materials) fires. The time to extinguishment of fires with water mist systems is longer than that for gaseous agents but cools the space and controls levels of carbon dioxide and carbon monoxide.

Testing of water mist systems indicates that the effectiveness of these systems is very dependent on fire size, degree of obstruction of the fire, ventilation, and compartment geometry. Larger fires were extinguished more rapidly than small fires, fires under obstructions were very difficult to put out[80-81], and fires in large spaces and/or with high ceilings were very difficult to extinguish[83]. This was attributed to the inability of the system to deliver sufficient water mist to the fire location. The systems were also affected by openings in the test space although an increase in the number of doorway nozzles (from 2 to 4) was found to mitigate the effect of the opening. US Navy full scale testing[75] indicated that the effect of openings on performance of water mist systems is dependent on the size of the fire. For small fires, openings increased extinguishment times while for larger fires there was no effect on extinguishment times.

The placement and number of water mist nozzles in a compartment has been investigated[72,73]. The full scale testing indicated that the ability of the system to extinguish fires was enhanced by placing nozzles at two heights in the compartment. High pressure single fluid nozzles have been found to perform better than low pressure single fluid and twin fluid systems[73,79]. This is attributed to the characteristics of the water droplets, specifically their small size and high momentum, produced by the high pressure nozzle. Low pressure nozzles used at higher flow rates and that produced larger droplet sizes were found to be effective against large pool fires and unshielded class A fires. The US Navy has identified a modified high pressure nozzle (70 bar) as the most effective for water mist systems while the Royal Navy has focused testing on low pressure nozzles (up to 7 bar)[84] with and without 1% AFFF. The results of the tests indicated that fine water mist produced with low pressure nozzles extinguished large obstructed spray and pool fires by oxygen depletion and extinguished some unobstructed spray fires at high oxygen content by cooling. The low pressure nozzles using 1% AFFF extinguished unobstructed pool fires at high oxygen content, inerted fuel in bilges and contained small obstructed pool and spray fires. The low pressure water mist system was found to improve the maintainability and survivability of the space whether or not the fire was extinguished and also provided boundary cooling.

Water mist systems have been investigated as replacements for Halon 1301 or carbon dioxide systems in spaces with electrical equipment such as electrical switchgear cabinets, computer rooms, electric motors, controllers, and switchboards[77,85]. The results of testing indicated that salt free potable water had low conductivity and shock hazards only existed after the mist had been applied for a long enough time for water to ‘plate-out’ or pool on the equipment surface. No current leakage from the 3-phase 450Volt AC motors or motor controllers used in the testing was observed. It should be noted that water mist has a number of advantages over gaseous agents for suppressing electrical fires. Water mist is more effective in extinguishing hot cable fires because of its ability to cool; additionally the compartment often does not have to be evacuated, and equipment can be operated while the system is discharging (especially if the system is zoned). In contrast to halocarbon gaseous agents, water mist does not produce corrosive gases and there is no concern about the effect of the gases in areas remote from the fire.

The use of water mist to suppress flashover and provide boundary cooling[86-87], to lessen the effects of a weapon hit in the primary damage area[88-92] and to mitigate blast effects has been studied[93,94].

Back et al.[95] reviewed the capabilities and limitations of total flooding water mist systems. The authors note that water mist systems extinguish fires in minutes as opposed to seconds for gaseous Halon replacements. Extinguishment times were reduced (optimized) in some instances by designing the system for the space to be protected and by reducing ventilation to the space prior to activation of the system. An important advantage of water mist systems is their ability to reduce temperatures in a space. This is important for fire fighters who have to enter the space, minimizes thermal damage in the space and prevents fire spread to adjacent compartments. Water mist is more effective against larger fires than smaller fires as a result of oxygen depletion in the space, steam generation and the turbulence created by the fire.

Low flash point fuel fires were harder to extinguish than high flash point fuel fires using water mist systems. Obstructed fires were more difficult to extinguish than unobstructed fires. This was attributed to the obstruction reducing the amount of water mist actually reaching the fire. Water mist systems could not extinguish small obstructed fires in many instances. Systems that produce small drops with high momentum, generally single fluid high pressure systems, were more effective against obstructed and unobstructed Class B fires. Large vent openings drastically reduced the effectiveness of water mist systems. This was due to the escape of mist and steam from the space and a lack of oxygen depletion. An increase in the rate of discharge of some water mist systems was found to increase extinguishment capabilities, that is, reduce extinguishment times, but primarily for unobstructed fires. Placement of mist nozzles and the resulting improved mist dispersion in a space was found to be more important than rate of discharge when extinguishing obstructed fires. For obstructed fires, there appeared to be a relationship between the size of the fire and extinguishment times. This was attributed to the time required for the oxygen concentration in the space to drop below that required to support combustion.

Some suppliers of water suppression systems, pumps, nozzles and electrical signalling systems are listed in Table 3 and applicable NFPA, UL, International Maritime Organization (IMO), International convention for Safety of Life at Sea (SOLAS), ANSI and European Norm (EN)performance codes for the systems and components are listed in Table 4.

Table 3. Some manufacturers of water mist systems and components.

TECHNOLOGY	MANUFACTURERS
Water Mist Suppression Systems	Chemetron Fire Systems, Matteson, Illinois, USA Tyco Fire and Security, Pennsylvania, USA Securiplex LLC, Mobile Bay, Alabama, USA CAFS Unit Inc., Colorado, USA Nanomist Systems, Georgia, USA Marioff Corporation OY, Finland Fike, Blue Springs, Missouri, USA Unifog, Phoenix, Arizona, USA Fogtec, Brandschutz GmbH, Germany
Water Mist Pumps	Edwards, Pentair Pump Group, Illinois, USA
Water Mist Nozzles	Chemetron Fire Systems, Matteson, Illinois, USA Grinnell Corporation, Cranston, Rhode Island, USA Tyco Engineered Products and Services, USA Spraying Systems Co., Illinois, USA BETE Fog Nozzle, Greenfield, Massachusetts, USA Lechler Nozzles North America, St. Charles, Illinois, USA Hago Manufacturing Co., Mountainside, New Jersey, USA

Table 4. Performance codes for water mist systems and components

TECHNOLOGY	PERFORMANCE CODE
Water Mist Suppression Systems	NFPA 750
Water Mist Pumps	NFPA 750 NFPA 20 UL 448
Water Mist Nozzles	IMO Assembly Resolution A 800 (19) SOLAS Regulation II-2 / 12
Electrical Signaling	ANSI / NFPA 12 / 12A ANSI / NFPA 13 ANSI / NFPA 15 ANSI / NFPA 16 ANSI / NFPA 17 / 17A ANSI / NFPA 72 ANSI / NFPA 92A / 92B European Norm EN 54

2.3.2 Gaseous agents

When the production of Halon-based gaseous fire suppression agents (Halon 1301 (bromotrifluoromethane)and Halon 1211 (Bromochlorodifluoromethane)) was banned, there was considerable effort to find suitable replacements or alternatives. The development and testing of water mist fire suppression systems was a significant part of this effort. In addition, gaseous agents with reduced or zero ozone depletion potential (ODP) have also been evaluated for fire suppression systems. It should be noted that to date no gaseous fire suppression agent has been developed that has all the positive attributes of the Halon-based agents. These attributes include suppression effectiveness, storage stability, effective delivery after discharge, low toxicity, low toxicity of its degradation products, no residue after discharge, low corrosiveness towards metals, and low electrical conductivity. Any gaseous replacement should also have short atmospheric life, zero ODP, and low global warming potential (GWP).

The NRCC reviewed Halon alternatives in 1995[96] as part of the Halon Alternatives Performance Evaluation (HAPE) project for the DND. It discussed work that had been done up to that point in time with respect to finding a replacement/alternative for Halon-based fire suppressants. The environmental impact, including ODP and GWP, of gaseous agents, evaluation of agents, toxicity of the agents and their decomposition products, and US Environmental Protection Agency (EPA) approved total flooding agents and their limitations were reviewed. The results of intermediate and full scale testing of replacement agents were also discussed and recommendations for further testing made. This led to a series of tests by the NRCC[97-100] to assess potential Halon 1301 drop-in total flooding replacements. Full scale testing of HCFC Blend A (a mixture of HCFC 22 (chlorodifluoromethane), HCFC 123 (dichlorotrifluoroethane), and HCFC 124 (2-chloro-1,1,1,2-tetrafluoroethane)) as a drop-in replacement for Halon 1301 indicated that it was not effective at the manufacturer's recommended design concentration (8.6%). It should be noted that the system used in the testing was designed for Halon 1301 and not optimized for use with HCFC Blend A. Using the same system, HCFC Blend A was found to be effective at 12% but produced very high levels of toxic degradation products. HFC-227ea (heptafluoropropane) was effective at its design concentration (7.6%) but produced high levels of acid gas (hydrogen fluoride) and carbon monoxide and dioxide. The levels of these gases produced was found to depend on a number of factors including the agent concentration, fire size and type, agent discharge time and the piping system.

A number of Halon replacement gaseous agents were also tested in the US in both intermediate (56m^3 compartment) and real scale tests (ex-USS Shadwell)[101]. The agents tested included HFC 23 (trifluoromethane), HFC-125 (pentafluoroethane), HFC-227ea, and CEA410 (decafluorobutane). The results of the real scale tests indicated that faster agent discharge times resulted in shorter extinguishment times, a more uniform agent concentration and lower acid and gas (hydrogen fluoride) concentrations. Larger fires were extinguished in shorter times but produced more hydrogen fluoride while more hydrogen fluoride was produced with decreasing agent design agent concentration.

The US Navy Technology Center for Safety and Survivability investigated the optimum fire suppression hold time prior to venting of a compartment and the effectiveness of a water spray cooling system in reducing compartment temperature and concentration of acid decomposition products in real scale tests of gaseous agents[102]. A low pressure water spray cooling system was found to be very effective in reducing compartment temperature. Heptafluoropropane was tested in a real scale test and the results compared to data for Halon 1301[103]. A number of parameters, including fire extinguishment times, oxygen depletion, and hydrogen fluoride production, were monitored. Compartment reentry following the fire was noted as the most critical and potentially the most dangerous part of a fire fighting event when gaseous agents are used.

The IMO's Gaseous Agent Test Protocol[104] has been evaluated[105]. The test protocol includes two types of fires, the first consisting of small heptane fires located in all corners of the space (500m^3 and dimensions10m x 10m x 5m). The second test involved larger pan and spray fires, fueled by diesel and n-heptane, and a wood crib fire. Extinguishing agents tested included heptafluoropropane (FM-200), perfluoropropane (CEA-308), CEA-410, HCFC Blend A, Envirogel (mixtures of ammonium polyphosphate and either pentafluoroethane or tetrafluoroethane), and Inergen (a blend of nitrogen, argon, and carbon dioxide). Delivery systems from commercial suppliers (Ansul (Inergen), Kidde-Fenwal, Metalcraft Sea-Fire, and Chementron) were also involved in the testing.

The extinguishment of the small heptane fires was found to be indicative of effective distribution of the agent in the test space and a useful tool in evaluating the effect parameters such a nozzle design, spacing, height, and pressure on distribution of the gaseous agent in the space. Some variation in extinguishment times were observed for an agent (FM-200) delivered by three commercial systems but all three systems met the IMO requirements.

Storage of agents at lower temperatures was found to have a detrimental effect on the performance of the agents in some cases. The authors indicated that more information on other factors, such as cylinder fill density, average nozzle pressure and discharge times resulting from lower agent temperature, needed to be studied. They also noted that the tests should be modified to ensure that variables other than uniform agent concentration, such as oxygen depletion, localized high agent concentrations and localized high flow velocities, do not impact extinguishment times. Ten recommendations to address these concerns were made.

The US EPA publishes lists of suitable alternatives to Halon 1301 for total flooding applications. This initiative is referred to as the Significant New Alternatives Program (SNAP). Alternatives are reviewed on the basis of ODP, GWP, toxicity, flammability and exposure potential.

Gaseous agents on the list[106] deemed feasible for use in normally occupied spaces include HFC-227ea (FM 200), HFC-227ea with 0.1% d-limonene (NAF S 227), HFC-23, and HCFC Blend A (NAF S-III), and 1,1,1,2,2,4,5,5,5-nonafluoro-4-(trifluoromethyl)- 3-pentanone (Novec 1230). One of these agents, HFC-23, has a GWP of 11,000 which is greater than the upper level of 3450 accepted by DND[107].

There a number of other EPA agents approved for use in normally unoccupied spaces. These include HCFC 22, HCFC 124, HFC 125, and HFC 134a. All have GWPs less than 3450 but the Lowest Observed Adverse Effect Level (LOAEL) is lower than the effective agent concentration. The LOAEL is defined as “the lowest tested dose of a substance that has been reported to cause harmful health effects”. This means that persons in the space when the agent is discharged may suffer adverse health effects. The EPA recommends that all these agents be used in accordance with the guidelines of the latest edition of NFPA 2001 – Standard for Clean Agent Fire Extinguishing Systems[108].

2.3.3 Relative Costs

Cost is a factor that must be considered along with safety and efficiency when selecting fire extinguishing agents. Wickham[109] prepared a cost comparison of water mist, carbon dioxide, FM-200, Inergen (IG-541) and Halon 1301 systems for shipboard machinery spaces in 2003. Halon 1301 was included to show the expense occurred to replace Halon 1301 systems. His results for spaces with volumes from 500 m^3 to 5000 m^3 are shown in Table 5. The cost of a total flooding FM-200 system is considerably less than a total flooding water mist system for a 500 m^3 space but the costs converge for a 5000 m^3 space. Carbon dioxide is less expensive than either FM-200 or water mist for spaces with volumes between 500 m^3 and 5000 m^3. The costs for a water mist system become more competitive with a carbon dioxide system if water mist is used for both total flooding and local application. The cost comparison is shown in Table 6. However, Wickham noted that it is still less expensive to use a carbon dioxide total flooding system with a water mist local application system.

Table 5. Cost comparison of full flooding systems for volumes from 500 m^3 to 5000 m^3. (from Reference 109)

AGENT	500 M^3	1000 M^3	3000 M^3	5000 M^3
	$	$	$	$
Halon 1301	5400	7900	19000	29400
Carbon Dioxide	11000	19000	52000	83000
FM-200	17000	31000	82000	130000
Inergen	20000	34000	95000	153000
Water Mist	60000	65000	100000	130000

Table 6. Cost comparison of full flooding and local application systems for volumes from 500 m^3 to 5000 m^3. (from Reference 109)

AGENT	500 M^3	1000 M^3	3000 M^3	5000 M^3
	$	$	$	$
Halon 1301	13400	37900	51000	61400
Carbon Dioxide	19000	49000	84000	115000
FM-200	25000	61000	114000	162000
Inergen	28000	64000	127000	185000
Water Mist	60000	75000	110000	140000

2.3.4 Water Mist or Gaseous Agents

Chen[110] has made a strong case for the use of high pressure water mist systems on naval ships. He notes that when fire breaks out in a machinery space on a naval vessels protected by a gaseous agent fire extinguishing system the sequence of actions required prior to discharging the agent take an appreciable length of time. Engines must be shut down, fans switched off, air dampers closed, fuel flow and electrical equipment shut down, and the space evacuated and sealed prior to activation of the system. The time required for these actions allows the fire to grow in size and potentially requires that fire crew be put at risk. A water mist system can be employed without taking most or all of these actions. Some questions and their answers concerning gaseous agent (FM-200, NAF S-III, and CO_2) and water mist fire suppression systems are shown in Table 7. These make a very strong case for the use of water mist systems on naval vessels even though the water mist system is more expensive.

Table 7. Comparison of water mist and gaseous agent fire suppression systems. (from Reference 110)

QUESTION	FM-200	NAF S-III	CO_2	MIST
Is the agent life threatening?	yes	yes	yes	no
Is it necessary to seal the protected space prior to discharge of the agent?	yes	yes	yes	no
Is it necessary to evacuate the space prior to discharge of the agent?	yes	yes	yes	no
Is it necessary to shut down machinery, turbo-chargers, fans, and flaps prior to discharge of the agent?	yes	yes	yes	no
Is ir permissible to enter the protected space during or immediately after discharge of the agent?	no	no	no	yes
Does the agent provide cooling of the space and the surrounding structure?	no	no	no	yes
Does the agent suppress smoke in the protected space?	no	no	no	yes
Is redundancy provided for the system?	yes	yes	yes	yes
Is the agent suitable for local protection of high risk items within a machinery space?	no	no	no	yes
Can the agent be safely employed in accommodation spaces?	no	no	no	yes
Is the agent always available for replacement at sea?	no	no	no	yes

A combination of water mist and Novec 1230 systems has also been proposed[111] to protect machinery spaces in commercial ships. The water mist system is used as a local application system, that is, a system that can be discharged without engine shut down or evacuation of a space, with sealing the space or shut down of forced ventilation, and has a twenty minute supply of water. This system controls temperature and fire growth and reduces levels of hydrofluoric acid produced when the Novec 1230 full flooding system is activated. The Novec 1230 can penetrate to areas where water mist cannot and complete extinguishment.

2.3.5 Foam Agents

Foam concentrate formulations are based on performance specifications and not on constituents. These include US Military Specification MIL Spec MIL-F-24385F[112] and

Underwriters Laboratory Inc. specification UL 162 (Foam Equipment and Foam Concentrates)[113].

It was noted in Section 2.3 that there is concern about the continued production of aqueous film forming foam products. The 3M Company has ceased production of its AFFF product, Light Water™, because of concern over a degradation product, perfluorooctane sulfonate, which is thought to be persistent, bioaccumulative and toxic. Scheffey[114] notes that other producers of foam concentrates do not use the same process to produce the fluorochemical surfactants and therefore the foams do not degrade to perfluorooctane sulfonate. However, the process they use involves perfluorohexyl iodide, which may degrade to perfluorohexanoic acid. This is a shorter chain homologue of perfluorooctanoic acid which has been found in some serum samples and therefore may bioaccumulate. As homologues have similar properties and if perfluorooctanoic acid is found to bioaccumulate, this may lead to regulation of the foams that involve perfluorohexyl iodide in their manufacture.

Sheinson et al.[115] have noted:
"The situation regarding AFFF resembles that of Halon 1301 in that, until environmental concerns were raised, little needed to be done to understand and improve its performance. Now, however, increasing United States and international environmental concerns regarding AFFF must be addressed as use restrictions can seriously impair operations."
They suggest that generating effective formulations that are 'more environmentally friendly' will depend on a better understanding of how AFFF works and may require that the Mil Spec may have to be reviewed to expand possibilities for foam formulations. Interestingly, the Australian Defence Forces have issued a new fire fighting foam specification Def(Aust)5706[116] that does not require fluorosurfactants in the formulation but does require a certain level of performance and that the foam formulations are compatible with seawater. The previous specification Def(Aust)5606D did require fluorosurfactants in the formulation. The performance of three fluorosurfactant free foams, RF6, Pyrocool FEF, and Micro Blaze Out, were compared to a fluorosurfactant containing foam formulation (FC-206CF)[117] using both fresh and synthetic seawater. The results of testing on a 0.28 m^2 pan fire indicated that the product containing the fluorosurfactant had better extinguishment times and burn back resistance than the formulations without fluorosurfactants. RF6 exhibited the best performance of the three fluorosurfactant free foams. Seawater had a negative effect on the performance of Micro Blaze Out.

The environmental impacts of firefighting foams have been have been reviewed[118]. Topics such as firefighting foams and systems, foam ingredients and properties, foam environmental properties, and US environmental laws are discussed.

2.4 Other Technologies

There are a number of other technologies that have direct application to damage and fire control on ships. These include smart valves, ventilation control systems, and damage and fire tolerant or resistant materials.

2.4.1 Smart Valves

As part of the DC-ARM Program, the US Navy developed a reflexive smart valve system[119-121]. This is an assembly of valve and control components for firemain, chilled water, and fuel systems. It was designed to reduce the time to detect and isolate ruptures and leaks thus reducing workload for ships crew. The concept smart valve was tested on ex-USS Shadwell and successfully isolated ruptures in between 15 and 90 seconds. The results of the testing indicated that the smart valve concept is applicable to a variety of valve designs. Differential pressure sensing was thought to be sufficiently accurate for both leak and rupture detection in valve designs with a reduced size seat. However, for valves with high flow coefficients (such as gate and full port ball valves) the range of flow detection may be limited. At the time of the publication of these reports valve hardware configurations, rupture logic, and leak detection methods were still under research and development.

The Royal Netherlands Navy has recently completed a project on Robust Automation[122-125]. The objective of this program was to improve the automation of ship's systems through the use of distributed intelligence. Distributed intelligence means that each computing node is attached to the components it monitors and controls as opposed to a single computing node monitoring and controlling all components. This results in reduced vulnerability of the automated system (control is decentralized to the component) and reduces the number of decisions that must be made by an operator as each node is programmed to make decisions on its own. Control commands that involve control actions require the involvement of several nodes.

Reference 125 describes a small scale demonstrator to prove the technical feasibility of robust automation. The demonstrator modeled a two zone chilled water system. Each computing node is placed as close as possible to the component in the system such as a pump or a valve that it controls. Therefore if the component is damaged the likelihood that the computing node is also damaged is high. Further research and development is planned to determine if the robust automation concept is scalable to larger systems composed of many components, to develop the small computing nodes so that they can be used on naval ships, and to build a full scale demonstrator.

2.4.2 Ventilation Control

Ventilation control in shipboard spaces is critical in minimizing smoke spread and managing heat in a fire situation. Zone pressurization and air flow are the parameters that allow this to be achieved. Options for smoke control on board ships have been reviewed[126]. Two series of tests[127-128] have been completed that address the incorporation of smoke ejection systems into advanced damage control systems. This would enable ventilation to be controlled from the damage control module.

2.4.3 Materials

Materials such as coatings, cable sheathing, polymeric insulation and composites will burn and contribute to the fire load on ships. There has been considerable effort to develop materials, inorganic and organic based, to replace, fire harden or protect vulnerable substrates.

DRDC Atlantic has been involved in the development of inorganic intumescent materials[129-137] for use as coatings or as additives to other polymers. Intumescent materials expand or swell when heated. This expansion results in an insulating layer that is considerably thicker than the coating was prior to heating and protects the substrate.

This resulted in the development of an intumescent filled latex bulkhead penetration sealant and intumescent filled thermoplastic polymer floor and bulkhead penetration seals. The intumescent materials were tested as coatings but problems with long term environmental stability (the intumescent materials were prone to the absorption of water and carbon dioxide and a loss in their ability to intumesce when heated) proved difficult to overcome.

The US has tested a number of commercial intumescent coatings that were proposed as substitutes for fire insulation on naval ships[138]. Small scale fire, adhesion, and impact tests, intermediate scale room corner fire tests, and full scale fire tests were used to evaluate the coatings. None met the minimum US Navy fire resistance criteria for passive fire coatings; 30 minute rating with backside average temperature less than 139^{o}C using the UL-1709 fire curve (post flashover fire). However, some of the coatings, when applied over substrates such as glass reinforced plastic reduced flame spread and smoke generation.

3. Conclusions

The developments in damage and fire control systems, sensors and related technologies have been shown to reduce the time between the initiation of an incident and its detection and reduce the time and crewing levels required to successfully deal with the incident. The decision on what technologies are incorporated into a new class of ships will depend on factors such the crewing level and cost. If a ship’s capabilities are to be maintained and there is a requirement for reduction in crew size then tasks that have been done by crew will have to be done through the use of technology. This is especially true for tasks, such as damage and fire control, where one might conclude that there is never enough crew.

There has been no effort to address human systems integration (HSI)/human computer interface (HCI) developments in this review. These will be of great importance if new technologies are introduced. Although a large number of sensors for fire, flooding, pipe rupture or leakage may appear to reduce the requirement for rounds and inspections of spaces, it is critical that the control systems be designed in such a way that the damage control operator is presented with useful situational information and not an overwhelming array of data that is difficult, if not impossible, to interpret and use in decision making.

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List of symbols/abbreviations/acronyms/initialisms

DND	**Department of National Defence**
DRDC	**Defence Research and Development Canada**
TOC	**Total Operating Cost**
BDCS	**Battle Damage Control System**
DC-ARM	**Damage Control – Automation for Reduced Manning**
eDCAMS	**enhanced Damage Control Action Management System**
ADCS	**Advanced Damage Control System**
CPRA	**Casualty Power Reconfiguration Assistant**
CCTV	**Closed Circuit Television**
EWFD	**Early Warning Fire Detection**
PNN	**Probabilistic Neural Network**
UL	**Underwriters Laboratory**
ANSI	**American National Standards Institute**
NFPA	**National Fire Protection Association**
AFFF	**Aqueous Film Forming Foam**
NRCC	**National Research Council of Canada**
AC	**Alternating Current**
IMO	**International Maritime Organization**
SOLAS	**Safety of Life at Sea**
EN	**European Norm**
Halon 1301	**Bromotrifluoromethane**

Halon 1211	**Bromochlorodifluoromethane**
ODP	**Ozone Depletion Potential**
GWP	**Global Warming Potential**
HAPE	**Halon Alternatives Performance Evaluation**
EPA	**Environmental Protection Agency**
HCFC Blend A	**A mixture of HCFC 22 (chlorodifluoromethane) and HCFC 123 (dichlorotrifluoroethane)**
HCFC 22	**Chlorodifluoromethane**
HCFC 123	**Dichlorotrifluoroethane**
HCFC 124	**2-chloro-1,1,1,2-tetrafluoroethane**
HFC-227ea	**Heptafluoropropane**
HFC 23	**Trifluoromethane**
HFC-125	**Pentafluoroethane**
CEA410	**Decafluorobutane**
FM-200	**Heptafluoropropane**
CEA-308	**Perfluoropropane**
SNAP	**Significant New Alternatives Program**
NAF S 227	**HFC-227ea with 0.1% d-limonene**
NAF S-III	**HCFC Blend A - mixture of HCFC 22 (chlorodifluoromethane) and HCFC 123 (dichlorotrifluoroethane)**
Novec 1230	**1,1,1,2,2,4,5,5,5-nonafluoro-4-(trifluoromethyl)- 3-pentanone**
HFC 134a	**1,1,1,2-tetrafluoroethane**
LOAEL	**Lowest Observed Adverse Effect Level**

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The costs associated with personnel and maintenance account for approximately 70% of the total operating costs of a ship. Of these costs more than 50% are associated with personnel. As the Canadian Forces have made the reduction of the total operating costs of ships a priority, approaches to the reduction in crewing levels without jeopardizing operational capabilities and safety are being investigated. Of particular concern is how labour intensive tasks, such as damage and fire control, can be carried out on ships with reduced crewing levels.

To aid in addressing the challenges arising from attempts to reduce crewing levels and maintain or enhance damage control, DRDC Atlantic initiated a project entitled Damage Control and Crew Optimization. This project has several objectives including a state-of-the-art review of damage and fire control technologies, modeling and simulation of damage control activities and the evaluation of how automation will affect crewing levels required to maintain damage and fire control capabilities, identification of materials with enhanced damage and fire resistance, and the evaluation and demonstration of wireless condition monitoring systems

In this memorandum the literature pertinent to developments in damage and fire control technologies that have the potential to allow reduced crewing while maintaining damage control capabilities has been reviewed. The technologies include damage control systems, fire and damage sensors, fire suppression agents and techniques such as water mist, gaseous agents and aqueous fire fighting foams, smart valves, ventilation control and fire hardened materials. In addition, specifications for and manufacturers/vendors of fire and damage control systems and hardware are reviewed.

14. KEYWORDS, DESCRIPTORS or IDENTIFIERS (technically meaningful terms or short phrases that characterize a document and could be helpful in cataloguing the document. They should be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location may also be included. If possible keywords should be selected from a published thesaurus. e.g. Thesaurus of Engineering and Scientific Terms (TEST) and that thesaurus-identified. If it not possible to select indexing terms which are Unclassified, the classification of each should be indicated as with the title).

Damage Control
Damage Control Systems
Fire sensors
Point sensors
Volume sensors
CCTV
Fire suppression
Halon replacements/alternatives
Water mist
Gaseous agents
Aqueous film forming foam
AFFF
Smart valves
Robust automation
Ventilation control
Intumescent materials

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