Development and Construction of Non-thermal Plasma Air Sterilization Device

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Final Report
April 1, 2007 – December 31, 2009
Drexel University – The National Bioterrorism Civilian Medical Response Center

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Development and Construction of Non-thermal Plasma Air Sterilization Device

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Glossary

PDRF: Pathogen Detection and Remediation Facility
DBD: Dielectric Barrier Discharge
Scfm: Standard Cubic Feet per Minute
CARULITE®: Registered Trademark for Ozone Removal Catalyst
DRDC: Defense Research and Development Canada
UV: Ultraviolet
HEPA: High Efficiency Particulate Air
PBS: Phosphate Buffered Saline
Cfm: Cubic Feet per Minute
Cfu: Colony Forming Units

Table of Contents

Executive Summary

The A. J. Drexel Plasma Institute has developed an Air Sterilization System using Non-Thermal Dielectric Barrier Discharge (DBD) Plasma technology. The system was designed to inactivate microorganisms that are airborne. Experiments were carried out at the Bioaerosol Test Facility at the Defense Research and Development Canada compound at Suffield, AB in Canada. The results indicate that the system developed by this group is effective in sterilizing airborne *B. Globigii* spores. After initial runs, further modifications were found to be necessary to the system. These modifications were performed and the new system is ready. The causes of this sterilization were investigated by investigating the interaction of DBD streamer with airborne bacteria. The results from those experiments further confirm the inactivation of airborne microorganisms by their interaction with DBD plasma.

The developed system offers significant advantage over existing technologies. For example, HEPA filters create a significant pressure drop when installed as part of HVAC ducts; these filters also need to be frequently replaced as they simply trap the pathogenic organisms without inactivation. Another example of air disinfection system is installation of UV lamps; however, these were shown previously to be significantly less effective at disinfection than plasma. Various bacterial species were also shown to mutate and develop resistance to UV. DBD plasma system offers many potential advantages over existing systems in its relative simplicity, ease of installation, relatively small footprint and power requirements, and lack of moving parts and pressure drop.

In the framework of this project a new system was constructed and shown to be effective at inactivation of bacterial spores. In the future such systems may be useful for bus and rail vehicle decontamination. The system's capability to provide effective sterilization and removal of volatile organic compounds, it's ability to operate 24/7 as part of existing air/gas supply systems without raising temperature of the gas flow or requirements for replacement parts make the system well suited for deployment in bus and rail vehicles for decontamination purposes. The purpose of this funding was to show that such a device is possible as a proof of concept and that it will work in bus and rail vehicle applications. That has been accomplished.

Introduction

This document is published as a final report upon completion of the proposed work. Contained herein is the report on the performance of the AJ Drexel Plasma Institute team during the project, milestones achieved and problems encountered with solutions. Resulting from this grant is a development and construction of a new system for air disinfection, sterilization, and treatment based on an earlier atmospheric air non-thermal plasma sterilization prototype. The system was evaluated and successfully performed air disinfection.

Background Information

The Plasma Institute at Drexel University has successfully developed a proprietary (U.S. Provisional application No. 60/871,045) non-thermal plasma based laboratory scale air sterilization system which can destroy airborne microorganisms. This is a novel capability with potential for use in the remediation of a biologically contaminated space (such as an office following an anthrax letter attack) or incorporation into a ventilation system to sterilize air-borne pathogenic microorganisms.

Objective and Methodology

The main objective of this work was to develop and construct a larger version of Drexel's non-thermal plasma air sterilization system to operate on the North American standard 110 volt 15 amp circuit. It is estimated that the "office-scale device" will have a plasma cross-sectional area of 400 cm^2 and a flow rate of 20-100 Liters per second. The device developed as part of this effort had successfully undergone a full scale tests at the testing site in Canada with our partners from Defense Research and Development Canada (DRDC).

Scope of project or study

The scope of the study was to investigate the effect of DBD discharge on airborne microorganisms in a real life setting. Therefore, the facilities at DRDC were employed. Testing was performed on the spore form of bacteria. This was done in order to test the system on dry spores, as all of the earlier studies had been performed on wet bioaerosol.

Organization of Content

The main text of the report consists of the following parts:

a) Non-thermal Plasma and DBD: Brief Introduction to the Technology
b) Microorganisms used: Description of Microorganisms used
c) Objective of Study: Reasons for carrying out the experiments
d) Progress Achieved with Design: The description of the system Design
e) Modification to the System after the test runs at DRDC: Improvements to the system
f) Scientific Investigation into the Inactivation of Airborne Bacteria: Study of Interaction of Airborne Bacteria with DBD Streamer

Development and Construction of Non-thermal Plasma Air Sterilization Device

Non-thermal Plasma and DBD

Non-thermal plasma-based technologies have demonstrated success in inactivating many different types of microorganisms such as viruses and various types of bacteria and spores on the surfaces and in aqueous solutions. The threat of contamination of *air* in buildings or transportation facilities by pathogenic microorganisms has been one of the major concerns since the anthrax attacks of 2001. In comparison with plasma-based surface and water sterilization, only a few plasma researchers have focused on air decontamination using non-thermal plasma. Most of them have been successful only when coupling plasma technology with high-efficiency particulate-air (HEPA) filters to both trap and kill microorganisms. The downside of relying on HEPA filters is that they have a limited efficiency in trapping sub-micrometer-sized airborne microorganisms and they also cause significant pressure losses in heating, ventilation, and air conditioning systems, giving rise to higher energy and maintenance costs.

Microorganisms

Bacteria in the form of spores are extremely resistant to various sterilization agents, because they are much better protected by multiple layers of their outer wall. Higher concentration of chemical agents or larger doses of gamma or UV radiation is required to eliminate *Bacillus* spores compared to that when deactivating bacteria in the vegetative state. It is somewhat different in the case of treatment of spores with plasma. Our investigations and other studies have shown that in many cases the rates of plasma deactivation of spores are comparable to rates of plasma sterilization of bacteria. This is a very good indication that the Plasma Detection and Remediation Facility (PDRF) system constructed in Drexel can provide similar efficiency in deactivating spores in air as it does in sterilizing bacteria. This hypothesis was validated in the framework of this project; a new system was constructed and successfully tested against spores in air.

Objective of Study

The objective of this work was to develop and construct a portable, Dielectric Barrier Discharge (DBD) plasma-based, non-thermal air sterilization unit capable of neutralizing air borne bacteria and spores, including Anthrax; a system that can demonstrate its efficiency on spores in a closed room. To be tested in the available room/chamber, the system should operate on the North American standard 110 volt keeping the circuit current not exceeding 15 amps. It is estimated that the office-scale device will have a plasma discharge cross-sectional area of 400 cm^2, or ~1000 cm^2 including the cross-sectional area of the electrodes grating. The estimated flow rate will be about 20-100 Liters per second. It is assumed, that the office-scale device will be an “open” system with a fan that will take contaminated air from the room and emit cleaned air back into the room. In that case, an exponential decrease in viable spores’ concentration is expected assuming that plasma system is effective in spore deactivation.

Progress Achieved with Design:

The modified design has been implemented using four plasma module units. This provides improved modularity, increase ease of transport and troubleshooting. Four individual, independent plasma units are housed into a single large external case to work as a single large unit.

The device consists of 3 components:

1. External housing
2. Plasma units
3. Accessories

Component 1: External housing

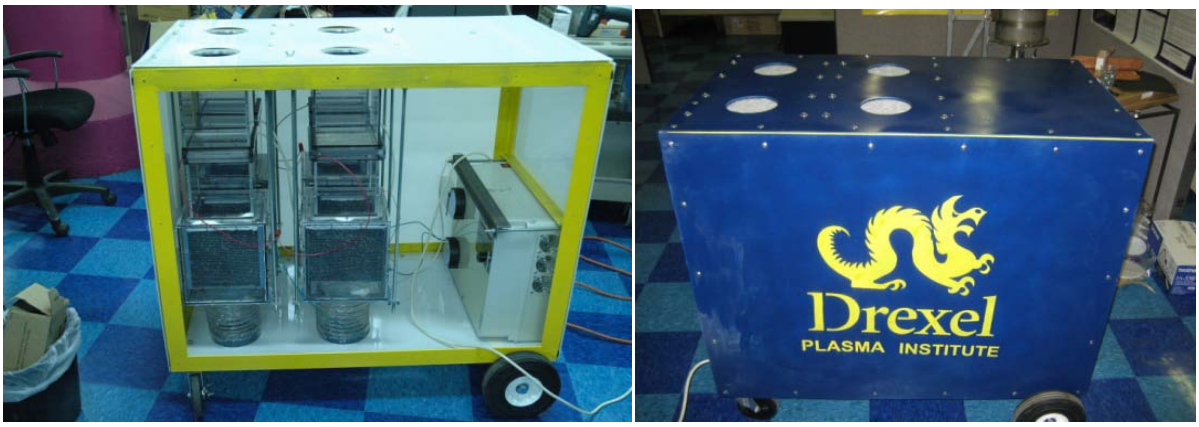

Figure 1: external housing with top and side wall removed, power supply in holder and 1 plasma unit in position. Painted completed unit.

Component 2: Plasma units.

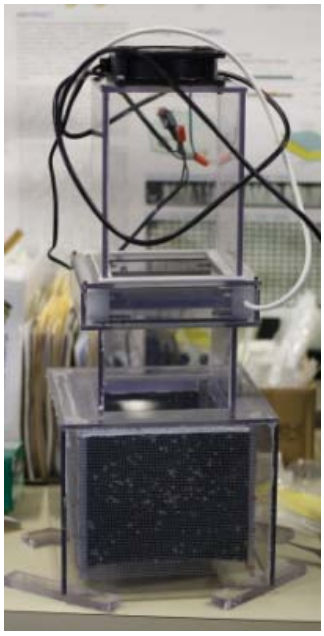

Figure 2: Photograph of a plasma unit assembled for durability tests and ozone generation tests.

Plasma modules had been assembled according the new improved design, and test runs had been conducted for each unit separately and all together powered from the same power supply. The test runs were conducted inside a chemical fume hood because of the substantial amounts of ozone produced during the runs. The estimated flow rate for each of the 4 fans was 25 scfm. The total flow rate was 100 scfm.

Component 3: Accessories.

Accessories include a variable autotransformer for adjusting fan speed, power strips for internal components, controls on the external, remote control with a timer.

Modification to the System after the test runs at DRDC:

The results of the test run in Canada in November 2009 showed that certain modifications should be made to the ozone filters.

New filter filler had been identified and implemented. CARULITE® 200 catalyst is used to effectively destroy ozone emitted from various off-gas emissions, converting ozone to oxygen.

Particle sizes available:
* 4 x 8 mesh granular (4.8 mm x 2.4 mm)
* 8 x14 mesh granular (2.4 mm x 1.4 mm)
* Other sizes available upon request

Chemical/Physical Data
Formula Manganese dioxide/copper oxide catalyst
Appearance Black/dark brown granular
Bulk Density 0.8 - 0.9 g/cc
Surface Area #8805; 200 m2/g
Weight Loss < 1%

The choice of the new filler was made due to the higher efficiency of the manganese dioxide/copper oxide compared to that of the activated carbon used previously. Also, the new filler provides for higher flow rates than activated carbon. The total flow rate for the system is 100cfm.

New filler holders for the filters have been made. Initial tests confirmed the expected properties of the new ozone filters. Additional tests of the new filters will be performed at the DRDC site in Canada.

Air Sterilization Experiments performed at DRDC Suffield

Experimental Setup:

The air sterilization experiments were performed at DRDC, Suffield AB, Canada. The testing facility consisted of an Aerosol Test chamber. This chamber was placed outside the main building. The chamber was connected to a control room from where the experiment could be monitored. The size of the chamber was 50m^3 (10'x18'x10'). The equipment placed inside the chamber included a sprayer for injection of the spores, multiple air samplers and a particle counter. The exhaust system consisted of a pair of HEPA filters and a purging system that heats up the air inside the system and then vents it (this process is called purge). The flow rate of the re-circulating airflow system is 1050 cfm = 495.54 L/s. This high flow rate is consistent with the required flow rate for large rooms.

Figure 3: The Aerosol Test Facility where the experiments were conducted

Materials and Methods:

The spores used for testing the system were *Bacillus globigii* (BG) spores. These *Bacillus globigii* spores (in dry powder form) were donated by the US Department of Defense (Dugway Proving Ground,

Utah). Stock concentration powder was ~1 x 10^{11} cfu/gm. *Bacillus globigii* (BG) spores are routinely used as a simulant for *Bacillus anthracis* (anthrax) spores. These dry spores in powder form were added to a sprayer. The total amount of spores that was injected was 0.1gm ≈ 10^{10} bacteria in total. The sprayer created a puff of air containing spores. This created a 'cloud' of aerosol inside the room. There were four fans located inside the room, directing this cloud away from the walls. The sampling was performed using the XMX/2L-MIL aerosol sampler kept inside the test chamber. XMX/2L-MIL (Dycor Technologies, Edmonton, Canada) is an aerosol separator, sample preparation, and high mass flow concentrator system. This system collects high volumes of air, removes the debris and concentrates the aerosols of interest. The particles are then impinged into a sample collection vial containing a specific liquid (Sterile Water/PBS). The plasma sterilizer was placed inside the room between the injection point and the air sampler. The plasma sterilizer was turned ON remotely from inside the control room. The spores were then injected into the air by the method described earlier. A sample was taken each minute for 30 minutes. The samples were then extracted and the concentration of bacteria was determined using standard plate count method.

Results:

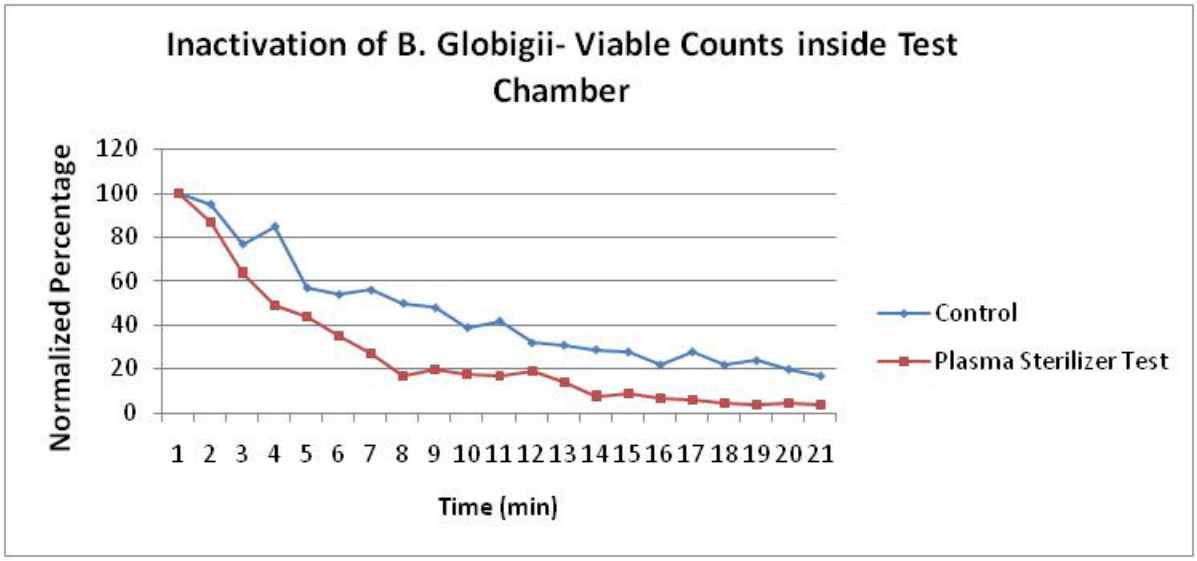

Figure 4: Results of Air Sterilization Experiments with the Plasma Sterilizer.

The results of the experiment are detailed in the above figure. The control samples were first analyzed and then the test run was performed. The numbers obtained from the test run were normalized to the controls and the percentage was plotted w.r.t. time. These results indicate for the test run using the plasma unit, **no viable spores were detected inside the aerosol test chamber after 21 minutes of treatment.** These results are encouraging and require further experimentation to analyze this sterilization effect.

The bacterial cells are being inactivated after coming in contact with the plasma discharge. This required further investigation into the interaction of the DBD streamer and airborne bacteria.

Scientific Investigation into the Inactivation of Airborne Bacteria: Study of Interaction of Airborne Bacteria with DBD Streamer

We made an attempt to delineate the mechanism through which the inactivation of spores by the plasma discharge occurred. The following experiments were performed.

Effect of direct interaction of plasma with bioaerosol:

Our earlier experiments have indicated that direct interaction of plasma discharge with airborne bacteria leads to the greatest amount of inactivation. This means that the bacteria have to come in contact with the filaments of the DBD discharge to be inactivated. Hence, the hypothesis for these experiments is that the interaction of DBD plasma filament with airborne bacteria in bioaerosol form produces inactivation. To test this, we have developed a single filament discharge and an experimental setup for the injection and collection of bioaerosol.

a. Development of Single Filament DBD for Inactivation Studies:

Figure 5: a) Electrode Setup for Single Filament DBD Discharge, b) The single filament DBD produced in the gap.

To study the effect of direct plasma discharge on aerosol droplet, a single filament DBD discharge has been developed. This setup consists of point-to-point/point-to-plane geometry of electrodes. The DBD plasma discharge is produced in the area as shown in figure 1.

Experimental Setup for the study of bioaerosol inactivation using a single filament:

Figure 6: a) Modified Single Filament DBD Setup with the nebulizer nozzle for injection of bioaerosol, b) The entire DBD single filament setup mounted on a micropositioner.

Experimental study of the inactivation of bacteria by single filament was carried out with the setup shown above. This setup consists of the single filament electrodes, a nebulizer with modified nozzle and a micropositioner. The bioaerosol was injected into the discharge gap by using this modified nebulizer. The treated bacteria are collected on the other side of the setup using impaction onto an agar plate. The filament is moved in vertical direction, using the micropositioner (Figure 5). The inactivation of bioaerosol will be compared for different positions of the single filament in space.

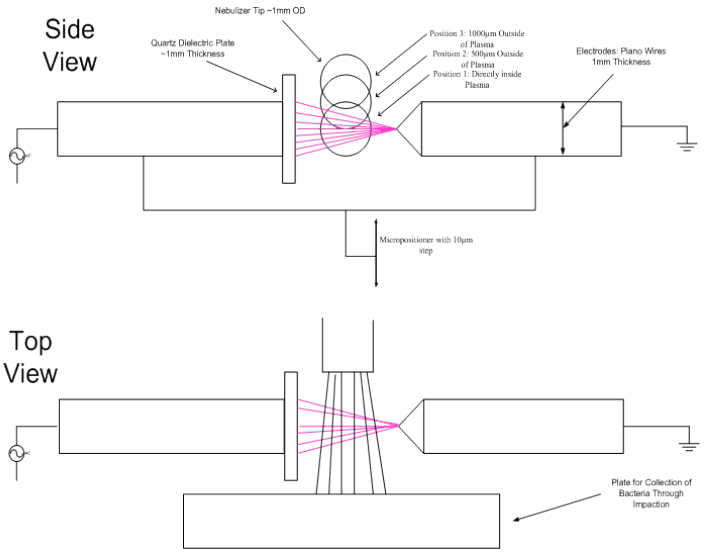

Figure 7. Single filament experimental setup schematic.

Results of the single filament experiment are summarized in Figure 6. If air stream containing bacteria is moved 0.5 mm or 1 mm away from plasma there is no inactivation as compared to bacteria that pass through plasma where complete inactivation is observed and no growth is seen on the plates.

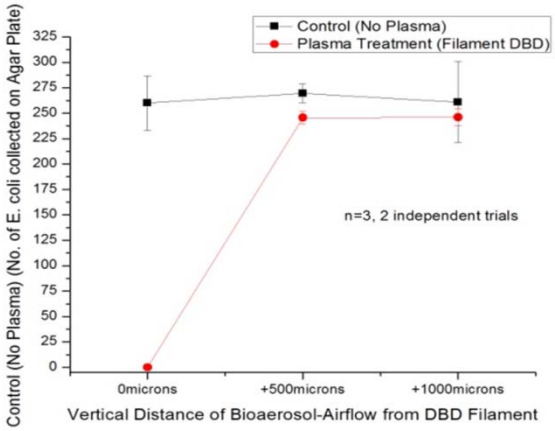

Figure 8. Results of single filament experiment show that bacteria that pass through plasma are inactivated completely.

Conclusion, Recommendations, and Future Research:

Prior to this project the results of air sterilization experiments have demonstrated the capability of the dielectric barrier discharge (DBD) device to inactivate microorganisms in air. In the framework of this project a new system was developed which is capable of inactivating pathogenic organisms in air in a room. The developed system is self-contained and only requires electricity. Essentially, the new plasma system is an air "filter" which provides no pressure drop, passing contaminated air through a mesh-like grid of plasma electrodes (1.5 mm opening between the electrodes). The system was successfully tested in a facility where controlled number of spores was released into the atmosphere and analyzed throughout the treatment time, assessing bacterial viability and total cell count. It was shown that spores were efficiently inactivated. Furthermore, research into the mechanism of inactivation was conducted. The results indicate an interaction between the airborne bacteria and the filaments of DBD discharge. These filaments carry charges and short-lived active species responsible for the fast inactivation of microorganisms, as compared to radiation and neutral species. Future improvements of this system would be to decrease the footprint of the setup allowing for installation as part of bus and rail vehicle HVAC systems and building HVAC ducts. Analysis of effectiveness of this system against viruses and harmful gases is also needed. This system can be used to inactivate pathogenic organisms in transit systems and other facilities. The system's capability to provide effective sterilization and removal of volatile organic compounds, it's ability to operate 24/7 as part of existing air/gas supply systems without raising temperature of the gas flow or requirements for replacement parts make the system well suited for deployment in bus and rail vehicles for decontamination purposes. The purpose of this funding was to show that such a device is possible as a proof of concept and that it will work in bus and rail vehicle applications. That has been accomplished.

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M. Laroussi, "Nonthermal Decontamination of Biological Media by Atmospheric-Pressure Plasmas: Review, Analysis, and Prospects," *IEEE TRANSACTIONS ON PLASMA SCIENCE,* vol. 30, pp. 1409-1415, 2002.

Michael J. Gallagher, N. Vaze, S. Gangoli, V. N. Vasilets, A. F. Gutsol, T. N. Milovanova, S. Anandan, D. M. Murasko, and A. A. Fridman, "Rapid Inactivation of Airborne Bacteria Using Atmospheric Pressure Dielectric Barrier Grating Discharge," *IEEE TRANSACTIONS ON PLASMA SCIENCE*, vol. 35, pp. 1501-1510, 2007.

IP section with pending patents

"PLASMA SYSTEM II FOR AIR STERILIZATION" Drexel University invention disclosure, docket #08-0885D.

Publications

Inactivation of Bacteria in Flight by Direct Exposure to Non-Thermal Plasma, Nachiket Vaze, Michael Gallagher, Sin Park, Gregory Fridman, Yurii Mukhin, Victor N. Vasilets, Alexander Gutsol, Donna Murasko , Shivanthi Anandan and Alexander Fridman, *IEEE Transactions on Plasma Science (Under Review)*

Direct Exposure to a Single Filament of DBD Plasma Leads to the Inactivation of Airborne Bacteria, Nachiket Vaze, Gregory Fridman, Alexander Fridman, *37th International Conference on Plasma Science*, Norfolk, VA June20-24 2010