Decontamination of chemical and biological warfare (CBW) agents using an atmospheric pressure plasma jet (APPJ)*

H. W. Herrmann,[†,a)] I. Henins, J. Park, and G. S. Selwyn
Physics Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545

(Received 19 November 1998; accepted 14 December 1998)

The atmospheric pressure plasma jet (APPJ) [A. Schütze *et al.*, IEEE Trans. Plasma Sci. **26**, 1685 (1998)] is a nonthermal, high pressure, uniform glow plasma discharge that produces a high velocity effluent stream of highly reactive chemical species. The discharge operates on a feedstock gas (e.g., $He/O_2/H_2O$), which flows between an outer, grounded, cylindrical electrode and an inner, coaxial electrode powered at 13.56 MHz rf. While passing through the plasma, the feedgas becomes excited, dissociated or ionized by electron impact. Once the gas exits the discharge volume, ions and electrons are rapidly lost by recombination, but the fast-flowing effluent still contains neutral metastable species (e.g., O_2^*, He*) and radicals (e.g., O, OH). This reactive effluent has been shown to be an effective neutralizer of surrogates for anthrax spores and mustard blister agent. Unlike conventional wet decontamination methods, the plasma effluent does not cause corrosion and it does not destroy wiring, electronics, or most plastics, making it highly suitable for decontamination of sensitive equipment and interior spaces. Furthermore, the reactive species in the effluent rapidly degrade into harmless products leaving no lingering residue or harmful by-products. © *1999 American Institute of Physics.* [S1070-664X(99)91405-2]

I. INTRODUCTION

The use of chemical or biological warfare (CBW) agents in either a domestic terrorist attack or military conflict is a growing threat. This has been made particularly evident by the 1995 sarin nerve gas attack on the Tokyo subway and by the threat of CBW in both the Persian Gulf and the Korean peninsula. To counter the possible use of these horrific agents, an effective decontamination (decon) defense is needed to reduce the lingering effects of such an attack.

A new approach to this challenging problem relies upon the use of a novel, low temperature, atmospheric pressure plasma source to produce chemically reactive, fast-flow effluents that are capable of rapidly destroying a broad spectrum of CBW agents. The key to this approach is the Atmospheric Pressure Plasma Jet (APPJ),[1–5] which produces short-lived reactive species and propels them onto the contaminated surface. The APPJ technology may be tuned for decontamination of large areas, such as airfields and ships, using relatively high-power application, or at much lower powers for decon of sensitive equipment (e.g., electronics, optics, avionics), the interiors of military vehicles (e.g., tanks, planes, ships) and quite possibly, even personnel.

Traditional decontamination of CBW agents involves use of ''wet'' solutions, such as bleaches or Decontamination Solution #2 (DS2). This requires storage, transport, and disposal of large volumes of hazardous chemicals. As the use of this existing decon approach also requires release of large amounts of these chemicals into the environment, one of the highest research priorities in reactive decontamination has been to identify environmentally ''green'' decontaminants.[6] Another major problem is that the current decon chemicals are corrosive to materials such as metals, plastics, rubber, paint, leather, and perhaps the most troublesome, skin. For this reason, ''wet'' decon methods are not acceptable for use on sensitive equipment, restricting their use in mission critical areas, such as command and control spaces, aircraft hangars and vehicle interiors. In addition, long exposure times, typically 30 min, are needed for wet methods to be effective.

A replacement decon technology is needed that is capable of selective and quick *destruction* of CBW agents, is preferably all-dry, does not require mass storage, is easily transported, does not affect personnel or sensitive equipment, is environmentally sound, and which can penetrate small cracks and porous materials. Potential alternatives to wet chemistry include ionizing and nonionizing radiation, thermal and ultrasonic energy, and reactive gases such as those produced by plasmas.[7] Most of these technologies suffer from significant shortcomings, as demonstrated in Table I. The use of ionizing radiation, such as γ-ray, requires highly radioactive sources, such as Co-60. This is best done in a heavily shielded fixed facility and is not easily implemented in the field. Also, this method can prove destructive to sensitive equipment. Nonionizing radiation, such as UV, requires line-of-sight application and can be quite time consuming. Application of thermal energy can also be quite slow at the temperature limits required to avoid damage to sensitive equipment and typically only evaporates CW agents without destroying them, allowing condensation on downwind surfaces. Ultrasonic removal of surface contaminants is neither fast nor dry. Until recently, plasmas could only meet a fraction of these requirements because of the severe limitation imposed by vacuum operation and the de-

*Paper F3I2.1 Bull. Am. Phys. Soc. **43**, 1704 (1998)
[†]Invited Speaker.
[a)]Corresponding author. Electronic mail: herrmann@lanl.gov

 © 1999 American Institute of Physics

TABLE I. Characteristics of existing and potential decontamination technologies (●=good, ◑=fair, ○=poor)

Technique	Fast	Dry	Portable	Safe	Non-destructive	"Green"	Penetrating
Wet chemistry	○	○	◑	○	○	○	◑
Ionizing (γ)	◑	●	○	◑	◑	◑	●
Nonionizing (UV)	○	●	●	●	◑	●	○
Thermal	○	●	●	◑	○	●	◑
Ultrasonic	○	○	◑	●	●	●	◑
APPJ	●	●	●	●	●	●	●

TABLE II. Typical APPJ parameters.

RF frequency	13.56 MHz
RF power	250 W
Plasma power density	35 W/cm^3
Discharge voltage	320 V_{rms}
Electron density	$\sim 10^{11}$ cm^{-3}
Electron temperature	~3–4 eV
He flow	92 slpm
O_2 flow	0.72 slpm
Gas velocity[a,b]	43 m/s
Effluent temperature[b]	150 °C
Ozone density[b]	$\sim 1\times 10^{15}$ cm^{-3}
Atomic oxygen density[b]	$\sim 5\times 10^{15}$ cm^{-3}
Metastable oxygen ($O_2\ ^1\Delta_g$) density[b]	$\sim 5\times 10^{15}$ cm^{-3}

[a]Using 8 mm diam nozzle.
[b]Measured or estimated at nozzle exit.

ficiencies of existing atmospheric pressure discharges. However, the APPJ has the potential to meet all of them. A U.S. Air Force Armstrong Laboratory report on BW countermeasures concluded that "the pulsed corona discharge reactor may have potential as a countermeasure, but its ability to destroy appropriate agents remains to be demonstrated. This is a high risk, but potentially high pay-off modality." [7] The current study intends to demonstrate that the APPJ should have even greater potential and less risk for development and application than corona and other types of plasma discharges.

Sec. II describes the laboratory scale APPJ used for these studies. The experimental methods and the CBW simulation agents are discussed in Sec. III. Section IV gives the results of exposures of these CBW simulants using the APPJ. The discussion in Sec. V compares these results to those of other plasma-based systems. Section VI discusses future work, and Sec. VII provides a summary of the results.

II. THE ATMOSPHERIC PRESSURE PLASMA JET (APPJ)

The design and operation of the APPJ have been discussed in greater detail elsewhere[1–5] and are only briefly summarized here for completeness. The capacitively coupled APPJ, shown schematically in Fig. 1, consists of two coaxial electrodes between which a feedgas flows at high rate. Typical APPJ parameters used in this decon study are listed in Table II. RF power at 13.56 MHz applied to the center electrode accelerates free electrons and causes the gas to break down, initiating a spatially uniform discharge. The energetic electrons undergo inelastic collisions with the feed gas, producing excited state molecules and atoms (e.g., metastables), free radicals, and additional ion–electron pairs. These chemically active species exit the nozzle at high velocity and impinge on a surface, where they can react with the contaminant. The ions and electrons, however, quickly recombine outside the jet and are probably not active in surface decontamination under these conditions.

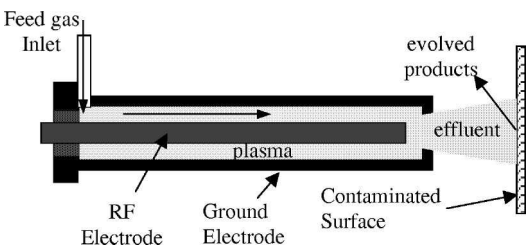

FIG. 1. Cylindrical design of the APPJ.

Stable operation of the APPJ requires the use of a carrier feedgas such as helium to avoid arcing and to produce a homogeneous, nonthermal discharge at atmospheric pressure. To this carrier, small quantities of other gases are added, such as oxygen, to produce the chemically active species. Oxygen introduction, typically up to 3%, actually improves the stability of the discharge. Of particular importance is the generation of reactive metastables [e.g., $O_2(^1\Delta_g)$], which are relatively long-lived (~10–100 ms) excited states of molecules and atoms that can be transported many tens of centimeters at the nozzle exit velocity. Even taking into account the slowing of the gas flow due to expansion and mixing with air, these reactive species can still be easily projected several tens of centimeters to surfaces beyond the nozzle. Perhaps of equal importance is the production of atomic oxygen, the lifetime of which has been inferred to be on the order of 1.0 ms, allowing these species to be propelled over 10 cm given high enough gas flow rate and nozzling.

III. METHODS AND MATERIALS

A. Biological decon

Biological warfare agents consist of spore forming bacteria (e.g., Anthrax), vegetative bacteria (e.g., Plague, E. coli), viruses (e.g., Small Pox, Yellow Fever), and biotoxins (e.g., Ricin, Botox).[7] Bacterial spores, such as *Bacillus anthracis* (BA) commonly known as Anthrax, are generally considered the most difficult to decontaminate and represent one of the greatest BW threats. For this reason *Bacillus globigii* (BG) spores, a relatively benign microorganism requiring the minimum of Biosafety Levels (i.e., BL1), were chosen as a surrogate for BA.

Exposure samples were prepared by inoculating ~10^7 BG spores suspended in 10 $\mu\ell$ of water onto a glass

coupon and allowing it to dry, forming a spot ~5 mm in diameter. The coupon is then placed on a stage at a known distance from the 8 mm diameter exit nozzle of the plasma jet. The APPJ is run at experimental conditions for 2 min to allow preheating and passivating of the electrodes, and the dried sample spot is then placed in the plasma effluent for a measured length of time. Temperature measurements are made before and after sample exposure using a thermocouple mounted on a blank glass slide. After exposure, the spores and debris are removed from the glass coupon by sonication into a potassium phosphate buffer. This spore/debris suspension is then serially diluted onto 1.5% nutrient agar (DIFCO) plates and incubated at 30 °C for 20 h. After incubation, the resulting colony forming units (CFU) are counted and compared to control cultures in order to determine decontamination efficacy.

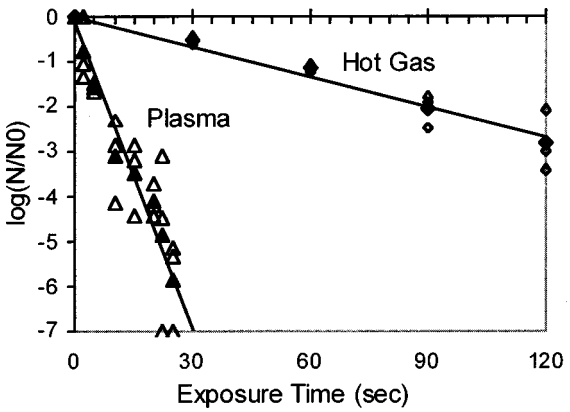

FIG. 2. Plasma and hot gas BG kill curves; sample temp=175 °C (hot gas power≈200 W, plasma power≈300 W) exposure distance=0.5 cm, He flow=92 slpm, O_2 flow=0.72 slpm, electrode gap=0.16 cm.

B. Chemical decon

Toxic chemical warfare agents consist primarily of blister agents (e.g., Mustards and Lewisite), nerve agents [e.g., V agents (VX) and G agents (Tabun, Sarin, Soman)], choking agents (e.g., Phosgene), and blood agents (e.g., Hydrogen Cyanide).[8] The most persistent, and therefore those most in need of decon, are Sulfur Mustard and VX, thus chemical simulants were chosen for these two CW agents. The simulant chosen for Sulfur Mustard ($ClCH_2CH_2SCH_2CH_2Cl$) was 2-chloroethyl phenyl sulfide ($C_6H_5SCH_2CH_2Cl$), also known as phenyl half-mustard, since it contains the $-SCH_2CH_2Cl$ arm of mustard attached to a phenyl group. Malathion, a commercially available pesticide, was chosen as a simulant for VX.

Chemical tests were conducted in a fashion similar to the biological tests with the following exceptions. Five microliters of neat chemical simulant were placed onto a 6 mm diameter piece of filter paper (#3 Whatman), which was then placed upon a glass coupon. The filter paper was used to hold a sizable quantity of simulant in the effluent of the plasma jet, since a 5 $\mu\ell$ drop placed directly onto glass tends to pool on the opposite end of the coupon from where the effluent is applied. A wire clip was used to hold the filter paper in place. After exposure, the samples are eluted in 2 mℓ methanol and analyzed by gas chromatography/mass spectrometer (GC/MS). To identify volatile by-products, a gas sample is drawn through a Tenax sorbent tube placed ~3 cm from the exit nozzle during selected exposures. The sorbent tube is subsequently thermally desorbed into the GC/MS and the volatile by-products identified.

IV. EXPERIMENTAL RESULTS

A. Biological decon

Figure 2 contains kill curves for dried BG spores exposed to plasma and hot gas. The vertical axis is the log of the ratio of the number of viable spores remaining (N) to the control number of $\sim 10^7$ (N_0). For each set of six samples run, an untouched control was also analyzed to give N_0. A total kill of 10^7 spores is plotted as -7 logs. The hot gas comparison curve was generated by blowing heated feedgas through the APPJ (without initiating a plasma) at the same composition and flow rate used to generate the plasma curve. Each exposed sample was plated twice and each exposure condition was conducted three times, as represented by the hollow symbols in Fig. 2, to test reproducibility. The mean value of these three exposures is plotted as the solid symbols.

The decimal reduction value (D), the time required to reduce the viable spore population by a factor of 10, is found to be about 4.5 s for plasma exposure under the conditions of Fig. 2. This is ten times faster than hot gas at the same temperature of 175 °C, a speed advantage which is found to increase with decreasing temperature. The D value obtained for hot gas is consistent with values obtained for BA spores exposed to dry heat.[9]

Operation of the plasma at sufficient power to attain a sample temperature of 175 °C required 50% more input power as compared to the input power required for resistive heating of the gas to reach the same temperature. Some fraction of this excess power goes into generating the reactive species of metastable and atomic oxygen through electron impact excitation and dissociation, allowing a much faster kill rate requiring less energy input through this chemical means. Under these experimental conditions, the plasma obtained the same level of kill as hot gas with only 15% of the energy input.

It was determined that if the oxygen is removed from the plasma discharge, the results become consistent with the purely thermal effect of hot gas, indicating that it is reactive oxygen species that are responsible for the increased kill rate. Also, plasma UV radiation has been eliminated as a significantly modality through experiments in which the plasma effluent was blocked by a quartz window but UV and heat were allowed to reach the spores. This observation is consistent with results in the literature that show that dried spores are highly resistant to U.V.[10]

Figure 3 depicts the effect of actively cooling the rf electrode. The solid center electrode used in the uncooled case was replaced with a water-cooled hollow electrode of the same external dimensions. Nearly twice as much rf power was required in the cooled case to obtain the same temperature as in the uncooled case. This resulted in a significant

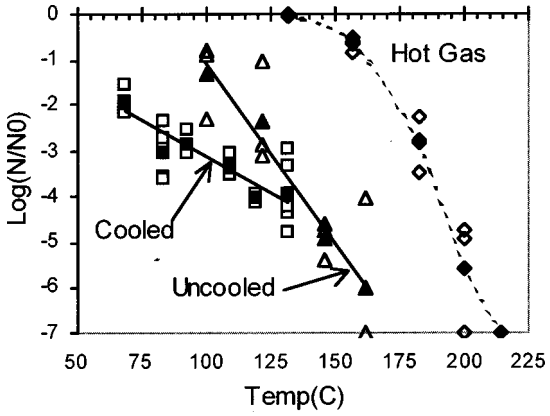

FIG. 3. Plasma (cooled and uncooled center electrode) and hot gas BG kill effectiveness vs temperature; exposure time=30 s, exposure distance=0.5 cm, He flow=92 slpm, O_2 flow=0.72 slpm, electrode gap=0.16 cm.

increase in kill efficacy at lower temperatures. For instance, ~2 log improvement was obtained at 100 °C. However, at higher temperatures little or no improvement was obtained. It is hypothesized that the production of reactive species saturates at some level of rf power, above which only a thermal dependence remains. These results show that the temperature and kill effectiveness of the APPJ effluent can be decoupled, implying that the effluent temperature may be reduced further while maintaining its reactivity. This is attractive, as reduced effluent temperature provides further opportunity for decontamination technology, including the use of plasma effluent to decontaminate field personnel. This offers a clear advantage over the corrosive solutions (typically bleach) currently used for personnel decon.

B. Chemical decon

As seen in Fig. 4, plasma exposures of the Sulfur Mustard simulant results in removal rates similar to that of hot gas. However, analysis of the volatile products shows that the effect of hot gas is simple evaporation, which would allow the agent to condense out on downwind surfaces. In the plasma case, however, none of the original simulant was detected during the thermal desorption of the sorbent tube. Instead only oxidized simulant was found, indicating complete chemical conversion (i.e., >5 log reduction) of the original agent. Tentatively identified compounds include 2-chloroethyl phenyl sulfone ($C_6H_5SO_2CH_2CH_2Cl$) and Phenyl vinyl sulfone ($C_6H_5SO_2CHCH_2$).

The results of exposures involving the VX simulant, malathion, are shown Fig. 5. Note that N/N0 is plotted on the vertical axis; not log(N/N0). The difficulty in decontaminating VX is revealed by the removal of <90% of the simulant at temperatures below 175 °C. However, the plasma exposure results in removal starting at temperatures as low as 50 °C, whereas removal does not begin for hot gas until 120 °C. Furthermore, hot gas only results in evaporation of the sample, not chemical conversion, as was also observed for the mustard simulant. In contrast, plasma exposure results in oxidation as evidenced by the thermal desorption of sorbent tubes sampling exposures at 170 °C. The majority of

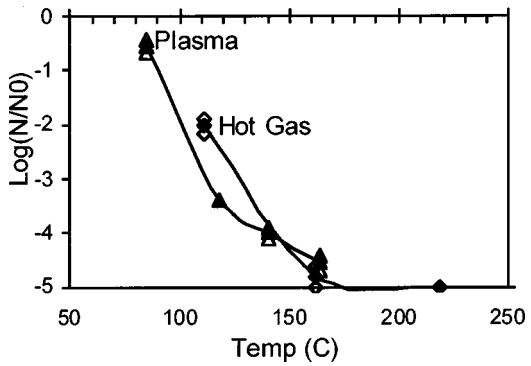

FIG. 4. Mustard simulant removal vs temperature; exposure time=30 s, exposure distance=0.5 cm, He flow=90 slpm, O_2 flow=0.6 slpm, electrode gap=0.16 cm.

the chemically-converted volatile products have been tentatively identified as Malaoxon, an oxidized form of Malathion. As this product resembles VX more so than Malathion, it may not be a suitable oxidation product, though it also is not clear what the chemical conversion product of VX might be.

V. DISCUSSION

Several studies have investigated the effects of plasmas on bacteria primarily for sterilization applications. These studies have included other glow discharges, including low pressure discharges and the one atmosphere uniform glow discharge plasma (OAUGDP). Other nonthermal atmospheric pressure discharges, such as corona, as well as thermal atmospheric pressure discharges as produced by arcs have also been studied. The production of atomic oxygen and ozone, as well as the resulting *D* values (defined in Sec. IV A) for BG or similar spores exposed to these discharges, are summarized in Table III.

As seen in Table III, the APPJ produces much larger fluxes of reactive species than are obtainable in low pressure glow discharges, presumably due to the larger number of precursors available to produce these species. The best reported *D* value resulting from a low pressure (~0.1 Torr) rf (35 MHz) hydrogen peroxide discharge is on the order of 20

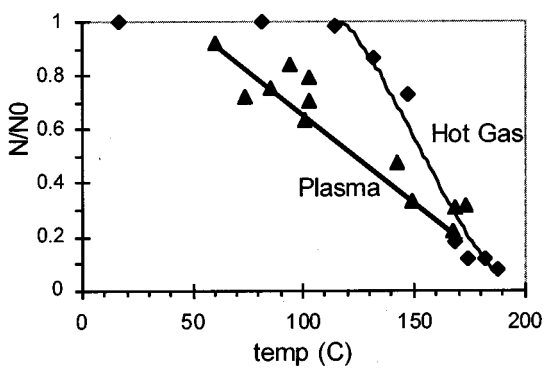

FIG. 5. VX simulant removal vs temperature; exposure time=30 s, exposure distance=0.5 cm, He flow=90 slpm, O_2 flow=0.6 slpm, electrode gap=0.16 cm.

TABLE III. Oxygen species densities and decimal reduction value (D).

Source	Typical density (cm^{-3}) O	Typical density (cm^{-3}) O_3	D (s)
APPJ (175 °C)	10^{16}	10^{15}	4
Low-pressure discharge	10^{14}	$<10^{10}$	20
OAUGDP	?[a]	?[a]	60
Corona	10^{12} [b]	10^{18} [b]	30
Arc	10^{18}	$<10^{10}$	<1
Dry heat (175 °C)	⋯	⋯	45

[a]Not reported.
[b]Spatial average.

s.[11,12] However, unlike low-pressure discharges, the APPJ does not require that the contaminated equipment or material fit inside a vacuum chamber.

The one atmosphere uniform glow discharge plasma (OAUGDP), similar to the APPJ in that it produces a uniform glow discharge at atmospheric pressure, has also been examined for sterilization applications.[13,14] The primary differences between the APPJ and OAUGDP is that the latter operates in the audio frequency range (~5 kHz), rather than rf, and it requires that at least one of the electrodes be covered by dielectric (similar to a dielectric barrier discharge) resulting in markedly different discharge characteristics.[3] The OAUGDP operates at a much lower plasma power density than the APPJ, ~0.1 W/cm^3 vs ~50 W/cm^3, respectively, allowing it to operate close to ambient temperatures. Although the APPJ produces higher temperatures, these temperatures can be maintained in an acceptable range for most decon applications (e.g., 50–300 °C). It is inferred that the OAUGDP produces much lower densities of reactive species as a result of the lower power density. The OAUGDP D value shown in Table III is a result of placing the object to be sterilized between closely spaced (i.e., 1–5 cm) electrodes located within a chamber. Although the chamber does not need to be pumped down as would otherwise be required for a vacuum chamber, the size and shape of the object to be decontaminated is severely constrained by the electrode spacing. The fast flowing effluent of the APPJ places its reaction zone downstream of a nozzle, allowing application to all accessible surfaces. Downstream application of the OAUGDP effluent, which would allow time for ions and electrons to recombine and for reactive species to decay or react, would likely significantly reduce its kill effectiveness even further.

Corona discharges are spatially localized regions of breakdown occurring in highly inhomogeneous electric fields. For instance, a corona will form in the high electric field near a sharp point on an electrode. Corona discharges require application of a large voltage with very little current being drawn between the electrodes. The APPJ produces several orders of magnitude larger densities of atomic oxygen than a corona discharge. While corona discharges are efficient producers of ozone, they are much less effective at producing the more reactive atomic oxygen. The homogeneous nature of the APPJ discharge is responsible for maintaining an appreciable concentration of atomic oxygen by providing a continuous source of electrons for dissociation of oxygen and ozone. In the case of corona and dielectric barrier discharges, only a small fraction of the interelectrode volume contains a significant electron density at any given time, resulting in the depletion of atomic oxygen and the build up of ozone. While ozone has shown some benefit in CBW decontamination, its long lifetime results in personnel and material corrosion hazards. The aim of the APPJ is to utilize the much more reactive and shorter lived atomic and metastable oxygen species to produce a safer and more selective method of decon. The D value for corona[15] seen in Table III is nearly an order of magnitude larger than that for the APPJ. Furthermore, this value is the result of placing spore samples inside a chamber containing the discharge, which again severely limits the nature and size of surfaces that can be deconed. It is assumed that dielectric barrier discharges, or silent discharges, due to similar reactive species production rates, would produce results very similar to corona.

Arcs are also characterized by spatially localized regions of gaseous breakdown, but at very high electrical currents. Arcs generally operate near thermal equilibrium at high temperatures (e.g., 3000–6000 °C). While a plasma torch does produce copious amounts of reactive species as seen in Table III, these high temperatures would damage most surfaces to be decontaminated. The nonthermal nature of the APPJ discharge allows operation at temperatures at least an order of magnitude lower than what is achievable in arc discharges. A study using a similar thermal discharge, namely a laser-initiated, inductively-coupled microwave discharge at atmospheric pressure to sterilize 10 mℓ glass vials, resulted in extremely short D values.[16] However, it was concluded that it was most likely the intense heat and burst of UV radiation, not the reactive species, which was responsible for the observed sterilization. These high temperatures severely limit the operational usefulness of this decon method.

VI. FUTURE WORK

There are considerable scientific and technical challenges that must be overcome in the development of a fieldable APPJ. On the physics side, an improved understanding of the plasma discharge physics is needed in order to optimize the source and reactive species production. Atmospheric pressure, uniform glow rf discharge is a new realm of plasma physics. APPJ discharge physics is now being modeled which should enable prediction of basic processes such as electron impact ionization, dissociation, and excitation. The ambiguity between atomic and metastable oxygen will be resolved experimentally and production of the more reactive species will be optimized through proper selection of electrode geometry, applied electromagnetic frequency, source excitation, and feedgas composition. On the biology side, we need to understand the neutralization mechanism for bacteria, viruses, and toxins in order to optimize decon efficiency. This will entail studying the effect of the plasma effluent on cell membranes, nucleic acids, and enzymes. On the chemistry side, alternate reactive feedgases and exposure conditions that can induce desired chemical changes will be

explored. Also, actual CW agents, in particular VX, will be studied at certified facilities to avoid the differences that are inherent with simulants.

On the engineering side, the APPJ must be scaled up. The current laboratory prototype is only capable of deconing on the order of 10 cm^2/min of anthrax or mustard, if the contaminated surfaces exposed to the effluent must be restricted to temperatures $<200\,^{\circ}C$. To be truly useful in the field, the APPJ must be scaled up to achieve decon rates on the order of 0.1–1.0 m^2/min, a 100–1000-fold increase. Scale up in size and power can probably account for a factor of 100 and still result in a manageable hand held unit. But it is hoped that further improvements providing additional orders of magnitude increase will result through use of alternate feedgases, electrode geometries and rf frequency and excitation. Various feed gas compositions and flow rates will be modeled and tested to find the optimum mix between plasma discharge characteristics and reactivity on CBW agents. Possible reactive additives include H_2, H_2O, H_2O_2, CF_4, SF_6 as well as the standard O_2. These improvements should allow reductions in the source effluent temperature, which will help avoid damage to sensitive equipment while maintaining a relatively short exposure time.

APPJ results presented in this study were all conducted at a stand-off distance of 0.5 cm. To be useful in the field, this distance shall have to be extended to 5–50 cm without significantly reducing the decontamination efficacy. Lifetimes of the current reactive species should be sufficient to achieve this range with adequate feedgas flow rate and nozzling. Alternatively, it may be possible to extend the lifetime of these species or to find longer lived reactive species.

The use of the helium carrier gas must be minimized through such means as recirculation or replacement to reduce the need to transport gas cylinders into the field. Helium recirculation may take place within a closed or semi-closed system. Recent results have shown that it may be possible to employ methods to produce stable operating windows for other carrier gases such as argon. Even if it is not possible to totally eliminate He in the discharge, it may be possible to substantially reduce its consumption through innovative techniques involving electrode geometry and excitation. Clearly, an all-air discharge is also highly attractive. If possible, use of an air discharge will likely allow the capture and treatment of off-gases to help avoid reaerosolization of the CBW agent and to improve process efficiency.

Ideally, the APPJ should be integrated with real-time sensors to facilitate identification of contaminated surfaces and to determine when the equipment is sufficiently decontaminated and ready for reuse or redeployment. The use of the APPJ's directed energy onto a surface should make spectroscopic techniques a possibility in identifying a broad spectrum of CW agents and quite possibly even BW agents.

VII. SUMMARY

APPJ technology represents a promising and revolutionary new technology for rapid decontamination of material and personnel. By choosing the correct combination of electromagnetic frequency, electrode geometry, and feedgas composition, the APPJ is capable of operating as a uniform, nonthermal discharge at atmospheric pressure. The APPJ produces a high density of highly reactive species at relatively low temperatures, thereby combining the best features of arc and corona discharges. It has been shown to neutralize a variety of pathogen and toxin surrogates without generating any harmful or toxic by-products. Because the APPJ operates at low temperatures, it offers a viable and much needed method of decontaminating sensitive, critical equipment without causing damage.

ACKNOWLEDGMENTS

The authors acknowledge collaborators on the APPJ project: W. L. Earl, L. Vanderberg, J. Davis, G. Wagner, J. Rau, H. Snyder, P. Bueno, and R. Trujillo, Los Alamos National Laboratory; B. Hicks, J. Jeong, University of California at Los Angeles; J. Weimaster, J. Hovanec, P. Bartram, and V. Henderson, U.S. Army Edgewood Chemical and Biological Center; J. Calomiris, J. Kiel, and E. Holwitt, U.S. Air Force Research Laboratory, CDR J. Wallace, Naval Research Laboratory, as well as members of the Office of Naval Research Reserve Program 38. This work was sponsored by the U.S. Department of Energy.

[1] A. Schütze, J. Y. Jeong, S. E. Babayan, J. Park, G. S. Selwyn, and R. F. Hicks, IEEE Trans. Plasma Sci. **26**, 1685 (1998).
[2] K. A. Svitil, Discover **18**, 30 (1997).
[3] J. Park, J. Y. Jeong, C. S. Chang, I. Henins, H. W. Herrmann, D. Shim, R. F. Hicks, and G. S. Selwyn, ''A novel atmospheric pressure plasma source,'' J. Appl. Phys. (submitted).
[4] J. Y. Jeong, S. E. Babayan, V. J. Tu, J. Park, I. Henins, J. Velarde, R. F. Hicks, and G. S. Selwyn, Plasma Sources Sci. Technol. **7**, 282 (1998).
[5] S. E. Babayan, J. Y. Jeong, V. J. Tu, J. Park, R. F. Hicks, and G. S. Selwyn, Plasma Sources Sci. Technol. **7**, 286 (1998).
[6] Y.-C. Yang, J. A. Baker, and J. R. Ward, Chem. Rev. **92**, 1729 (1992).
[7] G. Irving, T. McMurray, and J. Herbold, Non-Medical Dispersed Biological Weapons Countermeasures (USAF Armstrong Laboratory AL/OE-TR-1997-0081, 1997, NTIS order No. ADA327316). Copies are available from the National Technical Information Service, Springfield, VA 22161.
[8] Military Chemistry and Chemical Compounds (Army Field Manual No. 3–9, Air Force Regulation No. 355-7, Departments of the Army and Air Force, Washington, D.C. 1975).
[9] R. K. Oag, J. Pathology and Bacteriology **51**, 137 (1940).
[10] P. Dietz, R. Bohm, and D. Stauch, Zentralblatt fur Bakteriologie, Mikrobiologie und Hygiene-1-Abt-Originale B. Hygiene **171**, 158 (1980).
[11] C. Holler, H. Martiny, B. Christiansen, H. Ruden, and K. O. Gundermann, Zentralblatt fur Hygiene und Umweltmedizin **194**, 380 (1993).
[12] R. E. Baier, J. M. Carter, S. E. Sorensen *et al.*, J. Oral Implantology **18**, 236 (1992).
[13] M. Laroussi, IEEE Trans. Plasma Sci. **24**, 1188 (1996).
[14] K. Kelly-Wintenberg, T. C. Montie, C. Brickman, J. R. Roth, A. K. Carr, K. Sorge, L. C. Wadsworth, and P. P. Y. Tsai, Jml. Industrial Microbio. & Biotech. **20**, 69 (1998).
[15] J. G. Birmingham and P. M. Irving (private communication), Corona Discharge Plasma Reactor for Decontamination, 25th IEEE International Conference on Plasma Science, Raleigh, NC, June 1998.
[16] L. G. Tensmeyer, P. E. Wright, D. O. Fegenbush, and S. W. Snapp, Jml. Parental Sci. Tech. **35**, 93 (1981).