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Vaporous Decontamination Methods: Potential Uses and Research Priorities for Chemical and Biological Contamination Control

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ABSTRACT

Vaporous decontamination methods were used in the remediation of anthrax contaminated buildings following the 2001 attacks in the U.S.A. Since then the development of vaporous decontamination methods has received considerable interest with significant advancements in the area of CB decontamination of buildings and sensitive equipment. This document reviews the current state of vaporous decontamination methods, with reference to potential uses in CB contamination control. Common decontaminants considered are; formaldehyde, chlorine dioxide and hydrogen peroxide. The benefit of vaporous hydrogen peroxide is discussed in detail, and areas of research in which DSTO can contribute significantly to an international collaborative research program into the VHP decontamination process are outlined.

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Executive Summary

Following a major Chemical and Biological incident, such as the 2001 anthrax attacks in the U.S.A., the prompt containment and remediation of contaminated sites is vital to reduce secondary health risks and to enable the resumption of normal site activities. This is the case for affected sites, both civilian and military, which may include buildings, vehicles and/or sensitive equipment. The remediation of anthrax contaminated buildings in the U.S.A. involved the use of chlorine dioxide gas (ClO_2) and vaporous hydrogen peroxide (VHP). This was the first time that either decontaminants were used for this purpose and therefore considerable downtime of the sites was required. Since that time considerable advances have been made in the application of vaporous methods to CB decontamination.

This document outlines the current state of vaporous decontamination, with reference to the potential use of common vaporous decontaminants; formaldehyde, chlorine dioxide and hydrogen peroxide, for CB contamination control as may be used by Defence or civilian authorities. The process involved a review of the open literature and included journal articles, conferences proceedings, government reports, international patents, case studies, company technical notes, and personal communications. This document provides an overview of the currently available vaporous decontamination procedures, as well as a guide to further research and development which is needed to improve and optimise the decontamination process.

Overall, it was assessed that there is significant benefit in the further development and modification of the VHP decontamination procedure toward the implementation and verification of a broad-spectrum CB decontaminant for buildings and sensitive equipment. This is a common interest that Australia shares with the U.S.A., and as a result, an area that DSTO can contribute significantly to an international holistic research program via the TTCP CBD group AG50. It is proposed that HPPD conduct research into certain fundamental aspects of the VHP decontamination process, while the U.S.A. continues its termination of VHP for decon large equipment. This research is pertinent to the further development and optimisation of the VHP decontamination method. An exchange of information between Australia and U.S.A. will be a great benefit to both countries, with a measurable outcome of improved decontamination techniques.

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1. Introduction

In recent history, chemical and biological counter-terrorism have come to the forefront of defence due to the immense threat to public health and national security. In the last decade a number of chemical and biological (CB) attacks on civilian populations have occurred, including the release of sarin nerve gas in a Tokyo subway system (1995) and the release of anthrax spores through the mail system in the U.S.A. (2001). Advances in biotechnology have provided the capability for terrorist groups to produce bio-weapons in makeshift laboratories, secretly and inexpensively [1]. Anthrax is particularly noteworthy given the ease of procurement, ease of large-scale production, stability of the spores and ease of dissemination (i.e. aerosolised) [1]. Anthrax spores can persist in the environment for many years, for example, spores were detected 40 years after release on Gruinard Island (U.K.) [2]. It is evident that after the release of any CB agent some level of decontamination is required before normal activities on the site affected can resume.

In the event of a CB attack, environmental sampling plays an important role in the restoration of the affected area [1]. Firstly, environmental sampling is required to identify and/or confirm the CB agent used in the attack. This can then be followed by the determination of the extent of the contamination, a risk assessment and the implementation of the most appropriate decontamination* process. Environmental sampling is also used to monitor the progress of the decontamination process. However, some limitations do exist due to insufficient data on the efficiency of various sample collection and analytical methods used for the sampling of indoor environments, especially in cases involving category-A bio-agents, such as *Bacillus anthracis* [1]. Professional judgment must be used to interpret positive/negative results and/or any quantitative data. The important question of “how clean is safe?” must be informed and reliable. It is therefore critical that any decontamination process be as effective and complete as possible for each unique clean up operation.

Vaporous decontamination involves the application of a decontaminant in the vapour (or gas) phase to decontaminate enclosed spaces or sensitive equipment. The effectiveness of the vaporous decontamination process is dependent on a number of parameters, including; concentration of decontaminant, duration of exposure, rate of reaction, temperature, humidity, and the nature of the contaminated material [1].

Bacteria with spores, such as *Bacillus anthracis*, are resistant to commonly used disinfectants and require the use of chemical sterilants† to effectively decontaminate exposed areas. Since anthrax spores can aerosolise the use of vaporous sterilants in the remediation of contaminated areas is desirable. A number of vaporous sterilants exist which can be used to

* The term ‘decontamination’ is used in this document to describe the inactivation of B and/or C agents. When referring to biological species only, this is interchangeable with ‘sterilisation’ which describes the inactivation of all micro-organisms present, including B agents.

† Sterilants and disinfectants differ only in their potency; disinfectants have relatively low potency sufficient to inactivate commonly occurring pathogens only, whereas sterilants are highly potent reagents developed to inactivate all biological species.

inactivate *Bacillus anthracis*, including; beta-propiolactone, chlorine dioxide, ethylene oxide, propylene oxide, ozone, methyl bromide (MeBr), formaldehyde and hydrogen peroxide [1]. Some of these have considerable risks which make them unsuitable for use in indoor environments, for example ethylene oxide and propylene oxide are flammable at working concentrations and need to be used in carefully controlled chambers. Recently, the insecticide MeBr has been considered for use in CB decontamination, however, environmental concerns will likely limit its use [3]. Vaporous decontamination methods commonly used in pharmaceutical and medical industries based on proven efficiency in the lab and field trials are formaldehyde, chlorine dioxide and hydrogen peroxide [1,3].

Herein, the use of these commonly used vaporous decontamination methods is addressed, however this is not intended to be a complete review of all literature, but rather a guide which can be used to further develop and adapt the current technology to novel processes and applications relevant to CB decontamination.

2. Vaporous Decontaminants

2.1 Formaldehyde

2.1.1 Overview

Formaldehyde has been used in both liquid and gaseous states to decontaminate equipment and clean rooms. While effective against all contaminants handled in a typical pharmaceutical or medical setting, handling issues and health concerns have resulted in the use of this decontaminant being phased out in these industries. Formaldehyde is toxic, an irritant and has recently been reclassified as a human carcinogen [4]. Notwithstanding the irritant and carcinogenic properties of this chemical, the application of this process is extremely sensitive to environmental conditions, requiring relative humidity levels to be maintained above 70%. Condensate on surfaces will dissolve formaldehyde forming a concentrated formaldehyde solution which may act as a sporicide, however excess formaldehyde polymerises on surfaces leaving a hazardous residue which slowly releases formaldehyde gas over time. Ammonia gas is typically used to neutralise formaldehyde forming a white precipitate, hexamethylene-tetramine, which is then washed down with water.

2.1.2 Use of Formaldehyde in Decontamination

Historically, formaldehyde has long been used to decontaminate anthrax spores, e.g. more than 40 years after the release of anthrax spores on Griunard Island (U.K.), the island was successfully decontaminated using a formaldehyde solution [5]. Formaldehyde gas is formed by heating paraformaldehyde to 70 - 80°C in an environment with relative humidity of 75 - 100%.

Vaporous formaldehyde was used to fumigate mail sorting equipment contaminated with anthrax spores following the 2001 anthrax attacks in the U.S.A. [3]. The equipment was

enclosed inside a tent along with a number of pans containing paraformaldehyde which were heated on hot plates to release gaseous formaldehyde. An excess of paraformaldehyde ($> 10.6 \text{ g/m}^3$) was used to maintain the required level for the 12 hour period of the decontamination process. Water mist was introduced into the tent via an airless sprayer to maintain the relative humidity above 50%. After the decontamination phase was complete, ammonium bicarbonate (1.5 g per gram of paraformaldehyde) was heated inside the tent to neutralize the formaldehyde vapour.

In light of safety and handling issues of formaldehyde, as well as the availability of effective alternative decontaminants, the use of formaldehyde in building remediation and sensitive equipment decontamination is undesirable. Therefore, there exists no apparent need to actively investigate the use of formaldehyde under the current decontamination task.

2.2 Chlorine Dioxide Gas

2.2.1 Overview

Chlorine dioxide (ClO_2) gas is a biological sterilizer which acts as an oxidizing agent by a single-electron transfer process. It is thought that the oxidation of proteins by ClO_2 leads to functional disruption of micro-organisms [3]. Gaseous ClO_2 is not stable under pressure and so cannot be stored in high-pressure cylinders, but it is readily soluble in water and is stable for extended periods. ClO_2 must be generated on site and introduced directly into the enclosed space. Unlike chlorine, ClO_2 does not react with organics to form chlorinated products and so remains effective in dirty environments.

2.2.2 Use of Chlorine Dioxide in Decontamination

In response to the 2001 anthrax attacks in Washington D.C. the EPA granted a crisis exemption for the use of gaseous ClO_2 in the remediation of buildings on a case by case basis. The target conditions for the most recent crisis exemption were; 750 ppm of ClO_2 for 12 hours, while maintaining the temperature above 75°F (23.9°C) and the relative humidity above 75%. These conditions were shown in a field trial to produce a 6-log kill of *Bacillus anthracis* spores and were consistent with previous laboratory testing [3].

In each remediation, the building was sealed to prevent further spread of the spores and windows were covered to prevent UV light entering room which would decompose the ClO_2 gas [3]. The first time ClO_2 gas was used most office items and furniture were left in place, with only a few valuable and critical items removed for off-site treatment in an ethylene oxide sterilisation chamber. Paper items were either sent for off-site treatment or destroyed in a medical waste incinerator. Subsequent remediation of mail centres involved more significant source reduction steps, including the removal of carpets, prior to the use of gaseous ClO_2 . The ClO_2 was generated outside the building with the resulting aqueous ClO_2 solution pumped into the building and passed through air strippers to release the ClO_2 gas. Mixing fans were operated to achieve uniform mixing of the gas, vapour and heat throughout the enclosed area. Large exhaust fans were used during the decontamination process to maintain the enclosed space under negative pressure, and the exhaust passed through sodium sulphite scrubbers

and a carbon bed to prevent any leakage of the ClO₂ gas into the environment. The decontamination period (12 hours), was followed by the neutralisation of the gas which involved passing the gas through a sodium sulfite/bisulfite solution. The humidity was also lowered during this final phase to prevent mould growth and aid aeration of the space.

Environmental sampling after the first building remediation in the U.S.A. showed a reduction in the number of spores, however a significant amount remained. The area was then wiped down with aqueous ClO₂ to kill the remaining spores. However, it is clear that gaseous ClO₂ is an effective decontaminant for killing anthrax spores, as exemplified in the subsequent effective decontamination of buildings using this method. The initial failure was thought to have been due to the difficulties of maintaining the required fumigation conditions.

Gaseous ClO₂ is able to penetrate some materials, eg. porous materials, plastics, and rubbers. This property is ideal when decontaminating an office environment, provided that adequate aeration of the space occurs after decontamination. However, the partial failure of the gaseous ClO₂ decontamination of an anthrax-contaminated office shows that a greater understanding of the process is needed. Other problems associated with the use of ClO₂ in building decontamination include bleaching of synthetic fibres and photographic materials during the process and the possibility that surfaces may be affected by condensation (especially electrical systems)[3]. Additionally, a large volume of liquid waste is generated during the process. There is also a risk of explosion of the ClO₂ gas concentrations above 10% by volume in air; however this is orders of magnitude greater than those required for decontamination.

While the use of gaseous ClO₂ as a decontaminant has some difficulties, it is an effective alternative to formaldehyde in building remediation and has been successfully demonstrated in real decontamination scenarios. As such, there may be specific instances whereby the use of ClO₂ may be deemed appropriate and so further investigations may be considered at a later stage.

2.3 Vaporous Hydrogen Peroxide

2.3.1 Overview

Vaporous hydrogen peroxide (VHP) is an oxidizing agent effective against many micro-organisms including bacterial spores, while being less of a public health concern than formaldehyde [1,3,6]. VHP is generated by heating a solution of 30 - 35% hydrogen peroxide in water. Since hydrogen peroxide catalytically decomposes to water and oxygen, VHP has the benefit of being effective against micro-organisms while generating no harmful by-products or waste for disposal. The VHP technology has been used for over a decade as a sterilant in the medical, biological and pharmaceutical industries and continues to gain mainstream use as the technology advances. A number of commercial VHP generators are now available to decontaminate equipment and/or rooms. The VHP technology is commercially mature and has demonstrated scalability to large spaces up to 5,660 m³ [3].

2.3.2 Use of VHP in Decontamination

After the anthrax attacks in the U.S.A., VHP was one of the decontaminants permitted by the EPA to be used as a fumigant in the remediation effort and was successfully used to fumigate anthrax contaminated buildings [3]. Since then, there has been considerable interest in further developing VHP processes for the large scale decontamination of fixed sites and sensitive equipment after an attack involving a CB agent. Much of this research has been carried out in the U.S.A. by researchers at the Edgewood Chemical Biological Center (ECBC) in conjunction with STERIS Inc. who developed the VHP technology for the medical, biological and pharmaceutical industries [3,7,8,9].

As discussed further below, VHP has great potential for use in building remediation and sensitive equipment decontamination in a broad range of environmental settings following a CB incident. As such, the remaining discussions will focus on decontaminating properties of VHP and the research and development needed to apply the method to CB Defence.

3. VHP Decontamination

3.1 A Potential Broad-Spectrum Decontaminant for Rooms, Aircraft and Sensitive Equipment.

The use of VHP decontamination has gained considerable interest in Defence (and other industries) as a wide ranging decontaminant for use in multiple scenarios and against multiple biological and chemical contaminants. The technology has already been successfully used in real building remediation scenarios following the 2001 anthrax attacks in the U.S.A. Recently, the activation of VHP toward C agents including GD, VX and HD has been investigated by ECBC, who have demonstrated that modifying the VHP decontamination process (by adding low levels of ammonia gas) produces a broad-spectrum decontaminant against C agents [7]. However, initial studies have shown that the modified vaporous hydrogen peroxide (mVHP) is marginally less effective than standard VHP against B agents. Large-scale testing of mVHP was conducted last year in a building at ECBC and a C-141 aircraft at Davis-Monthan Airforce Base [7]. In the building test environment, a 24-hour mVHP treatment cycle, with 250 ppm VHP and 20 ppm NH₃, effectively reduced contact and vapour hazards of GD and VX to limits of detection. While hazards of HD were reduced, detectable amounts of HD vapour were detected, especially from porous surfaces. The aircraft test involved the use of a self-contained mVHP trailer unit which was used to obtain 125, 250 and 450 ppm levels of mVHP in the 14,000 m³ aircraft interior for a 5 hour treatment cycle. In the ECBC tests, computational modelling was used to model air flow in the space to be decontaminated to assist in setup of the decontamination system and placement of sensors. An ozone enhanced VHP (O₃-VHP) decontamination method and system has also been described and suggested to increase efficiency and/or reduce the usage of H₂O₂ [10]. Currently there is no reported data on the use of O₃-VHP against B or C agents.

The U.K. based BIOQUELL Corporation has also commercialized a decontamination system using hydrogen peroxide vapour (HPV, hereafter referred to as VHP). Distributed under the Clarus brand name these series of VHP generators are used for the decontamination of bio-safety cabinets and room bio-decontamination [11]. The company has recently launched a room bio-decontamination service in the U.K. to combat hospital acquired infections [12]. The room decontamination process is rapid, with a typical hospital ward taking 12 hours, and is reported not to damage any of the sensitive hospital equipment.

The exploration of outer space by NASA and other agencies requires various levels of spacecraft production and pre-mission protocols to reduce any potential risk of microbial contamination to other celestial bodies. Currently, the only method approved of spacecraft decontamination is dry heat microbial reduction requiring a temperature of 111.7 °C for 30 hours [13]. However, current electronics and other advanced materials could be damaged by such high temperatures and so NASA is currently investigating VHP as an alternative low temperature decontamination method [13]. Studies so far indicate that the VHP process is an effective alternative to the dry heat process.

3.2 The VHP Decontamination Process

There has been much debate as to the exact mechanism involved in the decontamination of surfaces by VHP. The traditional theory is that VHP decontaminates surfaces by a dry gas process. In this case, humidity needs to be controlled so as to avoid complications arising from condensation. Alternatively, it is thought that micro-condensation is the primary method causing decontamination. This theory asserts that condensation is difficult to avoid under normal operating conditions unless very low concentrations (< 700 ppm) of VHP are produced [14,15]. The micro-condensation theory claims to explain an observation that the decontamination of surfaces is effective at lower temperatures, since such conditions favour the condensation process, and the efficiency of a gas phase (dry) process should be decreased at lower temperatures. In the micro-condensation approach, a concentrated thin film (<1 micron) of hydrogen peroxide (H₂O₂) solution forms on surfaces which is effective in killing all micro-organisms present. The two distinct mechanisms described above are the basis for commercial VHP systems produced by STERIS and BIOQUELL respectively [9,12]. An independent report compared the two systems and determined that both can be validated and that the differences do not affect the effectiveness of either unit to decontaminate [16].

Recent trials conducted by BIOQUELL in association with hospitals in the U.K. have shown that while regular cleaning was poorly effective against high levels of (environmental) methicillin-resistant *Staphylococcus aureus* (MRSA), VHP was dramatically effective [17,18]. The BIOQUELL technology has also been tested by the EPA in the U.S.A. under the Environmental Technology Verification (ETV) program, for the application as a biological agent decontamination process [19]. The efficiency against *Bacillus anthracis* was demonstrated by a log reduction in spores of 6.9 (or better) on non-porous surfaces, while porous surfaces showed 3.0 (or better) log reduction in spores. VHP has also been shown to be effective against numerous other micro-organisms and a recent report indicates that VHP may also be effective against prions [20].

It is evident that both the micro-condensation and dry VHP processes can be used to kill micro-organisms effectively at room temperature, despite the marketing ploys of the companies involved in the debate. Regardless of VHP decontamination process used, scalability of the decontamination process is apparently relatively easy. For example, the room decontamination system of BIOQUELL is modular and simply requires additional modules for larger spaces and/or sectioning of the large spaces into smaller spaces [12]. Additionally, ECBC, in conjunction with STERIS Inc., have developed a self-contained mVHP system on a trailer for larger decontamination requirements [7].

3.3 Commercial VHP Generators

VHP generators have been developed as closed systems and the process cycle designed with up to four phases; dehumidifying, conditioning, decontaminating, and aerating. The first phase involves stabilising the enclosure to a pre-set temperature and (low) humidity level. The conditioning phase involves the flash vaporization of aqueous H₂O₂ (30 - 35 %) into a dry air stream which is then introduced into the enclosure until a predetermined concentration is reached, while the following decontamination phase involves maintaining the vapour/gas concentration in the chamber. Finally, the aeration phase involves ceasing the evaporation of fresh aqueous H₂O₂ while continually circulating the air through a catalytic destroyer to remove the VHP from the chamber.

Over the years, many variations have been applied to the VHP decontamination process. It was originally considered that VHP decomposed according to a half-life rule and therefore to maintain a steady concentration of VHP inside the chamber, the VHP was catalytically decomposed to water and oxygen on return to the generator, the air was then dried, re-heated and used to evaporate fresh aqueous hydrogen peroxide. In 1999, it was determined that VHP does not decompose according to a half-life rule, therefore it is not necessary to catalytically destroy the VHP as it returned to the generator [21]. Indeed, not destroying the VHP allows the predetermined concentration to be attained more rapidly, this is particularly important for larger enclosures [22]. Thus, VHP need only be catalytically destroyed during the final aeration phase, which is run continually until VHP levels are lowered to an accepted level (< 1ppm) and often run overnight for convenience.

3.4 Foundations for a HPPD Vaporious Decontamination Program

The decontamination work carried out in the U.S.A. following the 2001 anthrax attacks involved several large office buildings and mail centres. Various decontamination processes were used depending on effectiveness, toxicity, penetrability, material compatibility, and production. The site, potential by-products, cost and time also played a deciding factor in each remediation. In case of a similar attack occurring against Australia or its interests, it is essential to have a thorough understanding of available vaporious decontamination processes which could be utilised in the subsequent remediation efforts.

A vaporious decontamination evaluation program will provide the capability to assess vaporious decontamination efficiencies against a broad range of CB agents under variable environmental conditions and on common interior surfaces. While considerable work has

already been done with regards to bio-decontamination using vaporous decontamination technology, particularly in the pharmaceutical and hospital industries, questions remain regarding the decontamination of CB agents using this technology. A better understanding of the fundamental processes involved in vaporous decontamination is required in order to expand the scope of current applications as well as to optimise operational conditions to increase performance. These studies could be carried out using a small scale testing apparatus.

Prior to the utilisation of a vaporous decontamination method in the clean up of a CB agent, the vaporous decontamination cycle parameters would need to be determined based on the local environment, the extent of contamination and the specific C or B agent involved. An evaluation program would allow direct comparison of results obtained using different methods to help understand and improve the effectiveness of vaporous decontamination processes. The results obtained could be used to extrapolate to larger and more complicated decontamination areas, which could be tested using larger chambers. In addition, this capability will allow a more rapid approach to combat new threats as they become evident.

The current state of vaporous decontamination methods against CB agents is advanced. Most noteworthy in this regard is the work carried out by ECBC, in association with STERIS Inc., on (i) the large scale remediation of buildings and aircraft using VHP and (ii) the activation of VHP to effect decontamination of C agents. However, the focus has been on practical guidance of the technology, such as concentration and time required for decontamination, and not on the elucidation of fundamental processes involved. Currently, there are significant gaps in fundamental understanding of the mVHP decontamination process. This niche area of potential discovery is where Australia could contribute significantly to a holistic research program by collaborating with the U.S.A. via the TTCP CBD Group AG50. A collaborative research program between HPPD and ECBC would provide a mechanism for the exchange of ideas, experience and results to more effectively focus efforts toward decontamination requirements of common interest. The experience that ECBC has gained from field trials will assist HPPD initiate a vaporous decontamination research program, while in turn the results obtained from a fundamental research program in HPPD will assist ECBC researchers expand the scope of current applications and to optimise operational conditions to increase performance.

3.4.1 Required Equipment

The lab scale testing apparatus will be centred around a small (1 - 2 m³) air tight enclosure (the test box), a glove box would be practical if any manual manipulations are required while the decontaminant vapour is present in the enclosure, e.g. quenching of test strips during a time course study. However, when manual manipulations are not required the glove ports should be able to be sealed. The test box would need to have several openings for circulating air/vapour to and from the vapour generator as well as to introduce samples for investigation. A simple design of the test box will allow for considerable variability of the contaminant, decontaminant and material to be investigated. The temperature, decontaminant concentration and humidity need to be measured. However, consideration needs to be given to the interior of the test box which should be kept as simple as possible. It may be beneficial

to place the monitors outside the test box measuring air coming from and/or returning to the generator.

Outside the test box, gas-tight piping will connect the enclosed air to the vapour generator to form a closed loop system to re-circulate and handle the air contained within the test box. In addition, other components may also be added in the closed loop, for example an inlet system for the addition of NH_3 or O_3 to the air/vapour stream before it enters the enclosure. The VHP generator itself consists of a number of components including; an air drier, a heater, a fan to regulate airflow, a controlled inlet system for the flash vaporisation and injection of VHP into the air stream, and a catalytic destroyer for H_2O_2 . Commercial VHP generators encompass these features and therefore it will more efficient to obtain and use a commercial VHP generator rather than design, construct and troubleshoot all the necessary components for an efficient system. Additionally, by varying the H_2O_2 injection and gas flow rates, the STERIS VHP 1000ED System can be used for experiments involving the test box as well as enclosures up to approximately 200 m^3 . The larger capacity of this commercial VHP generator would allow for room bio-decontamination which could be validated to the requirements of the HPPD PC3 lab ($< 150 \text{ m}^3$), thus providing a dual purpose for the unit.

3.4.2 Possible Investigations

There are various modifications which can be made to the VHP decontamination process and need to be tested thoroughly. As mentioned previously, ECBC have studied the addition of an adjuvant (NH_3) to VHP to activate the decontaminant to be effective against some chemical agents and toxins. The ECBC research uses VHP systems designed by STERIS Inc. and are based on the dry decontamination concept using concentrations of H_2O_2 vapour below the dew point. This leads to the questions; what is the efficiency of the micro-condensate layer of H_2O_2 against chemical agents? i.e. does the increased concentration of H_2O_2 on the surface effectively neutralise the chemical agent hazard? What is the effect of adding an adjuvant to this process? Are other adjuvants, such as ozone, effective against CB agents? and, if so, what is the mechanism of action? Is the potential for surface damage increased or decreased by any of the modifications considered? These questions highlight the need for a more thorough understanding of the fundamental mechanisms involved in the decontamination process. Clearly, a systematic and unbiased approach is needed to compare all possible VHP generation cycles, particularly with respect to the efficiency, controllability, reagent usage and ease of operation.

It would be useful to be able to predict the effectiveness of a vaporous decontaminant against various CB agents deposited on different surfaces. How penetrating does vapour need to be? Do competing H_2O_2 decomposition reactions occur at the surface? and, if so, what is the relationship between surface area, VHP concentration and decomposition? Does micro-condensation lessen these problems? Can co-/pre- treatment of porous surfaces enhance efficiency? (c.f. a wetting agent, or surfactant, to prevent water beading) and how does this affect the activity of the vaporous decontaminant?

The use of biological indicators to be used as validation tests for remediation technology needs to be addressed. For example, which micro-organism should be used, and on what

surface should test strips be prepared? A recent study showed that under the same VHP decontamination cycle parameters *Clostridium spp.* spores were still detected despite the inactivation of the *G. stearothermophilus* spores which are typically used to indicate the effectiveness of the VHP process [23]. While, a study on the effectiveness of ClO₂ against *Bacillus anthracis* showed dramatic differences in the kill rate between spore slurries dried on glass slides and those dried on filter paper [3]. This is likely due to greater exposed surface area of the spores which adhere to the 3D fibre matrix of the paper, as opposed to the clumps of spores which form on the glass surfaces. These examples emphasize the need for additional data regarding the effect of surfaces on the vaporous decontamination process.

While initially the HPPD vaporous decontamination research program should focus on fundamentals of the VHP process, the knowledge and research capability gained will allow for investigations to be pursued in other areas of vaporous decontamination. Longer term studies to be considered include; an investigation to determine how dust and dirt affect the vaporous decontamination process, an examination of UV/photo/laser assisted vaporous decontamination processes, and an evaluation of ClO₂ and MeBr as potential vaporous decontaminants of CB agents.

4. Conclusions and Recommendations

Vaporous decontamination methods can be used in the remediation of buildings, vehicles and other valuable equipment following an incident involving CB agents. In recent years, there has been a shift in room bio-decontamination methods from formaldehyde to chlorine dioxide and VHP. The VHP process is a particularly attractive alternative due to the relative simple method of generation combined with the non-toxic by-products of water and oxygen. VHP has been used in industry for over a decade and since the 2001 anthrax attacks in the U.S.A. there has been continued interest in further developing the process for remediation use following CB attacks. Previous and continuing work include decontamination of buildings, aircraft and other sensitive equipment. In addition, advances have been made to activate the hydrogen peroxide toward chemical oxidation, with some encouraging results against VX, GD, and HD.

The development of the mVHP process by ECBC and STERIS Inc. has been focused on practical guidance of the technology toward decontamination of C agents. Significant gaps exist in the fundamental understanding of how mVHP achieves decontamination of C agents, the knowledge of which will be required to continue to develop and optimise the performance of the mVHP method. This represents a niche area where Australia could contribute significantly to an international research program with the U.S.A., and possibly other partner countries, via the TTCP CBD Group AG50.

Therefore, it is recommended that a vaporous decontamination research program be initiated within HPPD, with an initial aim to develop and implement a research program to investigate pertinent fundamental aspects of the VHP and mVHP decontamination methods. This program will directly address client requests as part of the current task, CB Contamination

Control (ARM 05/143). In addition, the development of expertise regarding numerous fundamental aspects of vaporous decontamination is consistent with the implementation of several recommendations of the recent CBRN DC S&T Review [24], in particular, an increased participation in the CBD group of the TTCP, and the creation of holistic programmes across TTCP nations. It is expected that this program will provide avenues to implement other recommendations of the S&T review and will reinforce the position of HPPD as “a purveyor of CBR expertise”.

It is also recommended that a VHP generator be obtained by HPPD for this research program, and that it be made available to decontaminate the PC3 laboratory as required. The VHP system could therefore serve a dual purpose as a research tool and room sterilisation system for the PC3 laboratory. The latter use in and of itself will be extremely beneficial for HPPD by reducing downtime and eliminating health risks associated with the current use of formaldehyde which has proved difficult in obtaining a desirable outcome. Furthermore, by using a commercial generator in our research program it will allow for acceptance by the scientific community. In particular, the use of a STERIS VHP system in the HPPD VHP research program will allow for the succinct relay of information between HPPD and ECBC researchers by using the same instrumentation. This will result in more rapid implementation in large scale testing and evaluation (T&E) trials. Ultimately, the practical guidance attained via T&E trials will be used by Defence forces of both countries, and possibly other TTCP partners, to assess and develop their individual decontamination capabilities.

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