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LLNL-TR-738385

The Use of Vaporous Hydrogen Peroxide for Building Decontamination Final Report CRADA No. TC-2053-02

M. F. Verce, L. I. Schwartz

September 12, 2017

Disclaimer

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

The Use of Vaporous Hydrogen Peroxide for Building Decontamination

Final Report
CRADA No. TC-2053-02
Date Technical Work Ended: March 31, 2007

Date: August 22, 2007 Revision: 3

A. Parties

This project was a relationship between The Regents of the University of California, Lawrence Livermore National Laboratory (LLNL) and Strategic Technology Enterprises, Inc. (STE), a subsidiary of STERIS Corporation.

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B. Project Scope

This was a collaborative effort between LLNL and STE to investigate the use of vaporized hydrogen peroxide (VHP®) to decontaminate spore-contaminated heating, ventilation, and cooling (HVAC) systems in a trailer sized room. LLNL's effort under this CRADA was funded by DOE's Chemical and Biological National Security Program (CBNP), which later became part of Department of Homeland Security in 2004.

Although this overall objective remained the same for the entirety of the project, the scope and schedule of the project changed due to the following events:

- DOE/DHS under funded the project in FY03 by ~ $80K;

- LLNL independently discovered that galvanized steel (GS) ducts catalyzed the decomposition of VHP, a result that was known to STE through prior work. As a result, the effort was re-focused on understanding the factors affecting the loss rate, and identification of strategies to minimize the loss;
- The instrument used to measure VHP had technical difficulties, including some cross-sensitivity to water vapor, which was corrected by the instrument's manufacturer providing a new "R value" used in the data acquisition software. However, this preliminary diagnostic work provided an opportunity to validate an alternative calibration method, and may result in an additional publication;
- DHS delayed funding of all projects at LLNL in FY04. This delayed completion of experiments involving duct decontamination; and
- Project received an additional ~$500K in funding in FY05. As a result, LLNL was able to complete an additional ~ 1 year of room decontamination experiments not in the original scope of work.

The net result of these events is that the project took longer to complete than originally planned, but much more was accomplished. STE proved to be very flexible, granting LLNL three no-cost time extensions.

All of the following tasks listed in the original statement of work were completed, except Task 1.6, which was satisfied by using spore strips qualitatively, as opposed to obtaining quantitative spore counts (see Fig. 4).

Task 1: Integration of STE VHP® generator
Task 1.1 Discussions between LLNL and STE on the design and equipment specifications
Task 1.2 Receipt and installation of VHP® generator and associated equipment into the trailer
Task 1.3 Optimization of temperature, flow, relative humidity, and hydrogen peroxide detectors for use with STE VHP® generator
Task 1.4 Installation of engineered health and safety controls; leak testing
Task 1.5 Initial "shake–down" testing of HVAC system, VHP® generator, and detectors
Task 1.6 Optimization of method for quantifying spore decontamination using spore strips
Task 2: Tentative trailer experiments with spore strips. Perform experiments at various temperature, VHP® concentrations, and exposure times, to be determined.
Task 3 Reduction and Analysis of data collected:
Task 3.1 Data reduction
Task 3.2 Progress report

Two additional tasks not part of the original statement of work that were completed were:

Task 4 Calibration of near-infrared analyzer
Task 5 Detailed room decontamination experiments

All of the deliverables established in the original statement of work were also met:

1. Phase I Progress Report; Due Month 4. This was met by Report 1, Section F
2. Summary of experimental conditions tested will be presented in a final report. Met by two manuscripts intended for publication in open literature (attached to this report; see also Section F)
3. Presentation of project results at meeting of appropriate public health, engineering, or environmental organizations. Met by Reports 1-4, section F.
4. Preparation of journal manuscript. Met by Reports 5-6, section F
5. Final CRADA Closeout Report; Due within 30 days of completion or termination of project. Met by completion of this report.

C. Technical Accomplishments

This CRADA resulted in three major technical accomplishments.

The first major technical accomplishment was the development of a relatively quick method to calibrate the near-infrared (NIR) vaporized hydrogen peroxide analyzer used in the subsequent decontamination experiments. This effort was not part of the original scope of the CRADA, but became necessary after the accuracy of this instrument came into question during initial experiments. This method is based on known published vapor pressure relationships for liquid hydrogen peroxide-water systems, which can be used to calculate the concentration of VHP at the dew point, if the water vapor (WV) concentration is independently measured. This method seemed particularly well suited to calibrate the NIR instrument used in this work, because it happens to measure both VHP and WV. The WV measured by the instrument at the dew point (e.g., during a brief condensation event created by the STERIS VHP 1000®) is used in conjunction with the known vapor pressure relationships to estimate the true VHP concentration present. This value is then compared to the actual VHP concentration measured to develop a calibration curve. The technical details of data analysis can be found in a manuscript prepared by LLNL entitled "Dew point calibration of a near-infrared vaporized hydrogen peroxide analyzer," which accompanies this report as an attachment. A representative calibration curve is shown in Fig. 1. Although a comparison of calibration methods was beyond the scope of this work, this method is believed to be more accurate than previously published methods, because it ensures the measurement is truly at the dew point, where published vapor pressures are valid. Other methods which rely on tubing and chemical analyses may incur additional decomposition of VHP that could affect the accuracy of calibration

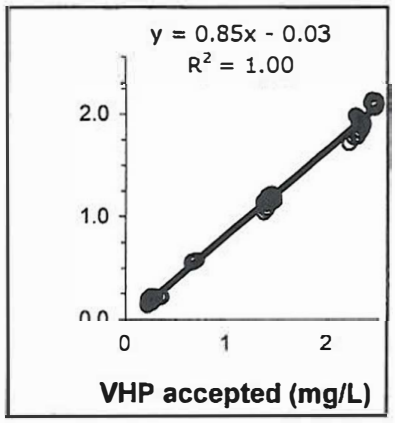

Fig 1. Calibration of NIR analyzer.

Though the calibration work was not part of the original scope of the CRADA, it is important for two reasons. First, the method was used to calibrate the NIR for all of the decontamination experiments that followed later. Second, the type of NIR instrument used in this work is a popular instrument used in a variety of pharmaceutical and decontamination applications, and is used often by STERIS. Therefore, a faster and more accurate calibration method should benefit these industries and applications.

The second major technical accomplishment was to determine how to minimize the decomposition of VHP in GS ducting by adjusting the temperature, flow rate, and concentration. To do this, a 90 ft duct of 6 inch round GS was constructed, and the VHP concentration was measured at six different locations along the length of the duct with NIR analyzer (Fig 2). Experiments were performed at different initial VHP concentrations (1.1 mg/L, 0.55 mg/L and 0.35 mg/L) flow rates (12 actual cubic feet per minute (acfm), 27 acfm, and 49 acfm), and temperatures (71°F, 85 °F, and 100 °F. Triplicate experiments on separate days were performed for each condition. The general effect of GS on VHP concentrations is shown in Fig. 3, which shows results of experiments performed at different injection, but same temperature (~85°F) and flow rate (~12 acfm). To demonstrate that the decrease in VHP was related to GS, all experiments were repeated (in triplicate) in a PVC coated steel duct of the same dimension and layout as the GS duct (Fig. 3b). As can be seen, (Fig. 3b), very little or no loss of VHP occurred in the PVC lined duct, suggesting that GS catalyzes the decomposition of VHP at its surfaces. This conclusion was supported further by the fact that a computational fluid dynamics (CFD) model of the duct, which included decomposition kinetics defined only at the duct's surface, gave a reasonable fit to the GS data (dashed line, Fig. 3a). The effect of decomposition on biological decontamination was tested in separate experiments in which biological indicators (BIs; spores of non pathogenic organisms that are more resistant to VHP than *B. anthracis*) were placed inside the GS duct. As seen in Fig. 4, indicators placed at the beginning of the duct (Fig. 4a) were killed much more quickly than those placed farther down the duct (Fig. 4b) where VHP concentrations were lower. Although decomposition lowers the amount of VHP available for decontamination, it can be

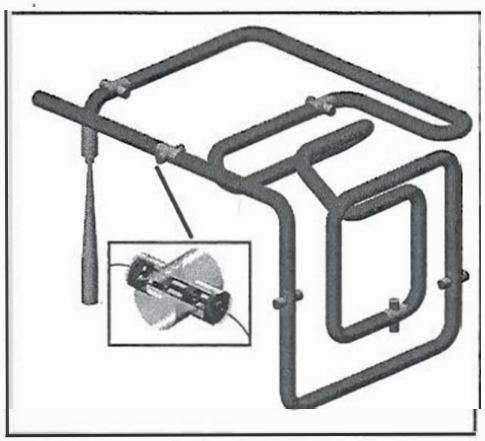

Fig. 2 Schematic of duct experiments. Inset shows positioning of NIR absorption cell within duct.

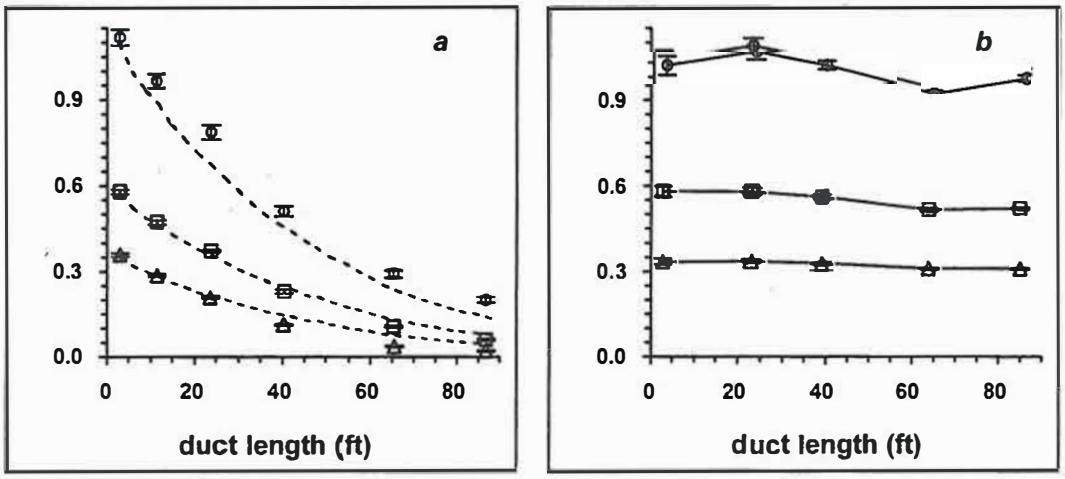

Figure 3. Effect of initial concentration on VHP profiles in GS (*a*) and PVC- lined steel (*b*) duct, respectively, at constant flow rate (12 acfm ± 0.5 acfm) and temperature (86 °F ± 2 °F). Different symbols represent experiments with the VHP 1000® generator set to different injection rates, giving rise to the different initial concentrations shown; each symbol is an average (± standard deviation as error bars) of triplicate experiments performed on separate days. Dotted lines in (*a*) are CFD simulations; solid lines in (*b*) connect data points and do not represent CFD simulations.

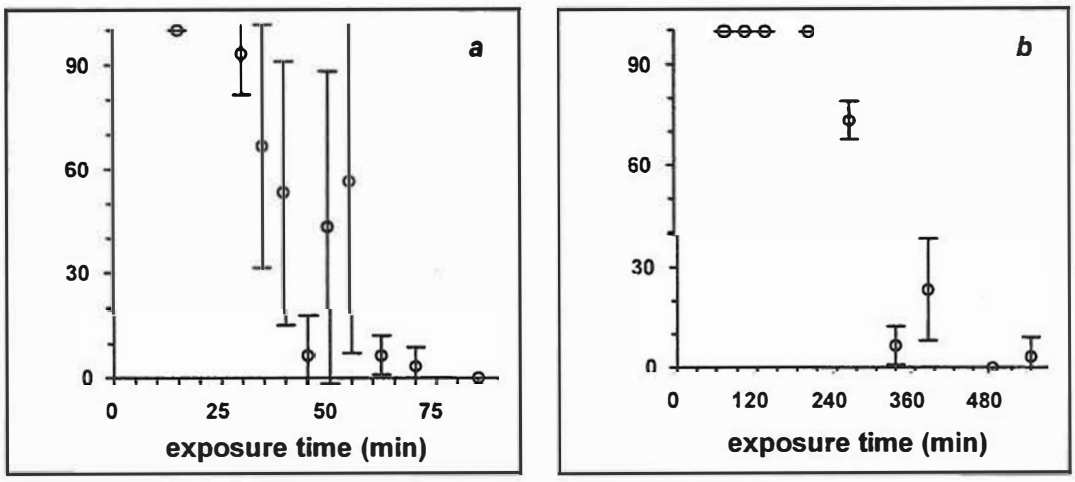

Figure 4. Kill of BIs placed in the immediate vicinity of the first (*a*) and fifth (*b*) absorption cells in the GS duct (Fig. 1). BIs were fixed to a plastic strip that conformed to the inside surface of the duct. Symbols are averages (± standard deviation as error bars) from triplicate experiments in which 10 BIs were used per experiment. The decontamination cycle was the same used to produce the highest initial VHP concentration tested (O, Fig. 2a), and the resulting VHP concentration profiles were similar.

minimized. Of the parameters tested, lowering the temperature to ~ 71°F and increasing the flow rate to ~ 49 acfm were equally effective in minimizing decomposition. Increasing the initial VHP concentration entering the duct also decreased decomposition, but not to the same extent. All data, modeling, and a more in-depth discussion of these experiments can be found in a manuscript entitled "An experimental and CFD study of biological decontamination of galvanized steel ducting with vaporized hydrogen peroxide" which accompanies this report as an attachment.

The results of the duct experiments and modeling are important for two reasons. First, simply knowing that GS catalyzes the decomposition of VHP will lead to a more effective application of VHP to duct decontamination. At the beginning of this project, it was thought that introducing VHP into a building's ventilation system would bring about decontamination of ventilation system and the rooms attached to the system. Due to decomposition, a more effective strategy may be to decontaminate the ventilation system and rooms separately. Second, this work shows how to minimize the decomposition by making practical changes to some decontamination parameters. Specifically, performing a decontamination during the coolest part of the day, or by using the building's cooling systems, may be a simple way to take advantage of the effect of temperature to decrease decomposition. Passing VHP through the duct at higher flow rates also will be beneficial, but may require larger generation capacity.

The third major technical accomplishment was the demonstration of the effect of mixing on VHP concentrations in a room. These experiments were performed on the room used for the duct experiments (above), except that the duct was removed, and several additional electrochemical VHP sensors were added to measure VHP concentrations throughout the room (Fig 5). Furthermore, the room was covered in plastic film to minimize decomposition of VHP. To test the effect of mixing, experiments were performed either under pseudo-quiescent conditions (in which the

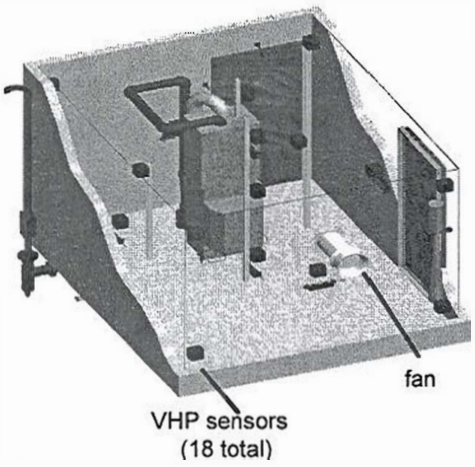

Fig. 5 Schematic of room experiments.

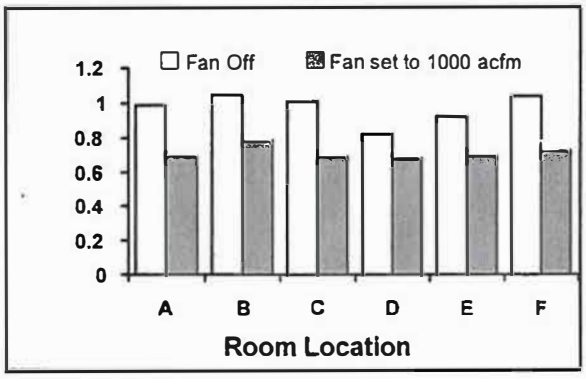

Fig. 6 The effect of mixing on the steady state VHP concentration at six arbitrary locations (A-E) within the room.

VHP 1000® generator was the only source of flow), or under well mixed conditions (provided by a precision speed controlled fan set to 1000 rpm). The mixing times for the room, estimated from theoretical correlations, were ~40 min for experiments when the fan was off, and ~1 min for experiments when the fan was run at 1000 rpm. As shown in Fig. 6, the steady state VHP concentrations were between 20% and 30% lower under well mixed conditions, as compared to poorly mixed conditions when the fan was off. Similar results were obtained at different VHP injection rates (data not shown). Although preliminary, these results suggest that like the duct experiments, VHP decomposes upon contact with surfaces within the room, whose effect becomes larger under well mixed conditions. This implies that there may be an optimal amount of mixing that efficiently disperses VHP throughout a room in a timely fashion, while minimizing the amount of decomposition. The detailed analysis of the room experiments was not part of this CRADA, but will likely be continued by LLNL as time permits, and will hopefully result in a manuscript for publication in an open scientific journal.

D. Expected Economic Impact

The primary economic impact of this work is to reduce the time required to re-open a building after a spectacular biological event. By identifying ways to minimize the decomposition of VHP in ducts and rooms, the results of this work can be used to shorten decontamination times, and restore buildings more quickly than was possible before the CRADA. The economic impact of closing vital infrastructure (e.g., a major transportation facility) due to a spectacular biological event is likely to be huge, so even a modest decrease in the time required for decontamination could represent a substantial cost savings.

D.1 Specific Benefits

Benefits to DOE

The primary benefit realized by DOE in participating in this CRADA is to further its general mission in national security, by conducting detailed R&D work that might not have otherwise

been completed, but may prove useful during a future event involving biological warfare agents. This project also adds to DOE's portfolio of capabilities in the area of decontamination, which previously have included detection, prediction, and restoration planning.

Benefits to Industry

The primary benefit realized by STE in participating in this CRADA is a more detailed understanding of some of the phenomena that can affect the use of VHP technology in a building setting. The decomposition of VHP by GS will likely impact the decontamination of HVAC systems, since most ducting is made of GS. The effects of temperature, flow rate, and injection concentration during this work can be used by STE to minimize decomposition, which will make future decontaminations more effective. Similarly, the possibility of an optimal mixing rate for whole room decontamination can be used by STE to refine the use of fans for more efficient large scale decontamination. STE should also benefit generally by positive exposure of their technology in the journal articles resulting from this work.

E. Partner Contribution

STERIS made the following contributions to the project:

- technical assistance, including:
  - assistance by I. McVey (STE) on the proposal submitted to DOE to continue this work (2003), and on providing literature references for preparation of manuscripts listed in Reports (below)
  - 3 separate training classes on use of VHP 1000® given by J. Thomas (STERIS) at LLNL
  - 2 separate site visits by L. Schwartz and other STE personnel to establish the CRADA (2003) and review project results (2004)
  - review and helpful comments on all presentations listed in Reports (below)

- materials contributions, including:
  - uninterrupted use of a VHP 1000® generator to LLNL for the entire project
  - 4 service calls for repair and maintenance of VHP 1000®
  - an estimated 24 cases (six 950 mL bottles per case) of Vaprox® 35% liquid hydrogen peroxide sterilant

F. Documents/Reference List

Reports

Report 1
Title: HVAC and building decontamination using gaseous reagents
Type: Presentation

Comment: Presented by M. Verce (LLNL) at the 2003 Chemical and Biological National Security Program Summer Meeting on 4 June 2003

Report 2
Title: Use of HVAC systems in building decontamination
Type: Presentation
Comment: Presented by T. Carlsen (LLNL) at the USEPA workshop on decontamination, cleanup, and associated issues for sites contaminated with chemical, biological, or radiological materials, 23-25 Feb 2005

Report 3
Title: Optimizing Decontamination of ductwork contaminated with BW agents: room scale testing and computational fluid dynamics simulations
Type: Presentation
Comment: Presented by M. Verce (LLNL) separately to STERIS, Edgewood Chemical Biological Center, and USEPA National Homeland Security Research Center during business development trip on week of 6 March 2006

Report 4
Title: The effects of process parameters and materials on hydrogen peroxide vapor concentration in model air ducts and rooms
Type: Presentation
Comment: Presented by M. Verce (LLNL) at the DTRA Joint Science and Technology Office's 2006 Denver DECON science and technology conference, 31 Oct-2 Nov 2007.

Report 5
Title: Dew point calibration of a near-infrared vaporized hydrogen peroxide analyzer
Type: Manuscript
Comment: Intended for publication in an appropriate technical, open literature, journal

Report 6
Title: An experimental and CFD study of biological decontamination of galvanized steel ducting with vaporized hydrogen peroxide
Type: Manuscript
Comment: Intended for publication in an appropriate technical, open literature, journal

An additional manuscript may be prepared by LLNL on room decontamination experiments at a later date.

Copyright Activity

This project produced scientific and engineering data (contained in manuscripts and presentations described above) of the type normally found in the open literature. Therefore, there has been no copyright activity as a result of this project. No software or drawings, other than the figures in the above manuscripts and presentations, were produced.

Subject Inventions

In short, no subject inventions resulted from this project. However, the work described above on the calibration of the NIR VHP analyzer directly involves some of STERIS's background intellectual property, as described below.

After the calibration experiments were completed, the LLNL PI (M. Verce) was encouraged to submit a Record of Invention (ROI) IL11644 on the subject. In preparing the ROI, a review of the patent literature revealed a patent entitled "A Physical Chemical Method for Verifying the Calibration of a Near – Infrared Vapor Phase Hydrogen Peroxide Analyzer" (US Patent # 4,843,867), which describes the same general principle of calibration. This patent is owned by STERIS, and is declared by STERIS as Background Intellectual Property in this CRADA (below). LLNL's Intellectual Property Group accepted the ROI IL11644 on 2/7/06, disclosed the ROI to STERIS on 5/9/06, and decided not to pursue the ROI on 11/15/06.

Given the above events and information, the LLNL PI prepared a draft manuscript which cites STERIS's Patent 4,843,867 as the source of the principle of this method, and then describes how the method was applied to the calibration of the near-IR instrument used in this work.

Background Intellectual Property

LLNL did not disclose any Background Intellectual Property (BIP) for this project.

STE disclosed the following BIP for this project:

U.S. Patent No. 5,527,508, "Method of Enhanced Penetration of Low Vapor Pressure Chemical Vapor Sterilants During Sterilization," issued 11/12/92

U.S. Patent No. 5,556,607, "Sterilization Apparatus and Method for Multicomponent Sterilant," issued 09/19/95

U.S. Patent No. 5,173,258, "Recirculation, Vapor and Humidity Control in a Sealable Enclosure," issued 10/11/89

U.S. Patent No. 4,744,951, "Vaporization Method to Enhance Sterilant Penetration," issued 05/10/85

U.S. Patent No. RE 33,007, "Method of Vaporizing Multi-Component Liquids," issued 02/09/88

U.S. Patent No. 4,843,867, "System for Monitoring Sterilant Vapor Concentration," issued 12/30/87

U.S. Patent No. 4,956,145, "Optimum Hydrogen Peroxide Vapor Sterilization Method," issued 12/30/87

U.S. Patent No. 5,068,087, "High Capacity Multicomponent Liquid Vaporizer," issued 12/30/88

U.S. Patent No. 4,941,519, "Liquid Feed System Using a Non-Reusable Container," issued 08/19/88

U.S. Patent No. 5,534,221, "Device and System for Sterilizing Objects," issued 07/29/94

U.S. Patent No. 5,317,896, "Method of Detecting Liquid in a Sterilization System," issued 03/13/92

U.S. Patent No. 5,482,683, "System for Detecting the Presence of Liquid in a Vapor Phase Sterilization System," issued 03/08/94

U.S. Patent No. 5,445,792, "Optimum Hydrogen Peroxide Vapor Sterilization Method," issued 05/02/94

U.S. Patent No. 5,508,009, "Optimum Hydrogen Peroxide Vapor Sterilization System," issued 05/16/95

U.S. Patent No. 5,364,590, "Method for Sterilization of Objects," issued 05/07/93

U.S. Patent No. 5,460,845, "Method of Decontamination of Food," issued 05/23/94

U.S. 5,535,667, "Method of Decontamination Of Food," issued 06/07/95

U.S. Patent No. 5,788,941, "Method of Sterilization Of Bone Tissue," issued 01/31/96

U.S. Patent No. 5,389,336, "Method of Decontaminating a Chamber That Has Movable Shelves," issued 01/13/94

U.S. Patent No. 5,527,507, "Accumulator Based Liquid Metering System and Method," issued 05/02/94

U.S. Patent No. 5,837,193, "Method of Decontaminating Freeze Dryers," issued 05/24/95

U.S. Patent No. 5,447,343, "Rigid Endoscope Connector," issued 09/28/93

U.S. Patent No. 5,830,409, "Method to Shorten Aeration after a Sterilization Cycle," issued 01/04/96

U.S. Patent No. 5,906,794, "Continuous-Operation, Closed Loop Decontamination System and Method," issued 06/14/96

U.S. Patent No. 5,876,664, "Continuous-Operation, Closed Loop Decontamination System and Method," issued 06/14/96

U.S. Patent No. 5,872,359, "Real-Time Monitor and Control System and Method for Hydrogen Peroxide Vapor Decontamination," issued 07/27/95

U.S. Patent No. 5,788,925, "Method for Real Time Monitoring and Control of Load Sterilization and Parametric Release," issued 02/16/96

U.S. Patent No. 6,156,267, "Apparatus and Method for Real-Time Monitoring and Control of Anti-Microbial Processing," issued 07/27/98

U.S. Patent No. 5,882,590, "Monitoring and Control of Sterilization Processes with Semiconductor Sensor Modules," issued 07/03/96

U.S. Patent No. 6,077,480, "Multiple Flashpoint Vaporization System," issued 06/19/97

U.S. Patent No. 5,779,973, "Vapor Phase Interstitial Microbial Decontamination of Overwrapped IV Bags," issued 04/01/97

U.S. Patent No. 5,792,435, "Vapor Phase Decontaminant Isolator Apparatus with Integral Vapor Phase Decontaminant Generator System," issued 04/08/97

U.S. Patent No. 5,600,142, "Measurement of Vaporized Hydrogen Peroxide," issued 05/26/95

U.S. Patent No. 5,847,392, "Determining the Concentration of Gaseous Hydrogen Peroxide," issued 12/03/96

U.S. Patent No. 5,847,393, "Control of Gaseous Hydrogen Peroxide Concentration During Sterilization," issued 12/03/96

U.S. Patent No. 7,157,046, "High Capacity Flash Vapor Generation System," issued 1/2/07

U.S. Patent No. 7,186,374, "Vapor Phase Decontamination of Containers," issued 3/6/07

U.S. Patent No. 6,936,434, "Vapor Phase Decontamination Process Biological Indicator Evaluator Resistomer (Bier) Vessel," issued 8/30/05

U.S. Patent No.6,875,399, "Non-Dispersive Mid-Infrared Sensor for Vaporized Hydrogen Peroxide," issued 4/5/05

U.S. Patent No. 7,189,349, "Flexible Walk-In Environmental Enclosure," issued 3/13/07

U.S. Patent No. 7,157,045, "Infrared Monitor and Control for Vapor Hydrogen Peroxide Processing Techniques," issued 1/2/07

U.S. Patent No. 6,734,405, "Vaporizer Using Electrical Induction to Produce Heat," issued 5/11/04

Patent Application No. 10/116,090, "Decontamination of Surfaces Contaminated with Prion-Infected Material with Gaseous Oxidizing Agents," filed 04/03/02

Patent Application No. 10/280,950, "Decontamination of Critical Mail" filed 10/25/02

Patent Application No. 10/377,557, "Hydrogen Peroxide Vapor System with Replaceable Desiccant Cartridge," utility filed 2/28/03

Reg. No. 1,766,654, VHP® Trademark (Class 11), filed 09/19/90

Reg. No. 2,122,053, VHP® Trademark (Class 10) filed 05/18/95

G. Acknowledgement

Industrial Participant's signature of the final report indicates the following:

1) The Participant has reviewed the final report and concurs with the statements made therein.
2) The Participant agrees that any modifications or changes from the initial proposal were discussed and agreed to during the term of the project.
3) The Participant certifies that all reports either completed or in process are listed and all subject inventions and the associated intellectual property protection measures generated by his/her respective company and attributable to the project have been disclosed and included in Section E or are included on a list attached to this report.
4) The Participant certifies that if tangible personal property was exchanged during the agreement, all has either been returned to the initial custodian or transferred permanently.
5) The Participant certifies that proprietary information has been returned or destroyed by LLNL.

Lewis S Schwartz — 11 Sept 07

Lewis I. Schwartz, Vice President, ~~Operations~~ DEFENSE / AEROSPACE — Date
Strategic Technology Enterprises, Inc.

Matthew F Verce — 26 Sept 2007

Matthew F. Verce, LLNL Principal Investigator — Date
Lawrence Livermore National Laboratory

for Veronica Lopez — 26 September 2007

Roger W. Werne, Acting IPAC Director — Date
Lawrence Livermore National Laboratory

Attachment I – Final Abstract

The Use of Vaporous Hydrogen Peroxide (VHP) for Building Decontamination

Final Abstract (Attachment I)
CRADA No. TC-2053-02
Date Technical Work Ended: March 31, 2007

Date: August 22, 2007 Revision: 2

A. Parties

This project was a relationship between Lawrence Livermore National Laboratory (LLNL) and Strategic Technology Enterprises, Inc. (STE), a subsidiary of STERIS Corporation.

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B. Purpose and Description

This was a collaborative effort between LLNL and STE to investigate the use of vaporized hydrogen peroxide (VHP) to decontaminate spore-contaminated heating, ventilation, and cooling (HVAC) systems in a trailer sized room. The project's scope and schedule increased beyond those proposed originally, in part due to additional funding provided by DHS. STE was very flexible and granted LLNL three no-cost time extensions to complete the work.

All original internal project and reporting deliverables were met. The most noteworthy deliverables were three presentations made on the project's findings at several stages throughout the project, and two manuscripts prepared for publication in open, scientific literature:

- *HVAC and building decontamination using gaseous reagents*. (Presented at the 2003 Chemical and Biological National Security Program Summer Meeting 4 Jun 2003);

- *Use of HVAC systems in building decontamination* (Presented at the USEPA workshop on decontamination, cleanup, and associated issues for sites contaminated with chemical, biological, or radiological materials, 23-25 Feb 2005);
- *Optimizing Decontamination of ductwork contaminated with BW agents: room scale testing and computational fluid dynamics simulations* (Presented separately to STERIS, Edgewood Chemical Biological Center, and USEPA National Homeland Security Research Center during business development trip on week of 6 March 2006);
- *The effects of process parameters and materials on hydrogen peroxide vapor concentration in model air ducts and rooms* (Presented at the DTRA Joint Science and Technology Office's 2006 Denver DECON science and technology conference, 31 Oct-2 Nov 2007);
- *Dew point calibration of a near-infrared vaporized hydrogen peroxide analyzer* (Manuscript intended for publication in an appropriate technical, open literature, journal); and
- *An experimental and CFD study of biological decontamination of galvanized steel ducting with vaporized hydrogen peroxide* (Manuscript intended for publication in an appropriate technical, open literature, journal).

C. Benefit to Industry

The primary benefit realized by STE in participating in this CRADA is a more detailed understanding of some of the phenomena that can affect the use of VHP technology in a building setting. Two specific results, namely how to minimize the decomposition of VHP by galvanized steel surfaces during the decontamination of ducts, and how to minimize VHP decomposition during the decontamination of whole rooms, can be used to make future decontamination events more effective.

D. Benefit to DOE/LLNL

The primary benefit realized by DOE in participating in this CRADA is to further its general mission in national security, by conducting detailed R&D work that might not have otherwise been completed, but may prove useful during a future event involving biological warfare agents. This project also adds to DOE's portfolio of capabilities in the area of decontamination, which previously have included detection, prediction, and restoration planning.

E. Project Dates

August 11, 2003 to March 31, 2007