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Critical Assessment of Damage/Fire Control Systems and Technologies for Naval Vessels in Support of Damage Control and Crew Optimization: Risks and Opportunities

Phase IIa: Fire Suppression Systems and Components

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Contract Number: W7707-053149

Contract Scientific Authority: Dr. John Hiltz, 902-427-3425

Defence R&D Canada – Atlantic

Contract Report

DRDC Atlantic CR 2007-175

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Original signed by Dr. John A. Hiltz

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Abstract

The Canadian Navy is currently in the process of developing the requirements and contracting for delivery of new classes of ships. The Navy has identified the reduction of through-life costs of new ships as a priority. As crew size is a major contributor to through-life costs, ways of reducing crew number are being investigated. However, crewing levels can only be reduced if the ability of the ship to complete its mission is not jeopardized.

In Phase I of this project, a critical assessment of available technologies, both commercial and militarized, in Battle Damage Control Systems (BDCS) was conducted with the goal of providing insight on the future vision for Naval damage control as it relates to the goal of crew reduction/optimization.

In this Phase II report, a critical assessment of fire suppression systems and components was completed to rationalize which systems/capabilities are sufficiently mature to be considered for implementation on new and/or existing Canadian Naval platforms.

Résumé

La Marine canadienne travaille actuellement à définir les caractéristiques des nouvelles classes de navire et à passer un contrat de production correspondant. La Marine a établi que la réduction des coûts du cycle de vie de ces nouveaux navires était une priorité. Puisque la taille des équipages explique la majeure partie des coûts du cycle de vie, on étudie actuellement les moyens d’appliquer cette mesure, qui ne sera possible que si elle ne compromet pas la capacité des navires à remplir leur mission.

Au cours de la phase I de ce projet, une évaluation critique des technologies commerciales et militaires disponibles dans le domaine des systèmes de lutte contre les avaries de combat a été réalisée dans le but de fournir des renseignements sur la vision future de la lutte contre les avaries à bord des navires du point de vue de la réduction/l'optimisation des équipages.

Dans le cadre la phase II (objet du présent rapport), une évaluation critique des systèmes d'extinction d'incendie et de leurs composantes a été réalisée pour déterminer quels systèmes/capacités sont suffisamment évolués pour que l’on puisse envisager leur mise en œuvre sur les plates-formes navales canadiennes nouvelles et/ou existantes.

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Executive summary

Background

The Canadian Navy is currently in the process of developing the requirements and contracting for delivery of new classes of ships. The Navy has identified the reduction of through-life costs of new ships as a priority. As crew size is a major contributor to through-life costs, ways of reducing crew are being investigated. However, crewing levels can only be reduced if the ability to complete labour intensive tasks such as damage control is not jeopardized.

In Phase I of this project, a critical assessment of Damage Control Systems (DCS) was conducted with the goal of providing insight on the future vision for Naval damage control as it relates to the goal of crew reduction/optimization. In this Phase II report, a critical assessment of fire suppression systems and components was completed to determine which systems/capabilities are sufficiently mature to be considered for implementation on new and/or existing Canadian Naval platforms.

Results

A literature review of fire suppression systems and components was conducted and leading agencies in the US and UK Navies were contacted to determine the current "State of the Art" in systems and components. The fire suppression systems and technologies reviewed included the current state-of-the-art as well as systems and technologies in the research and development phase. The assessment indicated that a number of technologies had a great potential for implementation on Canadian Naval ships and might lead to significant reductions in crew required for damage control activities. These included early warning fire detection systems, volume sensors, shipboard Local Area Networks (LANs), wireless technology, supervisory control systems, fire and smoke simulators, water mist fire suppression systems, advances in Halon replacement fire suppression systems and agents, smart valves and ventilation and smoke control systems.

The introduction of advanced DC technology will have an associated requirement for maintenance. This may require that system/sensor maintenance is conducted alongside, that sufficient redundancy is built in to eliminate at-sea maintenance or that an automated calibration/maintenance process is developed. Additional research in this area is required.

It is recommended that the individual technologies identified in this study as ready for implementation be scrutinized as part of the development process of the DC system for the next class of Naval vessel as well as for retrofit in existing classes of ships where appropriate. In addition, consideration should be given to joint Research and Development projects to develop a Canadian model for damage control as well as update current Navy damage control doctrine and procedures.

Future Plans

The technologies identified in this report will be used in developing crew level/technology mixes for a modeling and simulation project. This project will assess the impact of new technologies on crew levels required for damage control on Naval vessels.

Ellaschuk B. and Lienert, B. 2007. Critical Assessment of Damage Control System Technologies for Naval Vessels in Support of Damage Control and Crew Optimization: Risks and Opportunities - *Phase IIa: Fire Suppression Systems and Components*. DRDC Atlantic CR 2007-175. Defence R&D Canada - Atlantic. June 2007.

Sommaire

Contexte

La Marine canadienne travaille actuellement à définir les caractéristiques des nouvelles classes de navire et à passer un contrat de production correspondant. La Marine a établi que la réduction des coûts du cycle de vie de ces nouveaux navires était une priorité. Puisque la taille des équipages explique la majeure partie des coûts du cycle de vie, on étudie actuellement les moyens d'appliquer cette mesure, qui ne sera possible que si elle ne compromet pas l'exécution de tâches exigeantes sur le plan de la main d'œuvre, notamment la lutte contre les avaries.

Au cours de la phase I de ce projet, une évaluation critique des technologies commerciales et militaires disponibles dans le domaine des systèmes de lutte contre les avaries de combat a été réalisée dans le but de fournir des renseignements sur la vision future de la lutte contre les avaries à bord des navires du point de vue de la réduction/l'optimisation des équipages. Dans le cadre de la phase II (objet du présent rapport), une évaluation critique des systèmes d'extinction d'incendie et de leurs composantes a été réalisée pour déterminer quels systèmes/capacités sont suffisamment évolués pour que l'on puisse envisager leur mise en œuvre sur les plates-formes navales canadiennes nouvelles et/ou existantes.

Résultats

Une analyse documentaire des systèmes d'extinction d'incendie et de leurs composantes a été réalisée et on a communiqué avec les organismes chefs de file des forces navales des États-Unis et du Royaume-Uni pour déterminer les systèmes et les composantes qui sont actuellement « à la fine pointe de la technologie ». Les systèmes et les technologies d'extinction d'incendie étudiés comptaient notamment les capacités à la fine pointe de la technologie et les capacités à l'étape de recherche et de développement. L'évaluation a indiqué qu'un certain nombre de technologies disposaient d'un grand potentiel de mise en œuvre sur les navires de la Marine canadienne et pourraient permettre de réduire considérablement la taille des équipages requis pour les activités de lutte contre les avaries. Celles-ci comprennent les systèmes de détection incendie à avertissement rapide, les capteurs de volume, les réseaux locaux (RL) embarqués, la technologie sans fil, les systèmes de contrôle de surveillance, les simulateurs de tir et de fumée, les systèmes d'extinction d'incendie à brouillard d'eau, les progrès relatifs aux systèmes et aux agents d'extinction d'incendie servant de remplacement au halon, les clapets coupe-feu intelligents et les systèmes de contrôle de la ventilation et des fumées.

La mise en place de technologies avancées de lutte contre les avaries entraînera des besoins d'entretien connexes. Cela pourra exiger l'entretien des systèmes/capteurs à quai, l'intégration d'une redondance suffisante permettant d'éliminer l'entretien en mer ou l'élaboration d'un processus automatisé de calibration/d'entretien. D'autres travaux de recherche dans ce domaine sont nécessaires.

Il est recommandé que chaque technologie désignée dans la présente étude comme prête à être mise en œuvre soit examinée en profondeur dans le cadre du processus d'élaboration du système de lutte contre les avaries de la prochaine classe de navires de la Marine ainsi que de la modernisation des classes de navires existantes selon les besoins. En outre, il faudrait examiner les projets conjoints de recherche et de développement visant l'élaboration d'un modèle de lutte contre les avaries et la mise à jour de la doctrine et des procédures actuelles en matière de lutte contre les avaries.

Projets futurs

Les technologies indiquées dans le présent rapport serviront à élaborer des agencements équipages-technologies aux fins d'un projet de modélisation et de simulation. Ce projet permettra d'évaluer l'incidence des nouvelles technologies sur la taille des équipages requis aux fins de lutte contre les avaries sur les navires de la Marine.

ELLASCHUK B. et B. LIENERT. *Critical Assessment of Damage Control System Technologies for Naval Vessels in Support of Damage Control and Crew Optimization: Risks and Opportunities - Phase IIa: Fire Suppression Systems and Components*, Rapport de contrat 2007-175 de RDDC Atlantique, RDDC Atlantique, juin 2007.

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1 Introduction

1.1 Background

The Canadian Navy is currently in the process of developing the requirements and contracting for delivery of new classes of ships. The Navy has identified the reduction of through-life costs of new ships as a priority. As crew size is a major contributor to through-life costs, ways of reducing crew number are being investigated. However, crewing levels can only be reduced if the ability of the ship to complete its mission is not jeopardized.

There has been a significant change in crewing requirements from the manpower intensive steam powered warships in the 60's, through the introduction of the Tribal Class Destroyers in the 70's, and finally through the introduction of the Canadian Patrol Frigates in the 90's. Introduction of a machinery control and automated command and control systems on the Tribal Class ships led to a crew size of 255 which was modestly larger than the crew on the steam ships (215). However, the Tribal Class ships have twice the displacement. The significant advancement in integrated machinery control and advanced communications, navigation, and command and control systems on the Canadian Patrol Frigates led to a reduction in crew from 255 on the Tribal Class ships to approximately 200 on a platform of similar size. Most of the reductions came from the Marine Engineering Department due to the significantly reduced watchkeeping requirements. Despite the introduction of these advanced systems, there was a limit to crew reduction due to the requirement for labour intensive operations in battle, primarily damage control and fire fighting.

Navies around the world are now turning to enhanced damage control and firefighting systems, through automation of many aspects of these activities, to achieve further reductions in crew sizes. To this end, Defence Research and Development Canada – Atlantic (DRDC Atlantic) has initiated a project called "Damage Control and Crew Optimization" to investigate if the goal of further crew reductions on the new classes of ships can be achieved while maintaining or enhancing damage control capabilities.

This report is part of Phase 2 of an evaluation of available Damage Control Systems (DCS) and Fire Suppression Technologies. Phase 1 included a critical assessment of available technologies, both commercial and militarized, in Battle Damage Control Systems (BDCS). Phase 2 includes a critical assessment of Human factors research and the development of smart systems and decision aids related to Damage Control (DC) Systems and a critical assessment of fire suppression systems and components.

1.2 Purpose of Report

The objective of this report is to complete a critical assessment of fire suppression systems and components, both commercial and militarized, for use in Battle Damage Control Systems. The report examines existing and new technologies and assesses which systems/capabilities are sufficiently mature to be considered for implementation on new and/or existing Canadian Naval platforms.

1.3 Scope

Modern technology has profoundly impacted shipboard damage control operations [1]. In the future, the capability of a ship to absorb damage and retain the ability to continue its mission hinges on the technology solutions that influence the ships survivability, which is defined by:

- Susceptibility, or the degree that the ship is open to attack (which could be due to battle, but also equipment failure, weather or even accidents);
- Vulnerability, which is the likelihood that the ship would be lost if the attack was successful and the ship was hit; and
- Recoverability, which is the ability of the ship and its crew to survive an attack and maintain/restore capabilities essential to the mission.

Recoverability is the primary focus of advanced Battle Damage Control Systems. Such systems must have the capability to detect and assess the extent of damage, mitigate the effects through containment (of smoke, fire, flood etc.) and ultimately extinguish fires, control flooding, remove smoke and restore mission capabilities (in accordance with mission priorities), all the while protecting the lives of the crew.

The US Navy has defined eight key areas that affect Damage Control.

- Identification and Assessment;
- Communication;
- Management;
- Action;
- Damage Control Personnel Training;
- Logistics;
- Maintenance (of DC equipment); and
- Development and Assessment of Next Generation DC Tactics/Equipment.

This report will review current and future fire suppression systems and components and discuss them with respect to these key areas.

1.4 Structure

It was determined in Phase I that militarized damage control systems have a much greater set of features and overall effectiveness than their commercial counterparts. Notwithstanding this, to ensure that all developments in the area of fire suppression systems were considered, both militarized and commercial technologies have been reviewed. Consequently, the focus of this report will be on research and development of advanced Naval Damage Control systems.

A great deal of research is currently being conducted by modern Navies related to various types of casualty events (fires, floods, etc.) with the primary areas of focus being early detection, event management and automated mitigation. A literature review of this work was conducted and leading agencies in the US and UK Navies were contacted to determine the current "State of the Art" in Battle Damage Control Systems. The response from the US

Navy, particularly the Naval Sea Systems Command (NAVSEA) and the Naval Research Laboratory (NRL) was excellent. Unfortunately, there was no response from the UK Navy. Nevertheless, commercial DC components from European suppliers that would be utilized by the UK Navy were considered in the Research and Development work being done by NRL.

This report is organized into sections, structured upon information provided by and experiments performed by the US Navy. This is primarily because they were the most forthcoming, but also (as was evident from comparison of ex-USS SHADWELL trials with literature reviews) because they appear to be furthest advanced in the terms of research. Section 2 deals with the current state of research and development. Section 3 identifies those areas where further research and development is necessary before the technology is ready for Naval shipboard application, and Section 4 summarizes the findings of this study.

2 Current Research and Development

Modern technology has had a profound impact on shipboard damage control operations and in the future the capability of a ship to absorb damage and continue its mission hinges on the technology solutions that influence the ships survivability. To this end, recoverability has become the primary focus of advanced Battle Damage Control Systems (BDCS). However, it must also be noted, that ships can sustain damage from other events that are not related to a battle situation. These include equipment failures, weather and accidents and all can lead to catastrophic results. During such events, the lives of the crew and the survival of the ship may well be at stake. The BDCS must have the capability to detect and assess the extent of such damage, mitigate the effects through containment (of smoke, fire, flood etc.) and ultimately extinguish fires, control flooding, remove smoke and restore mission capabilities (in accordance with mission priorities), all the while protecting the lives of the crew.

Damage control is a complex, interactive, labor intensive and time-sensitive activity. Rapid decisions must be made and a well-directed, effectively coordinated and properly prioritized response is critical to achieving a high Recoverability factor. The definition of the US Navy's eight key areas that affect Damage Control are as follows:

- **Identification and Assessment -** The ability to quickly identify and assess damage, either as a result of conflict or routine daily operations, is critical to the effectiveness of damage control systems. Shipboard personnel perform the functions of identification and assessment on existing Naval platforms (especially in battle situations). Smoke detectors and simple point-level flood detectors are in use on some vessels; however, these sensors provide very limited information to the Damage Control organization.
- **Communication -** The speed and accuracy of information exchange has a direct effect on the capability of the damage control organization to mitigate the casualty event. Communication between command and on-scene personnel is currently limited to internal phone systems; main broadcast system (providing ineffective one-way communication); and messengers (which are slow). The requirement for an integrated approach to communication, encompassing ease of use, comprehensive and logical display of information, redundancy, etc. were discussed at length in Phase I.
- **Management -** Casualty events are currently managed through automated, semi-automated and manual damage control systems. The goal of modern damage control system research is to optimize communications through a comprehensive electronic damage control system. Such a system would provide both command and on-scene personnel with identical information regarding the casualty event, and also allow the users to take actions based upon command priorities and system-generated advice. The ability of such a system to effectively manage DC situations is achieved through a well-planned and integrated Human-Machine Interface.
- **Action -** The ability to take action, be it automated, semi-automated or manual, based upon the information from sensors, is a focal point for current and future Battle Damage Control Systems. Current state-of-the-art fire suppression technologies, as

they relate to implementation on the next generation of Naval platforms, includes (but is not limited to):
  - Water Mist systems.
  - AFFF systems.
  - Gaseous Agents; and
  - Smart Valves (including inherent staged response capabilities).
- **Damage Control Personnel Training -** The ability to train personnel in the proper use of advanced damage control systems is essential to the ship's survival during casualty events. This includes both basic trade qualification training and on board simulation training which must be supported by fitted damage control systems. The users must both trust the system and be capable of using it in an effective and efficient manner to achieve increased platform survivability. Training of DC Personnel as it relates to changing technologies and systems integrations was discussed in Phase I.
- **Logistics -**Introduction of advanced DC systems, especially Water Mist technologies, may have a significant impact on the layout and design of new warships. Furthermore, design limitations on modern warships may concurrently impose hurdles to implementation of advanced damage control solutions. Researchers and designers must be cognizant of these limitations in order to achieve effective and practical damage control survivability solutions.
- **Maintenance (of DC equipment) -** The reliability of DC systems is crucial to ensuring proper operation of these systems in emergencies. This can only be achieved through labour intensive maintenance activities. Reduction of maintenance requirements through redundant capabilities, self-diagnosing/self-calibrating sensors and valves, and effective system design will have a direct impact on crew reductions. This was a key area of concern identified in Phase I, and has a significant impact on the achievable reduction in crew size that can be realized through DC technology introduction.
- **Development and Assessment of Next Generation DC Tactics/Equipment -** Current fire suppression system and component research and development will have a direct impact on future Navy doctrine, tactics and/or equipment.

Currently available technology is the enabler for optimized manning, through elimination of the human element in damage control activities, and provides direct support to the crew in achieving effective results. The US Navy "Smart Ship" program clearly demonstrated that the insertion of advanced technology would reduce manning requirements while maintaining (or improving) damage control capabilities and shipboard quality of life [2].

The US Navy is conducting considerable research in improving damage control automation with the goal of achieving significant reductions in crew required for damage control on future classes of Naval ships [2]. To this end, the Naval Sea Systems Command (NAVSEA) and the Naval Research Laboratory (NRL) have initiated numerous programs aimed at Damage Control Research, Development, Testing & Evaluation [3]. Some of these programs include:

- **Passive Fire Program -** This program is designed to study the flammability and fuel loading of shipboard materials, with the aim of reducing the potential fuel load aboard ships/submarines. The program is actively developing modeling techniques to predict fire performance for use in fire hazard and ship vulnerability studies.

- **Submarine Fire Safety Improvement Program -** This program is designed to test and evaluate new technologies and procedures for submarine-specific fire fighting.
- **Halon Replacement Program -** This program is focused at developing a replacement for Halon which is no longer acceptable for use as a fire-fighting agent due to environmental concerns. The program has identified a number of Halon alternatives, with high-pressure water-mist being identified as the best.
- **Damage Control - Automation for Reduced Manning (DC-ARM) -** The DC-ARM program was designed to develop and test a full-scale automated shipboard damage assessment and casualty response system for managing fires and fluid systems under damage conditions. The program had four elements: (1) reflexive fluid system technologies ("Smart Valves"); (2) advanced fire detection technology; (3) zoned water mist/smoke control system; and (4) intelligent Supervisory Control System (SCS) technologies.
- **Advanced Damage Countermeasures (ADC) -** This program is designed to build on successes in the DC-ARM program in order to further expand automated damage control system capabilities. This program is has four independent research efforts: (1) development of an advanced volume sensor; (2) development of an automated hull damage & stability monitoring system; (3) the development of a high efficiency water mist system for electronic space protection; and (4) introduction of a water-based blast mitigation system.
- **DD-21 Damage Control Procedures/Doctrine Development Program -** This program is intended to evaluate the results of the other programs as they apply to the DD-21 DC reduced manning concepts, and to determine through Fleet evaluations if the goals for crew reductions can be met under realistic shipboard casualty conditions.

To support these programs, NAVSEA and NRL have established a full-scale Damage Control Research, Development, Test & Evaluation facility aboard the ex-USS Shadwell [3]. This facility permits the researchers to evaluate Commercial Off-The-Shelf (COTS) DC products and systems against (and in conjunction with) newly developed advanced DC system components. The findings of several of these programs form the basis for future DC systems, and are included in this report.

The following subsections review eight key damage control areas as a means of describing the current state-of-the-art in DC technologies and ongoing research and development.

2.1 Identification and Assessment

The key to a rapid and effective response to a casualty event is the ability sensors to detect the event as promptly as possible, while at the same time not causing frequent and annoying nuisance alarms. In an advanced DC system it is also important that the sensor suite have the capability to provide more information than an event alarm. This might include the ability to classify the event (i.e., fire, flood, etc.), provide details of the event and indicate any actions that have been taken (e.g., extent of fire, clear boundaries, passive systems affected, suppression systems activated, etc.).

Under the DC-ARM program, the Naval Research Laboratory has been developing and testing detection methodologies based upon existing commercial and prototype developmental sensors. Each of the new detectors/methodologies has been tested against current state-of-the art COTS fire detection systems (e.g., commercial smoke and fire alarm systems).

2.1.1 Early Warning Fire Detection

The intent of the Early Warning Fire Detection (EWFD) system was to create a multi-criteria sensor array, based upon COTS sensors, and combine this with a sophisticated multivariate data analysis algorithm to provide rapid and reliable casualty event detection [4]. The utilization of multiple detectors in an array should allow measurement of different environmental parameters that can be combined to produce a recognizable pattern that is characteristic of a casualty event and distinguishable from a non casualty event (e.g., welding, grinding, burning toast, etc.). The prototype multivariate classification system, utilizing a Probabilistic Neural Network (PNN), was used to analyze the sensor data from a number of events typical of a Warship environment (real events and nuisance sources). The data from the events was used to train the algorithm to classify the events as real or nuisance.

2.1.1.1 Prototype Fire Detection System

In order to find the best combination of sensor suite and analysis algorithm, the sensors were grouped in different configurations and exposed to varying conditions over a series of tests [4, 5, 6, &7]. For each test, the prototype systems were collocated with the COTS system, which consisted of Simplex Photoelectric and Ionization Smoke detectors along with its associated monitoring and reporting system. Also, the location (i.e., spacing) and proximity of the sensors to the casualty source was varied to determine changes in performance due to these parameters. The multivariate component sensors included in the tests were:

- Ionization Smoke Detector (Manufacturer: System Sensor);
- Photoelectric Smoke Detector (Manufacturer: System Sensor);
- Carbon Monoxide Detector 0-50 ppm (Manufacturer: City Technology);
- Relative Humidity Sensor (Manufacturer: Omega);
- Carbon Dioxide Detector 0-5,000 ppm (Manufacturer: Telaire/Engelhard); and
- Temperature Sensor -20C to 75C (Manufacturer: Omega).

In addition to the sensors noted above, an additional set of sensors was also mounted with the prototype sensor suite, and the data captured for future analysis (i.e., the information from these additional sensors were not part of the real time data analysis algorithm). These included:

- Oxygen Sensor (Manufacturer: City Technology);
- Hydrogen Sulfide Sensor ((Manufacturer: City Technology);
- Nitric Oxide Sensor (Manufacturer: City Technology);
- Hydrocarbon Sensor (Manufacturer: International Sensor Technology);
- Residential Ionization Smoke Detector (Manufacturer: First Alert); and

- Multi-Sensor Fire Detector "SamDirect" (Manufacturer: Daimler Chrysler).

2.1.1.1.1 Test Series 1

The primary objective of the first test series was to develop two prototype sensor suites along with a data analysis system that could operate in real time. During the test series, two prototypes were successfully integrated with a data acquisition system to operate in real time, and were subsequently evaluated against COTS fire detection capabilities. The prototype systems were capable of detecting a few more fires that the COTS system; however, the overall event classification performance of the prototype systems was comparable to the COTS systems. Similarly, the nuisance source event classification of the prototypes was also comparable to the COTS system.

2.1.1.1.2 Test Series 2

In the second test series, the two prototype systems were exposed to a broader range of real and nuisance sources, and an enhanced alarm algorithm was incorporated to improve the classification process. In addition, the ability of the prototype system to transmit alarm and classification data to a DC Supervisory System was tested.

The additional sources included fire events (e.g., smoldering cables) and input from non-fire activities such as steam generation, the use of aerosol products (e.g., hairspray), and sweeping up flour Although some increase in signature was measured for these nuisance events, they did not necessarily result in alarm conditions. It was noted during this test series that the sensors' response (both the COTS system and the Early Warning system) depended on the placement of the sensors and air movement within the space being monitored. Obstructions such as beams and ducts can easily disrupt air flow and prevent the smoke and/or fire gases from entering the measuring chamber of the relevant sensor(s) and triggering an alarm condition. This strongly suggests that the placement of the sensor arrays and their incipient design are very important to their overall effectiveness.

There were no conclusive results from this test series that indicated the EWFD Prototype system outperformed the COTS system.

2.1.1.1.3 Test Series 3

This test series exposed the Early Warning Fire Detection System, with its further refined classification algorithm, to a broader range of real and nuisance 'fire' sources. While the aim of the testing was to compare the performance of the revised EWFD prototypes to that of COTS systems, the learning and improvement process for the Probabilistic Neural Network was also continued. In this series only one prototype detection system and algorithm was tested utilizing the following sensors:

- Ionization Smoke Detector (Manufacturer: System Sensor);
- Photoelectric Smoke Detector (Manufacturer: System Sensor);
- Carbon Monoxide Detector 0-50 ppm (Manufacturer: City Technology);
- Relative Humidity Sensor (Manufacturer: Omega);
- Carbon Dioxide Detector 0-5,000 ppm (Manufacturer: Telaire/Engelhard); and
- Temperature Sensor -20C t0 75C (Manufacturer: Omega).

During the tests, only the Smoke Detectors (Ionization and Photoelectric) and the Carbon Monoxide and Carbon Dioxide sensors were actually used in real time to feed data to the classification algorithm. The additional sensors were used during the post-test evaluation period to gauge alternative combinations. To provide superior real time performance over that experienced in previous tests, the Probabilistic Neural Network classification algorithm was rewritten in a linear algebraic functional language (previously running in MATLAB) and compiled into a Windows Dynamic Link Library file (DLL), which communicated with the LabVIEW software that managed the data acquisition functions.

The average response time of the prototype detectors was compared to the commercial photoelectric and ionization smoke detectors. In general, the systems performed as follows:

- For nuisance sources, no meaningful conclusions could be drawn as not all sensors responded to all sources;
- In general, the COTS Simplex detectors (fitted on the SHADWELL) responded faster to flaming fires than the sensors used in the Prototype System; and
- The prototype system responded faster to smoldering sources than the COTS Simplex detectors;

Considering the overall response of the prototype and COTS systems, the average response time of the EWFD Prototype system was faster than the COTS Simplex detectors. The real advantage of the EWFD Prototype system was its ability to classify the events, and in general:

- The EWFD Prototype system, with its combined sensor array, outperformed the individual System Sensor detectors indicating that the multi-criteria algorithm provided greater sensitivity in detecting incipient fires than the commercial detectors alone;
- The EWFD Prototype system was able to reject the same or more nuisance sources than the COTS Simplex detectors; and
- The EWFD Prototype system was far superior to the COTS Simplex detectors in detection of real fires and rejection of nuisance sources that were remote from the sensor location.

During the post-test analysis phase, a number of alternate sensor combinations were analyzed, and it was determined that alternate combinations may have provided faster response time to flaming, smoldering and nuisance sources. In particular, it was determined that the prototype system could be made to respond faster to low energy smoldering fires.

This test series demonstrated an improved performance of the PNN alarm algorithm from previous test series, and that the PNN alarm algorithm coupled with alternate sensor combinations could outperform commercial smoke detectors. This test series also showed improved real-time performance of the PNN algorithm data processing capabilities, and its ability to provide continuous real-time information to a supervisory control system.

2.1.1.1.4 Test Series 4

The aim of the final test series was to evaluate the EWFD Prototype system in a configuration representative of a shipboard environment. For the tests, the EWFD Prototype systems were installed in twelve spaces aboard the SHADWELL covering the second and third forward decks within the Forward Test Area. The systems were connected to the latest version of the PNN Alarm Algorithm, and were exposed to varying fire source sizes and locations (in relation to the detectors) and compartment and ventilation configurations. The tests also included multiple source exposure at separate locations at the same time. During the tests, the system was continuously running, and sources were added/removed as required. Between exposures the compartments were ventilated thus exposing the system to the normal operating environment of a ship.

The COTS Simplex system fitted on the SHADWELL was used as a measure of performance. The systems were evaluated both for their ability to correctly classify the events and their speed of response (i.e., time to alarm). Overall, the EWFD Prototype system had equivalent or better results than the commercial smoke detectors. The EWFD system responded to both flaming and smoldering sources, while maintaining immunity to nuisance sources.

This test series showed that the use of multiple sensors and a PNN alarm algorithm is superior in performance to the use of Simplex ionization or photoelectric sensors alone.

2.1.1.2 Real-Time Probabilistic Neural Networks

The approach to early warning fire detection is based upon the premise that a combination of sensor technologies coupled with pattern recognition methods could provide faster, more accurate fire detection and classification than any single sensor that measures a physical quantity (i.e., heat, smoke, CO_2, CO, etc.) [8]. In the case of the alarm algorithm designed for the EWFD Test Series, the PNN was exposed to the raw sensor data vice the sensor alarm output, with the objective of determining:

- the importance of the sensor rate of change;
- the best sensor combinations;
- the earliest possible fire detection times; and
- the optimal procedures for training the PNN.

Pattern recognition methods provide an automated means of distinguishing between data classes, and for the EWFD system the sensor data was treated as a vector or pattern in three-dimensional space. Recognition of a fire is based on the recognition of a vector (pattern) related to either a fire or nuisance source. Successful identification is dependent on: (1) the ability of the PNN to numerically encode the sensor signals; and (2) the fire and nuisance sources having a reproducible difference in signature.

In this type of pattern recognition, prior information about class membership is known for each pattern (e.g., a fire or nuisance source) based upon the training set of information. In order to train the PNN, it was exposed to the data from a series of fire and nuisance events (120 in all), as well as normal background conditions common to a shipboard environment. In this way, the PNN pattern recognition algorithm "Learns" classification rules from the training set in order to predict the classification of information received from future events.

A number of issues were found during the development and deployment of the PNN alarm algorithm that are of importance [9]:

- The data acquisition system had a bottleneck that reduced the sampling time and caused the system to lag real-time. This was overcome by re-writing the PNN code into a DLL format instead of the inefficient and problematic Matlab format;
- The PNN can be sensitive to mismatches between the sensor outputs used in training and those in the production/test environment. A substitution of a sensor could cause temporal mismatches and cause the PNN to malfunction; and
- The PNN is sensitive to variations in background "noise", and a method for doing background subtraction is required to make the PNN less sensitive to differing environmental conditions.

2.1.1.3 Overall Results - EWFD Prototype System

The EWFD System showed improvement compared to the baseline provided by a commercial simplex point-detection system. The PNN alarm algorithm fielded with the EWFD system proved to give superior results compared to the COTS ion and photo detectors alone. It had faster response time and resulted in better classification with fewer nuisance alarms. Further optimization of training sets, and improved background subtraction would further enhance the PNN capability as well as the overall EWFD system.

A properly trained PNN alarm algorithm could be introduced to existing systems, utilizing currently fitted fire and smoke detectors, or fully integrated in a new design incorporating the additional sensors in the prototype systems developed as part of these test series. This flexibility and the relative ease of integration of this technology into existing and new fire detection systems would make it an excellent choice for further development.

2.1.2 Volume Sensors

The EWFD System tests demonstrated that such a system is, in general, an enhancement over COTS systems. These tests also demonstrated that combining COTS sensor arrays with a PNN alarm algorithm provides increased performance (i.e., detection and nuisance rejection) over commercial systems alone [10]. The inherent drawback of both the EWFD System and the COTS system is the requirement for the byproducts of the fire to reach the sensor array via thermal and molecular diffusion processes in order for the system to detect the event. In the case of a small or smoldering fire in the presence of physical obstructions and/or shipboard ventilation systems, the byproducts may not reach the detector for a period of time thereby reducing the effectiveness of the system. The networking of large numbers of point sensors in a ship could be very expensive and could also have a prohibitively large maintenance requirement. This could result in the loss of some of the cost savings anticipated from optimized crewing levels.

An alternative approach to point sensors is optical sensors which do not rely on diffusional processes. Such sensors can rapidly detect/identify a fire or other hazardous conditions since the relevant optical information travels at the speed of light [11].

The aim of the NRL program to advance spatial fire detection, known as the Volume Sensor Program, is to develop a detection system that monitors an entire space utilizing a limited number of sensors that do not rely on diffusion to carry heat, gases or smoke to the detector(s). The Volume Sensor Program initially had two parallel efforts, the first being Video-Based Fire Detection utilizing standard video imaging and pattern recognition methods (i.e., machine vision), and the second emphasizing spectrally resolved detection methods (both optical and physical sensing capabilities). Subsequently, the program was expanded to include other methods as advances in technology provided for improved detection capabilities (e.g., acoustic, electrochemical, etc.).

2.1.2.1 Video-Based Fire Detection

The basic concept of machine vision is to replace human visual monitoring by combining video imaging with computer processing schemes to extract the information required to characterize events. In addition to event detection, a video system operating in the visual range would also serve to improve situational awareness and damage control evaluation during a casualty event. The primary goal of NRL program was to develop a system with improved sensitivity and event discrimination compared to point detectors, and at the same time providing improved nuisance alarm rejection.

Video-based fire detection is not a new concept; however until recently the cost of implementing a comprehensive ship-wide system would have been prohibitive [12]. The ability to cover the relevant portions of the spectral region (i.e., ultraviolet (180-400 nm), visible (400-650 nm) and infra-red (>650 nm)) would have necessitated a number of video systems. This was further complicated by the infra-red region that is subdivided into the near-IR (650-3000 nm), mid-IR 3000-20,000 nm) and far-IR (> 20,000 nm). Standard optical materials (e.g., silica, glass) are practical up to approximately 3000 nm and charged-coupled devices up to only 1000 nm. Therefore a significant portion of the near-IR range and all of the mid-IR range were not accessible. The coverage of the mid-IR range would be the most reliable as it would allow both spectrally (IR) and spatially (visual) encoded information to be used in the detection process. Further complications of ship-wide video implementation included the cost and physical limitations of hard-wired multiple camera systems and the significant data processing requirement to attain real-time fire/event detection. Advances in technology, network integration and computing capabilities have largely overcome these cost drivers and limitations to the point that such systems may be attainable.

The high cost of mid-IR cameras may preclude them from being a practical solution for shipboard applications. To determine if a relatively inexpensive COTS video-based system that does not operate in the mid-IR range could be affordably implemented, the Naval Research Laboratory conducted an experimental evaluation of the ability of commercial video fire detection technologies to provide fire detection and minimize nuisance alarms [13]. The approach was similar to the evaluation of the EWFD System in that the commercial video-based systems were compared to the commercial point-detection systems fitted on the

SHADWELL. They were exposed to small and incipient fires to further challenge the systems.

In the initial evaluation phase [13], two commercial video-based fire detection systems were used. Each of the systems received identical video imaging from the three video cameras in the test area. Standard inexpensive CCD color cameras were utilized in these tests (i.e., below mid-IR range). The two commercial systems included:

- Fire Sentry VSD-8 system (manufactured in the US by Fire Sentry based on a design from ISL in the UK) - This system analyzes small areas within the raw image at the digitization stage and identifies areas of change. These areas are then passed through a series of software filters to find particular characteristics consistent with smoke (i.e., smoke detection system); and
- Fastcom Smoke & Fire Alert (SFA) system (manufactured by Fastcom in Switzerland) - This system uses the processed video signal and detects both fire and smoke. The fire detection algorithm is based upon dynamic characteristics of the image consistent with flames. The smoke algorithm relates the video image to a reference image to determine if smoky conditions exist. In this case, the smoke and fire alarms are dependent on size, activity, the speed of development and dynamic behavior of the event.

The video-based systems and the COTS simplex system were exposed to 13 flaming fires, 20 smoldering fires and 14 nuisance sources. The video-based systems alarmed to virtually all of the flaming and smoldering fires (significantly more than the COTS point detectors), but were slower when responding to small flaming fires than the COTS ionization smoke detectors. The video-based systems also alarmed to as many or more nuisance sources as the COTS detectors. However, the clear advantage of the video-based systems was the ability of the DC Operator to see the image remotely and determine if the event was from a legitimate source or as the result of a nuisance activity.

These results would indicate that the video-based systems using smoke alarm algorithms can provide comparable to better fire detection than point-type smoke detectors, except for small flaming fires where they had a slower response. The potential advantages include reduced maintenance and testing costs (i.e., no calibration required) and the provision of a much higher level of situational awareness to the DC Operator.

2.1.2.2 Spectral-Based Detection

The spectrally resolved optical approach attempts to exploit the fact that emitted radiation, particularly in the mid-IR region, is a sensitive indicator of the presence of gaseous emissions (e.g., CO, CO_2, etc.), and of elevated temperature from black body radiation (i.e., hot objects and/or soot) [10]. The optical sensor relies on a single or small number of sensing elements with a wide field of view that can remotely detect changes throughout the compartment that would indicate the outbreak of a casualty event. The selection of wavelengths is critical to increased sensitivity as well as minimization of false alarms. These wavelengths are taken from the IR and UV ranges and are chosen for high sensitivity and specificity. The primary IR band is normally the carbon dioxide (CO_2) band at 4.3 µm. If an UV band is monitored it is normally the short wavelength edge at 180-280 nm. A second and third IR band can also be monitored. Typically these bands are away from the 4.3 μm band and are used to discriminate against nuisance sources.

While spectrally resolved optical sensors are very effective at monitoring a wide area, they are limited by line-of-sight operation and are primarily a flame detector (relying on flicker rate or signal rise time), and are not particularly sensitive to smoke or smoldering fires. For this reason, the spectrally resolved optical sensor would have to be coupled with a secondary sensor (e.g., point ionization smoke detector, beam type smoke detector or a long-wavelength near-IR camera (i.e., thermal imaging or night vision camera)). Beam type smoke detectors work well in an area where conditions are relatively static, but would not be practical in a shipboard environment. A tunable diode laser absorption spectrometer (i.e., smart micro-sensors) to monitor relevant gas species could also be coupled to the spectrally based optical sensor.

To determine the best combination of these various elements, a series of developmental tests were done by NRL. These are reviewed in the following section.

2.1.2.2.1 Single/Multiple Element Spectral Detection

Optical flame detectors (OFD) detect emitted radiation in narrow spectral fields that are common to flames. Commercial OFDs are capable of detecting multiple IR bands simultaneously. They also have an UV tube that will monitor the 185-260 nm band. A second type of sensor was also incorporated that monitors spectral bands associated with molecular emissions from the hydroxyl radical (OH), which are known to be prevalent in flames. This sensor consisted of a photo-multiplier tube (PMT) and a 310 nm interference filter that was sensitive to this OH spectral region. Additional spectral filters associated with other emissions were also envisioned, but were not incorporated in these tests.

A spectral test bed was used to test various configurations of OFDs and filtered PMTs and the results showed that virtually all sensors tested would respond to the corresponding emissions and could be used for fire detection (with establishment of appropriate alarm thresholds).

2.1.2.2.2 Long Wavelength Nightvision Imaging

The standard optical or digital (CCD) camera lens is capable of detecting into the near-IR range and may provide spectral information on a fire that could be analyzed to provide additional information/capability to the volume sensor without the expense of the high-priced mid-IR sensor. This is not a standard practice of commercial optical fire detection systems, and as such no commercial system currently utilizes near-IR for fire detection.

In order to evaluate the capability of a near-IR camera to detect fires, a series of fires were recorded from various sources using a standard CCD camera with various wavelength long-pass filters that blocked out the visible spectrum. The videos showed the deep red response of the filtered CCD image, clearly providing an enhanced discrimination of flames and fire over the background. In addition, the images also showed higher contrast for reflected radiation, which would indicate that this type of sensor might not be limited to line-of-sight; thereby increasing the overall effectiveness of the detection capability.

As a further test of the long wavelength video to detect fires, a prototype system was tested against the fitted COTS simplex fire detection system as well as two commercial video-based fire detection systems in a series of fires aboard the ex-USS Shadwell [14]. All systems were fed the raw unfiltered data from the same CCD cameras. The prototype system relied on a simple algorithm to determine the overall luminosity of the filtered image and determine the alarm level based upon preset limits. The prototype software system was designed to exploit the unique nature of the nightvision video in terms of background intensity and high contrast image of flaming or hot objects.

During the tests it was determined that:

- The use of the long pass filter with the nightvision camera dramatically increases the contrast and sensitivity for flaming and hot objects, making event detection a much simpler task;
- The ability of the nightvision camera to respond to reflected near-IR light could be used to detect flames that are out of the field of view of the camera; and
- The nightvision cameras add an additional benefit to the DC functionality as they are capable of providing thermal-imaging data for ongoing events as well as live update information for on-scene event mitigation.

Overall, the nightvision camera offers an attractive, capable and cost-effective alternative to augmentation of the standard spectral video-based detection capability. In addition, the long wavelength night vision system shows promise as an inexpensive pseudo-thermal imaging system for remote monitoring of ongoing DC events.

2.1.2.3 Acoustic Event Detection

In addition to the optical approaches discussed above, the acoustic signature characterization of casualty events could yield successful remote detection of fire and smoke, as well as non-fire related types of events (e.g., flooding, pipe ruptures, etc.) [10]. The development of acoustic signature models that recognize casualty events over the background and can discriminate nuisance events is the key and is based upon machine hearing (non-human based monitoring interface). The value in acoustic signature recognition is the ability of such a system to augment video-based alarm systems when the event is not in the field of view.

As part of the acoustic signature verification, a series of laboratory tests were conducted to determine the characteristic signature of various shipboard water-based, damage control events such as pipe ruptures and flooding [15]. In addition, a series of noise measurements were taken aboard in-service Naval vessels to characterize the background broadband noise level. The background signatures were found to vary dramatically from compartment to compartment with the louder background signatures approaching the threshold of some of the quieter water events. A low frequency detector (7-17 kHz) was developed to optimize the signal-to-noise ratio and provide better water event detection. The upper limit was chosen to coincide with the frequency response upper limit for a standard low-cost microphone.

It was found to be possible to detect a wide range of acoustic events; however, the masking of the sound (hence the ability to detect) was affected by reverberant compartment effects. The size of the space as well as the ambient background noise also affects the ability of the acoustic system to detect the event.

The ability of acoustic detectors will be further verified in future testing with the SBVS.

2.1.2.4 Smart Micro-Sensors

Cermet sensors are a combination of ceramic and metallic materials that are used in electrochemical sensing applications [16]. They are capable of high temperature operation and are generally used to conduct electrochemical cyclic voltammetry on gases (e.g., automobile oxygen sensor). Using thick/thin film techniques, cermets can be fabricated into arrays with the outputs fed into microelectronic readouts, and are capable of monitoring hazardous chemicals in the parts-per-million to parts-per-billion range. When combined with a pattern recognition software, the output of smart microsensor arrays has the potential to provide a sensor/data analysis system to detect a wide range of chemical compounds.

Originally developed to detect Toxic Industrial Chemicals (TICs), the arrays are also able to monitor gaseous emissions normally associated with combustion. Consequently, the NRL introduced chemical microsensor arrays to the Volume Sensor program as a means of enhancing the detection capability compared to the conventional electrochemical sensors used in the EWFD program.

To demonstrate the concept of using smart microsensor arrays for detection of fires, a General Atomics Smart Microsensor was exposed to a series of burning material on the Shadwell. The microsensor arrays consisted of four sensors that were designed to detect a wide range of analytes including TIC's, fire effluent gases and other gases normally associated with a shipboard environment (i.e., nuisance sources). The data collected from these tests were post-processed using a PNN algorithm that had been exposed to a synthetic training set developed during laboratory testing of the microsensor arrays. For comparison of response time, the arrays were tested against COTS point-type ionization and photoelectric smoke detectors as well as a commercial multi-criteria detection system.

During the tests, a variety of fire and nuisance sources were used, as well as pipe ruptures and gas releases that would be typical of the shipboard environment. The fires were generally of a very small size to challenge the system and determine early detection characteristics of the sensor. The measure of performance was based upon both the speed of response and the ability to correctly classify the source.

The test series indicated that cermet sensors are a promising fire detection technology. During the tests, the cermet sensor arrays detected both flaming and smoldering fires at the same level as the commercial multi-criteria detection system, and out performed the COTS point-type smoke detectors in response time. The microsensor array had some difficulty in classifying fire-like nuisance events (e.g., welding, burning, etc.) and had mixed results detecting events not accounted for in the classification algorithm (e.g., pipe ruptures, gas releases, etc.). A secondary result of the tests was the ability of the cermet sensors to detect TICs, which could provide a significant asset to the CBRN collective protection of the ship.

2.1.2.5 Volume Sensor Development Test Series

The objective of the NRL Volume Sensor program was to develop an affordable, real-time detection system for identification of shipboard casualty events such as fire (flaming and smoldering), explosions, pipe ruptures, gas releases and flooding that could recognize nuisance sources that are part of a shipboard environment [17 & 18]. The approach to the advanced damage countermeasures Volume Sensor was to develop a remote detection system based upon existing and emerging technologies. These technologies included machine vision, enhanced data fusion algorithms, visual and spectral sensors, acoustic sensors, and pattern recognition techniques. In addition to recognizing a broad range of casualty events, a Volume sensor must provide improved performance over current state-of-the-art point fire detection system. The next section describes NRL's Volume Sensor prototype and testing to determine its capabilities..

2.1.2.5.1 Volume Sensor Development Test Series 1

The initial phase of the volume sensor development program consisted of a literature review of current and emerging technologies [19]. Based on this review, several technologies were identified as having potential for meeting the objectives of the volume sensor program. Preliminary test results indicated that the use of video-based systems for detection of fire and smoke could provide equivalent detection capabilities compared to existing state-of-the-art point detection systems.

As part of the CVN 21 Fire Threat to Ordnance program tests, conducted on the Shadwell in April 2003, the video-based fire detection systems were evaluated in a simulated shipboard environment. In addition to the CVN 21 tests, an additional set of tests (denoted Volume Sensor Development Test Series 1) were conducted to provide a broader range of fire and nuisance source exposures. These preliminary tests, conducted under relatively ideal conditions, indicated that there may be potential issues with video detection performance and that additional testing would be required.

2.1.2.5.2 Volume Sensor Development Test Series 2

This test series evaluated the video-based fire detection system performance when exposed to fire and nuisance sources under varying lighting conditions and camera settings [19]. Video-based detection systems using smoke and fire alarm algorithms could provide equivalent or better detection performance than point-type smoke detectors for most conditions evaluated. However, these tests were conducted under relatively ideal conditions and a further test under less than ideal conditions was warranted.

Three commercially available video image fire detection systems were exposed to fire and nuisance sources under less than ideal lighting and varying camera settings and the results were compared to multiple state-of-the-art point-type smoke detection technologies. The VSD-8, SFA, and SigniFire systems were tested. The three systems were fed the same video stream from the cameras used in the test. The cameras were commercial CCD cameras and Long Wavelength Video Detection (LWVD) nightvision cameras (commercial CCD with appropriate Long Pass (LP) or Short Pass (SP) filters) (Figure 1).

The fires were kept relatively small in order to challenge the systems. Several parameters were systematically varied and they included:

- Location of the fires relative to the detectors - the distance was varied and obstacles and obstructions (e.g., table, chairs, electrical cabinets, etc.) that partially or wholly obscured the view of the video camera were introduced;
- Lighting conditions - lighting on Naval ships varies from one compartment to another (general, detail, special, red, yellow, low level white, broadband blue, emergency and darkened ship as well as no light in unmanned storage spaces) and could affect video imaging; and
- Camera settings - the focus (sharp to blurry) and the contrast (bright to dark) were adjusted to determine the effect on the detection system.

Figure 1. Volume Sensor - ex-USS Shadwell

In addition to testing the video detection systems, this test series also evaluated spectral and acoustic sensors. The output of the spectral and acoustic sensors was used to develop casualty event signatures that could be integrated with the video-based technology to expand the video detection systems capabilities and to compensate for deficiencies with current video detection. The spectral sensors (shown next to the video cameras in Figure 1) included commercial UV and IR sensors, as well as custom-designed IR detectors operating at various wavelengths from the mid-IR to the UV. The acoustic recording system included two commercial microphones operating over differing frequency ranges (3 - 40,000 Hz and 20 - 20,000 Hz). The microphones had their own amplification and recording systems.

The test series produced the following results:

- The video detection systems performed as well as or better than the COTS point detectors for flaming and smoldering sources except when the source was distant from the detector or obscured;
- The effect of ship background color and minor variations in camera settings (contrast and focus) were insignificant in comparison to other issues (compartment coverage,

source type, source location, obstructions, etc.) as long as the video image was reasonable quality;

- The LWVD system was significantly more sensitive than the commercial video system to flaming fires out of the field of view, but less sensitive for smoldering fires;
- The SBVS yielded results comparable to more mature COTS systems; and
- Acoustic sensors are of limited use for fire events, but have good promise for determining nuisance sources (e.g., grinding, welding, personnel in a space, etc.).

2.1.2.5.3 Spectral Based Volume Sensor (SBVS) Test Series VS2

Based upon the promising preliminary results for the SBVS in Volume Sensor Development Test Series 2, a further series of tests were conducted by NRL to refine the spectral-based component of the Volume Sensor [20]. This series concentrated on spectral rather than spatial (i.e., visual) information to provide both detection and classification information that is not generally available to commercial video-based detection systems. The goal of this test series was to collect data for post-processing and development of various algorithms for the VS Prototype.

The SBVS system consisted of various commercial Optical Fire Detectors (OFDs) that detect broadband IR and additional sensors that were constructed to detect wavelengths that correspond to atomic or molecular emissions within flames. The SBVS system was exposed to flaming and smoldering fires and various nuisance sources typical of a shipboard environment.

Post-processing analysis of the test results included normalization to remove background variations and scaling of signals to ensure strong and weak signals were treated equally in the algorithm development phase). A Principle Component Analysis was then conducted to identify structural organization within the data and reduce the overall number of parameters through the definition of composite variables (i.e., interdependency identification). The normalized and resolved data sets were then analyzed and general event detection criteria were identified from which event classification criteria were defined. Using these results, algorithms for detection of specific events (i.e., fire, flood, welding, etc.) were developed and then tested against real-time data collected during the VS2 test series.

Overall the event detection algorithms developed during this test series showed detection sensitivity and significant classification capability (DC event versus nuisance source). Even for partially obscured, smoldering sources or sources outside the field of view of the sensors, the SBVS system provided a significant increase in detection capability over COTS OFDs while not responding to nuisance sources.

2.1.2.5.4 Volume Sensor Development Test Series 3

The results of Test Series 3 were reported in NRL Letter Report 6180/0353, 20 September 2004 [21]. In test series 3, a multi-component prototype volume sensor was developed. It consisted of suites of co-located sensors and fusion algorithms that were evaluated on the Shadwell in July, 2004. The ability of the system components to work as a unit was proven and a functioning VS Prototype was developed. The VS Prototype components able to detect and discriminate various sources, outperforming the individual system components in terms of both event detection and nuisance rejection. Some areas of improvement were identified, and as a result of Test Series 3 some enhancements were made at both the component level and the fusion system level of the VS Prototype.

2.1.2.5.5 Volume Sensor Development Test Series 4

The objective of Test Series 4 was to evaluate the VS Prototype enhancements in preparation for a full-scale multi-compartment evaluation of the system [21]. An additional objective of this test series was to identify the most effective use of sensors within a space (i.e., location, clustered or distributed). During this test series, the VS Prototype was exposed to a series of small fires including fires in adjacent spaces where no detectors were present and a variety of nuisance sources, pipe ruptures and gas releases that would challenge the system. The performance of the VS Prototype was compared to a COTS point-type smoke detection system.

The VS Prototype consisted of four components; a video camera, a LWVD camera (filtered Bullet camera), a microphone and a SBVS system. Data from the detectors was processed by the individual sensor subsystems (i.e., visible video-based, long wavelength video, spectral-based and acoustic-based detection systems) and then sent to a stand-alone PC that provided further analysis utilizing the fusion algorithms. The output was sent to the DC Supervisory Control System. Two VS Prototype variants were used; one using the Fastcom SFA and the other using the SigniFire commercial video-based detection software. As with previous test series, the VS Prototype system was compared to state-of-the-art COTS point-type smoke detection systems for evaluation of performance.

This test series successfully demonstrated the functionality and performance of the VS Prototype system. Some of the results of the test were:

- The VS components were successfully integrated into a functioning prototype system;
- The VS Prototype system outperformed the COTS smoke detection systems in detecting flaming and smoldering fires;
- The acoustic detection system correctly responded to pipe rupture events;
- The Fusion Machine integration of the component data showed improved performance over individual sub-system components; and
- The improved data fusion nuisance rejection algorithm and increased persistence requirements (ruling out spurious data) for all data fusion algorithms reduced false and incorrect alarms. The VS Prototype system was more successful in eliminating nuisance sources than the COTS systems.

2.1.2.5.6 Volume Sensor Test Series 5

The objective of test series 5 was to conduct full-scale tests in several compartments aboard the ex-USS Shadwell and compare the performance of the VS Prototype sensor suites and COTS smoke detection systems [22]. The detectors were exposed to a broad range of relatively small fires, adjacent space fires, nuisance sources, gas leaks and pipe ruptures to challenge the systems capabilities. Testing included both single and multiple source exposure scenarios.

The Shadwell has an Automated Fire Suppression System (AFSS) that is representative of the system envisioned the DD(X). The AFSS system provides an automated response to damage events including fires, fluid system (firemain) ruptures and device failures through the use of smart valves for firemain configuration management, activation valves for the water mist fire suppression system, smart pump controllers, and a fire/smoke detection system. For this test series, the VS Prototype system replaced the AFSS fire/smoke detection system for evaluation purposes.

This test was the last in a series that saw the development of the VS Prototype system from basic concept to functional capability. In general, the results of the Volume Sensor Program can be summarized as follows:

- The VS Prototype system demonstrated the ability to function in multiple compartments with specific discrimination capabilities against multiple sources in concurrent locations;
- The VS Prototype demonstrated the ability to correctly classify sources and reject nuisance sources in real time;
- The VS prototype generally outperformed the state-of-the-art COTS point detection systems as well as commercial video-based detection systems; and
- The VS Prototype system is capable of interfacing with automated fire suppression systems.

2.2 Communication

Future ships must possess advanced DC functions/technologies that are not available on today's warships and be capable of providing DC functions with a smaller crew [12]. To achieve this, artificial intelligence, smart sensors, and computerized controls and decision-making systems must perform functions not carried out by crewmembers. Future reduced manning requirements will drive the need for development of smart systems with the ability to respond automatically to casualty (damage) events. Sound decisions are based upon having correct and timely information, which in turn is based upon advanced technologies in the communication realm.

2.2.1 Shipboard LANs

Sensors may be able to detect the information necessary for making DC decisions, but if the sensor is unable to transfer that information to the decision maker then it is of little value. The implementation of a ship-wide LAN is considered a key component of a shipboard communication capability, as it will support implementation of advanced communication technologies such as video and wireless capabilities.

In this application, it is important to take into account the rapidly advancing technological improvements being made for LAN systems. To maximize the benefit of such a system as it relates to future DC capabilities, it is imperative to use network equipment, methods and communication systems that can be easily upgraded to prevent early obsolescence.

2.2.1.1 Shipwide Video

One important element of an advanced DC system is the ability to remotely monitor and observe conditions within individual ship compartments. Information on a compartment's environmental conditions (e.g., smoke, fire, flood, nuisance activity, etc.) can be gleaned from a video image of the compartment. As discussed earlier in this report, advanced fire and smoke detection algorithms could also utilize this same video information to provide an alarm system. Until recently, video equipment was cumbersome and costly, and a large-scale ship-wide implementation involved considerable wiring that was impractical.

Recent advances in communication technology have made it possible to implement large-scale camera systems without the need for the cumbersome wiring. State-of-the-art ethernet LANs provide the means for communication support necessary to implement a ship-wide video system to support advanced DC capabilities with a significantly reduced hardwired cabling requirement. Besides the support to DC functionality, a ship-wide video system could also be used for enhanced security, remote monitoring of machinery, electronic and electrical spaces, and would permit remote monitoring of shipboard functions that normally require two personnel (e.g., working in fridges/freezers, welding/grinding, etc.).

2.2.1.2 Wireless Technology

Wireless communication offers a number of benefits in shipboard applications and supports the implementation of advanced DC systems discussed in this report. The flexibility resulting from having a communication capability from anywhere in the ship at any time supports enhanced connectivity and mobility, which are critical factors in DC operations. A wireless system also has more tolerance to damage (fewer physical connections and less fixed hardware), and a reduced cabling requirement. The use of wireless communication to support the enhanced safety and survivability of Naval platforms was the subject of an investigation by the US Navy [23].

Wireless technologies lend themselves to a number of purposes on a Naval platform, including sensor data communications and personnel monitoring. In the case of sensor data communication, the current practice of connecting sensors via hard-wired cabling is expensive and often leads to a limit in the quantity of sensors that can be installed. In contrast, wireless technology overcomes such limitations and enables the installation of an increased number of sensors. This leads to better overall coverage of the ship. Wireless communications also allows flexibility in placement of sensors as there is no requirement for cable runs. In the case of personnel monitoring, wireless technology makes it possible to use mobile sensors such as Personnel Status Monitors (PSM), and in the case of DC event management, the use of mobile communication including voice, data and video streams.

Tests conducted by NRL have shown that wireless technology in a shipboard environment has a number of drawbacks. Some of these are:

- A wireless system is subject to wide variations in capability due to environmental changes within the ship (equipment operating, door closures, user errors, etc.) that lead to intermittent operation;
- Multi-path interference caused by the location of transmitters creates dead spots where communication is not possible;
- Multi-path interference also causes transceiver cross-talk that limits the effectiveness of RFID technology used in Personnel Status Monitors; and

- Short battery life (<90 days) issues must be resolved to permit the use of wireless sensors;

In general, although wireless technology has the potential to enhance communication in a shipboard environment, a number of issues need to be resolved before it will be deployable. Communication voids and reliability remain the major issues with wireless technology and additional research and development in these areas is required.

2.3 Management

Managing damage control response has traditionally been a labor-intensive manual activity; however, recent advances in technology have permitted more confidence in and reliance on automated systems to control aspects of the DC response and have reduced the requirement for human involvement. Many of the aspects of the management of a DC emergency are related to the ability of the operator to use the Supervisory Control System (SCS) effectively. The effectiveness depends on the human-computer interface. This topic is the subject of the concurrent Phase II Task One report and therefore is not addressed in this report. However, technical aspects of the integration of the SCS with other shipboard systems will be discussed in the following sub-section.

2.3.1 Supervisory Control Systems

The Supervisory Control System (SCS) is defined as a semi-automated system that monitors and controls multiple ship systems and enables a human supervisor to interact with the ship through a human-computer interface to manage DC response (and personnel) such that it compliments the automated functions of the SCS [24]. The SCS must first be able to survive the damage event and then be able to take action to mitigate the extent of damage through automated and cooperative actions with the DC repair and management personnel.

The key to SCS survivability is the network architecture which includes the extent of redundancy and separation of components. Greater redundancy means greater survivability, but also greater cost in terms of installation and maintenance. Modular design has the best chance of survival. The loss of the functionality of one component of the system can be quickly taken over by another component and maintains the operational capability of the overall system.

The ability to upgrade components of the SCS must be considered in the current environment of rapid technological advancement. To minimize cost, the redundant systems should utilize COTS components that can be replaced with a similar component in case of a unit failure or by a more advanced component for purposes of obsolescence management.

2.3.2 Fire and Smoke Simulation

One aspect of current manual and semi-automatic DC management is its inherent reactive capability. In the future, a fully functioning SCS with the ability to actively predict the event progression could take preventive (or pre-emptive) actions (i.e., activate fire suppression/ boundary cooling, close passages to smoke, etc.) far faster than is possible with current systems and technologies. Through the use of fire and smoke simulation models [25 & 26] the SCS would be able to predict the event progression and take action accordingly.

Fire modeling is also valuable tool in the evaluation of ship design and design philosophies and to make ship vulnerability assessments. During the operational phase the model must be able to provide real-time situational assessment faster than the actual event progression, such that the SCS and the DC management personnel are able to use this information to mitigate the growth of the DC event.

Fire modeling supports advanced ship design to reduce fire and smoke spread and allows the evaluation of conceptual designs and hazards. In terms of support to DC operations, this tool would also be useful for developing real-time fire scenarios for on-board training and development of DC tactics and doctrine.

2.4 Action

The ability to take action to mitigate or extinguish the casualty event is the primary role of a comprehensive DC system. Once an event is detected and classified, the DC system must, through automated, semi-automated or manual means, be able to take the appropriate actions to minimize loss of life and prevent loss of the ship. These actions, which can include activation of suppression systems, management of the firemain to restore pressure after a rupture, and reconfiguration of the ventilation system for smoke control are becoming more automated as technology evolves.

2.4.1 Water Mist Systems

Fine water mist systems have been an active area of research and development in recent years and numerous commercial systems are available. Water mist extinguishes fires by gas phase cooling (evaporation and heat capacity), oxygen displacement and attenuation of radiant heat transfer [27 & 28]. Water mist systems have attracted a great deal of attention as they are less toxic than most conventional gaseous fire suppression systems (e.g., halon, carbon dioxide, etc.), are capable of extinguishing both fuel and combustible material fires, and use significantly less water than conventional sprinkler systems. Water mist suppression relies on the saturation of the space with atomized water, and is particularly effective against large dynamic fires where interaction of the water droplets with the flames causes rapid gas phase cooling of the fire (steam generation) which in turn further displaces the oxygen content in the space.

The formation of fine water mist particles can be accomplished by a number of means, including the use of compressed air/nitrogen and the use of high pressure water. The use of compressed gases requires a dual piping system (gas and water) and the added weight of compressed gases and/or a compressed gas system. High pressure water systems have lower weight and space requirements and require less complex piping arrangements. The disadvantage of the high pressure water system is the requirement for a relatively clean water source. This is due to the smaller orifice size of the nozzles and rules out the use of seawater. Therefore, fresh water storage is mandatory.

The goal of a water mist system design is to provide a hydraulic distribution system that will meet the peacetime flow and pressure demands for fire suppression as well as the emergency flow condition expected/required in a battle damage control situation [33]. The system must be able to monitor flow conditions, react to abnormal flow conditions associated with a system rupture, and respond to isolate the ruptured area and return the system to full functionality (see Section 2.4.4 Smart Valves). A traditional "dual main" firemain architecture is insufficient to achieve the survivability requirements of a water mist system, necessitating the implementation of a sectional loop architecture with numerous cross-connection branches that provides the requisite reconfigurable redundancy.

Consideration of the water mist system pressure must be made in the design process. Testing has confirmed that high pressure (70 bar/1000 psig) water mist systems outperform the low pressure systems (12 bar/<175 psig). High pressure systems are more effective than the low pressure systems, both in extinguishing fires and maintaining boundary cooling/flash-over suppression, and require less than half the water needed by low pressure systems. High pressure systems also use smaller diameter pipe, use 40% fewer nozzles and have a greater survivability due to the lower cross-section of the system. The drawback of a high pressure system is the inability to have a single water service system that satisfies both the water mist system and the traditional shipboard systems (e.g., machinery cooling, etc.) serviced by the low pressure firemain.

Water mist systems are ideal for protection of machinery spaces, and are also suitable for collective protection of the entire ship. However, the cost of a high pressure water mist system is higher than that for a conventional sprinkler system. A balance between cost and capability must be made during the design process, whereby a hybrid system may be a more economic choice (i.e., water mist in machinery and weapons spaces, and traditional sprinklers in living and storage spaces). The design must also incorporate multiple redundant high pressure positive displacement pumps with sufficient fresh water supplies for response to both peacetime and wartime DC scenarios. Conservatively, for a peacetime scenario such as a machinery space fire, the system should be able to deliver approximately 1000 L/min for extinguishment and boundary cooling [33]. In a wartime scenario, with multiple events, the demand would increase and a conservative estimate indicates that the system should be able to supply 1350 L/min. From a redundancy perspective, a single large-capacity pump would be impractical. In addition, numerous small pumps would be costly in terms of the recirculation piping necessary to connect the positive-displacement pumps to the water supply. A number of pumps (e.g., one per watertight section) operating in parallel would provide redundancy at slightly higher cost than the single pump alternative and allow flexibility during their installation.

Water mist has shown additional capabilities and benefits. One of these is its use pre/post-weapon hit to mitigate the damage and control/mitigate the fire in the primary damage area (PDA) [34 & 35]. Water mist has also shown promise for use in electrical and electronic spaces [36]. The use of sidewall water mist nozzles were tested to determine their ability to thermally manage fires (i.e., prevent flashover and reduce the intensity of the fire) in the PDA following a missile hit. Sidewall nozzles are more likely to survive a weapon hit than overhead nozzles. The tests [35] concluded that the ability of the water mist system to prevent flashover following a weapon hit is a function of the opening to atmosphere created by the weapon; however, the sidewall water mist design does have the potential to reduce thermal conditions and prevent flashover and fire spread following such an event.

Modern Naval vessels will rely heavily on automation and therefore an electrical or electronic fire would have disastrous results, especially on a ship that relies on the DC control system to mitigate the effects of such fires [36]. Passive fire protection (e.g., insulation, improved fire resistance, etc.) of cables has proven effective for electrical cables, but the Naval electronic cables have very little resistance to fire, and burn profusely when the outer jacket is peeled off. Traditional fire suppression methods, using fog mist or fine spray cause considerable collateral damage to these systems, and halogenated hydrocarbon suppression systems have environmental and safety related drawbacks. The use of an ultra fine water mist system to extinguish electronic and electrical fires has been successfully tested. Electronic equipment that shut down during the exposure to the ultra-fine water mist regained functionality after drying. Overall, these tests showed that the use of ultra-fine water mist could provide adequate fire protection with minimal water damage to the electronics located within a ship compartment and in the sub-floor of an electronics space.

Full-scale tests of water mist fire suppression technologies have been conducted by numerous agencies, including the US Navy [29 & 30], the Australian Department of Defence [31] and the US Coast Guard [32]. Two types of water mist delivery systems were the focus of these tests including both a full-scale fire extinguishing capability (primarily suited for machinery spaces) and a flash-over suppression system with distributed horizontal nozzles (2-4 per space) to maintain the compartment temperature below flashover temperature and prevent the spread of the fire. The testing indicated that:

- Single-fluid (i.e., fresh water) high-pressure systems are the most effective water mist systems;
- Even under worst case fire conditions, water mist is able to significantly reduce the average overhead temperature, thus permitting a fire-fighting team to enter the compartment to extinguish the fire;
- Water mist fire protection is a viable alternative to halogenated hydrocarbons in the protection of machinery spaces. This is the result of its effectiveness of water mist against a wide range of fuel fires and the ability to activate the system quickly in a manned space;
- Nozzles mounted high in the space have a better overall performance (including flash-over prevention) than those installed over doors;
- Flash-over suppression systems are capable of providing boundary cooling that prevents the spread of the fire to adjacent spaces;
- The amount of water required to achieve flashover protection and extinguish or control the fire in the PDA was significantly less than that required for traditional marine sprinkler systems; and
- The ability to control ventilation is critical to the overall effectiveness of the water mist system (i.e., the system is not suited for spaces open to the atmosphere such as an upper deck hanger with the doors open).

Water mist systems are commercially viable and are being installed on both commercial and Naval vessels as an alternative to halogenated hydrocarbon fire suppression systems. For new build construction, water mist should be installed in all high risk spaces (e.g., machinery and weapons spaces) as a minimum. In addition, consideration should be given to installation in other areas to provide collective fire protection to the ship. As a retrofit to existing platforms, a water mist system would be an excellent choice for replacement of halocarbon systems in high risk spaces; however, due to cost water mist may not be a cost-effective choice for other spaces.

2.4.2 Aqueous Film Forming Foam (AFFF) Systems

AFFF is used extensively on Naval vessels as part of the fire attack team spray capability, in overhead spray systems for hanger bays and machinery spaces, and in bilge deluge systems. The continued wide use of AFFF is in question due to environmental concerns related to the use of fluorinated surfactants in the AFFF. AFFF formulations that contain perfluorooctanesulfonyl fluoride are no longer available. Perfluorooctanesulfonyl fluoride breaks down to produce perfluorooctane sulfonate (PFOS) which is believed to be persistent, bioaccumulative and toxic [37].

The International Maritime Organization (IMO) has developed a standard to ensure chemical compatibility of AFFF replacements with seawater [38]. During a series of tests, the US Coast Guard Research and Development Center evaluated the ability of a number of these replacements (developed by three independent manufacturers) as fire suppression agents in a machinery space application [39]. The objective of the testing, conducted at the US Coast Guard Fire and Safety Test Detachment (Mobile, Alabama) on the STATE OF MAINE, was to evaluate the capabilities and limitations of High Expansion Foam Fire Suppression Systems (HEFFSS) against simulated machinery space fires. The tests ranged from small incipient fires and wood-crib fires to large fuel-loaded pan fires representative of a major bilge fire. The systems tested were manufactured by Ansul Inc., Buckeye Fire Equipment and Chemguard Inc. The systems tested consisted of two parts, a foam proportioning system and a motor-driven foam generator, and were installed in accordance with the manufacturer recommendations.

The test results were consistent between suppliers; the systems were capable of extinguishing the smaller fires but had difficulty with the large pan-sized fuel fires. These systems require further development. HEFFSS systems may be a good choice for fire protection of hangers, where water mist systems are less effective, but are not the best choice for halon replacement in internal shipboard spaces.

2.4.3 Gaseous Agents

Since the 1989 Montreal Protocol was signed, calling for the reduction/elimination of ozone-depleting substances, Halon production has ceased in most parts of the world. A large body of work has been completed in an attempt to develop replacement gaseous agents [40]; however, no suitable alternatives to halon have been developed that are both as effective and environmentally acceptable (i.e., short atmospheric life, zero ozone-depleting potential and low global warming potential) [37].

The 3M Corporation currently markets a halon replacement (Novec 1230) that it claims is effective at concentrations below that which would cause health effects (i.e., can be used in occupied spaces), and is environmentally acceptable. Although 3M state that Novec 1230 would be suitable for shipboard applications (e.g., machinery spaces), it is unclear from their literature if it has been independently tested in such an application.

2.4.4 Aerosols

Aerosols are a class of agents that have potential as effective fire suppression agents and do not have the significant global environmental impacts associated with halocarbons. Two technologies that have been advanced include water mist (discussed earlier in this report) and particulate aerosols, which are similar to dry agent chemicals but have significantly smaller particle size.

The fire suppression aerosol is a solid particulate delivered to the protected space by a dispersion aerosol. The particulate size of the solid agent is related to the energy expended on crushing the agent as well as its physical properties (e.g., brittleness, porosity, crystalline flaws, etc.). Pyrotechnically generated solid particulate aerosols, which work by inhibiting chemicals reactions and thermal cooling of the flame have shown some promise for use in large shipboard spaces.

The US Coast Guard Research and Development Center have evaluated the ability of a three aerosol agents (developed by three independent manufacturers) to act as fire suppression agents in a machinery space application [41]. Two of the agents were pyrotechnically generated from a solid, and the third agent was generated from a pre-ground solid using a pressurized gas. The systems were tested in accordance with the IMO test protocol for approval of aerosol extinguishing agents [42]. The agents were tested against fires ranging from small incipient fires and wood-crib fires to large fuel-loaded pan fires representative of a major bilge fire. The systems were installed in accordance with the manufacturer's recommendations. The test results were similar for the three systems; all systems were capable of extinguishing the small to large class B fires but had difficulty with the large pan-sized fuel fires and ultimately failed to meet the criteria required by the IMO [42].

Although pyrotechnically generated fire extinguishing aerosols have been found to pose little if any health risk to personnel [43], the activation and release conditions of the aerosol could have be potentially dangerous to personnel in close proximity to the dispersion point. The aerosols are dispersed as a hot (several hundreds of degrees Celsius) white smoke that reduces visibility to less than a meter and raises the ambient temperature of the space by 20-50 degrees C.

2.4.5 Smart Valves

The function of the reflexive "Smart" valve is to locate piping and/or valve damage based upon data available in the immediate vicinity of the valve, and to take independent action (i.e., no intervention from the DC Management System or other personnel) to isolate the affected parts of the system [44]. Through the process of damage isolation and flow realignment, the smart valve acts to provide sufficient flow to essential operating services (e.g., fire teams, sprinklers systems, etc.).

The smart valve system must be able to detect and take action in case of ruptures to the fluid system following a DC casualty event autonomically. It must also be tolerant of multiple simultaneous failures including small leaks and major ruptures, it should be simple and reliable, and the cost must be reasonable to support the aims of life-cycle cost reduction. The smart valve [44] contains the following components:

- Commercial valve and actuator (suitable for shipboard applications);
- Microprocessor and communication transceiver;
- Pressure sensors (inlet and outlet);
- Control logic that can operate the valve based on commands from a remote supervisory system; and
- Rupture detection and isolation logic capable of operating the valve independently based upon local data (when remote communication is lost).

During a series of developmental tests, the US NRL evaluated a number of design schema for implementation of a reflexive smart valve system for a firemen including both the logic criteria and functional capability [45]. The tests determined that a hydraulic resistance logic, based upon detection of a loss of pressure or an unreasonable increase in flow rate (i.e., rupture), would be the most cost effective and reliable, especially considering its independent capability to isolate a rupture without communication to other firemain components or valves. The tests also determined that the smart valve concept and design, as developed in the test series, was ready for Fleet implementation, and that further work with commercial suppliers could lead to a variety of valves and components for multiple shipboard fluid systems.

2.4.6 Ventilation and Smoke Control

During a shipboard fire, smoke poses a significant disruption to all facets of the DC response. Smoke reduces visibility which results in disorientation and deterioration of communication and contains gases that are toxic and corrosive. These pose a threat to both personnel and sensitive electronic equipment [46].

The concept of smoke removal from Naval vessels is not new to the Canadian Navy; however, this is generally done after the fire event has been extinguished to prevent introduction of oxygen. The extension of the smoke removal process to the fire-fighting phase of the DC operation would improve the ability of the ships' personnel to mitigate the event as well as reduce or eliminate secondary damage due to smoke infiltration into non-affected compartments.

During a series of tests, the US NRL developed and evaluated an automated smoke control system based upon existing shipboard HVAC components and control logic capable of automatically reconfiguring the system to provide smoke management during a fire [47]. The tests showed that the use of a non-dedicated smoke control system, based upon the fitted HVAC and Collective Protection (i.e., Citadel) Systems, provided an enhanced ability to maintain the shipboard environment during a fire. This resulted in improved fire-fighting capabilities. The non-dedicated system had advantages over a dedicated system in that it required less space and was less costly; however, the complexity required of the control system is a challenge. This results from the requirement for a flexible response to a variety of environmental conditions associated with normal HVAC operation and emergency smoke control measures.

Development and implementation of an automated smoke evacuation capability for Canadian Naval vessels is a logical and practical progression from the current in-service semi-automated systems.

2.5 DC Personnel Training

The challenge of maintaining damage control capability with fewer crew is a balance between maximum insertion of automation to augment or replace decision-making and in some cases response actions, and effective integration of the smaller crew into the overall system. Integration is accomplished through development of appropriate doctrine, and in-service training of the crew.

The US Navy Damage Control Automation for Reduced Manning (DC-ARM) program ran a series of performance trials, using real DC organizations in a controlled "Live-Fire" environment aboard the Shadwell. The initial tests were based upon existing Fleet doctrine and practices, with existing (i.e., manual) damage control capabilities. As the tests progressed, new technologies were incorporated (much of which is discussed in this report) and Fleet doctrine was revised to consider the new technology. The later tests included the most advanced automated damage control capabilities and a sophisticated Supervisory Control System (SCS) and damage control team approximately half the size of that used in the original tests.

The US Navy DC-ARM program showed that effective fire protection and damage control can be accomplished in a reduced manning environment through the use of advanced automated systems and a Supervisory Control System to integrate the actions of the automated systems with the efforts of the DC organization [52]. The final results also indicated that the revised Fleet doctrine and advanced training received by the participants contributed significantly to the ultimate success of the program.

2.6 Logistics

The analysis of the logistics required to support the integration of new DC technology into existing or new build ships was not a specific task of this study, but must be mentioned in the context of how such an introduction may affect the ship structure and design. Changes, such as the introduction of water mist fire suppression systems that require significant quantities of fresh water, must be considered in the design process of a new ship. These changes may also be a limiting factor in the introduction new technologies on existing platforms. The ship must not only have sufficient capacity to house the equipment but it must also have the space to carry the necessary spares, tools and test equipment to support these systems. Other factors may also be a concern, such as a reliable electrical source that is critical to the SCS.

A simple introduction of technology alone is not sufficient to warrant replacing crew, a start-to-finish analysis of the affect of the introduction of technology, including how it will impact crewing levels and training, must be considered in the design and implementation process. The standard Government practices of accepting alternative solutions and replacements based upon fit-form-function may not satisfy the baseline requirements for an advanced DC system and ultimately jeopardize the resulting platform capability.

2.7 Maintenance (of DC Equipment)

The achievement of advanced damage control capability, to reduce/optimize manning, can be achieved through insertion of technology; however, the gains can quickly be offset with the introduction of complicated systems that require extensive and labor-intensive maintenance. The reduction the shipboard maintenance through the use of automated sensor calibration has been investigated. Although these technologies have some potential for shipboard application, they are not currently ready for implementation in an advanced DC system.

2.7.1 Micro-Electronic Sensors

The use of micro-electronic sensors, incorporating built-in calibration and/or remote network calibration, was investigated by NRL [48] as a means of reducing sensor calibration requirements. The investigation indicated that the reliability of these types of sensors was a greater issue than the calibration, and that redundancy was a superior means to ensuring performance than calibration. Calibration will confirm if a sensor has drifted, but will not identify the state of the sensor (i.e., the sensor may fail immediately after calibration making it useless). The advantage of an array of sensors, installed and calibrated as a set, is the ability to monitor the outputs of the array and discard the output from individual sensors that may have degraded and whose results drifted away from the group results. At some point in the degradation process the entire array would require recalibration, but less often than time-based calibration of individual sensors as is the current practice.

2.7.2 Network Calibration

It has been theorized that a virtual calibration standard could be used to calibrate sensors [49], and it may be possible to remotely calibrate sensors over a network may [50 & 51]. The use of computer-based algorithms and standards has the potential to reduce the shipboard sensor maintenance load significantly, and is an area that requires further research.

2.8 Development and Assessment of Next Generation DC Tactics/Equipment

A key aspect of research and development is determining when an emerging technology is ready for introduction into the fleet and, in many cases, when the fleet is ready for the introduction of a new technology. The introduction of new technology must include consideration of the application of this technology to current tactics and doctrine. This was discussed in Phase I of this project.

3 Research Opportunities

This study has reviewed a number of technologies and technological advances related to damage control capabilities. Many of these technologies are sufficiently mature to be considered for existing and future Canadian Naval platforms. Some of these are:

- Early Warning Fire Detection Systems - the EWFD system, developed and tested by NRL, outperformed existing commercial detection systems, both in terms of detection capability and nuisance source rejection. The system could be used on both existing and new built platforms as the PNN construct is flexible in terms of the input (i.e., point detection capability on existing platforms, with addition of additional sensors on existing/new platforms as time/funding permits);
- Volume Sensors - The Volume Sensor system has the potential to provide advanced detection capability compared to point and multi-sensor detection systems. The VS system provides enhanced detection and with video-based technology also gives the DC Manager and Console Operator greater situational awareness of unfolding DC events. The technology requires further developmental work to be ready for full-scale implementation; however, the installation of a ship-wide video system would be an initial viable alternative (i.e., fit for but not with, awaiting further development of the VS);
- Shipboard LANs - The integration of shipboard LANs is a reality that is essential to modern Navies. The LAN(s) provide the means to control the basic ship (e.g., machinery, electrical, weapons, sensors (internal/external), etc.) and administrative (including DC situational awareness and Personnel Management) functions. The shipboard LAN also supports implementation of advanced DC systems, such as the ship-wide video and wireless communications systems, at a significantly lower cost than traditional hard-wired systems.
- Wireless Technology - The use of wireless communication on ships has a number of advantages, but the current state of technology is not ready for full-scale implementation due to problems associated with reliability and interference. Additional research in application of wireless communication to ships is required;
- Supervisory Control Systems - Many commercial companies have made significant advances in DC control systems (as detailed in the Phase I report). The full implementation of such systems in modern Naval platforms must be tempered with the understanding of the mission of the vessel (i.e., supply/support vessel, major combatant, etc.) and the through-life cost (and savings, if any) associated with the maintenance of the systems in service. Although this may not be an area for advanced research on behalf of the Canadian Navy, it is an area that would benefit from analysis of the impact that the insertion of such systems would have on doctrine and DC practices currently in use;
- Fire and Smoke Simulators - This is an area that would benefit from further research and development. The ability to predict how smoke, fire or a flood might spread and the use of this information to take pre-emptive DC actions would contribute to the survivability of a Naval platform during a DC crisis situation;
- Water Mist Fire Suppression Systems - This technology has been shown to be an effective and environmentally friendly alternative for Halon. Water mist systems are

commercially available and are a suitable candidate (possibly the only, in many situations) for implementation on Canadian Naval platforms, both existing and new;

- High Expansion Foam Fire Suppression Systems - Further research and development may lead to more effective products and fire suppression.
- Aerosols/Gaseous Agents - Pyrotechnically dispersed and pressurized aerosol dispersed agents are potential candidates for applications where water mist is not an acceptable alternative. However, neither are an acceptable alternative in high-risk areas such as machinery spaces;
- Smart Valves - This technology is significantly mature to consider it for applications in new and existing Naval platforms. The autonomic smart valve, along with appropriate piping and pumping arrangements, will provide a significant improvement to existing (manual) water and firemain system management;
- Ventilation and Smoke Control - The technology for a full-scale smoke management system was demonstrated in US NRL tests and would provide a significant capability to the shipboard DC organization; and
- Maintenance - The introduction of advanced DC technology will have an associated requirement for maintenance. This may require that system/sensor maintenance is conducted alongside, that sufficient redundancy is built in to eliminate at-sea maintenance or that an automated calibration/maintenance process is developed. Additional research in this area is required.

Damage Control technology has undergone significant technological advancement over the past few years, primarily as a result of NAVSEA and NRL with the support of a number of commercial developers. To advance this technology to the next stage of maturity will (in some cases) require additional development and ultimately in-service evaluation, processes that clearly will require support from the scientific community.

4 Conclusions and recommendations

A critical assessment of damage control system technologies has been completed. In particular, commercial and militarized fire suppression systems and components were reviewed and recommendations of the applicability of these technologies to both existing and new Canadian Naval ships made.

The information on the commercial components and many of the developmental systems presented in this study were confirmed through first-hand observation of the use of these components and systems during real-time fire tests aboard the ex-USS Shadwell. Significant advances have been made by NAVSEA and NRL in advanced damage control capabilities, especially in the areas of detection and event mitigation. Similarly, the commercial advancement of a comprehensive and integrated Supervisory Control System has shown good potential. Together, these technological advances have the potential to reduce number of crew required for damage control on Naval vessels.

It is recommended that:

- The individual technologies identified in this study as ready for implementation be considered for use as part of the DC system for the next class of Naval vessel as well as retrofit in existing classes where appropriate;
- Efforts to contact the UK Navy and other industry leaders in damage control systems and components be continued with the goal of identifying additional technological advances; and
- Consideration be given to joint Research and Development projects, both with industry and with NRL as appropriate, to develop a Canadian model for damage control as well as update current Navy damage control doctrine and procedures.

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Annexes

Annex A - Site Visits

Site visits were arranged to gain first hand information from some of the leading experts in Naval damage control systems, components and doctrine. The three sites visited were: the US Naval Sea Systems Command (NAVSEA) in Washington, D.C.; L-3 Marine in Leesburg, Virginia; and the Naval Research Laboratory at the ex-USS Shadwell test site in Mobile, Alabama. A full trip report and summary of discussions and findings are found in this Annex.

US Naval Sea Systems (NAVSEA)

The Naval Sea Systems Command is the United States Navy's technical authority for surface ship and submarine damage control and fire extinguishing systems, equipment and doctrine. As such, NAVSEA is responsible for engineering support to both in-service Naval platforms as well as future developments. At NAVSEA, discussions were held with Hank Kuzma, who is a Commander (USN ret'd) working for NAVSEA/Damage Control and Personnel Protection Section as an engineering technical expert. The discussion was centered on current and future damage control concepts, and included an overview of a number of specific programs (e.g., DD(X), ALCS, LPD, CG/DDG Modernization Programs, etc.). Throughout the discussions, Mr. Kuzma outlined the current DC programs as well as the NAVSEA vision for the next generation of DC Systems (e.g., DD(X)). It should be noted that the goals and visions for current or future DC systems are very similar; however, the ways and means to achieve these goals vary somewhat.

Goals

The primary goals for current and future DC systems, as envisioned by NAVSEA, are as follows:

- **Save the Ship and Crew -** During a DC emergency, the ship and crew would be facing hazards from Fire, Smoke, Flooding, CBR agents, etc. The goal is to keep the ship afloat and the crew safe such that they can continue the mission:
- **Bring the Ship to a Safe Steady-State Condition -** Post casualty, once the primary hazards have been mitigated or contained, the primary goal is to bring the ship back to an operable state through re-introduction of systems capability. These systems are necessary to provide effective control of the platform, and must be re-introduced in a manner consistent with Command priorities and imminent threats;
- **Do No Harm -** Mitigating DC actions taken should not worsen the overall situation; and
- **Get Home -** Maintain system integrity for safe return through maintenance of buoyancy, stability, structural integrity and machinery operation;

Achievement of these goals must first take into account the passive system capability of the platform as a whole. The integrated physical platform, including its structure, material makeup, insulation (i.e., fire retardant capability), etc., define the ability of the ship to survive a casualty without intervention by external means (i.e., crew and/or protective systems). An effective DC System must have the following characteristics:

- Provide a timely response to a casualty event;
- Have a fail-safe operational capability at all times (e.g., wartime/peacetime operations and during minor/major maintenance periods). Continued reliable operation when portions of the system may be disabled is important, and is a challenge in a fully integrated DC/Machinery Control system;
- Be highly reliable (i.e., distributed, survivable architecture);
- Leverage capabilities of other shipboard systems (e.g., system health monitoring systems such as the Firemain and Ventilation, Machinery Control, etc.);
- Have the ability to operate in the Automatic, Semi-Automatic, Manual and Battle Override modes; and
- Have the ability to communicate with external systems (e.g., Battle Group, Shore Facilities, etc.) in order to coordinate rescue and assist parties when required.

The NAVSEA goal of advancing DC System technology is driven by the Navy requirement to reduce (optimize) manning to achieve lower life-cycle platform costs. In achieving these goals they must be cognizant of the Fleet desires, as insertion of technology too quickly will engender an atmosphere of mistrust between the DC System and the crew. If trust were not earned through reliable operation, training and practice, the operators would tend to abandon the system in a crucial moment during a casualty event and return to basic (i.e., manual) DC concepts, thereby sidelining the DC system.

In the effort to achieve these goals, there are a number of real world constraints that must also be considered:

- **Budgetary Limitations** - Fully automated systems have a large up front cost that must be borne in order to reduce the through-life cost. There is a tendency (during the acquisition/build process) to cut aspects of the overall ship capability, especially when cost over-runs occur, which could effectively reduce the effectiveness of a state-of-the-art DC system. Truly advanced DC systems are integrated to the point where the loss of components would make the system ineffective in critical situations. Furthermore, the increased maintenance load due to implementation of less than adequate DC components/systems to reduce up-front costs could also seriously affect through-life costs and negate the primary goal of reducing/optimizing the crew;
- **Increased Value of Crew** - The insertion of technology and overall reduction of the crew size will mean that the remaining personnel will have to be better trained, and are much more valuable in terms of minimizing losses of these personnel during a casualty. Personnel protection and collective protection are vital and must be considered in the overall design process of advanced DC systems;
- **Reliance on Electrical and LAN Networks** - One of the key components of the ships survivability is maintenance of "Power" and "Communications", without which a DC system, be it automated or manual, would not be effective and would put such a ship in severe jeopardy;
- **Multiple Simultaneous Casualty Response** - The ability of a DC system to effectively respond to cascading Damage Control and/or Failure events (as would be

seen post catastrophic event such as a missile hit) is a key issue that must be addressed through design and implementation. This is achieved through multiple redundant system capabilities and, until proven, remains a concern. One technology that may help to alleviate this is the Smart Valve, which has the capability to take independent action and does not rely on the larger DC system;

- **Obsolescence -** In a world of rapidly changing technology, obsolescence of system hardware is a considerable concern. The ability to rapidly update hardware components in an administrative system (LAN) is a challenge for a tightly controlled highly integrated system such as the Machinery Control System on modern warships; and
- **Commercial Reliance -** Modern integrated Damage Control (and Platform Management) systems are expensive to implement and maintain, and when employing COTS come with a requirement to have the system designer support the system through-life (due to proprietary issues). This reliance on commercial reach-back support could prove to be problematic in certain circumstances, and certainly comes with a significant associated cost.

Current DC Program

The current NAVSEA vision is focused around supporting in-service DC systems, and updating those systems as time, opportunity and funding become available. Within this vision, the focus for DC response is quite traditional and is based upon a reactive capability as depicted in Figure A-1.

The structure required to perform both Machinery Control and Damage Control within the construct of a Casualty Management capability includes a mixture of automated and manual processes and systems. The current construct for DC Systems is depicted in Figure A-2, and includes a Sensory Control and Monitoring System (SCM) (i.e., Machinery Control System) which is based upon proven technology and is built, tested, and locked down in terms of hardware and software to ensure continued reliable operation of the ship and its equipment. The DC System may also include a Damage Control Tactical Management (DCTM) system; which may be interfaced to the SCM System, but does not generally have the capability to do functional interaction with the SCM System. The DCTM System may include the capability to "Plot" casualty events (automatically or manually) including automated display replication, the ability to communicate with the active event participants (i.e., Command, Repair Parties, etc.), and possibly provide some redundancy in terms of event management through delegation of responsibility for certain aspects of the casualty (e.g., Firemain or Ventilation control).

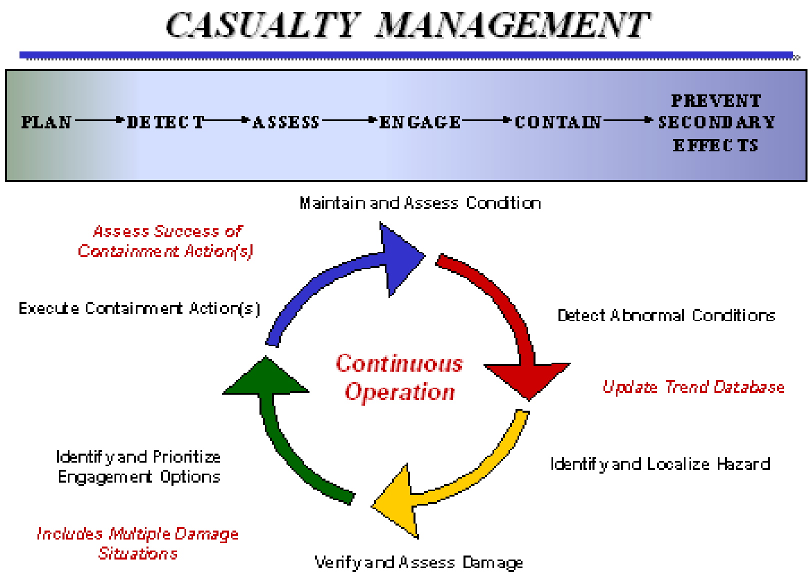

Figure A-1. Casualty Management

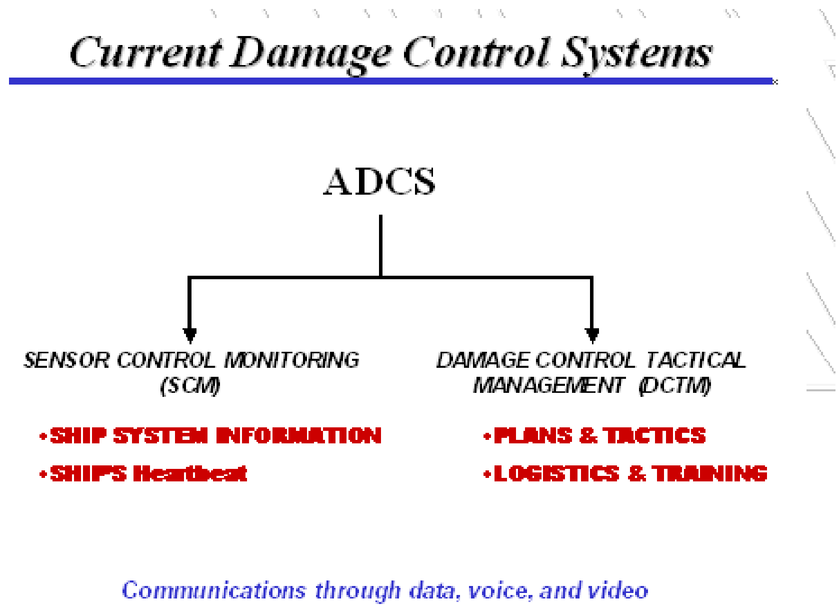

Figure A-2. Damage Control System Construct

The US Navy "Smart Ship" Program was based on the construct above and attempted to provide greater integration between the two systems. Despite the program demonstrating that technology insertion has the ability to reduce the overall manning requirements [2], it has not been widely proliferated within the US Fleet in the 10 plus years since the program began. The Smart Ship Program has now been absorbed into the CG/DDG Modernization Program (i.e., mid-life updates) that are currently in the planning phase. Implementation of these programs is programmed to begin in the next 2-3 years; however, a major shift from the current construct for DC System technology is not expected.

Next Generation DC Systems

There is much speculation about the make up of future generations of DC Systems. US Navy programs, such as the DC-ARM and Smart Ship initiatives have had a significant influence on this vision; however, the insertion of such advanced technology before it is proven (or, for that matter, ready) could have significant drawbacks if not properly managed. Furthermore, competing priorities of the various concerned parties (Government, Office of Naval Research (ONR), NAVSEA, etc.) can significantly affect the eventual outcome, and ultimately the in-service issues that will have to be managed by the US Navy.

The significant case in point is the US Navy DD(X) program that is currently in the concept development phase. The conceptual ideology behind this program, as directed by the Government and facilitated by ONR, is driven by the following concepts:

- **Manning** - a 70% reduction [2] of crew (based upon similar-sized in-service vessels) is to be achieved through insertion of technology to support DC functions;
- **Maintenance** - all maintenance will be provided via shore-based support. A very limited ability to conduct maintenance will be borne at sea;
- **Personnel** - shipboard personnel will be "Operations" centric with an at-sea focus of controlling shipboard functions vice repairing and/or maintaining these functions; and
- **DC Organization** - there will be a heavy reliance on an automated DC System to manage casualty events and the physical intervention capability will be minimal (or non-existent).

NAVSEA Vision

The objective of future DC Systems is to interface and integrate current and future Damage Control Methodology, Software and Systems to build a comprehensive and standard Advanced Damage Control System that responds to the specific Mission needs and requirements of the US Navy. These objectives can be summarized as follows:

- Tactical:
    - Provide information and decision making tools at all levels in a stressful environment;
    - Utilize contingency planning for every casualty scenario; and
    - Daily use ensures Total Ship Readiness.
- System:
    - Open Architecture;
    - Real time, multi-tasking system;
    - High reliability;
    - Distributed Networks and Voice Communications;

  - Failsafe design; and
  - Capability to rebuild the DC Tactical Information after loss of power and/or LAN's.

These goals will be achieved through a cooperative approach between NAVSEA, Fleet and industry in order to develop and refine total requirements and system objectives. The system architecture is to be based upon "Building Blocks" that allow users to have access to all available electronic information, data, and products, that is delivered on COTS hardware and non-proprietary software with the appropriate "Naval" technical insertions. A parallel life cycle support and development approach is to be taken, permitting update of technology as it becomes available, yet maintain supportability (i.e., logistics, training and maintenance). The hardware approach is to include:

- Utilization of Consoles, Workstations, Laptops, Wearable Computers, PDAs, Flat panels, Cameras, Wireless imaging devices, etc.;
- Communication into Damage Control Central (DCC) and each Damage Control Repair Station (DCRS) from all available media and cable plants; and
- Communication with the scene anywhere & anytime (i.e., Mobile Connectivity).

The future Advanced Damage Control System (ADCS) has three components that require integration; however, the means of achieving this integration is the key. These components are defined as follows:

- Damage Control and Fire Protection Systems (part of the Engineering Control System);
  - Sensor Control and Monitoring (SCM) - Damage Control & Fire Protection Systems include:
    - Sensors - Fire, Smoke, Flood, GFE and CBR
    - Firemain & Countermeasure Washdown
    - Ballasting and Main Drainage
    - AFFF and Bilge Sprinkling
    - Halon/CO_2/HFP/Water Mist
    - Sprinkler (wet and dry)
    - Fresh Water FF
    - HVAC and Smoke Ejection
    - CBR and Collective protection systems
    - Console Health and MCS LAN Communications
    - Display of propulsion, electrical, auxiliary, chill water systems configuration and status
- Damage Control Tactical Management (DCTM) includes:
  - Tactical - DC Plotting of damage, casualties, and stability on ship's views
  - Display of ship plan, profile, isometric and 3D views
  - Display of compartment and system detail views to aid in compartment isolation and system aggregation
  - Asset management for DC, Auxiliary, Electrical and ADP
  - Tactical DC aids to assist in the decision making process
  - Display of fixed and portable video and audio inputs

    - Personnel location tracking
    - Closure monitoring
    - Event logging including alarms, plots, MSFD, personnel movement
- Damage Control administration, training, maintenance and technical documentation.

Summary

The ADCS will provide the fleet with an overarching structure for modular improvements by interfacing current, state-of-the-art technology and advanced DC concepts to meet the future shipboard casualty damage and will be a portal for standardization of damage control information engineering both for the current and future fleet

Future Challenges

The road-blocks that must be overcome to achieve a truly "Integrated" and comprehensive DC System include the following:

- Wireless Technology - Advancement and proliferation of wireless technologies, both in terms of communications, data transfer, and sensors will significantly improve current capabilities. The use of wireless portable devices (PDA's, Tablets, Video, etc.) on ship would enhance the ability of the operators to manage critical events;
- Personnel Protection - In a high technology, low manned ship of the future, each individual on the ship must be better trained, more skilled, and extremely more valuable in terms of platform survivability and mission completion. The inherent ability to protect such personnel during a casualty event becomes vital;
- Training - Advanced technology may not be inherently easy to comprehend, and the ability to properly train shipboard personnel, both ashore and on-board ship, is very important. One of the key factors in minimizing the training load is a common look and feel (i.e., standardization) of such systems between differing platforms;
- Sensors - Miniaturization of sensor technology coupled with wireless technology could provide the means to restore sensing capabilities in a Primary Damage Area. A portable sensor array could be "Tossed" into a damaged area and provide the data necessary for the automated (and/or manual) operators to manage the casualty event where they would otherwise be acting blind;
- Structural - The ability to automatically sense structural damage and possibly to take counteractive steps to avoid critical instability is important, especially in a low-manning situation where the crew may not be able to physically deal with such situations;
- Fire Countermeasures - Advanced Water Mist systems, environmentally friendly halon replacements (e.g., Pyrogenes) and replacements for AFFF are the best current alternatives and must continue to be developed and implemented; and
- Simulation - Advanced DC Systems rely on simulation and modeling of events to predict possible outcomes in order to take action and/or provide recommendations for action in order to mitigate such events. This activity also provides significant information (i.e., scenario generation) required for development of advanced smart "Expert" systems and supports end-used training requirements.

Further information on the various NAVSEA and US Navy Programs can be found at the DC Website: www.DCFP.NAVY.MIL.

L-3 Marine

L-3 Marine Systems, located in Leesburg, Virginia, is a leading designer, manufacturer and integrator of marine platform control systems and training solutions for U.S. naval and commercial customers. Their systems are currently in use on the USS Yorktown, the CVN77, and the MHC-51 and the LPD17 class ships, as well as numerous other Naval and commercial vessels throughout the world. At L-3, discussions were held with Greg Gudger and Leon Nicholle, who are Business Development Managers. The discussion was centered on current and future damage control concepts from a leading commercial design point of view. Due to security concerns, and restricted access to the L-3 development laboratories, the discussion was very general in nature and, at times, was very sales oriented. It should be noted that the L-3 goal is ultimately to sell their systems, be that current or future, hence the tendency to provide a sales pitch was not unexpected.

L-3 follows a modular software design approach, which means that they are able to integrate various capabilities independently, and as such, a solely L-3 system is not necessarily required. They also believe that this modular approach means that they would be able to upgrade their system (hardware and software components) through-life without the requirement for major re-testing, thereby allowing for insertion of advances in technology while retaining the goal of reduced life-cycle cost, which was a concern expressed by NAVSEA.

In terms of platform integration, L-3 operates on the principle that their system can be integrated over and above any other fitted control and monitoring system and is capable of taking on as much (or as little) control as desired by the customer, depending on the level of complexity of the vessel and the degree of automation. However, they did admit that greater automation does come with a significant cost (both initially and through-life). In general though, L-3 is of the opinion that their systems are fully capable of integrating and managing an entire platform (e.g., Machinery, Weapons, Navigations, Sensors (internal and external), etc.), which includes all aspects of automated Damage Control. Furthermore, they believe that a distributed, survivable network will be able to recover from a major casualty event (such as a missile hit) and maintain the ship in an operating state with very little or no human intervention.

As a case in point, the DD(X) Autonomic Fire Suppression System (AFSS) developmental test series included a Weapons Effect Test (WET), conducted on the ex-USS PETERSON (DD 969) in the Gulf of Mexico, to demonstrate this key technology as a means to enable crew reductions [53]. The AFSS Prototype consisted of a advanced firemain and water mist architecture (e.g., smart valves, smart pumps, etc.), with a survivable device level control network. The system also deployed advanced piping architectures, intermediate pressure water mist and sidewall primary damage area water mist technology. Despite the severe damage to the ship as a result of the WET, the AFSS autonomically sensed the firemain ruptures and reconfigured the suppression systems within the allowed four minutes and activated, successfully containing the fire to within the primary damage area (with no human intervention). The test was overall very successful at demonstrating the various technologies, including the deployment of the intermediate pressure (250 PSI) sidewall water mist nozzle. Further testing on the AFSS was conducted on the ex-USS SHADWELL, which is reported in the next section of this report.

Two areas where L-3 has had resistance to insertion of advanced DC technologies (primarily related to Naval applications) are as follows:

- Video Monitoring - due to concerns over rights to privacy, there is currently no consideration being given to installation of video surveillance capabilities in living quarters. This equates to a significant loss of capability, especially if an advanced sensor program was being considered, as a significant percentage of non-action related fires originate in living spaces; and
- Personnel Tracking - the ability to monitor personnel locations, either through Infra-Red or RFID technologies, would provide a significant capability to senior DC management personnel in an emergency situation. Unfortunately, this has been reviewed by Human Rights and found to be an unacceptable invasion of privacy, especially when personnel are off duty (at sea or along side).

Further information on L-3 Marine can be found at their website:
www.mapps.l-3com.com/html/marine/locations/leesburg.html

Naval Research Laboratory (Ex-USS SHADWELL Site)

The Naval Research Laboratory (NRL) is the United States Navy's corporate research laboratory responsible for conducting a broad program of scientific research in support of advanced technology development. NRL is located in Washington, D.C; however they have a number of field sites that have active research programs including the Chesapeake Bay Detachment that provides facilities and support services for research in radar, electronic warfare, optical devices, materials, communications, and fire research; and the ex-USS Shadwell, which is a decommissioned United States Navy Landing Ship Dock that serves as the Navy's full-scale damage control research, development, test and evaluation platform.

The NRL approach to Damage Control research is three tiered, the first being laboratory research and development at the Washington labs, then controlled testing at the Chesapeake Bay facility, and finally full-scale testing aboard the ex-USS Shadwell. Technology tested on the Shadwell includes that developed as part of US Navy research programs as well as performance testing of COTS equipment. In order to gain a first hand view of state-of-the-art equipment, a two-day visit to the Shadwell was conducted.

On the Shadwell, discussions were held with Dr. Fred Williams, who is the Director, Navy Technology Center for Safety and Survivability as well as the lead technical authority for the Shadwell test facility. Dr. Williams was very open to discussing the tests that had been performed on the Shadwell over the past 18+ years and provided a good insight to current and future technologies as they relate to advanced Damage Control systems. In addition to the discussions, and a detailed tour of the facility and its unique capabilities, a number of live fire tests were witnessed. A full report of the facility, the discussions and the live-fire tests is detailed below.

Ex-USS Shadwell

The ex-USS Shadwell was acquired by NRL from the US Navy in the mid 1980's and is currently anchored in Mobile Bay, Alabama under the auspices of the Navy Technology Center for Safety and Survivability [3]. The Shadwell serves as a full-scale test platform in the development of fire models and other predictive tools, agents, systems and technology stemming from basic and theoretical concepts developed through research and development projects. The platform allows the application and consolidation of research developments in order to give an integrated picture of the interactions of man, equipment, materials, tactics, doctrine and related systems in a real shipboard environment. The Shadwell also serves as a realistic test platform for endeavors other than damage control that evolve from research, such as coatings, insulations, working fluids, cleaners and communication systems. A description of the Shadwell ands it's fitted system is included below.

Test Areas

The Shadwell is divided into five test areas as follows:

- Passive Fire Test Area - Located in the forward upper area of the vessel, this area is used by the Passive Fire Program (PFP) and includes a hood calorimeter that collects all fire products and passes them through the calorimeter stack. This allows the measurement of heat release rate from the fire, and provides complete gas analyses, flow and smoke measurements;

- Forward Surface Ship Test Area - This area is configured to simulate a DDG 51 platform and is used primarily for training. The area can be set up to simulate a range of casualty events (e.g., fires, floods, etc.) from the mundane up to a full-scale missile hit;
- Machinery Space Test Area - This multi-deck area encloses a large volume (395 m^3) and is configured to represent a typical machinery space including an engine mock-up, and has deck gratings, ladders and an operator control station. This area is used to test various components of a DC extinguishing system including AFFF, Halon, Water Mist, Pyrogenes and the hardware associated with these systems; and
- Submarine Test Area - This area contains fourteen spaces plus a Sail area that are connected by watertight doors and/or hatches. The area can be isolated from the rest of the ship, and is capable of testing fire, flood, hulls repair, pipe patching, shoring, dewatering and other DC-type activities.

Fitted DC Systems

The Shadwell is outfitted with a similar arrangement of DC systems and equipment that would be present on a modern Naval vessel as outlined below:

- DC Central and Repair Stations - Shadwell has one DC Central and three DC Repair stations. DC Central (Figure A-3) contains an intelligent Supervisory Control System (c/w automated decision aids) for displaying DC sensor information, plotting casualty events and for automatic and remote control of various DC systems. There is also a (simulated) machinery control station that displays shipboard machinery and system status. Each Repair Station contains standard US Navy DC equipment (e.g., communications, fire extinguishers, breathing apparatus, dewatering equipment, firefighting ensembles, forcible entry equipment, etc.) as well as a DC System Computer Work Station (Figure A-4) that is linked to the DC Central system;

Figure A-3. Damage Control Central

Figure A-4. Typical Repair Station - DC System Computer Work Station

- Firemain - The Shadwell is fitted with a 3.5 in horizontal loop firemain with two electrical driven fire pumps that services the fire plugs located throughout the ship. The system has numerous cross-connects and seventeen isolation valves, eight of which are Autonomous Smart Valves (Figures A-5 and A-6) that enable an automated isolation response to system damage;

Figure A-5. Autonomous Smart Valve (Overview)

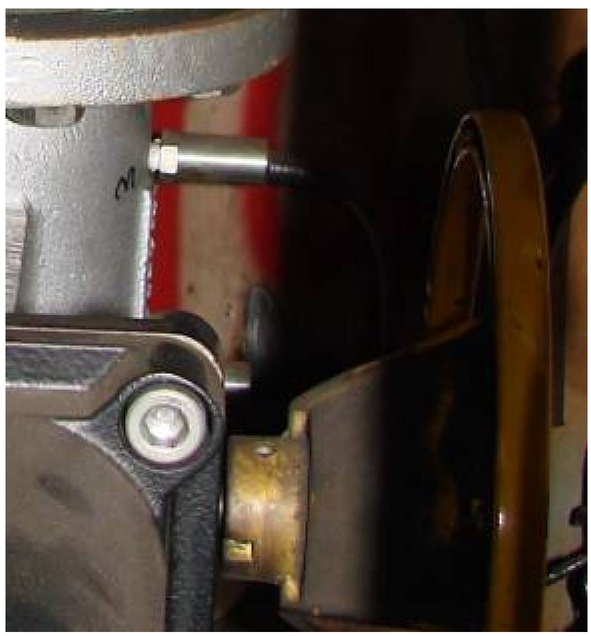

Figure A-6. Autonomous Smart Valve (Sensors)

- Portable Fire Fighting Equipment - Portable fire fighting equipment and extinguishers (CO_2, PKP and AFFF) are located throughout the ship as well as hose reels and AFFF stations associated with the fire plugs;

- Water Mist Suppression System - The Shadwell is fitted with two high-pressure (1000 PSI) water mist suppression systems (Figures A-7, A-8 and A-9). The first system is installed in the Forward Test Area and has a multi-branch sectional loop construction. Each branch is controlled by an electrical solenoid connected via the Ships' LAN to the Main Control Room. The second system is installed in the Machinery Space and has two zones corresponding to the first and second levels of the space. The Machinery Space system is also controlled from the Main Control Room as well as from three local control stations;

Figure A-7. Shadwell High-Pressure Water Mist Pump

Figure A-8. Securiplex Water Mist Nozzle in Machinery Space

Figure A-9. Water Mist Nozzles - Electronic Space

- Ventilation Systems - The Shadwell has a general service ventilation system for general heating, ventilation and air conditioning as well as three additional systems as follows:
    - Collective Protection System (CPS) - The CPS provides an overpressure of 0.5 kPa in the Forward Test Area and is also capable of providing a limited overpressure in the Machinery Space;
    - Smoke Ejection System (SES) - The CPS is capable of being reconfigured as the SES and is capable of removing smoke from various parts of the ship; and
    - Shadwell/688 - This system is designed to simulate the submarine recirculation system;

Figure A-10. Shadwell Main Control Room

Instrumentation

The Shadwell has an extensive sensor and systems control suite that is all connected via the Shadwell LAN to the Main Control Room (Figure A-10). The LAN consists of three subnets that are interconnected including:

- Fiber Backbone - Consists of an optical fiber plant system that manages Ethernet data between the ten Node Rooms, including network and video data;

- Shadwell Net - Supports the Main Control Room and Damage Control Central functions, as well as other administrative network requirements; and
- DCS Subnet - Consists of seven work stations located throughout the ship for displaying DC alarms and plotting, and for monitoring resource allocations;

All fire and test compartments are fitted with instrumentation to measure temperature, smoke density, heat flux, gas concentrations and air pressure, as well as a series of ship-wide pressure transducers to monitor firemain, liquid fuel, water mist and ventilation system parameters. All sensors are linked to a MassComp data acquisition system (via the Shadwell LAN) that can be programmed to capture up to 400 channels of data at a sampling rate of 10 Hz, and can display this information in real time on the Main Control Room monitors.

DC Discussion

During the first day on Shadwell, Dr. Williams provided a very detailed tour of the facility encompassing all of the equipment and areas described above, as well as many of the specific equipment detailed in previous sections of this report. Dr. Williams shared many of the same visions of advanced damage control as Hank Kuzma from NAVSEA; however, he believes that much of the technology that has been developed should be moved to the fleet more rapidly than NAVSEA is willing to support. He did caveat his statements though, in that the technology that has been developed by NRL, and tested on the Shadwell, is at the R&D level of maturity and that it would require a manufacturer to take this technology to the next level where it would be a viable commercial system for use on Naval and/or commercial vessels.

While on the Shadwell, Dr. Williams noted that many of the final reports that come from the various tests on the ship are produced as "NRL Letter Reports" and are not specifically released as part of the normal procedure to other interested nations. These reports are held by Dr. Williams himself, and contain information that would be of significant value to the Canadian Navy. Access to these reports may be possible, but must be requested through official channels. He provided two reports of interest (for review only), the details of which follows.

Water Mist System Testing Standard

The first report [54] was based upon the significant Water Mist trials done on the Shadwell in development of the LPD-17 system, and provided the standard against which all commercial water mist systems are compared. In order to understand the standard performance chart (Figure A-11), it is important to first understand the basic conceptual operation principles behind water mist systems. The extinguishment of the fire is caused by a reduction of the oxygen concentration in the space caused by first, the consumption of oxygen by the fire itself and; second the further reduction due to the presence of saturated water vapor mist and steam (vaporized by the fire). As a result of this effect, the time taken to extinguish a fire is a combination of the size of the fire, the compartment geometry (volume, surface area and ventilation rate) and the quantity of water mist reaching the fire.

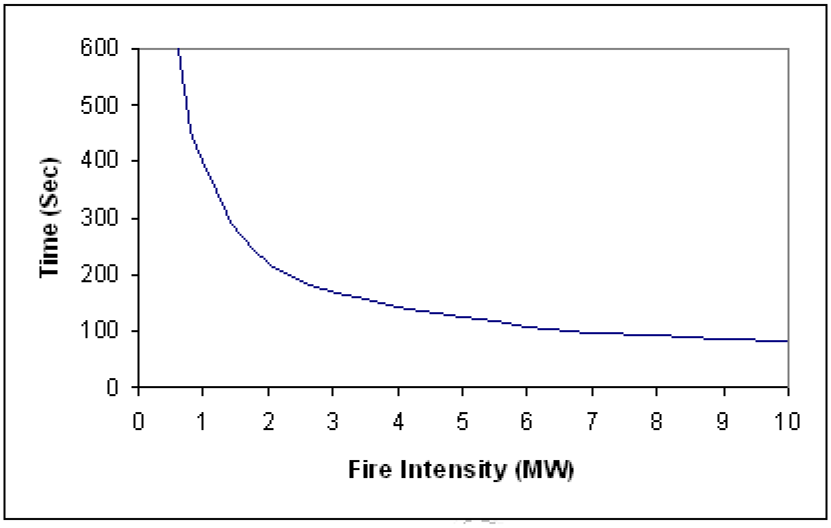

Figure A-11. Water Mist Performance Standard (Representation)

Given a given geometry and ventilation rate, the larger fire will be extinguished much quicker than the smaller fire, as the interaction of the water mist with the fire will reduce the oxygen concentration quickly. In the extreme, for a very large fire the oxygen is depleted rapidly by the fire and the water mist reaching the base of the fire is not critical. Conversely, for a small fire, the water mist reaching the base of the fire is important and, in the extreme, below a certain size the system is not capable of putting the fire out. The small fire that can't be extinguished by the water mist system could easily be put out by a hand-held extinguisher. On the performance graph (Figure A-11), a commercial system that is tested and falls below the line performs better than the LPD-17 system fitted on Shadwell (i.e., these systems would be certified for use on US Naval vessels), and those above the line do not perform as well.

It should be noted that reduction of oxygen concentration when the water mist is activated is not below that level required to support human life (i.e., there is no need to evacuate the space before activating the system) and, even though there is a very minor cooling/wetting effect due to the water mist, this is not the primary extinguishment means. The actual water consumption used by a water mist system to extinguish a major fire is considerably less that that of a conventional system (a few gallons vs hundreds of gallons).

DC Triad Communication System

The DC Triad Communication System [55] is being developed by MTS Technologies under contract from the Office Of Naval Research under the FNC-CRIDCC program. The objective of the project is to develop an advanced prototype DC communication system with redundant, reconfigurable, compatible (forward and backward) capabilities that will compliment and enhance current DC communication capabilities.

The system is based upon a "Triad" communication concept that has at the core a wireless communication interface between the DC decision makers at the scene of a casualty event and the DC Command and Control organization (i.e., DC Central and/or DC Repair Station). The system uses COTS equipment and capabilities, suitable for transmission of wireless voice and data; however, the transmission methodology is the key advancement. The system is capable of communicating as follows:

- Primary communication is over a wireless network (WLAN) using Voice/data over Internet Protocols (VOIP) via the ships' LAN;
- If the LAN is unavailable, the system automatically switches to transmission over the ships' AC power system; and
- To complete the triad, the system can also revert to transmission over the ships' Sound Power network.

The final report for the trials has not been published; however, the results were considered very good.

Live-Fire Tests

On day two of the visit, a series of live fire tests were conducted to determine if the Securiplex Water Mist Nozzles (Figure A-8) would be validated for use on US Navy ships. A total of six fire tests were conducted, two each at 1 MW, 3 MW and 6 MW intensity. The tests are managed and controlled from the Main Control Room (Figure A-12) and a viewing portal is available adjacent to the Main Machinery Space to view the test directly.

Figure A-12. Main Control Room (3 MW Live Fire Test)

During the test, all data (space temperatures, on-scene video, water pressure and flow rate, fuel flow, etc.) is recorded for future playback and assessment as part of the overall test process. This data is also displayed on the Main Control Consol during the test (Figure A-13).

Figure A-13. Main Control Console (3 MW Live Fire Test)

Overall, the Securiplex nozzles out-performed the LPD-17 baseline nozzles on the Shadwell in the 1,3 and 6 MW tests as well as the 10 MW tests performed the previous week.

Figure A-14. LPD-17 Firemain/Water Mist Pump (ex-USS Shadwell)

General Observations

During the discussions, Dr. Williams made a number of general comments that should be mentioned:

- Volume Sensors - It was noted that a significant effort has been made by NRL in the development and evaluation of the Volume Sensor described earlier in this document, and the Volume Sensor has shown excellent potential and should be further refined (in conjunction with industry) to make it a marketable tool. However, despite these efforts, the Volume Sensor has not been recognized by NAVSEA and/or the US Navy, and is currently not planned for the DD(X) program;

- Water Mist - Hank Kuzma mentioned that the integrated DC System must remain in tact as designed or deficiencies could be introduced that would reduce the system capability. A case in point is the LPD-17 Water Mist system, which has been installed in the 5 main machinery spaces. During the integration process, the design agent made the choice to combine the Water Mist and Firemain systems to reduce weight, and choose to install a medium pressure (300 PSI) system utilizing four 400 HP pumps (Figure A-14) that use fresh water (requirement of the water mist system). Unfortunately this has lead to a number of difficulties
    - The entire firemain was constructed from Stainless Steel, which has lead to significant corrosion due to dissimilar metals (flanges, bolts, etc.) and contamination of the water mist network making it less than optimal in performance;
    - The system pressure is too high for fire hose use, and leads to very high water consumption; and
    - Tests aboard the Shadwell have determined that the medium pressure system (even when optimal) is not capable of extinguishing a major space fire (e.g., Machinery Space).
- RF Wireless Communications - Dr. Williams noted that the tests aboard the Shadwell highlighted the issue of poor RF propagation in a ship environment. Numerous dead spots lead to a loss of communication and, during a major fire, the ionization effect of the fire will further interfere with RF propagation; and

List of Abbreviations

ADC	Advanced Damage Countermeasures
ADCS	Advance Damage Control System
ADP	Automated Data Processing
AES	Aerosol Extinguishing System
AES	Aerosol Extinguishing System
AFFF	Aqueous Film Forming Foam
AFSS	Automated Fire Suppression System
ALSC	Alternate Logistics & Sealift Capable
BDCS	Battle Damage Control System
CBR	Chemical Biological Radiological
CBRN	Chemical Biological Radiological Nuclear
CCD	Charge Coupled Device
CG/DDG	US Navy Cruiser/Destroyer
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COTS	Commercial Off-The-Shelf
CPS	Collective Protection System
CPS	Collective Protection System
CVN	US Navy Aircraft Carrier
CVNX	Future US Navy Aircraft Carrier
DC	Damage Control
DC-ARM	Damage Control - Automation for Reduced Manning
DCC	Damage Control Central
DCRS	Damage Control Repair Station
DCS	Damage Control System
DCS	Damage Control System
DCTM	Damage Control Tactical Management
DD	US Navy Destroyer
DD(X)	Future US Navy Destroyer
DLL	Dynamic Link Library
DRDC	Defence Research & Development Canada
EWFD	Early Warning Fire Detection
FF	Fire Fighting
FNC-CRIDCC	Future Naval Concepts - Crew Reduction through Improved Damage Control Communications
FSSIM	Fire & Smoke Simulator
FY	Fiscal Year

GFE	Gas Free Engineering
HBFC	Hydrobromofluorocarbon
HCFC	Hydrochlorofluorocarbon
HE	High Expansion
HEFFSS	High Expansion Foam Fire Suppression System
HFC	Hydrofluorocarbon
HVAC	Heating, Ventilation and Air Conditioning
Hz	Hertz
IMO	International Maritime Organization
Inc.	Incorporated
IPMS	Integrated Platform Management System
IR	Infra-Red
ISL	Intelligent Security Limited
JSS	Joint Support Ship
LAN	Local Area Network
LAN	Local Area Network
LP	Long Pass
LPD	Landing Platform Dock
LWVD	Long Wavelength Video Detection
MHC	US Navy Mine Hunter Class
MSFD	Machinery Space Fire Detection
MTS	Management & Technical Services
MW	Mega-Watt
NAVSEA	Naval Sea Systems Command
NRL	Naval Research Laboratory
OFD	Optical Fire Detector
OH	Hydroxyl radical
ONR	Office of Naval Research
PC	Personal Computer
PDA	Primary Damage Area
PDA'S	Personal Digital Assistants
PFOS	Perfluorooctane Sulfonate
PFC	Perfluorocarbon
PFP	Passive Fire Program
PKP	Potassium Bicarbonate (Purple K) Fire Extinguisher
PMT	Photo Multiplier Tube
PNN	Probabilistic Neural Network
ppm	parts per million
PSI	Pounds per Square Inch
PSM	Personnel Status Monitor

R&D	Research & Development
RDT&E	Research, Development, Test & Evaluation
RF	Radio Frequency
RFID	Radio Frequency Identification
SBVS	Spectral Based Volume Sensor
SCM	Sensory Control & Monitoring
SCS	Supervisory Control System
SCSC	Single Class Surface Combatant
SES	Smoke Evacuation System
SFA	Smoke & Fire Alert
SP	Short Pass
TIC	Toxic Industrial Chemical
UK	United Kingdom
US	United States
USN	United States Navy
USS	United States Ship
UV	Ultra Violet
VOIP	Voice Over Internet Protocol
VS	Volume Sensor
VSD	Visual Smoke Detection
WET	Weapons Effects Test
WLAN	Wireless Local Area Network

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Phase IIa: Fire Suppression Systems and Components

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The Canadian Navy is currently in the process of developing the requirements and contracting for delivery of new classes of ships. The Navy has identified the reduction of through-life costs of new ships as a priority. As crew size is a major contributor to through-life costs, ways of reducing crew number are being investigated. However, crewing levels can only be reduced if the ability of the ship to complete its mission is not jeopardized.

In Phase I of this project, a critical assessment of available technologies, both commercial and militarized, in Battle Damage Control Systems (BDCS) was conducted with the goal of providing insight on the future vision for Naval damage control as it relates to the goal of crew reduction/optimization.

In this Phase II report, a critical assessment of fire suppression systems and components was completed to rationalize which systems/capabilities are sufficiently mature to be considered for implementation on new and/or existing Canadian Naval platforms.

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