Copy No. _____

Defence Research and Development Canada / Recherche et développement pour la défense Canada

DEFENCE R&D DÉFENSE

Review of Portable, Manually Operated, and Non-Total Flooding Fire Extinguishing Technologies for Use on Naval Vessels

Charles Williams, Steve J. Bodzay and Robert Williams
CRW Regulatory Services

Prepared By:
CRW Regulatory Services
2057 Oxford Street
Halifax, Nova Scotia B3L 2T3

Contract Project Manager: Dr. Charles Williams, 902-422-2770
PWGSC Contract Number: W7707-115134/A
Contract Scientific Authority: Dr. John Hiltz, Defence Scientist, 902-427-3425

Defence R&D Canada – Atlantic

Contract Report
DRDC Atlantic CR 2011-293
December 2011

Canada

This page intentionally left blank.

Review of Portable, Manually Operated, and Non-Total Flooding Fire Extinguishing Technologies for Use on Naval Vessels

Charles Williams, Steve J. Bodzay and Robert Williams
CRW Regulatory Services

Prepared by:
CRW Regulatory Services
2057 Oxford Street
Halifax, Nova Scotia B3L 2T3

Contract Project Manager: Dr. Charles Williams, 902-422-2770
PWGSC Contract Number: W7707-115134/A
CSA: Dr. John Hiltz, Defence Scientist, 902-427-3425

Defence R&D Canada – Atlantic

Contract Report
DRDC Atlantic CR 2011-293
December 2011

Original signed by John A. Hiltz

John A. Hiltz
Scientific Authority

Approved by

Original Signed by Leon Cheng

Leon Cheng
Head Dockyard Laboratory (Atlantic)

Approved for release by

Original signed by Calvin V. Hyatt

Calvin V. Hyatt
Chair/Document Review Panel

This work was carried out as part of Applied Research Program (ARP) Project 11gy - Technologies for Fire and Damage Control and Condition Based Maintenance.

Abstract

Portable fire extinguishers are an integral part of fire fighting capabilities on board naval vessels. In many cases they allow crew to extinguish or suppress small fires before they can grow and become a significant threat to life and the vessel itself. There have been a number of developments in portable and handheld extinguishers in the last twenty years. Many of these use technologies that have been developed to replace Halons in total flooding and local application or portable extinguishment systems. These technologies include water mist, aqueous film forming foams, compressed air foam systems, cutting extinguishers and propelled extinguishing agents technologies (PEAT) or aerosols.

In this Contract Report fire extinguishment and suppression technologies that can be delivered by portable and/or handheld systems are reviewed and critically assessed. Some of the limitations and concerns associated with the use of these systems are discussed.

Résumé

Les extincteurs portatifs font partie intégrante de l’équipement de lutte contre les incendies à bord des navires militaires. Dans plusieurs cas, ils permettent d’éteindre ou de supprimer de petits incendies avant qu’ils ne prennent de l’ampleur et ne deviennent une menace importante pour le personnel à bord et pour le navire. Un certain nombre de mises au point ont été effectuées dans le domaine des extincteurs portatifs au cours des vingt dernières années. Certaines mises au point font usage de technologies conçues pour remplacer les systèmes au halon pour le noyage et la projection localisée ou les systèmes d’extinction portatifs. Ces technologies comprennent les extincteurs à brouillard d’eau, les extincteurs à mousse à formation de film flottant, les systèmes de mousse à air comprimé, les extincteurs à découpe par jet d’eau, ainsi que les technologies d’agents extincteurs propulsés ou d’aérosols.

Dans le présent rapport de contrat, les technologies d’extinction et de suppression d’incendies des systèmes d’extinction portatifs sont examinées et évaluées de façon critique. Certaines contraintes et certains problèmes relatifs à l’utilisation de ces systèmes sont mentionnés.

This page intentionally left blank.

Executive summary

Review of Portable, Manually Operated, and Non-Total Flooding Fire Extinguishing Technologies for Use on Naval Vessels

Charles Williams, Steve J. Bodzay, and Robert Williams; DRDC Atlantic CR 2011-293; Defence R&D Canada – Atlantic; December 2011.

Introduction: The detection, control and extinguishment of shipboard fires before they can develop is of great importance to a ship's crew. This is particularly important for naval vessels, which may carry large quantities of highly flammable fuel and an arsenal of explosives and their propellants. Naval vessels are also required to operate in hostile environments where the threat of fire resulting from battle damage is ever present. As a result, naval vessels must have at their disposal the most effective means of fighting fires.

Portable fire extinguishers are an integral part of fire fighting capabilities on board naval vessels. In many cases they allow crew to extinguish or suppress small fires before they can grow and become a significant threat to life and the vessel itself. There have been a number of developments in portable and handheld extinguishers in the last twenty years. In this Contract Report by CRW Regulatory Services fire extinguishment and suppression technologies that can be delivered by portable and/or handheld systems are reviewed and critically assessed. Some of the limitations and concerns associated with the use of these systems are discussed. This work was carried out as part of Applied Research Program (ARP) Project 11gy - Technologies for Fire and Damage Control and Condition Based Maintenance.

Results: There has been considerable research and development into new fire extinguishing technologies and systems to replace Halon-based systems for use in total flooding, local application and portable extinguishment systems. These technologies and systems include water mist, aqueous film forming foams, compressed air foam systems, cutting extinguishers and propelled extinguishing agent technologies (PEAT) or aerosols.

Most of these fire extinguishing technologies are adaptable to portable fire extinguishers. However, the requirement that the system be handheld or portable limits the volume of extinguishing agent that is available for fighting fires. The shipboard use of certain portable units will depend on whether or not the unit can be moved around the ship. This is the case for portable CAFS (non handheld) and the cutting extinguisher system.

Water mist systems using pure water pose no risk from a toxicity perspective. However, water mist systems that use additives must be evaluated on a case-by-case basis to determine any potential health hazards associated with the additives. The potential toxicity of aerosols and compressed air foams are also an area of concern if they are to be used in occupied spaces. Visual obscuration following discharge of either water mist or

powdered aerosol systems may be a concern. This may potentially limit individuals' ability to leave an area once the system has been discharged.

Significance: The effective use of portable and handheld fire extinguishing apparatus provides a ship's crew with important tools to prevent or slow the spread of a fire. As the nature of the combustible involved in a fire or the fire itself will vary, it is necessary to have portable or handheld extinguishers that can deals with different types of fires.

Future plans: DRDC Atlantic, Dockyard Laboratory (Atlantic) is involved in a Project Arrangement under the Canada/Netherlands/Sweden COOPERATIVE SCIENCE AND TECHNOLOGY Memorandum of Understanding on New Technologies for Fire Suppression On Board Naval Craft (FiST). Portable and handheld fire extinguishing systems are to be studied in the FiST Project.

Sommaire

Review of Portable, Manually Operated, and Non-Total Flooding Fire Extinguishing Technologies for Use on Naval Vessels

Charles Williams; Steve J. Bodzay; Robert Williams; DRDC Atlantic CR 2011-293; R & D pour la défense Canada – Atlantique; decembre 2011.

Introduction : La détection, le contrôle et l’extinction des incendies à bord d’un navire avant qu’ils ne prennent de l’ampleur sont très importants pour le personnel du navire, ainsi que pour les navires militaires, qui peuvent transporter une grande quantité de carburant hautement inflammable et un arsenal d’explosifs, accompagnés de leur carburant. Les navires militaires sont également appelés à naviguer dans des environnements hostiles où la menace d’incendies causés par des dommages de combat est omniprésente. Par conséquent, les navires militaires doivent comprendre à leur bord les dispositifs les plus efficaces pour lutter contre les incendies.

Les extincteurs portatifs font partie intégrante de l’équipement de lutte contre les incendies à bord des navires militaires. Dans plusieurs cas, ils permettent d’éteindre ou de supprimer de petits incendies avant qu’ils ne prennent de l’ampleur et ne deviennent une menace importante pour le personnel à bord et pour le navire. Certaines mises au point ont été effectuées dans le domaine des extincteurs portatifs au cours des vingt dernières années. Dans le présent rapport de contrat rédigé par CRW Regulatory Services Inc., les technologies d’extinction et de suppression d’incendies des systèmes d’extinction portatifs sont examinées et évaluées de façon critique. Certaines contraintes et certains problèmes relatifs à l’utilisation de ces systèmes sont mentionnés. Ces travaux ont été effectués dans le cadre du projet de recherche appliquée (PRA) 11gy, intitulé « Technologies de lutte contre l'incendie, de contrôle des avaries et de maintenance selon l'état ».

Résultats : De nombreuses recherches et mises au point ont été effectuées en matière de nouvelles technologies d’extincteurs et de systèmes d’extinction afin de remplacer les systèmes au halon pour le noyage et la projection localisée ou les systèmes d’extinction portatifs. Ces technologies et ces systèmes comprennent les extincteurs à brouillard d’eau, les extincteurs à mousse à formation de film flottant, les systèmes de mousse à air comprimé, les extincteurs à découpe par jet d’eau, ainsi que les technologies d’agents extincteurs propulsés ou d’aérosols.

La plupart des technologies d’extincteur peuvent être adaptées aux extincteurs portatifs, mais l’exigence selon laquelle le système doit être portatif limite le volume d’agent extincteur disponible pour lutter contre les incendies. L’utilisation de certains extincteurs portatifs à bord d’un navire dépend de la possibilité de les déplacer d’un endroit à l’autre

dans le navire. C’est le cas des systèmes de mousse à air comprimé (qui ne sont pas à main) et des extincteurs à découpe par jet d’eau.

Les systèmes à brouillard d’eau qui utilisent de l’eau pure ne présentent aucun risque du point de vue de la toxicité. Par contre, les systèmes à brouillard d’eau qui utilisent des additifs doivent être évalués au cas par cas afin de déterminer si les additifs présentent un danger pour la santé. La toxicité possible des aérosols et des mousses à air comprimé est également problématique s’ils doivent être utilisés dans des espaces occupés. L’obscurcissement visuel à la suite de l’actionnement d’un système de brouillard d’eau ou d’aérosol en poudre peut poser problème. Il peut limiter la capacité des personnes à quitter une zone une fois le système actionné.

Importance : L’utilisation efficace d’extincteurs portatifs fournit des outils importants à l’équipage d’un navire pour empêcher ou ralentir la propagation d’un incendie. Puisque la nature du combustible ayant causé l’incendie ou l’incendie lui-même varient, il est nécessaire de posséder des extincteurs portatifs servant à lutter contre divers types d’incendies.

Perspectives : Le laboratoire de l’arsenal maritime Atlantique de RDDC Atlantique participe présentement à un projet, dans le cadre du protocole d’entente entre le Canada, les Pays-Bas et la Suède sur les activités de coopération en sciences et en technologie, sur les nouvelles technologies de lutte contre l’incendie à bord de navires militaires. Des systèmes d’extincteurs portatifs doivent être étudiés dans le cadre de ce projet.

Table of contents

This page intentionally left blank.

1 Introduction

1.1 Background

The horrors of ship borne fires are well described in Frank Rushbrook's seminal book "Fire Aboard" which he fittingly dedicated to his "hated, but deeply respected enemy, fire"[1]. As such the early detection, notification and extinguishment of fires before they can develop is of great importance to a ship's crew. This is particularly important for naval vessels, which carry large quantities of highly flammable fuel, an arsenal of explosives and their propellants, and are required to operate in hostile environments. As a result, Navy vessels must have at their disposal the most effective means of fighting fires.[2]

In this review, known and developing technologies for portable fire extinguishers that can be used or adapted for use aboard marine vessels are described and discussed. It is noteworthy that new developments in fire extinguishment technologies are principally related to fixed and area flooding systems. Many of these advancements have not been fully adapted to portable extinguishers because of equipment size and time of use limitations. Also the development of novel systems for portable fire suppression requires full scale fire testing prior to their approval and this can be costly.

Another important requirement related to portable fire extinguishers is the appropriate training of personnel in their use; as such, standard and familiar technologies which are readily accessible and simple to use, and hence can be deployed rapidly are of great importance.

The need for easy accessibility of portable extinguishers is clearly described in various codes and references. For example, the National Fire Prevention Association (NFPA), in Standard NFPA-10 on Portable Fire Extinguishers, describes the need for:

- clear and obvious placement for portable fire extinguishers;
- placement of extinguishers in plain view with no visual obstructions;
- signage to show locations of the extinguishers, and
- the location of the extinguishers at an appropriate height for easy access.[3]

The FM Global loss prevention data sheet on portable extinguishers also calls for the distribution of portable fire extinguishers in locations where they will not be blocked or hidden.[4] Similar requirements are described in the International Oil Tanker and Terminal Safety Guide.[5] This reference also notes the size limitation of portable fire extinguishers and how this can limit their use. In addition portable fire extinguishers need to be selected on the basis of their effectiveness in extinguishing the fuel that has giving rise to the fire.

1.2 Brief History of Portable Extinguishers

Mouret de Sourville is credited with inventing the firefighting apparatus known as a "pare-flammes" in 1811. It was put in use in Parisian theatres and is considered a precursor to portable fire extinguishers.[6]

Rushbrook [1] credits Captain Manby with developing the first portable fire-extinguisher in 1816. He adapted a portable container to expel a pressurized water based chemical agent. The pressure was provided by compressed air. The chemical agent used in this device was 'Pearl Ash' which is primarily potassium carbonate (K_2CO_3).[i]

1.3 The Fire Tetrahedron

Combustion is characterised by four components; fuel, heat, an oxidizing agent and an uninhibited chemical chain reaction.[7] The removal of one of these elements can serve to extinguish the fire. The four components are described below.

Fuel is any matter that can undergo combustion. The fuel can be a solid, liquid or gas. Sufficient heat applied to flammable liquids and most flammable solids cause them to release flammable vapours or pyrolysis products which can burn. Flammable gases do not require vapourisation or pyrolysis.

The oxidizing agent, typically oxygen from air, drives the oxidation-reduction reaction that is the combustion process. The reducing agent in the combustion reaction is the fuel. Note that some fuels can also provide their own source of oxidizing agent. The oxidant need not be oxygen from air; other oxidants include nitrates, chlorates and perchlorates, hydrogen peroxide and organic peroxides, and chlorine gas.

The heat requirement is the minimum energy needed to initiate and maintain the release of pyrolysis products (flammable vapours).

Earlier models for the combustion reaction included the fuel, oxidizing agent and heat; these elements were collectively referred to as the fire triangle. However combustion, rather than simple oxidation, also requires that the process be self-sustainable. An uninhibited chemical chain reason is necessary for this to happen.

Portable fire extinguishers need only interfere with one of these four components to be effective.

---

[i] Pearl Ash is a mixed alkaline salt historically prepared by kiln heating potash or extracting the salts from the ash of vegetable matter; it is principally Potassium Carbonate (K_2CO_3).

1.4 Legacy Systems

In a discussion of fire extinguishing technologies it is important to discuss systems that have been widely used in the past and in many cases are still available and in use. In the following section, a Class A fire is one involving flammable solids, a Class B fire is one involving flammable liquid/liquefiable solids and a Class C fire is one involving flammable gas.

1. Chemical Extinguishers include Class BC dry chemical extinguishers that contain sodium bicarbonate or potassium bicarbonate. The chemicals are finely powdered and propelled by carbon dioxide or nitrogen. Similar to almost all extinguishing agents, the powder acts as a thermal ballast and cools the flames. Some powders also provide a minor chemical inhibition, although this effect is relatively weak. These powders provide rapid knockdown of flame fronts, but may not keep the fire suppressed. Consequently, they are often used in conjunction with foam for attacking large class B fires. Class BC powders have a slight saponification effect on cooking oils and fats due to their alkalinity and were used for kitchen fires prior to the invention of Wet Chemical extinguishers. Where an extremely fast knockdown is required potassium bicarbonate (Purple K) extinguishers can be used.

   Class ABC powders are mixtures of ammonium phosphate and ammonium sulphate. The powder is ground to selected particle sizes and treated with flow promoting and moisture repellent additives. In addition to the particle surface extinguishing effect, ABC powders have low melting/decomposition points (150°C to 180°C). When these powders are applied to hot and smouldering surfaces, the particles fuse and swell to form a barrier which excludes oxygen. This barrier extinguishes the fire and prevents re-ignition. These powders are acidic in nature and are effective on Class A, Class B, and Class C fires. They are electrically non-conductive; however they are less effective against three dimensional Class A fires, or those with a complex or porous structure. Different Class ABC powder blends are available.

2. Carbon dioxide works on class B and C fires by suffocating the fire. Carbon dioxide will not burn and displaces air. Carbon dioxide can be used on electrical fires because, being a gas, it does not leave residues which might further harm the equipment. Carbon dioxide can also be used on class A fires when it is important to avoid water damage, but in this application the carbon dioxide concentration must usually be maintained longer than is possible with a hand-held extinguisher. Carbon dioxide has a discharge horn on the end of the hose which slows down the jet of gas and prevents air being entrained. The relatively cold discharge temperature of carbon dioxide can lead to brittle failure of plastic and/or elastomeric components.

3. Water is the most common extinguishing agent for class A fires and is quite effective. Water cools the fuel surface, thereby reducing the pyrolysis rate of the fuel. Some

water based extinguishing agents also contain surfactants which help the water penetrate into the burning material and cling to steep surfaces. This is known as wet water.

4. Gaseous haloalkanes, such as Halon 1301 and Halon 1211, that can be readily compressed to liquids or exist as liquids are excellent fire extinguishing agents. The vapourized liquids extinguish fires by inhibiting the free radical chain reaction mechanism of combustion. This process and the environmental concern regarding their use are described in detail in Section 3.1.

2 Guidelines

The relevant guidelines related to portable fire extinguishers and ship fires are summarized below. It is beyond the scope of this investigation to elaborate on these guidelines but the summary gives an overview of the technologies available.

2.1 National Fire Protection Association

The mission of the international non-profit NFPA[8], established in 1896, is to reduce the worldwide burden of fire and other hazards on the quality of life by providing and advocating consensus codes and standards, research, training, and education. The NFPA develops, publishes, and disseminates consensus codes and standards intended to minimize the possibility and effects of fire and other risks. NFPA codes and standards are widely adopted because they are developed using an open, consensus-based process. NFPA standards applicable to this report include:

- 10 - Portable Fire Extinguishers
- 10L- Model enabling Act of Sale or Leasing of Portable Fire Extinguishers
- 10R - Portable Fire Extinguishing Equipment in Family Dwellings
- 301 - Code for Safety to Life from Fire on Merchant Vessels
- 302- Fire Protection Standard for Pleasure and Commercial Motor Craft
- 303 - Fire Protection Standard for Marinas and Boatyards
- 306 - Standard for the Control of Gas Hazards on Vessels
- 1005 - Standard for Professional Qualifications for Marine Fire Fighting for Land-Based Fire Fighters
- 1405 - Guide for Land-Based Fire Fighters Who Respond to Marine Vessel Fires
- 1925 - Standard on Marine Fire-Fighting Vessels

2.2 IMO – SOLAS[9]

“The SOLAS Convention in its successive forms is generally regarded as the most important of all international treaties concerning the safety of merchant ships. The first version was adopted in 1914.

The 1960 Convention was the first major task for IMO after the Organization's creation and it represented a considerable step forward in modernizing regulations and in keeping pace with technical developments in the shipping industry. The intention was to keep the Convention up to date by periodic amendments. However, in practice the amendment procedure proved to be very slow. It became clear that it would be impossible to secure the adoption of amendments within a reasonable period of time using the amendment procedure.

As a result, new Convention was adopted in 1974 which included not only the amendments agreed upon up to that date but also a new amendment procedure, the tacit acceptance procedure, designed to ensure that changes could be made within a specified (and acceptably short) period of time. Instead of requiring that an amendment would enter into force after being accepted by, for example, two thirds of the Parties, the tacit acceptance procedure provided that an amendment would enter into force on a specified date unless, before that date, objections to the amendment were received from an agreed number of Parties. As a result the 1974 Convention has been updated and amended on numerous occasions. The Convention in force today is sometimes referred to as SOLAS 1974, as amended. Fire protection, fire detection and fire extinction are described in Chapter II-2. Detailed fire safety provisions for all ships and specific measures for passenger ships, cargo ships and tankers are described. They include the following principles:

1. Division of the ship into main and vertical zones by thermal and structural boundaries;
2. Separation of accommodation spaces from the remainder of the ship by thermal and structural boundaries;
3. Restricted use of combustible materials;
4. Detection of any fire in the zone of origin;
5. Containment and extinction of any fire in the space of origin;
6. Protection of the means of escape or of access for fire-fighting purposes;
7. Ready availability of fire-extinguishing appliances; minimization of the possibility of ignition of flammable cargo vapour.”

Sections 4, 5 and 7 are directly applicable to portable fire extinguishers. It is noteworthy that the IMO-SOLAS guidelines are largely limited in scope and refer principally to legacy systems such as foam, CO_2 or dry chemical powder extinguishers. The organisation indicates that portable fire extinguishers shall comply with the requirements of the Fire Safety Systems Code. IMO has prohibited the installation of new Halon systems since 1994, but accepts existing Halon systems installed prior to that date.

Following the fifty-second session of the Sub-Committee on Fire Protection in January 2008, the Committee accepted the revised guidelines for the approval of fixed aerosol fire extinguishing systems equivalent to fixed gas fire-extinguishing systems.[10]

2.3. United States Department of Defense

Although the official definitions differentiate between several types of documents, all of these documents fall under the general heading of "military standard". These include defense specifications, handbooks, and standards. There are many standards that deal primarily with legacy systems and these do not give much insight into new fire extinguishing technologies.[11]

2.4. Test Standards

Fire extinguishers in North America are tested to Underwriter Laboratories (UL) or ULC specifications. The integrity of the UL or ULC mark assures manufacturers that their fire extinguishers, as well as fire extinguisher components and agents, meet the highest standards for safety and performance. UL or ULC listed extinguishers can be marketed anywhere in the United States and Canada based on their proven ability to extinguish specific classes of fires. UL or ULC lists certified products and components in their product directories.

UL tests to the current editions of the following Standards:

- ANSI/UL 8, CAN/ULC-S554, Water-Based Agent Fire Extinguishers
- ANSI/UL 154, CAN/ULC-S503, Carbon Dioxide Fire Extinguishers
- ANSI/UL 299, CAN/ULC-S504, Dry Chemical Fire Extinguishers
- ANSI/UL 626, CAN/ULC-S507, Water Fire Extinguishers
- ANSI/UL 2129, CAN/ULC-S566, Halocarbon Clean Agent Extinguishers

Fire Performance Test Standards:

- ANSI/UL 711, CAN/ULC-S508, Rating and Fire Testing of Fire Extinguishers

Installation and Maintenance Standard**:**

- NFPA 10, Standard for Portable Fire Extinguishers

3 Portable Technologies

3.1 Halons - Development, Use, Concern and Regulation

Halons are gaseous haloalkanes that are readily compressed to liquids or are liquids.[ii] They are molecules that combine carbon with the following halogens: usually fluorine, chlorine and/or bromine and occasionally iodine. The term Halon, derived from halogenated hydrocarbon, was coined by the US Army. They also defined the numerical nomenclature for Halons; the numbers, in order, represent the number of carbons, fluorines, chlorines, bromines and iodines in the Halon molecule.[12]

The vapourized liquid is known to extinguish fires by inhibiting the free radical chain reaction mechanism of combustion.[13] They effectively 'mop up' the free radicals formed at the seat of the fire. As these are necessary for the combustion process, Halons remove one of the components of the fire tetrahedron.[iii] This mode of extinguishment is the only true chemical (or reaction) mode of fire suppression. Other methods of fire extinguishment interfere with fire development and propagation via physical means. This, in large part, is why the Halons are highly effective fire extinguishing agents.[14]

The first haloalkane used to suppress fires was carbon tetrachloride (CCl_4) (Halon 104). It was supplied in portable canisters by the Pyrene Manufacturing Company of Delaware in 1911.[15] Due to its toxicity, primarily to the liver and kidneys, and the nature of its degradation products the use of carbon tetrachloride for fire suppression was discontinued.[16]

Chlorobromomethane (Halon 1011) was developed in Germany during the Second World War and was considered more efficient than Halon 104.[12] During the 1940s, the U.S. army contracted the Purdue Research Foundation to carry out a systematic search for effective and nontoxic (or relatively nontoxic) halogenated gaseous fire suppressants. More than 60 chemical compounds were studied.[17] Development afforded two notable Halons, namely Halon 1301 (bromotrifluoromethane) and Halon 1211 (bromochlorodifluoromethane). These could be used separately or in combination.[18]

Unfortunately the production and use of these highly effective extinguishing agents have been phased out because these agents are ozone-depleting substances (ODSs). Paul J. Crutzen, Mario J. Molina and F. Sherwood Rowland were awarded the 1995 Nobel Prize in Chemistry in *"for their work in atmospheric chemistry, particularly concerning the*

[ii] The two more familiar Halons are Halon 1301 and 1211 which have boiling points of approximately 158ºC and -4ºC respectively.

[iii] The four components of combustion - the fire tetrahedron - being as follows: the Fuel, Heat, Oxidizing agent, and Uninhibited Chemical Chain Reaction. NFPA 921-2011 "Guide for Fire and Explosion Investigations".

formation and decomposition of ozone".[19] The seminal paper, the first to identify the issue of atmospheric ozone depletion by chlorofluorocarbons (CFCs), was published in 1974.[20]

The international consensus to proceed with the phase out and replacement of Halons with environmentally safer materials started with the 1987 Montreal Protocol. At subsequent meetings further details and timelines for the phase out were developed (Montreal Protocol adjustments and/or amendments London 1990, Copenhagen 1992, Vienna 1995, Montreal 1997, Beijing 1999). [21] It has been also been recognized that these materials have appreciable global warming potential (GWP).

The significance of this phase out is reflected in recommendations made to industrial and commercial users by; for example, FM Global. In their Loss Prevention data sheet on Halon 1301 it was noted that "FM Global has advised against installing new Halon 1301 systems since 1992 as a result of the Montreal Protocol on Substances that Deplete the Ozone Layer."[22]

Canadian Federal Halocarbon regulations (2003) specifically prohibit the charging of portable extinguishers with Halon. It is notable that an explicit exception regarding Halons is provided for military vehicles and military ships.[23],[24]

Similar stipulations are made by various provincial bodies; for example the Ontario Ministry of the Environment regulation on Ozone Depleting Substances "prohibits the refilling of portable Halon containing fire extinguishers with the exception of critical uses". Military use and aircraft purposes are defined as critical uses.[25] European nations must also follow strict regulations regarding the use of Halons.[26]

As a result of this, there has been a significant effort made to find non-toxic and environmentally safe fire suppression agents to replace Halons.

3.2 Halogenated Halon replacements (PFCs and HFCs)

Halon replacements which are gaseous agents include fully fluorinated hydrocarbons or perfluorocarbons (PFCs) and hydrofluorocarbons (HFCs).

There was a short period when hydrochlorofluorocarbons (HCFCs), hydrobromofluorocarbons (HBFCs) and/or fluoroiodocarbons (FICs) were considered as potential Halon replacements. These substances are now recognized as having some ozone depleting potential (ODP) and have global warming potential (GWP). Global warming potential (GWP) is referenced to Carbon Dioxide (CO_2; GWP=1).[27]

A number of halogenated chemicals have been considered as Halon replacements. Some of these are described below.

HFC-125 or Pentafluoroethane (C_2F_5H) (also known as FE-25) has been used on aircraft.[28] It has a zero ozone depletion potential but has a relatively GWP potential of 3450.

HFC-227ea or 1,1,1,2,3,3,3-heptafluoropropane (CF_3CHFCF_3) (also known as FM-200) is a common HFC presently in use.[29] It has a zero ozone depletion potential but it has a relatively high GWP of 2000 (or greater).[30]

Other known HFCs include: HFC-23 or trifluoromethane (CHF_3); HFC-134a or 1,1,1,2-tetrafluoroethane (CF_3CH_2F); HFC-236fa or 1,1,1,3,3,3-hexafluoropropane ($CF_3CH_2CF_3$). These have relatively high GWPs.[31]

A new Halon alternative which is considered to be safe and have favourable environmental characteristics is perfluoro-2-methyl-3-pentanone ($CF_3CF_2C(O)CF(CF_3)_2$), known as Novec 1230.[iv],[32] It has a ODP potential and a reported GWP of 1; that is, its GWP is similar to CO_2.[33] Novec 1230 extinguishes by cooling the fire. Once discharged it forms a gaseous mixture with air that has a much larger heat capacity than air alone. It is considered to have the highest heat capacity of any of the commercially available halon replacements. Novec 1230 has numerous marine approvals including those from the Canadian Coast Guard; United States Coast Guard, Det Norske Veritas (DNV), Lloyds Register of Shipping and the American Bureau of Shipping (ABS).[34]

Corrosion problems arising from the use of perfluoro-or hydrofluorocarbon agents have been investigated and are of concern. The concern centers on the generation of hydrofluoric acid (HF) and its effect on electronic equipment.[35],[36] The levels of hydrogen fluoride produced are dependent on type of fuel consumed in the fire, time of burn and on the degree of ventilation. During testing with HFC 227ea and Novec-1230 it was noted that hydrogen fluoride accumulated in poorly ventilated locations such as electronics cabinets.[37],[38],[39] However, for small fires, the overall effect of the hydrogen fluoride produced and its toxicity is considered to be relatively minor. Peatross and Forssell used three different hydrofluorocarbons to extinguish small and large fires and found HF levels much reduced for small fires.[40]

These newly developed fluorinated hydrocarbons are non ozone depleting substances and have potential for use as extinguishing media. However their effective concentration, which is the concentration necessary to extinguish a fire, renders them less practical for use in portable extinguishers.[41] Their effective concentrations are 2x-3x greater than that of Halon 1301.[42] Perfluoro-2-methyl-3-pentanone (Novec 1230) is viable for

[iv] Novec is the 3M trademark name for perfluoro-2-methyl-3-pentanone $CF_3CF_2C(O)CF(CF_3)_2$.

portable use. It is typically used in concentrations of approximately 6-7% compared to 3% for Halon 1301.[43],[v]

Some research has been carried out on halocarbons containing iodine atoms. Extinguishing gases that contain iodine tend to be readily degraded in the troposphere and hence are less likely to contribute to ozone depletion by releasing iodine radicals in the stratosphere. However, they are generally considered to be less stable and hence there is an issue with storage. Moreover there are known compatibility issues with certain materials.[44]

3.3 Inert Gas Agents (Ar, N_2, CO_2)

Inert gas agents extinguish fires by oxygen depletion, that is, they lower the oxygen concentration in a space to levels below that required to support combustion.

Argon and Nitrogen are naturally occurring gases [45] and are considered to be environmentally friendly as they have zero ODP and zero GWP. Moreover, these inert extinguishing media are not subject to thermal decomposition and hence do not form decomposition products in the fire.[46] However, as has been noted by Kim and others "To suppress a fire, a sufficient volume of inert gas must be injected into the enclosure to reduce the oxygen content to a level at which combustion cannot be maintained. This is generally considered to be about 14.3%. In order to provide an adequate safety factor, the normal objective is to reduce the oxygen level to about 12.5%."[47] Typically, 30-40 volume percent of these gases are required for flame suppression. The reported volume percent levels of Argon and Nitrogen to extinguish a typical n-heptane pool fire are 40.8% and 36.6% respectively, and for extinguishing a wood test crib are 30.7% and 28.6% respectively.[48]

Currently, there are three commercially available inert gas systems used as total flooding systems. These are: pure argon (100% Ar) known commercially as Argotec (ASHREA designation - IG-01); a 50/50 mixture of argon and nitrogen (50% Ar - 50% N_2) known commercially as Argonite (ASHRAE designation - IG-55); a mixture of 40% argon, 52% nitrogen and 8% carbon dioxide known commercially as Inergen (ASHRAE designation - IG-541). Pure nitrogen (100% N_2, ASHRAE designation - IG-100) can also be used.

However it must be stressed that these inert gas agents function by depleting oxygen and hence can cause asphyxiation at elevated concentration. It has been reported that healthy individuals can tolerate oxygen levels as low as 12% for short periods however lower oxygen levels will result in impairment and other symptoms.[49] It has been found that

[v] 3M Novec 1230 Fire Protection Fluid product information data sheet, provided by the manufacturer 3M, suggests a concentration for use on various fuels that ranges between 4.5% for diesel fuel up to 8.5% for methanol.

the addition of CO_2 to the Argon/Nitrogen mixture facilitates breathing, that is, the addition of CO_2 induces a higher breathing rate. This lessens the effects of the lowered oxygen concentration and has been tested to 30 min with human volunteers. [50]

The potential use of these agents in portable extinguishers requires that the oxygen concentration at the location of application of the inert gas be monitored or fire fighting personnel exposed to these gases (at the area of localized use) are equipped with self-contained breathing apparatus. Moreover, and of particular importance to their use in portable extinguishers, inert gases are not readily liquefiable. They are stored as high pressure gases. The implications with respect to size and weight may restrict their use in portable extinguishers.

There have been developments in Inert Gas generators. This is an adaptation of the USSR initiated technology that produces a mixture of inert gases and fine particulates. These combustion and pyrotechnically generated aerosols are effective fire suppression agents. The inert gas generator systems developed by the US Navy for use in navy aviation systems are designed to minimize the discharge of particulates. The process is analogous to air bag inflator systems on automobiles. These inert gas generators are considered to be an effective replacement for Halon 1301.[51]

3.4 Aerosols - Powdered Extinguishing Agent Technology

Most of the traditional extinguishing agents are delivered by the standard portable fire extinguishing systems. The primary difference is the material contained in the fire fighting apparatus. As discussed below, these modifications have led to small incremental improvements in the fire fighting technology.

Aerosols produced using powdered extinguishing agent technology (PEAT) are a recent innovation in firefighting technology. Powdered aerosol extinguishing systems produce and deliver solid particle aerosol fire suppressants. These systems have promise as portable fire extinguishing technologies but have been adapted primarily for use in total flooding systems in enclosed spaces. [52],[53],[54]

There are two types of powdered aerosol systems, dispersed and condensed. In a dispersed system the powder forming the aerosol is stored in a pressurized container with a carrier gas such as a halocarbon or an inert gas. When the system is activated the aerosol is introduced into a space through a delivery system similar to that used for gaseous agents. In a condensed system the aerosols are produced pyrotechnically using a solid compound in the generator. The aerosol particles are released in the exhaust of the burning compound along with the degradation products of the pyrotechnic compound such as nitrogen (N_2), oxygen (O_2), carbon monoxide (CO), carbon dioxide (CO_2) and water. Potassium salts are generally used to produce the aerosol particles.

The fire suppression mechanisms of PEAT aerosols have been reviewed by Agafonov.[55] The primary extinguishing mechanism of condensed aerosols involves slowing the uninhibited chain reaction mechanism that drives the combustion process. The aerosols react with the free radicals formed at the flame front and therefore interfere with the combustion process. Typically, condensed aerosols consist of potassium carbonate (K_2CO_3) particles that are produced from the thermal decomposition of solid aerosol-forming compounds that include potassium nitrate as an oxidizer. As the aerosol particles surround and come into contact with the flame, the particulates absorb the flame heat energy. They break down and release large concentrations of potassium radicals (atoms with an unpaired electron). The potassium radicals bond with other free radicals which sustain the flame's combustion process and produce by-product molecules such as potassium hydroxide (KOH) and water (H_2O).

Based on his summary Agafonov concluded that "The way to lift up the effectiveness of the aerosols in fire suppression is to increase the content of solid particles in the aerosol mixture and to decrease the size of the particles."

There are several types of aerosols. They include, as identified by the Unites States Environmental protection agency, the following:[56]

- Powdered Aerosol A, known as SPE powdered aerosol
- Gelled Hydrocarbon/Dry Chemical Suspension with additives (formerly Powdered Aerosol B), known as PGA powdered Aerosol
- Powdered Aerosol C, known as Pyrogen and Dynemeco
- Powdered Aerosol D (Aero-K® and Stat-X®): acceptable subject to use conditions which limit use to normally unoccupied areas
- Powdered Aerosol E (FirePro®): acceptable subject to use conditions which limit use to normally unoccupied areas

Powdered Aerosol A produces approximately 60% gaseous products (CO_2, N_2, O_2 and H_2O) and 40% solids (potassium chloride (KCl), potassium oxide (K_2O) and potassium carbonate (K_2CO_3)). It extinguishes a fire by inhibiting the radical chain reaction in the flame zone. Powdered Aerosol A is effective against Class A, Class B and Class C fires and is used in engine enclosures, computer rooms, aircraft nacelles, electronics cabinets, telecommunications enclosures, flammable liquid and gas storage areas, and sub floor wiring enclosures. It has a shelf life of greater than 10 years.

Gelled hydrocarbon/dry chemical suspension, which was formerly known as Powdered Aerosol B, can be used on Class A, Class B, and Class C fires. These agents are a blend of several halocarbons (hydrofluorocarbons (HFCs)) and additives such as sodium bicarbonate $NaCO_3$ or ammonium polyphosphate that reduce the amount of hydrogen fluoride (HF) released when the HFCs decompose in the fire. The release of the agent is activated by heat. This agent is used to provide fire suppression in air cargo areas, ship compartments, engines and enclosed spaces.

Powdered Aerosol C is a polymer formulation containing potassium nitrate (KNO_3) and plasticized nitrocellulose. The aerosol produced by this agent is primarily micron sized potassium carbonate (K_2CO_3) and potassium bicarbonate ($KHCO_3$) particles and N_2, CO_2, and water. The agent interferes with the combustion process by inhibiting the radical chain reaction in the flame zone, cuts the flame off from the combusting material, and absorbs heat. It is effective against Class A, Class B, Class C, and Class K (cooking) fires. It is used to protect pumping stations, mining equipment, power substations, electrical distribution systems, aviation and marine cargo holds, and helicopters.

Powdered Aerosol D consists of alkaline metal nitrates that are released following a pyrotechnic reaction. It is used in total flooding fire suppression and for explosion suppression applications. It is effective against Class A, Class B, and Class C fires. And can be used in warehouses, industrial facilities, flammable liquid storage areas, turbine enclosures, marine engine rooms, and aircraft engines.

Powdered Aerosol E consists of potassium carbonate (K_2CO_3), N_2, CO_2, and water. The potassium carbonate forms potassium radicals in the presence of heat. These acts as radical scavengers and interfere with the reactions that are responsible for the combustion process.

The Federal Aviation Administration in "Options to the Use of Halons for Aircraft Fire Suppression Systems—2011 Update" 2011-03-07 noted that dry chemical agents, as now used, do not provide explosion inertion or fire suppression for time periods similar to those provided by Halon systems due to settling of the particles.[57]

It should be noted that powdered aerosol agents A and D are for use in unoccupied spaces only and that powdered aerosols agents C and D are for use in spaces that are normally unoccupied.

Although highly effective in protecting closed spaces (total flooding extinguishment), powdered aerosol technology has limited effectiveness in open areas where environmental conditions (airflows and winds) reduce their efficiency. The highly buoyant aerosol particles can be blown out of the area by the fire heat and environmental airflows.[58]

These systems have promise for portable fire extinguishing systems. There are two commercially available systems:

- Bomb or grenade type application (Stat-X first responder and DSPA-5)
- A portable fire extinguisher which is pointed at the fire. (Manual Aerosol Fire Extinguisher (MAFE))

One example is the STAT-X fire suppression system “First responder”.[59] Stat-X announced that they had received marine approval in Finland on June 6, 2011. The Stat-X First Responder is a small, light, handheld unit with a pull initiator. The unit is designed to be tossed into rooms with active fires and provide immediate fire suppression. When used by firefighters, it buys time for the arrival of additional fire suppression technologies, may prevent flashover, and can be used to provide an emergency egress route for crew through a space with a fire.

DSPA 5, nicknamed “the extinguishing bomb”, is a portable unit. The DSPA 5 is activated by pulling a cord. It can be thrown at the seat of the fire from a distance. Its round shape enables rapid and efficient dispersal of the active material. Dutch and Swedish tests have shown that the DSPA 5 can prevent a backdraft or a flashover. DSPA 5 is useful in cases where a direct attack does not seem to be an option.

Small portable fire extinguishers are designed for fighting small fires and are based on BS 6165:2002 (Specification for small disposable fire extinguishers of the aerosol type) and UL 711a (Fire test method for portable hand-held extinguishers intended for use on residential cooking equipment).[60] A specific example is the Manual Aerosol Fire Extinguisher (MAFE) by Aerotekng.[61] The portable aerosol unit is designed to be used to fight small fires. The MAFE can be compared to conventional dry chemical powder (DCP) or CO_2 fire extinguishers. It is equivalent to a 6kg DCP or a 3kg CO_2 fire extinguisher and can be used on Class A, B, and C fires and common electrical fires. The MAFE is discharged by electrostatic means using an activation button. Alletec Fire Protection Services has also produced a small aerosol fire extinguisher.[62] These systems show great promise as portable fire extinguishing systems.

3.5 Water Mist

Water mist technologies have been extensively reviewed.[63],[64],[65],[66] The following discussion is based on these reviews. Water mist systems and technologies have been developed as a replacement for halon systems and/or to improve sprinkler systems. Little research has been carried out on the use of water mist in portable extinguishers until recently. This was due in large part to the requirement that any new use of a technology or modification of a technology be evaluated using full scale fire testing. This can be very expensive.

The term water mist was adopted by the National Fire Protection Association Committee, in NFPA750, *Standard for Water Mist Fire Protection System* in the early 1990s. This term distinguishes the technology of NFPA 750 from that of NFPA 15, *Standard for Fixed Water Spray Systems,* and NFPA 13, *Standard for Installation of Sprinkler Systems.* Water mist is defined as a fine water spray with no drops larger than 1000 μm (microns) in diameter.[67] Such sprays are not true mists. A mist in the scientific sense consists of water droplets with diameters somewhere between those in an aerosol (particles with diameter ~5 µm) and a fog (droplet diameters ranging between 10 and 100 µm). Particles less than 20 µm in diameter take a long time to settle out, and hence create a "mist". A water mist used for fire protection purposes is a fine water spray consisting of droplets of various sizes, many of which are true mist particles and some of which are considerably larger. Water mist nozzles produce sprays that have a higher fraction of very fine droplets, in the range of a mist, than is typical of standard sprinklers or water spray nozzles.

Water mist fire suppression research performed in the past 50 years typically referred to "fine water sprays" or "finely divided water sprays" as their subject of study. Fine water sprays with mean diameters less than 300 µm were remarkable successful at cooling and extinguishing diffusion flames.[68] Research in the 1950s confirmed the expected improvement in heat absorption of water as the droplet size is decreased. This is due to the increase in surface area available for heat transfer. Also, as particles become smaller they settle out less quickly, providing more time for heat absorption and subsequent evaporation to take place. Therefore increasing the fraction of very fine water droplets contained in a water spray reduces the amount of water needed for fire suppression. This improves the efficiency of application.

For various reasons, the knowledge regarding the advantages of using fine water sprays for fire suppression did not result in an immediate movement to finer sprays for fire protection. Technical concerns included the negative effects of increasing operating pressures to improve atomization, the potential plugging of small orifices with corrosion products, and doubts about the long-term maintainability of equipment. Cost was also a factor as there were less expensive alternatives: such as standard sprinklers or the halon systems, that could be used.

3.5.1 Spray Characteristics

Measuring and understanding the characteristics of sprays produced by different nozzles are prerequisites for understanding the differences in performance of the nozzles. To fully characterize a spray requires information about the following elements:

- Drop size distribution (DSD)
- Cone angle of the nozzle
- Velocity of the discharge jet(s)
- Mass flow rate
- Spray momentum (product of velocity and mass)

These spray characteristics are critical factors that influence the fire suppression capabilities of a water mist system.

3.5.2 Additives

Low concentrations of additives can improve the extinguishment capabilities of water mist.[69],[70] These additives include surfactants, such as aqueous film forming foam (AFFF), that result in the formation of foams that spread over a burning liquid surface, block the generation of fuel vapours, and help extinguish obstructed fires. Antifreeze and biocides are also potential water mist additives.

A recent report on the use of different additives in portable water mist systems indicates that additives can improve the efficacy of water mist.[71] Investigation of alternative additives has been hampered by the costs involved in completing toxicology studies and fire testing.

3.5.3 Portable Water Mist Extinguisher

A portable water mist extinguisher is an example of local application (LA) water mist system. However, unlike a fixed LA water mist system, it has a limited water supply and small spray coverage area. In addition, its discharge pressure declines quickly during use.

Underwriters Laboratories have listed a portable water mist fire extinguisher for use on Class A and Class C fires. The portable water mist unit can extinguish Class A fires in a manner that does not cause electrical shock to the user when directed against energized electrical targets. A number of companies sell portable mist fire extinguishers. Some of them are listed below.

Advanced Firefighting Technology (AFT) (www.aftwatermist.com/home/1/) supply portable water mist systems (backpack unit or a trolley system). They also supply portable compressed air foam systems (CAFS).

Murli Techno Pvt. Ltd. (http://www.murlifiresafety.com/ water_mist_technology_features.html) supply portable water mist systems (extinguishers or as backpack units). They also manufacture a wheeled cart water mist system. Their systems can be used with water mist and AFFF.

Ultra Suppression Systems Ltd. (http://www.ultrafiregroup.co.uk/FireSuppressionRange/WaterMist/UltraGuard.aspx) supply a movable unit but its mass (50 kg empty) precludes true portability.

Aska Equipments Limited (http://www.askagroup.com/ffe.html) supply portable water mist systems (backpack unit or a trolley system).

Amerex Corporation (http://www.amerex-fire.com/products/product/30) supply portable water mist systems for the extinguishment of Class A/C fires.

The NRC Institute for Research in Construction, Ottawa, have studied the water mist characteristics required to extinguish various types of fires from both theoretical and experimental perspectives.[72] Two prototype water mist extinguishers were developed and their capabilities and limitations for suppressing flammable liquid, cooking oil, wood crib, and electric equipment fires were investigated in full-scale experiments. In all cases water mist worked adequately.

Cold Cut Systems AB[73] has developed a ”cutting extinguisher”. A mixture of water and cutting agent are passed through a special nozzle at high pressure (>250 bar). The mixture can cut through building and construction materials. Once a space has been breached, the cutting agent is no longer added to the water. Water mist is then injected into the space. The method allows a fire to be attacked from outside a space. Very little oxygen is admitted to the fire as the penetration hole is so small. This technology requires a significant amount of water and a high pressure pump system. It is readily adaptable to common mobile pumper trucks. Its use on naval vessels will require a trolley system to facilitate movement. It should be noted that this system could also be used to gain access to a space where doors and hatches have become inoperable due to damage resulting from a fire, explosion or weapon strike.

3.6 Foam Agents and AFFF

Foam agents have been used in fire fighting for many years and are the subject of numerous reviews and books.[74],[75] Most recent advances in foams are related to the development of new formulations and foam characteristics.

Foam systems are covered by a number of NFPA standards including:

- NFPA 11 Standard for Low-, Medium-, and High-Expansion Foam
- NFPA 11A Standard for Medium- and High-Expansion Foam Systems
- NFPA 11C Standard for Mobile Foam Apparatus
- NFPA 16 Standard for the Installation of Foam-Water Sprinkler and Foam-Water Spray Systems
- NFPA18 Wetting Agents
- NFPA 1150 Standard on Foam Chemicals for Fire in Class A Fuels

Other NFPA standards mention foam and its use in specific spaces, for example in aircraft hangers.

Fire-fighting foams are produced by aerating aqueous solutions of foam concentrates. Some foam concentrates, notably those that are protein based, form thick, viscous foam blankets that are particularly effective on hydrocarbon fuel surfaces. Other foams, such as film-formers, are much less viscous and spread rapidly over the fuel surface. The film-formers produce a vapour-sealing foam film on most hydrocarbon fuels. Since the foam is lighter than flammable or combustible liquids, it floats on the fuel surface. The floating foam produces an air-excluding layer of aqueous agent, which suppresses and prevents combustion by halting fuel vaporization at the fuel surface. If the entire surface is covered with foam, the fuel vapour will be trapped and the fire will be extinguished.

3.6.1 Description of Foam Agents

There are no universally accepted definitions of foam agents or terms associated with fire-fighting foams. For example, where foam is referenced in NFPA standards, definitions vary from document to document. Because foams vary in performance, application rates and quantities required for extinguishment will vary. Often agent descriptions, such as "rapid knockdown" or "superior burnback resistance", are written to accentuate positive attributes,

There are a number of designations for foaming agents and include the following.

- Aqueous Film Forming Foam (AFFF)
- Alcohol Resistant Aqueous Film Forming Foam (AR-AFFF)
- Synthetic – medium or high expansion types (detergent)
- Class "A" Foam Concentrate
- Wetting Agent
- Fluoroprotein
- Protein
- Film Forming Fluoroprotein (FFFP)
- Alcohol Resistant Film Forming Fluoroprotein (AR-FFFP)

3.6.2 How Foams Work

Fire fighting foams work by blanketing the fuel surface. This separates the flames/ignition source from the fuel surface. They also cool the fuel and any adjacent metal surfaces and suppress/prevent the release of flammable vapours that can mix with air and combust.

The type of foam used on a flammable liquid fire will depend on the nature of the flammable liquid. For instance, alcohol resistant foams must be used on certain polar solvent/alcohol type fuel spills or fires.

3.6.3 Foam Concentrates

Class A foam is a biodegradable mixture of foaming and wetting agents. When mixed in correct proportions with water, it can change two properties of the water. Firstly, it increases the wetting effectiveness of the water, which allows for greater penetration into Class "A" fuels. It also forms foam which allows the water in the foam to cling to vertical and horizontal surfaces and absorb more heat. By adding a small quantity of a Class "A" foam concentrate into a water stream, the effectiveness of the water can be increased up to 5 times.

Class B foams are designed for class B fires (flammable liquids) The use of class A foam on a class B fire may yield unexpected results, as class A foams are not designed to contain the explosive vapors produced by flammable liquids. Class B foams have two major subtypes; synthetic foams and protein foams.

Synthetic foams are based on synthetic surfactants. Synthetic foams provide better flow, faster knockdown of flames, but limited post-fire security. Aqueous film forming foams (AFFF) are water-based and frequently contain hydrocarbon-based surfactant such as sodium alkyl sulfate, and fluorosurfactants. They have the ability to spread over the surface of hydrocarbon-based liquids. Alcohol-resistant aqueous film forming foams (AR-AFFF) are foams resistant to the action of alcohols and are able to form a protective film when alcohols are present.

Protein foams contain natural proteins as the foaming agents. Unlike synthetic foams, protein foams are bio-degradable. They flow and spread slower, but provide a foam blanket that is more heat resistant and more durable. Protein foams include regular protein foam (P), fluoroprotein foam (FP), film forming fluoroprotein (FFFP), alcohol resistant fluoroprotein foam (AR-FP), and alcohol-resistant film forming fluoroprotein (AR-FFFP).

3.6.4 Compressed Air Foam (CAFS)

A compressed air foam system is defined as a standard water pumping system that has an entry point where compressed air can be added to a foam concentrate/water solution to generate foam. Typical components of a CAFS include a centrifugal pump, a water source, foam concentrate tanks, a rotary air compressor, a direct-injection foam proportioning system on the discharge side of the pump, a mixing chamber or device, and control systems to ensure the desired mixture of concentrate, water, and air are achieved. The compressed air also provides energy which propels compressed air foam farther than foam from aspirated or standard water nozzles.

CAF suppresses fires by affecting three sides of the fire quadrangle simultaneously. The foam blankets the fuel reducing the availability of oxygen, the foam absorbs heat from the fire, and it shields the fuel source from radiant energy.

3.6.5 Portable Foam Systems

Portable CAFS are pressurized water style extinguishers that are charged with a foam solution and pressurized with compressed gas. Their usefulness is limited to stored pressure and volume of water/foam mixture in the unit. This is also true of water foam systems. Many companies sell portable systems. Some are listed below.

Amerex (http://www.amerex-fire.com/products/product/32) distributes pressurized AFFF extinguishers. Firedot (http://www.firedot.com/mall/AR_AFFF.htm) market a portable AR-AFFF foam extinguisher. The AR-AFFF is specially formulated to maximize the effectiveness of this portable extinguisher. Protection R.T. Inc (http://www.protectionrt.com/foamport.html) supplies portable foam extinguishers that are optimized to prevent re-ignition of hydrocarbon and grease fires.

Naffco (http://www.naffco.com/products.php?groups_id=229) sell portable AFFF foam systems using a CO_2 cartridge or mobile AFFF foam systems using stored pressure. Intelagard (http://www.intelagard.com/Products/Merlin.html) market both a mobile wheeled CAFS unit (57 L) and a portable CAFS backpack unit.

4 Summary

There have been significant developments in fire-extinguishing systems over the last 20 years. Many of these have resulted from the banning of halocarbon agents such as the Halons. The effectiveness of Halons (in particular, Halon 1211 and Halon 1301) in suppressing and extinguishing combustion, coupled with their limited toxicity and ease of use made them a fire extinguishing medium of choice in fixed, portable and 'in-cabinet' systems. They were widely used on Canadian naval vessels.

A large effort has been made to introduce new fire extinguishing systems to replace Halons-based systems. These include systems using water mists and water fogs (where the attention is on water droplet size not water volume), gaseous agents such as fluorinated hydrocarbons and fluorinated ketones and powdered aerosol systems (PEAT). In addition there have been developments in the areas of inert gas mixtures, compressed air foam systems and novel methods/technologies such as the cutting extinguisher technique.

Most new fire extinguishing technologies are adaptable to portable fire extinguishers. However, the requirement that the system be handheld or portable limits the volume of extinguishing agent that is available for fighting fires. The shipboard use of certain portable units will depend on whether or not the unit can be moved around the ship. This is the case for portable CAFS (non handheld) and the cutting extinguisher system.

Water mist systems using pure water pose no risk from the toxicity perspective. However, water mist systems that use additives must be evaluated on a case-by-case basis to determine potential health hazards associated with the additives. The potential toxicity of aerosols and compressed air foams are also an area of concern if they are to be used in occupied spaces. Visual obscuration following discharge of either water mist or powdered aerosol systems may be a concern. This may potentially limit individuals' ability to leave an area once the system has been discharged.

The extinguishment or control of fires by portable extinguishers is very dependent on several other factors such as early detection, notification (alarm), rapid response, and training of the first responder.[76]

References

[1] Rushbrook, Frank "Fire Aboard, the problems of prevention and control in ships, port installations and offshore structures" Brown Son & Ferguson Ltd (1961); Rushbrook, Frank "Fire Aboard, the problems of prevention and control in ships, port installations and offshore structures" 2nd ed. Brown Son & Ferguson Ltd (1979). Rushbrook, Frank and Lygate, James F. (ed.) "Fire Aboard, the problems of prevention and control in ships, port installations and offshore structures" 3rd ed. Brown Son & Ferguson Ltd (1998).

[2] Fire Suppression Substitutes and Alternatives to Halon for U.S. Navy Applications (1997) Naval Studies Board.

[3] NFPA 10-2007 "Standard for Portable Fire Extinguishers": section 6.1.3 on Placement (sub-sections 6.1.3.1-6.1.3.8).

[4] FM Global Property Loss Prevention Data Sheets 4-5 "Portable Extinguishers" (1990, revised September 2000).

[5] Oil Companies International Marine Forum, "International Oil Tanker and Terminal Safety Guide", 2nd ed. John Wiley and Sons (1974).

[6] Viger, Raoul, "30 Conseils face au feu", Hatier (1977).

[7] NFPA 10-2011 "Guide for Fire and Explosion Investigations".

[8] http://www.nfpa.org

[9] International Maritime Organization (www.imo.org/conventions/solas).

[10] MSC.1/Circ.1270 - Revised Guidelines for the Approval of Fixed Aerosol Fire-Extinguishing Systems Equivalent to Fixed Gas Fire-Extinguishing Systems, as Referred to in SOLAS 74, for Machinery Spaces.

[11] For all specifications See www.everyspec.com

[12] Gann, Richard, "Whence the NGP?" Halon Options Technical Working Conference (HOTWC), 2006.

[13] Gann, Richard, "Technology for Fire Suppression in Aircraft: Findings of the Next Generation Fire Suppression Technology Program" 2007 SUPDET conference proceedings.

[14] "Fire Suppression Substitutes and Alternatives to Halon for US Navy Applications", Committee on Assessment of Fire Suppression Substitutes and Alternatives to Halon; ISBN 0-309-57942-2 (1997).

[15] US patent 1,105,263 (Jan. 1911).

[16] "Hamilton and Hardy's Industrial Toxicology" 4th ed. PSG Publishing, pp. 229-231 (1985).

[17] Purdue Research Foundation and Department of Chemistry "Final Report on Fire Extinguishing Agents for the Period 1 September 1947 to 30 June 1950" Purdue University (1950).

[18] FM Global Property Loss Prevention Data Sheets 4-5 "Portable Extinguishers" (1990, revised September 2000).

[19] Nobel Prize Organization (www.nobelprize.org)

[20] Molina, M.J., Rowland, F.S. "Stratospheric sink for chlorofluoromethanes: chlorine atom catalysed destruction of ozone" Nature pp 810-812 (1974).

[21] "The Montreal Protocol on Substances that Deplete the Ozone Layer" as adjusted/and or amended in London 1990, Copenhagen 1992, Vienna 1995, Montreal 1997 and Beijing 1999, UNEP Ozone Secretariat United Nations Environment Program.

[22] FM Global Property Loss Prevention Data Sheets 4-8N "Halon 1301 Fire Extinguishing systems" (2001).

[23] Canadian Federal Halocarbon Regulation (2003) - SOR/2003-289 current to September 2010.

[24] Environment Canada Fact Sheet No. 2009-02 "Phase-out and Disposal of Halons in Fire – extinguishing Systems in Canada".

[25] Ontario Ministry of the Environment, "Ozone Depleting Substances". See also "Québec's Strategy for Managing Ozone-Depleting Substances and their Replacement Products", Québec.

[26] European Commission EC regulation 303/2008 "F-Gas and ODS Regulations".

[27] United Nations Framework Convention on Climate Change (UNFCCC), "Global Warming Potentials". Kim, Andrew, "Overview of recent progress in fire suppression technology" National Research Council Canada NRCC-45690 (2002).

[28] Gann, Richard, "Technology for Fire Suppression in Aircraft: Findings of the Next Generation Fire Suppression Technology Program" 2007 SUPDET conference proceedings.

[29] Dupont FM-200 Physical Properties data sheet.

[30] Kim, Andrew, "Overview of recent progress in fire suppression technology" National Research Council Canada NRCC-45690 (2002).

[31] "Fire Suppression Substitutes and Alternatives to Halon for US Navy Applications", Committee on Assessment of Fire Suppression Substitutes and Alternatives to Halon; ISBN 0-309-57942-2 (1997). Kim, Andrew, "Advances in Fire Suppression Systems" National Research Council Canada NRCC-52712 (2009).

[32] 3M Novec 1230 Fire Protection Fluid product information.

[33] Kim, A. and Crampton, G. "Performance of Novec 1230 in Electronic Facility Fire Protection" NRCC-53526, Proceedings SUPDET 2010 pp. 1-6 (2010).

[34] 3M Novec 1230 Fire Protection Fluid product information, p. 2, 7. (2011).

[35] Kim, A., Crampton, G., Kanabus-Kaminska, M. "Corrosion effect of hydrogen fluoride (HF) on electronic components" National Research Council Canada NRCC-45997 (2003).

[36] Kim, A., Crampton, G. "Corrosion effect of electronic components by hydrogen fluoride (HF)" Journal of Fire Protection Engineering v.18 pp.55-73 (2008).

[37] Liu, Z.G. and Kim, A. K. "A literature review of the impact of thermal decomposition products generated by halon replacements in electronic equipment" National Research Council Canada IR-780 (1999).

[38] Kim, A., Su, J. "Thermal decomposition products from fire suppression with HFC-227ea in an electronic facility" National Research Council Canada NRCC-46778 (2004).

[39] Kim, A., Crampton, G., Kanabus-Kaminska, M. "Performance of Novek1230 in electronic facility fire protection" National Research Council Canada NRCC-53526 (2010).

[40] Peatross, M. and Forssell, E. "A comparison of thermal decomposition product testing of Halon 1301 alternative agents" HOTWC (1996).

[41] Dr. Andrew Kim, National Research Council Canada, private communication May 2011.

[42] Kim, Andrew, "Overview of recent progress in fire suppression technology" National Research Council Canada NRCC-45690 (2002).

[43] Kim, A., Crampton, G., Kanabus-Kaminska, M. "Explosion Suppression with Hybrid Gas Generator System" National Research Council Canada NRCC-50291 p.5 (2008).

[44] "Fire Suppression Substitutes and Alternatives to Halon for Navy Applications", The National Academy Press, p. 10 (1997).

[45] Air comprises approximately 78% Nitrogen (N_2) and approxiamtely1% Argon (Ar); "Handbook of Chemistry and Physics" CRC Press 60^{th} ed. p. F-211 (1980).

[46] Su, J.Z., Kim, A. K., Crampton, G.P., Liu, Z. "Fire Suppression with Inert Gases" J. Fire Protection Engineering 11:72 (2001).

[47] Kim, Andrew, "Gaseous Fire Suppression Systems" given at Carleton University, May 26th 920110, and Kim, Andrew, "Advances in Fire Suppression Systems" National Research Council Canada NRCC-52712 (2009).

[48] SFPE Handbook of Fire Protection Engineering, 3rd ed. National Fire Protection Agency and Society for Fire Protection Engineers, pp. 4: 175-177 (2002).

[49] Laursen, T. "Overview of Toxicity Effectiveness Issues" HOTWC conference proceedings pp. 357-367 (1993).

[50] Kim, Andrew, "Advances in Fire Suppression Systems" National Research Council Canada NRCC-52712 (2009).

[51] "Fire Suppression Substitutes and Alternatives to Halon for Navy Applications", the National Academy Press, pp. 51-52 (1997).

[52] **MSC.1/Circ.1270** - Revised Guidelines for the Approval of Fixed Aerosol Fire-Extinguishing Systems Equivalent to Fixed Gas Fire-Extinguishing Systems, as Referred to in SOLAS 74, for Machinery Spaces.

[53] Back, G.G., Boosinger, M., Beene, D., and Nash, L., "An Evaluation of Aerosol Extinguishing Systems for Machinery Space Applications," U.S. Coast Guard Research and Development Center, Groton, CT, 2005.

[54] International Standards Organization, "Condensed Aerosol Fire Extinguishing System - Physical Properties and System Design - General Requirements," ISO 15779-1:2005(E),International Standards Organization, Geneva, Switzerland, 2005.

[55] Agafonov V., et. al. 2004. The Mechanism of Fire Suppression by Condensed Aerosols. "Proceedings of the 15th HOTC." NIST, pp 984-993.

[56] http://www.epa.gov/ozone/snap/fire/SNAP_Fire_Factsheet.html

[57] Federal Aviation Administration in "Options to the Use of Halons for Aircraft Fire Suppression Systems—2011 Update" 2011-03-07. http://www.fire.tc.faa.gov/pdf/DraftHalonOptionsReport2011-03-15.pdf

[58] Estee Jacobson, Jerry Brown and Len Stepp, *Enhancement of Fire Survivability by Employing Pyrotechnically Generated or Propelled Agents* www.fire.nist.gov/bfrlpubs/fire05/PDF/f05063.pdf

[59] http://www.statx.com

[60] *Standard for Fire Extinguishers, Rating and Fire Testing*, UL Standard 711, Underwriters Laboratories, Inc., Northbrook, Illinois, April 1989.

[61] http://aerotekng.com

[62] http://alltecservice.eu/

[63] Liu, Z.; Kim, A.K. (2000) A Review of water mist fire suppression systems – fundamental studies Journal of Fire Protection Engineering, 10: 32-50.

[64] Liu, Z.; Kim, A.K. (2001) A review of Water Mist Fire Suppression Technology: Part II - Application Studies Journal of Fire Protection Engineering, Vol. 11: 16-42.

[65] Santangelo, P.E.; Paolo Tartarini, P. (2010) Fire Control and Suppression by Water-Mist Systems the Open Thermodynamics Journal, 4: 167-184.

[66] Mawhinney, J.R.; Back III, G.G. (2002) Water Mist Fire Suppression Systems in SPFE Handbook of Fire Protection engineering. pp 4-311 - 4-337.

[67] NFPA 750, *Standard on Water Mist Fire Systems,* NFPA, Quincy, MA, 2000 edition.

[68] D.J. Rasbash, Z.W. Rogowski, and G.W.V. Stark, "Mechanisms of Extinction of Liquid Fuels with Water Sprays," Combustion and Flame, 4, pp. 223–234 (1960).

[69] J.R. Mawhinney, "Characteristics of Water Mists for Fire Suppression in Enclosures," *Halon Alternatives Technical Working Conference,* Albuquerque, NM (1993).

[70] M. Edwards, S. Watkins, and J. Glockling, "Development of Low Pressure Fine Water Spray for the Royal Navy: Additive Concentration and Spray Fire Testing," *Halon Alternatives Technical Working Conference,* Albuquerque, NM (2000).

[71] Chang W.-Y., Fu, P.-K., Chen, C.-H., and Shu, Y.-L. (2008) Evaluating the performance of a portable water-mist fire extinguishing system with additives. Fire and Materials 32: 383-397.

[72] Liu, Z., Kim, A.K., Carpenter, D. (2007) Study of Portable Water Mist Fire Extinguisher used for Extinguishment of Multiple Fire Types. Fire Safety Journal 42:25-42.

[73] http://www.coldcutsystems.com

[74] Scheffey, J.L. (2002) Foam Agents and AFFF System Design Considerations. In SPFE Handbook of Fire Protection engineering. pp 4-88 - 4-122.

[75] Scheffey, J.L. and Harry E. Hickey, H.E. (2002) Foam System Calculations. In SPFE Handbook of Fire Protection engineering. pp 4-88 - 4-122.

[76] Private communication, May 2011 with: Dr. Andrew Kim, National Research Council of Canada; Mr. Paul Lhotsky, (PhD student Carleton University and President of Civelec Consultants (Extinguishing Systems Design)), and Mr. Ron Cornelow (Modern Sprinklers (Systems Installers)).

List of symbols/abbreviations/acronyms/initialisms

AES	Aerosol Extinguishing Systems
AFFF	Aqueous Film Forming Foam
ANSI	American National Standards Institute
ASHREA	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CAFS	Compressed Air Foam System
CFC	Chlorofluorocarbon
DND	Department of National Defence
DRDC	Defence Research & Development Canada
DRDKIM	Director Research and Development Knowledge and Information Management
EPA	Manual Aerosol Fire Extinguisher
FFFP	Film Forming Fluoroprotein
FM	Factory Mutual
GPO	Global Warming Potential
GWP	Global Warming Potential
HFC	Hydrofluorocarbon
IMO	International Marine Organization.
MAFE	Manual Aerosol Fire Extinguisher
NFPA	National Fire Protection Association
ODS	Ozone Depleting Substance
R&D	Research & Development
SOLAS	Safety of Life at Sea
UL	Underwriters Laboratory
ULC	Underwriters Laboratory of Canada
USCG	U.S. Coast Guard

This page intentionally left blank.

Distribution list

Document No.: DRDC Atlantic CR 2011-293

LIST PART 1: Internal Distribution by Centre

2 Dr. John Hiltz (1CD, 1 Hardcopy)
1 Dr. Leon Cheng H/DL(A)
1 Dr. Royale Underhill GL/MC
1 Dr. Calvin Hyatt CSci
1 Mr. Gary Fisher H/DL(P)
1 Dr. Neil Pegg H/WP
3 DRDC Atlantic Library (2CDs, 1 Hardcopy)

10 TOTAL LIST PART 1

LIST PART 2: External Distribution by DRDKIM

National Defence Headquarters
101 Colonel By Drive
Ottawa ON K1A 0K2
1 DMSS 4-2-6
1 DMSS 3-5
1 DMSS 4-2
1 DMPOR 3-2
1 DMSS 4-2-3
1 DMRS 3
1 DMSS 3-6-3
1 DSTM 7
1 DMSS 4-2-8
1 DMSS 3

1 Library and Archives Canada
Attn: Military Archivist, Government Records Branch

1 DRDKIM

12 TOTAL LIST PART 2

22 TOTAL COPIES REQUIRED

This page intentionally left blank.

DOCUMENT CONTROL DATA

(Security classification of title, body of abstract and indexing annotation must be entered when the overall document is classified)

1. ORIGINATOR (The name and address of the organization preparing the document. Organizations for whom the document was prepared, e.g. Centre sponsoring a contractor's report, or tasking agency, are entered in section 8.) CRW Regulatory Services 2057 Oxford Street Halifax, Nova Scotia	2. SECURITY CLASSIFICATION (Overall security classification of the document including special warning terms if applicable.) UNCLASSIFIED (NON-CONTROLLED GOODS) DMC A REVIEW: GCEC JUNE 2010

3. TITLE (The complete document title as indicated on the title page. Its classification should be indicated by the appropriate abbreviation (S, C or U) in parentheses after the title.)

Review of Portable, Manually Operated, and Non-Total Flooding Fire Extinguishing Technologies for Use on Naval Vessels

4. AUTHORS (last name, followed by initials – ranks, titles, etc. not to be used)

Charles Williams; Steve J. Bodsay; Robert Williams

5. DATE OF PUBLICATION (Month and year of publication of document.) December 2011	6a. NO. OF PAGES (Total containing information, including Annexes, Appendices, etc.) 42	6b. NO. OF REFS (Total cited in document.) 76

7. DESCRIPTIVE NOTES (The category of the document, e.g. technical report, technical note or memorandum. If appropriate, enter the type of report, e.g. interim, progress, summary, annual or final. Give the inclusive dates when a specific reporting period is covered.)

Contract Report

8. SPONSORING ACTIVITY (The name of the department project office or laboratory sponsoring the research and development – include address.)

Defence R&D Canada – Atlantic
9 Grove Street
P.O. Box 1012
Dartmouth, Nova Scotia B2Y 3Z7

9a. PROJECT OR GRANT NO. (If appropriate, the applicable research and development project or grant number under which the document was written. Please specify whether project or grant.) 11gy	9b. CONTRACT NO. (If appropriate, the applicable number under which the document was written.) W7707-115134/A
10a. ORIGINATOR'S DOCUMENT NUMBER (The official document number by which the document is identified by the originating activity. This number must be unique to this document.)	10b. OTHER DOCUMENT NO(s). (Any other numbers which may be assigned this document either by the originator or by the sponsor.) DRDC Atlantic CR 2011-293

11. DOCUMENT AVAILABILITY (Any limitations on further dissemination of the document, other than those imposed by security classification.)

Unlimited

12. DOCUMENT ANNOUNCEMENT (Any limitation to the bibliographic announcement of this document. This will normally correspond to the Document Availability (11). However, where further distribution (beyond the audience specified in (11) is possible, a wider announcement audience may be selected.))

Unlimited

13. ABSTRACT (A brief and factual summary of the document. It may also appear elsewhere in the body of the document itself. It is highly desirable that the abstract of classified documents be unclassified. Each paragraph of the abstract shall begin with an indication of the security classification of the information in the paragraph (unless the document itself is unclassified) represented as (S), (C), (R), or (U). It is not necessary to include here abstracts in both official languages unless the text is bilingual.)

Portable fire extinguishers are an integral part of fire fighting capabilities on board naval vessels. In many cases they allow crew to extinguish or suppress small fires before they can grow and become a significant threat to life and the vessel itself. There have been a number of developments in portable and handheld extinguishers in the last twenty years. Many of these use technologies that have been developed to replace Halons in total flooding and local application or portable extinguishment systems. These technologies include water mist, aqueous film forming foams, compressed air foam systems, cutting extinguishers and propelled extinguishing agents technologies (PEAT) or aerosols.

In this Contract Report fire extinguishment and suppression technologies that can be delivered by portable and/or handheld systems are reviewed and critically assessed. Some of the limitations and concerns associated with the use of these systems are discussed.

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

Fire extinguishers; Portable, Handheld; Water mist; Aqueous film forming foams; Compressed air foam systems; Cutting extinguishers; propelled extinguishing agents technologies (PEAT); aerosols

This page intentionally left blank.

Defence R&D Canada

Canada's leader in defence
and National Security
Science and Technology

R & D pour la défense Canada

Chef de file au Canada en matière
de science et de technologie pour
la défense et la sécurité nationale

DEFENCE R&D DÉFENSE

www.drdc-rddc.gc.ca