ELECTRICAL AND COMPUTER ENGINEERING DEPARTMENT

Final Scientific Report

TTERING OF MICROWAVES BY STEADY-STATE
PLASMA SLABS, COLUMNS, AND LAYERS
AT ATMOSPHERIC PRESSURE

Covering the Period
April 1, 1995 to March 31, 1998

By
Mounir Laroussi, Principal Investigator
UTK Microwave & Plasma Laboratory

AFOSR Contract F49620-95-1-0277

UNIVERSITY OF TENNESSEE

KNOXVILLE
TN 37996-2100

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SCATTERING OF MICROWAVES BY STEADY-STATE PLASMA SLABS, COLUMNS, AND LAYERS AT ATMOSPHERIC PRESSURE

Submitted to
The Air Force Office of Scientific Research

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I. ABSTRACT

This report describes the research activities carried out at the Microwave & Plasma Laboratory of the University of Tennessee, Knoxville, under AFOSR Contract F49620-95-1-0277. During the duration of this project a detailed study of the attenuation and scattering of microwaves by atmospheric pressure plasmas was conducted. Our results clearly show that such plasmas can play an effective role as a rampart or shield only if the number density approaches 10^{13} cm^{-3}, and the thickness of the plasma layer exceeds the wavelength of the incident wave.

To research the means of maintaining a relatively high plasma number density in air, much more in-depth experimental investigations had to be done. For this purpose advanced diagnostics techniques such as Optical Emission Spectroscopy (OES), and ultra-fast photography, correlated with wide band electric measurements had to be applied in order to adequately characterize the physical and chemical properties of the discharge. Unfortuanately, these experimental techniques require expensive instrumentations, which were unaffordable to us due to the very limited funds available under this contract.

Several important spin-offs of our research have been developed. These include the design of a high power microwave detector, a new atmospheric pressure discharge reactor which doesn't require electrodes inside the reactor chamber, and a decontamination device using a dielectric barrier controlled discharge. Our decontamination work resulted in a collaboration between our laboratory, the UTK Center for Environmental Biotechnology, and General Thermal Inc., a small East Tennessee company. This collaboration led to the award of an AFOSR STTR contract.

II. Introduction

This document is a report on the activities conducted under AFOSR contract F49620-95-1-0277, at the Microwave & Plasma Laboratory which is affiliated with the Electrical Engineering Department of the University of Tennessee, Knoxville. Spin-offs of our research which are of interest to the Air Force are also described. These include the design of a high power microwave detector, the design of a new electrodeless discharge at atmospheric pressure(EDAP), and the use of the Glow Discharge at Atmospheric Pressure(GDAP) as a decontamination device.

The material in this document is organized as follows: Section III describes our work on the interaction of microwaves with air plasmas. Section IV describes a collaborative theoretical effort with Professor Igor Alexeff on the physics of the GDAP. Section V describes spin-offs of our research (Detector, EDAP, Decon.). Section VI outlines the utility of our technical accomplishments to the Air Force. Section VII lists the archival papers and the conference presentations supported directly or indirectly by this contract. Section VIII briefly presents the individuals who contributed to the advancement of our research activities. Appendices A and B are respectively copies of archival manuscripts, and conference poster papers. In Appendix C we include articles published by the local media covering some of our research.

III. Interaction of Microwaves with Atmospheric Pressure Plasmas

Our analytical and computational work showed that highly collisional plasmas such as atmospheric pressure plasmas, interact with electromagnetic waves in a very distinctive fashion.

Unlike low pressure plasmas, air plasmas do not display a frequency cut-off region: i.e. a microwave incident on a layer of air plasma would suffer attenuation as it propagates through, wether its frequency is lower or higher than the plasma frequency. Two archival papers (shown in Appendix A) were published on the subject in the International Journal of Infrared and Millimeter Waves. In these two papers we also show that substantial attenuation occurs only if the electron number density is greater than 10^{13} cm^{-3}, and the thickness of the plasma layer is greater than the wavelength of the incident wave. An additional archival paper(see Appendix A) dealing with the scattering of microwaves from a plasma-covered cylindrical conducting object was also published in the same above mentioned journal. This work simulates the case of a plasma-covered airplane fuselage interacting with an interrogating radar signal.

The atmospheric pressure plasma used in our laboratory is generated by a GDAP(see Fig.1), which is a dielectric barrier controlled discharge. Unfortunately, the number densities generated by such a discharge are below 10^{12} cm^{-3}. Our theory (see details in papers included in Appendix A) shows that a wave propagating through such a plasma will suffer practically no attenaution. Our experiments, where a microwave in the K-band was launched across a plasma layer, confirmed our theoretical prediction.

IV. Physics of the Glow Discharge At Atmospheric Pressure (GDAP)

A theoretical collaboration between the Principal Investigator and Professor Igor Alexeff(Electrical Engineering, The University of Tennessee) with regards to the physics of the GDAP took place during the last few months of this research program. An analytical

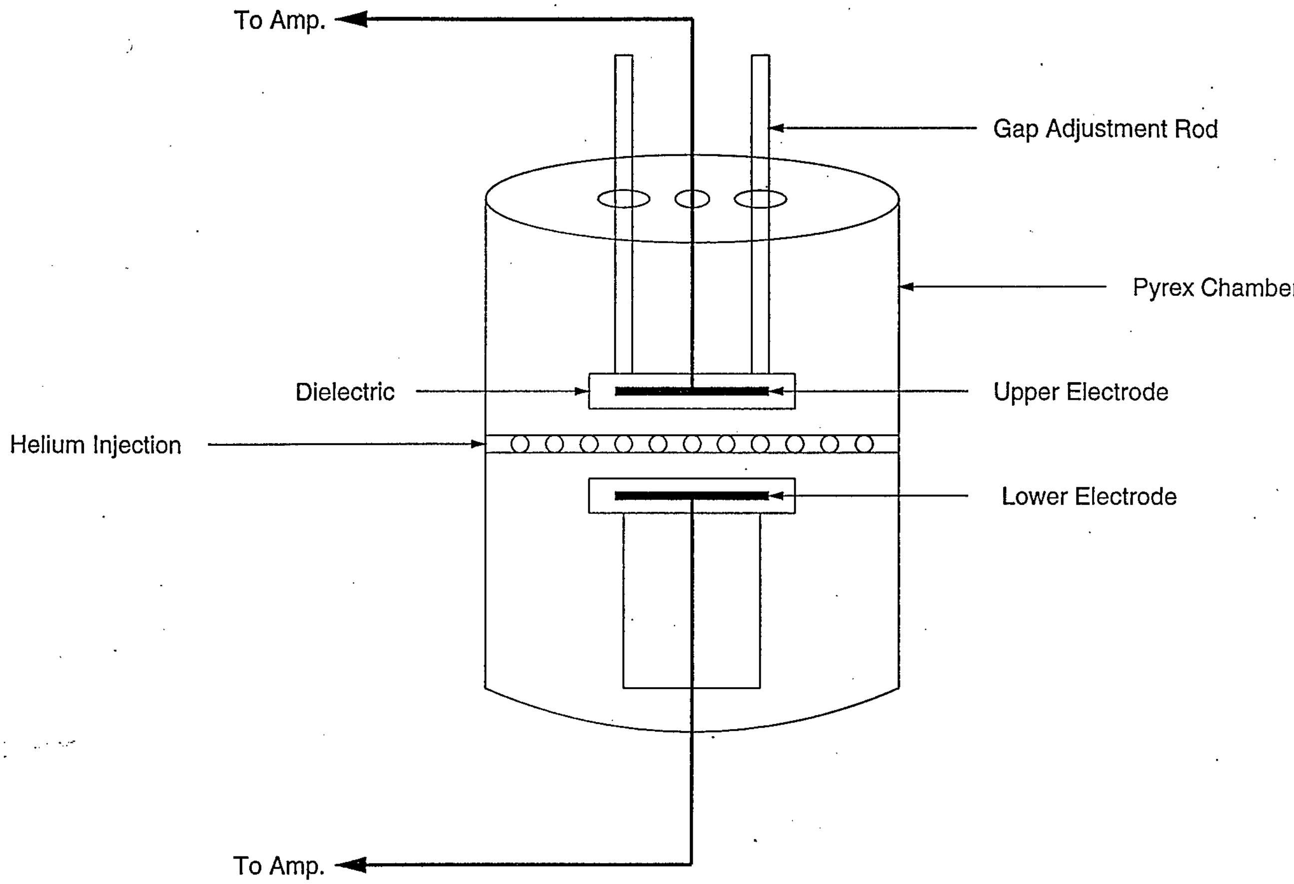


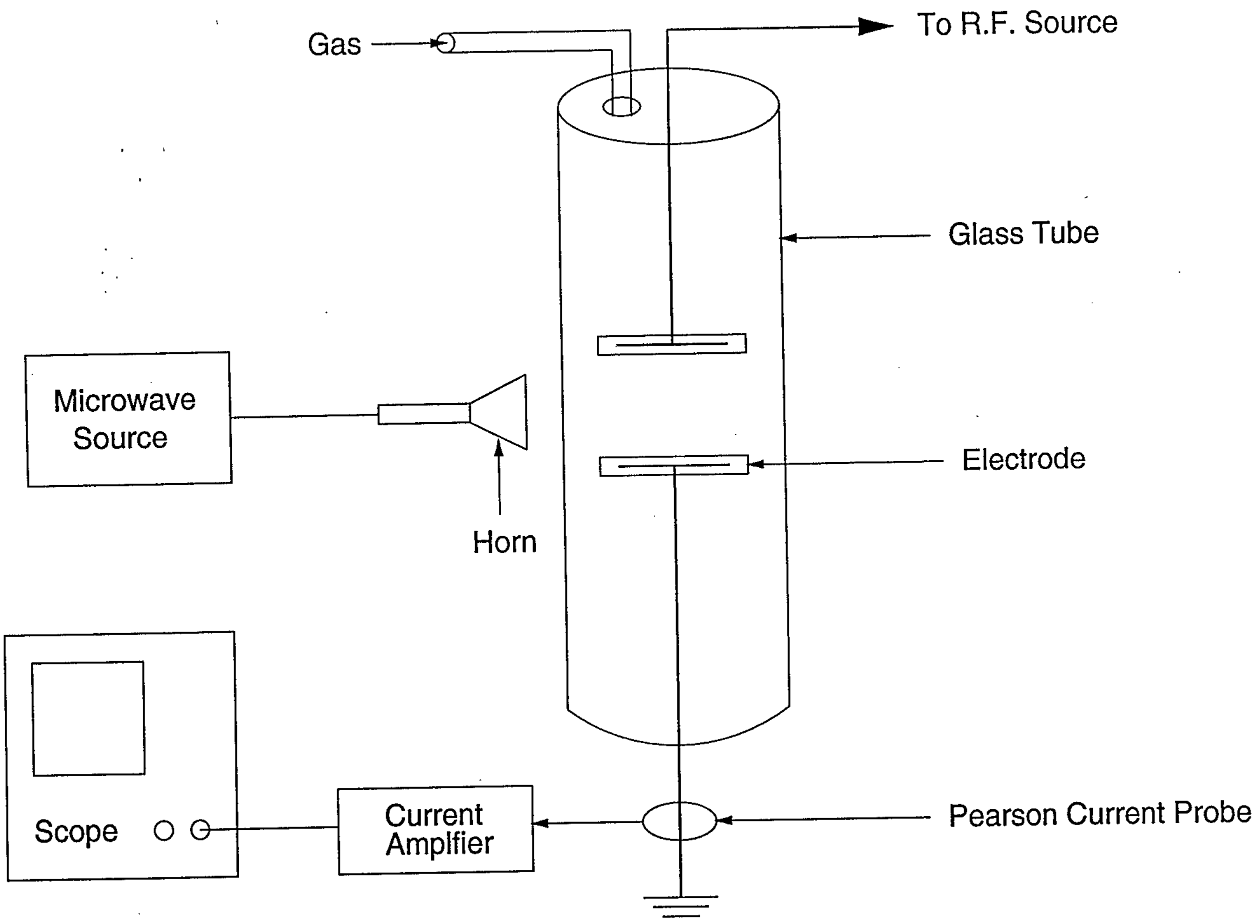
Fig. 1. Glow Discharge at Atmospheric Pressure (GDAP) reactor.

development led to the derivation of the equations governing the electrical characteristics of the discharge. With these equations, the discharge current, the input power, the power deposited in plasma, the charges accumulated on the dielectric, the number density, and the resistivity of the plasma can all be derived. Some of our results are the subject of an archival paper jointly authored by the P.I. and Prof. Alexeff. This manuscript is currently under review by the IEEE Transactions on Plasma Science. A copy of the manuscript which is titled " The Current-Voltage Relationship in the Glow Discharge at Atmospheric Pressure" is included in Appendix A.

V. Research Spin-offs

High Power Microwave Detector

Using a miniaturized GDAP and putting the device in the propagation path of a microwave we noticed that the discharge current changes in value(see Fig.2). This observation led to the idea of using the discharge as a detector of millimeter radiation. The current change is a direct measure of the power of the incident wave. We believe that this detection property of the GDAP is due to a change of the resistivity of the discharge when a microwave is impinging on it. The change of resistivity leads to a change in the current through the discharge. An invention disclosure titled " Discharge Tube Microwave Detector" was submitted by Mounir Laroussi and Igor Alexeff, and approved by the Research Office of the University of Tennessee. Also, a poster paper was presented at the 1998 IEEE International Conference on Plasma Science. A copy of this paper which titled " The One Atmosphere Glow Discharge as a Detector of Millimeter Radiation" is included in Appendix B.



Discharge Tube Microwave Detector

Fig.2

Electrodeless Discharge at Atmospheric Pressure (EDAP)

This is a capacitevely coupled RF discharge which operates at atmospheric pressure. It simply consists of a hollow glass tube with two separate loops of wire wrapped around it at some distance from each other. One end of the tube is completely open to the outside air. The plasma is generated within the tube. This configuration is ideal for the breaking down of polluting gases which can be injected at one end of the tube and exhausted at the open end after interacting with the discharge. This device can be used in various applications requiring the treatment of environmentally damaging gases. An invention disclosure titled " Electrodeless Discharge at Atmospheric Pressure" was submitted by Mounir Laroussi, Gary S. Sayler, and Battle B. Glascock, and approved by the Research Office of The University of Tennessee.

Plasma-Aided Decontamination

The sterilization/decontamination of matter by atmospheric pressure plasmas has recently received a lot of attention. Early work (1994-1995) by the P.I. showed that the plasma generated by the GDAP can be an excellent sterilization agent (see in Appendix A the manuscript titled " Sterilization of Contaminated Matter with an Atmospheric Pressure Plasma", published in June 1996, in the IEEE TPS). Subsequently, a collaboration between the Microwave & Plasma Laboratory, The UTK Center for Environmental Biotechnology, and General Thermal Inc., a small East Tennessee company led to the award of an AFOSR STTR contract. Under this contract the potentials of the GDAP as a decontamination device were investigated. A poster paper (see Appendix B) titled " Decontamination of Media by a Gaseous

Discharge at Atmospheric Pressure" was presented at the 1998 IEEE International Conference on Plasma Science.

VI. Utility of our Research to the Air Force

Interaction of Microwaves with Air Plasmas

Our results on the attenuation and scattering of microwaves by air plasma layers have direct impact on the use of air plasmas as ramparts or shields against directed electromagnetic weapons. However the initiation and maintenance of plasmas with a number density at or above 10^{13} cm^{-3} in air is a major challenge. For this reason the P.I. has been actively involved in the MURI Air Plasma Rampart Program. The P.I. has attended all meetings and teleconferences held by the MURI APRP groups where various approaches to the problem of maintaining air plasmas with relatively high number densities, low temperatures, and reasonable power inputs are discussed.

The Atmospheric pressure plasmas generated by the GDAP are cold, uniform, and require a relatively small power input for initiation and maintenance. However, the number density is below the 10^{13} cm^{-3} necessary to have substantial attenuation of microwave power. Future improvements in our generation method might lead to an increase in the plasma number density, which would result in a plasma effective in rampart applications.

High Power Microwave Detection

The rapid detection of the presence of high power microwave radiation might prove essential in the defense against high energy directed electromagnetic weapons. Conventional detectors (crystal detectors) do not meet the power requirements in such an application. The

GDAP can be miniaturized and used as a detector under high microwave power conditions, without the risk of burnout. The detection is based on the variation of the discharge current in the presence of microwaves. The change in the current is a direct measure of the power of the incident wave.

Plasma-aided Decontamination

The GDAP has proved to be an excellent sterilization agent. Harmful microorganisms can be neutralized in few minutes. Since the GDAP can be easily made into a portable unit, its potential use as a sterilization device in a battlefield situation seems promising. This use includes the rapid sterilization of reusable medical tools, the decontamination of military equipment which has been exposed to biological warfare agents, the purification of water supplies, etc...

VII. Publications

The following is a comprehensive list of archival papers and conference presentations which were supported in whole or in part by AFOSR contract F49620-95-1-0277.

Archival Manuscripts

1. M. Laroussi, " Interaction of Microwaves with Atmospheric Pressure Plasmas", Int. J. IR & Millimeter Waves, Vol. 16, No. 12, pp.2069-2083, 1995.
2. M. Laroussi, " Scattering of Electromagnetic Waves by a Layer of Air Plasma Surrounding a Conducting Cylinder", Int. J. IR & Millimeter Waves, Vol. 17, No. 12, pp.2215-2232, 1995.
3. M. Laroussi, " Sterilization of Contaminated Matter with an Atmospheric Pressure Plasma", IEEE Trans. Plasma Sci., Vol. 24, No. 3, pp.1188-1191, 1996.
4. M. Laroussi and William T. Anderson, " Attenuation of Electromagnetic Waves by a Plasma Layer at Atmospheric Pressure", Int. J. IR & Millimeter Waves, Vol. 19, No. 3, pp.453-464, 1998.
5. M. Laroussi and I. Alexeff, " The Current-Voltage Relationship in the Glow Discharge at Atmospheric Pressure". Under review by the IEEE Trans. Plasma Sci.
6. M. Laroussi, G. S. Sayler, B. B. Glascock, B. McCurdy, M. E. Pearce, N. G. Bright, and C. M. Malott, " Images of Biological Samples Undergoing Sterilization by a Glow Discharge at Atmospheric Pressure". Under review by the IEEE Trans. Plasma Sci.

Conference Papers

1. M. laroussi, " Scattering of Microwaves by a Plasma Column at Atmospheric Pressure", in Proc. IEEE Int. Conf. Plasma Sci., pp.105-106, 1995.
2. M. Laroussi, " Sterilization of Tools and Infectious Waste by Plasmas", APS DPP Bull., Vol. 40, No. 11, pp.1685-1686, 1995.
3. M. Laroussi, " Scattering of Microwaves with Atmospheric Pressure Plasmas", in Proc. Int. Conf. IR & Millimeter Waves, pp.509-510, 1995.
4. M. Laroussi, " Studies on the Reflectivity and Backscattering of the One Atmosphere Glow Discharge", in Proc. IEEE Int. Conf. Plasma Sci., p.294, 1996.
5. M. Laroussi, M. Rader, F. Dyer, M. Dever, and I. Alexeff, " Plasma-Aided Sterilization", APS DPP Bull., Vol. 41, No. 17, pp.1539-1540, 1996.
6. M. Laroussi, " Interaction of an Air Plasma Layer Covering a Conducting Surface with Microwaves", in Proc. IEEE Int. Conf. Plasma Sci., p.135, 1997.
7. M. Laroussi, I. Alexeff, K. Gillispie, and G. Sayler, " The One Atmosphere Glow Discharge as a Sterilization Agent", in Proc. Int. Conf. Phenomena in Ionized Gases, Vol. III, pp.102-103, 1997.
8. M. Laroussi and W. T. Anderson, " Attenuation of Microwaves by an Air Plasma Layer", APS DPP Bull., Vol. 42, 1997.
9. M. E. Pearce, C. M. Malott, G. S. Sayler, M. Laroussi, B. B. Glascock, and B. McCurdy, " Decontamination of Media by A Gaseous Discharge at Atmospheric Pressure", in Proc. IEEE Int. Conf. Plasma Sci., p.287, 1998.

10. M. Laroussi, " The One Atmosphere Glow Discharge as a Detector of Millimeter Radiation", in Proc. IEEE Int. Conf. Plasma Sci., p.282, 1998.

VIII. Staffing

The Principal Investigator was supported by this contract on an average of 75% time. One Graduate (Mr. William T. Anderson), and one Undergraduate (Mr. Chad M. Malott) students were also involved in our research efforts in the last year of this contract. They were supported by AASERT contract F49620-97-1-0472. These two students carried out experimental and theoretical work on the generation of atmospheric pressure plasmas, and their interactions with microwaves. Mr. William T. Anderson attended a training seminar on the use of the MAGIC software, in the summer of 1997. He also helped build our Glow Discharge at Atmospheric Pressure (GDAP) reactor. The Undergraduate student (Mr. Malott) assisted Mr. Anderson, and helped carry out several sterilization experiments.

Appendix A

Archival Papers

International Journal of Infrared and Millimeter Waves, Vol. 16, No. 12, 1995

INTERACTION OF MICROWAVES WITH ATMOSPHERIC PRESSURE PLASMAS

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Received October 14, 1995

Abstract

In this paper, the interaction of microwaves with a plasma, generated at atmospheric pressure, is studied. The refractive index, attenuation index, skin depth, attenuation coefficient, phase coefficient, and reflectivity are investigated as functions of the plasma number density, the wave frequency and type of polarization, and the grazing angle. It is found that two frequency regimes characterize these type of plasmas. The first is a range where the phase velocity and attenuation of the wave both increase with frequency. The second is a frequency range in which the phase velocity and attenuation of the wave remain constant. It is also found that to have a shallow skin depth, the plasma number density has to be in the 10^{13} cm^{-3} range. The reflectivity is found to be an increasing function of the number density. In horizontal polarization, the reflectivity is a decreasing function of the grazing angle. But in vertical polarization and for grazing angle less than 20°, the reflectivity has a maximum at a frequency $f = f_s = \frac{2\pi f_{pe}^2}{\nu}$, where f_{pe} is the electron plasma frequency and ν is the collision frequency.

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A-1

I. Introduction

Plasmas are usually generated at low pressures, where the collision frequency of the ionized particles is relatively low as compared to the electron plasma frequency and wave frequencies in the microwave range. These plasmas have a refractive index less than unity, and their interaction with electromagnetic waves is characterized by three frequency regions. A low frequency region where the conductivity of the plasma is real and the plasma acts as a good metallic conductor (especially at high kinetic temperatures). At intermediate frequencies, the plasma acts as a wave guide beyond cutoff, where the wave does not propagate through, and is mainly reflected back. At high frequencies the plasma becomes a low-loss dielectric, allowing the wave to propagate with little attenuation.

This paper shows that at atmospheric pressure, where the electron collision frequency is in the THz (10^{12} Hz), plasma acts quite differently from the usual low pressure case. The refractive index can be greater than unity, and two frequency regimes characterize the interaction with microwaves. At frequencies below a characteristic frequency $\omega_s = \frac{\omega_{pe}^2}{\nu}$, where ω_{pe} is the electron plasma frequency, and ν is the collision frequency, an electromagnetic wave propagates through the plasma with an attenuation which increases with frequency and number density, and with a phase velocity which increases with frequency and decreases for increasing number densities. At frequencies greater than ω_s the refractive index goes to unity, the phase velocity approaches the speed of light and the wave attenuation factor becomes independent on frequency but increases with the number density.

The reflectivity of a plasma generated at atmospheric pressure is found to greatly depend on the type of wave polarization, the grazing angle, frequency, and the number density. Plots of the reflectivity in both vertical and horizontal polarizations, are presented in the 1GHz - THz frequency range, with the grazing angle or the number density as a variable parameter.

II. Propagation Characteristics

The dispersion relation of a plane wave with a phase dependence $\exp\left(j\omega t - \tilde{\gamma} x\right)$, in a lossy medium of relative permeability unity is: (Fig. 0)

$$\tilde{\gamma}=j\frac{\omega}{c}\left(\tilde{\varepsilon}_r\right)^{1/2}, \tag{1}$$

where $\tilde{\gamma}$ is the complex propagation coefficient, ω is the wave frequency, and $\tilde{\varepsilon}_r$ is the complex dielectric constant.

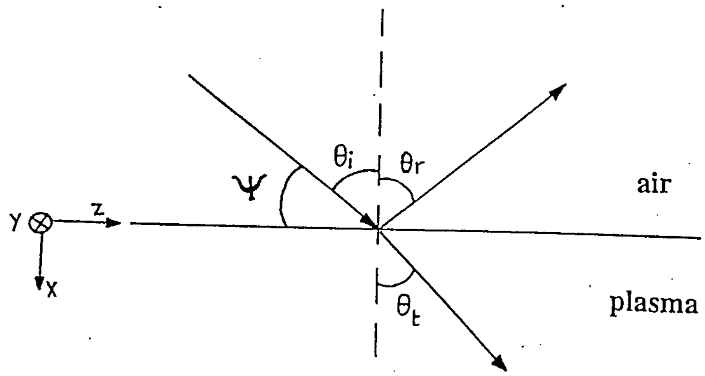

Fig. 0 Wave propagating through air, then plasma, with reflection at the boundary.

$\tilde{\gamma}$ can be expressed as

$$\tilde{\gamma}=\alpha+j\beta, \tag{2}$$

where α is the attenuation coefficient, and β is the phase coefficient. The complex refractive index $\tilde{\mu}$ is given by

$$\tilde{\mu}=\left(\tilde{\varepsilon}_r\right)^{1/2}=\mu-jX, \tag{3}$$

where μ is the refractive index, and X is the attenuation index. μ and X are related to α and β by the following relations

$$\alpha = \frac{\omega}{c} X , \tag{4}$$

and

$$\beta = \frac{\omega}{c} \mu . \tag{5}$$

For a collisional unmagnetized plasma we have [1]

$$\mu = \left\{ \frac{1}{2}\left(1 - \frac{\omega_{pe}^2}{\omega^2+\nu^2}\right) + \frac{1}{2}\left[\left(1 - \frac{\omega_{pe}^2}{\omega^2+\nu^2}\right)^2 + \left(\frac{\omega_{pe}^2}{\omega^2+\nu^2}\frac{\nu}{\omega}\right)^2\right]^{1/2} \right\}^{1/2} , \tag{6}$$

and

$$X = \left\{ -\frac{1}{2}\left(1 - \frac{\omega_{pe}^2}{\omega^2+\nu^2}\right) + \frac{1}{2}\left[\left(1 - \frac{\omega_{pe}^2}{\omega^2+\nu^2}\right)^2 + \left(\frac{\omega_{pe}^2}{\omega^2+\nu^2}\frac{\nu}{\omega}\right)^2\right]^{1/2} \right\}^{1/2} , \tag{7}$$

where ω_{pe} is the electron plasma frequency, and ν is the collision frequency (electron-neutral).

For an atmospheric pressure plasma the electron collision frequency is extremely high, $\nu \sim 10^{12}$ Hz. Thus we have

$$\nu >> \omega_{pe} ,$$

and

$\nu >> \omega$ (for microwave frequencies of our interest)

The refractive index μ and attenuation index X can be approximated as follows [2]:

$$\mu = \left\{ \frac{1}{2} + \frac{1}{2}\left[1 + \left(\frac{\omega_{pe}^{2}}{\omega \nu} \right)^{2} \right]^{1/2} \right\}^{1/2}, \tag{8}$$

and

$$X = \left\{ -\frac{1}{2} + \frac{1}{2}\left[1 + \left(\frac{\omega_{pe}^{2}}{\omega \nu} \right)^{2} \right]^{1/2} \right\}^{1/2}. \tag{9}$$

Fig. 1 is a plot of the refractive index, μ, in the 1 GHz - 1 THz frequency range, with the number density as a variable parameter. Fig. 1 shows that μ starts as a decreasing function of frequency then reaches the unity value. Since $\mu = \frac{c}{\upsilon_\phi}$, it follows that the phase velocity of the wave increases with frequency, and eventually reaches the speed of light c. It is also shown that at a single frequency, the phase velocity decreases for increasing number densities. Note that the frequency at which υ_ϕ reaches c (or $\mu \sim 1$) is higher for higher number densities.

Fig. 2a and Fig. 2b show that the slope of the phase coefficient, β, starts with a different value for different number densities, but takes the same value, $\left(\frac{2\pi}{c}\right)$, at higher frequencies, independently on the number density.

Fig. 3 shows that for $f > f_s$, the attenuation index, X, is a function of $\frac{1}{f}$, and n. Analytically this can be proved as follows:

$$X = \left\{ -\frac{1}{2} + \frac{1}{2}\left[1 + \frac{\omega_{pe}^{4}}{\omega^{2} \nu^{2}} \right]^{1/2} \right\}^{1/2}. \tag{10}$$

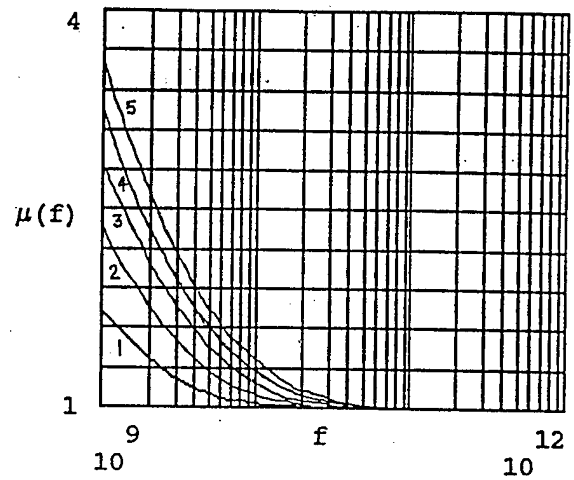

Fig.1 Refractive index Vs. frequency, 1. $n=10^{13}$ cm^{-3}; 2. $n=2.10^{13}$ cm^{-3}; 3. $n=3.10^{13}$ cm^{-3}; 4. $n=4.10^{13}$ cm^{-3}; 5. $n=5.10^{13}$ cm^{-3}.

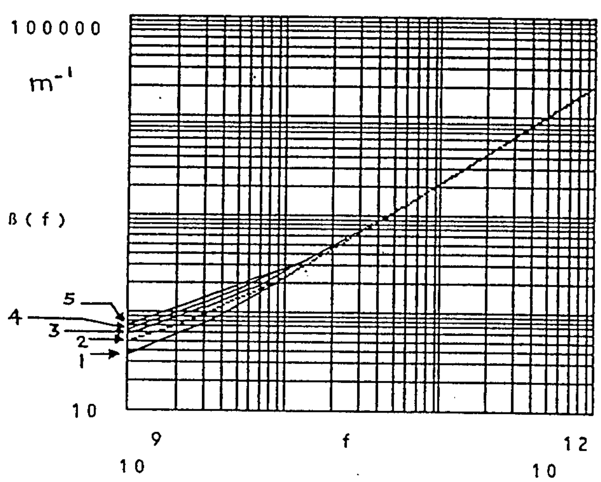

Fig.2a Phase coefficient Vs. frequency for 1. $n=10^{13}$ cm^{-3};2. $n=2.10^{13}$ cm^{-3}; 3. $n=3.10^{13}$ cm^{-3}; 4. $n=4.10^{13}$ cm^{-3}; 5. $n=5.10^{13}$ cm^{-3}.

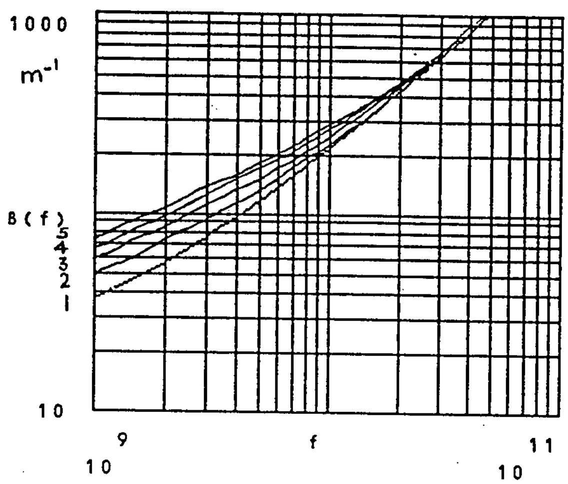

Fig.2b Phase coefficient Vs. frequency (expanded scale) for 1. $n=10^{13}$ cm^{-3};2. $n=2.10^{13}$ cm^{-3}; 3. $n=3.10^{13}$ cm^{-3}; 4. $n=4.10^{13}$ cm^{-3}; 5. $n=5.10^{13}$ cm^{-3}

For $f >> f_S$, X can be expanded as follows:

$$X = \left\{ -\frac{1}{2} + \frac{1}{2}\left(1 + \frac{1}{2}\, \frac{\omega_{pe}^4}{\omega^2 \nu^2} \right) \right\}^{1/2}, \tag{11}$$

or

$$X = \frac{1}{2}\, \frac{\omega_{pe}^2}{\omega \nu}. \tag{12}$$

Knowing that $\omega_{pe}^2 = \dfrac{n\,e^2}{m \epsilon_o}$, we get

$$X = \frac{ne^2}{4\pi \epsilon_o m \nu f}. \tag{13}$$

Fig. 4 shows that the attenuation coefficient α, starts as an increasing function of both frequency and number density, and reaches a frequency range where it is independent on frequency but is still a function of n. The constant value taken by α is given by:

$$\alpha = \frac{2\pi f}{c} X, \tag{14}$$

substituting X by expression (13) we get

$$\alpha = \frac{ne^2}{2\epsilon_o\, m\, c\, \nu}. \tag{15}$$

The skin depth is defined as

$$\delta = \frac{1}{\alpha}, \tag{16}$$

or

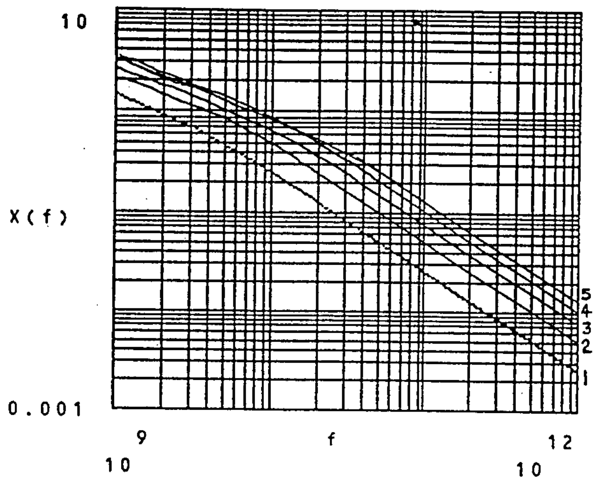

Fig.3 Attenuation index Vs. frequency, 1. n=10^{13} cm^{-3}; 2. n=2.10^{13} cm^{-3}; 3. n=3.10^{13} cm^{-3}; 4. n=4.10^{13} cm^{-3}; 5. n=5.10^{13} cm^{-3}.

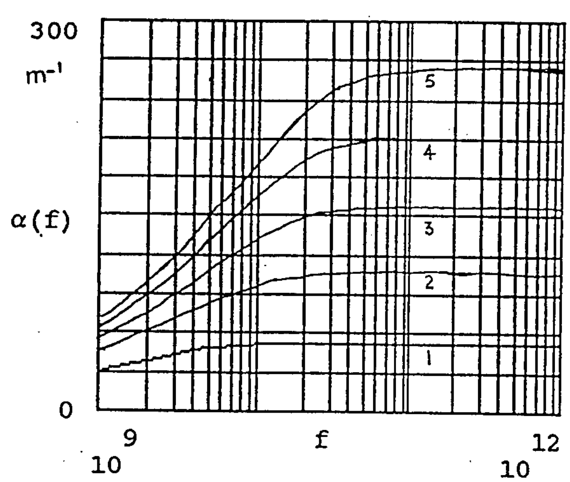

Fig.4 Attenuation coefficient Vs. frequency, 1. n=10^{13} cm^{-3}; 2. n=2.10^{13} cm^{-3}; 3. n=3.10^{13} cm^{-3}; 4. n=4.10^{13} cm^{-3}; 5. n=5.10^{13} cm^{-3}.

$$\delta = \frac{c}{\omega X}. \tag{17}$$

At $\omega = \omega_s = \frac{\omega_{pe}^2}{\nu}$, we have:

$$\delta = 2.2\frac{\nu c}{\omega_{pe}^2}, \tag{18}$$

or

$$\delta = 2.2\frac{\nu c\, \varepsilon_o\, m_e}{n\, e^2}. \tag{19}$$

For a skin depth $\delta < 1$ cm we need,

$$n > 220\frac{\nu c\, \varepsilon_o\, m_e}{e^2}. \tag{20}$$

Assuming $n = 10^{12}$ Hz, we get

$$n > 2 \times 10^{13}\ cm^{-3}$$

Thus for applications where it is only practical to generate a thin slab or layer of plasma to interact with the wave, a number density in the 10^{13} cm^{-3} range is needed in order to attenuate and reflect the incident wave.

Fig. 5 shows that the skin depth, δ, starts as a decreasing function of both frequency and number density, and eventually reaching a constant plateau, the value of which decreases for increasing number densities.

III. Reflectivity Calculations

In the following development we assume that:

a/ Medium 1 is air
b/ Medium 2 is a plasma at atmospheric pressure with $\frac{\sigma}{\omega\varepsilon} < 1$

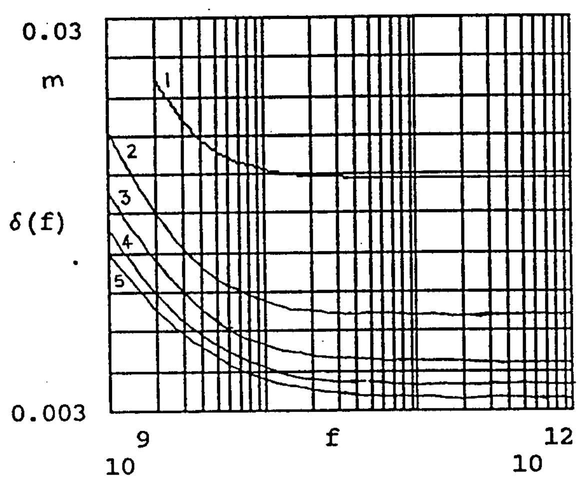

Fig.5 Skin depth Vs. frequency, 1. $n=10^{13}$ cm^{-3}; 2. $n=2.10^{13}$ cm^{-3}; 3. $n=3.10^{13}$ cm^{-3}; 4. $n=4.10^{13}$ cm^{-3}; 5. $n=5.10^{13}$ cm^{-3}.

c/ Dimensions of the plasma are comparable to the wave wavelength

d/ A sharp air-plasma interface

1./ Vertical Polarization: (E parallel to the plane of incidence)
The reflection coefficient is calculated as [3]

$$\Gamma_v = \frac{\tilde{\varepsilon}_r \sin\Psi - \left(\tilde{\varepsilon}_r - \cos^2\Psi\right)^{1/2}}{\tilde{\varepsilon}_r \sin\Psi + \left(\tilde{\varepsilon}_r - \cos^2\Psi\right)^{1/2}}, \quad (21)$$

Where Ψ is the grazing angle, defined as the angle between the air-plasma interface, and the direction of propagation of the incident wave.

2./ Horizontal polarization: (E Perpendicular to plane of incidence.)

The reflection coefficient is calculated as [3]

$$\Gamma_h = \frac{\sin\Psi - \left(\tilde{\varepsilon}_r - \cos^2\Psi\right)^{1/2}}{\sin\Psi + \left(\tilde{\varepsilon}_r - \cos^2\Psi\right)^{1/2}}. \quad (22)$$

Fig. 6 shows that for a vertical polarization case the reflectivity $V(f) = |\Gamma_v|$ is a decreasing function of frequency, for grazing angles $\Psi > 20°$. For $\Psi \leq 20°$, V(f) has a maximum at the frequency $f = f_S$. Fig. 6 also shows that for a fixed frequency, the reflectivity is minimum at a grazing angle around 40°, and is greater for small grazing angles. Fig. 7 shows that V(f) is an increasing function of the number density.

Fig. 8 shows that for a horizontal polarization case, the reflectivity $H(f) = |\Gamma_h|$ is a decreasing function of both frequency and grazing angle. Finally, Fig. 9 shows that H(f) is an increasing function of the number density.

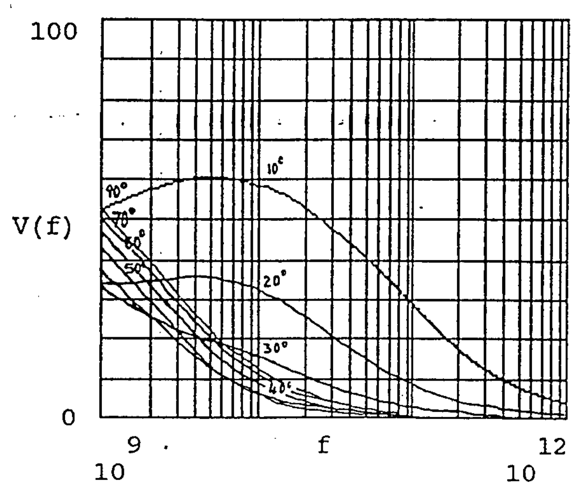

Fig.6 Magnitude(in percent) of the reflectivity in vertical polarization Vs. frequency for $n=10^{13}$ cm^{-3}, and various grazing angles.

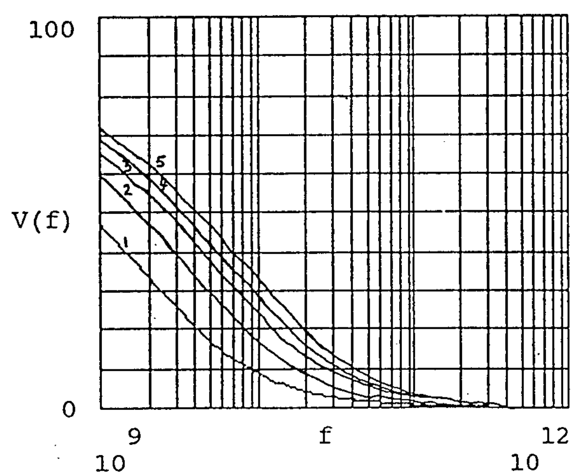

Fig.7 Magnitude(in percent) of the reflectivity in vertical polarization Vs. frequency, for a grazing angle of 60° and n=1, 2, 3, 4, and 5 x 10^{13} cm^{-3}.

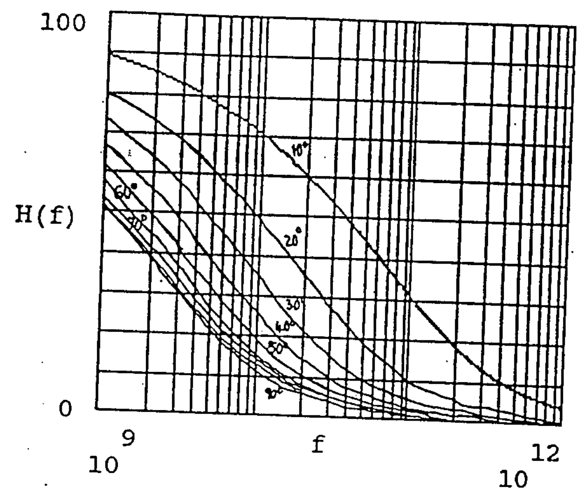

Fig.8 Magnitude(in percent) of the reflectivity in horizontal polarization Vs. frequency for $n=10^{13}$ cm^{-3}, and various grazing angles.

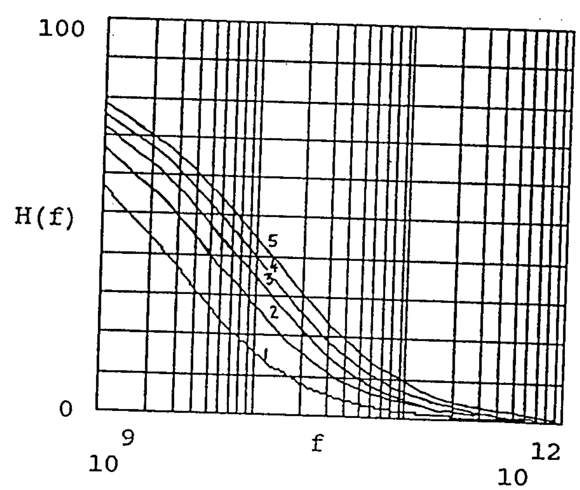

Fig.9 Magnitude(in percent) of the reflectivity in horizontal polarization Vs. frequency, for a grazing angle of 60°,and n=1, 2, 3, 4, and 5 x 10^{13} cm^{-3}.

IV. Conclusion

This paper shows that the interaction of microwaves with atmospheric pressure plasmas, where $\nu >> (\omega, \omega_{pe})$, differs substantially from the usual case of low pressure plasmas. The refractive index, μ, the phase coefficient β, the attenuation index X, the attenuation coefficient α, and the skin depth δ, are studied in the 1 GHz - 1 THz frequency range, for various plasma number densities. The reflectivity of the plasma is investigated for both types of polarization and for various grazing angles and plasma number density. The results of this paper are useful for the understanding of the electromagnetic properties of high pressure plasmas, and complement the already established knowledge at low pressure conditions.

Acknowledgement

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SCATTERING OF ELECTROMAGNETIC WAVES BY A LAYER OF AIR PLASMA SURROUNDING A CONDUCTING CYLINDER

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Abstract

In this paper, the total scattering and back-scattering cross-sections (respectively represented by σ and σ_b) of an air plasma layer surrounding a conducting cylinder are studied. The plasma layer can be turned ON and OFF to allow for a comparison between the scattering cross-section of the bare cylinder and the plasma covered cylinder. The plasma layer is generated at atmospheric pressure, which results in a very highly collisional case. The scattered fields are calculated using a cylindrical expansion, with coefficients satisfying the appropriate boundary conditions, and which are a function of the refractive index of the air plasma. The results of our study are presented as plots of the total scattering cross-section, σ, and back-scattering cross-section, σ_b, versus frequency. The scattering cross-section gives an average characteristic of the scattering process from obstacles. Once the scattering cross-section is known, the actual scattered energy per unit length per second can be calculated by multiplying σ by the incident energy per unit area per second.

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I. Introduction

The dispersion relation of a plane wave with a phase dependence $\exp\left(j\omega t - \tilde{\gamma} x\right)$, in a lossy medium of relative permeability unity is:

$$\tilde{\gamma} = j\frac{\omega}{c}\left(\tilde{\varepsilon}_r\right)^{1/2}, \tag{1}$$

where $\tilde{\gamma}$ is the complex propagation coefficient, ω is the wave frequency, and $\tilde{\varepsilon}_r$ is the complex dielectric constant.

$\tilde{\gamma}$ can be expressed as

$$\tilde{\gamma} = \alpha + j\,\beta, \tag{2}$$

where α is the attenuation coefficient, and β is the phase coefficient. The complex refractive index $\tilde{\mu}$ is given by

$$\tilde{\mu} = \left(\tilde{\varepsilon}_r\right)^{1/2} = \mu - jX, \tag{3}$$

where μ is the refractive index, and X is the attenuation index. μ and X are related to α and β by the following relations

$$\alpha = \frac{\omega}{c}X, \tag{4}$$

and

$$\beta = \frac{\omega}{c}\mu. \tag{5}$$

For a collisional unmagnetized plasma the refractive index, μ, is given by [1]

$$\mu = \left\{ \frac{1}{2}\left(1 - \frac{\omega_{pe}^2}{\omega^2 + \nu^2}\right) + \frac{1}{2}\left[\left(1 - \frac{\omega_{pe}^2}{\omega^2 + \nu^2}\right)^2 + \left(\frac{\omega_{pe}^2}{\omega^2 + \nu^2}\frac{\nu}{\omega}\right)^2\right]^{1/2} \right\}^{1/2} \tag{6}$$

where ω_{pe} is the electron plasma frequency, and ν is the collision frequency (electron-neutral).

For an atmospheric pressure plasma the electron collision frequency is extremely high, $\nu \sim 10^{12}$ Hz. Thus we have [2], [3]

$\nu >> \omega_{pe}$,

and

$\nu >> \omega$ (for microwave frequencies of our interest)

The refractive index μ can be approximated as follows:

$$\mu = \left\{ \frac{1}{2} + \frac{1}{2}\left[1 + \left(\frac{\omega_{pe}^2}{\omega\nu}\right)^2\right]^{1/2} \right\}^{1/2} \tag{7}$$

This paper, presents the calculation of the total scattering cross-section and back-scattering cross-section of an air plasma layer, with a refractive index, μ, covering a conducting cylinder. The refractive index, μ, contains such plasma parameters as the number density and collision frequency. The thickness of the plasma layer is assumed much smaller than the cylinder radius, and comparable to the wavelength of the incoming electromagnetic wave. The frequency range of interest covers a wide band, from 100 MHz to 10 GHz.

II. Scattering Studies

In this study the electromagnetic wave encounters three different media (see Fig. 1). The first medium is air (region 1), the second is a layer of atmospheric pressure plasma with a thickness comparable to the wave wavelength (region 2), and the third is the surface of the conducting cylinder (region 3). In cylindrical coordinates the incident and scattered fields can be expressed as follows:

$$E_i = E_o\, e^{-j\omega t} \sum_{o}^{\infty} \varepsilon_n (j)^n J_n(K_1 r) \cos(n\theta)\,, \tag{8}$$

and

$$E_s = E_o\, e^{-j\omega t} \sum_{o}^{\infty} A_n \varepsilon_n (j)^n H_n^{(1)}(K_1 r) \cos(n\theta)\,. \tag{9}$$

The field in region 1 is given by

$$E_1 = E_i + E_s\,, \tag{10}$$

the field in region 2 is given by

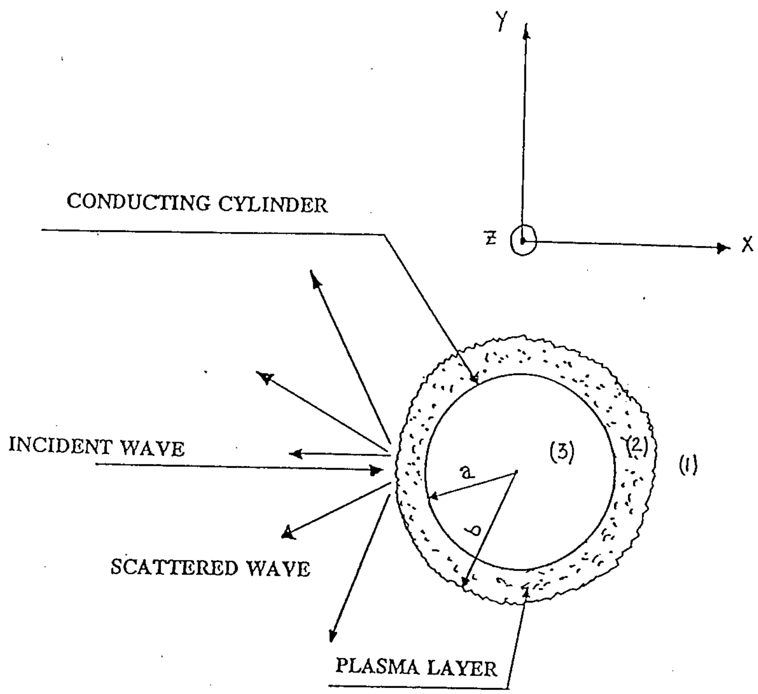

Fig. 1. Conducting cylinder of radius a, surrounded by a plasma layer of thickness (b-a). The electric field of the incident wave is parallel to the z-axis, and multiple scattering at the boundaries is neglected.

$$E_2 = E_o\, e^{-j\omega t} \sum_{o}^{\infty} \varepsilon_n (j)^n \left[B_n H_n^{(2)}(K_2 r) + C_n H_n^{(1)}(K_2 r) \right] \cos(n\theta) \,, \tag{11}$$

and the field in region 3 is given by

$$E_3 = 0,$$

where

$$K_1 = \frac{\omega}{c}$$

$$K_2 = \frac{\omega}{c} \cdot \mu$$

J_n: Bessel function of the first kind

$H_n^{(1)} = J_n + j\, Y_n$: Hankel function of the first kind

$H_n^{(2)} = J_n - j\, Y_n$: Hankel function of the second kind.

The total scattering cross-section is given by

$$\sigma = \frac{P_s}{P_i \text{ (per unit area)}}$$

where P_s is the total scattered power, and P_i the incident power per unit area. Using the expressions of the fields given above, σ can be expressed as [3] - [7]

$$\sigma = \frac{4}{K_1} \sum_{o}^{\infty} \varepsilon_n A_n A_n^* \,. \tag{12}$$

The coefficients A_n are calculated using the boundary conditions, [3], [4]

$$A_n = \frac{\begin{array}{l}\mu J_n(K_1 b)\left[H_n^{(1)'}(K_2 b)H_n^{(2)}(K_2 a) - H_n^{(2)'}(K_2 b)H_n^{(1)}(K_2 a)\right] \\ -J_n'(K_1 b)\left[H_n^{(1)}(K_2 b)H_n^{(2)}(K_2 a) - H_n^{(2)}(K_2 b)H_n^{(1)}(K_2 a)\right]\end{array}}{\begin{array}{l}-\mu H_n^{(1)}(K_1 b)\left[H_n^{(1)'}(K_2 b)H_n^{(2)}(K_2 a) - H_n^{(2)'}(K_2 b)H_n^{(1)}(K_2 a)\right] \\ +H_n^{(1)'}(K_1 b)\left[H_n^{(1)}(K_2 b)H_n^{(2)}(K_2 a) - H_n^{(2)}(K_2 b)H_n^{(1)}(K_2 a)\right]\end{array}} \qquad (13)$$

The back-scattering cross-section which is the ratio of the power scattered back toward the source to the incident power per unit area is given by

$$\sigma_b = \frac{4}{K_1}\left|\sum_{0}^{\infty}(-1)^n \varepsilon_n A_n\right|^2 . \qquad (14)$$

If the conducting cylinder is removed so as to have just a column of air plasma, the expression of the coefficient A_n are in this case given by

$$A_n = \frac{k_2 J_n(k_1 a) J_n'(k_2 a) - k_1 J_n(k_2 a) J_n'(k_1 a)}{k_1 J_n(k_2 a) H_n^{(1)'}(k_1 a) - k_2 J_n'(k_2 a) H_n^{(1)}(k_1 a)} , \quad (15)$$

where a is the radius of the air plasma column.
The scattered wave field is given by

$$E_s = E_o\, e^{-j\omega t} \sum_{o}^{\infty} \varepsilon_n (j)^n A_n H_n^{(1)}(k_1 r)\cos(n\theta). \qquad (16)$$

The ratio of the scattered power to the incident power is given by [8]

$$S(\theta) = \frac{|E_s|^2}{|E_i|^2} = \left| \sum_{o}^{\infty} \varepsilon_n (j)^n A_n H_n^{(1)}(k_1 r)\cos(n\theta) \right|^2 . \qquad (17)$$

The total scattering and back-scattering cross-section are respectively given by

$$\sigma = \frac{4}{k_1} \sum_{o}^{\infty} \varepsilon_n A_n A_n^* ,$$

and

$$\sigma_b(\omega) = \frac{4}{k_1} \left| \sum_{o}^{\infty} (-1)^n \varepsilon_n A_n \right|^2 .$$

III. Numerical Results

The total and back-scattering cross-sections are computed in the 10^8 - 10^{11} Hz frequency range, for various plasma number densities, and various thicknesses of the air plasma layer. The results are presented as plots of σ and σ_b versus frequency.

Figure 2 is a plot of σ and σ_b when the plasma is OFF. This plot allows us to compare the plasma effects on the scattered power as compared to a bare conducting cylinder case.

Figure 3 is a plot of the total scattering cross-section of a 10 cm radius cylinder covered by a 3 cm thick layer of air plasma. This figure shows that as the plasma number density increases, a pronounced minimum and maximum appear, at frequencies which shift toward the left of the frequency scale.

Figure 4 shows that the thickness of the air plasma layer plays a significant role in the structure of the total scattering cross-section plot: As the thickness increases, the minimum and maximum of the plot become more pronounced.

Figure 5 and 6 show that both the number density and plasma thickness have significant effects on the back-scattering cross-section: The higher the number density and the thicker the plasma, the less σ_b resembles the structure of Figure 2 (bare cylinder). The plot of σ_b displays an increasing number of maxima and minima , which seem to occur randomly along the frequency axis.

Figure 7 is a plot of σ versus frequency of a column of air plasma (without the conducting cylinder.) Along most of the frequency axis, σ is a decreasing function of the wave frequency, and an increasing function of the number density. σ is also an increasing function of the plasma thickness.

Figure 8 shows that σ_b has an average value which decreases with frequency and increases with plasma number density and thickness. However, σ_b displays several peaks at various frequencies especially for higher plasma number density and thickness.

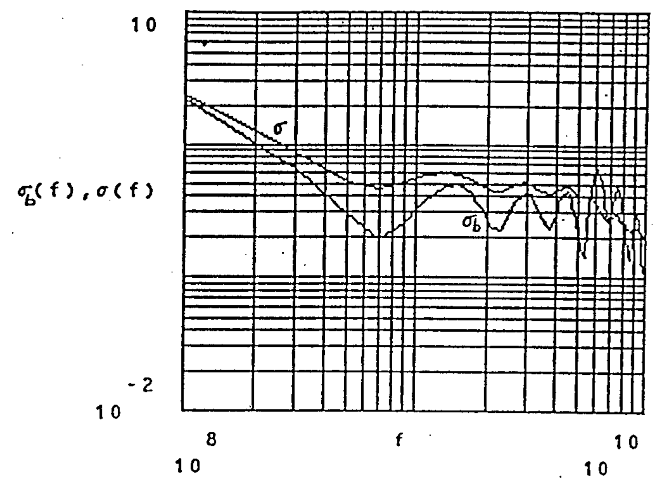

Fig. 2. Back-scattering cross-section and total scattering cross-section (in m) of a 10 cm radius conducting cylinder (Plasma is OFF), versus frequency (in Hz).

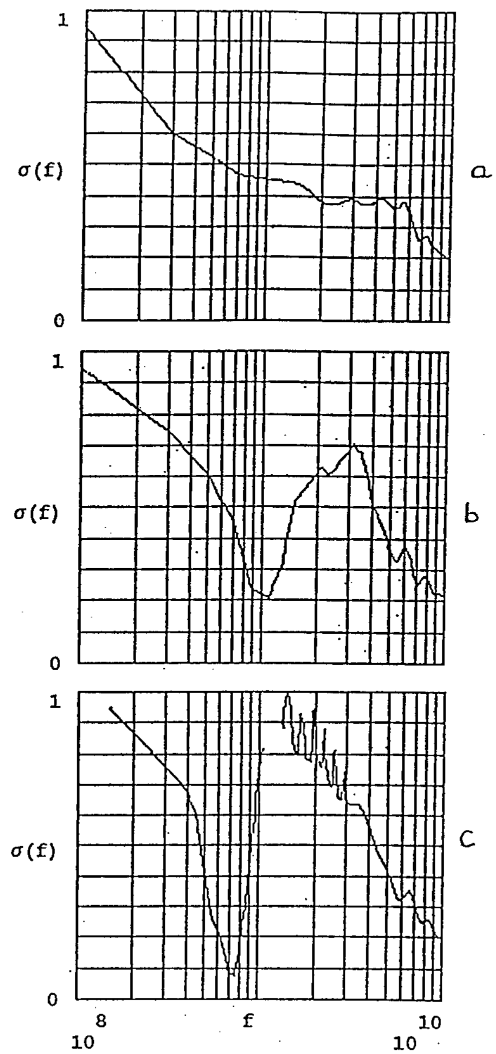

Fig. 3. Total scattering cross-section (in m) versus frequency, (in Hz) for cylinder of 10 cm radius covered by a 3 cm plasma layer with a) $n = 10^{13}$ cm^{-3}; b) $n = 2 10^{13}$ cm^{-3}; and c) $n = 3 10^{13}$ cm^{-3}.

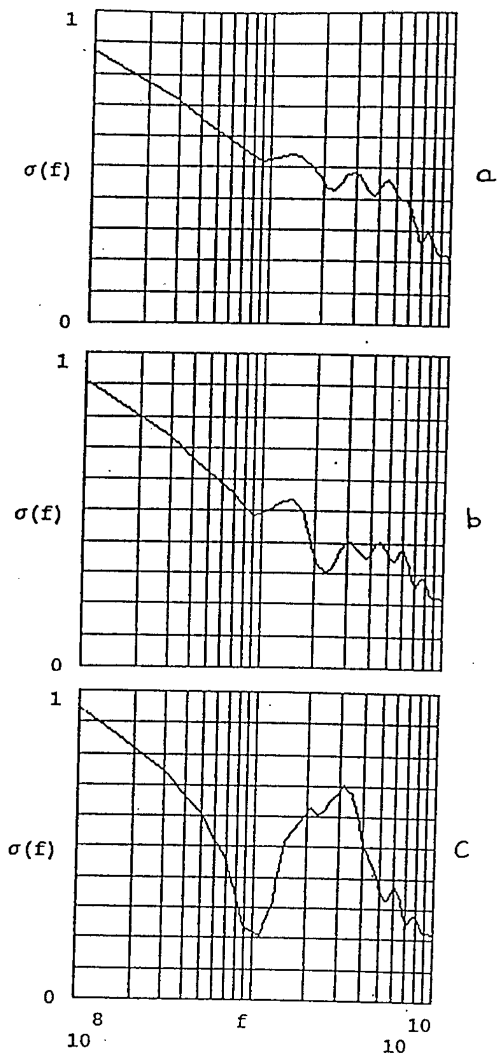

Fig. 4. Total scattering cross-section (in m) versus frequency (in Hz) for a cylinder of 10 cm radius covered by a plasma layer with n = 210^{13} cm^{-3}, and a thickness of a) 1 cm; b) 2 cm; and c) 3 cm.

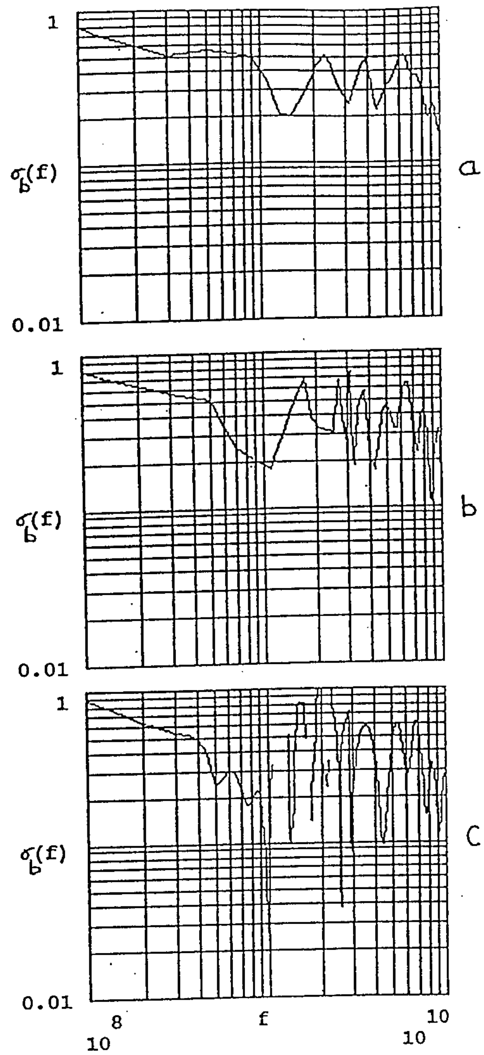

Fig. 5. Back-scattering cross-section (in m) versus frequency (in Hz) for a cylinder of 10 cm radius covered by a 3 cm plasma layer with a) $n = 10^{13}$ cm^{-3}; b) $n = 2 10^{13}$ cm^{-3}; and c) $n = 3 10^{13}$ cm^{-3}.

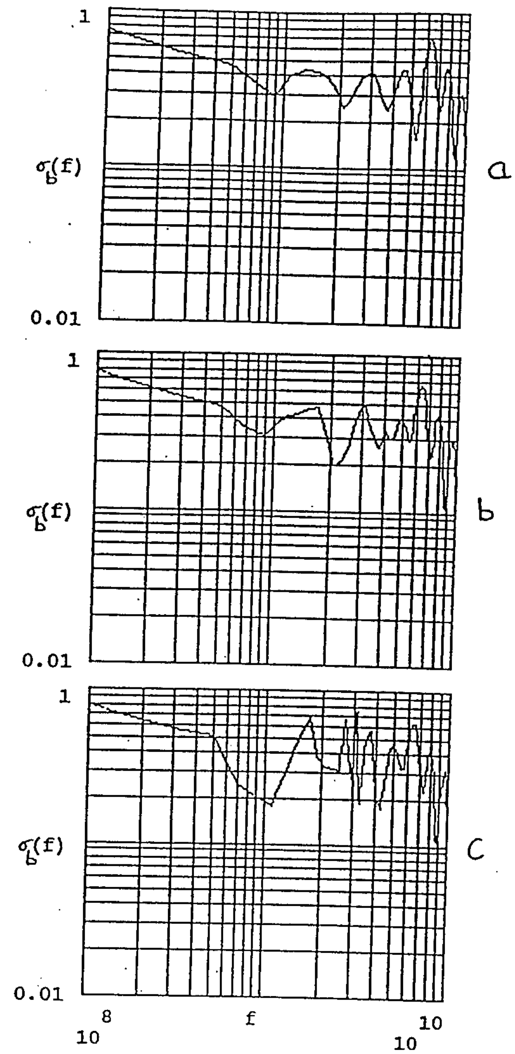

Fig. 6. Back-scattering cross-section (in m) versus frequency (in Hz) for a cylinder of 10 cm radius covered by a plasma layer with $n = 2 10^{13}$ cm^{-3}, and a thickness of a) 1 cm; b) 2 cm; and c) 3 cm.

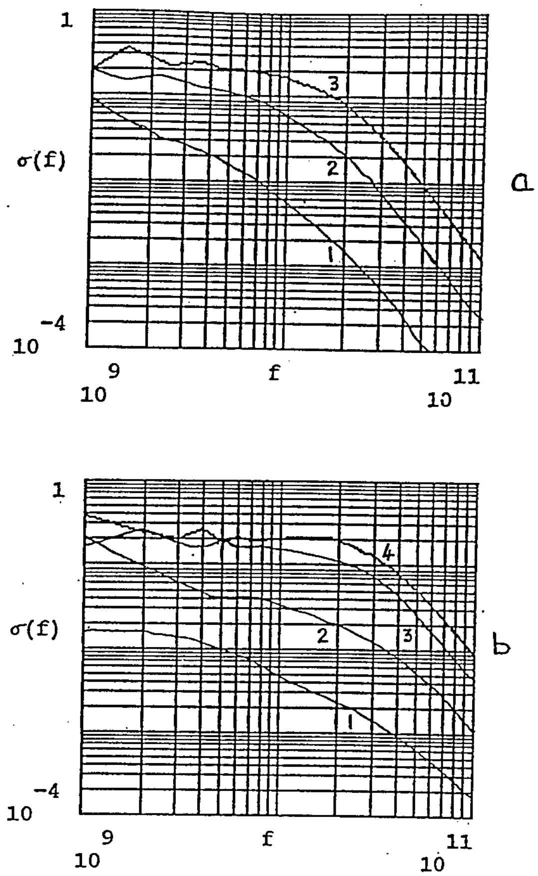

Fig. 7. total scattering cross-section (in m) versus frequency (in Hz) of an air plasma column: a) column radius is 3 cm and (1) $n = 10^{13}$ cm^{-3}; (2) $n = 2 10^{13}$ cm^{-3}; (3) $n = 3 10^{13}$ cm^{-3}. b) $n = 5 10^{13}$ cm^{-3} and column radius is (1) 0.5 cm; (2) 1 cm; (3) 2 cm, and (4) 3 cm.

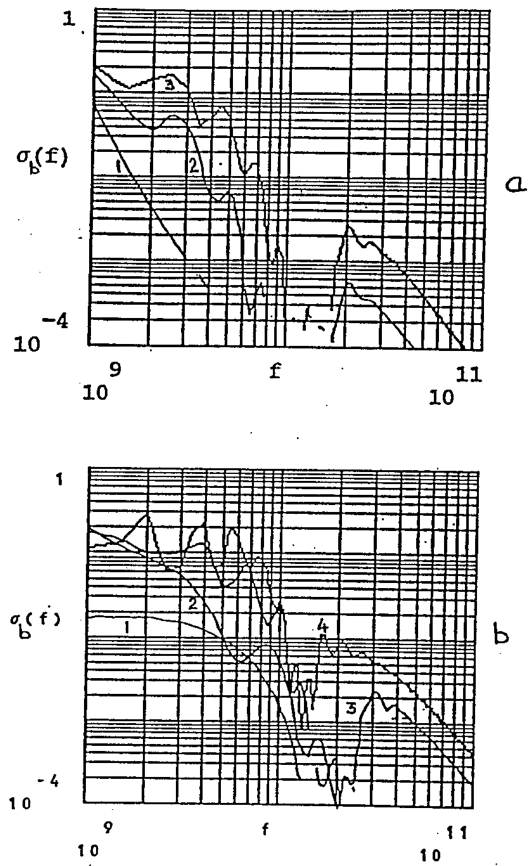

Fig. 8. Back-scattering cross-section (in m) versus frequency (in Hz) of an air plasma column: a) column radius is 3 cm and (1) n = 10^{13} cm^{-3}; (2) n = $2 10^{13}$ cm^{-3} ; (3) n = $3 10^{13}$ cm^{-3}. b) n = $5 10^{13}$ cm^{-3} and column radius is (1) 0.5 cm; (2) 1 cm; (3) 2 cm; and (4) 3 cm.

IV. Conclusion

The total scattering, σ, and back-scattering, σ_b, cross-sections of a conducting cylinder covered by a layer of an air plasma are computed. The results show that the plasma number density and thickness are factors which determine the functional dependence of σ and σ_b in the 10^8 - 10^{11} frequency range. The case of an air plasma column is also analyzed. σ and σ_b are computed and their dependence on the plasma number density and thickness is also presented.

Acknowledgment

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Sterilization of Contaminated Matter with an Atmospheric Pressure Plasma

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***Abstract*—The primary methods now used to sterilize contaminated media (infectious waste, tools, liquids, ...) are exposure to UV radiation, incineration, or autoclaving. These methods have recently raised public controversies concerning their environmental effects and other health issues. In an attempt to eliminate these drawbacks, new approaches based on different technologies are being investigated. Irradiation by electron beam is an example of such new sterilization means. This paper describes a new sterilization technique which has recently been developed at the Plasma Science Laboratory of the University of Tennessee. This technique involves the generation and use of a glow discharge plasma at atmospheric pressure. The fact that no pressurized or vacuum system is needed in this apparatus makes this sterilization method practical, economical, and technically very attractive. The plasma, in which the medium to be sterilized is immersed, is generated between two insulated metal plate electrodes powered by a low-frequency RF supply. Inside the plasma, the medium is constantly bombarded by charged particles, active free radicals, and radiation (including UV radiation). It is found that an exposure of a few minutes is sufficient to destroy the microorganisms living in the exposed medium, without damaging the medium itself.**

I. Introduction

IN THIS PAPER, we describe a novel sterilization method which uses a uniform glow discharge plasma generated at atmospheric pressure [1], [2]. We first start by an overview of the various sterilization methods now in use, then we present the apparatus which generates the discharge, and last we describe some sterilization tests which clearly show the effectiveness of this new method.

Sterilization by the atmospheric pressure glow discharge is found to be very effective in terms of the length of time of exposure and complete destruction of living microorganisms [3]. Also, since the power density is not high, the plasma does not damage the medium where the unwanted microorganizms live. This could be very attractive in applications where medium preservation is an issue. Some examples are food (solid or liquid) sterilization, pharmaceutical applications, and environmental applications (soil treatment, for example). Other applications where destruction of the medium is not a problem (or desired) would be waste treatment, sterilization of medical infectious waste, etc. Finally, this method could be used to sterilize reusable tools (metallic, plastic, cloth, ...) such as medical or beauty parlor tools.

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II. Methods of Sterilization

Sterilization is the process of destroying the life of unwanted organisms. Generally, it also damages the medium where those organizms live. The agents which cause sterilization range from heat to lethal chemicals to physical processes [4], [5].

A. Sterilization by Heat

This can be achieved by moist or dry heat. Moist heat generally used for sterilization is saturated steam. Pressurized steam has the advantage of sterilizing penetrable materials and exposed surfaces quickly. Dry heat requires high temperature and longer times, but will penetrate a wide range of materials.

Sterilization by steam is only applicable if damage by heat and moisture is not a problem. The apparatus using pressurized steam is called an autoclave, where a pressure of 15 psi, a temperature of 121°C, and exposure times of about 20 min are typical.

Examples of sterilization by dry heat are infrared radiation and incineration. The penetration of the heat caused by the infrared radiation at the surface of the material is by means of conduction. On the other hand, incineration is a very effective sterilization method, but destructive to the medium. If hot air is used, it is estimated that at a temperature of 170°C, it takes approximately 60 min to get complete sterilization [4]. Dry heat is well suited for the sterilization of oils, powders, and glassware.

B. Sterilization by Gases

Some gases are well suited for sterilization purposes. The most widely used gas is ethylene oxide. It is mostly used in medical applications to sterilize items which are heat sensitive. Ethylene oxide reacts with many chemicals such as alcohols, amines, organic acids, and amides. Ethylene oxide is generally used in combination with carbon dioxide to reduce fire hazards. The way by which ethylene oxide reacts with bacteria is a process referred to as alkylation [4]. Alkylation is the replacement of a hydrogen atom by an alkyl group. In a bacterial cell this substitution is lethal.

An ethylene oxide sterilizer is basically a pressure vessel with an air supply port, an evacuation port, an ethylene oxide supply port, and a steam supply port. Other gases such as formaldehyde and ozone are widely used [5]. Ozone is mainly used for the disinfection of water and for the preservation of food from spoilage [5]. The effectiveness of ozone as a bactericidal is due to its interference with cellular respiration.

C. Sterilization by Radiation

Sterilization by radiation can be achieved by using electromagnetic radiation (ionizing and nonionizing), or particle radiation.

1) Electromagnetic (EM) Radiation: The destruction of microorganisms can be achieved by using microwaves, ultraviolet, gamma-rays, and X-rays. Each type of EM radiation affects living cells in different ways. Electromagnetic ionizing radiation, for example, affects microorganisms by creating pairs of negative and positive electrons, ions, free radicals, and activated molecules. Since no heat is produced in the process, this form of sterilization is termed cold sterilization [4].

Ionizing radiation is applied to the preservation of food, treatment of sewage and industrial sludge, and extensively in the sterilization of medical products. The lethal effect of radiation on a microorganisms is due to lesions caused by direct energy transfer between the radiation and target molecules. Ionizing radiation, for example, causes a variety of physical and biochemical effects on the DNA of the target cells [4]. Most types of radiation interfere on the molecular scale with cell metabolism. These interferences induce a breakdown or changes in the structure of essential metabolites, causing the death of the cell.

2) Particle Radiation: Even though, α-particle and protons could be used, electrons are the usual choice in this method. Since β-particles from radioactive sources cannot penetrate too far, accelerated electrons are used. Electron beam irradiation is presently an active research area for the treatment of infectious medical waste.

3) Ultraviolet Radiation: Sunlight has been known as a sterilizing agent for hundreds of years. It provides some degree of protection from infection with pathogenic microorganisms. Ultraviolet radiation is most effective against bacteria in the 2300 Å–2400 Å range [5]. Ultraviolet radiation is not ionizing. Its lethality comes from exciting large molecules the size of proteins. It appears that UV induces changes in the cellular nucleic acids structure. It is also suggested that UV irradiation of the cellular DNA results in the formation of photoproducts which may have a detrimental effect on the DNA structure [4].

In practice, the UV radiation is produced by low-pressure mercury vapor lamps made of quartz tubes. They emit 95% of their total radiation at 2537 Å.

D. Sterilization by Filtration

Filtration as a means of sterilization is used in the pharmaceutical industry and in the purification of public water supplies. Filtration is not strictly a sterilization procedure since it does not remove or kill all microorganisms. The filters available for sterilization purposes are made mostly of unglazed porcelain, asbestos, or sintered glass. These filters come in disc, candle, or sheet forms [5].

III. The Atmospheric Pressure Glow Discharge

Uniform steady-state glow discharges are much easier to generate at pressures below one atmosphere. However, to decrease the pressure, one has to use some form of vacuum system. This makes access to the inside of the apparatus somehow tedious and time consuming. One has to bleed air into the system first, open up the vacuum port, do the desired task or repair, close the system back up, and pump it down to the required pressure.

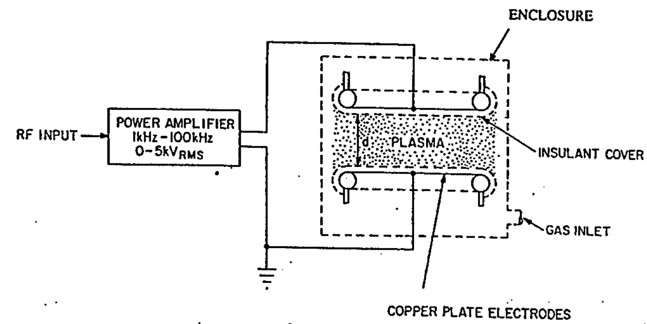

Fig. 1. The atmospheric pressure glow discharge generator.

A uniform steady-state glow discharge generated at atmospheric pressure eliminates the need for a vacuum system, thus making the process much more practical and much less expensive.

At the Plasma Science Laboratory of the University of Tennessee, we have developed an apparatus which can routinely generate a uniform steady-state glow discharge at atmospheric pressure [1], [2]. Fig. 1 is a schematic of such a device. It consists of a plexiglass enclosure containing two insulated electrodes separated by a variable distance d. The plasma is generated by applying an RF voltage (1 to 5 KV) between the two electrodes. It is found that if the frequency of the RF voltage falls in a range around a critical frequency f_o, a uniform glow discharge fills the entire space between the electrodes [1]. The critical frequency f_o is given by [1]

$$f_o = \frac{eV_{\mathrm{rms}}}{\pi m \nu_c d^2} \tag{1}$$

where V_{rms} is the rms value of the voltage between the two electrodes, ν_c is the collision frequency (dominated by electron–neutral collisions and is in the 10^{12} Hz range), and d is the distance between the electrodes. The rms voltage necessary to start the discharge depends on the type of gas between the electrodes and the distance d. For Helium gas and a 1–5 cm gap between the electrodes, f_o is in the few KHz range. Fig. 2 shows typical waveforms of the voltage, V, and the current, I, when the discharge is generated. The phase shift, θ, between V and I, is found to depend on the frequency of the RF voltage [1], [2]. Fig. 3 is a plot of θ versus f. The power deposited in the plasma is a function of the value of RF voltage and its frequency [1], [6]. Figs. 4 and 5 are, respectively, the plots of the power density versus frequency and power density versus V_{rms}.

IV. Sterilization Application

The plasma generated by the atmospheric pressure glow discharge described above is a source of electrons, ions, excited atoms and molecules, active free radicals, and radiation (from the infrared to the ultraviolet). This fact qualifies it as a unique sterilization agent. This section presents some

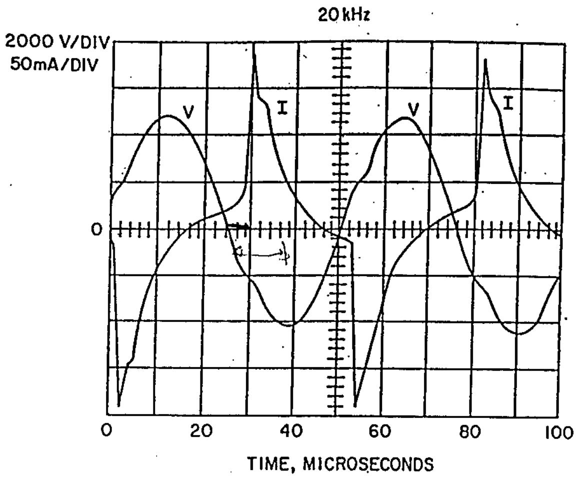

Fig. 2. Typical voltage and current waveforms.

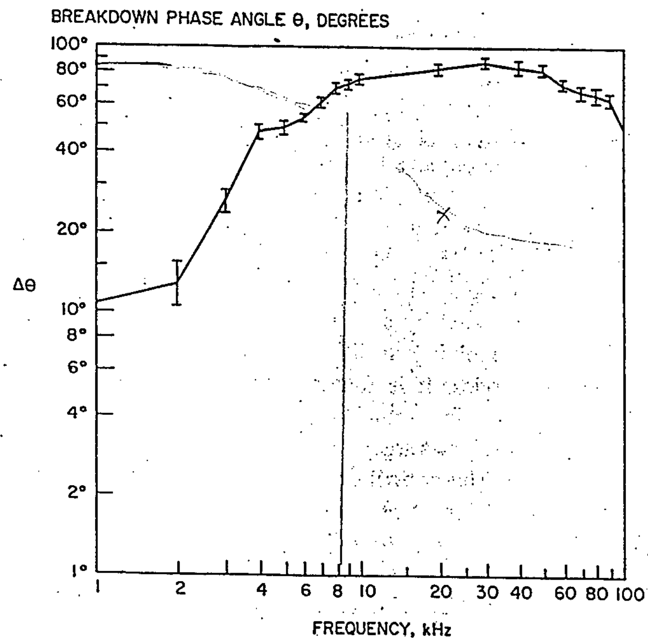

Fig. 3. Voltage–current phase shift as a function of the driving frequency.

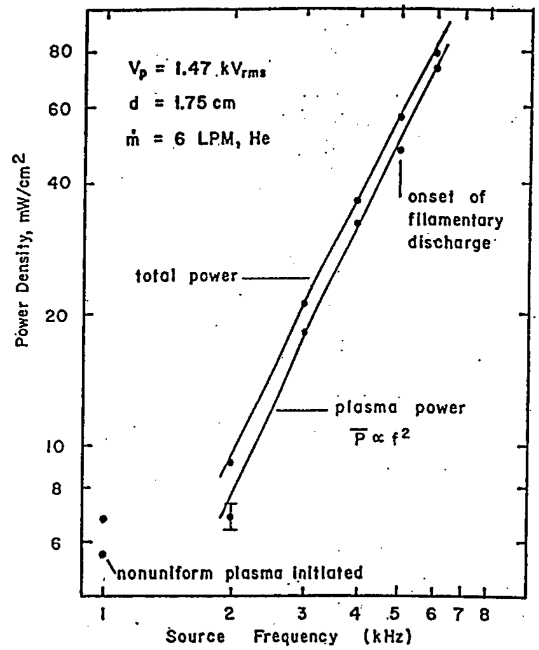

Fig. 4. Power density versus driving frequency.

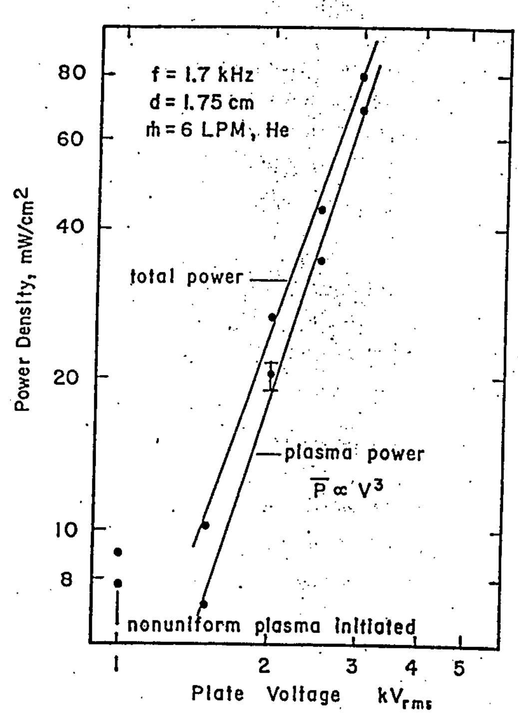

Fig. 5. Power density versus the rms value of the electrode voltage.

laboratory tests which show that this type of plasma does sterilize matter, and does it effectively and in a practical manner. Since this sterilization method differs substantially from autoclaving and incineration (no excessive heat and no damage to the medium), a paired comparison is not needed. However, a comparison with UV radiation tests is presented.

A. Experimental Procedure

The glow discharge was generated between two plate electrodes, with only one insulated electrode. Helium gas at atmospheric pressure was used (other gases such as air, argon, carbon dioxide, etc. could also be used). The rms voltage between the electrodes was 5 KV, the frequency range in which a stable steady-state glow discharge was obtained was between 300 Hz and 4 KHz, and the distance, d, between the electrodes was about 1 cm. The medium to be sterilized was in a glass petri dish and placed on top of the insulated lower electrode (see Fig. 6). The plasma was turned on after the petri dish was securely put in place. Samples of the medium were extracted from the petri dish at equally timed intervals. The plasma was turned off before sampling.

The medium used was a "yeast extract polypeptone glucose" solution (YEPG). The YEPG medium was contaminated by *Pseudomonas fluorescens* bacteria, strain HK 44. The cells concentration was $4 \cdot 10^6$/mL. Fifteen milliliters of the contaminated YEPG were placed in a Petri dish and 100 μL samples were taken in five minute intervals. The treated

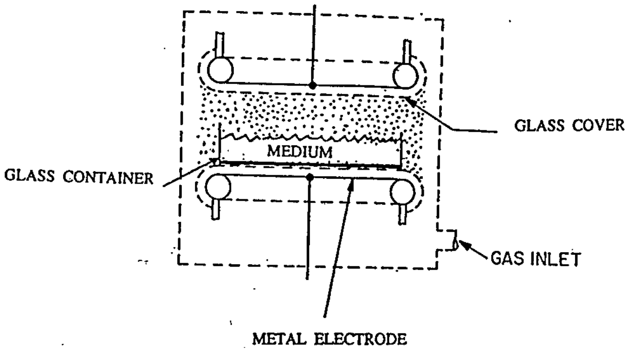

Fig. 6. Contaminated medium being treated by plasma.

TABLE I
VARIOUS STERILIZATION METHODS AND THEIR CHARACTERISTICS

Charac. / Methods	Heat	Pressure	Vacuum	Exposure Time	Sterilization Effectiveness	Damage to the Medium	Environmentally Friendly
Incineration	Yes	No	No	> 20 min	Good	Yes	No
Autoclaving	Yes	Yes	No	> 20 min	Good	Yes	No
U.V. irradiation	No	No	No	< 20 min	Good	—	Yes
Electron beam irradiation	No	No	Yes	—	Good	—	Yes
Glow Discharge at One Atmosphere	No	No	No	< 10 min	Good	No	Yes
Filtration	No	No	No	NA	—	No	Yes

samples were then placed in test tubes containing 9.9 mL of a sterile phosphate buffer. The samples were incubated for 48 h at 30°C and a colony count was then performed.

B. Results and Comparison with UV Tests

After the incubation process, a colony count was performed on the samples. It was found that the 10 min, 15 min, and 20 min samples underwent complete sterilization. No bacteria cells were left alive.

Similar tests under the same conditions as above were conducted by exposing a contaminated YEPG medium to UV radiation. It was found that a 10 min exposure time of the samples to UV radiation was not enough to achieve complete sterilization. A cell count showed that the 10 min sample had 2000 cells/mL which were alive. This result led us to the conclusions that sterilization by plasma could be more effective and that the UV radiation generated by the plasma was not the only agent of sterilization. Charged particles and active free radicals appeared to play a significant role.

Table I shows the characteristics of some of the sterilization methods now in use and the one atmosphere glow discharge. Sterilization by the one atmosphere glow discharge clearly has very attractive features in terms of practicality and effectiveness.

V. CONCLUSIONS

This paper shows that a plasma generated at atmospheric pressure is a very effective sterilization agent. Certainly more tests and an in-depth study of this process are needed, but since this paper is not aimed at a readership of biologists, but at plasma scientists, it is enough, as a preliminary step, to show that the glow discharge at atmospheric pressure is a powerful sterilization agent. More "biology" oriented work is underway and will be published in an appropriate journal at a later time. Some of the questions to be answered are: which plasma regime is the most effective (uniform of filamentary)? What is the minimum plasma power density sufficient to kill unwanted microorganisms? Which physical process plays the dominant sterilization role? What biological and chemical processes induce the death of the cells? Which type of gas is more desirable for a particular application? Some of these questions will be more appropriately answered by biologists after more work is done on this method. However, it appears that plasma-aided sterilization requires short exposure times, is very practical and inexpensive, and is environmentally friendly. Applications could range from medical use (sterilization of reusable medical tools) to research laboratory use to environmental use such as soil and water treatment.

ACKNOWLEDGMENT

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ATTENUATION OF ELECTROMAGNETIC WAVES BY A PLASMA LAYER AT ATMOSPHERIC PRESSURE

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Abstract

Plasma layers at atmospheric pressure, are good broad band absorbers of electromagnetic radiation. However, to get substantial attenuations, two parameters have to be optimized. These are the plasma number density, and the thickness of the plasma layer. It is found that in order to be an effective attenuator of microwave radiation, a plasma layer has to have a number density in the 10^{13} cm^{-3} range, and a thickness equal or larger than the wavelength of the incident wave. However, as the frequency increases, the amount of attenuation tends to reach a limiting value directly proportional to the number density.

Key words: Plasma, Layer, Attenuation, Microwave, Atmospheric pressure.

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I. Introduction

Plasmas at atmospheric pressure are highly collisional. Unlike low pressure plasmas, their refractive index is greater than unity across a frequency band in the microwave range, and no sharp propagation cut-off at intermediate frequencies is observed [1]. Consequently, if a wave travels through a layer of plasma at atmospheric pressure, it undergoes some level of absorption regardless if its frequency is below or above the plasma frequency. At frequencies higher than a characteristic frequency $\omega_s = \frac{\omega_{pe}^2}{\nu}$ (where ω_{pe} is the plasma frequency and ν the collision frequency) the reduction in the magnitude of the transmitted wave is more due to absorption, through collisional momentum transfer, than to reflection or scattering of the incident wave [2]. However, only number densities at or above 10^{13} cm^{-3} result in substantial attenuation magnitudes. It is also found that although the thickness of the plasma layer is important, the attenuation ultimately reaches a saturation plateau, at high frequencies. The dB value of the attenuation corresponding to the plateau is directly proportional to the plasma number density, and to the thickness of the plasma layer.

II. Total Attenuation

Figure 1 illustrates the case of a wave propagating through air, then encountering a layer of uniform air plasma, of thickness d. The grazing angle is defined as $\Psi = 90° - \theta_i$, where θ_i is the incident angle. It is assumed that the plasma is a lossy dielectric, and the thickness of the plasma layer is comparable or larger than the wavelength of the incident wave. After undergoing some reflection and scattering, the wave is further attenuated as it crosses the plasma layer. The transmitted wave emerges from the air plasma layer with a substantially reduced field.

As was shown in previous work [1] - [5], atmospheric pressure plasmas are highly collisional, and good broad

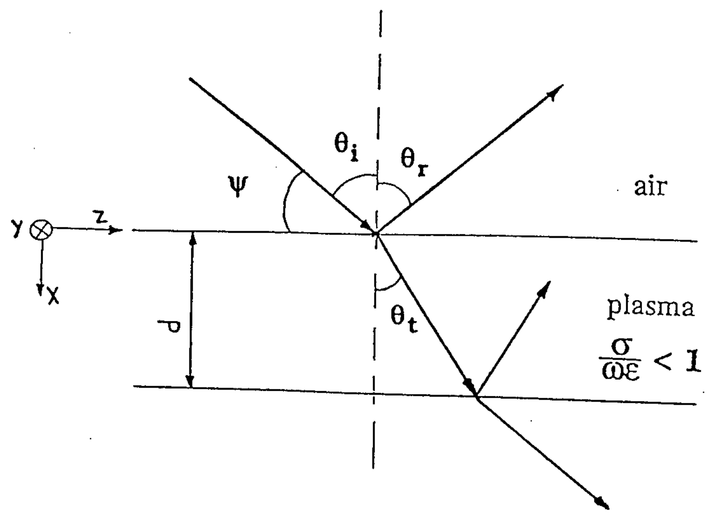

Fig. 1 Wave propagating through air, then an air plasma layer.

band absorbers. Their refractive index, μ, and their attenuation index, X, can be expressed as [2], [6],

$$\mu = \left\{ \frac{1}{2} + \frac{1}{2}\left[1 + \left(\frac{\omega_s}{\omega} \right)^2 \right]^{1/2} \right\}^{1/2}, \tag{1}$$

and

$$X = \left\{ -\frac{1}{2} + \frac{1}{2}\left[1 + \left(\frac{\omega_s}{\omega} \right)^2 \right]^{1/2} \right\}^{1/2}, \tag{2}$$

where the frequency ω_s is given by

$$\omega_s = \frac{\omega_{pe}^2}{\nu}, \tag{3}$$

where ω_{pe} is the plasma frequency, and ν is the collision frequency ($\nu \sim 1$ THz). The attenuation coefficient, α, is given by

$$\alpha = \frac{\omega}{c} X, \tag{4}$$

where ω is the wave frequency, and c the speed of light.

An electromagnetic wave crossing a uniform layer of atmospheric pressure plasma of thickness d, will have its field attenuated by a factor, T, given by

$$T = \mathrm{Exp}\left(-\alpha \frac{d}{\cos\theta_t} \right), \tag{5}$$

where θ_t is the transmission angle. Using snell's law, the angle θ_t can be expressed as a function of the referative index, and the grazing angle as follows

$$\theta_t = \sin^{-1}\left(\frac{\cos \psi}{\mu}\right). \tag{6}$$

For frequencies much higher than ω_s ($\omega >> \omega_s$) the attenuation index, X, and the attenuation coefficient, α, can be approximated by [1]

$$X = \frac{ne^2}{4\pi\varepsilon_o m\nu f}, \tag{7}$$

and

$$\alpha = \frac{ne^2}{2\,\varepsilon_o mc\nu}, \tag{8}$$

where $\omega_{pe}^2 = \frac{ne^2}{m\,\varepsilon_o}$ was used.

III. Data Analysis

Figure 2 shows the total attenuation, T, in dB, versus the wave frequency, for plasma number densities in the 10^{12} cm^{-3} range, and a plasma layer thickness of 3 cm. It can be easily concluded that attenuation reaches a substantial level only when the plasma number density, n, approaches 10^{13} cm^{-3}. Figure 3 and Figure 4 further emphasize this fact.Also, as predicted by Equation (8), for

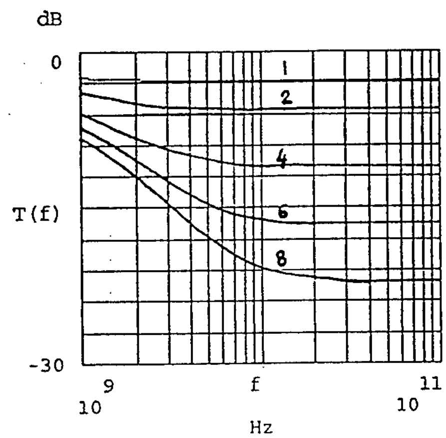

Fig. 2 Total attenuation (in dB) versus frequency (in Hz) for a grazing angle $\Psi = 30°$, a layer thickness d= 3 cm, and 1. $n = 10^{12}$ cm^{-3}; 2. $n = 2\ 10^{12}$ cm^{-3}; 4. $n = 4\ 10^{12}$ cm^{-3}; 6. $n = 6\ 10^{12}$ cm^{-3}; 8. $n = 8\ 10^{12}$ cm^{-3}.

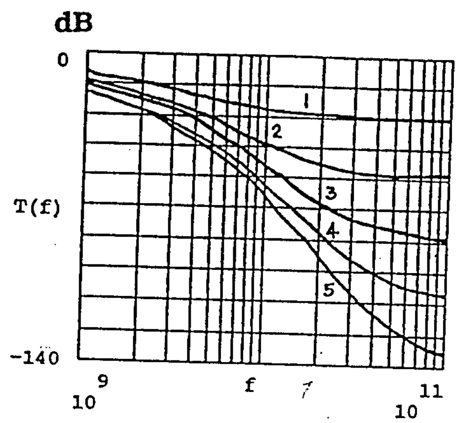

Fig. 3 Total attenuation (in dB) versus frequency (in Hz) for a grazing angle $\Psi = 30°$, a layer thickness d = 3 cm, and 1. $n = 10^{13}$ cm^{-3}; 2. $n = 2\ 10^{13}$ cm^{-3}; 3. $n = 3\ 10^{13}$ cm^{-3}; 4. $n = 4\ 10^{13}$ cm^{-3}; 5. $n = 5\ 10^{13}$ cm^{-3}.

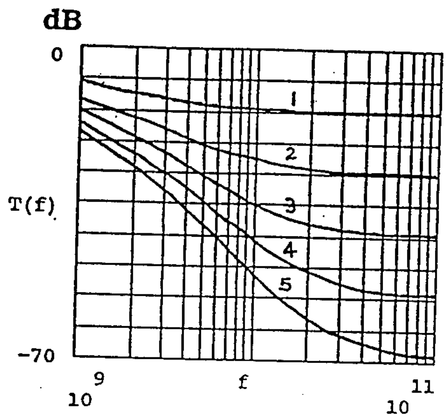

Fig. 4 Total attenuation (in dB) versus frequency (in Hz) for a grazing angle $\Psi = 90°$, a layer thickness d = 3 cm, and 1. $n = 10^{13}\ cm^{-3}$; 2. $n = 2\ 10^{13}\ cm^{-3}$; 3. $n = 3\ 10^{13}\ cm^{-3}$; 4. $n = 4\ 10^{13}\ cm^{-3}$; 5. $n = 5\ 10^{15}\ cm^{-3}$.

$\omega \gg \omega_s$ the level of attenuation becomes independent of the wave frequency, and directly proportional to the plasma number density. Figure 3 shows that as the number density reaches the 10^{13} cm^{-3} range, attenuation increases to high levels. For example, at f = 10 GHz (λ = d = 3 cm) the incident power is attenuated by about 60 dB at n = 5 10^{13} cm^{-3}. However as the frequency increases and the wavelength becomes shorter than the plasma layer thickness, the attenuation reaches values up to 130 dB at f = 100 GHz. Figure 4 shows that at normal incidence, the wave is less attenuated than oblique incidence, since it travels a shorter distance through the plasma. This fact is better illustrated by Fig. 5, which shows that at low grazing angles, the attenuation is substantially higher. Under this condition the wave also undergoes increased reflection [1] - [3].

Figure 6 shows the importance of the thickness of the plasma layer for increased attenuations. This is especially significant, since the attenuation saturates at higher frequencies, which renders its value independent on the d/λ ratio. However, for a fixed frequency, the dB value of the attenuation is directly proportional to the plasma layer thickness.

IV. Conclusion

This paper showed that if a plasma layer at atmospheric pressure is to be used as an attenuator of electromagnetic waves, two parameters have to be optimized: The plasma number density, and the thickness of the plasma layer. If the number density, n, is in the low 10^{12} cm^{-3} range, the plasma is practically transparent to microwaves at frequencies higher than the characteristic frequency ω_s. Only when n approaches and surpasses 10^{13} cm^{-3} would substantial attenuation occur. However, the thickness of the plasma layer has to be at least comparable

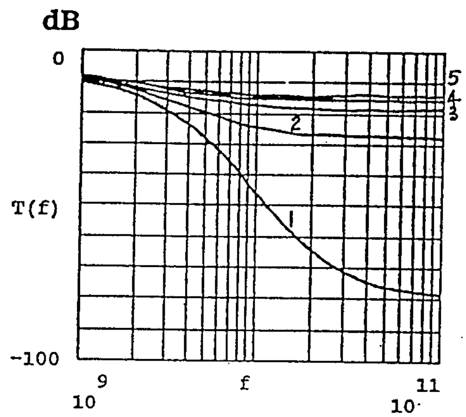

Fig. 5 Total attenuation (in dB) versus frequency (in Hz) for n = 10^{13} cm^{-3}, a layer thickness of d = 3 cm, and 1. Ψ = 10°; 2. Ψ = 30°; 3. Ψ = 50°; 4. Ψ = 70°; 5. Ψ = 90°.

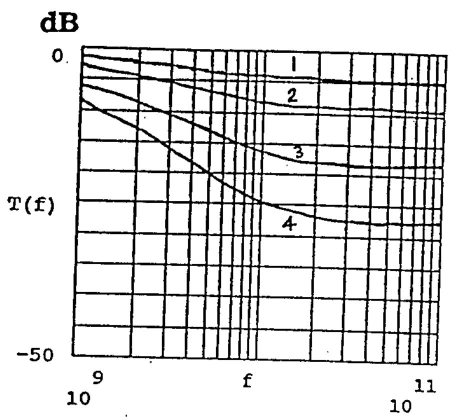

Fig. 6 Total attenuation (in dB) versus frequency (in Hz) for a grazing angle $\Psi = 30°$, $n = 10^{13}$ cm^{-3}, and a layer thickness of 1. d = 0.5 cm; 2. d = 1 cm; 3. d = 2 cm; 4. d = 3 cm.

to the wavelength of the incident wave, if high attenuation values are to be maintained.

Acknowledgement

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THE CURRENT-VOLTAGE RELATIONSHIP IN THE GLOW DISCHARGE AT ATMOSPHERIC PRESSURE

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ABSTRACT

A glow discharge at atmospheric pressure (GDAP) can be generated between two insulated electrodes excited by an R.F. voltage if the frequency is within a certain range (few KHz). The current crossing the gap between the two electrodes is a function of the applied voltage, the frequency, and various processes occurring within the discharge, such as the rates of electron production and attachment. In this paper we derive two non-linear differential equations for the current and the number density which can be solved using a seeded iteration method. The results are compared to experimental data, and good agreement is reached. Our computer simulation and experimental results also show that if the frequency of the applied voltage is greater than 20 KHz, the discharge operates in a different mode clearly distinct from the well known lower frequency regime ($f < 20$ KHz). In this new mode, the current ceases to be impulsive, and the average power needed to maintain a uniform stable glow discharge can be substantially reduced.

I. INTRODUCTION

The glow discharge at atmospheric present (GDAP) [1], [2], has recently been widely used in a variety of applications, such as surface modification [1], [3], and biological [4], [5] applications. It is therefore important to derive from first principles a straight forward analytical relationship between the driving R.F. voltage and the resulting current and number density. Taking into account the rates of production and loss of particles, we derived two interrelated non-linear first order differential equations which can be easily solved by the seeded iteration method. These two equations directly relate the current, voltage and number density, and when solved produce the time evolution of the current and density, starting from some assumed initial conditions. The results are then compared to experimental data taken on a GDAP reactor. Very good agreement is reached.

II. MODEL

The electrical model for a GDAP type reactor is simply a resistor in series with a capacitor, (See Fig. 1). The equation relating the voltage to the current is

$$V(t) = R_p i + \frac{1}{C_d} \int i dt \ , \qquad (1)$$

where R_p is the discharge resistance, C_d the dielectric capacitance, and V(t) the applied voltage, given by

$$V(t) = V_o \sin(\omega t)$$

Taking the derivative of Equation (1) we get

$$\frac{dV}{dt} = \frac{dR_p}{dt} i + R_p \frac{di}{dt} + \frac{i}{C_d} . \tag{2}$$

The resistivity of the plasma is given by,

$$\rho = \frac{m\nu_c}{e^2 n} , \tag{3}$$

where ν_c and n are respectively the collision frequency and the number density. The resistance R_p can therefore be expressed as

$$R_p = \frac{K_1}{n} , \tag{4}$$

where K_1 is given by

$$K_1 = \frac{m\nu_c}{e^2} \cdot \frac{d}{A} , \tag{5}$$

where d and A are respectively the gap distance between the electrodes and A the area of one electrode. Substituting Equation (4) into Equation (2) we get

$$\frac{dV}{dt} = - \frac{K_1}{n^2} \frac{dn}{dt} i + \frac{K_1}{n} \frac{di}{dt} + \frac{i}{C_d} , \tag{6}$$

or

$$\frac{di}{dt} = \frac{n}{K_1} \frac{dV}{dt} + \left(\frac{1}{n} \frac{dn}{dt} - \frac{n}{K_1 C_d} \right) i , \tag{7}$$

The rate of change of the number density, $\frac{dn}{dt}$, is due to the production and loss of particles. This can be expressed as

$$\frac{dn}{dt} = \left(\frac{dn}{dt}\right)_{prod} - \left(\frac{dn}{dt}\right)_{loss} \tag{8}$$

The production term is proportional to the power deposited in the plasma, P, which is given by

$$P = R_p i^2 .$$

Hence

$$\left(\frac{dn}{dt}\right)_{prod} = K_2 R_p i^2 , \tag{9}$$

where the constant K_2 is per Joule, per unit volume. Equation (9) is then expressed as follows

$$\left(\frac{dn}{dt}\right)_{prod} = K_1 K_2 \frac{i^2}{n} . \tag{10}$$

The loss term is given by

$$\left(\frac{dn}{dt}\right)_{loss} = K_3 n^2 . \tag{11}$$

The loss term in our model is due to bulk ion-electron recombinations in a non-electronegative gas such as helium. Other models may give other rates such as exponential decay. The rate of change of the number density is therefore given by

$$\frac{dn}{dt} = K_1 K_2 \frac{i^2}{n} - K_3 n^2 . \tag{12}$$

Substituting Equation (12) into Equation (7) we get

$$\frac{di}{dt} = \frac{n}{K_1}\frac{dV}{dt} + K_1 K_2 \frac{i^3}{n^2} - \left(K_3 + \frac{1}{K_1 C_d}\right) ni . \tag{13}$$

Equations (12) and (13) constitute two interdependent nonlinear equations which can be solved with the seeded iteration method, starting from some initial conditions i_o and n_o. The constants K_2 and K_3 are given by

$$K_2 \approx \frac{\text{cste} \cdot \text{ionization efficiency}}{\text{ionization potential} \cdot \text{volume}}$$
$$K_3 \approx \text{cste} \cdot \sigma \cdot v$$

where σ is the bulk recombination cross-section, and v the electrons mean velocity.

III. RESULTS

The following results are obtained for two insulated electrodes, 3 cm apart, with an area of 7.85 10^{-3} m^2 (copper disks of 10 cm diameter), a helium gas environment, a sinusoidal applied voltage of 6KV and 3.5KV peak, and a frequency of 15.6 KHz and 35.7 KHz. The electron-neutral collision frequency is 10^{12} Hz. An initial current of 1 μA and a initial ion density of 10^{10} m^{-3} are assumed. Setting up Equations (12) and (13) for simultaneous iteration we get

$$n_{j+1} = n_j + \left(K_1 K_2 \frac{i_j^2}{n_j} - K_3 n_j^2\right)\Delta t , \tag{14}$$

$$i_{j+1} = i_j + \left(\frac{n_j}{K_1} V_o \,\omega \cos \omega t_j + K_1 K_2 \frac{i_j^3}{n_j^2} - \left(K_3 + \frac{1}{K_1 C_d}\right) n_j i_j\right)\Delta t . \tag{15}$$

Equations (14) and (15) are solved and the voltage, current, density, and power are plotted versus time. Experimental runs under similar conditions as ones described above are carried out. Photographs of the scope traces representing the applied voltage and the current are taken and compared to the computational results. Fig. 2 is a schematic of the reactor on which measurements were taken. Figures 3, 4, 5, and 6 show that very good agreement between our calculations and measurements exists. The value of K_1, K_2, and K_3 used in our simulation are respectively 3.4 10^{19} Ω m^{-3}, 8.7 10^{17} J^{-1} m^{-3}, and 5 10^{-10} m^3 s^{-1}. These values were obtained after several iterations, and gave us the closest fit to our experimental measurements. Our experiments also show that the discharge operate in two different modes depending if the frequency is less or greater than 20 KHz. As two typical cases, two frequencies more than 20 KHz apart are presented (see Figures 4 and 6). For f = 15.6 KHz the current is of an impulsive nature, showing that the discharge turns on for few microseconds then is gradually extinguished until a new discharge is started at the negative half cycle. However, as the frequency increases and exceeds 20 KHz, the current assumes a more gradual variation, approaching a sinusoidal wave form. Figure 6 (f = 35.7 KHz) shows a current waveform that is quite distinct from that of Figure 4 (f = 15.6 KHz). To the best of the authors' knowledge this second mode of operation has not previously been reported in the literature. One very attractive feature of the "high-frequency" mode is the fact that substantially less input power is needed to maintain a uniform and stable discharge. This is well illustrated by Figures 7 and 8 which show the power versus time for two stable glow discharges, with comparable number densities, one at a frequency of 15.6 KHz (Fig. 7), and the other at a frequency of 35.7 KHz (Fig. 8). Finally, Figures 9 and 10 show the number density versus time for both modes. Comparison between these two cases leads to the conclusion that the higher frequency mode produces a more temporally uniform discharge since the number density doesn't oscillate around its mean as much as the lower frequency mode. It is also noted that although the input power for the f = 35.7 KHz case is about one third that of the f = 15.6 KHz case, the mean number density in the higher frequency case is a little greater than the lower frequency case.

The results discussed above lead us to conclude that the higher frequency mode produces more stable and uniform plasmas and is more efficient in terms of generating higher number densities with less input power.

IV. CONCLUSION

Two differential equations relating the voltage, current, and number density in a dielectrically controlled glow discharge have been derived. The rates of production and loss of particles have been taken into account. Good agreement between the experimentally measured current and that derived by our equations is reached. Both the experiment and the theory show that the discharge operates in two distinct modes depending on the driving frequency range. For frequencies below 20 KHz, the current waveform shows an impulse each half cycle, and the average power needed to maintain a stable discharge with a number density in the 10^{15} m^{-3} range is about 90 W. For frequencies greater that 20 KHz the current varies more smoothly, and the average power needed to maintain a stable discharge with a number density in the same range as above is about 35 W. The transition between the two modes is not sharp, but rather gradual (i.e. the 20 KHz is not a threshold frequency that sharply separates the two modes). The higher frequency mode appears to produce a more stable, more uniform discharge, and requires less input power to maintain a comparable number density as the lower frequency mode.

ACKNOWLEDGMENT

This work was supported in part by AFOSR contract F49620-95-1-0277.

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BIOGRAPHY

MOUNIR LAROUSSI

M. Laroussi was born in Sfax, Tunisia, on August 9, 1955. He received his B.S. degree from the Faculty of Technical Sciences of Sfax, Tunisia, his M.S. degree from the School of Electricity and Radio of Bordeaux, France, and his Ph.D. degree in June 1988 from the University of Tennessee, Knoxville, all in Electrical Engineering. Since 1995, he has been co-directing the research activities of the Microwave & Plasma Laboratory of The University of Tennessee. Dr. Laroussi's interests are industrial applications of plasmas, and microwaves interaction with plasmas. He authored or co-authored more than 40 papers in archival journals and conference proceedings. Dr. Laroussi is a senior member of IEEE and of the IEEE Nuclear and Plasma Sciences Society. He is a member of Sigma Xi, and Assistant Editor of "Physics Essays".

BIOGRAPHY

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Professor Igor Alexeff is President - Elect of the IEEE Nuclear and Plasma Sciences Society. He is Professor Emeritus of the Electrical Engineering Department at the University of Tennessee, Knoxville (UTK). He has worked extensively in Plasma at UTK, the Oak Ridge National Laboratory, and overseas. He worked in Nuclear Engineering at the Westinghouse Research Laboratory, and the University of Zurich, Switzerland. He holds over 10 patents in the Nuclear and Plasma area. He has authored over 100 refereed papers. He has a PE from the State of Tennessee. His undergraduate work was at Harvard, and his Ph.D. work at Wisconsin. He is a Fellow of the IEEE, and the APS, and holds the Centennial Medal from the IEEE.

Figure Captions

Fig. 1 Electrical Model of the discharge

Fig. 2 Schematic of the GDAP reactor

Fig. 3 Voltage and Current versus time for V_o = 6 KV, and f = 15.6 KHz

Fig. 4 Scope traces of the voltage and current for f = 15.6 KHz. Vertical axis is 2 KV/Div and 50 mA/Div, horizontal axis is 20 μs/Div.

Fig. 5 Voltage and Current versus time for V_o = 3.5 KV, and f = 35.7 KHz.

Fig, 6 Scope traces of the voltage and current for f = 35.7 KHz. Vertical axis is 2 KV/Div and 50 mA/Div, horizontal axis is 10 μs/Div.

Fig. 7 Power versus time for the f = 15.6 KHz case

Fig. 8 Power versus time for the f = 35.7 KHz case

Fig. 9 Number density versus time for the f = 15.6 KHz case

Fig. 10 Number density versus time for the f = 35.7 KHz case

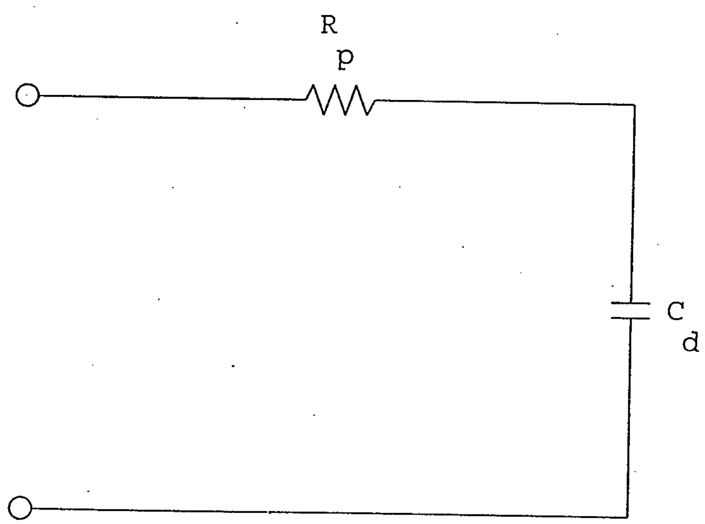

Fig. 1

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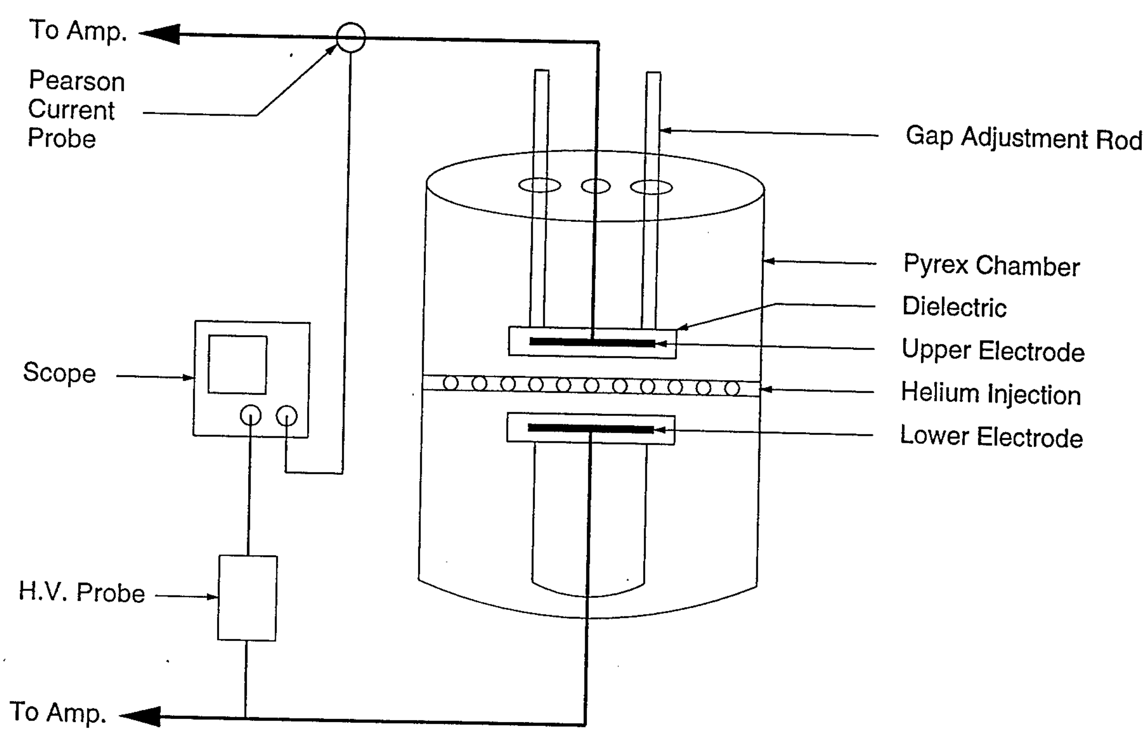

To Amp.
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Current
Probe
Gap Adjustment Rod
Pyrex Chamber
Dielectric
Upper Electrode
Helium Injection
Lower Electrode
Scope
H.V. Probe
To Amp.

Fig.

TOP

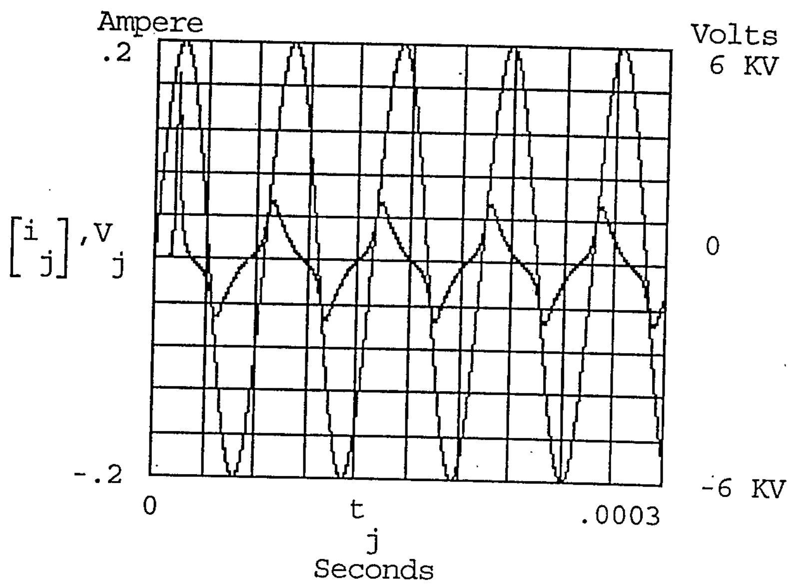

Fig. 3

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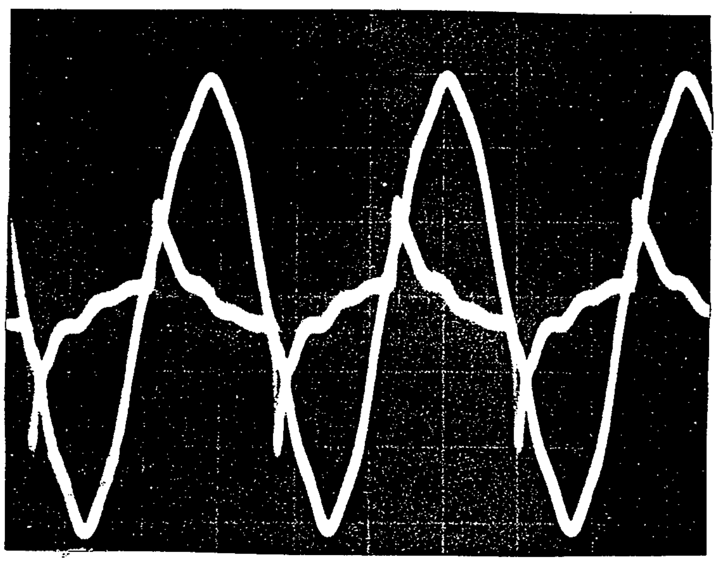

Fig 4

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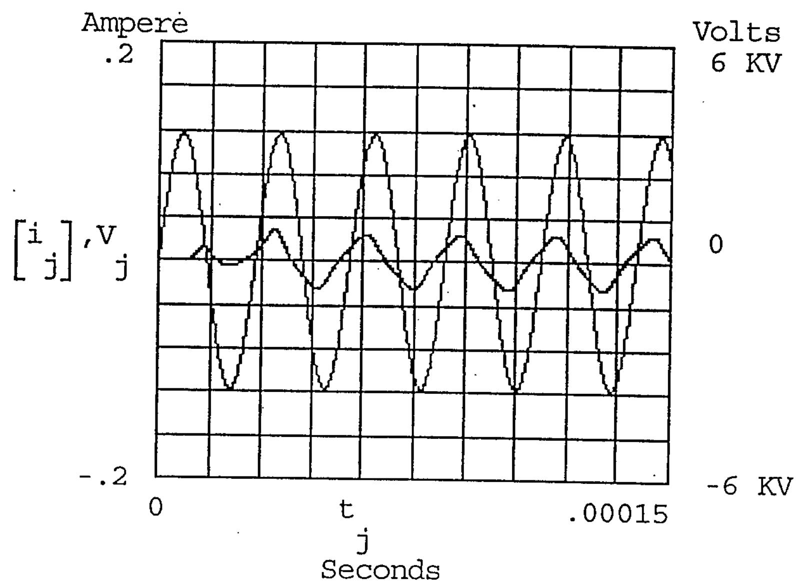
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Fig. 5

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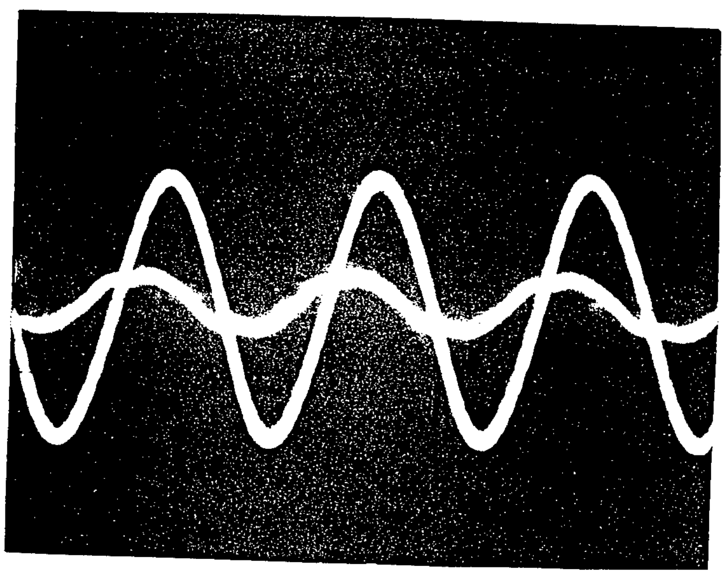

Fig 6

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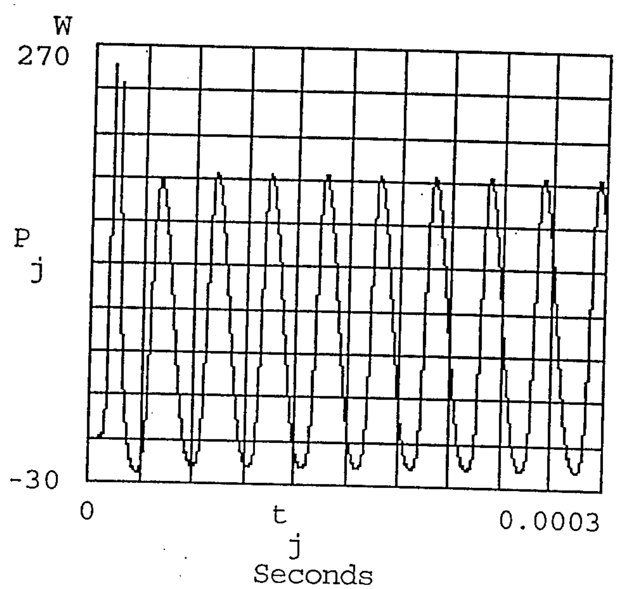

Fig 7

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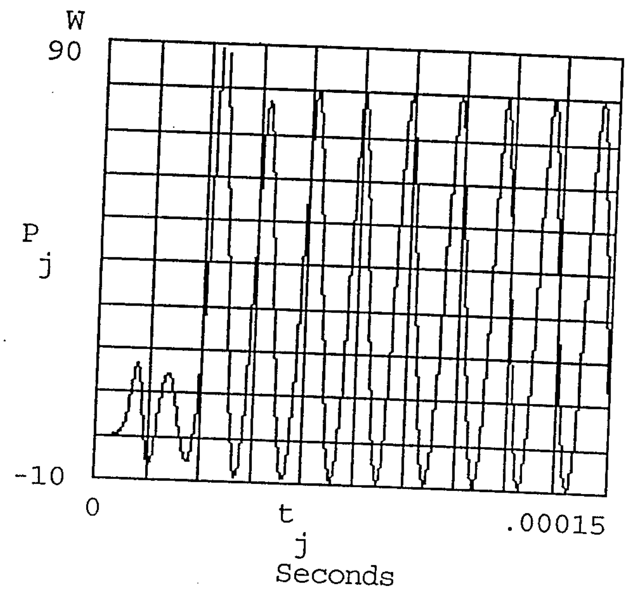

Fig. 8

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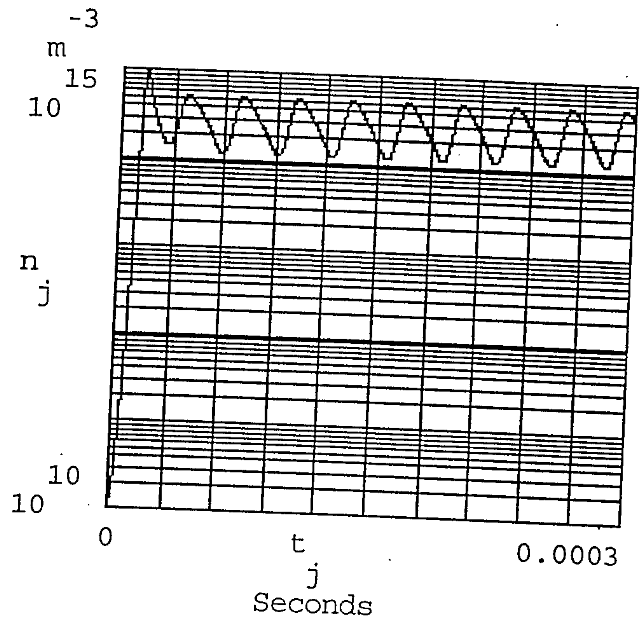

Fig 9.

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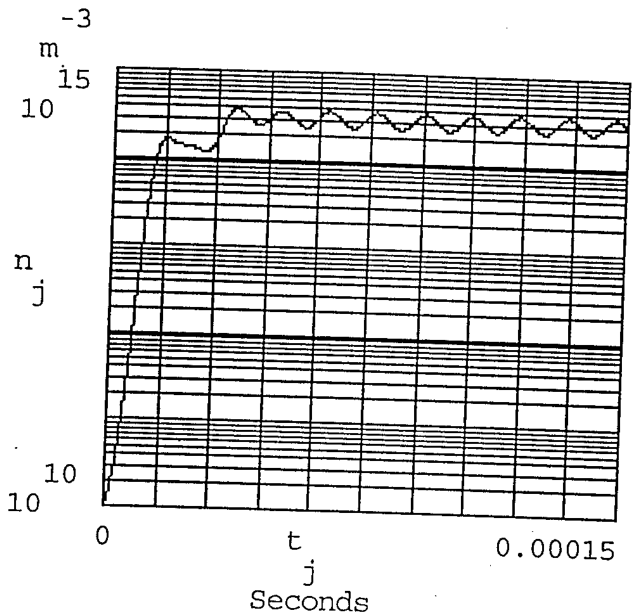

Fig. 10

IMAGES OF BIOLOGICAL SAMPLES UNDERGOING STERILIZATION BY A GLOW DISCHARGE AT ATMOSPHERIC PRESSURE

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(2) Center for Environmental Biotechnology, The University of Tennessee
(3) General Thermal Inc., Chattanooga, Tennessee

ABSTRACT

Among the various industrial uses of the Glow Discharge at Atmospheric Pressure (GDAP), biological applications such as sterilization are under investigation. In this paper we present images of media contaminated by Escherichia coli bacteria (strain PBR 322) undergoing plasma treatment. In most cases it is found that an exposure time of 2 to 20 minutes leads to nearly complete kill of a 10^8/ml E. coli population. The treatment time necessary to obtain complete kill depends on the plasma power density, the type of gas used, the type of bacteria, and the type of medium.

The Glow Discharge at Atmospheric Pressure (GDAP), is a dielectric barrier controlled discharge. It is made of a chamber containing two electrodes at least one of which is insulated by a dielectric material (See Fig. 1). An AC voltage of few hundred volts to few kilovolts, at a frequency of few kilohertz applied between the two electrodes generates a uniform glow discharge [1], [2]. The gap distance between the electrodes can be varied from a few millimeters to a few centimeters. The discharge current is an impulse each half cycle of the applied voltage. This is due to charge accumulation on the dielectric, which prevents the transition of the discharge to an arc. The plasma power density is in the 50-100 mW/cm^3 range.

The Glow Discharge at Atmospheric Pressure has been recently used for various applications such as surface modifications [1], [3], and biological applications [4]. Since this discharge is of the non-equilibrium type, the neutrals, ions, and electrons have different temperatures. The electrons are much hotter than the ions, with kinetic temperature in the 1-10 eV range. This is a perfect range for the breaking of chemical bonds [5], which leads to the generation of chemically reactive free radicals. The free radicals along with the UV radiation generated by the discharge interact with the cells of the microorganisms at the molecular and atomic levels causing cell damage or death depending on the exposure time. Fig. 2 shows the case of three liquid samples (r1, r2, and r3) containing 3×10^{7}/ml of E. coli bacteria. After a plasma exposure time of 10 minutes, a reduction of two orders of magnitude in the population of E. coli is observed in the three samples. A plasma treatment of 20 minutes of sample r1 reduces the population of E.coli to approximately 300/ml, a reduction of five orders of magnitude. Fig. 3 is a photograph of a sample undergoing sterilization. A helium and air mixture is used. For liquid samples, the best results are obtained when the plasma comes in direct contact with the liquid. Fig. 4 is a Scanning Electron Microscope (SEM) photograph of a healthy E. coli bacterium undergoing cell division.

Fig. 5 shows E. coli cells after 30 seconds exposure to plasma. Unlike the cells of Fig. 4, the treated cells lost their rounded shape and appear to be in the process of losing internal matter.

ACKNOWLEDGMENT

The authors would like to thank Professor David C. Joy for his help with the Scanning Electron Microscope. This work was supported by AFOSR STTR contract F49620-97-C-0074.

FIGURE CAPTIONS

Fig. 1 Experimental setup of the Glow Discharge at Atmospheric Pressure (GDAP).

Fig. 2 E. coli live-cells number versus exposure time: r1, r2, and r3 are three samples treated under the same plasma conditions, and the Control is a similar untreated sample.

Fig. 3 Sample undergoing plasma treatment.

Fig. 4 SEM photograph of an E.coli bacterium undergoing cell division.

Fig. 5 Appearance of E. coli cells after 30 seconds exposure to the plasma.

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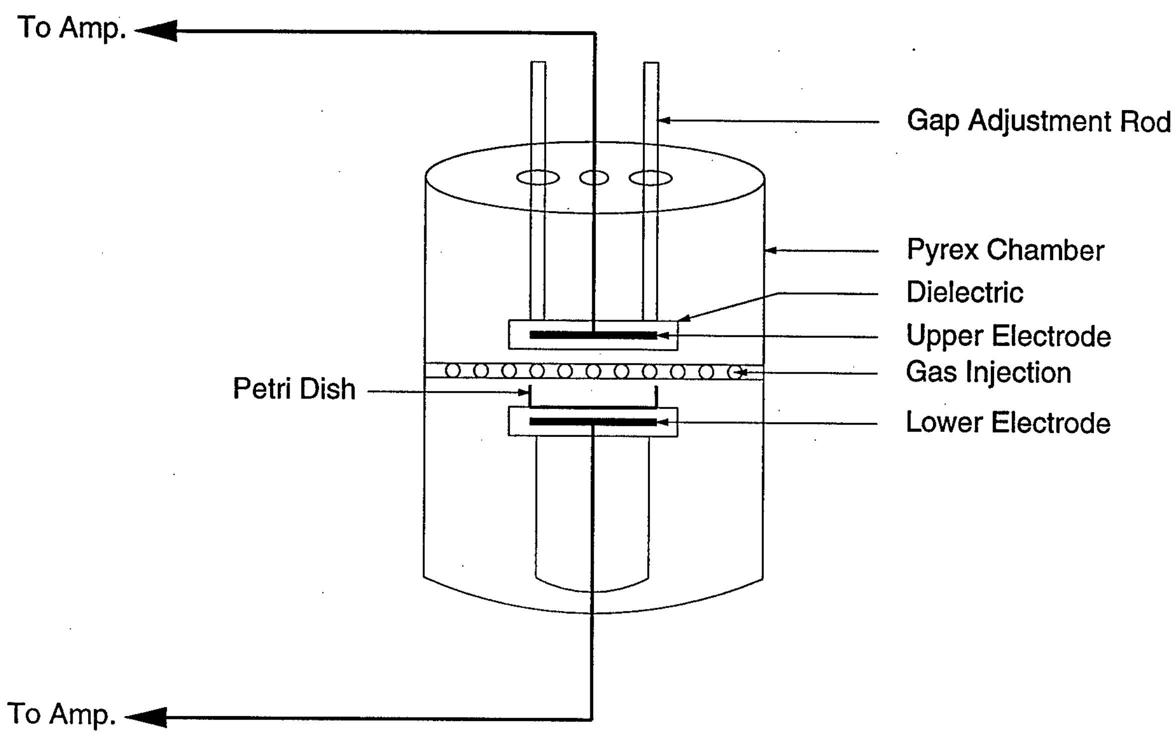
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Pyrex Chamber
Dielectric
Upper Electrode
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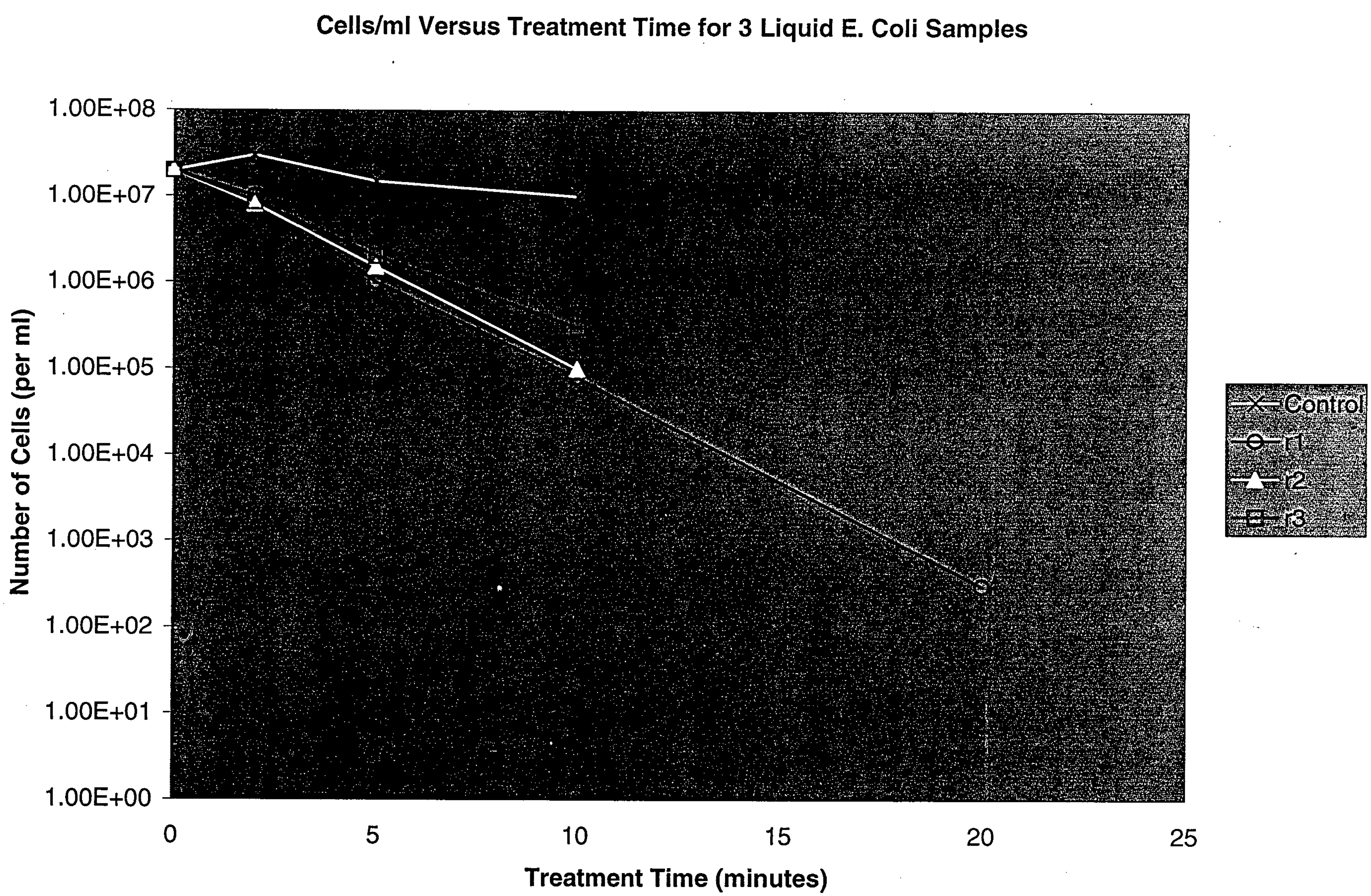
Petri Dish
Lower Electrode
To Amp.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1.00E+06
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1.00E+03
1.00E+02
1.00E+01
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Number of Cells (per ml)
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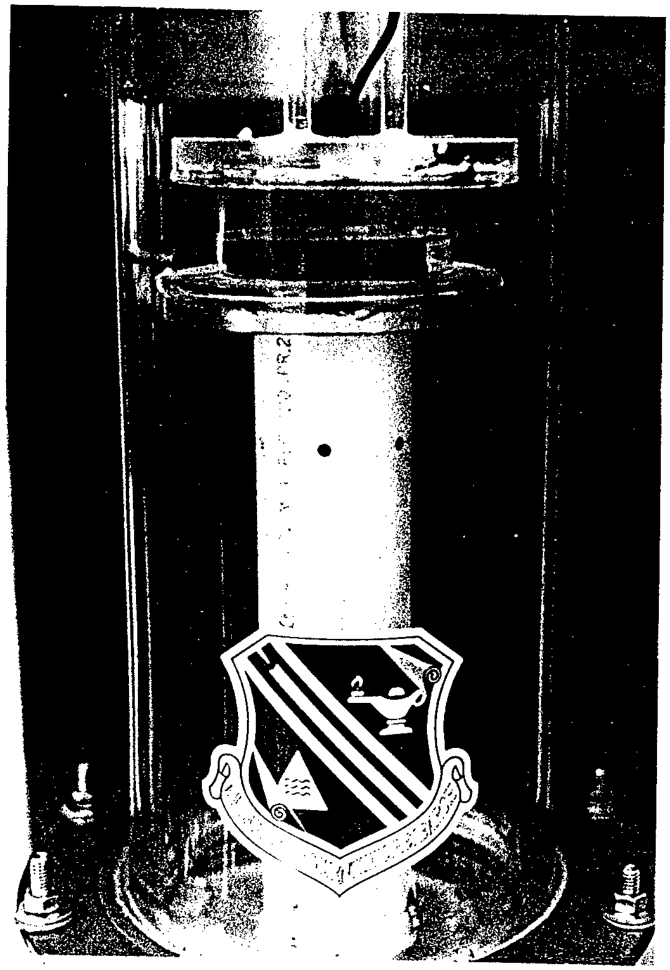
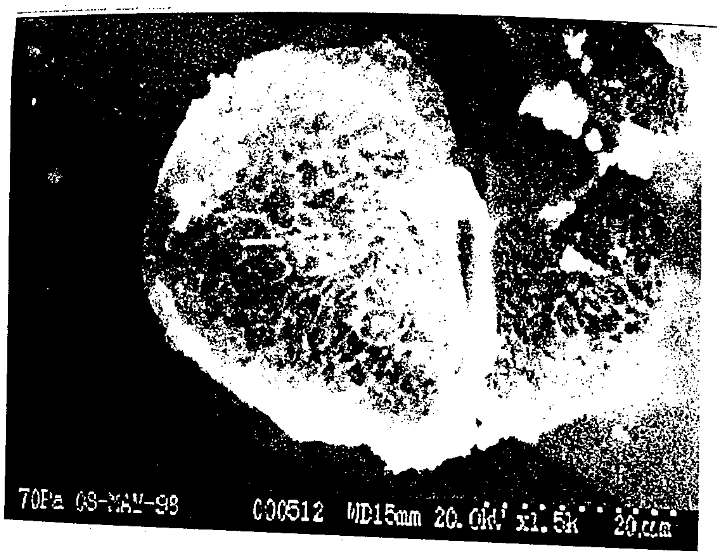
20
25
Treatment Time (minutes)
Control
r1
r2
r3

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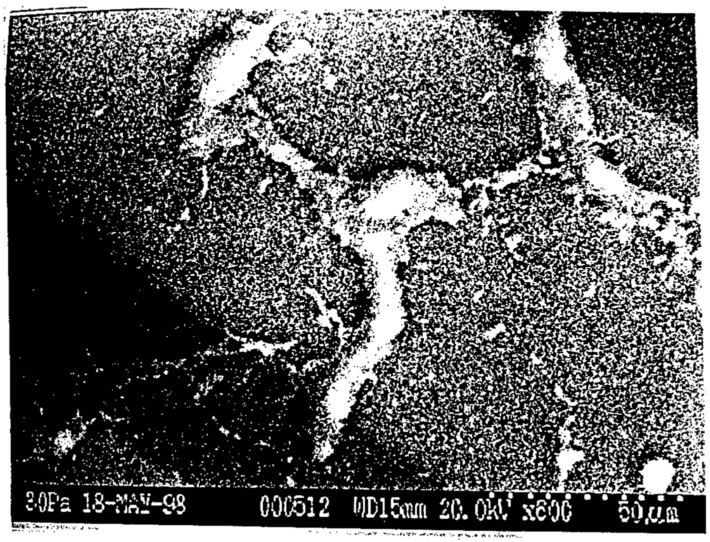
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50µm

Appendix B

Conference Papers

20th Int. Conf. on infrared & mm. waves, 1995

Scattering of Microwaves by Atmospheric Pressure Plasmas*

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Abstract

In this paper, the interaction of microwaves with a plasma, generated at atmospheric pressure, is studied. The refractive index, attenuation index, skin depth, attenuation coefficient, phase coefficient, and reflectivity are investigated as functions of the plasma number density, the wave frequency and type of polarization, and the grazing angle. It is found that two frequency regimes characterize these type of plasmas. The first is a range where the phase velocity and attenuation of the wave both increase with frequency. The second is a frequency range in which the phase velocity and attenuation of the wave remain constant. It is also found that to have a shallow skin depth, the plasma number density has to be in the 10^{13} cm^{-3} range. The reflectivity is found to be an increasing function of the number density. In horizontal polarization, the reflectivity is a decreasing function of the grazing angle. But in vertical polarization and for grazing angle less than 20^{o}, the reflectivity has a maximum at a frequency $f = f_s = \frac{2\pi f_{pe}^2}{v}$, where f_{pe} is the electron plasma frequency and v is the collision frequency.

Discussion

A/ Dispersion Relation

The dispersion relation of a plane wave with a phase dependence $\exp\left(jwt - \tilde{\gamma}x\right)$, in a lossy medium of relative permeability unity is:

$$\tilde{\gamma} = j\frac{\omega}{c}\left(\tilde{\varepsilon}_r\right)^{1/2}, \qquad (1)$$

where $\tilde{\gamma}$ is the complex propagation coefficient, ω is the wave frequency, and $\tilde{\varepsilon}_r$ is the complex dielectric constant. $\tilde{\gamma}$ can be expressed as

$$\tilde{\gamma} = \alpha + j\beta \qquad (2)$$

where α is the attenuation coefficient, and β is the phase coefficient. The complex refractive index $\tilde{\mu}$ is given by

$$\tilde{\mu} = \left(\tilde{\varepsilon}_r\right)^{1/2} = \mu - jX \qquad (3)$$

where μ is the refractive index, and X is the attenuation index. μ and X are related to α and β by the following relations

$$\alpha = \frac{\omega}{c}X \qquad (4)$$

and

$$\beta = \frac{\omega}{c}\mu \qquad (5)$$

For a collisional unmagnetized plasma we have [1]

$$\mu = \left\{\frac{1}{2}\left(1 - \frac{\omega_{pe}^2}{\omega^2 + v^2}\right) + \frac{1}{2}\left[\left(1 - \frac{\omega_{pe}^2}{\omega^2 + v^2}\right)^2 + \left(\frac{\omega_{pe}^2}{\omega^2 + v^2}\frac{v}{\omega}\right)^2\right]^{1/2}\right\}^{1/2} \qquad (6)$$

and

$$X = \left\{\frac{1}{2}\left(1 - \frac{\omega_{pe}^2}{\omega^2 + v^2}\right) + \frac{1}{2}\left[\left(1 - \frac{\omega_{pe}^2}{\omega^2 + v^2}\right)^2 + \left(\frac{\omega_{pe}^2}{\omega^2 + v^2}\frac{v}{\omega}\right)^2\right]^{1/2}\right\}^{1/2} \qquad (7)$$

where ω_{pe} is the electron plasma frequency, and v is the collision frequency (electron-neutral).
For an atmospheric pressure plasma the electron collision frequency is extremely high, $v \sim 10^{12}$ Hz. Thus we have

$$v >> \omega_{pe},$$

and

$$v >> \omega \text{ (for microwave frequencies of our interest)}$$

The refractive index μ and attenuation index X can be approximated as follows [2]:

$$\mu = \left\{\frac{1}{2} + \frac{1}{2}\left[1 + \left(\frac{\omega_{pe}^2}{\omega v}\right)^2\right]^{1/2}\right\}^{1/2} \qquad (8)$$

and

$$X = \left\{-\frac{1}{2} + \frac{1}{2}\left[1 + \left(\frac{\omega_{pe}^2}{\omega v}\right)^2\right]^{1/2}\right\}^{1/2} \qquad (9)$$

Two frequency regimes characterize the interaction of microwaves with this highly collisional plasmas:

1. Propagation with increasing phase velocity and increasing attenuation.
2. Propagation with constant phase velocity ($\vartheta_{\phi} \sim c$), and constant attenuation

The attenuation index has a substantial value only for frequencies,

$$\omega < \omega_s = \frac{\omega_{pe}^2}{\nu}, \text{ or } f < f_s = \frac{2\pi f_{pe}^2}{\nu}$$

For a plasma with a number density n = 5 x 10^{13} cm^{-3} this range of frequencies is f < 25 GHz which includes the P, L, S, C, X, and K microwave bands.

The skin depth is defined as

$$\delta = \frac{1}{\alpha} \tag{10}$$

or

$$\delta = \frac{c}{\omega X} \tag{11}$$

At $\omega = \omega_s = \frac{\omega_{pe}^2}{\nu}$, we have:

$$\delta = 2.2\frac{\nu c}{\omega_{pe}^2} \tag{12}$$

or

$$\delta = 2.2\frac{\nu c\, \varepsilon_o\, m_e}{n\, e^2} \tag{13}$$

For a skin depth $\delta <$ 1cm we need,

$$n > 220\frac{\nu c\, \varepsilon_o\, m_e}{e^2} \tag{14}$$

Assuming $\nu = 10^{12}$ Hz, we get

$$n > 2 \times 10^{13}\ cm^{-3}$$

Thus for applications where it is only practical to generate a thin slab or layer of plasma to interact with the wave, a number density in the 10^{13} cm^{-3} range is needed in order to attenuate and reflect the incident wave.

B/ Reflectivity Calculations

In the following development we assume that:

a/ Medium 1 is air

b/ Medium 2 is a plasma at atmospheric pressure with $\frac{\sigma}{\omega\varepsilon} < 1$

c/ Dimensions of the plasma are comparable to the wave wavelength

d/ A sharp air-plasma interface

1./ Vertical Polarization: (E parallel to the plane of incidence)

The reflection coefficient is calculated as [3]

$$\Gamma_v = \frac{\tilde{\varepsilon}_r \sin\Psi - \left(\tilde{\varepsilon}_r - \cos^2\Psi\right)^{1/2}}{\tilde{\varepsilon}_r \sin\Psi + \left(\tilde{\varepsilon}_r - \cos^2\Psi\right)^{1/2}} \tag{15}$$

Where Ψ is the grazing angle defined as the angle between the air-plasma interface, and the direction of propagation of the incident wave.

2./ Horizontal polarization: (E Perpendicular to plane of incidence.)

The reflection coefficient is calculated as [3]

$$\Gamma_h = \frac{\sin\Psi - \left(\tilde{\varepsilon}_r - \cos^2\Psi\right)^{1/2}}{\sin\Psi + \left(\tilde{\varepsilon}_r - \cos^2\Psi\right)^{1/2}} \tag{16}$$

The ratio of the reflected power to the incident power is given by

$$\frac{P_r}{P_i} = |\Gamma|^2 \tag{17}$$

C/ Computational Treatment

Based on the development discussed in part A and B of this section, a program was written to compute the refractive index μ, the attenuation index X, the skin depth δ, the attenuation coefficient α, the phase coefficient β, and reflectivity of the plasma for a vertical and horizontal polarization cases. The plasma number density, the frequency range, and the grazing angle are entered as independent parameters which can be varied. The results of the computations are presented as semilogarithmic plots of the relevant quantity versus the wave frequency. The number density, frequency, and grazing angle, are respectively in the following ranges, 10^{13} - 5 10^{13} cm^{-3}; 1 - 1000 GHz, and 10^o - 90^o . The collision frequency which is dominated by electron-neutral collisions is chosen to be 1000 GHz. The computations are meaningful for frequencies $\omega << \nu$.

D/ Results and Conclusions

It is found that the interaction of microwaves with atmospheric pressure plasmas, where $\nu >> \omega, \omega_{pe}$ differs substantially from the usual case of low pressure plasmas where $\nu << \omega_{pe}$. Below a characteristic frequency $\omega_s = \frac{\omega_{pe}^2}{\nu}$, the wave propagates through the plasma with an attenuation and a phase velocity which are increasing functions of the frequency. For frequencies above ω_s , the attenuation and phase velocity of the wave become independent on frequency. The skin depth δ, is a decreasing function of frequency, and is below 1 cm for number densities above 2 10^{13} cm^{-3}. In vertical polarization, the reflectivity of the plasma is an increasing function of the number density, and for small grazing angles it has a maximum at a frequency approximately equal to ω_s . In horizontal polarization, the reflectivity increases with the number density and decreases with frequency and increasing grazing angles.

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*Supported by Contract AFOSR 95-0277

23rd ICPIG 97

The One Atmosphere Glow Discharge As A Sterilization Agent

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1. Introduction

This paper describes the generation of a uniform glow discharge at atmospheric pressure [1], and its use to effectively destroy microorganisms. The fact that no vacuum system is used to generate the discharge makes the apparatus very practical and inexpensive to build. Among the various potential industrial applications of this kind of plasma, investigations of its capability to sterilize contaminated matter, have been recently conducted [2]-[5].

2. Using the Discharge as a Sterilization Agent

Corona discharges and R.F. discharges have already been tested as sterilization means. However most R.F. discharges are operated at pressures below one atmosphere, and corona discharges have a small reactive volume, which renders them not suitable for large industrial applications. The One Atmosphere Glow Discharge, developed at the University of Tennessee Plasma Laboratory [1], combines the advantages of a large reactive volume, a relatively low input power, and the absence of a vacuum system.

The plasma in the One Atmosphere Glow Discharge (see Fig. 1) is generated between two plate electrodes, at least one of which is insulated by a dielectric material. The two electrodes are powered by a low frequency R.F. source (1 to 100 KHz). It is found that when the source frequency is within a narrow range, a uniform glow discharge fills up the gap between the electrodes. The frequency range is set by the gap distance between the electrodes, the applied RMS voltage, and the type of gas used. Outside this frequency range, the discharge becomes filamentary, or unstable. The typical input power is in the 50-150 W range, and the plasma power density, which is a function of the frequency and the RMS voltage, is in the 10-80 mw/cm^3 range. Usually, the electrodes setup is contained within an enclosure with a gas inlet port and an exhaust port. The discharge can be operated in air, or a mixture of air and another gas such as helium, argon, etc... The gap between the electrodes is adjustable so as to accommodate the medium to be treated.

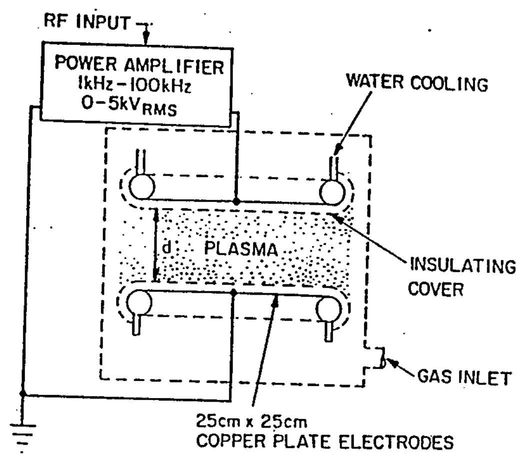

Fig. 1 One Atmosphere Glow Discharge Reactor

The plasma generated by the One Atmosphere Glow Discharge is a source of reactive free radicals, charged particles, and radiation. The free radicals interact with microbial cells at the molecular and atomic levels, inducing lethal changes to the chemical composition of the cells. Also, serious lesions and complete fragmentation of the cells have been observed. Hence, the discharge constitutes a very destructive environment for microorganisms with which it comes in contact. Laroussi et al. [2]-[4], and Ku et al. [5] have exposed various media contaminated by various types of bacteria. Sterilization was achieved in less than 10 minutes in most cases, and in as low as 15 seconds in some cases.

The results obtained so far, indicate that the One Atmosphere Glow Discharge can be used as a sterilization apparatus. The absence of a vacuum system makes it practical and inexpensive, and the short treatment times makes it more versatile, more effective, and more practical than most presently used methods. Finally, this new method poses no environmental drawbacks, since no toxic byproducts or residues are generated in the process.

3. References

[1] J. R. Roth, M. Laroussi, and C. Liu: Proc. IEEE Int. Conf. Plasma Sci., (1992), 170-171.

[2] M. Laroussi: Bull. Amer. Phys. Soc. **40**, (1995), 1685-1626.

[3] M. Laroussi: IEEE Trans. Plasma Sci. **24**, (1996) 1188-1191.

[4] M. Laroussi, et al.: Bull. Amer. Phys. Soc. **41**, (1996), 1539-1540.

[5] Y. Ku, et al.: Proc. IEEE Int. Conf. Plasma Sci. (1996), 175.

Work supported in part by the United States Air Force Office of Scientific Research.

Paper 6P47

THE ONE ATMOSPHERE GLOW DISCHARGE AS A DETECTOR OF MILLIMETER RADIATION*

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Electrical Engineering Department
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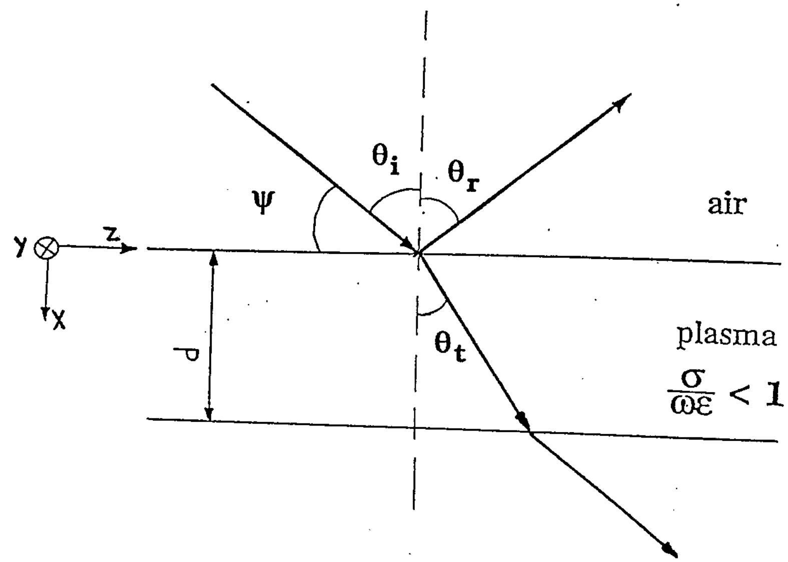
Presented at the 25th IEEE International Conference on Plasma Science
Raleigh, North Carolina, June 1-4, 1998

*Supported by AFOSR Contract F49620-95-1-0277

ABSTRACT

Previous work has showed that the One Atmosphere Glow Discharge is a broad-band absorber of microwave radiation [1], [2]. The absorbed radiation causes fluctuations in the discharge current [3], [4]. The change in the discharge current is a direct measure of the incident wave power. The fact that the plasma is generated at atmospheric pressure renders this type of glow discharge a very practical detector of millimeter waves. Also since the amount of power attenuation (in dB) of a wave propagating through a uniform plasma at atmospheric pressure is proportional to the ratio of the plasma number density and the collision frequency [1], [2], the former or the later can be accurately determined if either quantity is measured by another diagnostics.

[1] M. Laroussi, Int. J. IR and Millimeter Waves, Vol.16, No.12, pp.2069-2083, 1995.
[2] M. Laroussi and W.T. Anderson, Int. J. IR and Millimeter Waves, Vol.19, No.3, 1998.
[3] P.J. W. Severin and A.G. Van Nie, IEEE Trans. Microwave Theory and Tech., Vol.MTT-14, No.9, pp.431-436, 1996.
[4] A. Rosenberg, J. Poltich, J. Felsteiner, and R. Opher, J. Phys. D: Appl. Phys., Vol. 13, pp.813-821, 1980.



Wave propagating through air, then an air plasma layer.

An electromagnetic wave crossing a uniform layer of an atmospheric pressure plasma of thickness d, will have its field attenuated by a factor:

$$A = \mathrm{Exp}\left(-\alpha \frac{d}{\cos \theta_t}\right)$$

where

$$\alpha = \frac{n\, e^2}{2\, \varepsilon_0\, m\, c\, \upsilon}$$

υ : electron-neutral collision frequency

n : plasma number density

Neglecting reflections, and assuming a normal incidence, the ratio of the transmitted power, P_t , to the incident power, P_i, is given by

$$\frac{Pt}{Pi} = \mathrm{Exp}\left(- \frac{ne^2 d}{\varepsilon_0 m \upsilon c}\right)$$

or

$$\ln\left(\frac{Pt}{Pi}\right) = - \frac{ne^2 d}{\varepsilon_0 m \upsilon c}$$

The transmitted power can be expressed in terms of the absorbed power, P_a ,

$$P_t = P_i - P_a$$

$$\ln\left(1 - \frac{P_a}{P_i}\right) = -\frac{ne^2 d}{\varepsilon_0 m \upsilon c}$$

For the range of number densities in the discharge we have

$$\frac{P_a}{P_i} \ll 1$$

therefore

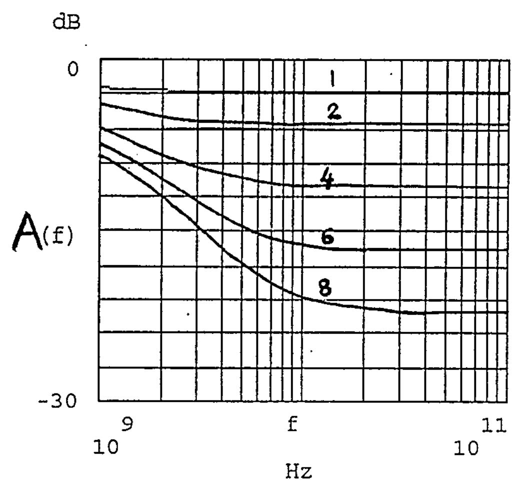
$$\frac{P_a}{P_i} = \frac{ne^2 d}{\varepsilon_0 m \upsilon c}$$

or

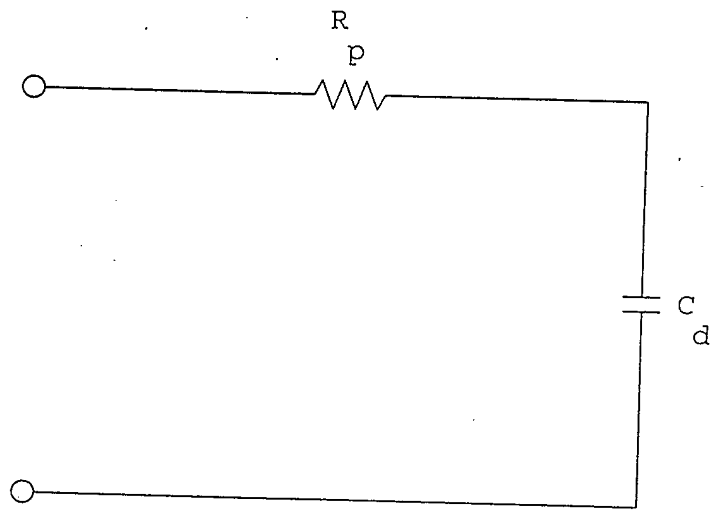
$$n = \frac{\varepsilon_0 m \upsilon c}{e^2 d} \frac{P_a}{P_i}$$

Since the current density, J, is proportional to n, it follows that

$$J \propto \frac{P_a}{P_i}$$



Total attenuation (in dB) versus frequency (in Hz) for a grazing angle $\Psi = 30°$, a layer thickness d= 3 cm, and 1. $n = 10^{12}$ cm^{-3}; 2. $n = 2\ 10^{12}$ cm^{-3}; 4. $n = 4\ 10^{12}$ cm^{-3}; 6. $n = 6\ 10^{12}$ cm^{-3}; 8. $n = 8\ 10^{12}$ cm^{-3}.



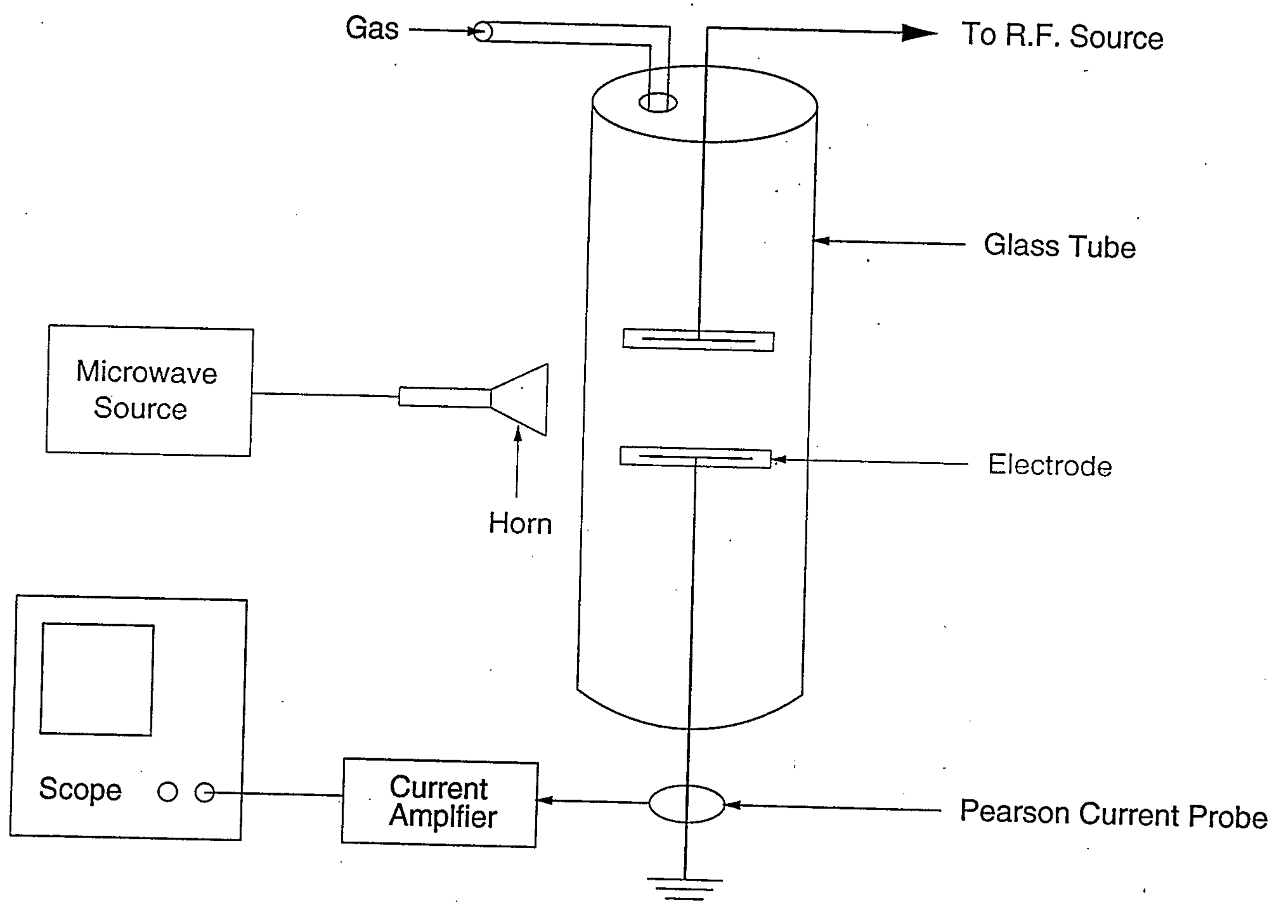
Electrical Model of the Discharge

Attractive Features

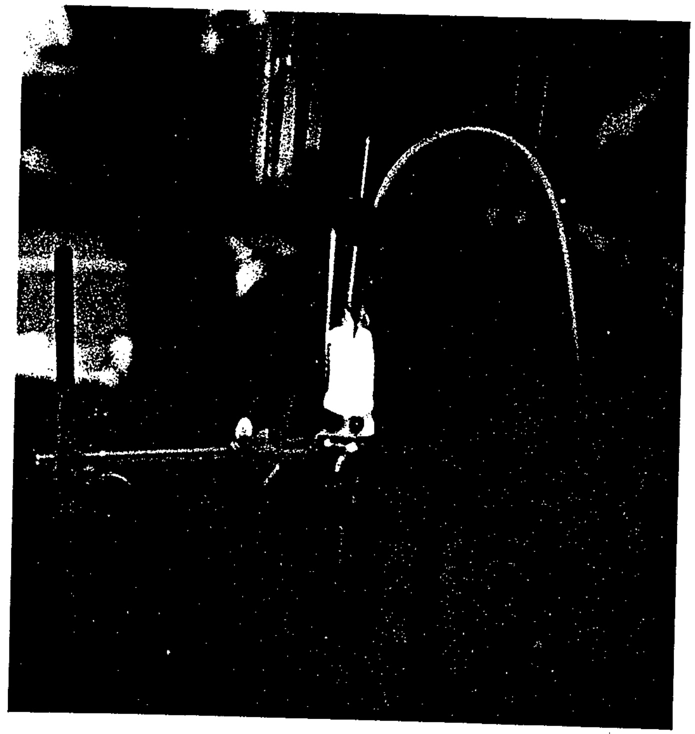
- Broad band detection
- Robustness :
  - Withstands high power microwave radiation
- Simple design :
  - No vacuum
  - Low power supply
  - Inexpensive components

Disadvantages

- Not suitable for the detection of low power radiation
- Relatively noisy signal
- Needs a low ionization seed gas



Discharge Tube Microwave Detector



Photograph of the DTMD

M&PL
Microwave and Plasma Laboratory

C.E.B.
Center for Env. Biotechnology

Paper 6P59

DECONTAMINATION OF MEDIA BY A GASEOUS DISCHARGE AT ATMOSPHERIC PRESSURE*

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Presented at the 25th IEEE International Conference on Plasma Science
Raleigh, North Carolina, June 1-4, 1998

***Supported by AFOSR STTR Contract F49620-97-C-0074**

G.T.Inc.
General Thermal Inc.

M&PL
Microwave and Plasma Laboratory

C.E.B.
Center for Env. Biotechnology

ABSTRACT

The use of plasmas to decontaminate matter has recently received a lot of attention [1]-[3]. The plasma generated by the One Atmosphere Glow Discharge has been found to be an excellent sterilization agent [1]-[3]. This is due to the production of UV radiation and reactive free radicals, which interact, with the cells of the microorganisms, causing their death. In this paper we present our latest results and report our findings concerning the killing process as observed by a Scanning Electron Microscope (SEM).

[1] M. Laroussi, Bull. Amer. Phys. Soc., Vol.40, No.11, pp.1685-1686, 1995.
[2] M. Laroussi, IEEE Trans. Plasma Sci., Vol.24. No.3, pp.1188-1191, 1996.
[3] Y. Ku et al., Proc.1996 IEEE Int. Conf. Plasma Sci., p.175

Work Supported by AFOSR STTR Contract F49620-97-C-0074

G.T.Inc.
General Thermal Inc.

CONVENTIONAL STERILIZATION METHODS

- **Sterilization with Heat**
  - **Moist heat :** $T = 121°C$; $P = 15$ psi (steam pressure); $\Delta t = 15$ min
  - **Dry heat :** $T = 150\text{-}160°C$; $\Delta t = 2$ hr
    $T = 180°C$; $\Delta t = 30$ min
    $T = 280°C$; $\Delta t = 15$ min
    (High vacuum infrared oven)

- **Sterilization with Chemicals**
  1) Gases
  - **Ethylene oxide :** $T = 45 - 60°C$; $\Delta t = 1$ hr 45 min + aeration cycle
  - **Formaldehyde :** $T = 70 - 80°C$; $\Delta t = 1 - 2$ hr

- Hydrogen Peroxide : $T = 90°C$, $\Delta t = 3 - 4$ sec

2) Liquids
- Glutaraldehyde
- Hydrogen Peroxide
- Peracetic Acid
- Chlorine Dioxide
- Formaldehyde

- <u>Radiation Sterilization</u>
  - EM Radiation : Microwaves, gamma rays, ultraviolet, and x-rays.
  - Particle Radiation : β, α, p.

- <u>Sterilization by Filtration</u>
  - Depth filter
  - Membrane filter
  - Air filtration

BRIEF HISTORICAL OVERVIEW OF PLASMA BASED STERILIZATION METHODS

- **In 1857, Siemens used a silent discharge to produce ozone to disinfect water.**
- **In 1968, Menashi used a Corona discharge at atmospheric pressure to sterilize the surfaces of materials.**
- **In 1974, Fraser et al. used radio frequency-generated plasmas. Gases such as argon, nitrogen, oxygen, helium, and xenon were used.**
- **In 1978, Boucher et al. used a Glutaraldehyde gas plasma. The plasma was generated by R.F. in the 1-10 MHz range at subatmospheric pressure.**
- **In 1980, Bithell suggested a cyclically pulsed pressure plasma system to sterilize objects of irregular shape.**
- **In 1988, Jocobs and Lin sterilized paper discs and surgical blades using a hydrogen peroxide plasma.**

EXPERIMENTAL CONDITIONS

Voltage :	**5 kV (R.M.S.)**
Frequency :	**17 kHz**
Gap Distance :	**3 cm**
Gas :	**Helium & Air**
Power Density :	**≈ 100 mW/ cm^3**
Media :	**Nitrocellulose (Filter Membrane)** **Luria-Bertani broth with tetracycline (Liquid)**
Bacteria :	***Escherichia coli* PBR322 & *Pseudomonas aeruginosa* FRD1**
Treatment Times :	**30 sec. – 20 min.**

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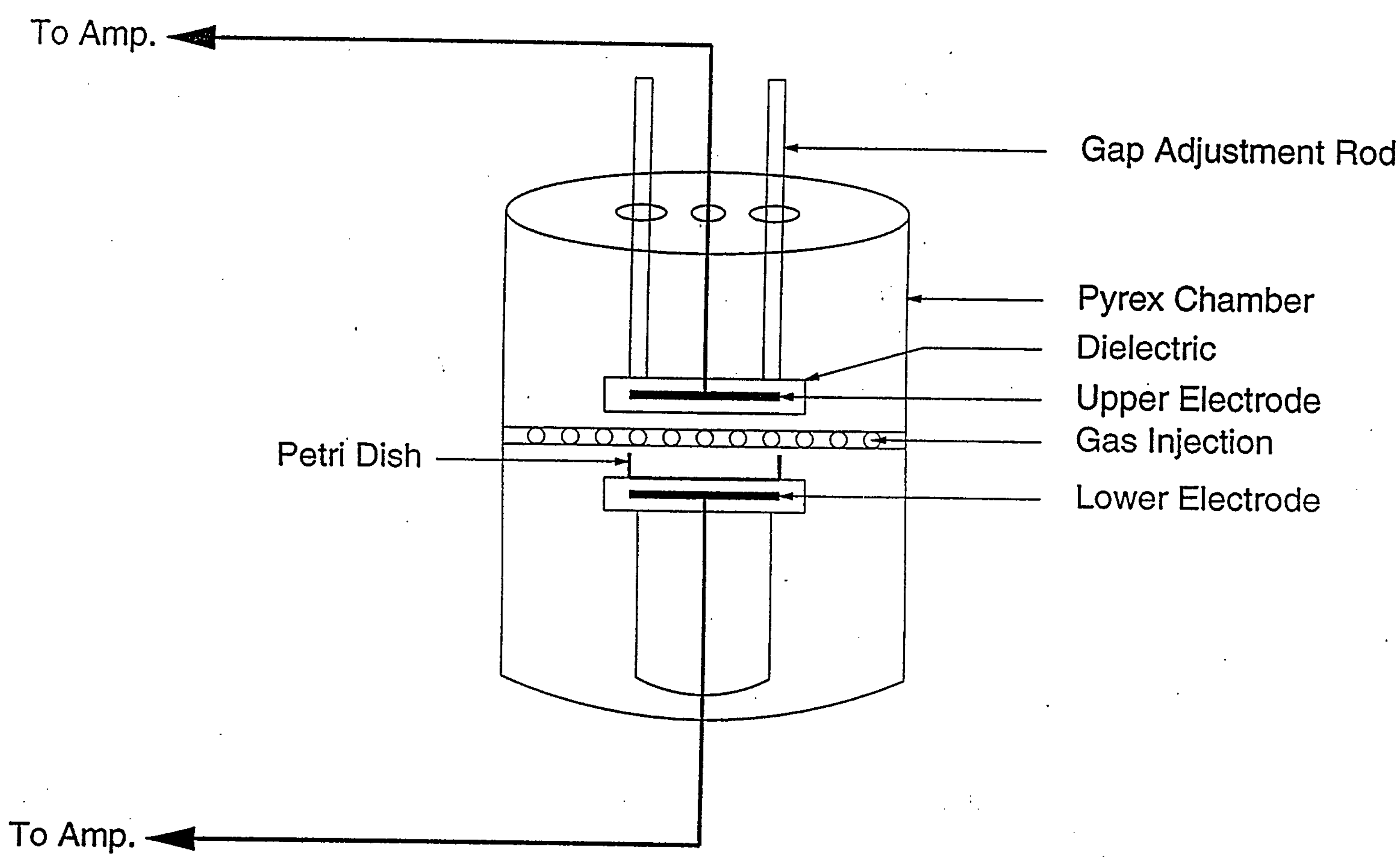

Fig. 1 The Atmospheric Pressure Glow Discharge Generator

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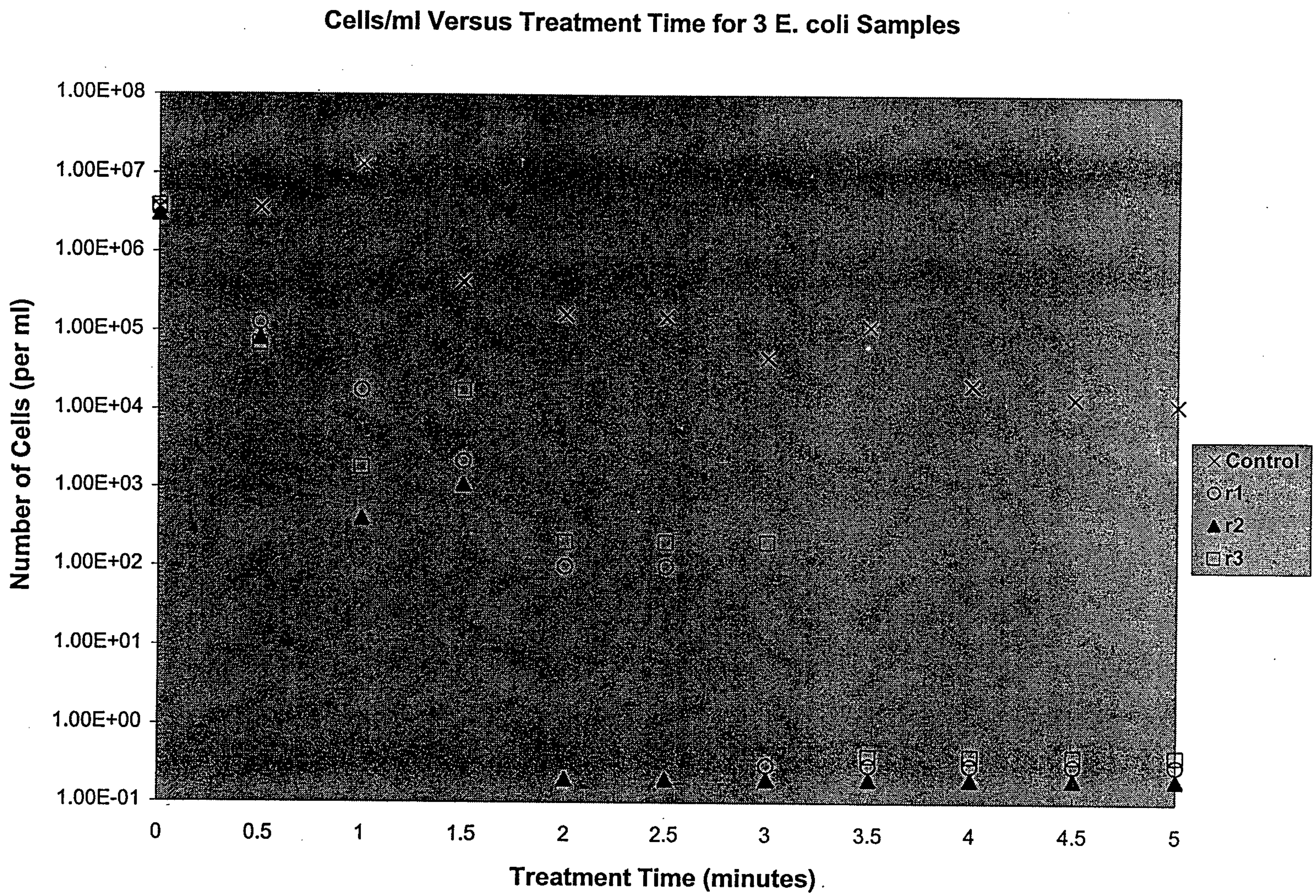
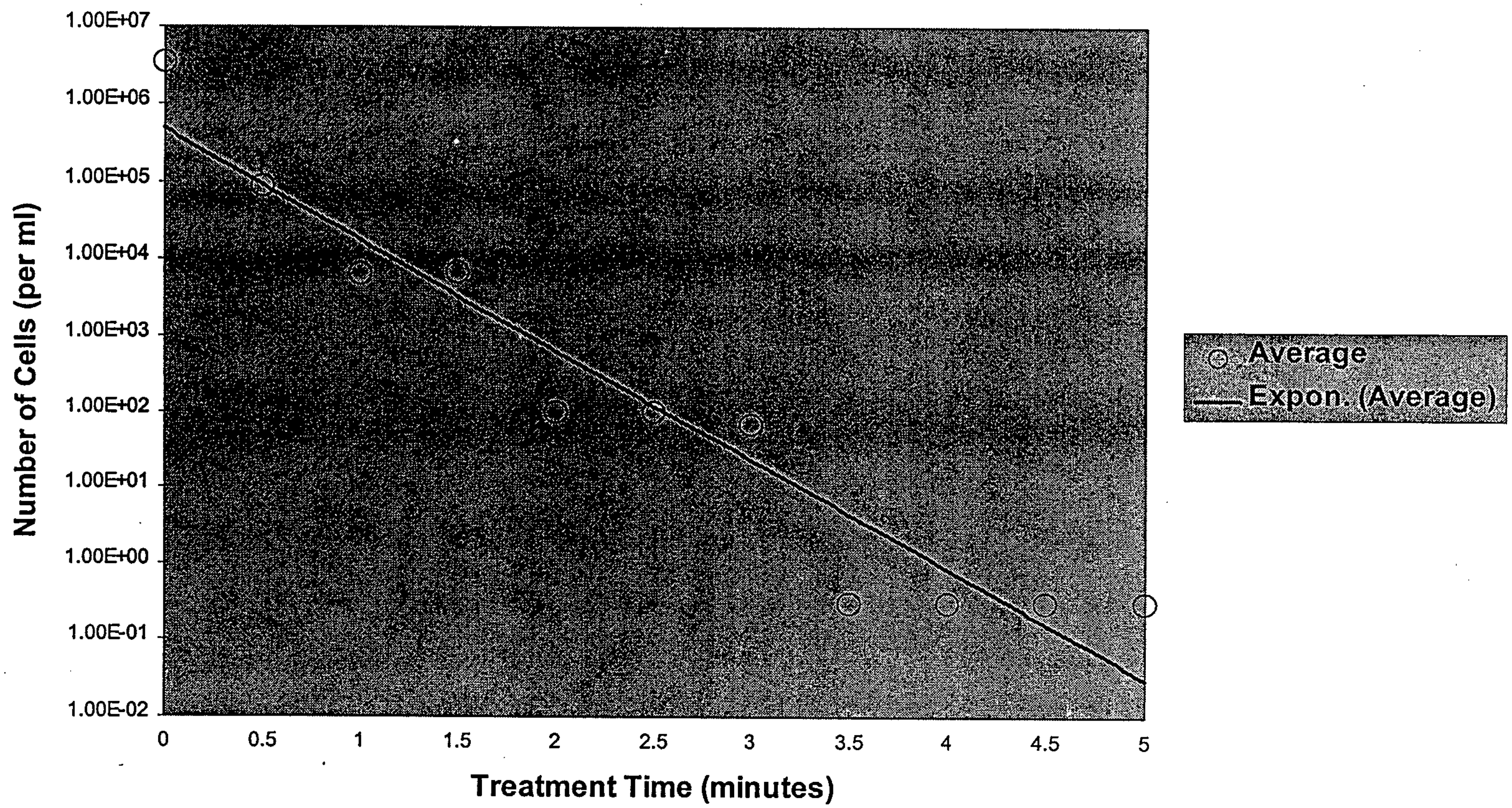
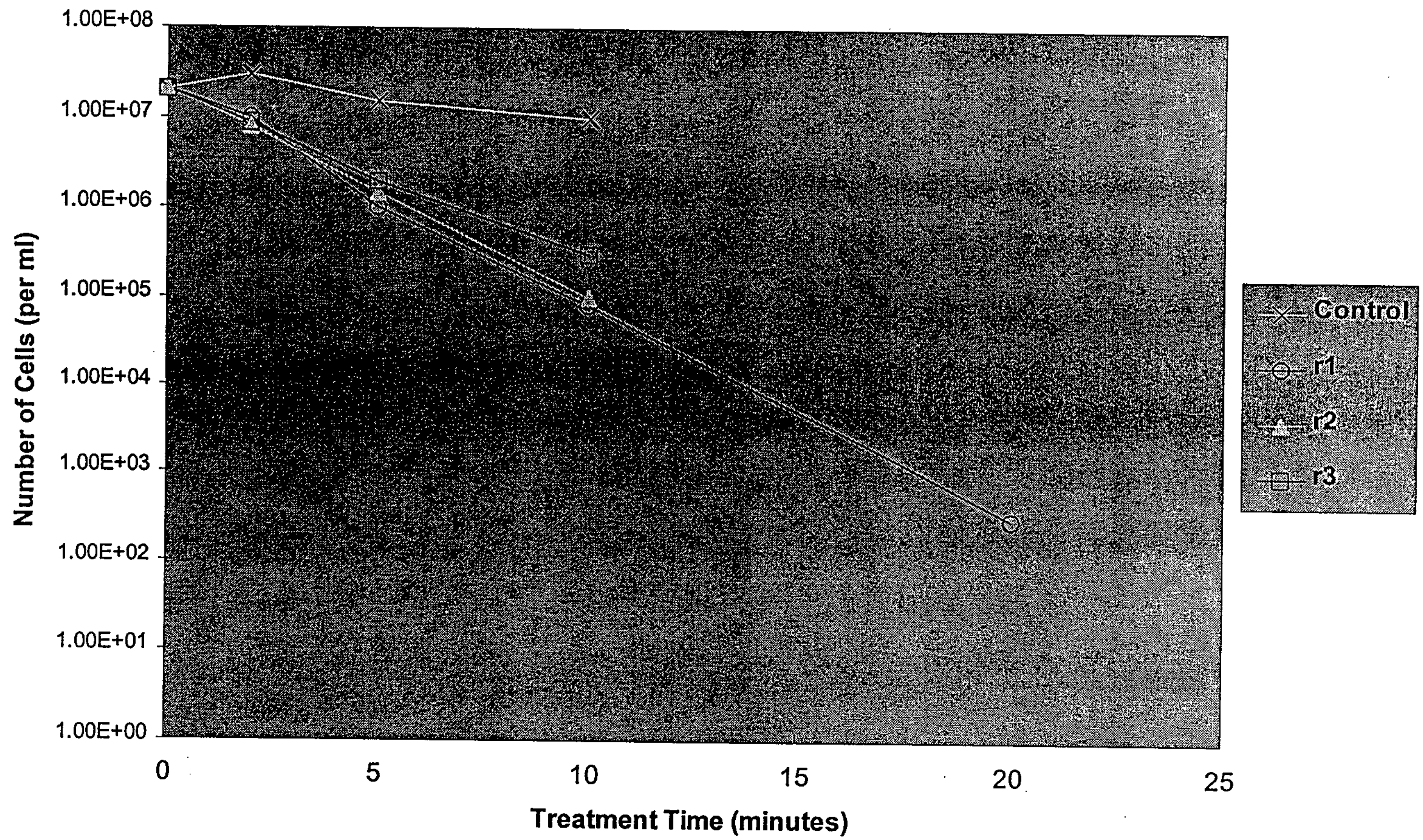

Cells/ml Versus Treatment Time for 3 E. coli Samples
1.00E+08
1.00E+07
1.00E+06
1.00E+05
1.00E+04
1.00E+03
1.00E+02
1.00E+01
1.00E+00
1.00E-01
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Number of Cells (per ml)
Treatment Time (minutes)
Control
r1
r2
r3

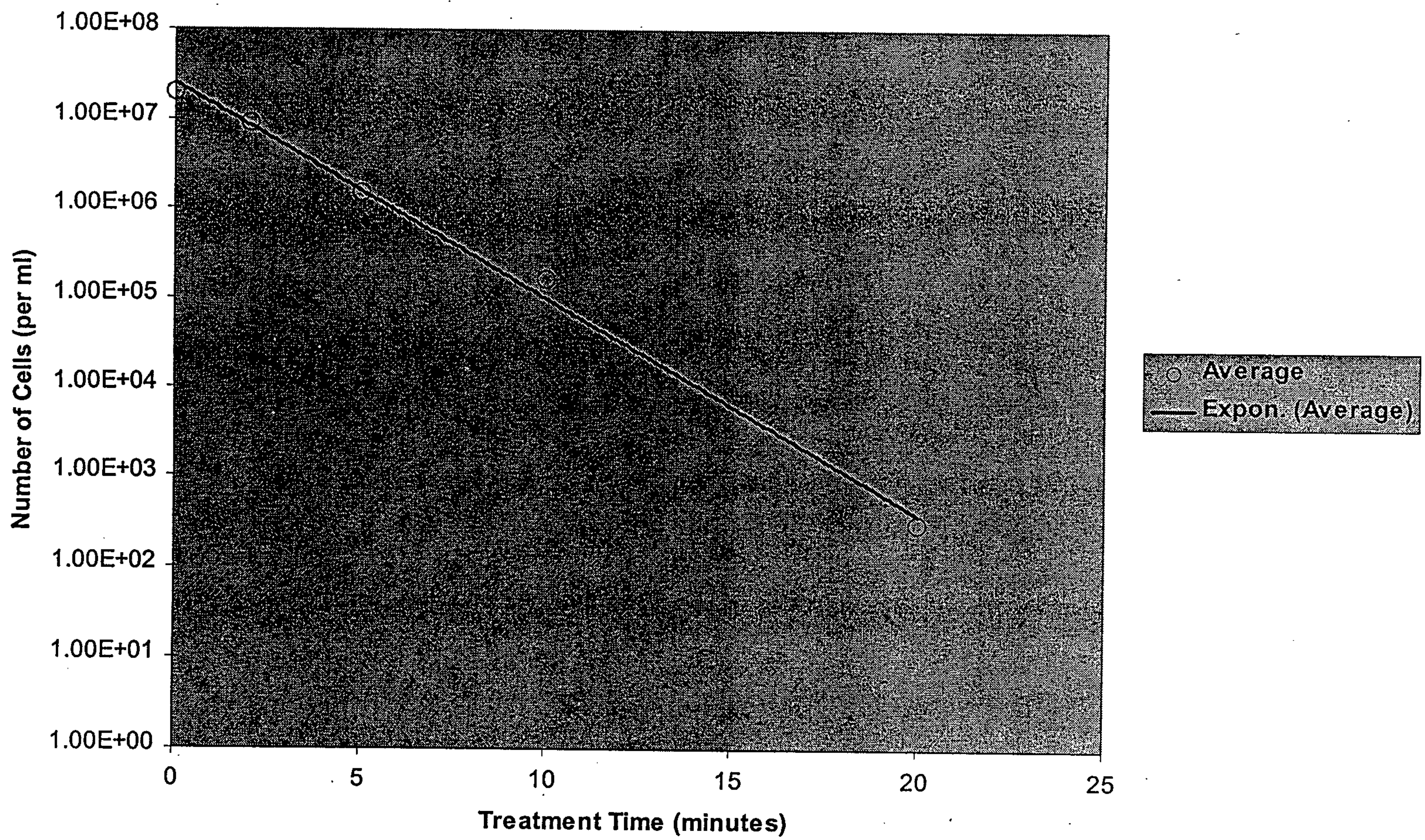
Average Number of Cells/ml for the 3 E. coli Samples with Best-Fit



Cells/ml Versus Treatment Time for 3 Liquid E. Coli Samples



Average Number of Cells/ml for the 3 Liquid E. Coli Samples with Best-Fit



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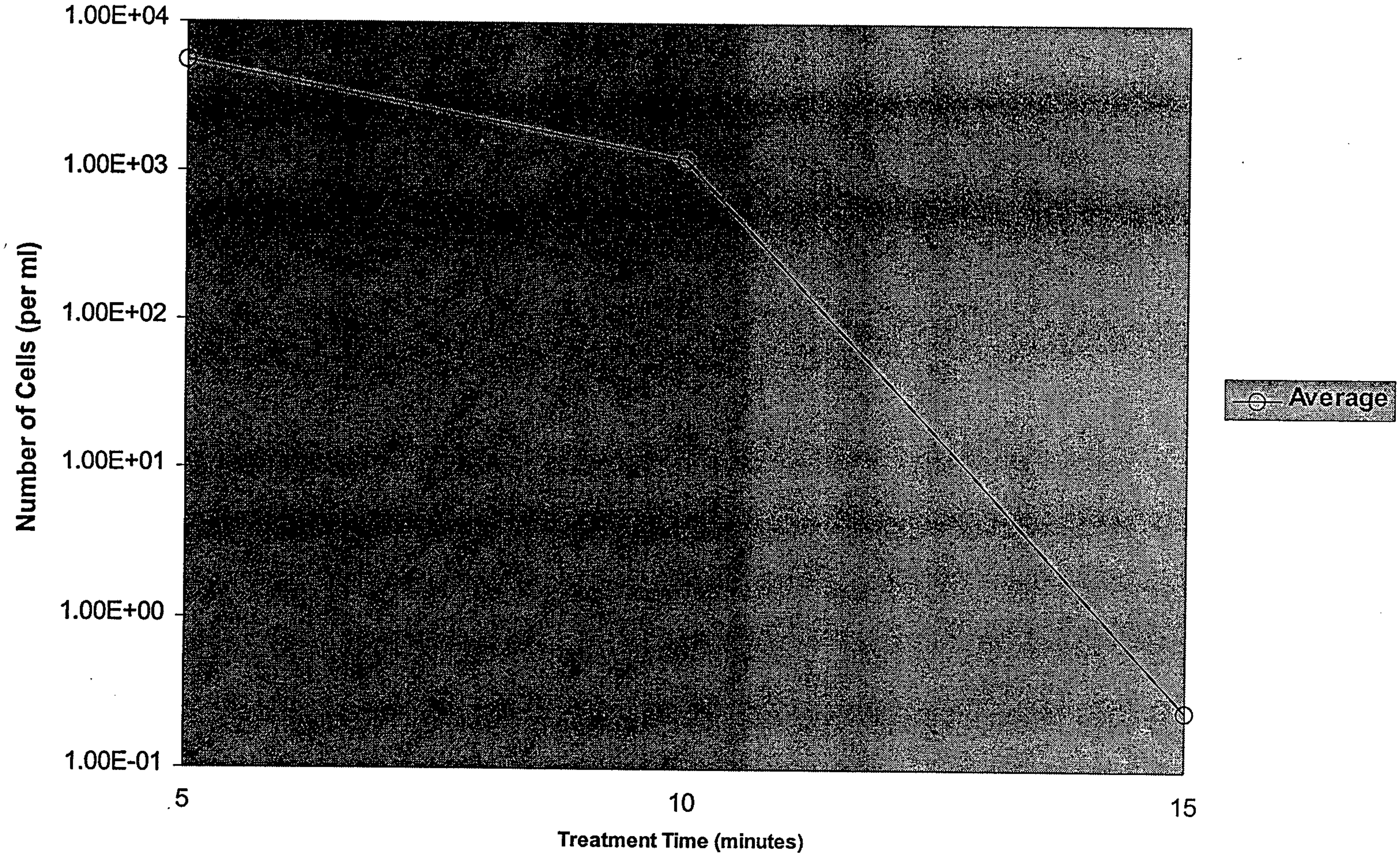
Average Number of Cells/ml for 2 Pseudomonas Aeruginosa Samples



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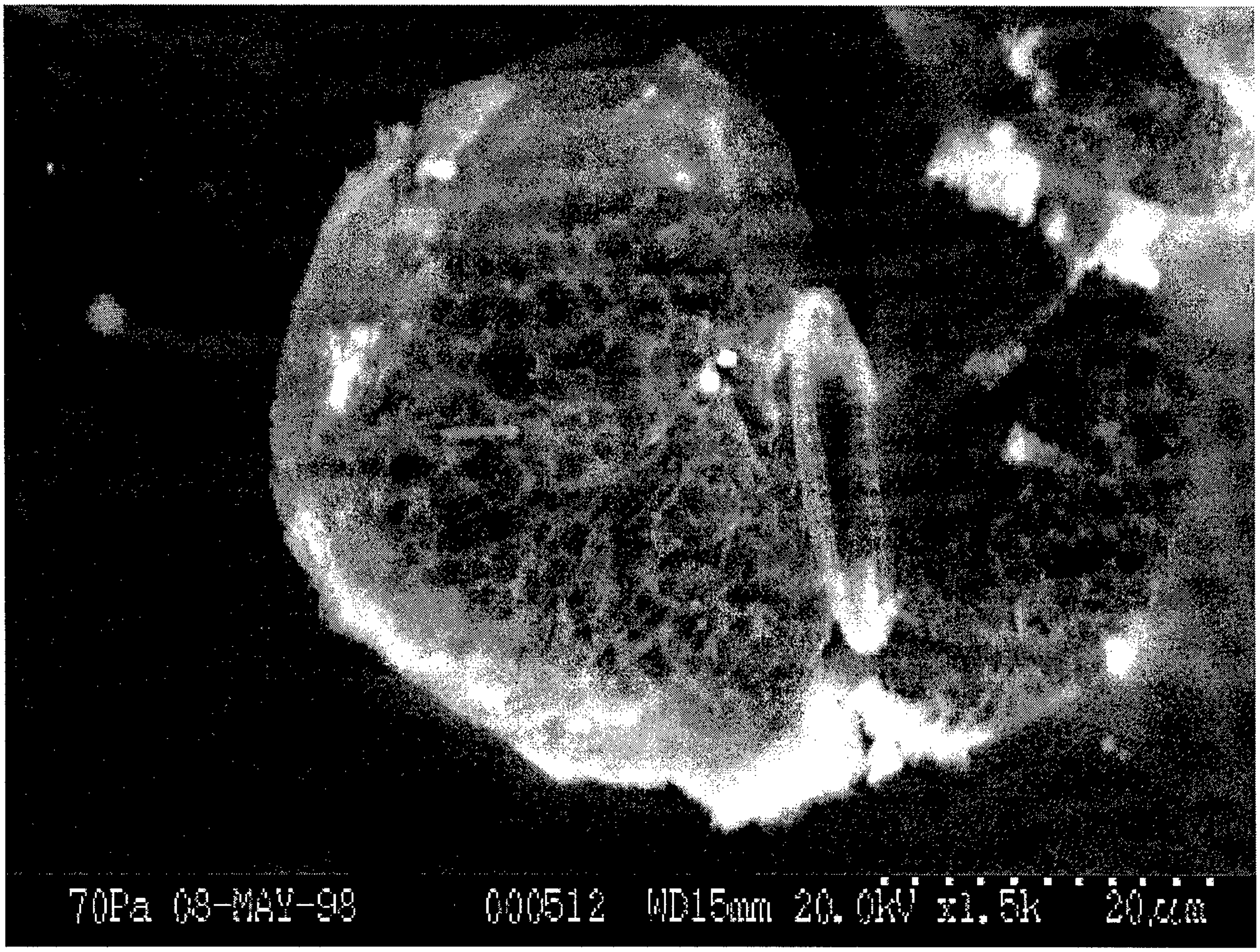
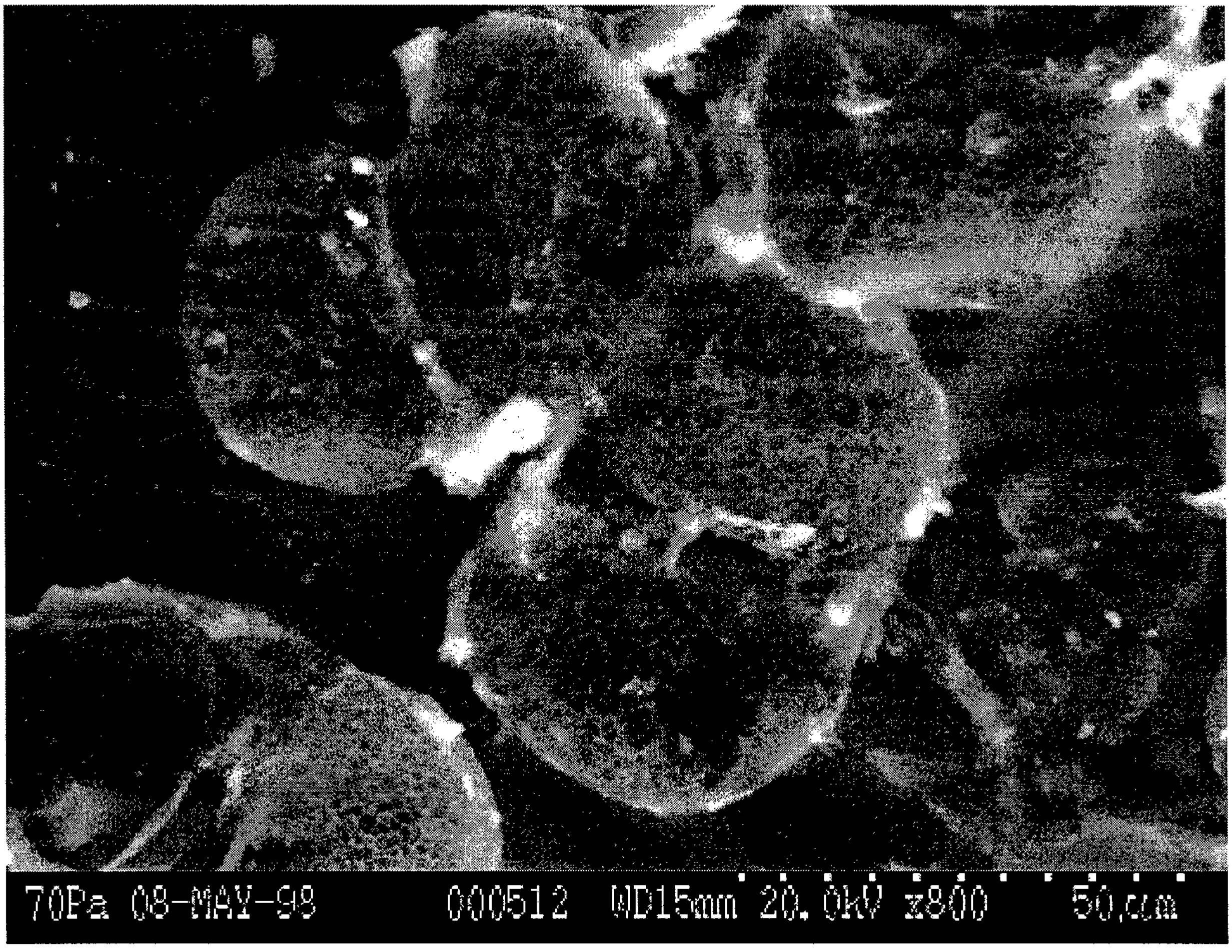
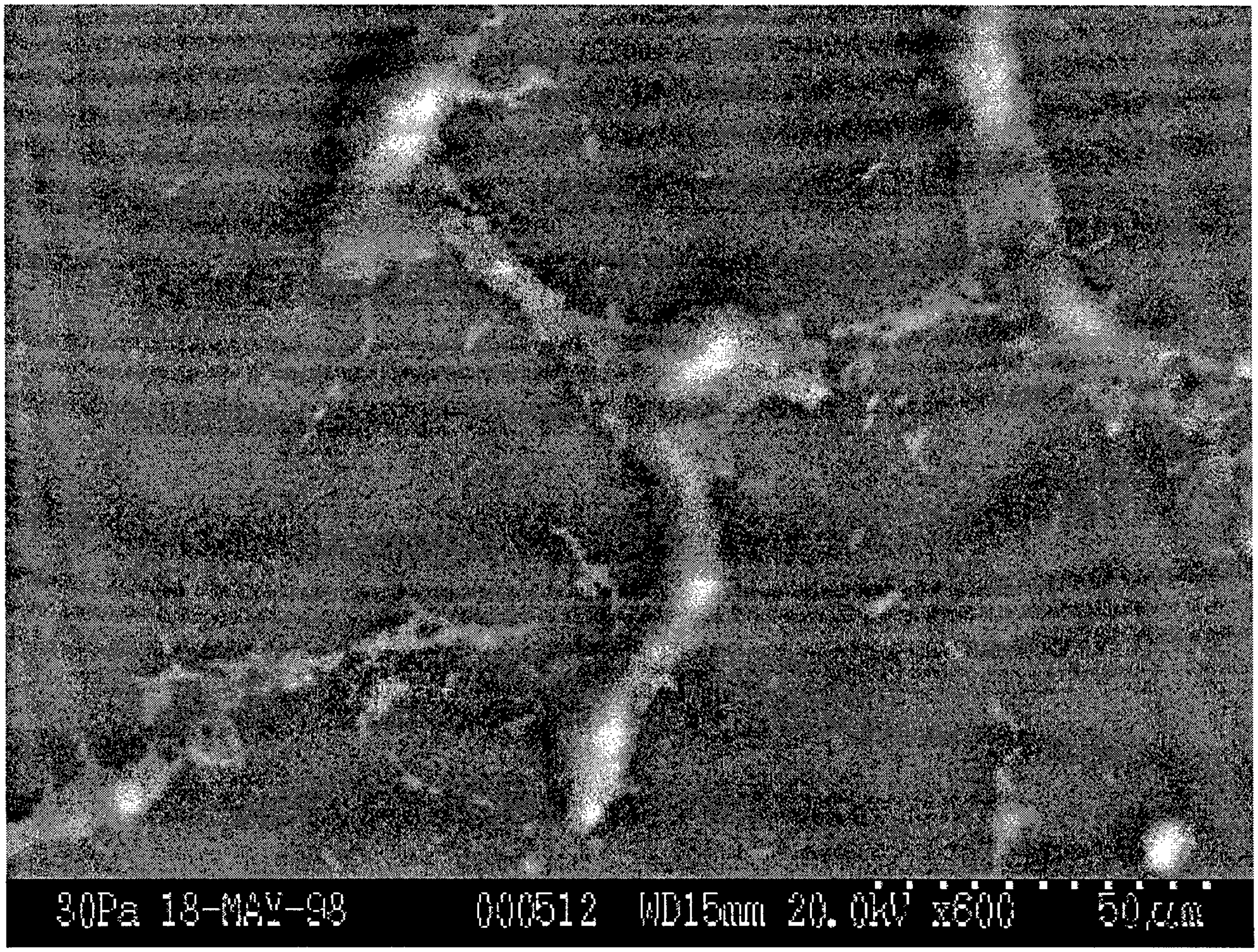
General Thermal Inc.



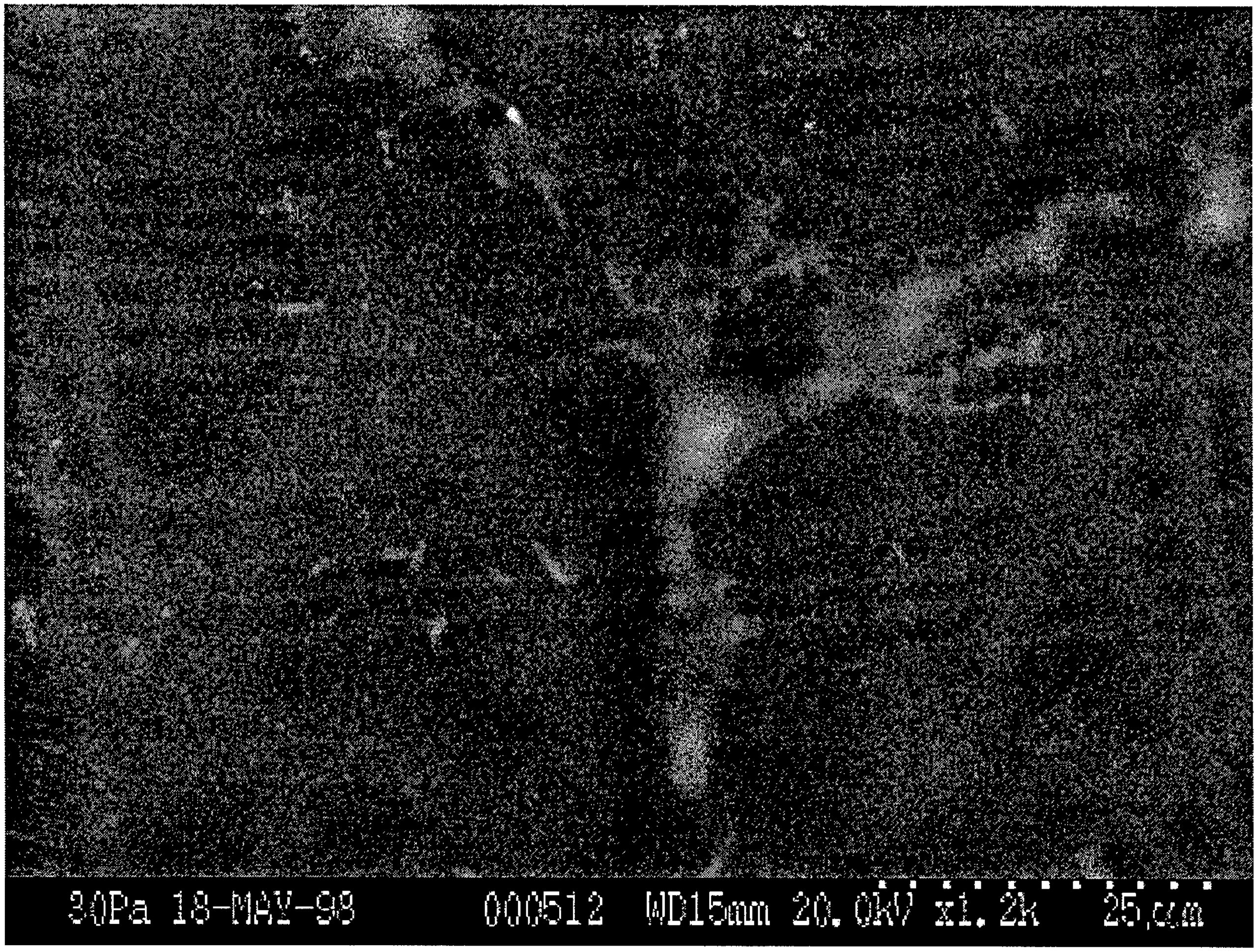
Untreated control sample showing E. coli bacterium undergoing cell division.



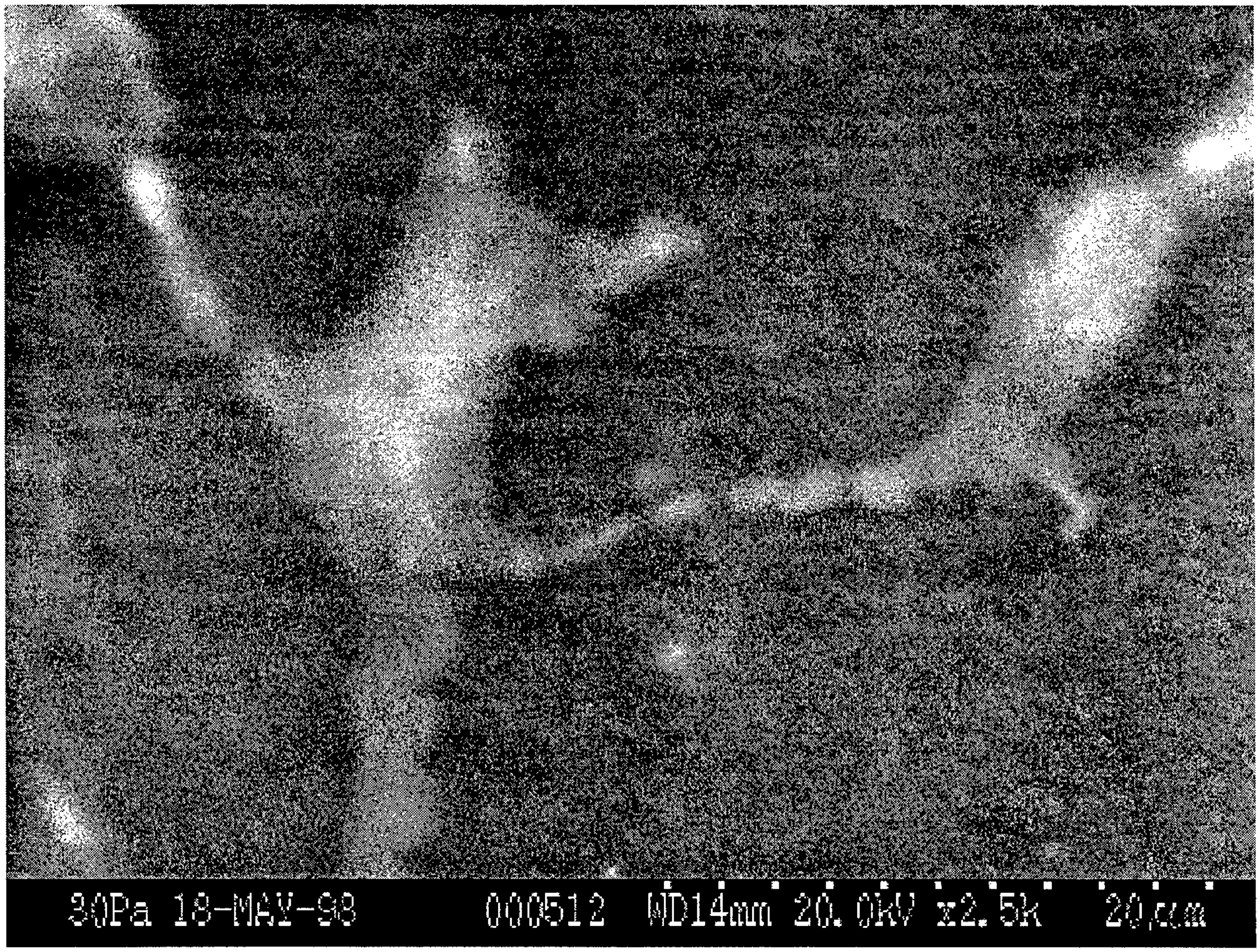
Untreated control sample showing E. coli bateria.



E. coli bacteria after 30 seconds of plasma exposure.



E. coli bacteria after 1 minute of plasma exposure.



E. coli bacteria after 2 minutes of plasma exposure.

POTENTIAL APPLICATIONS

Ongoing research on the decontamination/sterilization by the Glow Discharge at Atmospheric Pressure shows that this method can be efficient, practical, and environmentally friendly. The potential applications of this novel method are numerous.

- **Medical Applications:**
  - Sterilize re-usable medical tools.
  - Sterilize hospitals infectious waste before disposal.
  - Sterilize pharmaceutical products.

- **General Laboratory Applications:**
  - Sterilize various equipment used in labs (biology,----).
  - Sterilize various media used in biology experiments.
  - Use in conjunction with other sterilization methods.
  - Sterilize media without damage. These media will then be used to grow only one specific microbial culture.

- **Environmental Applications:**
  - **Remediation of soil and water.**
  - **Kill harmful micro-organisms without damaging the media (soil, food, liquids,----).**
- **Food Industry:**
  - **Sterilize foods without leaving harmful residues.**
  - **Sterilize food packages for longer shelf life.**
- **Military Applications:**
  - **Decontamination of equipment, supplies, and gear exposed to biological warfare agents.**

Appendix C

Media Coverage

The DAILY BEACON

NIVERSITY OF TENNESSEE, KNOXVILLE

Tuesday, June 25, 1996

© 199

Professors dominate electrical engineering awards

TEVIS SMITH
Daily Beacon Staff Writer

Five UT professors recently swept the Hall of Fame Awards in Atlanta as electrical engineering faculty members brought home five out of eight Advanced Technology Awards at the 35th International Hall of Fame Awards Banquet.

"It is an honor for the electrical engineering department to receive the awards by so many of the professors in their department," said Leanne Ellis, contract coordinator for the laboratory for information technology.

According to a press release, these professors received the following awards:

•Mounir Laroussi, research assistant professor-the award for his innovative work on using plasma at atmospheric pressure for sterilization applications.

•Douglas Birdwell and Roger D. Horn-the award for "Methods and Apparatus Using a Decision Tree in an Adjunct System Cooperating with Another Physical System."

•Paul Crilly-the award for "Method for Analyzing Chromotograms."

•Mark Rader-the award for "Plasma Processing Equipment," according to the press release.

"This is the first year we have had so many awards from the same organization, and this is quite an accomplishment from our faculty members," said Rafael C. Gonzales, professor and head of electrical engineering. "It is well-deserved recognition for work done over a decade."

It takes years to bring an invention to its final stages, Gonzales said.

Laroussi said his research involved the use of a special kind of plasma for a sterilization process.

He defines plasma as a fourth state of matter that comprises 99 percent of the universe and consists of electrons and ions.

Although plasma has been known since the 1960s as an agent for sterilization, Laroussi's research allows it to be generated at atmospheric pressure. Some applications of use would be for sterilization of infectious waste, food and medical tools. For example the current method of incineration of infectious waste produces undesirable environmental effects. The use of plasma would be more environmentally friendly, he said.

Another example would be food. His process would allow sterilization without damage to the food. Medical tools also could be sterilized without the heat and pressure of the autoclave process.

BRIDGE TO THE FUTURE

ENGINEERING News

VOLUME 7, NUMBER 2

THE UNIVERSITY OF TENNESSEE, KNOXVILLE/COLLEGE OF ENGINEERING/SUMMER 1996

* ELECTRICAL & COMPUTER ENGINEERING

Ralph Gonzalez
Head

Five Electrical Engineering faculty members received awards at the 35th International Hall of Fame awards banquet in Atlanta, Ga., on May 11, 1996. *Dr. Paul Crilly* was selected to receive an advanced technology award for his work with the "Method for Analyzing Chromatograms."

Dr. Doug Birdwell and *Dr. Roger Horn* were also selected to receive an advanced technology award for their-work on the patented "Method and Apparatus Using a Decision Tree in an Adjunct System Cooperating with Another Physical System."

Dr. Mounir Laroussi, research assistant professor, received an advanced technology award for "Sterilization Apparatus Using Plasma at Atmospheric Pressure." This apparatus is capable of killing microorganisms in a time range from a few seconds to a few minutes. It uses a glow discharge at atmospheric pressure, generated by an R.F. source between two insulated electrodes. This new sterilization method is more practical, faster, and environmentally friendly as compared to traditional methods like autoclaving and incineration.

Dr. Mark Rader received a New Product Award for "Plasma Processing Equipment Book".

The sponsoring organization was the Inventors Club of America, Inc.

*

Tim Powell, a graduate student in *Dr. Don Bouldin's* research group, won first place in the Mentor Graphics PCB/MCM design contest. Powell used the Mentor toolset to design a multi-chip module that has been fabricated by MicroModule Systems in California. He also published a conference paper on the design which was the basis for his M.S. thesis.

*

Dr. Bimal K. Bose was honored in June by the Institute of Electrical and Electronics Engineers (IEEE). Bose received the IEEE Lamme Medal for his contribution to the advancement of power electronics and electrical machine drives. The award, which includes a gold medal, $10,000, a bronze replica and a certificate is sponsored by the IEEE Foundation and the Westinghouse Foundation. Bose is an IEEE Life Fellow. IEEE is the world's largest technical professional society.

Inventors Clubs of America
1996
International Hall of Fame

ADVANCED TECHNOLOGY AWARD

for

STERILIZATION APPARATUS USING PLASMA AT ATMOSPHERIC PRESSURE

Mounir Laroussi

University of Tennessee

Presented May 11, 1996
Atlanta, Georgia, U.S.A.

Alexander Marinaccio
Chairman of the Board
The Inventors Clubs of America

Enabling each member's capacity to respond to the rapid changes in the way the world now works is a special responsibility for IEEE. Intelligence is increasingly distributed, accessible anywhere, and malleable for different needs. Engineers can either be diminished by this or learn to work smarter to augment their capacity to learn and create - informed intelligence reaps reward. IEEE must help its members to creatively transform themselves continuously to enjoy rewarded as well as rewarding careers. This responsibility can be led well by a president with engineering leadership experience in the entities which collectively enable the innovation process - industry, academe, government - integrated with career-long activity as an IEEE volunteer. I hope you may see these qualities in my candidacy and offer me a chance to serve you.

ADVANCED TECHNOLOGY AWARD

Mounir Laroussi

Dr. Mounir Laroussi, a Research Assistant Professor, at the Plasma Science Laboratory of the Electrical Engineering Department of the University of Tennessee has received an Advanced Technology Award from the Inventors Clubs of America, for his work on a new sterilization technique which uses a one atmosphere glow discharge plasma. The award was given at the International Hall of Fame annual banquet, held in Atlanta, GA, in early May.

Dr. Laroussi has successfully demonstrated that a glow discharge generated by a low frequency R.F. source, at atmospheric pressure, is a very effective means to sterilize contaminated matter and objects. Early tests showed that the treatment time is much shorter than that of other conventional methods such as autoclaving. Also, this new technique is environmentally friendly, and very practical, since it doesn't involve a heating system, a pressurized system,or a vacuum system.

Dr. Laroussi's research interests include the interaction of microwaves with plasmas, and the industrial applications of plasma. Under AFOSR sponsorshiphe developped a novel tunable notch absorber microwave filter, and was a co-inventor of an apparatus capable of generating a glow discharge at atmospheric pressure which can be used in various industrial processes. He also did theoretical and experimental work on the transient sheath during plasma ion implantation. Dr. Laroussi is a member of IEEE NPSS, and of Sigma-Xi.

Mounir Laroussi, who studied under Igor Alexeff (well known to NPSS members and currently an elected Ad Com member) can be reached at the University of Tennessee, Knoxville, TN 37996; Phone: ~~(615)~~ 974-~~6223~~; E-mail ~~mlarous@uthkux.utk.edu~~ 423 5866
mlarouss@utk.edu

1997 EDWARD TELLER MEDAL NOMINATIONS REQUESTED

The Advisory Board of the international workshop series, Laser Interaction and Related Plasma Phenomena, with the kind permission of Professor Edward Teller, requests nominations for the 1997 Edward Teller Medal. This medal is given "in recognition of pioneering research and leadership in the use of laser and ion-particle beams to produce unique high-density matter for scientific research and for controlled thermonuclear fusion." It will be awarded at the workshop, to be held in Monterey, California, April 13-18, 1997. Prior recipients of the medal include Nikolai G. Basov, Lebedev Physical Institute of the Russian Academy of Sciences (Russia); Michael Campbell, Lawrence Livermore National Laboratory (USA); Robert Dautray, Commissariat l'Energie Atomique (France); Heinrich Hora, University of New South Wales (Australia); Gennady Kirillov, Arzamas-16 (Russia); John Lindl, Lawrence Livermore National Laboratory (USA); Robert McCrory, University of Rochester (USA); George Miley, University of Illinois (USA); Sadao Nakai, Institute of Laser Engineering (Japan); John Nuckolls, Lawrence Livermore National Laboratory (USA); and Chiyoe Yamanaka, Institute of Laser Technology (Japan).

Nominations should contain the name and address of the nominee, a brief curriculum vitae, and a one-page narrative of the nominee's key achievements in relevant fields. In order to permit the committee full consideration of each nomination, the deadline for submissions is October 1, 1996. Further details are available from Lawrence Livermore National Laboratory, telephone: (510) 422-5435; facsimile: (2170 333-2906; and e-mail: nuckolls2@llnl.gov.

Please direct nominations to: John H. Nuckolls, Chair Selection Committee, 1997 Teller Medal, Lawrence Livermore National Laboratory, P.O. Box 808, L-1, Livermore, California 94550

ENGINEERING NEWS
THE UNIVERSITY OF TENNESSEE, KNOXVILLE • COLLEGE OF ENGINEERING
VOLUME 9, NUMBER 1, FALL 1997

Dr. Mounir Laroussi was awarded an STTR contract from the Air Force Office of Scientific Research to develop a Decontamination/Sterilization process which uses Atmospheric Pressure Glow Discharges. The research work involves the collaboration of an East Tennessee company, the University of Tennessee Center for Environmental Biotechnology, and the Microwave & Plasma Laboratory of the EE Dept.

Dr. Laroussi was also recently elected as a senior member of the Institute of Electrical and Electronics Engineers. He is among less than 10 percent of the membership to achieve that level of professional recognition.

HEALTH FITNESS & SCIENCE

The Knoxville News-Sentinel

From battlefield to kitchen

Engineering group collaborates on experimental sterilization device

FOCUS ON SCIENCE

By Wynne Brown
News-Sentinel staff writer

A friendship forged in a University of Tennessee dormitory could eventually lead to safer food for all.

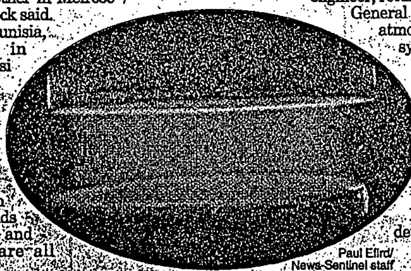
Mounir Laroussi and Battle Glascock were both students at UT in the early '80s.

"We lived next door to each other in Melrose Hall and became buddies," Glascock said.

Laroussi was a student from Tunisia, and Glascock grew up in Chattanooga. Since then, Laroussi has received a doctorate degree in electrical engineering and works in the Microwave and Plasma Laboratory at UT.

Plasma, for those who've forgotten high school physics or are only familiar with blood plasma, is considered the fourth state of matter, after solids, liquids and gas. Lightning, neon signs and the crackle of static cling are all examples of plasma.

"Ninety-nine percent of the universe is made up of plasma, and we need to find ways to use it beneficially," Laroussi explained.



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An experimental ionized gas device at the University of Tennessee is being developed as a way to kill biological warfare pathogens and sterilize medical equipment.

There are some beneficial applications for plasmas, but they all require either huge and expensive apparatus or a great deal of heat, as in arc welding, he said.

During the years since the two were students, Glascock, now a mechanical engineer, returned to Chattanooga and started General Thermal Inc., a firm that builds atmospherically controlled chambers and systems for industry. "Everything you can imagine requires controlled atmospheres," Glascock said, and he listed candy makers and battery manufacturers as examples.

A year ago, the United States Air Force entered the lives of Glascock and Laroussi.

"With all the germ warfare and biological threats, the Department of Defense became interested in developing a novel method to deal with harmful pathogens," Laroussi said. What they were looking for was a simpler, cheaper, portable sterilization device – one that could

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be used on the battlefield, such as a medivac situation.

From there came the idea of a battery-operated, portable unit that could use cold plasmas to sterilize contaminated items – without melting them.

As the ions interact with the electric field in a plasma, some are converted into light, and free radicals (a reactive group of atoms) are generated.

"The combination of free radicals and ultraviolet light interacts with microorganisms and destroys them," Laroussi explained. "The process is clean. Right now ethylene oxide is used to clean medical equipment. It's a very toxic substance. It leaves a residue and takes more than an hour" to sterilize equipment.

Gary Sayler, professor of microbiology at UT, said his lab is helping evaluate the prototype.

Betsy Pearce is a doctoral student in Sayler's lab, and her role is to grow bacteria, expose them to a contaminant, put them in the prototype and then monitor the percentage loss.

They started with *E. coli*, the standard experimental bacteria.

"If you can't get it to kill *E. coli*, then there's really no point," she said.

Once the team proved that *E. coli* could be killed, the team moved on to a hardier organism, *Pseudomonas aeroginosa*.

"This is the same organism that's involved in cystic fibrosis. It even grows on soap – that's why I don't use bar soap," Pearce said. The process killed those bacteria as well.

The next step will be to test members of the Bacillus group – part of the family of organisms that can cause anthrax, she said.

The technique is still very much in the experimental stage, but there are many potential environmental uses for plasma-based technology, Sayler said.

"In a broader sense, it could be used for softening up some kinds of more toxic chemicals" as in oil spills or PCBs, he said.

"Now we're using UV light make these substances easier to degrade. It's costly and not particularly efficient."

But Glascock and Laroussi have ideas beyond either ecological or military applications for this process.

"We're more interested in applying the technique to liquids – apple juice, milk, maybe orange juice – other liquids for human consumption," Glascock said. Possibilities include replacing the pasteurization process in milk or purifying the water in the wash-down facilities in fruit processing plants.

Another application would be food packaging, Glascock said. If any microorganisms in the food were killed before packaging, the food would have a much longer shelf life.

"It's the same as it must have felt working in Jim Watson and Francis Crick's (the discoverers of DNA and the genetic code) lab – it's new, it's real exciting to discuss and to ponder all the possibilities," said Glascock.

"It's a lot of fun."

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University of Tennessee microbiology doctoral student Betsy Pearce, General Thermal Inc. president Battle Glascock and professor Mounir Laroussi pose with a prototype of an ionized gas sterilization device at the University of Tennessee's Microwave and Plasma Laboratory.